LATTICE DESIGN OF PEP-X AS A LIGHT SOURCE MACHINE AT SLAC*

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Abstract

SLAC is studying an option of building a high brightness synchrotron light source machine, PEP-X, in the existing PEP-II tunnel [1]. The new machine will replace the PEP-II High Energy Ring (HER) with the goal of achieving an ultra low emittance of ∼0.1 nm-rad at 4.5 GeV. The PEP-X will utilize the same layout as in the PEP-II with 6 arcs and 6 long straight sections. The existing RF and injection systems will be re-used. The two HER FODO arcs will be replaced with the DBA arcs providing 30 dispersion free 4.26 m sections for magnetic undulators. The other four arcs will be replaced with the TME lattice for attaining the low emittance. Finally, a 89.3 m long damping wiggler with 10 cm period and 1.5 T maximum magnetic field will be installed in a long straight section to reduce the natural emittance to 0.094 nm-rad. The PEP-X dynamic aperture was studied and found sufficient for a vertical injection.

LATTICE DESIGN

In order to fit into the PEP-II tunnel, the PEP-X uses the same layout as in the PEP-II with 6 arcs and 6 long straight sections and the same circumference of 2199.32 m as shown in Fig. 1. To provide a large number of dispersion free sections for the undulator Insertion Devices (ID), two arcs will use the Double Bend Achromat (DBA) lattice with 16 cells per arc yielding the total of 30 ID straights. Fig. 2 shows the optics functions in one 15.21 m DBA cell. It consists of 6 quadrupoles, 3 two family sextupoles and two 1.0 m combined function dipoles. Beta functions at center of the 4.26 m ID straight are $\beta_x = 9.1$ m, $\beta_y = 8.1$ m. The cell phase advance is adjusted to $\mu_x/2\pi = 0.737$ and $\mu_y/2\pi = 0.238$ to minimize the chromatic and sextupole aberrations for maximum dynamic aperture.

The other four arcs are based on the Theoretical Minimum Emittance (TME) lattice with 32 regular and 2 matching cells per arc. In this design, the TME cell is not adjusted for the theoretical minimum emittance because it would yield a very strong focusing degrading dynamic aperture. Instead, the cell is set up to obtain a compromise between a low emittance and large dynamic aperture. Nevertheless, for the sake of naming convention, we will use the TME name for this cell. The optics functions in one 7.297 m regular TME cell are shown in Fig. 3. It contains 4 quadrupoles, 3 two family sextupoles and one 2.7 m dipole. The large number of cells per arc decreases the dipole bending angle, thus reducing the emittance $\epsilon_x \propto \theta^3$.

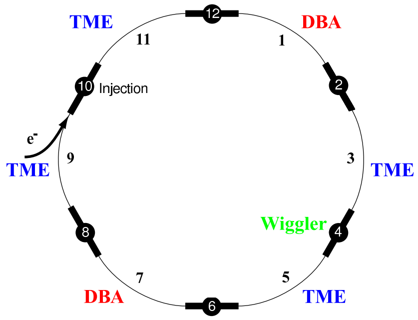

Figure 1: PEP-X layout with 2 DBA and 4 TME arcs.

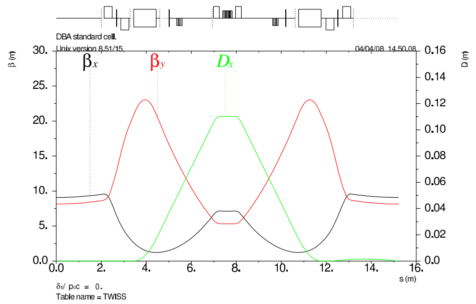

Figure 2: Optics functions in one DBA cell.

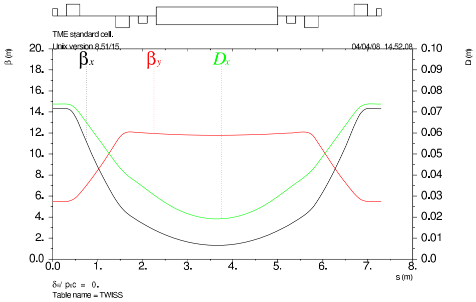

Figure 3: Optics functions in one regular TME cell.

