ANL/XFD/CP--87844
CONF-9510119--18

APS Undulator Radiation - First Results

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Abstract

The first undulator radiation has been extracted from the Advanced Photon Source (APS). The results from the characterization of this radiation are very satisfactory. With the undulator set at a gap of 15.8 mm (K=1.61), harmonics as high as the 17th were observed using a crystal spectrometer. The angular distribution of the third-harmonic radiation was measured, and the source was imaged using a zone plate to determine the particle beam emittance. The horizontal beam emittance was found to be 6.9 ± 1.0 nm-rad, and the vertical emittance coupling was found to be less than 3%. The absolute spectral flux was measured over a wide range of photon energies, and it agrees remarkably well with the theoretical calculations based on the measured undulator magnetic field profile and the measured beam emittance. These results indicate that both the emittance of the electron beam and the undulator magnetic field quality exceed the original specifications.

DISCLAIMER

I. Introduction

The 7-GeV Advanced Photon Source (APS) at Argonne National Laboratory is a third-generation synchrotron-radiation source, designed to provide x-ray beams of high brilliance using undulators.[1] It is well known that, at a given current and energy of the particle beam in the storage ring, the brilliance of the x-ray beam from an undulator relies on a low emittance of the particle beam and a high quality of the undulator.[2] As the APS begins operation with undulators, measurements of the particle beam emittance and the spectral flux of undulator beams are an essential part of the commissioning process.

Characterization of the radiation from the first installed Undulator A has been carried out during the commissioning of the 1-ID beamline at the APS. This paper reports the results of absolute-spectral-flux measurements of the undulator radiation and the results of emittance measurements of the stored electron beam using the undulator radiation. The measured absolute spectral flux agrees quantitatively with a theoretical calculation of the undulator brilliance based on the magnetic measurements of the undulator. Also, the emittance derived from the measured beam parameters indicates that the emittance of the stored electron beam has well exceeded the initial design specifications.

II. Undulator A

Undulator A is a planar insertion device capable of generating high-intensity x-rays in the spectral range from 2.9 keV to 60 keV by using the first, third, and fifth harmonics of radiation. It has a 3.3-cm period and is of a hybrid design (consisting of Nd-Fe-B magnets with vanadium permendur poles) with 72 periods and is 2.4 m in length. The device has been optimized for the APS so that the variation in brilliance is small when tuning from one harmonic energy to the next.[3] This was achieved by maximizing the magnetic field at a given gap and by allowing a smaller minimum gap when installed in the storage ring. The characteristics of the Undulator A are listed in Table I.

The undulator was fabricated by STI Optronics. The original magnetic field quality specifications were: a first field integral that varies by no more than 100 G-cm vertically and 50 G-cm horizontally through the entire range of gaps; horizontal and vertical second field integrals that vary by no more than 10^5 G-cm^2 through the entire range of gaps; and a phase error of less than 8° at all gaps. The undulator, as delivered by STI, met these requirements. However, in order to further reduce the effect the undulator has on the closed orbit of the electron beam in the storage ring and to ensure high brilliance of the undulator harmonics, a fine tuning of the undulator's magnetic field was carried out at the APS. Final magnetic measurements found first field integral variations of 38 G-cm in the vertical direction and 21 G-cm in the horizontal, second field integral variations of 6.2×10^4 G-cm^2 in the vertical direction and 1.1×10^4 G-cm^2 in the horizontal, and a phase error less than 5.4°. As a result, the closed orbit displacements in both the vertical and horizontal directions were measured to be less than 0.5% of the beam size over the gap range from 15.7 to 40 mm. The tune shift was measured to be as small as 100 Hz, almost the same as one would expect from an ideal device.

III. Absolute Spectral Flux Measurement

A gas-scattering spectrometer and a crystal spectrometer were used to measure the absolute spectral flux of the undulator radiation. The gas-scattering spectrometer measures the x-rays scattered at 90° from a well-defined helium gas volume at a controlled pressure.[4] The spectrum of the scattered radiation is recorded using an energy-dispersive Si(Li) detector and a calibrated multichannel analyzer (MCA). By using scattering from a gas, this method makes absolute measurements possible at a high stored beam current. The parameters of the scattering geometry, such as the detector solid angle and the scattering volume, can be varied to accommodate a wide range of beam current and to get an appropriate count rate of the detector. Alternatively, the crystal spectrometer can measure the spectral flux to higher energies with better resolution than those possible with the gas-scattering spectrometer.

