STATUS OF THE PEP-X LIGHT SOURCE DESIGN STUDY[†]

Robert Hettel, Karl Bane, Kirk Bertsche, Yunhai Cai, Alex Chao, Xiaobiao Huang, Yi Jiao, Cho Ng,
Yuri Nosochkov, Alexander Novokhatski, Thomas Rabedeau, Claudio Rivetta, James Safranek,
Gennady Stupakov, Lanfa Wang, Min-Huey Wang, Liling Xiao
SLAC National Accelerator Laboratory, Menlo Park, CA, U.S.A.

Abstract

The SLAC Beam Physics group and other SLAC collaborators continue to study options for implementing a near diffraction-limited ring-based light source in the 2.2-km PEP-II tunnel that will serve the SSRL scientific program in the future. The study team has completed the baseline design for a 4.5-GeV storage ring having 160-pm-rad emittance with stored beam current of 1.5 A, providing $>10^{22}$ brightness for multi-keV photon beams from 3.5-m undulator sources. The team has also investigated possible 5-GeV ERL configurations which, similar to the Cornell and KEK ERL plans, would have ~30 pm-rad emittance with 100 mA current, and ~10 pm-rad emittance with 25 mA or less. Now a 4.5-GeV "ultimate" storage ring having emittance similar to the ERL and operating with ~200 mA is under study. An overview of the progress of the PEP-X design study and SSRL's plans for defining performance parameters that will guide the choice of ring options is presented.

OVERVIEW

An accelerator physics team at SLAC has been studying ways that the 2.2-km-circumfernce PEP-II accelerator tunnel, previously used for the B-Factory program, might be used for a future, very low emittance light source for the Stanford Synchrotron Radiation Lightsource (SSRL) that would replace SPEAR3 in the 2020 decadal time frame. The six 242-m tunnel arcs enable implementation of a very low emittance storage ring lattice. The six 120-m long straight sections provide space not only for injection and rf components, but also for performance-enhancing components such as very long insertion devices (IDs), damping wigglers, multi-ID chicanes, specialized beam manipulation sections, switched bypasses for soft X-ray FELs, or localized bunch compression systems for short bunch generation. The tunnel could also be used to house a multi-GeV, ultralow emittance ERL.

The availability of modern simulation tools, the evolving accuracy of models for impedances, lifetime, and collective effects, together with the experience gained over the past decade in the designs of high performance rings (e.g. damping rings, low emittance light sources such as NSLS-II, MAX-IV and hypothetical "ultimate" rings [1,2]), ERL-based light sources and FEL X-ray sources have enabled consideration of more aggressive designs for PEP-X having capabilities beyond those envisioned in the past [3,4].

BASELINE DESIGN

In the first phase of PEP-X studies, several storage ring configurations were investigated, including the possibility of a modest upgrade, similar to that for PETRA-III [5], where only one of the six arcs would be converted to a 16-cell DBA cell structure to provide straight sections for 3.5-m long IDs, while the remaining arcs would use a reconfigured PEP-II magnet lattice structure. Longer IDs could be accommodated in the adjacent long straight sections. With a 4.5-GeV electron energy, chosen as a first-order optimization of the trade-off between brightness at photon energies <~20 keV and the dynamical properties of the electron beam, this configuration would reach an emittance of order 1 nm-rad at 4.5 GeV using ~100 m of damping wigglers. Additional lattice and vacuum chamber conversion in the five arcs, still using modified PEP-II magnets, would yield 0.4 nm-rad emittance.

