Lattice Design and Performance for PEP-X Light Source

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Existing PEP-II rings

- 2.2 km existing rings in PEP tunnel
- Six 243 m arcs and six 123 m long straights
- 60 or 90 deg FODO lattice
- Can reach ~5 nm-rad emittance at 4.5 GeV (w/o wiggler) – too high for a modern light source
Design a new low emittance ring in the PEP-II tunnel.

**Goals:**
- ~0.1 nm-rad emittance at 4.5 GeV for high brightness
- >24 dispersion free straights for insertion devices
- Use existing PEP-II tunnel and utilities

**New optics with:**
- Two DBA arcs yielding 30 ID straights
- Four TME arcs for low emittance
- ~90 m wiggler to reach ~0.1 nm-rad emittance at 4.5 GeV
- FODO optics in long straights
- PEP-II based injection system
Layout of PEP-X with photon beamlines at SLAC

Figure 1.1: A conceptual layout of PEP-X light source with two experimental halls containing 30 X-ray beamlines reaching a brightness of $10^{22}$ (ph/s/mm$^2$/mrad$^2$/0.1% BW) at 10 keV.
Initial DBA design: Standard cell

- Initial design: 15.2 m DBA cell with gradient bend and 4.3 m ID straight
- 16 DBA cells per arc for 30 ID straights
- X and Y phase advance near $3\pi/2$ and $\pi/2$ for compensation of sextupole geometric and chromatic aberrations and maximum dynamic aperture
- Optimized for low emittance, maximum momentum compaction and aperture
- ID $\beta_x$ and $\beta_y = 10.4$ m and 8.0 m – lower $\beta$ is desired for higher brightness
Present DBA design: Supercell

- Two standard cells are combined into one supercell with a low and high ID beta: $\beta_{x,y} = 3.00, 6.07$ m and $\beta_{x,y} = 16.04, 6.27$ m.
- Phase advance is optimized for compensation of both sextupole and octupole driving terms and maximum dynamic aperture: $\mu_x/2\pi = 1.5+3/128$, $\mu_y = \mu_x/3$.
- Harmonic sextupoles are added for further reduction of the resonance effects and amplitude dependent tune spread.
• 7.6 m cell with ~0.1 nm-rad intrinsic emittance.
• 32 standard and 2 matching cells per arc.
• X and Y phase advance is set near $3\pi/4$ and $\pi/4$ for compensation of sextupole and octupole effects and maximum dynamic aperture.
• Optimized for maximum momentum compaction.
Injection straight

- Existing PEP-II injection straight with 4 additional quads.
- PEP-II vertical injection optics is changed to horizontal to avoid vertical injection oscillations in the IDs.
- Large horizontal $\beta_x = 200 \text{ m}$ at septum for larger injection acceptance.
- Existing 4 DC bump magnets and 2 fast kickers.
Phase space diagram at injection point

- Conventional off-axis injection using SLAC linac.
- 3 mm septum placed at edge of stored beam dynamic aperture (~10 mm).
- Stored beam placed at $8\sigma_x$ from the septum (2.2 mm w/o wiggler).
- Minimal size for injected beam: $6\sigma_{xi}$.
- Assume low emittance injector ($\gamma\epsilon \sim 1 \mu m\cdot rad$).
- Injection beta optimized for a best match to stored beam acceptance phase space.
- Kick amplitude: 7.67 mm.
- Minimal required dynamic aperture: 5.5 mm.
Wiggler straight

• DBA and TME arcs without wiggler yield \( \varepsilon = 0.38 \text{ nm-rad} \).
• 89.3 m wiggler is inserted in one long straight section yielding \( \varepsilon = 0.086 \text{ nm-rad} \).
• Wiggler is split in 18 identical sections to fit FODO cells.

Dispersion in ~5 m wiggler section

• Wiggler parameters optimized for strong damping effect: 10 cm period, 1.5 T field.
• The long wiggler can be split in half and placed in two separate straights for better handling of radiated power (4.7 MW at 1.5 A).
Optimization of wiggler parameters

Based on analytic formulas:
- Most efficient damping for $L < 100$ m.
- More damping with a shorter period, higher field and lower $\beta_x$, but the rate of reduction gradually decreases.
- High peak field requires a smaller gap which reduces vertical acceptance and increases resistive wall impedance.
- Selected parameters: 10 cm period, 1.5 T peak field, 89.3 m total length.
Complete ring lattice

Symmetric locations of DBA and TME arcs and mirror symmetry with respect to injection point.
Chromatic correction

- DBA and TME sextupole positions and strengths as well as cell and long straight phase advance are optimized for maximum energy dependent aperture.
- Optimization of non-linear chromatic terms using MAD HARMON and empiric optimization of momentum dynamic aperture in LEGO tracking simulations.