The experimental setup is schematically shown in Fig. 1. Upstream from the two spectrometers, a water-cooled conical pinhole with an exit diameter of 0.8 mm was used to remove a substantial fraction of the undulator power from the beam. Vertical and horizontal water-cooled slits made of 1.4-mm-thick molybdenum were located at 32.8 m from the source, downstream of the pinhole. The slit size, which defined the angular acceptance of the incident beam, was found to be 240 μm horizontally and 122 μm vertically, by measuring the size of the x-ray beam after the slits. In order to collimate the bremsstrahlung radiation, a 100-mm-thick tungsten block with a 5-mm-diameter hole was placed downstream from the slits. The pinhole, slits, and the tungsten collimator were placed in a helium enclosure and were carefully shielded with lead.

Helium gas is used in the gas-scattering spectrometer because of its small coherent-scattering cross section for energies above 10 keV at the 90-degree-scattering angle. It also minimizes the energy broadening due to the electron-momentum distribution (Compton profile). Thus the measured data are easier to interpret. A Si(Li) detector was mounted vertically 222 mm from the beam. A 1-mm-thick tungsten slit of size 3.0 mm was placed in the scattering path, 31.5 mm from the incident beam, to define the length of the scattering volume. The efficiency of the detector (EG&G ORTEC SLP 06165PS) was determined by calculating the fraction of x-rays absorbed in a 3.2-mm-thick Si(Li) sensitive volume. The radial distribution of the efficiency across its active surface was effectively eliminated by the use of a 3-mm diaphragm in front of the detector. The absorption due to the detector's beryllium window and frontal dead layers and the escape peak corrections were not taken into account because they are negligible for energies above 6 keV. Detector efficiency was calibrated at 6 keV. The energy range of the spectrometer is from 5 to 45 keV.

The crystal spectrometer employs a Si(111) crystal and an ion chamber detector filled with nitrogen gas. The single reflection geometry makes spectral measurements quite insensitive to thermal distortion of the crystal in the sense that the integrated reflectivity of the crystal can be calculated by the dynamical diffraction theory even in the presence of the moderate thermal bump. The efficiency of the ion chamber was determined by calculating the fraction of x-rays absorbed in a 100-mm active path. The silicon crystal was characterized using surface topography and x-ray diffraction and was found to be a perfect crystal.

The measurements were performed with an electron beam of 7.0-GeV energy and about 1-mA current, and the results shown in this report were obtained at a undulator gap of 15.8 mm (K=1.61). Fig. 2 shows the on-axis spectral brilliance of the undulator from 4 to 40 keV derived from the absolute spectral flux measured using the gas-scattering method and the measured beam emittance (discussed later). The first six harmonics are clearly visible. The measured spectrum is a convolution of the incident spectrum with the energy broadening due to the detector response function, the Compton profile, and the finite detector acceptance angle. Deconvolution to obtain the initial undulator spectrum is limited by the noise present in the data. In order to evaluate the performance of the undulator, the initial spectrum was calculated using the measured magnetic field of the undulator at the same gap, the measured electron beam emittance, and an electron beam energy spread of 0.1%. To compare with the experimental results, the calculated spectrum was further convolved with the broadening function mentioned earlier. The resulting spectral brilliance is shown in Fig. 2. As is clearly seen from the figure, the measurements are in remarkably good agreement with the calculation.

Fig. 3 shows the on-axis undulator spectral brilliance obtained using the crystal spectrometer, together with the result of a similar calculation. This calculation, however, does not include convolutions with the energy broadening functions, which are either negligible or not applied in this measurement. The contributions from higher order reflections of the crystal were removed from the measured spectrum. Once again, a good agreement is obtained between measured and calculated spectra. Note that the peak brilliance in Fig. 2 is lower than that in Fig. 3, a consequence of the larger instrumental broadening associated with the gas-scattering spectrometer. Fig. 4 shows the spectrum of the undulator radiation from 40 to 110 keV measured using the crystal spectrometer. Higher order harmonics up to the 17th are clearly observed.

The accuracy of the brilliance measurement depends on the uncertainties associated with the flux and the emittance measurements. The uncertainty in the flux measurement arises from uncertainties of the x-ray transmission of the filters and the air path, the detector efficiency, the entrance slit size, and the beam current. For the measurement using the gas-scattering spectrometer, it also involves the uncertainties of the helium gas density, the detector collecting angle, and the photon counting statistics. The uncertainties of the measurement at 6.1 keV (first harmonic) are listed in Table II. The total rms uncertainty is found to be less than 19% for both methods.

