A BASELINE DESIGN FOR PEP-X: AN ULTRA-LOW EMITTANCE STORAGE RING*

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Abstract

We completed a design of PEP-X [1] as a high-brightness light source that could reside in the existing 2.2-km PEP-II tunnel. The design features a hybrid lattice with double bend achromat (DBA) cells in two arcs and theoretical minimum emittance (TME)cells in the remaining four arcs. The baseline design will produce photon beams achieving a brightness of 10^{22} (ph/s/$\mathrm{mm}^2/\mathrm{mrad}^2/0.1\%$ BW) at 10 keV in a 3.5-m conventional planar undulator. Our study shows that an optimized lattice has adequate dynamic aperture, while accommodating a conventional off-axis injection system. In the paper, we will summarize the results of the study, including the lattice properties, nonlinear dynamics, intra-beam scattering and Touschek lifetime, and collective instabilities.

INTRODUCTION

The large circumference tunnel of PEP-II, its high power and low emittance injector, and its infrastructure, combined with the SLAC expertise in high-current operation of PEP-II, present a unique opportunity to design and build an ultra-low emittance, extremely high brightness next-generation synchrotron light source.

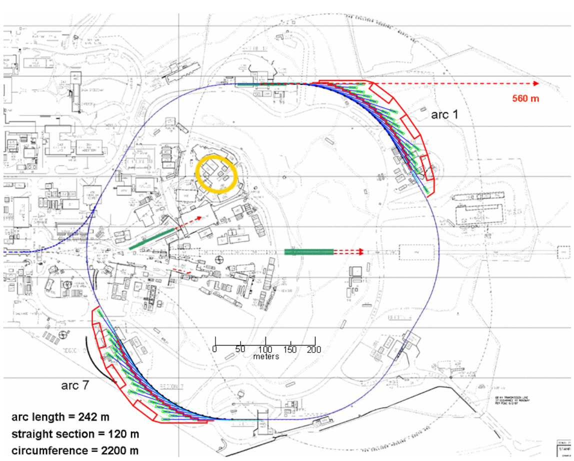

Figure 1: A conceptual layout of the PEP-X light source with two experimental halls containing 30 X-ray beamlines reaching a brightness of 10^{22} (ph/s/$\mathrm{mm}^2/\mathrm{mrad}^2$/0.1% BW) at 10 keV.

This future light source has a potential to reach high coherence in both transverse dimensions for multi-keV photons and to lase partially in a very long undulator at soft x-ray wavelengths. Achieving these features would make this storage ring-based light source very competitive to a source based on an energy recovery linac (ERL).

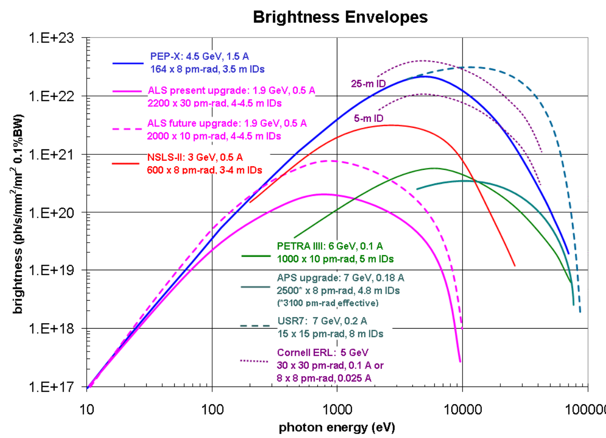

Figure 2: Brightness envelopes for representative existing and future ultimate ring light sources.

Over the past year, we have firmly established a baseline design [2] for PEP-X as an ultra-low emittance storage ring that could reside in the existing 2.2-km PEP-II tunnel. The main parameters of the design are tabulated in Table 1. The design features a hybrid lattice with DBA cells in two of the six arcs that provide a total of 30 straight sections for insertion device (ID) beam lines extending into two new experimental halls as illustrated in Fig. 1. The remaining four arcs contain TME cells to minimize the emittance. Damping wigglers are used to further reduce the horizontal emittance to 86 pm-rad at zero current for a 4.5 GeV electron beam. At a design current of 1.5 A, the horizontal emittance increases, due to intra-beam scattering, to 164 pm-rad when the vertical emittance is maintained at a diffraction limited 8 pm-rad. The baseline design will produce photon beams achieving a brightness of 10^{22} (ph/s/$\mathrm{mm}^2/\mathrm{mrad}^2$/0.1% BW) at 10 keV in a 3.5-m conventional planar undulator. This brightness is approximately two orders of magnitude higher than the existing 3$^{\mathrm{rd}}$ generation light sources such as ALS and APS and an order of magnitude higher than the NSLS-II and PETRA-III sources currently under construction or in commissioning.

