Performance Calculations of APPLE II Undulator for Soft X-Rays at the Advanced Photon Source

R. Dejus and S. Sasaki - MD Group/XFD

Date: December 8, 2005, Revised from note regarding APPLE II undulator for sector 4: Added information on a 5.6-cm-period length device optimized for high brilliance in the energy range 2 – 6 keV (Table 2 and Fig. 6). Changed the title and minor edits in the text.

Introduction

We present preliminary design studies of an APPLE II device for the XOR CAT which meets the following requirements as desired for the experimental program in sector 4 using variable polarization:

- Minimum energy 200 eV in the first harmonic, spanning the range up to about 3 keV (horizontal and vertical linear polarization)
- Minimum energy 200 eV, spanning the range up to about 3 keV (circular polarization).

Additionally, we present calculations for a device with 5.6 cm period length, which is optimized for high brilliance in the energy range 2 – 6 keV. This device will not satisfy the needs for the sector 4 program but it was included for the purpose of showing the performance over a wider energy range albeit it has a higher minimum energy of 1 keV. Regarding power management, in order to handle the maximum emitted *total* power, it may be necessary to do additional design studies for the front-end components, especially if long devices (> 2.4 m) devices will be used. The power density is however not of concern as it is typically less than for Undulator A.

This note presents calculations for APPLE II-type devices, which have period lengths that are shorter than the circularly polarized undulator (CPU), which has a period length of 12.8 cm. We present on-axis brilliance and on-axis flux tuning curves for the first three odd harmonics in linear mode and the first harmonic in circular mode and discuss the performance compared to the CPU. The code XOP[1] was used to calculate the on-axis brilliance tuning curves from ideal undulators with no magnetic field errors, and the code TCAP[2] was used to calculate the on-axis aperture flux.

Magnet Modeling Of APPLE II Design

We have done preliminary magnetic design calculations using the code RADIA[3] for undulators with period lengths 5.6 cm, 7.8 cm, 10.0 cm, 11.0 cm, and 12.0 cm to estimate the effective magnetic field on-axis and hence the harmonic energies versus gap. The APPLE II type device consists of pure permanent magnets in four independent movable jaws (two jaws are located above the electron beam orbit and two jaws below and at least two jaws have to be movable simultaneously).[4]

The permanent magnet material was NdFeB, grade N42SH from Shin-Etsu, with a vendor-specified minimum B_r of 1.27 Tesla. (This magnet grade was used for the recently constructed 2.70-cm-period device.[5]) Each magnet block has the dimensions 4.0 (X) x 5.5 (Y) x $\lambda/4$ (Z) cm^3, where λ is the period length (see Fig. 1). These dimensions were set so that the device would fit into the existing insertion device vacuum chamber using the APS standard support structure.

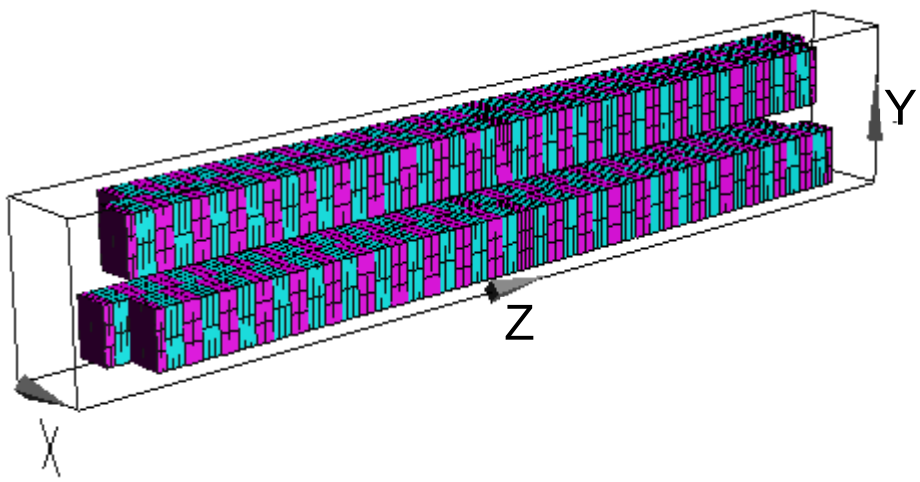

Fig. 1 Magnet model of APPLE II device with period length λ; λ = 5.6 cm, 7.8 cm, 10.0 cm, 11.0 cm, 12.0 cm. Each magnet block has the dimensions 4.0 (X = width) x 5.5 (Y = height) x $\lambda/4$ (Z = longitudinal) cm^3.

The results of the calculations and derived important parameters are given in Tables 1 and 2. We have also included data on the total power and the power density for a device length of 2.4 m, which are important for the beamline design. The total power and power density scale linearly with the device length so it is simple to estimate the powers for any length.

Table 1: RADIA-calculated effective magnetic fields and first harmonic energies versus undulator gap near 200 eV for APPLE II-type devices with period lengths ranging from 7.8 cm to 12.0 cm at 7.0 GeV beam energy. For the power calculations, a device length of 2.4 m was assumed. A magnetic design with NdFeB magnets (B_r = 1.27 Tesla) was used.

