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Advantages of Using a Mirror as the First Optical Component for APS Undulator Beamlines

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Abstract

The advantages of using a mirror as the first optical component for an APS undulator beamline for thermal management, radiation shielding mitigation, and harmonic rejection are presented.

Introduction

X-ray mirrors have been widely used in synchrotron x-ray beamlines for a broad range of applications, such as beam separation, focusing, harmonic rejection, and power filtering.[1-5] In the Sector 2 insertion-device (ID) beamlines Synchrotron Radiation Instrumentation Collaborative Access Team (SRI-CAT) at the Advanced Photon Source, an x-ray mirror with three stripes of different coating materials is used to achieve the following advantages. First, the peak radiation heat flux and total power on the downstream optical components are substantially reduced, thus the thermal design for those components are significantly simplified. For example, a water-cooled first crystal in a conventional symmetric double crystal monochromator (DCM) geometry can be used. Second, the radiation shielding requirement is substantially reduced to a level similar to that required for a beam monochromatized by a crystal.[5] As a consequence, the layout of the optical components downstream of the mirror can be optimally arranged to achieve the designed goals without additional shielding and thus to reduce the related construction cost and maintenance effort. For example, undulator radiation in the 0.5-32 keV spectral range can be delivered to the experimental stations with shielding requirements similar to those for a monochromatic beam, and a DCM with a small offset between the incident and diffracted beam can be used as a quasi-channel-cut monochromator with small displacement of the diffracted beam for energy scan. Third, the high order harmonics of the undulator radiation is significantly suppressed when an appropriate mirror coating is selected. This suppression is particularly important for high energy storage rings like the Advanced Photon Source (APS) and high quality insertion devices with small magnetic errors.

In addition, horizontal deflection was selected for the following three reasons: (1) preservation of the source brilliance and the beam coherence in the vertical direction, this is because the horizontal divergence of the undulator radiation in the horizontal direction is typically much larger than that in the vertical direction and the mirror tangential slope errors are dominantly responsible to the degradation of beam brilliance, (2) reduction in gravity-induced slope errors because the gravity-induced sagging is parallel to the reflecting surface, and (3) maintenance of the standard beam height facilitating utilization of standard beamline components and subsequent survey and alignment. In this paper, the advantages of using a mirror as the first optical component are discussed and presented in detail using the SRI-CAT Sector 2 ID beamline as an example. Unless otherwise stated, the energy of the stored positron beam is assumed to be 7 GeV and the current to be 100 mA.

Brief Description of SRI-CAT Sector 2 Beamline Layout and The first Mirror

The SRI-CAT Sector 2 insertion-device beamline consists of three branch lines sharing the same straight section of the storage ring, front end, first optical enclosure, and the first horizontally deflecting mirror (M1), located about 31 m from the undulator. Two of the branchlines are designed to use soft x-rays energies down to 500 eV, so no vacuum window is used between the storage ring vacuum chamber and the mirror.

The grazing incidence angle of x-rays on the mirror is 0.15^o, which was selected to obtain high reflectivity for x-rays with energies up to 32 keV (see Fig. 1), and to produce an adequate offset for the reflected beam at the exit wall of the first optic enclosure to separate it from the bremsstrahlung radiation. A fixed mask is used to reduce the maximum total power incident on the mirror to 1.4 kW from the 3.8 kW total power of the APS standard Undulator A at a closed gap of 11.5 mm. The peak heat flux incident on the mirror surface is 0.36 W/mm^2. Because this grazing angle is much smaller than that for a typical crystal monochromator, the surface heat flux on the mirror surface is substantially smaller than that on the surface of a first crystal monochromator used as the first optical component. Therefore, the thermal loading problem is easier to solve for a mirror than for a crystal monochromator. In addition, a broader range of materials with favorable thermal and mechanical properties may be used for the mirror because crystalinity of the substrate is not required.