IV. Emittance Measurements

The particle beam emittance was determined by measuring the x-ray beam size at a selected photon energy. The measured vertical beam size σ_m at a distance D from the source can be approximated by

$$\sigma_m{}^2 = \sigma_y{}^2 + (D\sigma_{y'})^2 + (D\sigma_{r'})^2 + (a_y / 3)^2 , \qquad (1)$$

where σ_m, is the rms size of the x-ray beam at a distance D from the source, σ_y and $\sigma_{y'}$ are, respectively, the particle beam size and the particle beam divergence, and $\sigma_{r'}$ is the undulator radiation opening angle. The parameter a_y represents the scanning slit width and $a_y / 3$ is an approximation of a square function by a Gaussian function. Given the betatron function, β_y, at the center of the straight section, the particle beam size and divergence are then only functions of the emittance:

$$\sigma_y = \sqrt{\varepsilon_y \beta_y} , \qquad \sigma_{y'} = \sqrt{\varepsilon_y / \beta_y} . \qquad (2)$$

For β_y =10 m and D=32.8 m, the photon beam size is dominated by the particle beam divergence rather than by the particle beam size. In order to determine the emittance accurately, proper wavelength selection should be made so that $\sigma_{r'} << \sigma_{y'}$. For a single electron, $\sigma_{r'}$ can be approximated by $\sigma_{r'} \cong \sqrt{\lambda_n / 2L}$ at the peak of the nth harmonic (n-odd), where λ_n is the wavelength of the harmonic and L is the length of the undulator (2.4 m). This suggests that undulator radiation from higher harmonics should be used if $\sqrt{\lambda_1 / 2L} > \sigma_{y'}$. Also, a small "blue-shift" of the third harmonic peak gives a substantially narrow vertical radiation distribution about 3.3 μrad in our case, similar to what has been utilized recently with "red-shifted" radiation.[5] Fig. 5 shows the x-ray beam profile measured by scanning the entrance slit in the vertical direction. The crystal was tuned to diffract 18.37-keV x-rays, where the on-axis flux is about half of that at the peak of the third harmonic (18.30 keV). In order to determine the vertical emittance, the single electron radiation profile at the chosen energy was calculated using the Bessel-function approximation,[6] and further convolved numerically with the electron beam emittance to fit the measured radiation profile. From the measured vertical beam profile (σ_m = 0.179 mm), we obtained a best fit with a vertical emittance value of ε_y=0.20 ± 0.04 nm-rad for a β_y of 10.0 m in the straight section, corresponding to σ_y = 45 μm and $\sigma_{y'}$ = 4.5 μrad.

Using a similar procedure for the measured horizontal beam profile, the horizontal emittance was fitted to be 6.9 ± 1.0 nm-rad, corresponding to σ_x=346 μm and $\sigma_{x'}$=20 μrad for a β_x value of 17.3 m. Thus, the emittance coupling ($\varepsilon_y / \varepsilon_x$) is less than 3%, considerably less than the design value of 10%.

The measurement of the source size σ_x and σ_y was confirmed by a separate experiment in which the particle beam was imaged by a zone plate onto a CCD x-ray camera. A horizontally deflecting Si(111) crystal was tuned to diffract the first harmonic of the undulator beam at 7.8 keV (gap=18.2 mm), followed by a high resolution zone plate (0.25-μm minimum linewidth) of 1-m focal length. The CCD camera was placed at the focal plane of the zone plate to capture the demagnified image of the source. Compared to a pinhole camera setup,[7] the zone plate method introduces considerably less diffraction broadening to the image. From this experiment we obtained σ_x=346 ± 35 μm and σ_y=109 (+0,-63) μm, which should be regarded as an upper bound due to the limited spatial resolution of the CCD. In the future, we plan to supplement the CCD camera with high resolution knife-edge scans to precisely determine the image size.

VI. Conclusions

The APS Undulator A was designed to provide brilliant x-rays without perturbing storage ring operation. Initial experience found that the device produced almost no observable net effect on the stored beam. Also, the radiation from the undulator was characterized, and the results confirmed the high magnetic field quality of the device. A low emittance electron beam (smaller than the initial design goal), high brilliance radiation, and harmonics as high as the 17th were all successfully demonstrated during this initial phase of operation.

VII. Acknowledgments

The authors would like to thank all the APS members who participated in this work. This research was supported by the U.S. Department of Energy, BES-Materials Sciences, under contract #W-31-109-ENG-38.

