Future Synchrotron Light Sources Based on Ultimate Storage Rings

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JLab, Newport News, VA, USA
3rd Generation Light Sources

Existing

ESRF
SSRF

Under construction

NLSL-II
Max-IV
Storage Ring Light Sources

Energy (GeV)

Emittance (nm)

Courtesy of R. Bartolini, Low Emittance Rings Workshop, 2010, CERN
Synchrotron Radiation

Electron beam in undulator

Photon spectral flux in 0.1% BW

$n^{th}$ harmonic wavelength:

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

$$F_n = \frac{\pi}{2} \alpha \gamma_n Q_n \left( \frac{nK^2}{4 + 2K^2} \right) \frac{\Delta\omega I}{\omega e}$$
Spectral Brightness

Brightness of electron beam radiating at \(n^{th}\) (odd) harmonics in a undulator is given by

\[
B_n = \frac{F_n}{(4\pi^2 \sum_x \sum_x' \sum_y \sum_y')}
\]

If the electron beam phase space is matched to those of photon’s, the brightness becomes optimized

\[
B_n = \frac{F_n}{4\pi^2 (\varepsilon_x + \lambda_n / 4\pi)(\varepsilon_y + \lambda_n / 4\pi)}
\]

Finally, even for zero emittances, there is an ultimate limit for the brightness

\[
B_n = \frac{4F_n}{\lambda_n^2}
\]

Spectral brightness of PEP-X

A diffraction limited ring at 1 angstrom or 10 pm-rad emittance
USRs - Spectral Brightness

Brightness Envelopes
not including SC IDs

1. ALS upgrade: 1.9 GeV, 0.5 A, 195 m
   2200 x 30 pm-rad, 4-4.5 m IDs

2. NSLS-II: 3 GeV, 0.5 A, 792 m
   600 x 8 pm-rad, 3-4 m IDs

3. MAX-IV: 3 GeV, 0.5 A, 528 m
   263 x 8 pm-rad, 3.8 m IDs

4. PETRA III: 6 GeV, 0.1 A, 2304 m
   1000 x 10 pm-rad, 5 m IDs

5. APS upgrade: 7 GeV, 0.18 A, 1060 m
   2500 x 8 pm-rad, 4.8 m IDs

6. Cornell ERL: 5 GeV, ~3150 m
   30 x 30 pm-rad, 0.1 A or
   8 x 8 pm-rad, 0.025 A

7. SDLS: 2 GeV, 0.5 A, 250 m
   40 x 40 pm-rad, 4 m IDs

8. PEP-X: 4.5 GeV, 0.2 A, 2200 m
   11 x 11 pm-rad, 4 m IDs

9. USR7: 7 GeV, 0.2 A, 3160 m
   15 x 15 pm-rad, 8 m IDs

10. TevUSR: 11 GeV, 0.1 A, 6283 m
    1.3 x 1.3 pm-rad, 4 m IDs

Courtesy of R. Hettel
<table>
<thead>
<tr>
<th>Parameter</th>
<th>PEP-X</th>
<th>Spring8-II</th>
<th>TeVUSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>4.5</td>
<td>6.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Circumference [m]</td>
<td>2200</td>
<td>1436</td>
<td>6283</td>
</tr>
<tr>
<td>Current [mA]</td>
<td>200</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Betatron tune (H/V)</td>
<td>113.23/65.14</td>
<td>141.865/36.65</td>
<td>403.098/222.198</td>
</tr>
<tr>
<td>Natural chromaticity (H/V)</td>
<td>-162/-130</td>
<td>-477/-191</td>
<td>-580/-468</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>4.96x10^{-5}</td>
<td>1.55x10^{-5}</td>
<td>4.47x10^{-6}</td>
</tr>
<tr>
<td>Emittance [pm-rad]</td>
<td>12/12</td>
<td>68 (natural)</td>
<td>1/1</td>
</tr>
<tr>
<td>Bunch length [mm]</td>
<td>3</td>
<td>3.8</td>
<td>3</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1.25x10^{-3}</td>
<td>0.96x10^{-3}</td>
<td>1.4x10^{-3}</td>
</tr>
<tr>
<td>Energy loss per turn [MeV]</td>
<td>2.95</td>
<td>4.0</td>
<td>18</td>
</tr>
<tr>
<td>RF voltage [MV]</td>
<td>8.3</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>476</td>
<td>508</td>
<td>500</td>
</tr>
<tr>
<td>Wiggler length [m]</td>
<td>90</td>
<td>50 (may be)</td>
<td>188</td>
</tr>
<tr>
<td>Length of ID straight [m]</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Beta at ID center (H/V) [m]</td>
<td>4.9/0.8</td>
<td>1.0/1.4</td>
<td>5/0.8</td>
</tr>
</tbody>
</table>
Energy Spread and Emittance