We have completed two cooling designs of the mirror that will meet our specifications in terms of surface slope errors and surface roughness requirements under the anticipated thermal loading conditions. The first design is an internally cooled Si substrate with three parallel reflecting surfaces, one being the polished Si surface and the other two being stripes of Rh and Pt. The mirror is 120 cm (L) x 9 cm (W) x 12 cm (D). This mirror has been designed, and procured. In order to be in compliance with the APS vacuum policy which forbids direct vacuum-to-water joints in a windowless beamline, a vacuum guard has been designed and machined in the mirror. The expected root mean square (rms) surface slope error under thermal loading conditions is estimated to be 2 μrad and 30 μrad in the tangential and saggital directions, respectively. The expected rms surface roughness is 3Å. The vacuum and mechanical systems for this mirror have been designed and are currently being manufactured.

Because of inherent complexity in the manufacturing of the internally cooling mirrors and fragile nature of Si material, the reliability of the vacuum guard on the mirror is of some concern. As a fallback, we have designed a second mirror consisting of a Si substrate with side contact cooling, which is presented in a separate paper in this session. Apart from the cooling method, all other parameters of the mirror are very similar to those of the internally cooled mirror. The mirror is expected to be delivered in early 1996.

Advantages of Using a Mirror as the First Optical Component

The x-ray mirror in the SRI-CAT Sector 2 ID beamline is used to obtain the following three main advantages. First, a substantial reduction in the peak radiation heat flux and total power is obtained on the downstream optics such as crystal monochromator, photon shutter, slit aperture, and other critical components.. For example, we have designed a water cooled crystal without using of the inclined geometry, cryogenic cooling, asymmetric crystal cut, or diamond crystal as the first crystal for our double crystal monochromator. Second, a significant reduction in radiation shielding requirement for the downstream beamline because of suppression of high energy x-rays in the reflected beam and the separation of the undulator radiation from the bremsstrahlung. For example, undulator radiation in the 0.5-32 keV spectral range can be delivered to the experimental stations with shielding requirements similar to those for a monochromatic beam, and a small offset between the incident and diffracted beam of the double crystal monochromator (DCM) can be used. This will allow the DCM to be used as a quasi-channel-cut monochromator with negligible displacement of the diffracted beam. Third, significant suppression of unwanted higher-order undulator harmonics for a mirror/monochromator combination. Finally, the first mirror can be used at a later date for focusing or collimation purpose. In the following sections, those three advantages are discussed in detail.

Reduction in Thermal Load to Downstream Optics

The peak power density of the raw Undulator A spectrum as a function of the undulator gap is shown in Fig. 2. Also shown in the figure are the power densities of the undulator spectrum integrated over the three energy bands indicated. It is clear from the figure that a substantial reduction in the peak power density can be obtained by using a mirror to filter out the high energy part of the raw undulator spectrum. Because the reflectivity of a mirror is small for x-rays of energies greater than the cut-off energy at a given incidence angle, the power densities calculated for the three energy bands in Fig. 2 can be approximated as the power densities of the Undulator A spectrum reflected by the three mirror coatings. Note that a power density reduction of about 10 is obtained at a undulator gap of 11.5 mm when using a mirror with a cut-off energy of 10 keV.

Similarly, the total power reflected by the mirror is also reduced. Fig. 3 shows the total power of the raw undulator A spectrum as a function of the undulator gap size. Also shown in the figure are the total powers of the spectrum integrated over the four energy-integration bands. The reduction of the total power reflected by the mirror also reduces the total power load on the downstream optical components, and, thus, the design of those components can be simpler. The maximum peak power density and the total power incident on the mirror surface and reflected from the three different mirror coatings are listed in Table I.

Table I Peak Power Density and Total Power before and after the Mirror for Undulator A with a Gap of 11.5 mm

	Total Power	Peak Power Density
Undulator A (11.5 mm Gap)	3.8 kW	133 kW/mrad^2
After Fixed Aperture	1.8 kW	133 kW/mrad^2
Incident on M1	1.26 kW	0.32 W/mm^2 @ 0.15°
Reflected from M1*:		
Si-coated	255 W (78W)	23 kW/mrad^2
Rh-coated	540 W (163W)	47 kW/mrad^2
Pt-coated	627 W (190W)	55 kW/mrad^2

* The number in parenthesis of the total power column are calculated for a central cone of Undulator A containing 4σ in both horizontal and vertical directions.