Period Length (cm)	Undulator Gap (mm)	B_{eff} (Tesla)	K_{eff}	E_1 (eV) [a]	$P_{density}$ [b] (kW/mrad^2) @ 200 eV	P_{total} [b] (kW) @ 200 eV
7.8	13.0	1.007 (linear mode, vertical polarization)	7.336	214	84	8.1
	15.0	0.707 (circular mode)	5.151	217	0.05, 30 [c]	8.1
	18.0	1.009 (linear mode, horizontal polarization)	7.351	213	84	8.1
10.0	22.0	0.714 (linear mode, vertical polarization)	6.669	200	45	3.8
	24.0	0.536 (circular mode)	5.006	179	0.05, 16 [c]	3.8
	33.0	0.712 (linear mode, horizontal polarization)	6.650	201	45	3.8
11.0	26.0	0.630 (linear mode, vertical polarization)	6.473	193	35	2.9
	30.0	0.446 (circular mode)	4.582	192	0.05, 12 [c]	2.9
	40.0	0.623 (linear mode, horizontal polarization)	6.401	197	35	2.9
12.0	30.0	0.561 (linear mode, vertical polarization)	6.288	187	28	2.2
	36.0	0.376 (circular mode)	4.214	207	0.05, 10 [c]	2.2
	47.0	0.550 (linear mode, horizontal polarization)	6.164	194	28	2.2

[a] Zero-emittance calculation using K_{eff} for on-axis radiation for a beam energy of 7.0 GeV. First harmonic energies are approximate and 200 eV may be reached near the gaps indicated.

[b] Zero-emittance calculated values at a beam energy of 7.0 GeV and a beam current of 100 mA using B_{eff} corresponding to 200 eV first harmonic energy and the full number of undulator periods corresponding to a device length L of 2.4 m. Compare versus Undulator A (3.30 cm period): on-axis power density 168 kW/mrad^2 and total power 6.0 kW at 10.5 mm gap. The power and power density scales linearly with device length L. The total power scales quadratically with the magnetic field.

[c] The first value is the power density on-axis and the second value is the power density off-axis at the angle K_{eff}/γ (~ 0.38 mrad for 7.8 cm period length), which is the maximum value. Both values are for circular mode. The off-axis power density is $2\sqrt{2}$ smaller than the on-axis power density in linear mode for the same harmonic energy.

Table 2: RADIA-calculated effective magnetic fields and first harmonic energies versus undulator gap near 1.0 keV for an APPLE II-type device with period length 5.6 cm at 7.0 GeV beam energy. This device is optimized for high brilliance in the energy range 2 – 6 keV. The minimum reachable first harmonic energy is 1.0 keV. For the power calculations, a device length of 2.4 m was assumed. A magnetic design with NdFeB magnets (B_r = 1.27 Tesla) was used.

Period Length (cm)	Undulator Gap (mm)	B_{eff} (Tesla)	K_{eff}	E_1 (eV) [a]	$P_{density}$ [b] (kW/mrad^2) @ 1.0 keV	P_{total} [b] (kW) @ 1.0 keV
5.6	13.0	0.765 (linear mode, vertical polarization)	4.001	923	81	4.0
	15.0	0.530 (circular mode)	2.772	957	1.25, 29 [c]	4.0
	18.0	0.780 (linear mode, horizontal polarization)	4.080	891	81	4.0

[a] Zero-emittance calculation using K_{eff} for on-axis radiation for a beam energy of 7.0 GeV. First harmonic energies are approximate and 1.0 keV may be reached near the gaps indicated.

[b] Zero-emittance calculated values at a beam energy of 7.0 GeV and a beam current of 100 mA using B_{eff} corresponding to 1.0 keV first harmonic energy and the full number of undulator periods corresponding to a device length L of 2.4 m. Compare versus Undulator A (3.30 cm period): on-axis power density 168 kW/mrad^2 and total power 6.0 kW at 10.5 mm gap. The power and power density scales linearly with device length L. The total power scales quadratically with the magnetic field.

[c] The first value is the power density on-axis and the second value is the power density off-axis at the angle K_{eff}/γ (~ 0.20 mrad), which is the maximum value. Both values are for circular mode. The off-axis power density is $2\sqrt{2}$ smaller than the on-axis power density in linear mode for the same harmonic energy.

As an example of the gap dependence of the first harmonic energy for the different polarization modes for the APPLE II undulator, we show the dependence over the whole usable energy range in Fig. 2 for the 7.8 cm period length.