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Figure Captions

1. Illustration of the experimental setup for absolute-spectral-flux measurements.

2. Measured on-axis spectral brilliance (solid line), using the gas-scattering spectrometer, and calculated on-axis spectral brilliance (dotted line) of the undulator radiation from a 7-GeV electron beam at a gap of 15.8 mm (K=1.61). The calculation included the measured magnetic field of the undulator, the measured electron beam emittance (ε_x=6.9 nm-rad, ε_y=0.2 nm-rad), and the design value for the electron beam energy spread (0.1%). The calculated spectral brilliance was further convolved with the energy broadening functions mentioned in the text. The measured spectrum has been corrected for the Compton shift.

3. Measured on-axis spectral brilliance (solid line), using the crystal spectrometer, and calculated on-axis spectral brilliance (dotted line) of the undulator radiation from a 7-GeV electron beam at a gap of 15.8 mm (K=1.61). The calculation included the measured magnetic field of the undulator, the measured electron beam emittance (ε_x=6.9 nm-rad, ε_y=0.2 nm-rad), and the design value for the electron beam energy spread (0.1%).

4. Measured on-axis spectral flux of the undulator radiation, using the crystal spectrometer, from a 7-GeV electron beam at a gap of 15.8 mm (K=1.61). Undulator harmonics up to the 17th are clearly visible.

5. Measured (open circle) and calculated (solid line) vertical beam intensity profile of the undulator radiation at an energy of 18.37 keV (slightly above the third harmonic) at a gap of 15.8 mm (K=1.61). The calculation used the vertical beam emittance (ε_y =0.2 nm-rad) and the design value for β_y=10.0 m.

Table I. Undulator A parameters and specifications

Parameter	Value
magnet material	Nd-Fe-B
pole material	Vanadium permendur
period length	3.30 cm
number of periods	72
length	2.4 m
minimum gap	10.5 mm
minimum range of gap taper	0 to 2 mrad
deflection parameter, K_{eff}*	2.76
maximum field, B_{eff}*	0.896 T
first harmonic energy**	2.9 keV
rms peak magnet field error***	< 0.5%
rms phase error****	< 8°

* measured at the minimum gap of 10.5 mm.

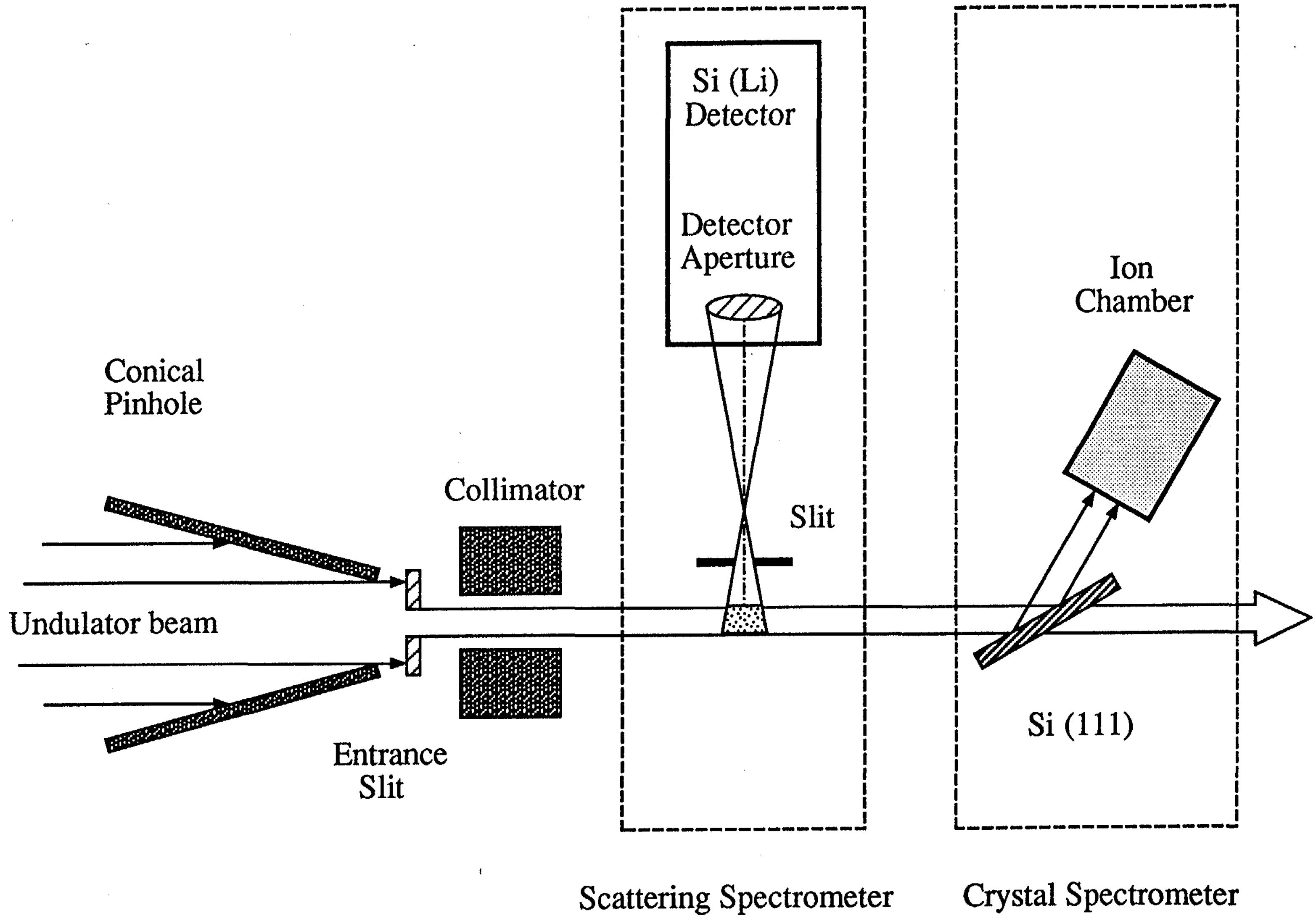
** predicted at the minimum gap of 10.5 mm.