Because of the heat flux and power reduction in the reflected beam, the thermal loading problem for subsequent optical elements such as a DCM is significantly reduced. The reduction of radiation shielding also allows us to use the standard beam transport sections for monochromatic beyond the FOE allowing a DCM to be placed at a large distance from the source. For a DCM located 65 meters from the undulator source, which is the case for one of our branch lines, the calculated heat flux incident on the first crystal of a Si DCM tuned for (111) Bragg reflection is shown in Fig. 4. Note that when the appropriate mirror coating is used, the maximum heat flux ever on the first crystal is less than 2 W/mm^2. For this level of heat flux, it will be possible to use a simple cooling geometry for the first crystal to obtain a thermally-induced slope error of a few microradians (reference).

The reduction in peak power density and total power also eases the design of other downstream optical and non-optical components to deal with thermal loading problems, such as photon shutters, beam defining apertures, and multilayer monochromators.

Reduction in Radiation Shielding of the Downstream Beamline of the Mirror

Radiation shielding is one of the most important aspects in the design of a synchrotron beamline for high-energy storage rings, such as the APS. The radiation shielding for an APS insertion-device beamline using a mirror as the first optical element requires fairly complicated analysis and a brief summary of the results and conclusions are given here.

In the first optical enclosure, the bremsstrahlung is separated from the reflected synchrotron beam by the mirror M1 and is subsequently stopped by a tungsten stop. Downstream of the first optical enclosure, the radiation shielding for the beamline transport is determined mainly by the high energy synchrotron radiation. Because of the low reflectivity of the mirror for x-rays with energies greater than 32 keV (see Fig. 5), the amount of shielding required for the reflected wide-band beam is similar to that for a beam monochromatized by a typical double-crystal Si monochromator without the presence of a mirror.

The reduction of radiation shielding allows one to obtain following three benefits: (1) The use of the mirror allows us to deliver the undulator beam containing nearly all x-rays in 0-32 keV spectral range to the experimental stations with the radiation shielding requirements similar to those for a monochromatic beamline; (2) the DCM can be located far away from the undulator source and thus the heat flux on the surface of the first crystal is reduced and a water-cooled first crystal can be used; and (3) the separation of the synchrotron radiation from Bremmsstrhalung allows one to use the DCM with a small offset between the incident and diffracted beams for quick energy scan with small beam displacement.

Harmonic Rejection

At a grazing incidence angle of 0.15^{o}, the high energy cut-offs of the three reflecting surfaces are about 12 keV for Si, 24 keV for Rh, and 32 keV for Pt. Therefore, suppression of unwanted higher-order harmonics of the undulator radiation can be obtained by properly selecting an appropriate reflecting surface over the 6-32 keV undulator spectral range.

Consideration on Source Brilliance and Coherence Preservation

Horizontal deflection of the synchrotron beam by the mirror is used to preserve the high brilliance of the undulator beam. The brilliance is preserved due to two reasons. First, for a given mirror slope error, the relative reduction in the beam brilliance for undulator radiation at the third generation synchrotron source is less compared to that when the beam is deflected in the vertical direction. This is because the beam divergence in the horizontal direction is generally larger than that in the vertical direction. For example, the FWHM beam divergence of the standard undulator A radiation at the APS in the horizontal direction is about 2.5 times that in the vertical direction for 10% coupling between the vertical and horizontal beam emittance. For smaller coupling value, this number is even bigger. In addition, because the increase in rms divergence of the reflected beam in the tangential direction is approximately 4 times the rms tangential slope error of the mirror and is approximately equal to $\omega \sin\theta$ in the saggital direction, where ω is the mirror rms saggital slope error and θ the grazing incidence angle. We also expect the beam coherence in the vertical direction to be preserved. Second, the gravitational force is parallel to the mirror surface, thus gravity-induced sagging of the mirror will have only a small effect on the mirror surface figure in the tangential direction.