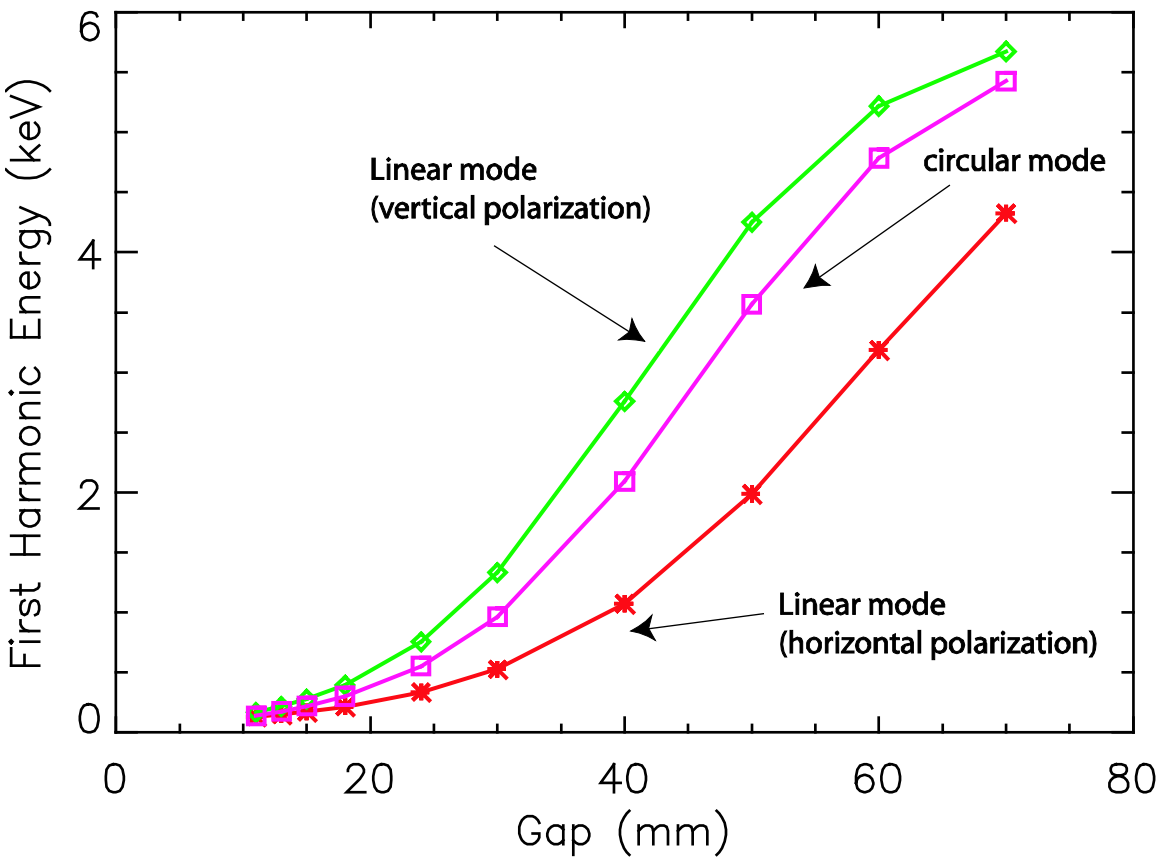

Fig. 2. Gap dependence of the first harmonic energy for the different polarization modes for the APPLE II undulator with 7.8 cm period length at the APS for 7.0 GeV beam energy. The minimum reachable energy is 200 eV for all polarization modes. The gaps for 200 eV in the first harmonic are approximately 13 mm (linear mode, vertical polarization), 15 mm (circular polarization), and 18 mm (linear mode, horizontal polarization).

Radiation Calculations

We have performed calculations of the on-axis brilliance, the on-axis flux through an aperture that covers the central cone of radiation, and power calculations using the APS beam parameters for the 2.5 nm-rad low-emittance lattice for top-up operations (on-axis power density calculations used zero emittance). The results of those calculations are given in this section for the following beam parameters: σ_x = 0.275 mm, σ_y = 0.009 mm, $\sigma_{x'}$ = 0.0113 mrad, $\sigma_{y'}$ = 0.0030 mrad, and beam energy spread 9.6 x 10^{-4}.

Generally, the shorter the period length, the higher the intensity (on-axis brilliance and aperture flux). We have therefore tried to achieve the desired minimum first harmonic energy with as short a period length as possible However, the shorter the period length, the larger the power and power density for any given harmonic energy. The power management for the shortest period length (7.8 cm) to reach the smallest desirable energy (200eV) appears manageable for a 2.4 m long device. However, for longer devices, a longer period length may be necessary. For all calculations, ideal magnetic fields were assumed. For real devices, the intensities will be reduced slightly for the third and fifth harmonics (in linear mode).

On-Axis Brilliance

The calculated on-axis brilliance tuning curves for a period length of 7.8 cm for harmonics 1, 3, and 5 are shown in Figs. 3 and 4 for the APPLE II device and compared to the CPU (included for reference only). The tuning ranges for the different harmonic energies are overlapping widely for both devices.