Balance between the quantum excitation and radiation damping results in an equilibrium Gaussian distribution with relative energy spread \( \sigma_\delta \) and horizontal emittance \( \varepsilon_x \):

\[
\sigma_\delta^2 = \frac{\tau_s}{2E_0^2} < \dot{N}_{ph} < u^2 > >_s = C_q \frac{\gamma^2}{J_s} \left\langle 1/\rho^3 \right\rangle_s,
\]

\[
\varepsilon_x = \frac{\tau_x}{4E_0^2} < \dot{N}_{ph} < u^2 > \mathcal{H}_x >_s = C_q \frac{\gamma^2}{J_x} \left\langle \mathcal{H}_x/\rho^3 \right\rangle_s,
\]

where

\[
C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}, \quad \mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'_x^2
\]

- The quantum constant \( C_q = 3.8319 \times 10^{-13} \) m for electron
- \( \gamma \) is the Lorentz factor (energy)
Minimization of Emittance

For an electron ring without damping wigglers, the horizontal emittance is given by

\[ \varepsilon_0 = F_c \frac{C_q \gamma^2}{J_x} \theta^3 \]

where \( F_c \) is a form factor determined by choice of cell and \( q \) is bending angle of dipole magnet in cell. In general, stronger focusing makes \( F_c \) smaller. Often there is a minimum achievable value of \( F_c \) for any a given type of cell. For example, we have

\[ F_{min}^{DBA} = \frac{1}{4\sqrt{15}} \]
\[ F_{min}^{TME} = \frac{1}{12\sqrt{15}} \]

There is a factor of three between the minimum values of DBA and TME cells. That's the price paid for an achromat, namely fixing the dispersion and its slop at one end of dipole.
7 Bend Achromat, at 3 GeV

Innovations:

• **Multi-bend achromat**
• **Compact and combined function magnets**
• **Octupoles**

**FIG. 6. (Color) Illustration of the unit cell dipole magnet block.** The common iron block integrates the unit cell dipole and the two flanking defocusing sextupoles. Further integration of the unit cell focusing quadrupoles and focusing sextupole is presently under consideration.
PEP-X Layout & Parameters

An ultimate storage ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV</td>
<td>4.5</td>
</tr>
<tr>
<td>Circumference, m</td>
<td>2199.32</td>
</tr>
<tr>
<td>Natural emittance, pm</td>
<td>11</td>
</tr>
<tr>
<td>Beam current, mA</td>
<td>200</td>
</tr>
<tr>
<td>Emittance at 200 mA, x/y, pm</td>
<td>12 / 12</td>
</tr>
<tr>
<td>Tunes, x/y/s</td>
<td>113.23 / 65.14 / 0.007</td>
</tr>
<tr>
<td>Bunch length, mm</td>
<td>3.1</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1.25x10^-3</td>
</tr>
<tr>
<td>Energy loss per turn, MeV</td>
<td>2.95</td>
</tr>
<tr>
<td>RF voltage, MV</td>
<td>8.3</td>
</tr>
<tr>
<td>RF harmonic number</td>
<td>3492</td>
</tr>
<tr>
<td>Length of ID straight, m</td>
<td>5.0</td>
</tr>
<tr>
<td>Wiggler length, m</td>
<td>90.0</td>
</tr>
<tr>
<td>Beta at ID center, x/y, m</td>
<td>4.92 / 0.80</td>
</tr>
<tr>
<td>Touschek lifetime, hour, hour</td>
<td>10</td>
</tr>
<tr>
<td>Dynamic aperture, mm</td>
<td>10</td>
</tr>
</tbody>
</table>

To be Built with 4th-order geometrical achromats in the PEP tunnel.
PEP-X 7 Bend Achromat

Cell phase advances: $\mu_x = (2 + 1/8) \times 360^\circ$, $\mu_y = (1 + 1/8) \times 360^\circ$. 
Resonance in Storage Rings

Dynamic aperture in a two-dimensional tune scan for the baseline design of PEP-X (2008).

