Beam Parameters, Spectral Brightness, Harmonics and Wiggler Radiation

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(http://www.coe.berkeley.edu/AST/srms)
Finite Electron Beam Size and Divergence Affect Undulator Radiation

Preserving the spectral line shape of undulator radiation requires

\[ \sigma'^2 \ll \theta_{cen}^2 \]  \hspace{1cm} (5.55b)

Define effective, or total central cone half-angles

\[ \theta_{Tx} = \sqrt{\theta_{cen}^2 + \sigma_x'^2} \quad \text{and} \quad \theta_{Ty} = \sqrt{\theta_{cen}^2 + \sigma_y'^2} \]  \hspace{1cm} (5.56)
Brightness and Spectral Brightness

Brightness is defined as radiated power per unit area and per unit solid angle at the source:

\[
B = \frac{\Delta P}{\Delta A \cdot \Delta \Omega} \tag{5.57}
\]

Brightness is a conserved quantity in perfect optical systems, and thus is useful in designing beamlines and synchrotron radiation experiments which involve focusing to small areas.

Spectral brightness is that portion of the brightness lying within a relative spectral bandwidth \(\Delta \omega/\omega\):

\[
B_{\Delta \omega/\omega} = \frac{\Delta P}{\Delta A \cdot \Delta \Omega \cdot \Delta \omega/\omega} \tag{5.58}
\]
The Synchrotron radiation community prefers to express spectral brightness in units of photons/sec, rather than power, and has standardized on a relative spectral bandwidth of $\Delta \omega / \omega = 10^{-3}$, or 0.1% BW. To obtain a relationship for spectral brightness of undulator radiation we can use our expression for $\tilde{P}_{\text{cen}}$, radiated into a solid angle $\Delta \Omega = \pi \theta_{\text{cen}}^2 = \pi \theta_T \theta_T$, from an elliptically shaped source area of $\Delta A = \pi \sigma_x \sigma_y$, and within a relative spectral bandwidth $\Delta \omega / \omega = 1/N$. Defining the photon flux in the central radiation cone as

$$\tilde{F}_{\text{cen}} = \frac{\tilde{P}_{\text{cen}}}{h \omega / \text{photon}}$$

(5.59)

$$\tilde{B}_{\Delta \omega / \omega} = \frac{\tilde{F}_{\text{cen}}}{\Delta A \cdot \Delta \Omega \cdot N^{-1}} = \frac{\tilde{F}_{\text{cen}} \cdot (N/1000)}{\Delta A \cdot \Delta \Omega \cdot (0.1\% \text{BW})}$$

(5.60)

on-axis

$$\tilde{B}_{\Delta \omega / \omega}(0) = \frac{\tilde{F}_{\text{cen}} \cdot (N/1000)}{2\pi^2 \sigma_x \sigma_y \theta_T \theta_T (0.1\% \text{BW})}$$

(5.64)

or

$$\tilde{B}_{\Delta \omega / \omega}(0) = \frac{7.25 \times 10^6 y^2 N^2 I(A)}{\sigma_x (\text{mm}) \sigma_y (\text{mm}) \left(1 + \frac{\sigma_x'}{\theta_{\text{cen}}^2}\right)^{1/2} \left(1 + \frac{\sigma_y'}{\theta_{\text{cen}}^2}\right)^{1/2}} \cdot \frac{K^2 f(K)}{(1 + K^2/2)^2} \frac{\text{photons/s}}{\text{mm}^2 \text{mrad}^2 (0.1\% \text{BW})}$$

(5.65)

Assumes $\sigma^2 << \theta_{\text{cen}}^2$. Note the $N^2$ factor.
Spectral Brightness is Useful for Experiments that Involve Spatially Resolved Studies

- Brightness is conserved (in lossless optical systems)

\[
\theta_{\text{source}} \cdot d_{\text{source}} = \theta_{\text{optic}} \cdot d_{\text{focus}}
\]

- Starting with many photons in a small source area and solid angle, permits high photon flux in an even smaller area