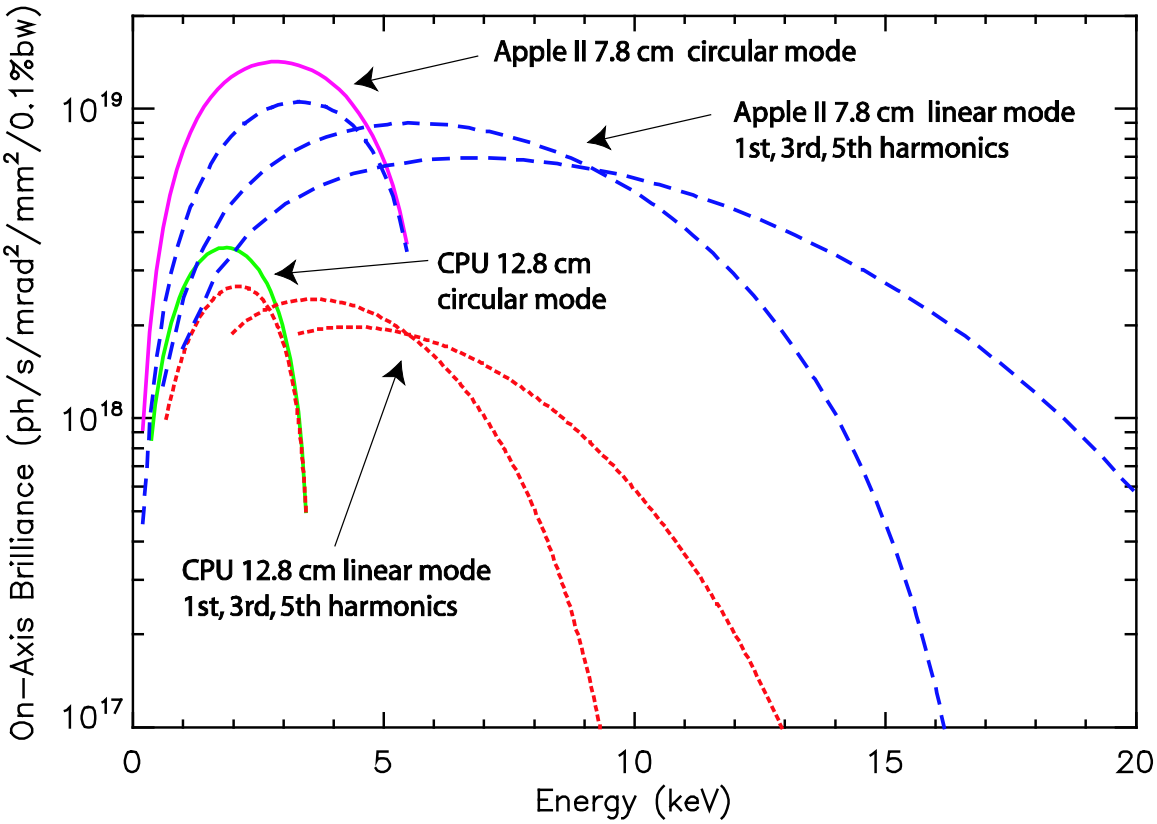

Fig. 3. On-axis brilliance tuning curves for the proposed APPLE II device (7.8 cm period length) compared to the existing CPU (12.8 cm period length) for harmonics 1, 3, and 5 at the APS for 7.0 GeV beam energy and 100 mA beam current. Both devices are 2.4 m long and the APPLE II undulator minimum gap is about 13 mm. The minimum reachable energy is 200 eV for the APPLE II undulator for all polarization modes. The CPU was included for reference purpose only.

