LATTICE DEVELOPMENT FOR PEP-X HIGH BRIGHTNESS LIGHT SOURCE*

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Abstract

Design of PEP-X high brightness light source machine is under development at SLAC. The PEP-X is a proposed replacement for the PEP-II in the existing 2.2 km tunnel. Two of the PEP-X six arcs contain DBA type lattice providing 30 dispersion free straights suitable for 3.5 m long undulators. The lattice contains TME cells in the other four arcs and 89.3 m wiggler in a long straight section yielding a horizontal emittance of ~0.1 nm-rad at 4.5 GeV. The recent lattice modifications are aimed at increasing the predicted brightness and improving beam dynamic properties. The standard DBA cells are modified into supercells for providing low-β undulator straights. The DBA and TME cell phase advance is better optimized. Harmonic sextupoles are added to minimize the sextupole driven resonance effects and amplitude dependent tune shift. Finally, the injection scheme is changed from vertical to horizontal plane in order to avoid large vertical amplitudes of injected beam within small vertical aperture of undulators.

INTRODUCTION

Design of the PEP-X high brightness light source is under development at SLAC [1]. The PEP-X is a proposed replacement for the PEP-II e+e- collider in the existing tunnel. For this reason, it adopts the same ring geometry and the same circumference of 2199.32 m as in the PEP-II. Fig. 1 shows schematic of the PEP-X ring layout with the six arcs and six long straight sections labeled from 1 to 12.

The initial design of PEP-X lattice [2] uses standard Double Bend Achromat (DBA) cells in arcs 1 and 7, Theoretical Minimum Emittance (TME) cells in the other four arcs, and 89.3 m damping wiggler in the long straight section-4. This lattice yields 94 pm·rad equilibrium emittance at 4.5 GeV and zero current, and provides 30 dispersion free straight sections in the DBA cells suitable for 3.5 m undulator Insertion Devices (ID).

Unfortunately, the standard DBA cell in the initial design has very limited range for variation of ID β-functions. This is because the strengths of the cell quadrupoles are determined by other constraints: the chosen cell phase advance and condition for dispersion cancellation. As a result, the ID β-functions are rather modest: $\beta_x = 10.4$ m and $\beta_y = 8.0$ m. In order to reduce them for a higher brightness, the standard DBA cells are modified into DBA supercells in the new lattice described below.

Another drawback of the initial PEP-X design is that it assumed a vertical injection scheme as in the PEP-II. However, this would result in injected beam vertical oscillations reducing beam acceptance in the small vertical gap of undulators. To avoid this effect, the injection section has been modified to adopt it to a horizontal injection.

The other lattice modifications include a higher momentum compaction factor and insertion of harmonic sextupoles in the DBA arcs. Details of the lattice modifications are presented below.

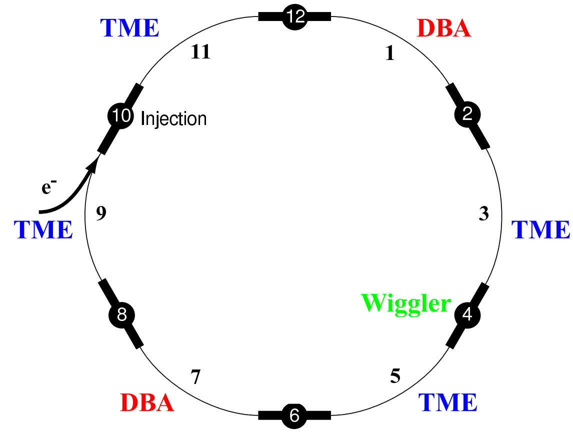

Figure 1: PEP-X layout with 2 DBA arcs, 4 TME arcs and 6 straight sections.