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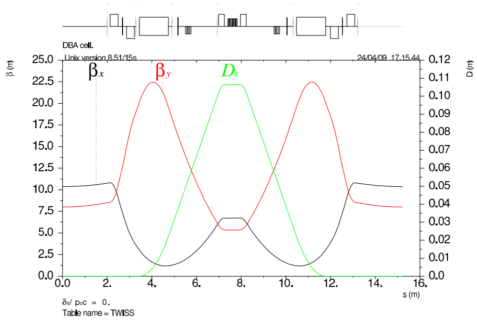

Figure 3: Optics functions in one DBA cell.

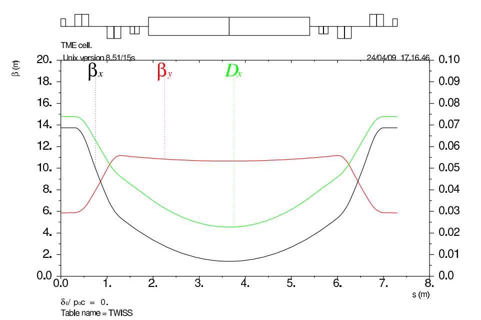

Figure 4: Optics functions in one regular TME cell.

As one can see in Fig. 2, the design is also very competitive with the proposed ERL-based source at Cornell.

Table 1: Main parameters of the design for PEP-X as an ultra-low emittance storage ring.

Parameter	Value
Energy, E [GeV]	4.5
Circumference, C [m]	2199.32
Beam current, I [A]	1.5
Emittance, ϵ_x/ϵ_y [pm·rad]	86/8
Tunes, $\nu_x/\nu_y/\nu_s$	87.23/36.14/0.0077
Damping times, $\tau_x/\tau_y/\tau_s$ [ms]	20.3 / 21.2 / 10.8
RF frequency, f_{RF} [MHz]	476
Number of bunches, n_b	3154
Bunch length, σ_z [mm]	3.0
Relative energy spread, σ_δ	1.14×10^{-3}
Momentum compaction, α	5.81×10^{-5}
Energy loss, U_0[MeV/turn]	3.12
RF voltage, V_{RF} [MV]	8.9
Damping wiggler length [m]	89.3
Length of arc ID straight [m]	4.0
Number of arc ID straights	30
β_x/β_y at low beta ID [m]	3.00 / 6.07
β_x/β_y at high beta ID [m]	16.04 / 6.27

LATTICE

As shown in Fig. 1, the PEP-X configuration contains six arcs. They are designed to provide a large number of undulator ID and attain a low emittance and sufficiently large dynamic aperture. Two arcs will use the DBA lattice with 16 cells per arc yielding the total of 30 dispersion free 4.26 m straights for the IDs. Recently, we combined every pair of DBA cells into a supercell [3] for a better matching of the phase spaces of electron beam and radiated photons at the IDs.

Fig. 3 shows the optics in one 15.21 m DBA cell, where the cell phase advance is near $\mu_x = 3/4$, $\mu_y = 1/4$ $[2\pi]$ to minimize the chromatic and sextupole aberrations. The other four arcs are based on the TME lattice with 32 regular and 2 matching cells per arc. The TME cells do not provide the ID straights, but they help to attain the low emittance.

The TME cell phase advance is chosen to be conservatively low, $\mu_x = 3/8$, $\mu_y = 1/8$ $[2\pi]$, as a compromise between a low emittance and sufficient dynamic aperture. It provides cancellation of chromatic and sextupole aberrations in every 8 cells. The optics of one 7.30 m TME cell is shown in Fig. 4. Bend magnets in the DBA and TME cells are made as long as reasonably possible in order to maximize the momentum compaction factor for a longest possible bunch length as well as to minimize the emittance.

PEP-X has six 123.35 m long straight sections as shown in Fig. 1. The straights will contain the RF accelerating cavities, the betatron tune and coupling correction systems, damping wigglers, and injection system.

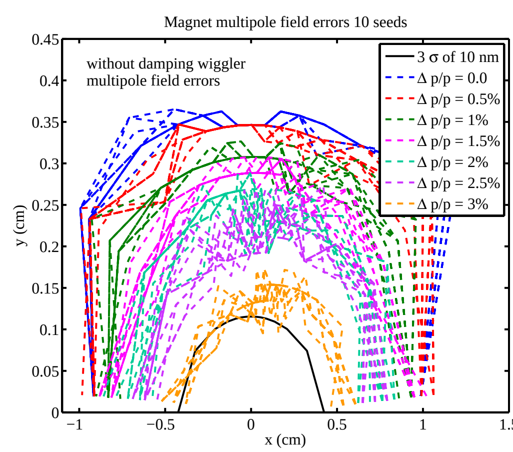

Figure 5: Dynamic aperture including magnetic errors of ten random seeds.

