PERFORMANCE EVALUATION OF UNDULATOR RADIATION AT CEBAF*

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Abstract
The performance of undulator radiation (UR) at CEBAF with a 3.5 m helical undulator is evaluated and compared with APS undulator-A radiation in terms of brilliance, peak brilliance, spectral flux, flux density and intensity distribution.

GENERAL FORMULAS [1]

For helical undulator, K ≦ 1, where $K = \frac{ceB}{mc^2}\frac{\lambda_u}{2\pi} = 0.934B[T]\lambda_u[cm]$, the fundamental wavelength of UR is

$$\lambda_1 = \frac{1+K^2+\gamma^2\theta^2}{2\gamma^2}\lambda_u \quad (1)$$

Here, γ is the Lorentz factor, θ is the polar angle with respect to the undulator axis. The expression for the wavelength of the n-th harmonic is

$$\lambda_n = \frac{1+K^2+\gamma^2\theta^2}{2n\gamma^2}\lambda_u \quad (2)$$

In practical units, it is given by

$$\lambda_n\left[\mathring{A}\right] = \frac{13.056\lambda_u[cm]}{nE^2[GeV]}\left(1+K^2+\gamma^2\theta^2\right) \quad (3)$$

The corresponding energy, in practical units, is

$$\varepsilon_n[keV] = 0.95\frac{nE^2[GeV]}{\left(1+K^2+\gamma^2\theta^2\right)\lambda_u[cm]} \quad (4)$$

These formulas are similar to those for planar undulator, with term $K^2/2$ being replaced by K^2.
The relative bandwidth of n-th harmonic is

$$\frac{\Delta\lambda}{\lambda} \cong \frac{\Delta\omega}{\omega} \cong \frac{1}{nN} \quad (5)$$

N is the number of periods of the undulator.

BASIC PARAMETERS

To evaluate undulator radiation performance at CEBAF, and further explore the possibility of realizing sub-ps monochromatic hard x-ray source at CEBAF, it is necessary to calculate and simulate the UR in terms of brilliance, angular distribution and spectral flux. Comparison of these results with a typical storage ring light source (APS undulator-A is chosen here) will help us understand the difference or may give us strong justification of implementing such experiment at CEBAF.

The undulator being considered for CEBAF is the helical undulator developed by the HeLiCal collaboration in the UK for the ILC positron source [2]. The parameters of the ILC undulator and APS undulator-A are listed in Table 1.

Table 1: Parameters of ILC and APS Undulator

Device	ILC undulator	Undulator-A
λ_u [cm]	1.15	3.2
N	306	72
L [m]	3.5	2.4
Beff [T]	0.86	0.7
K	0.924	2.17
E1 [keV]	31.44	4.2

The relevant electron and positron beam parameters will be used in the calculation are listed in Table 2 for both CEBAF and APS [3].

Table 2: Beam Parameters at CEBAF and APS

	CEBAF	APS
E [GeV]	8.4	7
I [mA]	0.1	100
ΔE/E	1E-5	1E-4
ε_x [m-rad]	0.035E-9	8.2E-9
ε_y [m-rad]	0.035E-9	0.82E-9
β_x [m]	67.26	14.27
β_y [m]	67.26	10.16

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CALCULATIONS AND ANALYSIS

Calculations are done with Synchrotron Radiation Workshop (SRW) [4].

Tuning Curves

Brilliance, measured at x=y=x'=y'=0, is an important figure of merit used to characterize an undulator radiation source. The tuning curves show the brilliance at various photon energies corresponding to a gradually varying deflection parameter K. It means a continuous gap change for a permanent magnet undulator.

Figure 1 is the average brilliance tuning curves at 8.4 GeV, in which only the first 3 odd harmonics are shown. As can be seen, the brilliance at higher harmonics drops dramatically due to the weak deflection of the helical undulator.

Figure 2 show the first order tuning curves for discrete electron energies at CEBAF versus APS tuning curves. Here we suppose an external beam line after north linac, and second, third, forth and fifth turn beam, which correspond to electron energy 3.6, 6, 8.4 and 10.8 GeV, can be extracted to this beam line for UR. The changing trend of tuning curves are consistent with the running modes of these two sources: although a relative strong planar undulator at APS is used, the brilliance decreases with higher order harmonics, however, not that dramatically as in Fig. 1; with increasing electron energy and decreasing emittance at CEBAF, brilliance increases at higher photon energy.