DBA SUPERCELLS

High brightness is an important goal of the PEP-X design. Photon brightness in an undulator is proportional to

$$B \propto \frac{1}{\sigma_x \sigma_{x'} \sigma_y \sigma_{y'}}, \qquad (1)$$

where the effective photon source sizes for diffraction limited photon emittance are [3]

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y} + \frac{\lambda L}{8\pi^2}}, \quad \sigma_{x',y'} = \sqrt{\frac{\epsilon_{x,y}}{\beta_{x,y}} + \frac{\lambda}{2L}}, \qquad (2)$$

λ is the photon wavelength, L is the ID length, and ϵ, β are the electron emittance and β-function at ID center. One can verify that $1/\sigma\sigma'$ is maximized at $\beta = L/2\pi$. The latter indicates that the ID β-functions in the initial DBA design (10.4 m and 8.0 m) are an order of magnitude higher then the optimal values at L = 3.5 m. Therefore, lower ID β-functions are desirable for a higher brightness.

As mentioned earlier, variation of ID β-functions in the standard DBA cell is limited because the strengths of three quadrupole families are determined by other constraints:

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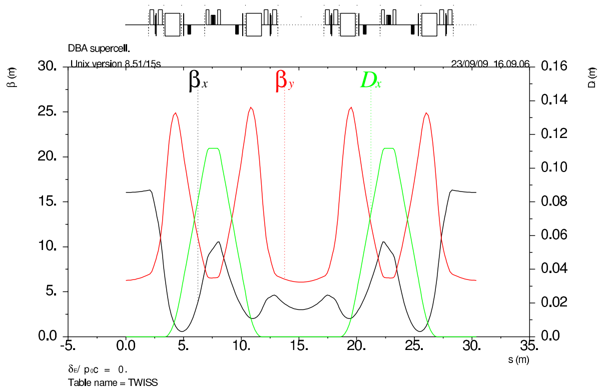

Figure 2: Lattice functions in the DBA supercell.

the value of phase advance and dispersion cancellation. In order to provide β adjustment additional quadrupole families are needed. In the new design, this is achieved by converting every two standard DBA cells into one supercell keeping the same magnet positions. In this case, each supercell has two ID straights, where strengths of the quadrupole doublets near the first and second ID straights are adjusted independently, thus providing two additional quadrupole families. Such adjustment allows to lower β-functions in one of the two ID straights, but the other will have higher β-functions in order to keep the same phase advance $\mu = \int ds/\beta$.

Lattice functions in the DBA supercell are shown in Fig. 2, where the low-β straight is at center and the higher β straight is split in half between the two ends in this figure. The supercell is 30.422 m long and symmetric with respect to center of either straight. Dispersion is locally canceled at each ID straight. Beta functions are β_x/β_y = 3.0/6.1 m and 16.0/6.3 m at center of the low and high-β ID straights respectively. Compared to the standard DBA cell, the supercell yields ~50% higher brightness at the low-β ID, but ~10% lower at the high-β ID [4]. In total, the two DBA arcs provide 16 low-β and 14 high-β straights for 3.5 m IDs.

A higher momentum compaction is desired in order to increase threshold for microwave instabilities. Since the momentum compaction in the DBA cells is linearly proportional to the dipole length, the length of the supercell combined function dipoles was increased from 1.0 to 1.3 m. Further increase is not desirable since the sextupole positions become too close to each other thus greatly increasing sextupole strengths. The longer DBA dipoles also reduce emittance generated in the supercells.

Each half of the supercell contains three sextupoles located in the dispersive region for chromaticity correction. They are presently arranged in two families. The supercell design also includes one harmonic sextupole at each doublet location near the ID straights where dispersion is zero. These sextupoles help compensating the resonance effects and amplitude dependent tune shifts generated by the chromatic sextupoles.

Supercell phase advance and sextupole strengths were empirically optimized in tracking simulations with LEGO [5] for maximum dynamic aperture. Initially, the phase advance was set to near $\mu_x = 3\pi$, $\mu_y = \pi$ to provide nearly $-I$ transformation between sextupoles separated by one supercell for compensation of the 3rd order sextupole resonance effects. However, the $n\pi$ phase advance would amplify the 4th order resonance effects caused by finite sextupole length and overlap of the sextupole $-I$ pairs. The optimized values are slightly detuned to $\mu_x = 3\pi\,(1 + \frac{1}{64})$, $\mu_y = \mu_x/3$ for a compromise between compensation of the 3rd and 4th order resonance effects.