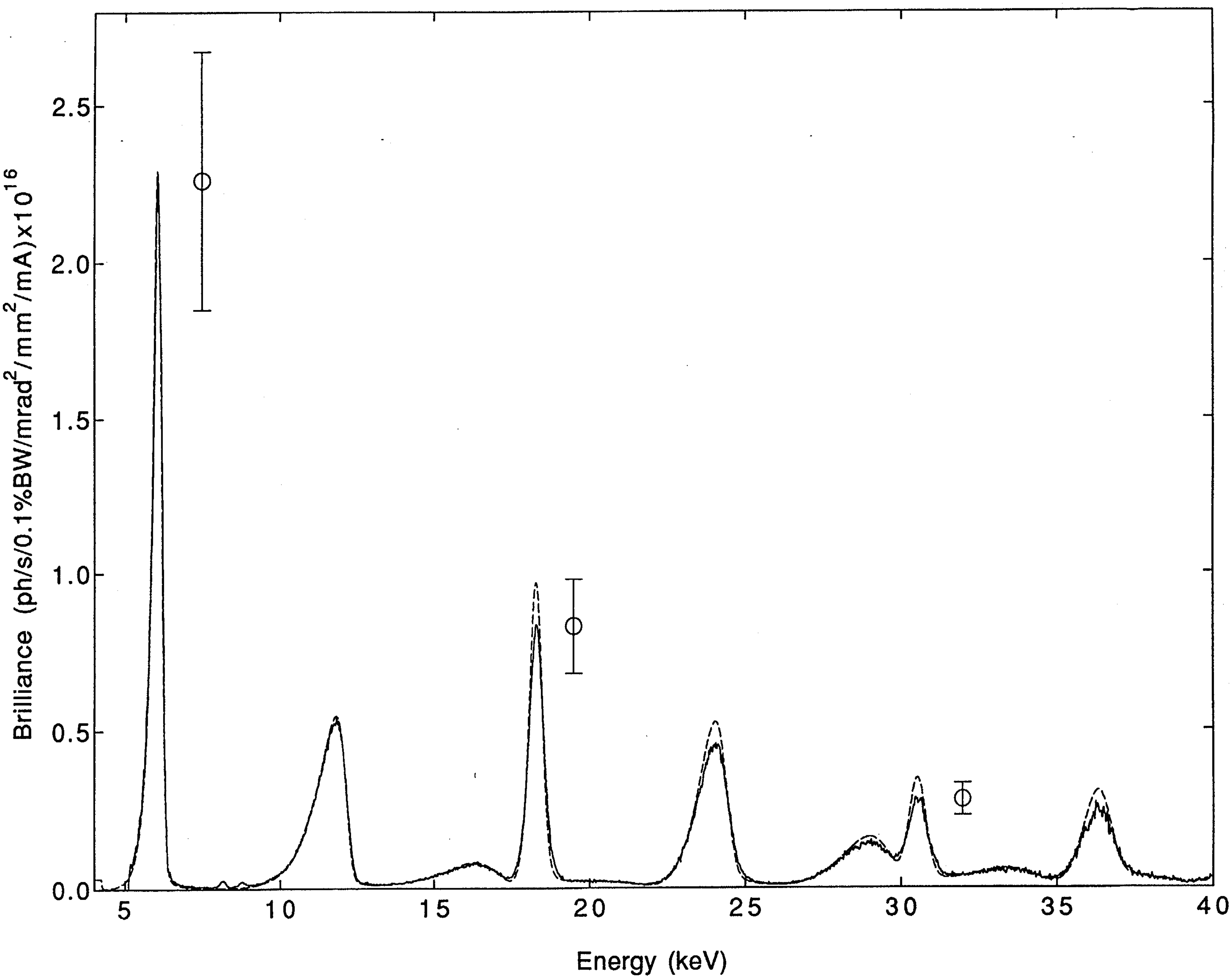
*** specified at a gap of 11.5 mm.