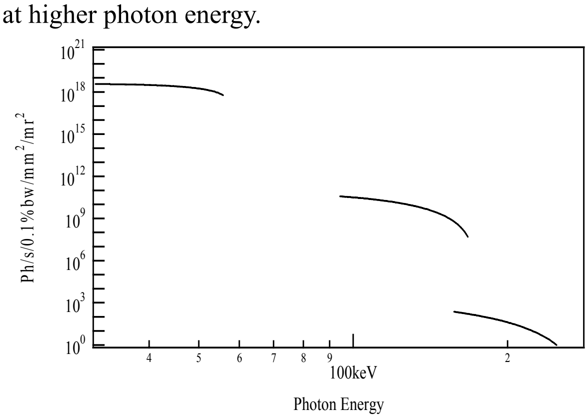

Figure 1: Tuning curves for 8.4 GeV CEABF, 1st to 5th harmonics (only odd).

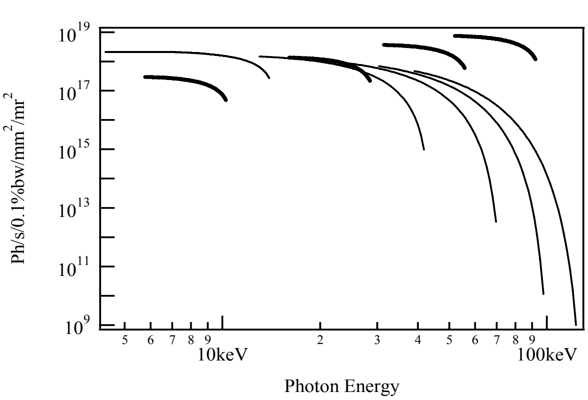

Figure 2: Tuning curves: CEBAF vs. APS; tuning curves for APS (thin black), 1st to 9th harmonics (only odd) from low to high energy; tuning curves for CEBAF (thick black), from left to right corresponding to 3.6, 6, 8.4 and 10.8 GeV (only 1st harmonic)

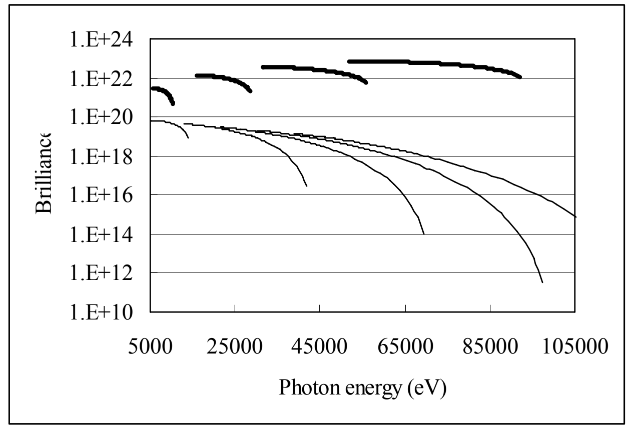

Figure 3: Peak brilliance tuning curves, 1st to 9th harmonics for APS (only odd) from low to high energy, 3.6, 6, 8.4 and 10.8 GeV (only 1st harmonic) from left to right for CEBAF, thin black for APS, thick for CEBAF.

Figure 3 shows the peak brilliance from CEBAF and APS. Please note the peak brilliance is calculated with 500 MHz rep rate, 200 fs FWHM bunch length for CEBAF, 352 MHz rep rate, 100 ps FWHM bunch length for APS [5].

Flux Spectra

The brilliance is obtained at one observation point. Usually, an aperture is used in the beam line. It is more practical to evaluate the radiation within the finite acceptance. Figure 3 shows the CEBAF spectral flux from 20 keV to 160 keV on a 1 mm^2 target 30 m downstream the undulator. It is reasonable to neglect higher harmonics in case of a helical undulator with strength 0.924 due to the much lower flux at higher harmonics (shown in Fig. 1). The corresponding spectral flux for APS is shown in Fig. 5.

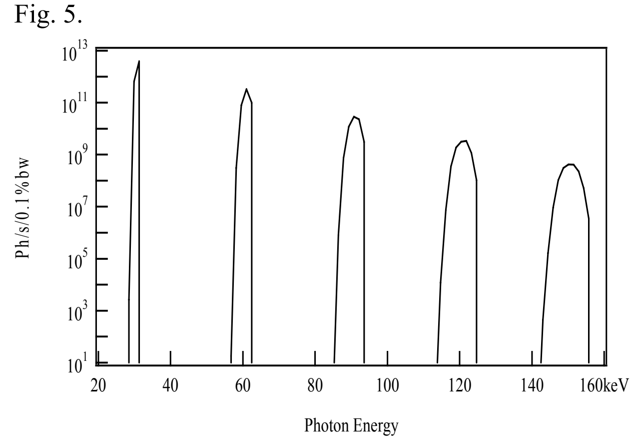

Figure 4: Spectral flux at first 5 harmonics of 8.4 GeV CEBAF.