TME CELL OPTIMIZATION

Main function of the TME cells in four arcs is to minimize the PEP-X emittance while providing large dynamic aperture. The initial TME design [2] is not changed except that dipole length is increased from 2.7 to 3.5 m for a higher momentum compaction factor. The longer dipole also reduces the TME generated emittance by ~7%. Further dipole lengthening is not desirable since the cell quadrupoles and sextupoles become too strong.

In addition, the TME cell phase advance is better optimized. Initially it was set to $\mu_x = 3\pi/4$, $\mu_y = \pi/4$ for exact $-I$ transformation between identical sextupoles separated by 4 cells. However, similar to the DBA optimization, LEGO tracking showed that it should be slightly detuned by less than a degree per cell to $\mu_x = (3\pi/4)\,(1 - \frac{1}{192})$, $\mu_y = \mu_x/3$ for a compromise in compensation of the 3rd and 4th order resonance effects.

INJECTION

The initial PEP-X design adopted the PEP-II injection system with the vertical injection [2]. However, the latter would create the injected beam vertical oscillations within the small vertical gap of undulators thus reducing the effective vertical beam acceptance. To avoid this potential problem, the new design changes the injection from vertical to horizontal plane. In this case, magnet positions in the injection straight section-10 are not changed, but the quadrupole strengths are adjusted to provide large β_x = 200 m at the septum and 180° horizontal phase advance between the two fast kickers for a closed injection bump. Beta functions in the injection section are shown in Fig. 3.

Diagram of the horizontal phase space at injection point is shown in Fig. 4. The stored beam acceptance A_x is represented by the large ellipses with half-widths of

$$X_A = \sqrt{A_x \beta_x}, \quad X'_A = \sqrt{A_x/\beta_x}, \tag{3}$$

where X_A is dynamic aperture and β_x is the ring beta function. The septum is positioned at the outside edge of the stored beam dynamic aperture. This avoids a reduction of the dynamic aperture while minimizing the required amplitude for the injection bump.

In order to obtain maximum acceptance area for the injected beam on the outside of the septum, the stored beam

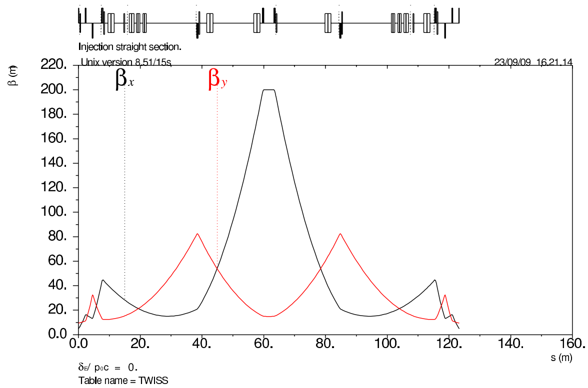

Figure 3: Beta functions in the injection section.

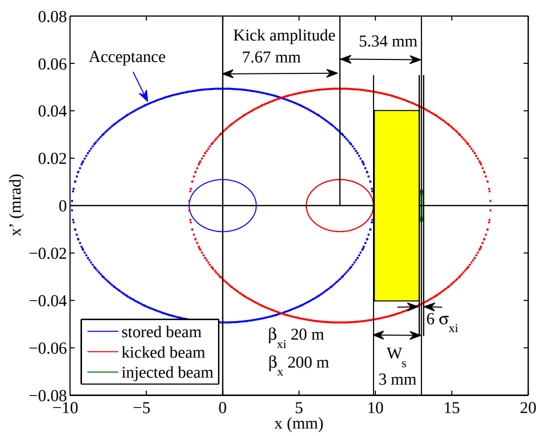

Figure 4: Injection phase space diagram.

is moved toward the septum during injection using an injection bump created by the injection kickers. For minimal beam perturbation and loss at the septum, the distance from center of the bumped stored beam to the edge of the septum is specified at $8\sigma_x$ of the stored beam size, where $\sigma_x = \sqrt{\beta_x \epsilon_x}$. The septum effective width $W_s = 3$ mm is determined by 1 mm physical thickness and 1 mm allowance for stray field on each side.