With complete replacement of vacuum chambers and magnets, a ring having emittance on the order of 100 pm-rad or less can be configured. For its "baseline design" [6], the team developed a hybrid lattice comprised of two 16-"super cell" DBA arcs (alternating high- and low- β_x straights) for 32 beam lines, four arcs of TME cells [7], and 93 m of damping wigglers result in a zero-current emittance of 86 pm-rad at 4.5 GeV (Figure 1). This emittance for this lattice increases due to intrabeam scattering (IBS) as bunch charge increases. When ~3200 bunches out of the 3492 available are filled with 3.4 nC each to produce 1.5 A stored beam current, the emittance grows to 164 pm-rad if horizontal-vertical coupling is set for 8-pm-rad vertical emittance, the diffraction limit for 1-
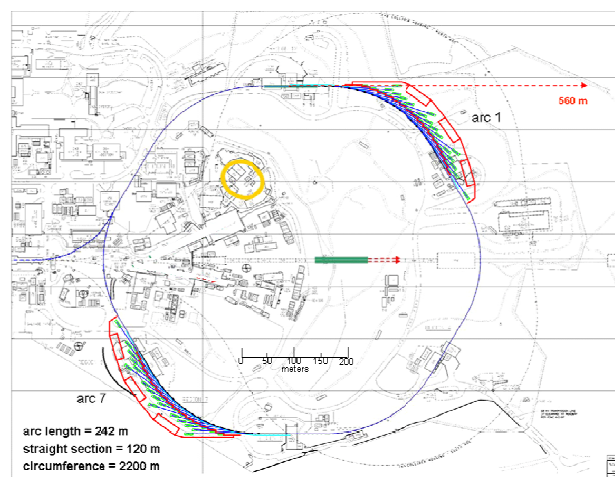

Figure 1: Conceptual layout of the PEP-X light source having two experimental halls containing a total of 32 X-ray beam lines. SPEAR3 is shown in yellow.

Å X-rays. A 3rd harmonic rf cavity is needed with this coupling to increase the electron bunch length so that a lifetime of ~1 hr can be achieved at 1.5 A. Top-up injection every few seconds from a full-energy linac will be required to maintain percent-level current constancy.

Each DBA arc and adjacent upstream straight section in the baseline design would serve 16 ID beam lines 110-140 m in length with experimental stations located in a hall having ~125,000-square-foot floor space. Longer beam lines, up to 600 m, can be accommodated in special locations. The brightness envelope for this design is compared with other existing and future ring-based sources in Figure 2.

While the PEP-II rf cavity system that might be used for PEP-X could easily support >1.5-A operation, the practical operating current is limited by the photon power handling capability of the beam lines. At 1.5 A, the angular photon power density from 3.5-m ID sources to 1 MW/mrad^2 at 60-70 m from the source, approximately half the photon beam line length, a value that can be handled by present-day beam line optical components.
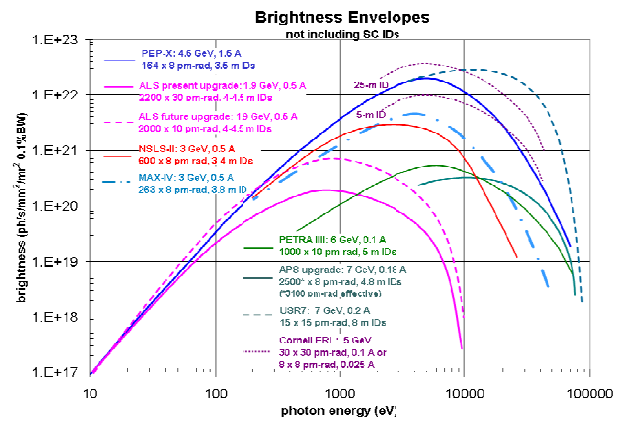

Figure 2: Approximate brightness envelopes for existing and future ultimate ring light sources assuming non-superconducting ID lengths as specified in the figure. Brightness from a 3.5-m PEP-X ID is shown in blue.