1-2 GeV Undulators

6-8 GeV Undulators

Wigglers

Bending magnets

Photon energy

Spectral brightness

10 eV 100 eV 1 keV 10 keV 100 keV

10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}

12 nm 1.2 nm 0.12 nm
Comments on Undulator Harmonics

First and second harmonic motions

Radiation patterns in the electron and laboratory frames

\[
\lambda_n = \frac{\lambda_u}{2\gamma^2 n} \left( 1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) \quad (5.30)
\]

\[
\left( \frac{\Delta \lambda}{\lambda} \right)_n = \frac{1}{nN} \quad (5.31)
\]
Undulator Harmonics

Recall that the axial velocity has a double frequency component

\[ v_z = c \left[ 1 - \frac{1 + K^2/2}{2\gamma^2} + \frac{K^2}{4\gamma^2} \cos(2k_u z) \right] \]

which in the frame of reference moving with the electrons, gives

\[ z'(t') \simeq \frac{K^2}{8k'_u} \sin 2\omega'_u t' \] (5.70)

where \( k'_u = \gamma^* k_u \) and \( \omega'_u = \gamma^* \omega_u \). The transverse motion in this frame is

\[ x'(t') \simeq -\frac{K}{k'_u \gamma^*} \cos \omega_u \gamma^* \left( t' + \frac{z'}{c} \right) \]

To a higher degree of accuracy, we now keep the \( z'/c \) term

\[ x'(t') \simeq -\frac{K}{k'_u} \cos \left( \omega'_u t' + \frac{K^2}{8} \sin 2\omega'_u t' \right) \] (5.71)

for small \( K \)

\[ x'(t') \simeq -\frac{1}{k'_u} \left[ K \cos \omega'_u t' + \frac{K^3}{16} \cos 3\omega'_u t' \right] \] (5.72)

Taking second derivatives to find acceleration, and squaring \( |a'(t')|^2 \)

\[ \frac{dP'}{d\Omega'} \propto n^4 K^{2n} \]

Thus harmonics grow very rapidly for \( K > 1 \).
The Transition from Undulator Radiation \((K \leq 1)\) to Wiggler Radiation \((K >> 1)\)

Undulator radiation \((K \leq 1)\)
- Narrow spectral lines
- High spectral brightness
- Partial coherence

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2 \gamma^2}{2} \right) \]

Wiggler radiation \((K >> 1)\)
- Higher photon energies
- Spectral continuum
- Higher photon flux \((2N)\)

\[ \omega_c = \frac{3}{2} \frac{\hbar K^2 eB_o}{m} \]

\[ n_c = \frac{3K}{4} \left( 1 + \frac{K^2}{2} \right) \]

\(\lambda_u = 5 \text{ cm}, N = 89\)

\(\lambda_u = 6.0 \text{ cm}\)

(Elettra
2 GeV
0.4 A
\(\lambda_u = 6.0 \text{ cm}\)

\(N = 72\)

\(K = 3.7\)

\(n_c = 22\)

(Courtesy of K.-J. Kim)

(Courtesy of R.P. Walker and B. Diviacco)
For Very Large $K >> 1$, and Large $Dq$, a Continuum Emerges

- $\alpha \neq 0$ (finite $\sigma'$)
- finite $\Delta\theta$
- Central radiation cone \( \frac{1}{\gamma^* \sqrt{N}} \)
- Even harmonics appear for large $k$. 

\[
\frac{dP}{d\Omega}
\]

- Frequency ($f$)
- $1/N$
- $f_1$
- $f_3$
- $f_n$
- $f_n + 2$
Wiggler Radiation

At very high \( K >> 1 \), the radiated energy appears in very high harmonics, and at rather large horizontal angles \( \theta \approx \pm K/\gamma \) (eq. 5.21). Because the emission angles are large, one tends to use larger collection angles, which tends to spectrally merge nearby harmonics. The result is a continuum at very high photon energies, similar to that of bending magnet radiation, but increased by \( 2N \) (the number of magnet pole pieces).