Conclusion and Discussion

In conclusion, use of a mirror as the first optical component for undulator beamlines results in several significant advantages. These include power filtering, reduction of radiation shielding requirements, and suppression of undulator high order harmonics. Power filtering greatly simplifies the thermal design of downstream optical components such as monochromators. A reduction in radiation shielding requirements enables more effective use of the undulator radiation and reduces the beamline design, construction, and maintenance cost. Harmonic suppression is particularly important for many experiments for using undulator radiation at the high energy third generation synchrotron sources (e.g., APS).

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References:

1. J B. Kortright, P. Plag, R. C. C. Perera, P. L. Cowan, D. W. Lindle, and B. KKarlin, Nucl. Instrum. Methods, A266, 452 (1988).

2. S. Sato. H. Maezawa, M. Yanagihara, E. Ishigura, S. Matsuo, Optical Engineering, 34, 377 (1995).

3. J. Susini, Optical Engineering, 34, 361 (1995).

4. M. R. Howells, Optical Engineering, 34, 410 (1995).

5. W. Yun, A. Khounsary, B. Lai, and E. Gluskin, "Use of a Mirror as the First Optical Component for an Undulator Beamline at the APS," ANL/APS/TB-2, 1992.

6. W. Yun, B. Lai, K. Randall, S. Davey, D. R. Haeffner, P. K. Job, and D. Shu, "Radiation Shielding of Insertion-Device Beamlines Using a Mirror as the First Optical Element," ANL/APS/TB-21, 1995 .

