On-Axis Brilliance of APPLE II 3.3-Cm-Period Undulator

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Introduction

Upon request by the x-ray microscopy group at the APS, this note presents on-axis brilliance and power calculations of an APPLE II undulator with the same period length as undulator A (3.3 cm). We compare the on-axis brilliance tuning curves for the first three odd harmonics in linear modes and the first harmonic in circular mode and discuss the performance relative to the undulator A. The code XOP[1] was used to calculate the on-axis brilliance tuning curves and powers from ideal undulators (magnetic field errors were not taken into account and are not particularly important in this context).

A minimum undulator gap of 11.0 mm and an undulator length of 2.4 m were assumed in all calculations. The APS beam parameters for the 2.5 nm-rad, low-emittance lattice, in top-up operation was used, with σ_x = 0.275 mm, σ_y = 0.009 mm, $\sigma_{x'}$ = 0.0113 mrad, $\sigma_{y'}$ = 0.0030 mrad, and a beam energy spread of 9.6 x 10^{-4}. No specific requirements were requested to date as to the minimum energy reachable in different undulator modes of operation.

Magnet Modeling Of APPLE II Design

Preliminary magnetic design calculations were performed using the code RADIA[2] for an APPLE II-type undulator with a period length of 3.3 cm. The APPLE II undulator consists four independent movable rows of permanent magnets (two rows of magnets are located above the electron beam orbit and two rows are located below the electron beam mid plane).

Permanent magnets made of NdFeB (grade N39UH from Shin-Etsu), were used in the modeling of the APPLE II undulator. The actual magnet grade used for the fabrication of the undulator will be chosen at a later date. The N39UH is a realistic choice because it has a high coercivity (vendor-specified H_{cj} > 21 kOe), yet it retains a high remanence magnetic field (vendor-specified B_r > 1.22 Tesla). Also, this particular grade has been used in planar permanent magnet undulators fabricated recently at the APS. The relevant important parameters are listed in Table 1. (The parameters for the undulator A were obtained from the APS technical bulletin TB-45.[3])

Table 1: RADIA-calculated effective magnetic fields and first harmonic energies for an APPLE II-type device with 3.3 cm period length at 11.0 mm gap. The first harmonic energies and the power calculations were made for a beam energy of 7.0 GeV, a beam current of 100 mA, and a device length of 2.4 m. A magnetic design with NdFeB magnets was used (B_r = 1.20 Tesla; slightly less than the minimum vendor-specified value of 1.22 Tesla for grade N39UH from Shin-Etsu).

Undulator Type	B_{eff} (Tesla)	K_{eff}	E_1 (keV) [a]	$P_{density}$ [b] (kW/mrad^2) @ 11.0 mm	P_{total} [b] (kW) @ 11.0 mm
APPLE II (3.30 cm)	0.6979 (linear mode, horizontal polarization)	2.150	4.26	128.6	3.59
	0.3909 (circular mode)	1.204	5.76 [c]	27.4, 46.0 [d]	2.25
	0.4701 (linear mode, vertical polarization)	1.449	6.88	85.4	1.63
UA (3.30 cm)	0.8455 (linear mode, horizontal polarization)	2.605	3.21	159.0	5.42

[a] Zero-emittance calculation using K_{eff} for on-axis radiation for a beam energy of 7.0 GeV.

[b] Zero-emittance calculation using B_{eff} for the APPLE-II undulator and B_{peak} (not shown) for the undulator A for a device length L of 2.4 m (total number of periods N = 72) for a beam energy of 7.0 GeV and a beam current of 100 mA. The total power and the on-axis power density scale linearly with L. The total power is proportional to the square of the magnetic field.

[c] For the undulator A, set to operate at a first harmonic energy of 5.76 keV (15.2 mm gap), the on-axis power density is 101.6 kW/mrad^2 and the total power is 2.25 kW.

[d] The first value indicates the on-axis power density and the second value indicates the maximum power density, which occurs off-axis at an angle of 0.068 mrad. Both values are for circular mode.

On-Axis Brilliance

The on-axis brilliance tuning curves for the APPLE II-type undulator for different modes of operation at the APS compared to the standard undulator A is shown in Fig. 1. The APPLE II undulator shows a considerably higher brilliance than undulator A in the energy range 6 – 10 keV, with the highest increase at the lower end of the energy range (~ 45% near 6 keV). The trade-off of using an APPLE II undulator would be a much smaller tuning range for all modes of operation: circular mode provides only first harmonic radiation, and the low-energy cut off for the first harmonic for horizontal linear polarization is 4.46 keV and 6.88 keV for vertical linear polarization. Consequently, large energy gaps with zero intensity will occur in the coverage for the vertical linear polarization. It is interesting to note that the brilliance for the vertical linear polarization mode is about 5 – 10% higher than the brilliance for the horizontal linear polarization mode. The reason is due to the asymmetry of the angular radiation pattern below the zero-emittance harmonic energies (maximum brilliance occurs slightly below the zero-emittance harmonic energies due to the beam emittance and the beam energy spread).