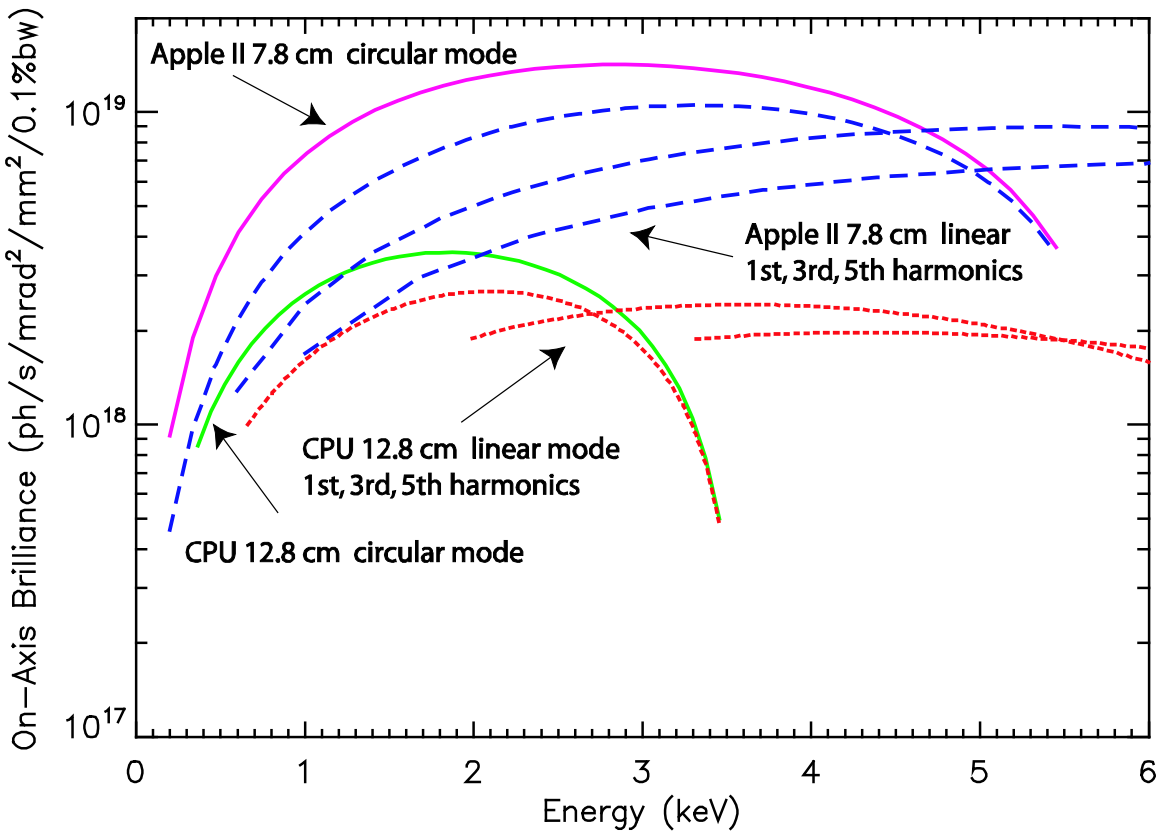

Fig. 4. On-axis brilliance tuning curves for the proposed APPLE II device (7.8 cm period length) compared to the existing CPU (12.8 cm period length) for the 0 – 6 keV energy range. Data and notations are the same as in Fig. 3.

Fig. 5 compares the on-axis brilliance (circular polarization mode only) for different period lengths (7.8 cm, 10.0 cm, 11.0 cm, 12.0 cm) versus the existing CPU, which has a period length of 12.8 cm. The shorter the period length the higher the brilliance at any given harmonic energy. For example, at 200 eV, the on-axis brilliance is 9.2×10^{17}, 6.8×10^{17}, 6.2×10^{17}, and 5.5×10^{17} (ph/s/mrad^2/mm^2/0.1%bw) at 7.0 GeV beam energy and 100 mA beam current for the four APPLE II period lengths studied (short to long).

Fig. 6 shows the on-axis brilliance (circular polarization mode only) for the 5.6 cm period compared to the longer 7.8 cm period length and the existing CPU. The 5.6-cm-period length device has a minimum reachable first harmonic energy of 1.0 keV whereas the 7.8-cm-period length has a minimum energy of 200 eV. The 5.6-cm-period device shows a maximum on-axis brilliance of 2.0×10^{19} (ph/s/mrad^2/mm^2/0.1%bw) near 4 keV at 7.0 GeV beam energy and 100 mA beam current.

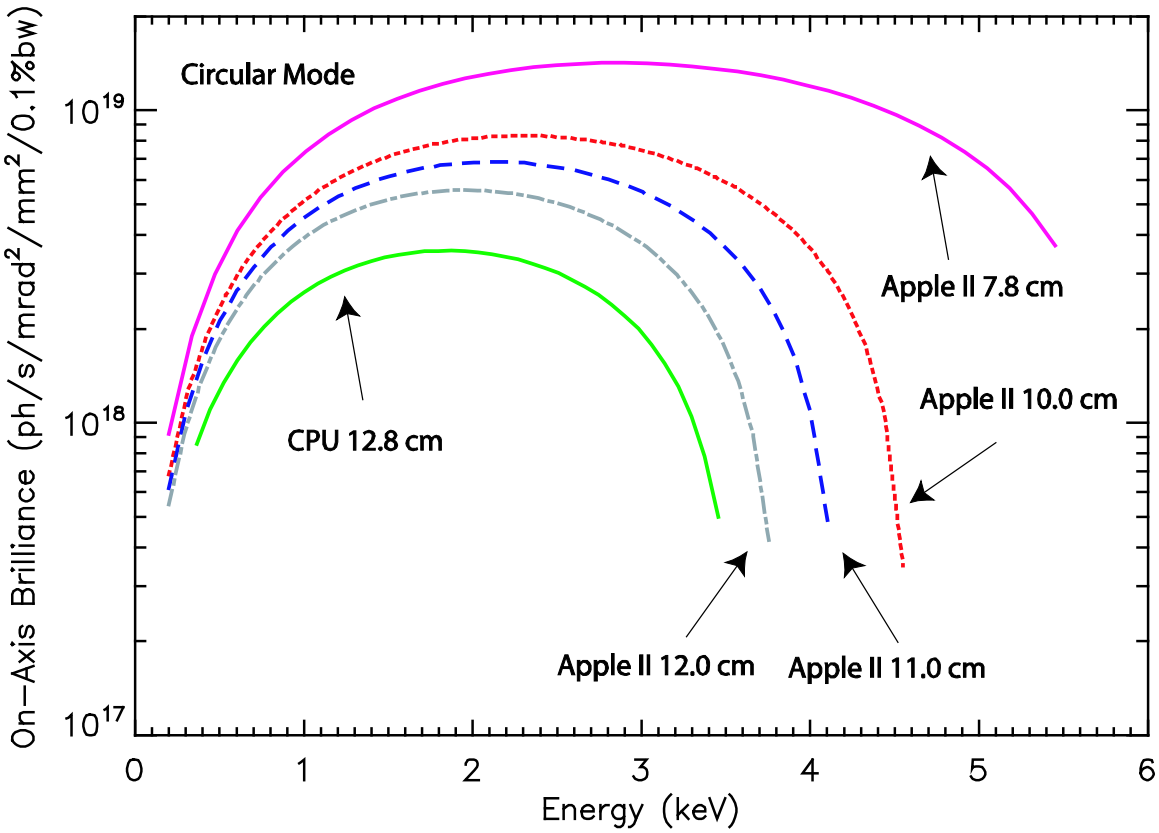

Fig. 5. On-axis brilliance tuning curves for circular polarization for the proposed APPLE II device with period lengths ranging from 7.8 cm to 12.0 cm compared to the existing CPU (12.8 cm period length) for the 0 – 6 keV energy range. The APS beam energy is 7.0 GeV and the beam current is 100 mA. All devices are 2.4 m long. The minimum reachable energy is 200 eV for the APPLE II undulators for all polarization modes (the linear modes are not shown and the CPU was included for reference purpose only).