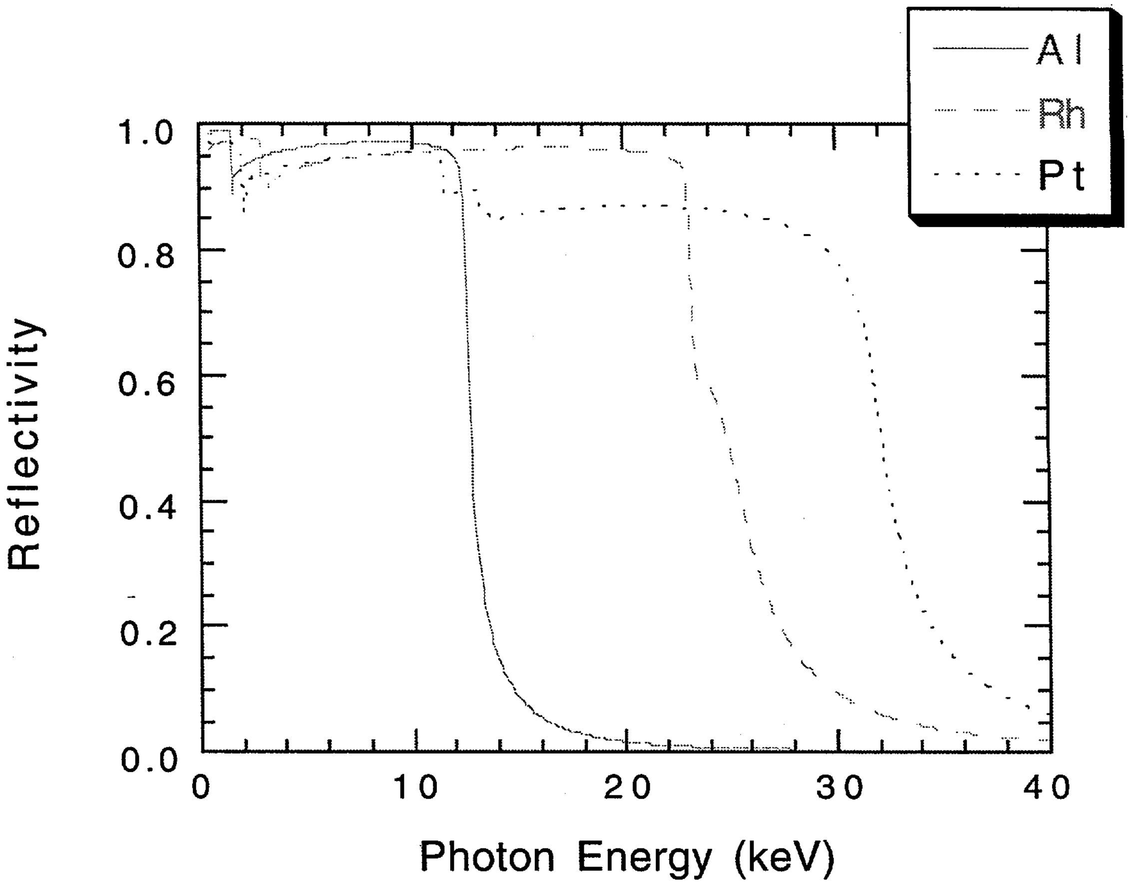

Fig. 1 X-ray reflectivity as a function of x-ray energy for Al, Rh, and Pt mirrors at 0.15 degree of incidence angle. Note the cut-off energy for the Pt mirror is about 32 keV.

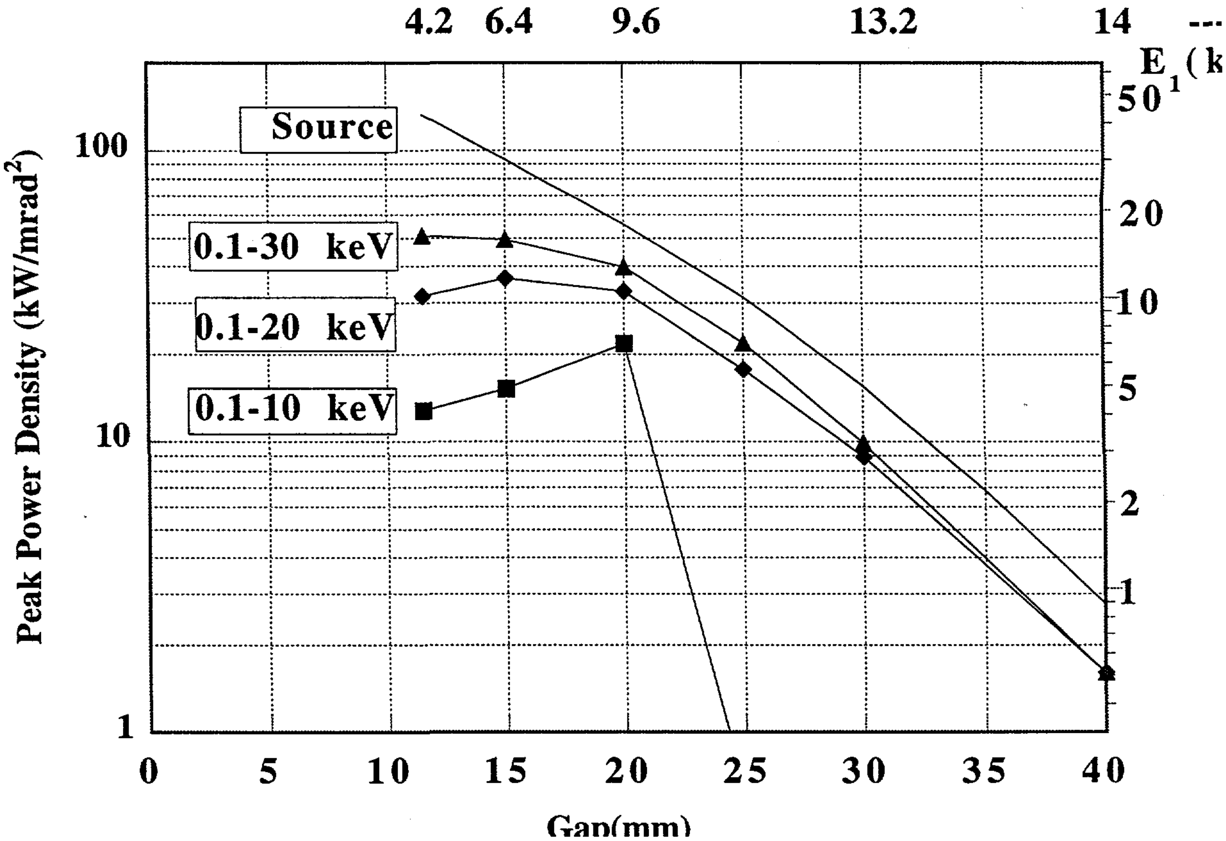

Fig. 2 Calculated peak power densities for the entire Undulator A spectrum as a function of undulator gap and for the three energy bands indicated. The first harmonic energy corresponding to the undulator gap is shown at the top.