**** specified at a gap of 11.5 mm, actual device < 5.4° at all gaps.

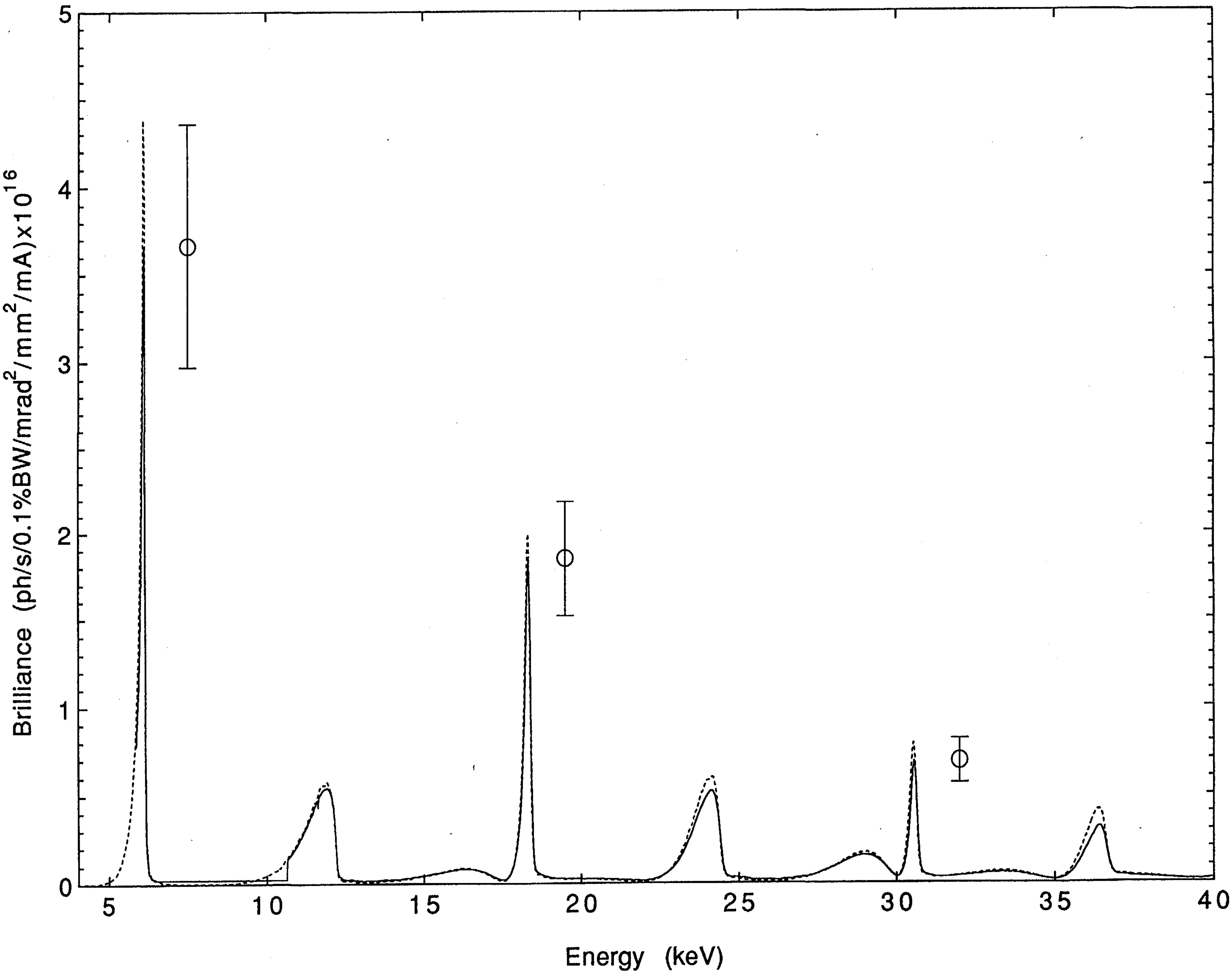
Table II. The rms uncertainties in percentage of the undulator radiation brilliance measurement at the first harmonic (6.1 keV).