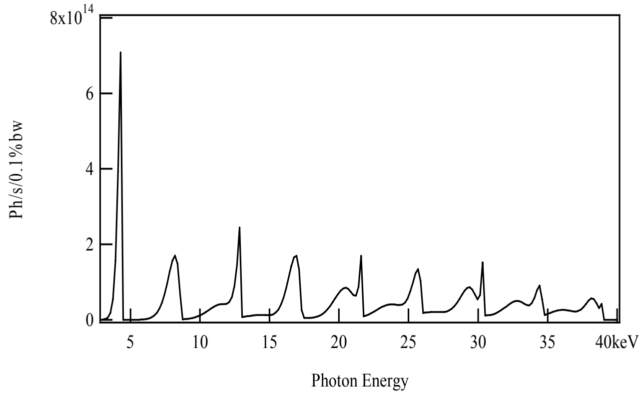

Figure 5: Spectral flux of first 9 harmonics for APS.

Flux Density

For micro-size target application, flux density which is flux over unit area is an important figure of merit for the UR light. As shown in Fig. 6 and 7, on-axis flux density for 8.4 GeV CEBAF and APS are about the same, however, the relative bandwidth for CEBAF is much narrower than APS. Furthermore, higher flux density can be achieved with higher electron energy at CEBAF.

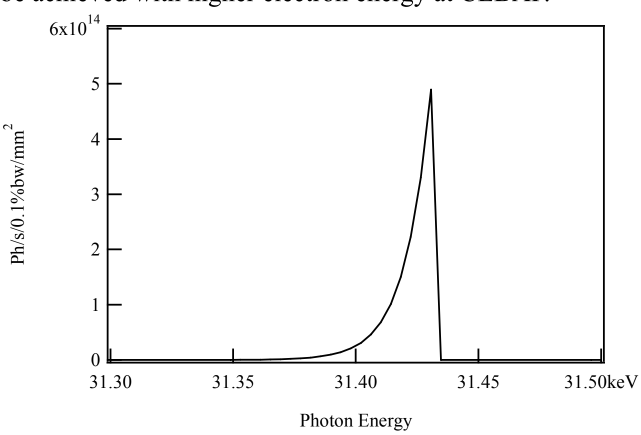

Figure 6: On-axis flux density for 8.4 GeV CEBAF.

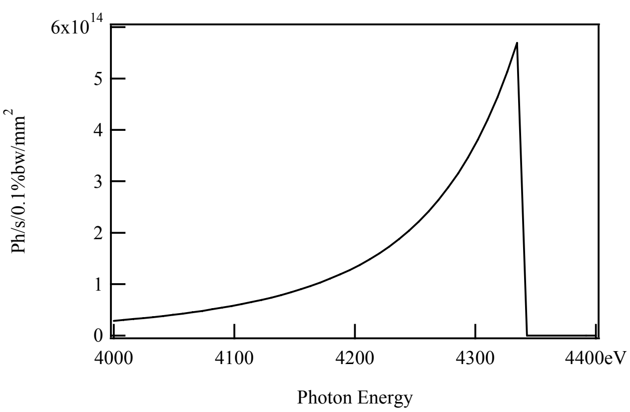

Figure 7: On-axis flux density for APS first harmonic.

Intensity Distribution

For comparison, the intensity distributions of APS and CEBAF's first harmonic on-momentum photon are displayed in Fig. 8 and 9.

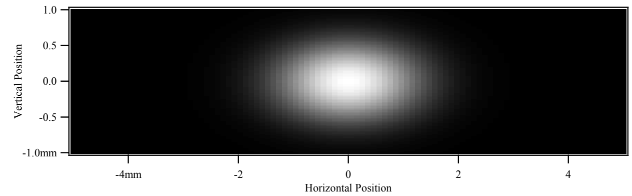

Figure 8: Intensity distribution of APS's first harmonic on-momentum photon.

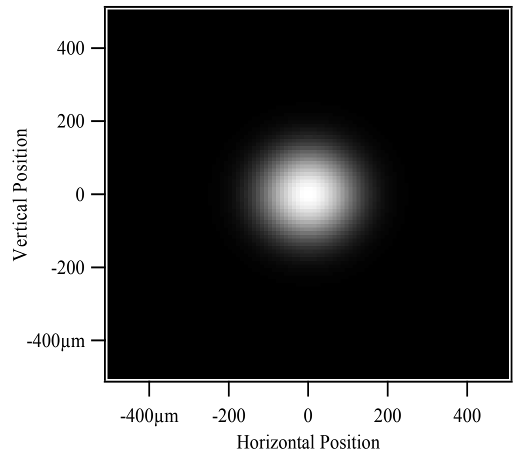

Figure 9: Intensity distribution of CEBAF's first harmonic on-momentum photon.

SUMMARY

8.4 GeV CEBAF with 3.5 m ILC helical undulator produces same flux density, higher brilliance than APS, and UR from CEBAF for all cases have much narrower bandwidth due to low emittance, therefore, an optics-free beam line is possible. The performance of multi-energy mode UR at CEBAF is better than APS.

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