\[
E_c = \hbar \omega_c = \frac{3e \hbar B \gamma^2}{2m} ; \quad n_c = \frac{3K}{4} \left( 1 + \frac{K^2}{2} \right) \tag{5.7a & 82}
\]

\[
\left. \frac{d^2 F}{d\theta d\psi d\omega/\omega} \right|_0 = 2.65 \times 10^{13} N E_e^2(\text{GeV}) I(A) H_2(E/E_c) \frac{\text{photons/s}}{\text{mrad}^2(0.1\%\text{BW})} \tag{5.86}
\]

\[
\frac{d^2 F}{d\theta d\omega/\omega} = 4.92 \times 10^{13} N E_e(\text{GeV}) I(A) G_1(E/E_c) \frac{\text{photons/s}}{\text{mrad} \cdot (0.1\%\text{BW})} \tag{5.87}
\]
Stanford Permanent Magnet Wiggler

LBNL/EXXON/SSRL (1982), SSRL Beamline VI
55 pole (N = 27.5), $\lambda_w = 7$ cm
Typical Parameters for Synchrotron Radiation

<table>
<thead>
<tr>
<th>Facility</th>
<th>ALS</th>
<th>ELETTRA</th>
<th>Australian Synchrotron</th>
<th>APS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy (GeV)</td>
<td>1.90</td>
<td>2.0</td>
<td>3.0</td>
<td>7.0</td>
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<tr>
<td>Current (mA)</td>
<td>400</td>
<td>300</td>
<td>200</td>
<td>100</td>
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<tr>
<td>Circumference (m)</td>
<td>197</td>
<td>259</td>
<td>216</td>
<td>1100</td>
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<tr>
<td>RF frequency (MHz)</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>352</td>
</tr>
<tr>
<td>Pulse duration (ps)</td>
<td>35-70</td>
<td>37</td>
<td>~100</td>
<td>100</td>
</tr>
</tbody>
</table>

**Bending Magnet Radiation:**

| Bending magnet field (T)  | 1.27       | 1.2        | 1.31                    | 0.599     |
| Critical photon energy (keV) | 3.05      | 3.2        | 7.84                    | 19.5      |
| Critical photon wavelength | 0.407 nm  | 0.39 nm    | 1.58 Å                  | 0.636 Å   |

**Undulator Radiation:**

| Number of straight sections | 12         | 12         | 14                      | 40        |
| Undulator period (cm)      | 5.00       | 5.6        | 22.0                    | 3.30      |
| Number of periods          | 89         | 81         | 80                      | 72        |
| Photon energy ($K = 1, n = 1$) (eV) | 457       | 452 eV    | 2.59 keV                | 9.40 keV  |
| Photon wavelength ($K = 1, n = 1$) | 2.71 nm    | 2.74 nm    | 0.478 nm                | 1.32 Å    |
| Tuning range ($n = 1$)     | 230-620 eV | 2.0-6.7 nm | 0.319-0.835 nm          | 3.5-12 keV |
| Tuning range ($n = 3$)     | 690-1800 eV| 0.68-2.2 nm| 0.106-0.278 nm          | 10-38 keV |
| Central cone half-angle ($K = 1$) | 35 µrad   | 35 µrad   | 23 µrad                 | 11 µrad   |
| Power in central cone ($K = 1, n = 1$) (W) | 2.3       | 1.7        | 6.6                     | 12        |
| Flux in central cone (photons/s) | $3.1 \times 10^{16}$ | $2.3 \times 10^{16}$ | $1.6 \times 10^{16}$ | $7.9 \times 10^{15}$ |
| Brightness ($K = 1, n = 1$)$^a$ | $2.3 \times 10^{19}$ | $9.9 \times 10^{18}$ | $1.3 \times 10^{19}$ | $5.9 \times 10^{18}$ |
| Total power ($K = 1, n, all \theta$) (W) | 83         | 126        | 476                     | 350       |
| Other undulator periods (cm) | 3.65, 8.00, 10.0 | 8.0, 12.5 | 6.8, 18.3              | 2.70, 5.50, 12.8 |

**Wiggler Radiation:**

| Wiggler period (cm)       | 16.0       | 14.0       | 6.1                     | 8.5       |
| Number of periods         | 19         | 30         | 30                      | 28        |
| Magnetic field (T)        | 2.1        | 1.5        | 1.9                     | 1.0       |
| Critical photon energy (keV) | 5.1        | 4.0        | 11.4 keV                | 33        |
| Critical photon wavelength | 0.24 nm    | 0.31 nm    | 0.11 nm                 | 0.38 Å    |
| Total power (max. $K$) (kW) | 13         | 7.2        | 9.3                     | 7.4       |

$^a$Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma_{x,y} = \theta_{cen}$. 