The cell phase advance is $\mu_x/2\pi = 3/8$ and $\mu_y/2\pi = 1/8$ providing cancelation of chromatic and sextupole aberrations in every 8 cells. The special matching cell at each arc end cancels the dispersion and helps with matching of the β function and adjustment of the arc geometry.

The PEP-X six long straight sections maintain the same position and length (123.353 m) as in the PEP-II. Five straights have an identical FODO lattice with 21 quadrupoles. They will contain the RF accelerating cavities, the 89.3 m damping wiggler and the betatron tune correction system. The quadrupole strengths in these straights depend on the type of adjacent arcs (DBA or TME) and presence of the damping wiggler. The 6th straight section will utilize the HER injection optics with 4 extra quadrupoles, and will re-use the HER injection system.

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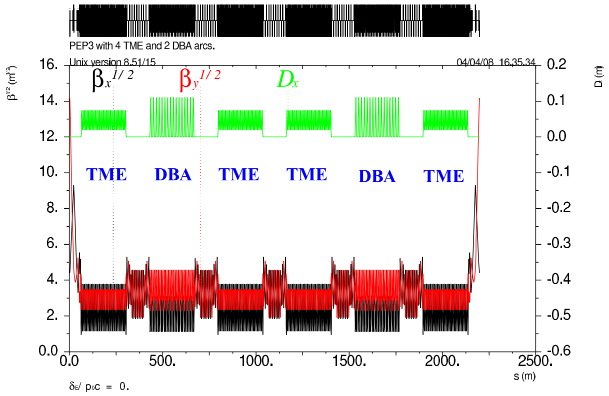

Figure 4: Optics functions in the complete PEP-X ring.

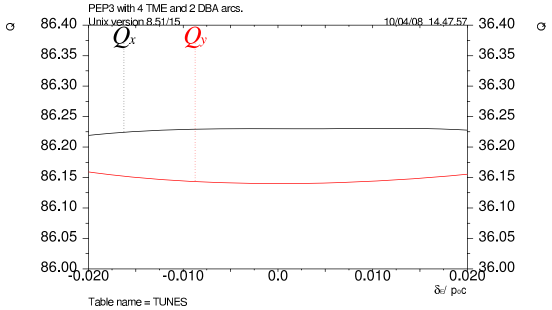

Figure 5: PEP-X tune versus momentum error $\Delta p/p$.

Optics functions in the complete PEP-X ring are shown in Fig. 4. Compensation of chromatic tune variation is very good for a range of $\Delta p/p = \pm 2\%$ as shown in Fig. 5. This helps to maximize the momentum acceptance by keeping the off-momentum particles within the design tune area and away from strong resonances. The PEP-X parameters with damping wiggler are listed in Table 1. The 0.094 nm emittance value does not include the intra-beam scattering (IBS) effect which results in ~50% emittance growth.

DAMPING WIGGLER

The PEP-X damping wiggler is optimized to attain the design low emittance. Dependence of relative emittance on the lattice and wiggler parameters is given by [2]:

$$\frac{\epsilon_w}{\epsilon_0} = \frac{1+\frac{4C_q}{15\pi J_x} N_p \frac{\beta_x}{\epsilon_0 \rho_w} \gamma^2 \frac{\rho_0}{\rho_w} \theta^3}{1+\frac{1}{2} N_p \frac{\rho_0}{\rho_w} \theta_w}, \qquad (1)$$

where $C_q = 3.81 \cdot 10^{-13}$m, $<\beta_x>$ is the average horizontal β function in the wiggler, N_p is the number of wiggler periods, ρ_w is the bending radius at peak wiggler field, $\theta_w = \frac{\lambda}{2\pi\rho_w}$ is the peak trajectory angle in the wiggler, λ_w is the wiggler period length, ρ_0 is the bending radius of the ring dipole, ϵ_0 is the emittance without the wiggler.