Where these resonances come from?
Presentations for Magnetic Elements

Lie factors

Dragt-Finn

Taylor map

TPSA

Symplectic Integrator

\[
\mathcal{M}^n(z) = \prod_{i=1}^{n} e^{\frac{H_0}{2} \Delta s} e^{-\frac{H_1}{2} \Delta s} e^{-\frac{H_0}{2} \Delta s}
\]

- engine in MARYLIE (A. Dragt)
  - violates symplecticity when evaluates

- engine in TRANSPORT, MAD, COSY (K. Brown and M. Berz), simple R-matrix
  - but high-order one violates

- engine in TEAPOT, SAD, TRACY, LEGO, PTC (E. Forest, R. Ruth, and K. Hirata)
  - preserves symplecticity
  - simple and based on several known solutions
  - emphasis on numerical process

3/5/2012 Yunhai Cai, SLAC
Cancellation of All Geometric $3^{rd}$ and $4^{th}$ Resonances Driven by Strong Sextupoles except $2\nu_x - 2\nu_y$

There are still three tune shift terms.

K.L. Brown & R.V. Servranckx


Yunhai Cai

Harmonic Sextupoles
For Tune Shifts and $2\nu_x-2\nu_y$ Resonance

Without harmonic sextupoles

With harmonic sextupoles

OPA is used for optimizing the setting of 10 families of sextupoles. Due to the cancellation of many resonances, the optimization becomes much simpler and easier. OPA is an Accelerator Design Program from SLS PSI developed by A. Streun.
There are 4 families of chromatic sextupoles and 6 families of harmonic ones. The 4th order geometric achromat ($f_3=f_4=0$) was obtained with the analytical Lie method. It was documented in SLAC-PUB-14785 and submitted to PRSTAB.
The dynamic aperture is in unit of sigma of the equilibrium beam size. The USR design is built with 4th-order geometric achromats and therefore no 3rd and 4th order resonances driven by the sextupoles seen in the scan.
The dynamic aperture is in unit of mm at the injection. The baseline design has a factor of ten larger emittance than the one in the USR design.
Reduce Emittance with Damping Wigglers

Emittance = 11 pm-rad at 4.5 GeV with parameters $\lambda_w=5$ cm, $B_w=1.5$ T

Wiggler Field Optimization

Wiggler Length Optimization

Average beta function at the wiggler section is 12.4 meter.
Dynamic Aperture with Machine Errors

ELEGANT Tracking

LEGO Tracking

1% coupling & 1% beta beating

Misalignments 20 microns in x.
Intra-Beam Scattering

The growth rate in the relative energy spread $\sigma_\delta$ is given by

$$\frac{1}{T_p} = \frac{r_e^2 c N_b (\log)}{16 \gamma^3 \epsilon_x \epsilon_y \sigma_z \sigma_\delta^3} < \sigma_H g(\alpha) (\sigma_x \sigma_y)^{-1/2} >,$$

where $N_b$ is the bunch population and $(\log)$ the Coulomb log factor and the other factors are defined by

$$\frac{1}{\sigma_H^2} = \frac{1}{\sigma_\delta^2} + \frac{\mathcal{H}_x}{\epsilon_x}, \alpha = \sqrt{\frac{\epsilon_y \beta_x}{\epsilon_x \beta_y}},$$

$$g(\alpha) = \alpha^{(0.021 - 0.044 \ln \alpha)}.$$

And the horizontal growth rate is given by

$$\frac{1}{T_x} = \frac{\sigma_\delta^2}{\epsilon_x} < \mathcal{H}_x \Delta \left( \frac{1}{T_p} \right).$$