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Univ. California, Berkeley
# Typical Parameters for Synchrotron Radiation

<table>
<thead>
<tr>
<th>Facility</th>
<th>ALS</th>
<th>MAX II</th>
<th>BESSY II</th>
<th>APS</th>
<th>ESRF</th>
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<tbody>
<tr>
<td>Electron energy</td>
<td>1.90 GeV</td>
<td>1.50 GeV</td>
<td>1.70 GeV</td>
<td>7.00 GeV</td>
<td>6.04 GeV</td>
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<td>$\gamma$</td>
<td>3720</td>
<td>2940</td>
<td>3330</td>
<td>13,700</td>
<td>11,800</td>
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<tr>
<td>Current (mA)</td>
<td>400</td>
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<td>100</td>
<td>200</td>
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<td>Circumference (m)</td>
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<td>884</td>
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<td>RF frequency (MHz)</td>
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<td>352</td>
<td>352</td>
</tr>
<tr>
<td>Pulse duration (FWHM) (ps)</td>
<td>35-70</td>
<td>200</td>
<td>20-50</td>
<td>100</td>
<td>70</td>
</tr>
</tbody>
</table>

**Bending Magnet Radiation:**
- Bending magnet field (T): 1.27, 1.48, 1.30, 0.599, 0.806
- Critical photon energy (keV): 457, 274, 373, 9.40 keV, 5.50 keV
- Critical photon wavelength: 2.71 nm, 4.53 nm, 3.32 nm, 1.32 Å, 0.225 nm
- Bending magnet sources: 24, 20, 32, 35, 32

**Undulator Radiation:**
- Number of straight sections: 12, 10, 16, 40, 32
- Undulator period (typical) (cm): 5.00, 5.20, 4.90, 3.30, 4.20
- Number of periods: 89, 49, 84, 72, 38
- Photon energy ($K = 1, n = 1$): 457 eV, 274 eV, 373 eV, 9.40 keV, 5.50 keV
- Photon wavelength ($K = 1, n = 1$): 2.71 nm, 4.53 nm, 3.32 nm, 1.32 Å, 0.225 nm
- Tuning range ($n = 1$): 230-620 eV, 130-410 eV, 140-500 eV, 3.5-12 keV, 2.6-7.3 keV
- Tuning range ($n = 3$): 690-1800 eV, 400-1200 eV, 410-1100 eV, 10-38 keV, 7.7-22 keV
- Central cone half-angle ($K = 1$): 35 µrad, 59 µrad, 33 µrad, 11 µrad, 17 µrad
- Power in central cone ($K = 1, n = 1$) (W): 2.3, 0.88, 0.95, 12, 14
- Flux in central cone ($K = 1, n = 1$) (photons/s): $3.1 \times 10^{16}$, $2.0 \times 10^{16}$, $1.6 \times 10^{16}$, $7.9 \times 10^{15}$, $1.6 \times 10^{16}$
- Brightness ($K = 1, n = 1$): $2.3 \times 10^{19}$, $7.8 \times 10^{17}$, $4.6 \times 10^{18}$, $5.9 \times 10^{18}$, $5.1 \times 10^{18}$

**Wiggler Radiation:**
- Wiggler period (typical) (cm): 16.0, 17.4, 12.5, 8.5, 8.0
- Number of periods: 19, 13, 32, 28, 20
- Magnetic field (maximum) (T): 2.1, 1.80, 1.15, 1.0, 0.81
- $K$ (maximum): 32, 29.3, 12.8, 7.9, 6.0
- Critical photon energy (keV): 5.1, 2.69, 2.11, 33, 20
- Critical photon wavelength (å): 0.24 nm, 0.46 nm, 0.59 nm, 0.38 Å, 0.62 Å
- Total power (max. $K$) (kW): 13, 5.9, 1.8, 7.4, 4.8