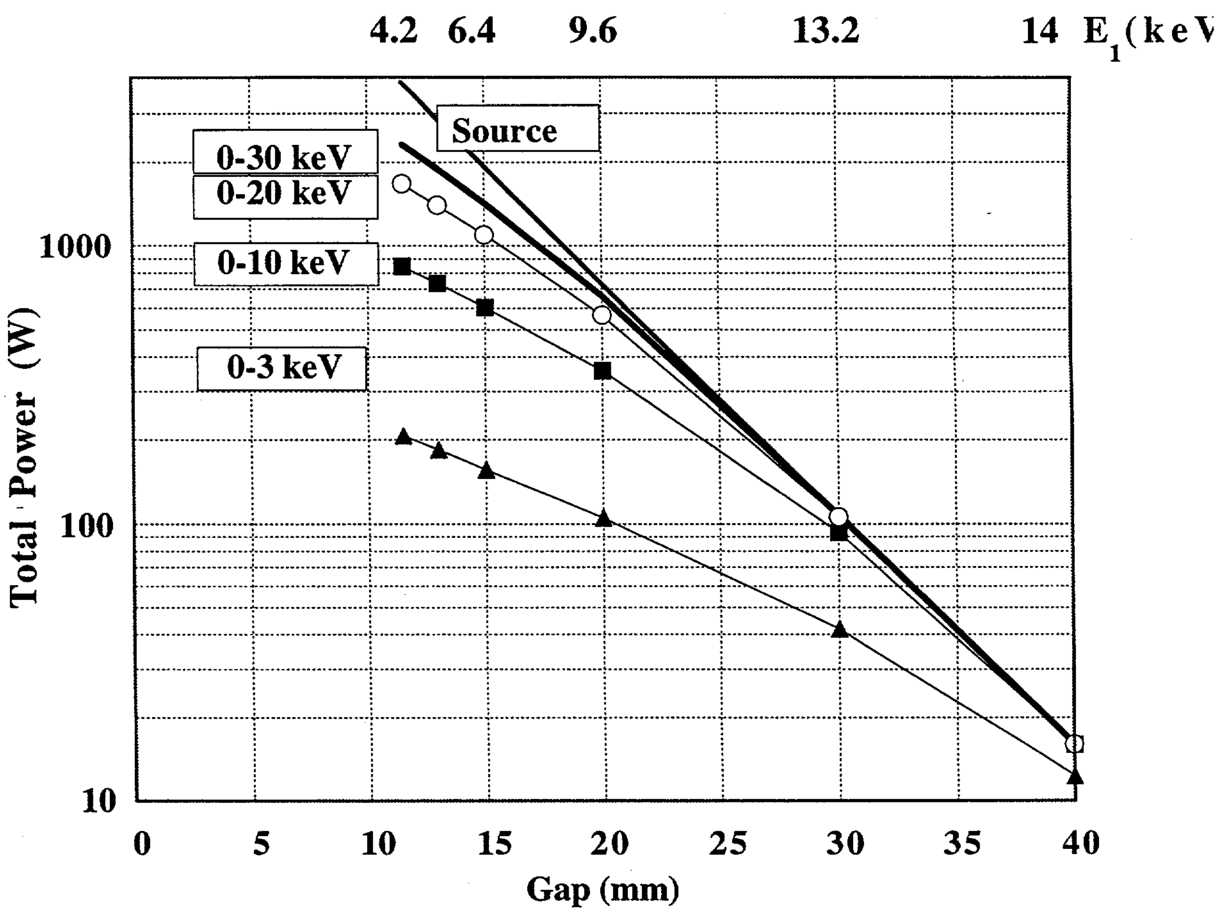

Fig. 3 Calculated total power of the entire Undualtor A spectrum and the total powers integrated over the four energy bands that are indicated in the Figure.