Terms	Crystal Spectrometer	Gas-Scattering Spectrometer
thickness of windows & air path	6.1	2.5
detector efficiency	2.3	2.9
entrance slit size	2.2	2.2
emittance	17.3	17.3
electron beam current	0.3	0.3
crystal energy bandwidth	2.8	
helium gas density		0.8
scattering volume and detector solid angle		2.9
statistics		0.9
total	18.9	18.2

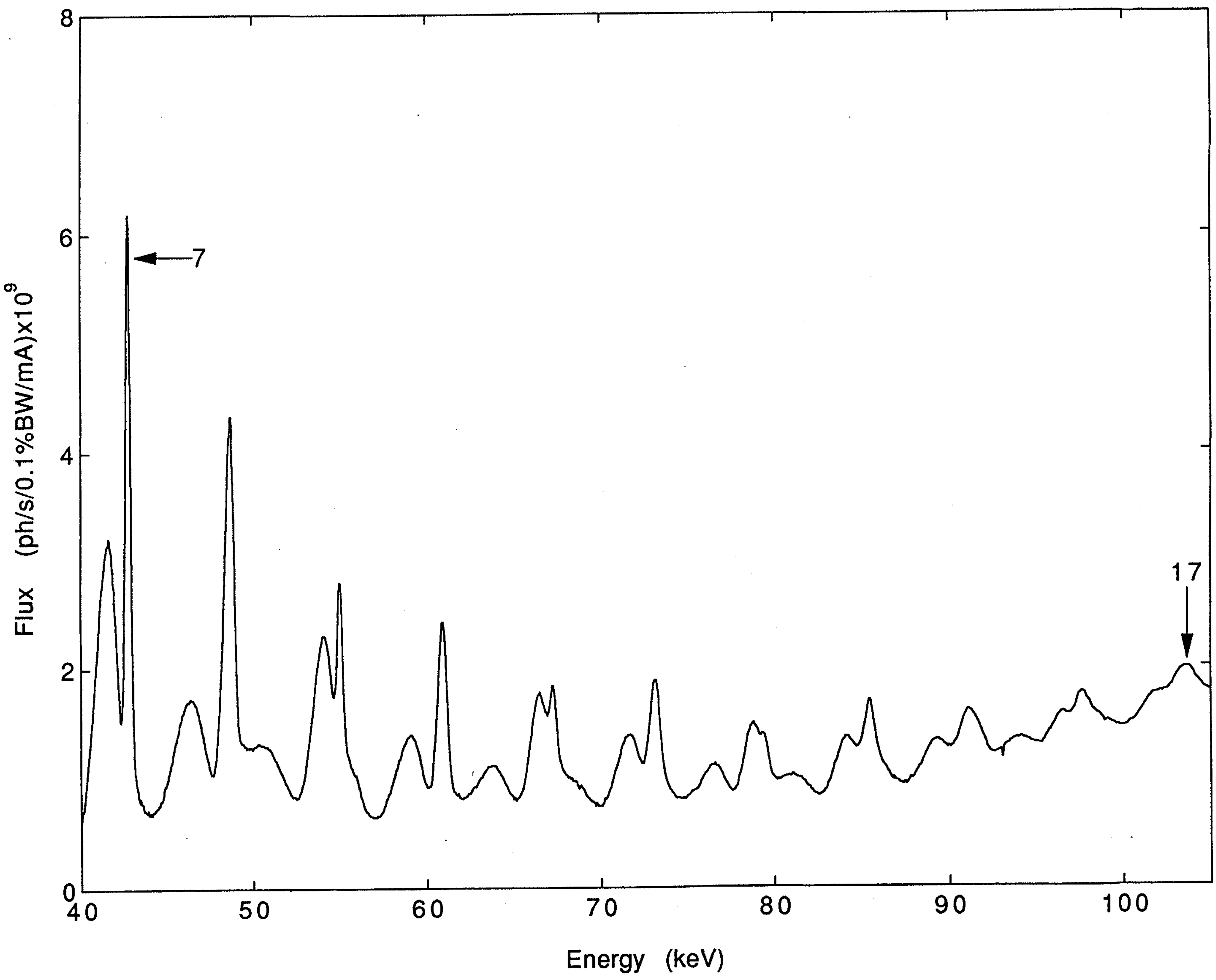

Si (Li)
Detector
Detector
Aperture
Ion
Chamber
Conical
Pinhole
Collimator
Slit
Undulator beam
Si (111)
Entrance
Slit
Scattering Spectrometer
Crystal Spectrometer