ERL CONFIGURATIONS

In recent months the team has studied 5-GeV, 1.3-GHz superconducting ERL implementations for PEP-X, similar to those for Cornell [8] and KEK [9]. Like Cornell and KEK, the PEP-X ERL would have 3 basic operating modes: 100 mA with 30 pm-rad emittance (77 pC/bunch, 2 ps rms bunch length), 25 mA with 8 pm-rad emittance (2 ps rms bunch length), and a 100-fs mode having >100 pm-rad emittance. The study is focused on the possible ERL geometries given the orientation of the PEP tunnel, the SLAC linac tunnel, and the LCLS facility layout [10]. Two main geometries are identified: one where the superconducting linac is situated in the main SLAC linac tunnel, requiring transport lines to and from the PEP-X ring and a beam return loop at the front end of the linac, and another where the superconducting linac is located in the infield of the PEP-X ring (Figure 3).

Because of the inherent low energy spread of the 5-GeV beam (~10^{-4}), a superconducting ERL linac could drive high repetition rate FELs, either by "stealing" one out of a thousand or more bunches in the ERL bunch train or by single-pass acceleration of one bunch at MHz or less repetition rates. If the linac is situated in the main SLAC tunnel, the FELs could be aligned with the existing LCLS

photon beam transport lines. As is being considered by KEK, X-ray FEL oscillators [11] might be configured.

With the infield configuration, long transport lines and the turn-around arc are avoided. This configuration could readily accommodate a cost-saving two-pass accelerating mode, where the 2.5-GeV beam from the first pass would be transported around the PEP-X tunnel in a separate transport line, perhaps providing a source of softer X-rays, before being accelerated to a second time to 5 GeV.

Studies so far indicate that the 2-ps ERL beam can be transported around the PEP-X ring with only 10% increase of emittance from beginning to end, while 100-fs bunches can be transported with 30% emittance growth due to CSR effects. However, given the short-bunch capabilities of the LCLS, it is not clear that the short-bunch capability of the ERL will be a major factor in making a technology choice.

It is well known that, due to many technical challenges, a light source-quality ERL cannot be built today. These include photocathode guns having sufficiently low beam, emittance and cathode lifetime, and beam instabilities, halo losses and higher order modes with high current operation in the superconducting linac. Nevertheless, groups at Cornell, KEK and elsewhere are working to develop this technology so that it might be ready on the timescale that PEP-X would actually be built.
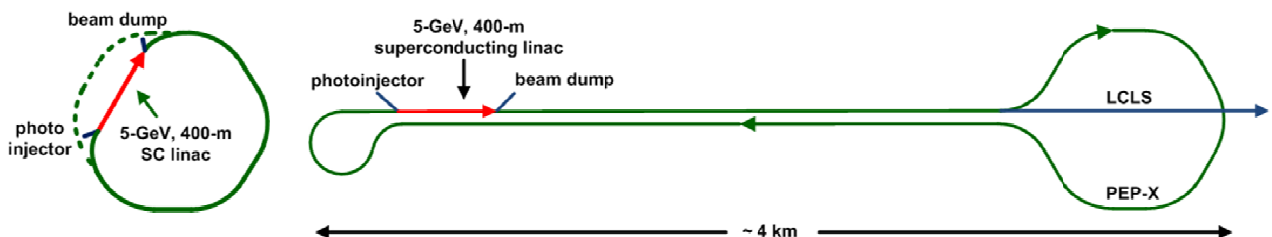

Figure 3: Conceptual layouts of two 5-GeV PEP-X ERL configurations: an in-field version where the ~400-m 1.3-GHz superconducting linac is housed within the ring perimeter (left), and a version where the linac is housed in the main SLAC linac tunnel where it might drive high repetition rate FELs for the LCLS (right).

"ULTIMATE" RING

At present the design team is investigating a storage configuration having emittance comparable to an ERL. The preliminary lattice for this ultimate ring is based on MAX-IV design [12] using seven-bend achromat (7BA) cells (Figure 4). Each 30.4-m cell contains 5 main combined function dipoles with focusing quadrupoles between them, two normal matching dipoles at each end and quadrupole triplets at each end of a 5- m ID straight. Each arc is comprised of 8 cells allowing up to 9 ID straights per arc. The cell phase advance of $\mu_x = 2.125$ x 2π and $\mu_y = 1.125$ x 2π provides cancellation of sextupole driving terms in each arc. Without damping wigglers, the natural emittance with 200 mA is 55 pm-rad (29 pm-rad at zero current) which can be coupled to produce either a round beam (27.5 pm per plane), or a flatter beam (e.g. 47 x 8 pm). Dynamic aperture is $\sim 200\sigma$ of the 12 μm rms horizontal x 5 μm rms vertical beam size in straight sections. Further reduction of emittance (a factor of 2 or more) and damping times using a damping wiggler has yet to be studied. Baseline and ultimate ring parameters are compared in Table 1.