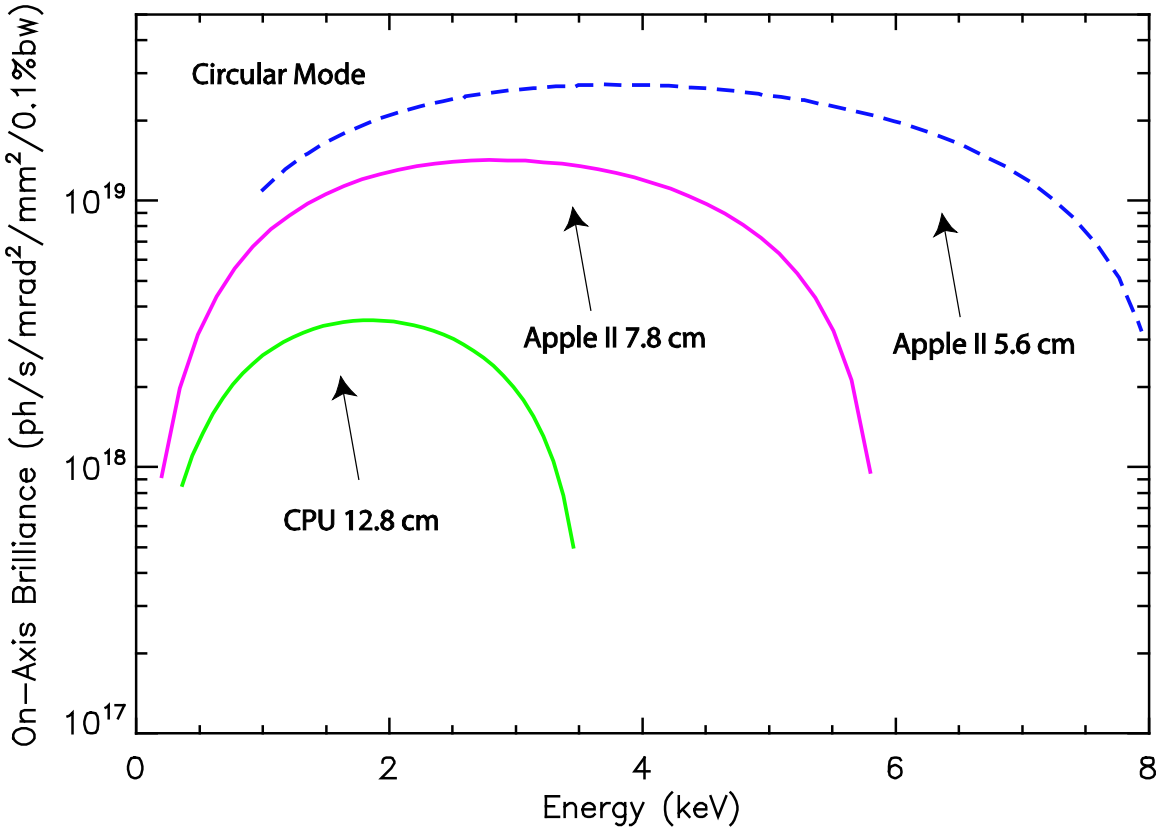

Fig. 6. On-axis brilliance tuning curves for circular polarization for the proposed APPLE II device with period lengths 5.6 cm and 7.8 cm compared to the existing CPU (12.8 cm period length) for the 0 – 8 keV energy range. The APS beam energy is 7.0 GeV and the beam current is 100 mA. All devices are 2.4 m long. The minimum reachable energy is 200 eV for the APPLE II undulator for the 7.8 cm period length and 1.0 keV for the 5.6 cm period length for all polarization modes (the linear modes are not shown and the CPU was included for reference purpose only).

On-Axis Flux

The on-axis flux for a 2.0 mm (h) x 1.0 mm (v) rectangular aperture at 30 m shows similar behavior, see Figs. 7 and 8. The chosen aperture covers roughly the central cone of radiation at the harmonic energies.