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*a* Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma_{x,y}^{\theta} = \theta_{cen}$.
## Typical Parameters for Synchrotron Radiation

<table>
<thead>
<tr>
<th>Facility</th>
<th>ALS</th>
<th>New Subaru</th>
<th>APS</th>
<th>SP-8</th>
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</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>1.90 GeV</td>
<td>1.00 GeV</td>
<td>7.00 GeV</td>
<td>8.00 GeV</td>
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<td>$\gamma$</td>
<td>3720</td>
<td>1957</td>
<td>13,700</td>
<td>15,700</td>
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<tr>
<td>Current (mA)</td>
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<td>100</td>
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<td>Circumference (m)</td>
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<td>RF frequency (MHz)</td>
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<td>509</td>
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<td>Pulse duration (FWHM) (ps)</td>
<td>35-70</td>
<td>26</td>
<td>100</td>
<td>120</td>
</tr>
</tbody>
</table>

### Bending Magnet Radiation:
- Bending magnet field (T)
  - ALS: 1.27
  - New Subaru: 1.03
  - APS: 0.599
  - SP-8: 0.679
- Critical photon energy (keV)
  - ALS: 3.05
  - New Subaru: 0.685
  - APS: 19.5
  - SP-8: 28.9
- Critical photon wavelength
  - ALS: 0.407 nm
  - New Subaru: 1.81 nm
  - APS: 0.636 Å
  - SP-8: 0.429 Å
- Bending magnet sources
  - ALS: 24
  - New Subaru: 4
  - APS: 35
  - SP-8: 23

### Undulator Radiation:
- Number of straight sections
  - ALS: 12
  - New Subaru: 4
  - APS: 40
  - SP-8: 48
- Undulator period (typical) (cm)
  - ALS: 5.00
  - New Subaru: 5.40
  - APS: 3.30
  - SP-8: 3.20
- Number of periods
  - ALS: 89
  - New Subaru: 200
  - APS: 72
  - SP-8: 140
- Photon energy ($K = 1, n = 1$)
  - ALS: 457 eV
  - New Subaru: 117 eV
  - APS: 9.40 keV
  - SP-8: 12.7 keV
- Photon wavelength ($K = 1, n = 1$)
  - ALS: 2.71 nm
  - New Subaru: 10.6 nm
  - APS: 1.32 Å
  - SP-8: 0.979 Å
- Tuning range ($n = 1$)
  - ALS: 230-620 eV
  - New Subaru: 43-170 eV
  - APS: 3.5-12 keV
  - SP-8: 4.7-19 keV
- Tuning range ($n = 3$)
  - ALS: 690-1800 eV
  - New Subaru: 130-500 eV
  - APS: 10-38 keV
  - SP-8: 16-51 keV
- Central cone half-angle ($K = 1$)
  - ALS: 35 µrad
  - New Subaru: 44 µrad
  - APS: 11 µrad
  - SP-8: 6.6 µrad
- Power in central cone ($K = 1, n = 1$) (W)
  - ALS: 2.3
  - New Subaru: 0.15
  - APS: 12
  - SP-8: 16
- Flux in central cone (photons/s)
  - ALS: $3.1 \times 10^{16}$
  - New Subaru: $7.9 \times 10^{15}$
  - APS: $7.9 \times 10^{15}$
  - SP-8: $7.9 \times 10^{15}$
- $\sigma_x, \sigma_y$ (µm)
  - ALS: 260
  - New Subaru: 450
  - APS: 320
  - SP-8: 380
- $\sigma_z^0, \sigma_{y}^0$ (µrad)
  - ALS: 23.3
  - New Subaru: 89
  - APS: 23.7
  - SP-8: 16.8
- Brightness ($K = 1, n = 1$)$^a$
  - [(photons/s)/mm$^2$ · mrad$^2$ · (0.1%BW)]
  - ALS: $2.3 \times 10^{19}$
  - New Subaru: $1.7 \times 10^{17}$
  - APS: $5.9 \times 10^{18}$
  - SP-8: $1.8 \times 10^{20}$
- Total power ($K = 1, all n, all \theta$) (W)
  - ALS: 83
  - New Subaru: 27
  - APS: 350
  - SP-8: 2000
- Other undulator periods (cm)
  - ALS: 3.65, 8.00, 10.0
  - New Subaru: 7.60
  - APS: 2.70, 5.50, 12.8
  - SP-8: 2.4, 10.0, 3.7, 12.0