Similarly, to minimize the injected beam oscillations in the ring, the distance from center of the injected beam to the septum edge is specified at $3\sigma_{xi}$, where $\sigma_{xi} = \sqrt{\beta_{xi}\epsilon_{xi}}$ and β_{xi}, ϵ_{xi} are the beta function and emittance of the injected beam. Therefore, the required minimal size of the stored beam dynamic aperture for injection is

$$(X_A)_{min} = 8\sigma_x + 6\sigma_{xi} + W_s, \tag{4}$$

and the corresponding minimal ring acceptance is

$$(A_x)_{min} = \left(8\sqrt{\epsilon_x} + 6\sqrt{\epsilon_{xi}\beta_{xi}/\beta_x} + W_s/\sqrt{\beta_x}\right)^2. \tag{5}$$

Eq. 5 shows that a large ring β_x at septum relaxes the requirement for large ring acceptance. The injection β_{xi} must be optimized for a best match of the injected beam phase space to the stored beam acceptance.

The injection scheme is compatible with a large stored beam emittance $\epsilon_x = 0.38$ nm·rad without the damping wiggler. In this case $\sigma_x = 0.275$ mm and the injection bump is 7.67 mm for PEP-X dynamic aperture of $X_A = 9.9$ mm [6] as shown in Fig. 4. The corresponding kicker strength is 16.5 Gs·m at 4.5 GeV.

For maximum injection acceptance, the PEP-X will use an injector with low normalized emittance of $\gamma\epsilon_{xi} \approx 1$ μm·rad, similar to the LCLS injector. In this case, the optimized injected beam parameters are: $\beta_{xi} = 20$ m and $\sigma_{xi} = 0.047$ mm at 4.5 GeV energy. The corresponding minimal size of dynamic aperture in Eq. 4 is $(X_A)_{min} = 5.5$ mm, well below the estimated PEP-X dynamic aperture [6].

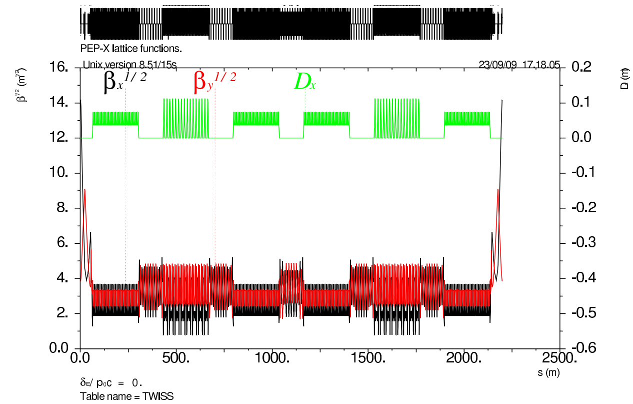

Figure 5: Lattice functions in the complete PEP-X ring.

COMPLETE RING LATTICE

Lattice functions in the complete PEP-X ring starting from injection point are shown in Fig. 5. The DBA supercells in two arcs provide 16 ID straights with $\beta_x/\beta_y = 3.0/6.1$ m and 14 straights with $\beta_x/\beta_y = 16.0/6.3$ m suitable for 3.5 m devices. The longer arc dipoles increase the momentum compaction factor by 23% for a higher threshold of microwave instabilities, and bunch length from 2.5 to 3 mm. The equilibrium emittance at zero current with the 89.3 m damping wiggler is reduced to 86 pm·rad. The DBA harmonic sextupoles reduce the leading amplitude dependent tune shift $d\nu_x/d\epsilon_x$ by a factor of 6. In combination with the optimization of sextupole strengths and cell phase advance this yields a larger dynamic aperture and momentum acceptance described in more detail in [6]. The complete list of PEP-X parameters can be found in [7].

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