The wiggler period length, the peak field, and the total wiggler length need to be optimized for a low emittance. Using the above formula, Fig. 6 shows the relative emittance as a function of the wiggler field and total wiggler length for various wiggler period lengths for the PEP-X lattice. In PEP-X, one of the long straight sections is filled with 89.3 m wiggler with the period of 10 cm and 1.5 T field. It reduces the emittance from 0.37 nm-rad to 0.094 nm-rad as calculated by MAD-8 [3]. Table 2 shows the parameters for this wiggler (first line) as well as for other, more challenging, options including a soft X-ray FEL undulator and a superconducting wiggler.

Table 1: PEP-X lattice parameters.

Energy, GeV	4.5
Circumference [m]	2199.32
Betatron tune, x/y	86.23 / 36.14
Synchrotron tune	0.00742
Momentum compaction	$4.72 \cdot 10^{-5}$
Emittance without IBS [nm]	0.094
RMS bunch length [mm]	2.50
RMS momentum spread	$1.12 \cdot 10^{-3}$
Damping time, $x/y/s$ [ms]	19.7 / 20.2 / 10.2
Natural chromaticity, x/y	-132.7 / -72.8
Energy loss [MeV/turn]	3.27
RF voltage [MV]	10
Total wiggler length [m]	89.325
Wiggler period [m]	0.1
Wiggler field [T]	1.5
Regular ID straight length [m]	4.26
Number of regular ID straights	30
β_x/β_y at ID center [m]	9.09 / 8.14

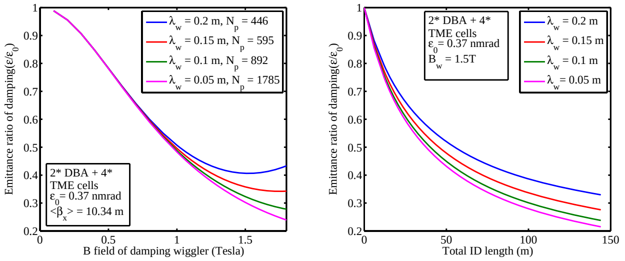

Figure 6: Emittance dependence on (a) wiggler field and (b) total wiggler length for various wiggler period length.

DYNAMIC APERTURE

Achieving a low equilibrium emittance requires a small dispersion and, therefore, a strong quadrupole focusing. As a result, the chromaticity correcting sextupoles in such a lattice are very strong. For example, the PEP-X sextupoles are an order of magnitude stronger than sextupoles in the PEP-II HER. The nonlinear effects driven by such strong sextupoles can result in a significant reduction of dynamic aperture. In PEP-X design, these effects are minimized by choosing the optimum sextupole locations and the optimum cell phase advance. The former is achieved by putting the sextupoles at locations where dispersion and β function are large and where the two family sextupoles are most orthogonal resulting in the lowest sextupole strength. The DBA and TME arcs are designed to provide a period with phase advance near $\pi/2 + n\pi$ which results in first or-

Table 2: Damping wiggler options for PEP-X.

λ_w (cm)	B_w (T)	ϵ_w/ϵ_0	Gap (mm)	K	λ_r (Å)
10	1.5	0.32	15.4	14.1	647
Other options to accommodate a soft x-ray FEL undulator					
5	1.27	0.36	9.39	5.93	60.0
5	0.5	0.78	20.0	2.33	12.0
Superconducting wiggler magnets					
1.4	1.5	0.30	5.0	1.96	2.64

der cancelation of chromatic distortion of β function (every 90°) and sextupole geometric aberrations (every 180 °). Additionally, since the vertical focusing does not affect the emittance, the cell vertical phase advance is chosen to be a factor of 3 lower compared to the horizontal value for further reduction of the sextupole and quadrupole strengths.

PEP-X tracking simulations are done using the LEGO code [4]. Fig. 7 shows dynamic aperture as a function of the betatron tunes which were varied using the tune correction system in the long straight sections. The working tune is selected at ν_x=86.23, ν_y=36.14 away from major resonances and where dynamic aperture is large. Fig. 8 shows dynamic aperture at injection point for lattice (a) without magnet errors and (b) with multipole field errors for momentum error from $\Delta p/p$ = 0 to 1.5%. The 3σ injected beam size shown by the black ellipse is for the injection emittance and β of the storage ring. The vertical dynamic aperture is found to be sufficient for the vertical injection.