W-functions

2nd order dispersion

Tune vs $\Delta p/p$
Tune shift with amplitude

• 2 weak harmonic sextupoles near each ID straight reduce the amplitude dependent tune shift and resonance driving terms generated by chromatic sextupoles and increase dynamic aperture for horizontal injection.
• Minor adjustment will be needed to accommodate realistic length harmonic sextupoles.

<table>
<thead>
<tr>
<th></th>
<th>(\frac{d\nu_x}{d\epsilon_x})</th>
<th>(\frac{d\nu_y}{d\epsilon_y})</th>
<th>(\frac{d\nu_y}{d\epsilon_x})</th>
</tr>
</thead>
<tbody>
<tr>
<td>with SH1, SH2</td>
<td>(-2.41 \times 10^4)</td>
<td>(-1.10 \times 10^5)</td>
<td>(3.02 \times 10^4)</td>
</tr>
<tr>
<td>without SH1, SH2</td>
<td>(-1.39 \times 10^5)</td>
<td>(-6.94 \times 10^4)</td>
<td>(2.86 \times 10^4)</td>
</tr>
</tbody>
</table>
Parameters with wiggler on and off

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wiggler on</th>
<th>Wiggler off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, $E_0$ [GeV]</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Circumference, $C$ [m]</td>
<td>2199.32</td>
<td></td>
</tr>
<tr>
<td>Emittance, $\varepsilon_x$ [pm-rad, 0 current]</td>
<td>85.7</td>
<td>379</td>
</tr>
<tr>
<td>Beam current, $I$ [A]</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Harmonic number, $h$</td>
<td>3492</td>
<td></td>
</tr>
<tr>
<td>Number of bunches, $n_b$</td>
<td>3154</td>
<td></td>
</tr>
<tr>
<td>Bunch length, $\sigma_z$ [mm]</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Energy spread, $\sigma_\delta$</td>
<td>1.14 x 10^{-3}</td>
<td>0.55 x 10^{-3}</td>
</tr>
<tr>
<td>Momentum compaction, $\alpha_p$</td>
<td>5.81 x 10^{-5}</td>
<td>5.81 x 10^{-5}</td>
</tr>
<tr>
<td>Tunes, $\nu_x/\nu_y/\nu_s$</td>
<td>87.23 / 36.14 / 0.0077</td>
<td>87.23 / 36.14 / 0.0037</td>
</tr>
<tr>
<td>Damping times, $\tau_x/\tau_y/\tau_s$ [ms]</td>
<td>20.3 / 21.2 / 10.8</td>
<td>101 / 127 / 73</td>
</tr>
<tr>
<td>Energy loss, $U_0$ [MeV/turn]</td>
<td>3.12</td>
<td>0.52</td>
</tr>
<tr>
<td>RF voltage, $V_{RF}$ [MV]</td>
<td>8.9</td>
<td>2.0</td>
</tr>
<tr>
<td>$\beta_x/\beta_y$ at ID center, [m] (low/high $\beta$)</td>
<td>[ 3.00 / 6.07 ]</td>
<td>[ 16.04 / 6.27 ]</td>
</tr>
</tbody>
</table>
Momentum aperture

Acceptance versus $\Delta p/p$

Obtained in LEGO dynamic aperture tracking w/o errors
IBS emittance and Touschek lifetime

<table>
<thead>
<tr>
<th>$\kappa$</th>
<th>$\epsilon_{x0}$ [pm]</th>
<th>$\epsilon_x$ [pm]</th>
<th>$\epsilon_y$ [pm]</th>
<th>$\sigma_p$ [$10^{-3}$]</th>
<th>$\sigma_z$ [mm]</th>
<th>$\mathcal{T}$ [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>.049</td>
<td>82.</td>
<td>164.</td>
<td>8.0</td>
<td>1.20</td>
<td>3.16</td>
<td>29.</td>
</tr>
<tr>
<td>1.</td>
<td>43.</td>
<td>69.</td>
<td>69.</td>
<td>1.17</td>
<td>3.08</td>
<td>92.</td>
</tr>
</tbody>
</table>