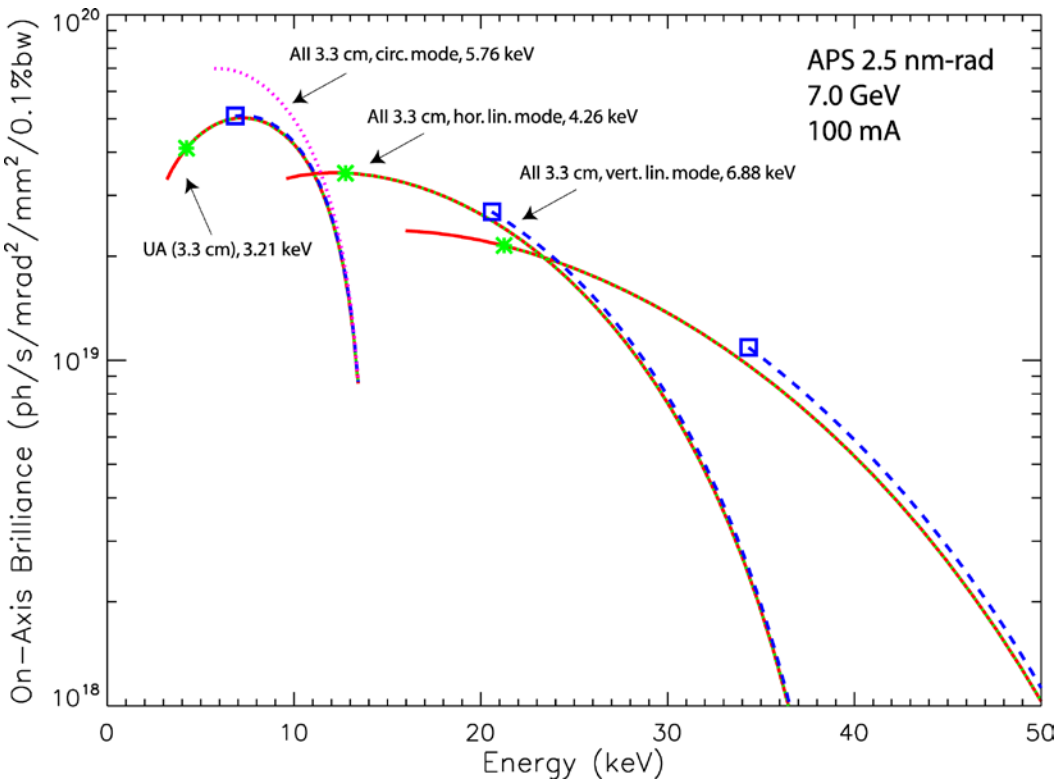

Fig. 1. On-axis brilliance tuning curves for the first, third, and fifth harmonics for an APPLE II undulator (AII) with 3.3 cm period length compared to the undulator A at 7.0 GeV beam energy and 100 mA beam current. A minimum undulator gap of 11.0 mm and device length of 2.4 m were assumed. The minimum first harmonic energies and labels are: 4.26 keV (APPLE II, horizontal linear polarization, green stars and green dotted curves), 5.76 keV (APPLE II, circular polarization, first harmonic only, dotted purple curve), 6.88 keV (APPLE II, vertical linear polarization, blue squares and blue dashed curves), and 3.21 keV (undulator A, horizontal linear polarization, red solid curves).

Total Power and Power Density

For a given undulator gap setting, the emitted total power of the APPLE II undulator is substantially less than the power emitted of the undulator A (for the same harmonic energy however, the powers are the same). The total power versus the harmonic energy for the first three odd harmonics of undulator A compared to the APPLE II undulator is shown in Fig. 2. Markers indicate the powers at the smallest gap setting (11.0 mm) for the different modes of operation. For larger gaps, the powers follow the undulator A power curves.