INJECTION

The PEP-X will adopt the HER vertical injection system located in straight section 10 (Fig. 1). Four extra quadrupoles are added to the present HER optics for a better match to the TME arcs. The stored beam will be vertically bumped by the existing four DC bump magnets and then kicked by the two identical pulse kickers separated by 180° vertical phase advance.

Dynamic aperture at injection point must include at least 6σ of full width injected beam plus the effective septum width and 4σ of the stored beam size. The effective septum width of 4 mm includes 1 mm physical septum thickness plus allowance for a stray field of 1 mm on the injection side and 2 mm on the stored beam side. The 4.5 GeV injected beam has emittance of 5.2 and 1.3 nm-rad in horizontal and vertical planes from the linac. The injection line has β_y=40 m at the ring entrance which maximizes the available phase space for the injected beam as shown in Fig. 9. The ring has a large β_y=200 m value at the injection point to attain a large injection dynamic aperture as compared to the injected beam size and septum width. For conservative estimate of required injection acceptance, the stored beam size is based on a large fully coupled emittance without the effect of damping wiggler. In Fig. 9, the stored beam is kicked by the DC bump as close as possible to the septum to minimize the betatron amplitude of the injected beam in the ring. The kick amplitude is 16.1 mm and the injected beam betatron amplitude is 6.2 mm.

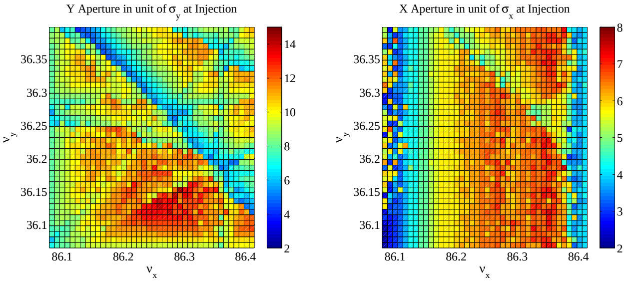

Figure 7: Dynamic aperture versus ν_x, ν_y betatron tunes.

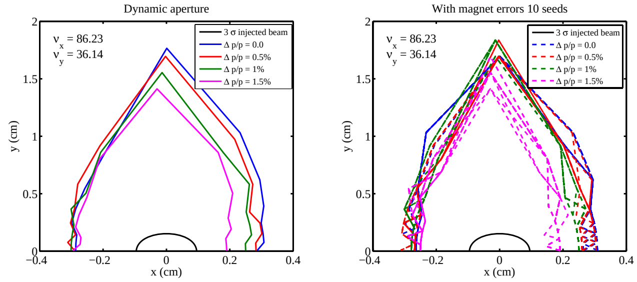

Figure 8: Dynamic aperture without errors (left) and with multipole field errors based on the specifications of PEP-II magnets for 10 random settings (right).

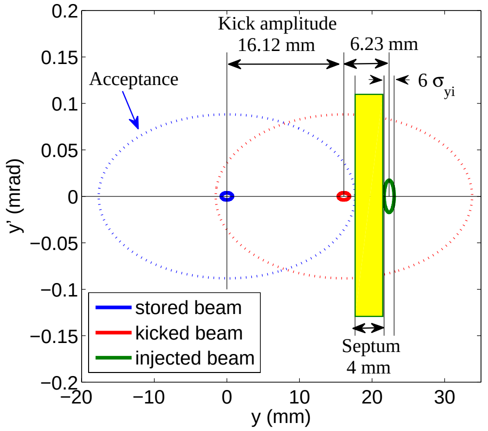

Figure 9: Schematic of phase space at injection.

CONCLUSION

The PEP-X lattice design demonstrates the feasibility of a synchrotron light source machine with an ultra low emittance of ∼0.1 nm-rad at 4.5 GeV. Further studies are needed in order to attain lower β functions at the ID undulators, increase dynamic aperture, and investigate a possibility of horizontal injection.

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