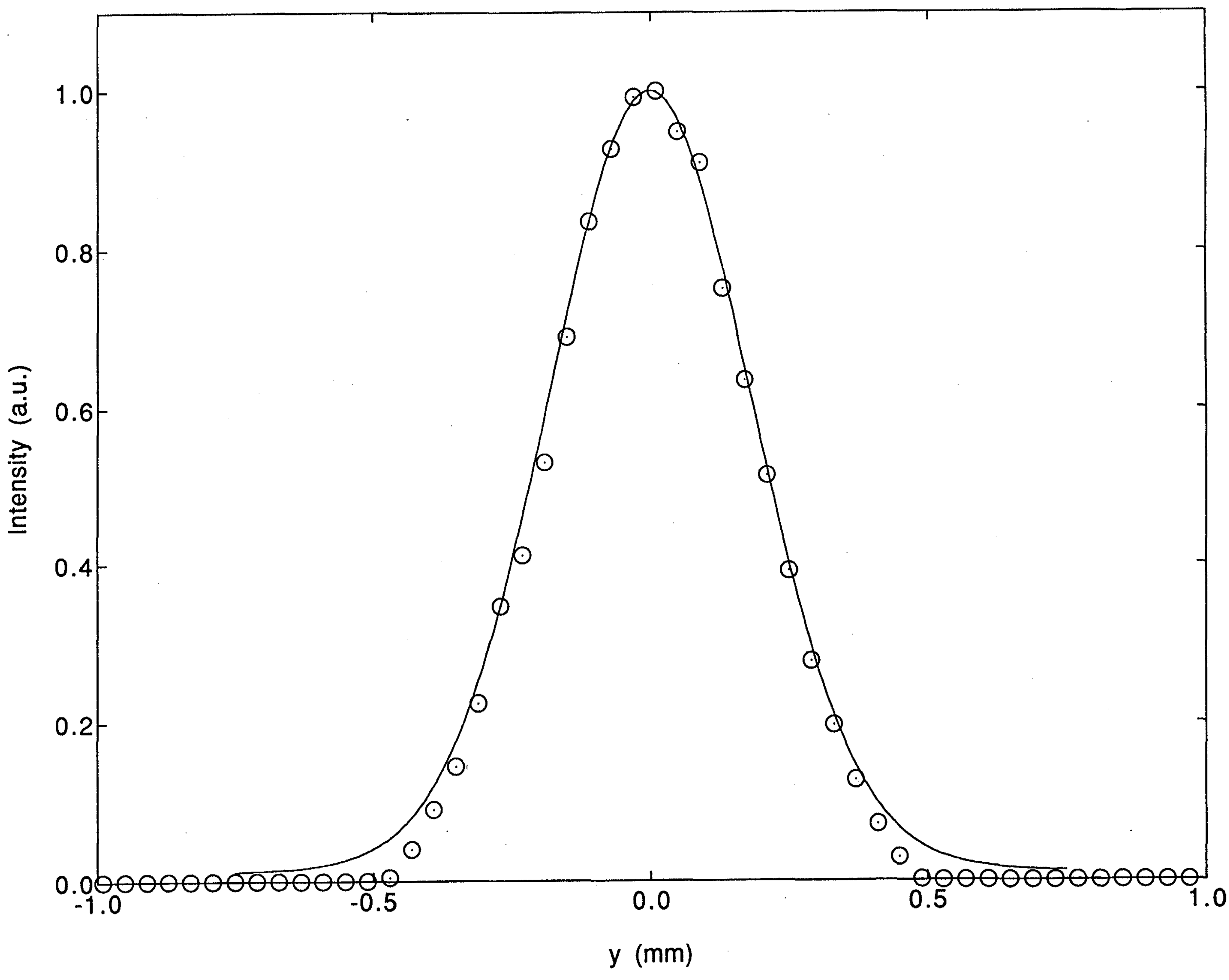


Brilliance (ph/s/0.1%BW/mrad²/mm²/mA)x10¹⁶
0.0
0.5
1.0
1.5
2.0
2.5
5
10
15
20
25
30
35
40
Energy (keV)



5
4
3
2
1
0
5
10
15
20
25
30
35
40
Brilliance (ph/s/0.1%BW/mrad²/mm²/mA)x10¹⁶
Energy (keV)


Flux (ph/s/0.1%BW/mA)x10^9
0
2
4
6
8
40
50
60
70
80
90
100
Energy (keV)
7
17



1.0
0.8
0.6
0.4
0.2
0.0
Intensity (a.u.)
-1.0
-0.5
0.0
0.5
1.0
y (mm)