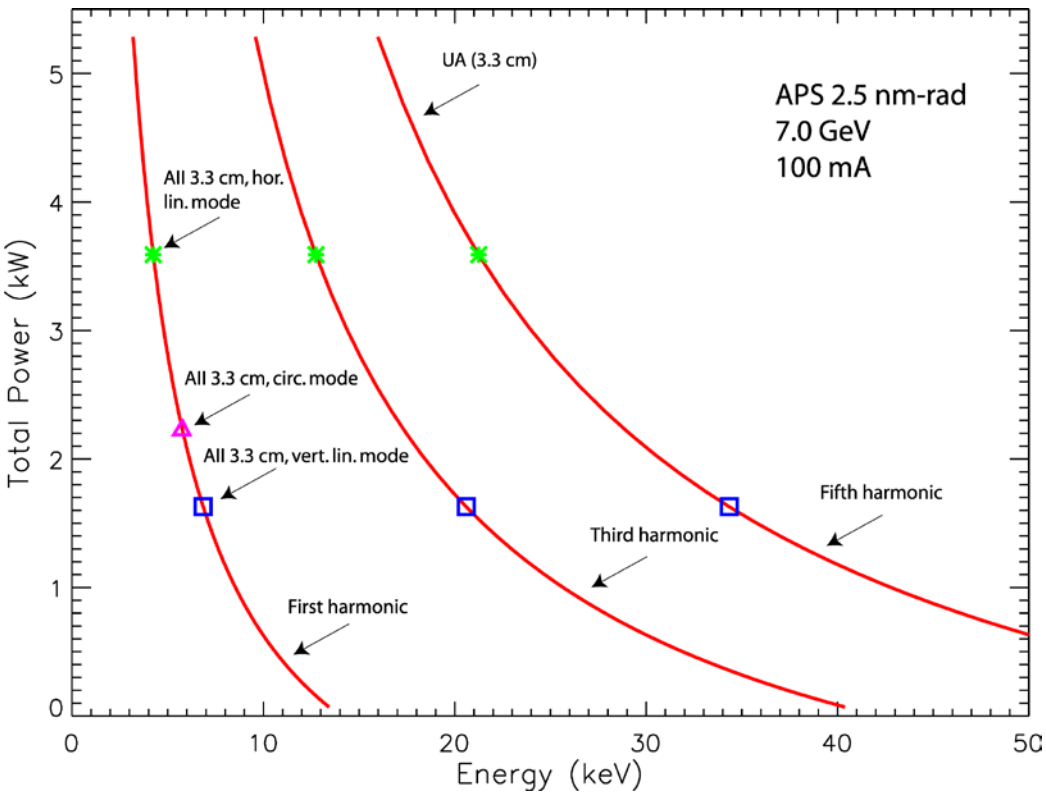

Fig. 2. Emitted total power for undulator A (3.3 cm period length) versus harmonic energy compared to a 3.3-cm-period APPLE II undulator (AII) at 7.0 GeV beam energy and 100 mA beam current. A minimum undulator gap of 11.0 mm and device length of 2.4 m were assumed. The maximum powers are: 5.42 kW (UA), 3.59 kW (APPLE II, horizontal linear polarization, green stars), 2.25 kW (APPLE II, circular polarization, purple triangle), 1.63 kW (APPLE II, vertical linear polarization, blue squares).

One of the attractive features of a helical undulator is the reduced on-axis power density compared to a planar undulator. Figure 3 compares the on-axis power densities for the two undulators. At the smallest gap in circular mode (a first harmonic energy of 5.76 keV), the APPLE II undulator shows an on-axis power density of only ~ 27 W/mrad^2, which is nearly 4 times smaller than for undulator A. The advantage gradually diminishes as the harmonic energy is being increased, see Fig. 3.