### Wiggler Radiation:
- Wiggler period (typical) (cm)
  - ALS: 16.0
  - New Subaru: 8.5
  - APS: 12.0
- Number of periods
  - ALS: 19
  - New Subaru: 28
  - APS: 37
- Magnetic field (maximum) (T)
  - ALS: 2.1
  - New Subaru: 1.0
  - APS: 1.0
- $K$ (maximum)
  - ALS: 32
  - New Subaru: 7.9
  - APS: 11
- Critical photon energy (keV)
  - ALS: 5.1
  - New Subaru: 33
  - APS: 43
- Critical photon wavelength
  - ALS: 0.24 nm
  - New Subaru: 0.38 Å
  - APS: 0.29 Å
- Total power (max. $K$) (kW)
  - ALS: 13
  - New Subaru: 7.4
  - APS: 18

$^a$Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma_x^0, \sigma_y^0 \approx \theta_{cen}$. 

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Beam Parameters, Spectral Brightness, Harmonics and Wiggler Radiation, EE290F, 20 Feb 2007  
Ch05_T1b_VG_Nov05.ai
Beamlines are Used to Transport Photons to the Sample, and Take a Desired Spectral Slice

- Photon flux
  - \( h\omega \)
  - Grating or crystal
  - Monochromator
  - Curved focusing mirror (glancing incidence reflection)

Observe at sample:
- Absorption spectra
- Photoelectron spectra
- Diffraction

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Beam Parameters, Spectral Brightness, Harmonics and Wiggler Radiation, EE290F, 20 Feb 2007
A Typical Beamline: Monochromator Plus Focusing Optics to Deliver Radiation to the Sample

Courtesy of James Underwood (EUV Technology Inc.)
Sample

- Vertical focusing mirror
- Horizontal deflection/focusing mirror
- Translating exit slit
- Spherical grating
- Translating entrance slit
- Vertical focusing mirror

- Horizontal focusing mirror

- Elliptically Polarizing Undulator
The axial electric field within the RF cavity, used to replenish lost (radiated) energy, forms a potential well “bucket” system that forces electrons into axial electron “bunches”. This leads to a time structure in the emitted radiation.

E = 1.90 GeV  
C = 197 m  
I = 400 mA

328 buckets available, nominally operated with some fraction unfilled. \( \Gamma_{\text{FWHM}} \approx 35 \text{ ps (nominal)} \)

\( V_{\text{RF}} \) (500 MHz RF)

\( \sigma_\tau \) (rms)

\( \Gamma_{\text{FWHM}} = 2.35 \sigma_\tau \)
Variable Polarization Undulator Radiation

(Courtesy of Kwang-Je Kim)

(Following S. Sasaki)
## What are the Relative Merits?

<table>
<thead>
<tr>
<th>Bending magnet radiation</th>
<th>Wiggler radiation</th>
<th>Undulator radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad spectrum</td>
<td>Higher photon energies</td>
<td>Brighter radiation</td>
</tr>
<tr>
<td>Good photon flux</td>
<td>More photon flux</td>
<td>Smaller spot size</td>
</tr>
<tr>
<td>No heat load</td>
<td>Expensive magnet structure</td>
<td>Partial coherence</td>
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<tr>
<td>Less expensive</td>
<td>Expensive cooled optics</td>
<td>Expensive</td>
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<td>Easier access</td>
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</table>

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References