# CONCEPTS FOR THE PEP-X LIGHT SOURCE[†]

Robert Hettel, Karl Bane, Kirk Bertsche, Yunhai Cai, Alex Chao, Valery Dolgashev, John Fox, Xiaobiao Huang, Zhirong Huang, Themistoklis Mastorides, Cho Ng, Yuri Nosochkov, Alexander Novokhatski, Thomas Rabedeau, Claudio Rivetta, James Safranek, John Seeman, Joachim Stöhr, Gennady Stupakov, Sami G. Tantawi, Lanfa Wang, Min-Huey Wang, Ulrich Wienands, Liling Xiao (SLAC, Menlo Park, CA), Ingolf Lindau (Stanford University, Stanford, CA), Claudio Pellegrini (UCLA, Los Angeles, CA)

*Abstract*

SSRL and SLAC groups are developing a long-range plan to transfer its evolving scientific programs from the SPEAR3 light source to a much higher performing photon source that would be housed in the 2.2-km PEP-II tunnel. While various concepts for the PEP-X light source are under consideration, including ultimate storage ring and ERL configurations, the present baseline design is a very low-emittance storage ring. A hybrid lattice has double bend achromat (DBA) cells in two of the six arcs that provide a total 30 straight sections for insertion device (ID) beam lines extending into two new experimental halls. The remaining arcs contain TME cells. Using 90 m of damping wigglers the horizontal emittance at 4.5 GeV would be 100 pm-rad with 1.5-A stored beam. PEP-X will produce photon beams having brightnesses near $10^{22}$ (ph/s/mm$^2$/mrad$^2$/0.1% BW) at 10 keV. Studies indicate that a 90-m undulator could have FEL gain and brightness enhancement at soft x-ray wavelengths with the stored beam. Crab cavities or other beam manipulation systems could be used to reduce bunch length or otherwise enhance photon emission properties. The present status of the design of PEP-X as a storage ring is presented.

## OVERVIEW

The future of x-ray science lies in the ability to exploit complementary features of photon beams, such as high average brightness vs. high peak brightness, high energy resolution vs. very short pulse length, and high flux vs. high coherence. While storage rings presently provide the first set of these complementary beam properties, linac-based FEL facilities now in construction promise to provide the second set. Future energy recovery linacs (ERLs) and high-repetition rate, superconducting linac FELs may ultimately offer high overall performance, but their implementations are subject to the success of extensive R&D over many years in the future. SSRL at SLAC presently uses the SPEAR3 storage ring to provide 3rd generation-quality synchrotron radiation and experimental facilities optimized for selected x-ray techniques and scientific areas that employ high average brightness. With the LCLS, the complementary photon beam features of high peak brightness, short bunch length and high transverse coherence of 1-Å x-rays will also be provided at SLAC.

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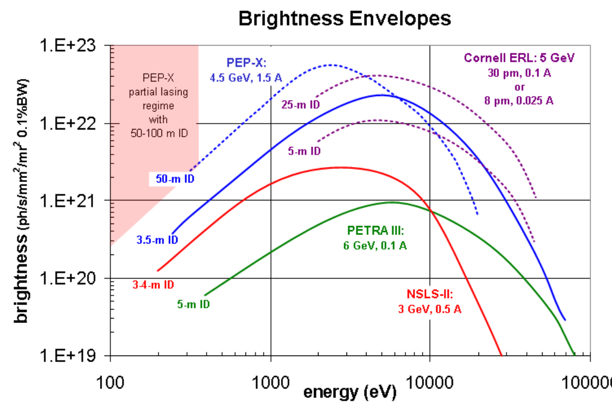


Figure 1: Brightness B of PEP-X (with optimized lattice functions) compared with various storage ring and proposed ERL light sources. A fully evolved ERL with 6-pm emittance at 100 mA would reach B >$10^{23}$.

Nevertheless, over time, SSRL users will seek enhanced performance over SPEAR3 and a new facility. With the recent termination of operation of the PEP-II B-Factory for the DOE's High Energy Physics program, it is only natural that SLAC should investigate what type of new high average brightness source could be implemented in the 2.2-km tunnel. To this end, a study group was formed in 2007 and, after considering a few conceptual options, it converged on the most practical as the initial machine of interest: PEP-X, a very bright, high-flux storage ring having 100 pm-rad emittance at 4.5 GeV and capable of operating with a beam current up to 1.5 A [1], chosen to limit the power density from 3 to 5-m undulator sources to 1 MW/mrad$^2$, a value that can be handled by present-day beam line front-end components 50-60 m from the source. While the group has not discounted the possibility of other options – an ERL source having lower emittance and reduced current, for example – the PEP-X storage ring implementation provides a performance benchmark using known technology against which other future implementation possibilities can be compared. The study indicates that PEP-X could deliver a factor of ten or more higher brightness than existing or planned future storage ring sources (Fig. 1). The facility would support two experimental halls, each containing 16 ID photon beam lines, typically 110 to 140-m long, but which could reach up to 600 m in some cases. Much higher brightness in the soft x-ray regime might be reached with partial lasing in 50-100-m undulators. Picosecond bunch lengths might be produced with crab cavities or other devices.