While dynamic aperture is large compared with beam dimensions, it is likely to be insufficient for off-axis injection. On-axis "swap-out" injection [2] of ~10 nC in trains of ~20 bunches from an at-energy linac would limit total current to 100-200 mA in a pattern of 100-130 such trains in the ring, separated by gaps to accommodate kicker rise- and fall-times. Photon brightness would be equivalent to the 1.5-A baseline design but would have higher coherent fraction and far less photon heat loads for accelerator and beam line components. A re-optimization of arc straight section length to accommodate longer IDs may yield higher source brightness. Higher current could be stored using an injection accumulator ring. Preliminary studies indicate that this lattice configuration might support a nm-wavelength FEL in a switched bypass [13].
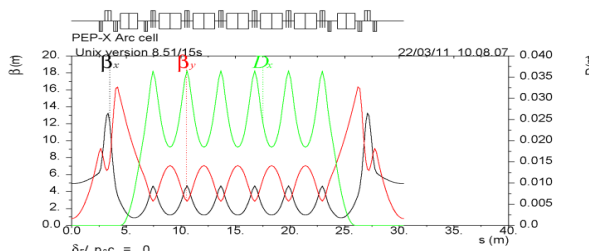

Figure 4: One 7-bend achromat cell.

CHALLENGES

Common to both the ultimate ring and ERL configurations is the need for advances in beam line optical design, including mirrors, refractive optics, monochromators, and other components that will be required beyond existing technology to preserve the extraordinary emittance and coherence of the beam and to handle its high power densities. Micron-level beam

Table 1: Main Parameters of PEP-X as a Storage Ring

Parameter	Baseline damp wigg	Ultimate no damp wigg
Energy, E_0 [GeV]	4.5	4.5
Circumference, C [m]	2199.32	2199.32
Emittance @ I, $\varepsilon_x/\varepsilon_y$ [pm]	160/8	47/8
Beam current, I [A]	1.5	0.2
Harmonic number, h	3492	3492
Number of bunches, n_b	3154	~2500
Bunch length, σ_z [mm]	3.01	3.1
Energy spread, σ_δ	1.14×10^{-3}	7.23×10^{-4}
Mom. compaction, α	5.74×10^{-5}	5.0×10^{-5}
Tunes, ν_x / ν_y / ν_s	86.23 /36.14 / 0.0076	114.23/66.14 / 0.0041
Damp times τ_x /τ_y /τ_s [ms]	21 / 21 / 11	75/ 184/ 326
E loss/turn, U_0 [MeV]	3.12	0.36
RF voltage, V_{RF} [MV]	8.7	2.7
Lifetime @ I [hr]	1	tbd (> 1 est.)
β_x/ β_y at ID center [m]	10.4 / 8.0	4.9 / 0.8

stability between source and experiment will be required, most likely attainable only with advanced integrated electron orbit and beam line stabilizing feedback systems.

Successful realization of PEP-X depends not only resolving technical challenges, but also on establishing a compelling scientific justification for building such a machine. A series of workshops have already been convened by the photon science community to explore new applications and capabilities that could be served by diffraction-limited, high average brightness, low peak brightness, high repetition rate sources for hard X-rays, complementary the X-ray FELs [14], which include imaging with nanometer or better resolution and X-ray photon correlation spectroscopy (XPCS). Articulation of the scientific goals will help define more specific design parameters and functional modes for the future machine, as well as the technology needed to realize it.

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