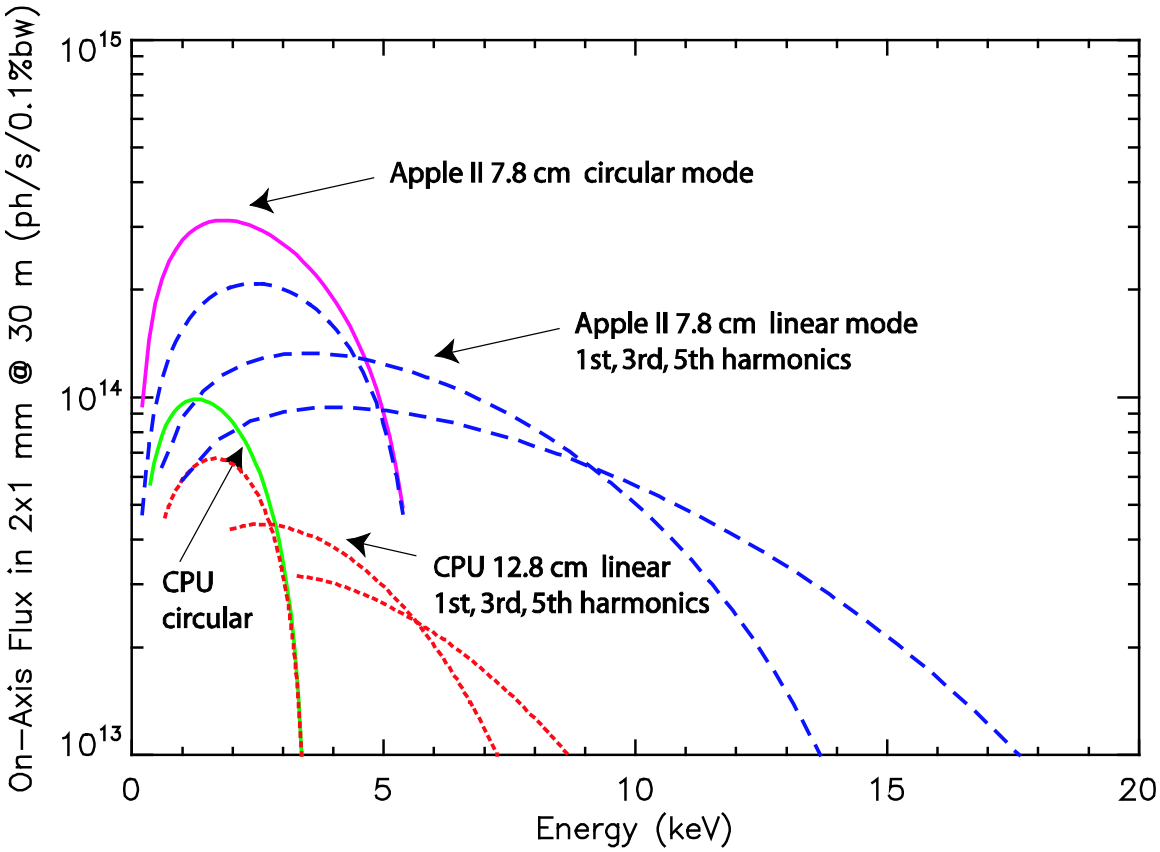

Fig. 7. On-axis flux tuning curves through a 2.0 mm (h) x 1.0 mm (v) rectangular aperture at 30 m at the APS for 7.0 GeV beam energy and 100 mA beam current. Notations and conditions otherwise same as in Fig. 3.