Table 1: Main parameters of PEP-X as a storage ring.

| | |
|---|---|
| Energy, $E_0$ [GeV] | 4.5 |
| Circumference, C [m] | 2199.32 |
| Emittance, $\varepsilon_x$ [pm-rad, 0 curr] | 67 |
| Beam current, I [A] | 1.5 |
| Harmonic number, h | 3492 |
| Number of bunches, $n_b$ | 3154 |
| Bunch length, $\sigma_z$ [mm] | 3.01 |
| Energy spread, $\sigma_\delta$ | 1.14 x $10^{-3}$ |
| Momentum compaction, $\alpha$ | 5.74 x $10^{-5}$ |
| Tunes, $\nu_x$ / $\nu_y$ / $\nu_s$ | 86.23 / 36.14 / 0.0076 |
| Damping times, $\tau_x$ /$\tau_y$ /$\tau_s$ [ms] | 20.7 / 21.2 / 10.7 |
| Energy loss, $U_0$ [MeV/turn] | 3.12 |
| RF voltage, $V_{RF}$ [MV] | 8.7 |
| $\beta_x$/ $\beta_y$ at ID center [m] | 10.4 / 8.0 |

The main parameters of PEP-X designed as a storage ring are tabulated in Table 1. The main change made since the preliminary study is an increase of the bunch length from 2.5 mm [2] to 3 mm, achieved by a combination of raising the momentum compaction factor and lowering the rf voltage. The longer bunch could mitigate the effects of coherent synchrotron radiation (CSR) and eliminate the necessity of high harmonic cavities in the design. This change also leads to a lower emttance because the main bending magnets were made weaker and longer in both DBA and TME cells. Variation of bunch length along the bunch train following the ion clearing gap caused by transient rf beam loading can be reduced either by using superconducting cavities or energy storage cavities for the normal conducting rf and/or harmonic cavities, and by implementing new LLRF compensation techniques [3].

## LATTICE

The PEP-X ring layout, shown in Fig.2, will be the same as in PEP-II in order to fit into the existing tunnel. The six arcs are designed to attain a low emittance and sufficiently large dynamic aperture. Two arcs will use a DBA lattice with 16 cells per arc yielding 30 dispersion-free 4.26-m straights for 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 [2π] 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 and having no ID

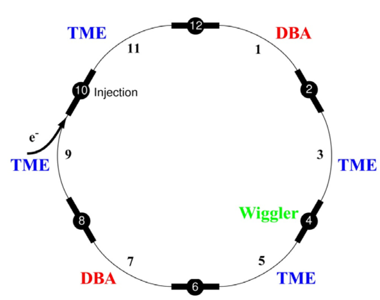


Figure 2: PEP-X ring layout.

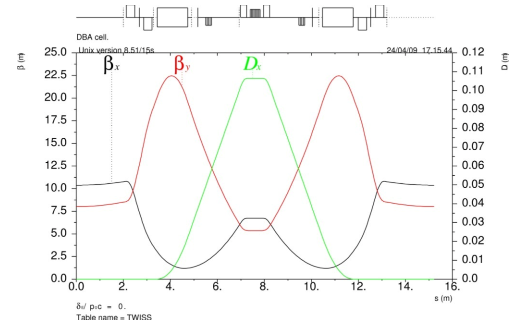


Figure 3: Optics functions in on DBA cell.

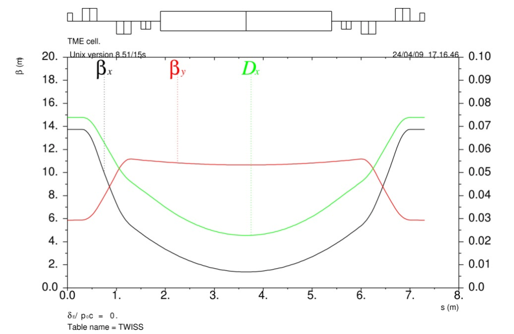


Figure 4: Optics functions in one TME regular cell.

straights. Conservatively low TME cell phase advance has been chosen ($\mu_x$ = 3/8, $\mu_y$ = 1/8 [2π]) 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 possible 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. 2. Five straights with identical FODO lattices will contain the rf accelerating cavities, the betatron tune and coupling correction systems, and the 89.3-m damping wiggler. The 6th straight section will be used for horizontal beam injection based on the existing PEP-II injection optics, requiring a 200-m horizontal β function at the injection septum. Compensation of non-linear chromatic tune variation is very good (Fig. 5). A preliminary study of dynamic aperture indicates that there is not much change with respect to the previous lattice. More detailed study remains to be carried out.