Dynamic aperture both for on- and off-momentum particles is one of the major challenges in the design. As one can see from Fig. 5, our study [4] shows that the optimized lattice has adequate acceptance to accommodate a conventional off-axis injection system based on the SLAC linac. The off-momentum aperture allows a minimum Touschek lifetime of a half hour, which is short but acceptable, provided that the powerful linac is used as its injector. Stored current constancy of 1% or less can be maintained with top-up injection every few seconds.

INTRA-BEAM SCATTERING AND TOUSCHEK LIFETIME

Intra-beam scattering (IBS) describes multiple Coulomb scattering that, in electron machines, leads to an increase in all bunch dimensions and in energy spread, whereas the Touschek effect concerns large single Coulomb scattering events where energy transfer from transverse to longitudinal leads to immediate particle loss. In low emittance machines, such as PEP-X, both effects tend to be important.

For the beam parameters of $\sigma_z = 3$ mm, $\epsilon_x = 86$ pm-rad, and others listed in Table 1, we calculated the equilibrium emittances including the IBS scattering. The results are summarized in Table 2:

Table 2: Emittance with the IBS growth and Touschek lifetime at $I = 1.5$ A.

κ	ϵ_x (pm-rad)	ϵ_y (pm-rad)	T_l (min)
1	69	69	92
0.049	164	8	29

The vertical emittance is proportional to the horizontal emittance, namely $\epsilon_y = \kappa\epsilon_x$, with κ the coupling constant. For the flat beam, the horizontal emittance is doubled due to the IBS. The increased emittance is used to calculate the brightness of the machine shown in Fig. 2. The Touschek lifetime is calculated assuming a half aperture δ_E/E_0= 2%.

INSTABILITIES

Collective instabilities, driven both by conventional impedance and coherent synchrotron radiation, are evaluated for single bunch or multiple bunches in the ring. A detailed impedance model is constructed from the existing PEP-II cavities, resistive-wall, and a scaled version of the PEP-II components. Our study shows that the bunch current is limited by the vertical head-tail instability driven largely by the resistive wall of narrow gap inside the undulators. For a 6-mm full gap, the single bunch threshold is 0.67 mA, a comfortable margin above the nominal 0.48 mA stored in each of 3154 bunches for 1.5-A operation. Similarly, the resistive-wall impedance also causes a growth rate of 0.14 ms (corresponding to approximately 19 revolution periods) in a coupled-bunch mode for a 1.5-A beam. Clearly, a bunch-by-bunch feedback system is necessary to damp down the vertical motion.

To study the microwave instability of the beam, driven by the ring impedance, we used the wake calculated [5]. This wake includes short range contributions from the beam position monitors, RF cavities, resistive wall impedance, tapers of wigglers and undulators, as well as some other elements of the ring. This function is shown in Fig. 6. It corresponds to the wakefield of a bunch with rms length of 0.5 mm.

Two different simulation techniques [6] were employed to study the microwave instability. In the first one we used a linearized Vlasov solver which computes the growth rate of the instability for a given wake and parameters of the beam. In the second one we used a Vlasov-Fokker-Planck solver to simulate longitudinal beam dynamics. The solver not only finds the threshold of the instability, but also simulates evolution of the beam dynamics above the instability threshold. Our analysis shows a threshold of the instability at about $I \approx 6.3$ A. The corresponding peak current is high enough and enables a partial lasing [7] in a 100-meter undulator in a straight section.

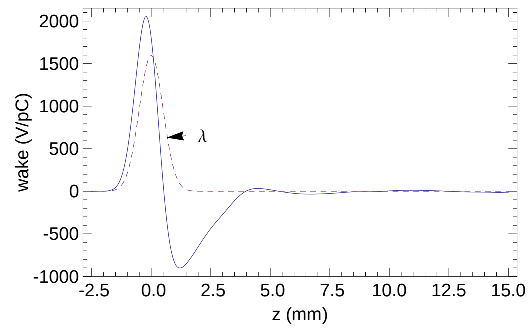

Figure 6: Longitudinal wakefield for a 0.5 mm bunch. Positive values of the wake correspond to energy loss, and positive values of the coordinate z is behind the source particle.

CONCLUSION

The design utilizes much of the existing infrastructure at SLAC, including the PEP tunnel, its high-power linac and low emittance injector, and the PEP-II RF system. Most importantly, the baseline design does not rely on any new technology developments and is therefore essentially ready to be built.

Our study covers essential aspects of accelerator physics, including the lattice properties, nonlinear dynamics, intra-beam scattering and Touschek lifetime, and collective instabilities. The study will provide a solid foundation and performance benchmark for any future design improvements or configuration ideas that could lead to the construction of the new light source.

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