1% current stability will require top-up injection every few seconds

**PEP-X parameters used for IBS calculations**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, $E$</td>
<td>4.5</td>
<td>GeV</td>
</tr>
<tr>
<td>Circumference, $C$</td>
<td>2199.</td>
<td>m</td>
</tr>
<tr>
<td>Average current, $I$</td>
<td>1.5</td>
<td>A</td>
</tr>
<tr>
<td>Bunch population, $N_b$</td>
<td>2.18</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Number of bunches, $M$</td>
<td>3154</td>
<td></td>
</tr>
<tr>
<td>Relative rms energy spread, $\sigma_{p0}$</td>
<td>1.14</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Rms bunch length, $\sigma_{x0}$</td>
<td>3.0</td>
<td>mm</td>
</tr>
<tr>
<td>Horiz. emittance parameter, $\epsilon_{x00}$</td>
<td>85.7</td>
<td>pm</td>
</tr>
<tr>
<td>Horiz. radiation damping time, $\tau_x$</td>
<td>13.5</td>
<td>ms</td>
</tr>
<tr>
<td>Long. radiation damping time, $\tau_p$</td>
<td>7.2</td>
<td>ms</td>
</tr>
</tbody>
</table>
PEP-X working point on tune diagram

$Q_{x,y} = 87.23, 36.14$ (Red: chromatic tune spread for $\delta=\pm2.5\%$)
Dynamic aperture tune scan

X Aperture in unit of $\sigma_x$ at Injection

Y Aperture in unit of $\sigma_y$ at Injection

Nominal tune:
$v_x = 86.23$ and $v_y = 36.14$

$2v_x + 2v_y = 247$

$2v_x + 2v_y = 247$

$2v_x + 2v_y = 248$

$2v_x + 2v_y = 160$

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Frequency map analysis: tune spread

Strong chromatic sextupoles generate high order resonance driving terms
Frequency map analysis: dynamic aperture
Dynamic aperture (1)

- Δp/p up to 3%
- Effect of multipole errors is small

Without errors

PEPX--V6--Lat

χ = 87.23, ψ = 36.14

2*DBA

\[ \frac{\phi_x}{2\pi} = 1.523436 \]

\[ \frac{\phi_y}{2\pi} = 0.507815 \]

PEP-II multipole field errors only (10 seeds)

- Δp/p up to 3%
- Effect of multipole errors is small
Dynamic aperture (2)

Multipole + field + quad misalignment
Magnet multipole field + Quadrupole alignment + field errors, 5 seeds

Multipole + field + all misalignment
Magnet multipole field + all alignment + field errors, 4 seeds

<table>
<thead>
<tr>
<th></th>
<th>$\Delta x$ (μm)</th>
<th>$\Delta y$ (μm)</th>
<th>Roll (m-rad)</th>
<th>$\frac{\Delta B_{y}}{B_{y}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>100</td>
<td>100</td>
<td>0.5</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>30</td>
<td>30</td>
<td>0.2</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Sextupole</td>
<td>30</td>
<td>30</td>
<td>0.2</td>
<td>$5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- Quad misalignment is ok.
- Sextupole misalignment needs better orbit correction at sextupoles.
- Horizontal injection aperture is ok.
Wiggler effect on dynamic aperture

No magnet errors, with and w/o wiggler

- Wiggler intrinsic non-linear field is studied using tracking table method (insert kick maps in the wiggler) and tracking simulation with AT code.
- The resultant effect on dynamic aperture is sufficiently small, both without and with magnet errors.

With magnet errors
PEP-X brightness

Brightness Envelopes
excluding superconducting undulators

- PEP-X: 4.5 GeV, 1.5 A, 2.2 km
  154 x 8 pm-rad, 3.5 m IDs
- ALS upgrade: 1.9 GeV, 0.5 A, 0.197 km
  200 x 30 pm-rad, 4.4 m IDs
- ALS existing ring: 1.9 GeV, 0.5 A, 0.197 km
  200 x 10 pm-rad, 4.4 m IDs
- NSLS-II: 3 GeV, 0.5 A, 0.792 km
  600 x 8 pm-rad, 3.4 m IDs
- PETRA III: 6 GeV, 0.1 A, 2.3 km
  1000 x 8 pm-rad, 5 m IDs
- APS: 7 GeV, 0.2 A, 1.1 km
  2500 x 8 pm-rad, 4.8 m IDs
- APS USRT (new ring): 7 GeV, 0.2 A, 3.1 km
  45 x 15 pm-rad, 8 m IDs
- Cornell ERL: 5 GeV
  30 x 30 pm-rad, 0.1 A or
  8 x 8 pm-rad, 0.025 A
Summary

* The baseline lattice for PEP-X is designed.

* It uses DBA and TME cell optics and ~90 m damping wiggler yielding 30 ID straights and an ultra-low emittance.

* Photon brightness of \( \sim 10^{22} \) (ph/s/mm\(^2\)/mrad\(^2\)/0.1 % BW) can be reached at 1.5 A for 3.5 m IDs at 10 keV.

* Dynamic aperture is adequate to accommodate a conventional off-axis injection system.

* Work is in progress to define specification for alignment tolerances, to improve the correction schemes, and to further increase momentum aperture.