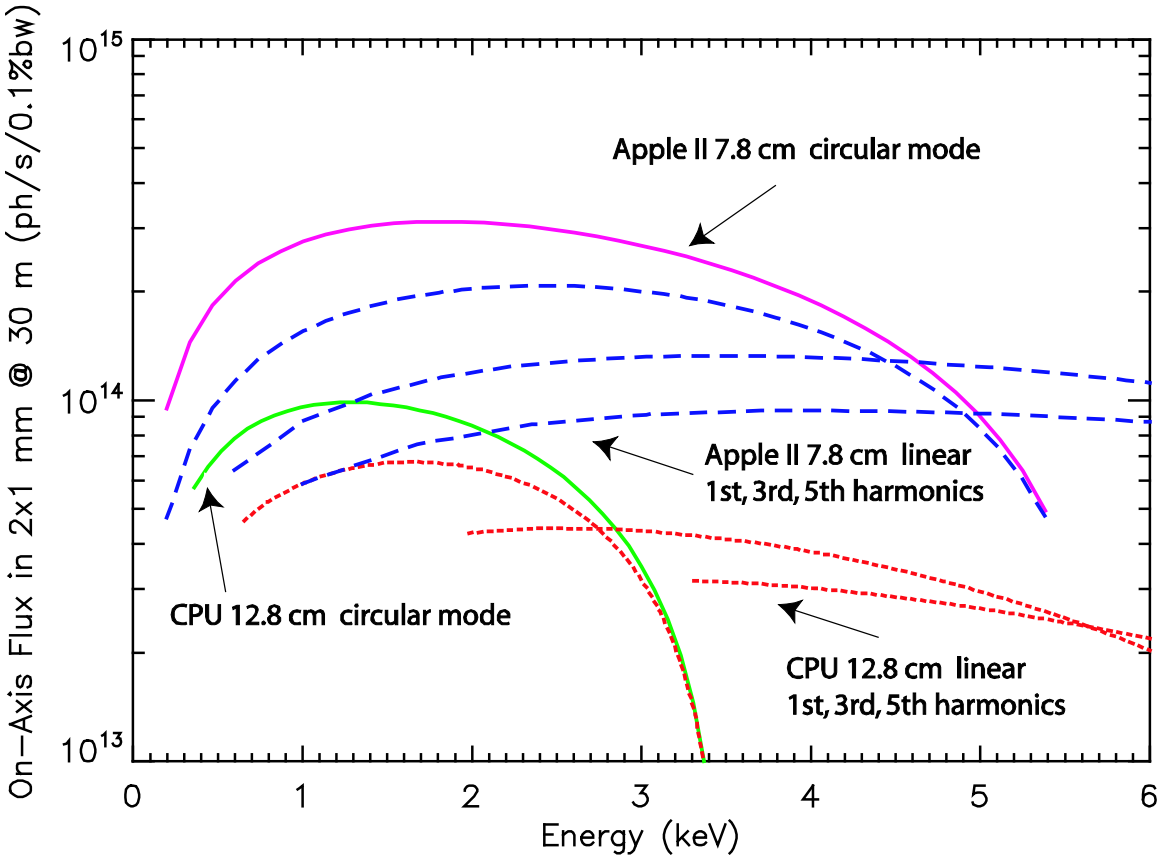

Fig. 8. On-axis flux tuning curves for the 0 – 6 keV energy range. Notations and conditions otherwise same as in Fig. 3.

Total Power and Power Density

The emitted total power for the APPLE II device (L = 2.4 m, λ = 7.8 cm) is 8.1 kW at the minimum energy of 200 eV. This is larger than for Undulator A by 35% and warrants further investigations.

We have also made calculations for a longer period lengths, which can reach the energy of 200 eV at a much lower power, e.g., 3.8 kW for 10.0 cm period length (see Table 1), but at a loss of intensity and a smaller upper energy limit. There may be a trade-off of the desired period length based on what power loads will be allowed, especially if longer devices (L > 2.4 m) will be considered.

The maximum power density for the circular mode is located off-axis in a donut-shaped ring. Its location is at the angle K_{eff}/γ and the intensity is reduced by a factor $2\sqrt{2}$ compared to the on-axis power density in linear mode for the same harmonic energy. For all cases, the power density is smaller than for the Undulator A and will not cause any concerns. Both the total power and the power density scales linearly with the device length. The total power scales quadratically with the undulator magnetic field.

Discussion

- The desired first harmonic energy of 200 eV for the three different polarization modes can be met with an APPLE II device with period length as short as 7.8 cm. The minimum undulator gap would be about 13 mm (linear vertical polarization).

- The maximum on-axis power density will not cause any concerns, even for a double-length (L = 4.8 m) device with 7.8 cm period length. The total power will pose challenging design issues for longer than 2.4 m devices at the same period length. The on-axis brilliance and the aperture-limited flux scale by a factor of about 2.9 in the first harmonic (both polarization modes and for all period lengths studied here, i.e., 7.8 cm, 10.0 cm, 11.0 cm and 12.0 cm) when doubling the undulator length whereas the power and power density scales linearly with length.

- For a single APPLE II device, the frequency of polarization switching cannot be faster than 0.5 Hz (Spring-8, 12.0-cm-period device) because the jaws move mechanically. For the APS, we would not expect to achieve that because we use smart motors with a high gear ratio for phasing. The highest switching rate would be about 0.1 Hz. A different scheme can be used when a high switching rate is required. Two identical APPLE II devices can be placed in tandem in the same straight section with a chicane/phase-shifting magnet between them. This scheme is used at BESSY and one can switch the polarizations at any frequency up to 100 Hz.

- The 5.6-cm-period length APPLE II device was included in this note to show the performance for a device that is optimized in the energy range 2 – 6 keV. The smallest reachable first harmonic energy for such a period length is about 1 keV. The emitted total power (L = 2.4 m) is 4.0 kW (67% of Undulator A) at the minimum energy and will not cause any concerns, unless a very long device is being considered.

- If installed in the APS storage ring, this would be the first device of this kind although it is used at many other facilities (most popular in Europe). Its impact on the APS storage ring operation needs to be investigated before any commitment of such a device can be made.

- Detailed design issues need to be addressed for an APS specific installation, e.g., large (attractive and repulsive) forces exist between the jaws, especially for longer period devices.

References

[1] Manuel Sánchez del Río and Roger J. Dejus, "XOP 2.1 - A New Version of the X-ray Optics Software Toolkit," in the Proceedings of the 8th International Conference on Synchrotron Radiation Instrumentation, August 25-29, 2003, San Francisco, CA (2004) 784 – 787.

[2] R.J. Dejus, code TCAP version 1.2, unpublished.

[3] Code RADIA. Web site: http://www.esrf.fr/Accelerators/Groups/InsertionDevices/Software

[4] Shigemi Sasaki, "Analyses for a planar variably-polarizing undulator," Nucl. Instrum. Methods, A 347 (1994) 83 – 86.

[5] J. Grimmer, "The Annual Report of the Advanced Photon Source at Argonne National Laboratory, APS Science 2004," ANL-05/04, May 2005, 151 – 153. Proc. of Particle Accelerator Conference 2005 at Knoxwille, TN, article RPAE004.