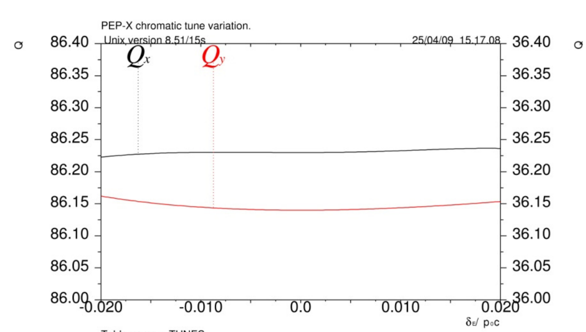


Figure 5: PEP-X tune versus momentum error Δp/p.

## IBS AND TOUSCHEK LIFETIME

Intra-beam scattering (IBS) concerns multiple Coulomb scattering in electron bunches that can lead to an increase in all bunch dimensions and in energy spread, whereas the Touschek effect describes large single Coulomb scattering events where energy transfer from transverse to longitudinal leads to immediate particle loss. Both effects are important in a low-emittance machine like PEP-X.

With $\sigma_z$ = 3 mm, $\varepsilon_x$ = 67 pm-rad and other parameters listed in Table 1, the equilibrium emittances including IBS were calculated employing the so-called "high energy approximation" [4] with results summarized in Table 2. For a flat beam, with the vertical emittance given by $\varepsilon_y = \kappa\varepsilon_x$, the horizontal emittance is doubled due to the IBS. The increased emittance is used to calculate the ID brightness shown in Fig. 1. The Touschek lifetime is calculated assuming a half aperture $\delta_E/E_0$ = 2%.

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

| κ | $\varepsilon_x$ (pm-rad) | $\varepsilon_y$ (pm-rad) | $T_l$ (min) |
|---|---|---|---|
| 1 | 70 | 70 | 115 |
| 0.053 | 150 | 8.1 | 35 |

## INSTABILITIES

While accurate assessments of instability thresholds and growth rates are not possible without detailed component designs, some plausible assumptions were made to estimate the effects of impedance in PEP-X with a preliminary, and largely incomplete, impedance model.

To study the microwave instability of the beam, driven by the ring impedance, we used the wake calculated for the PEP-II Low Energy Ring [5,6]. This wake includes short range contributions from the beam position monitors, rf cavities, resistive wall impedance, and some other elements of the ring. To smooth out the singularity of the wake at the origin (due to the accepted models for the resistive wall and the inductive wakefields [6]), this wake was convolved with a Gaussian distribution having an rms length of 0.5 mm (Fig. 6). The positive value means energy loss, and s > 0 corresponds to positions behind the source particle. We found the threshold of the instability to occur at a total ring current of ~3.2 A in 3154 bunches.

The threshold current of the CSR driven instability is typically determined by the wavelengths shorter than the natural bunch length. We used a model of shielded CSR wake [7] to calculate the threshold of the CSR driven microwave instability [8]. For a vertical gap of 2g and Gaussian bunches, the threshold bunch current $I_b^{th}$ is given by

$$\frac{I_b^{th}}{I_A} = \frac{\sqrt{2\pi}\gamma\alpha\,\sigma_\delta^2\sigma_z}{2^{8/3}g}$$

where $I_A = m_e c^3/e \approx 17$ kA is the Alven current and $\gamma = E_0/m_e c^2$. Taking g = 2 cm for a typical vacuum chamber and using the parameters listed in Table 1, we obtain the threshold to occur at 2.0 A total current. More studies on the microbunching instability driven by CSR with realistic vacuum chamber geometry are necessary to determine the threshold current more accurately.

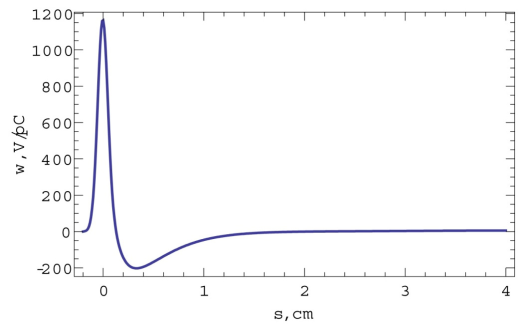


Figure 6: The LER short range wake (in units of V/pC) convolved with a 0.5-mm Gaussian.

## CONCLUSION

The emphasis of the PEP-X study group so far has been to establish a baseline design from which many future improvements can be made. First, a factor of two increase in brightness can be achieved by introducing a super cell with smaller β functions for the IDs. Second, dynamic aperture may be improved by using octupole magnets, resulting in a further increase of the Touschek lifetime. As mentioned, a third harmonic rf system is being considered to double the bunch length. The increased momentum compaction factor should help partial lasing [9] in a 50 to 100-meter undulator. Finally, we plan to investigate the option of not only an ERL for PEP-X, but also the possibility of increasing the rf frequency and the number of bunches so that bunch charge can be reduced to counteract IBS and reach a lower emittance with reasonable total current.

The large number of design challenges associated with the implementation of PEP-X are summarized in [1] and [10]. In addition to the lattice and rf issues discussed above, these include developing high performance electron and photon BPMs, beam trajectory feedback systems and optics supports that can meet the very tight stability requirements, improved beam line component thermal designs and optical components that can preserve the extraordinary emittance and coherence of the beam.

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