Combined with synchrotron radiation

$$\epsilon_x = \frac{\epsilon_{x0}}{1 - \tau_x/T_x}, \sigma_\delta^2 = \frac{\sigma_{\delta0}^2}{1 - \tau_s/T_p},$$

$$\epsilon_y = \kappa \epsilon_x.$$
Optimization of Energy

![Graph showing the relationship between energy (E in MeV) and emittance (in pm)]
When a pair of electrons go through a hard scattering, their momentum changes are so large that they are outside the RF bucket or the momentum aperture. This process results in a finite lifetime of a bunched beam. The lifetime is given by

\[
\frac{1}{\tau} = \frac{r_e^2 e N_b}{8\sqrt{\pi} \gamma^4 \delta \varepsilon_x \varepsilon_y \sigma_z \sigma_\delta} \langle \sigma_H F(\delta_m) \rangle ,
\]

with

\[
F(\delta_m) = \int_{\delta_m^2}^{\infty} \frac{d\tau}{\tau^{3/2}} e^{-\tau B_x} I_0(\tau B_x) \left[ \frac{\tau}{\delta_m^2} - 1 - \frac{1}{2} \ln \left( \frac{\tau}{\delta_m^2} \right) \right],
\]

\[
B_\pm = \frac{1}{2\gamma^2} \left| \frac{\beta_x (\beta_x \varepsilon_x + \eta_x^2 \sigma_\delta^2) + \beta_y \varepsilon_y}{\varepsilon_x (\beta_x \varepsilon_x + \beta_x \eta_x^2 \sigma_\delta^2) \pm \eta_y \varepsilon_y} \right|,
\]

where \( \delta_m \) is the momentum acceptance.
Achievements

• We have developed an excellent design of an ultimate storage ring
  – Diffraction limit at 1 angstrom
  – Reasonable beam current 200 mA
  – Good beam lifetime 3 hours
  – Good injection with 10 mm acceptance
  – Achievable machine tolerances 20 microns
General R&D Items for Ultimate Storage Rings

1. Better understanding of beam dynamics
2. How to make a round beam in storage ring
3. New injection scheme for smaller dynamic aperture
4. Compact and strong magnets (sextupoles)
5. Higher harmonic RF system
6. Precise magnet alignment
7. Accurate beam position monitors
8. Undulator with shorter period

Lengthen the beam
Beyond the Ultimate Brightness

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PEP-X</th>
<th>LCLS-(1.5nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Normalized emittance [um-rad]</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Peak current [A]</td>
<td>17</td>
<td>500-3000</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1.25x10^{-3}</td>
<td>(0.5-3.0)x10^{-4}</td>
</tr>
</tbody>
</table>

- Increase the peak current by much stronger longitudinal focusing
  - 1.5 GHz, 200 MV CW SCRF
- Any FEL schemes to accommodate larger energy spread?
- Can we achieve lasing or at least partial lasing?

Yunhai Cai, SLAC 3/5/2012
Threshold of Instability
Driven by CSR

Based on the bunched beam theory, the threshold can be written as

\[ \sigma_z^{7/3} = \frac{c^2 Z_0}{8\pi^2 \xi_{th}^2} I_b \rho^{1/3} \left( V_{r_f} \cos \phi_s f_{r_f} f_{rev} \right) \]

where \( \xi_{th} \) is given by

\[ \xi = \left( \frac{\sigma_z}{\rho^{1/3}} \right)^{3/2} \]

My talk, IPAC 2011, San Sebastian, Spain

Measured bursting threshold at ANKA
See M. Klein et al. PAC09, 4761 (2009)

(courtesy of M. Klein, \( \xi_{th}=0.5 \) used.)
Reduce Bunch Length from 10 ps to 1 ps without reducing bunch current

Calculation of threshold

An illustration using PEP-X nominal parameters: \( f_{rf} = 476\) MHz, \( V_{rf} = 8.3\) MV, \( f_{rev} = 136.312\) kHz, \( \sigma_z = 3\) mm, \( I_b = 0.067\) mA.
Conclusion

- Diffraction limited (1 angstrom) light source is clearly feasible. Some R&D are necessary to further advance the design for construction.
- High-order achromats can be used in realistic design of ultimate storage rings. This approach significantly simplified the optimization process and improved the dynamic aperture.
- Analytical and numerical methods are complementary to each other. We should spend more time to understand what computers have provided us.
- Longitudinal beam dynamics will be the key to break the barrier of the ultimate brightness in the storage-ring-based light source.
Acknowledgements

• PEP-X-USR design team:
  Karl Bane, Robert Hettel, Yuri Nosochkov,
  Min-Huey Wang (SLAC)
• Michael Borland (ANL) for collaboration of the
  PEP-X-USR design
• K. Kubo (KEK) for verifying the IBS calculation using
  SAD
• Michael Borland (ANL) and K. Soutome (Spring8) for
  provided their talks about the ultimate storage rings