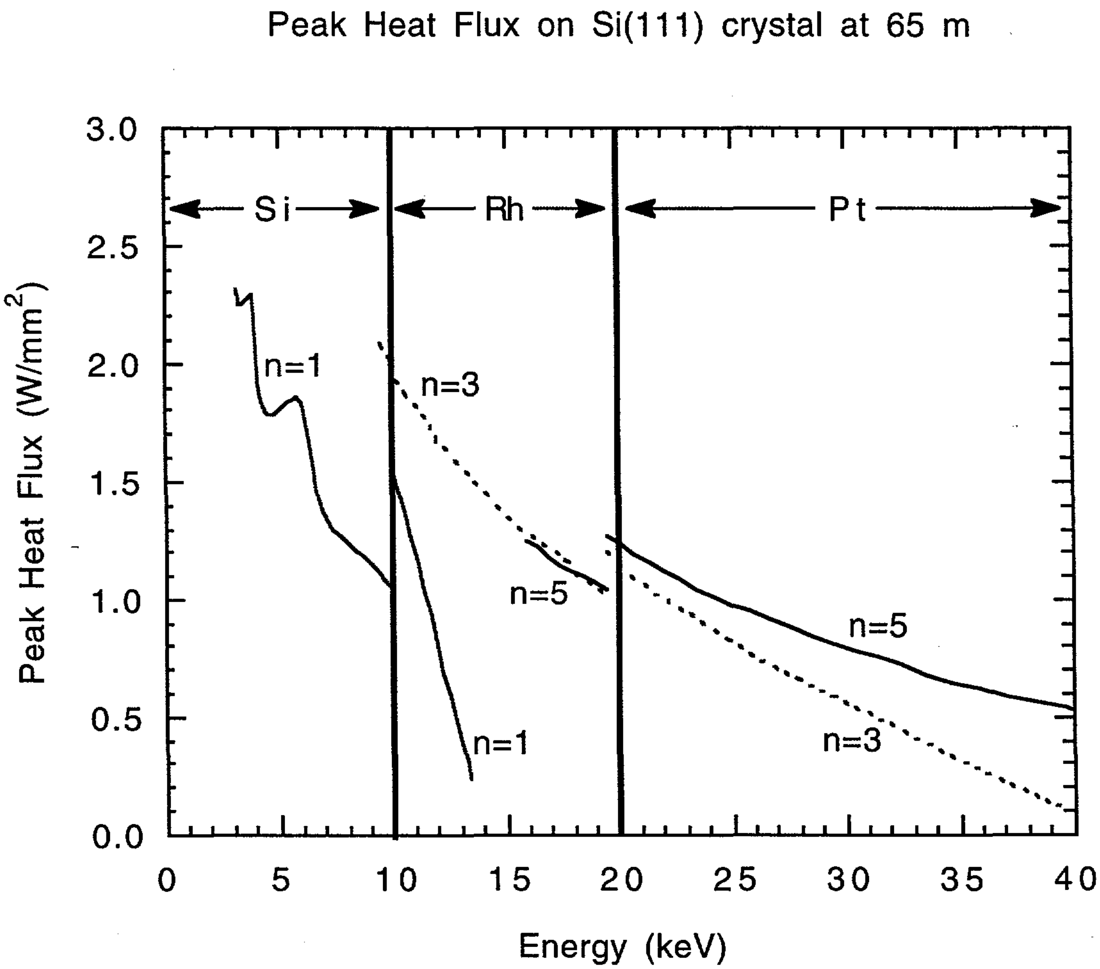

Fig. 4 Peak heat flux on the surface of a Si(111) crystal located at 65 m from Undulator A. The Si crystal is tuned to diffract the energy labeled along the axis, which can be obtained from the first, third, and fifth harmonics of the undulator. It is also assumed that the Si mirror will be used to cover an x-ray energy range of 0-10 keV, the Rh and Pt mirrors to cover the 10-20 keV and 20-40 keV energy ranges, respectively. The grazing angle of incidence on the mirror is 0.15^{o}.