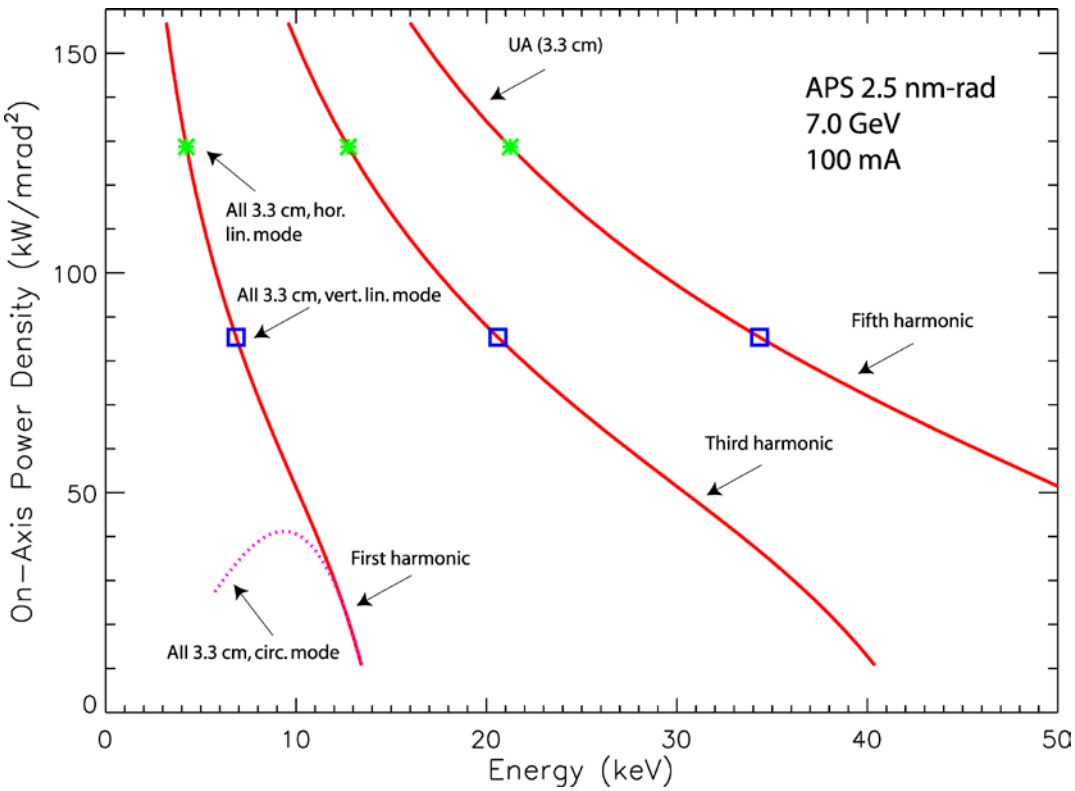

Fig. 3. On-axis power density for undulator A (3.3 cm period length) versus harmonic energy compared to a 3.3-cm-period APPLE II undulator (AII) at 7.0 GeV beam energy and 100 mA beam current. A minimum undulator gap of 11.0 mm and device length of 2.4 m were assumed. The maximum on-axis power densities are: 159.0 kW/mrad^2 (UA), 128.6 kW/mrad^2 (APPLE II, horizontal linear polarization, green stars), 41.2 kW/mrad^2 (APPLE II, circular polarization at 9.3 keV), 85.4 kW/mrad^2 (APPLE II, vertical linear polarization, blue squares).

The maximum power density for an APPLE II undulator in circular mode occurs off-axis in a donut-shaped ring. For large K values (> 3.0), the position approaches the angle K/γ and the power density becomes reduced by roughly a factor of $2\sqrt{2}$, when compared to the on-axis power density in linear mode at the same harmonic energy. For the circular mode at a given harmonic energy, both the on-axis and off-axis power densities are smaller than for the undulator A.

Summary

In comparison with the 2.4-m-long undulator A (3.3 cm period), a helical undulator of APPLE II-type, with the same period length at 11.0 mm minimum gap will provide:

- a higher on-axis brilliance by about 45% in circular mode near 6 keV,
- a reduced on-axis power density by almost a factor of 4 near 6 keV,
- three modes of polarization; circular, horizontal linear, and vertical linear,
- reduced tuning ranges; minimum first harmonics energies are approximately 4.3 keV (horizontal linear mode), 5.8 keV (circular mode), and 6.9 keV (vertical linear mode).

The power through a beam-limiting aperture will also be reduced, the amount will depend on the angular size of the aperture (in the limit of being very small aperture, one would approach the factor of 4 given above).

The minimum harmonic energies given in this note were obtained by using conservative assumptions in the magnet design. There is an option of using magnets with somewhat higher remanent magnetic field, which in turn would translate into somewhat extended tuning ranges. The choice of magnet grade and magnet vendor will ultimately be done at the time of fabrication and we will take into consideration potential radiation of the magnets. The more radiation-resistant magnets we chose, the lower the remance magnetic field. Realistically, one should not expect the minimum harmonic energies to be lowered by more than ~ 0.3 keV (for all polarization modes using a B_r of 1.25 Tesla instead of 1.20 Tesla).

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

[3] ANL/APS/TB-45, "Undulator A Magnetic Properties and Spectral Performance," by R.J. Dejus, I.B. Vasserman, S. Sasaki, and E.R. Moog, Argonne National Laboratory, May 2002.