1. Overview

1.1. Long Range Goals for SSRL

SSRL provides 3rd generation storage ring-based synchrotron radiation and experimental x-ray facilities optimized for selected x-ray techniques and scientific areas to a broad scientific user community. The near-to-medium term SSRL program is based on the storage ring SPEAR3, which in 2003 was upgraded to an intermediate energy (3 GeV) high-brightness source. SPEAR3 enhances existing programs and facilitates the development of new scientific capabilities based on micro- or nano-sized x-ray beams with high intensity and high brightness, well defined polarization and time structure in the picosecond range. New instruments and methodologies which utilize these opportunities, coupled with incremental improvements in SPEAR3 performance, like top-off and higher current operation, are the highest near term goals. The *storage ring* concept underlying SPEAR3 which is complementary to LCLS is broadly used at existing x-ray user facilities around the world. Storage rings provide a sure path towards obtaining detailed information on the fundamental interactions between the electrons, spins and atoms in matter “near equilibrium”. An improved understanding of these interactions forms a large part of what we envision as “grand scientific challenges” today and SPEAR3 remains a vital tool in our pursuit of many, but not all, aspects of these questions.

The physical size (circumference) of SPEAR3 constitutes a barrier to upgrading it to achieve significantly higher brightness, a direction increasingly driven by the need to study complex materials on the nano-scale. Therefore the longer term future of SSRL is based on the transfer of the evolving scientific programs from SPEAR3 to a higher-performing synchrotron source. To be viable, such an evolution must result in transformational new capabilities measured on an international scale. In order to avoid a “dark period” for the SSRL user community and maintain one of the three vibrant and essential elements of photon science at SLAC (the other two being LCLS and the Centers of Excellence), we envision an adiabatic transition from SPEAR3 to a future state-of-the-art storage ring: PEP-X.

The scientific need for PEP-X is based on its ability to deliver an unprecedented *average* brightness. This allows the study of complex materials, the foundation of advances in key areas of societal impact like energy, environment, health and technology, in an unprecedented phase space, simultaneously covering the fundamental degrees of freedom of space, time and energy. In the past, x-rays have been known for their ability to yield information on atomic and nanoscale length scales through diffraction and imaging. On larger length scales, ranging from microscopic to macroscopic dimensions, spectroscopic techniques have revealed details of the electronic structure through energy and time resolved x-ray measurements. The new scientific paradigm, however, is the recognition of the complexity of matter derived from nanoscale ordering in the charge and spin degrees of freedom and their as yet ill understood dynamics. Such order exists either naturally in macroscopic “correlated materials” or, more generally, in nanoscale materials and liquids through imposed spatial constraints. At present we have only seen the tip of the iceberg because we lack the ability to probe real materials on the nanoscale with energy and time resolved spectroscopies. For example, future studies will focus on the determination of the electronic structure of distinct nanoscale regions by (spin resolved) photoemission spectroscopy or the unveiling of the dynamic behavior of nanoscale regions through x-ray correlation spectroscopy (coherent scattering) that extends well below the timescale of seconds presently needed for imaging. Such problems are at the very heart of the "grand challenges" identified by BESAC.

The future of x-ray science lies in the use of two complementary sources, x-ray lasers which emphasize *peak* brightnesss (coherence) and the ultrafast *time* domain, and ring based sources which emphasize *average* brightness (coherence) and ultrahigh *energy* resolution. While linac based sources may also produce very high average brightness by combining peak brightness with moderate repetition rates (up to 100 kHz), ring based sources purposely circumvent the effects of peak photon fields by reducing the number of photons per pulse while operating at high pulse repetition rates (~500 MHz). In addition, ring sources employ pulse lengths in the picosecond range compared to linac based sources which emphasize femtosecond pulses. For many experiments picosecond pulses are ideal because the matching picosecond timescale of the electron-phonon coupling allows the electronic system to remain "cool" during and after the pulse. In addition, the laws of physics allow experiments with high energy resolution. The latter arises from the coupled uncertainties in energy (ΔE) and time (Δt) according to $\Delta E \Delta t \sim 4$ fs eV. Hence a 1 femtosecond pulse corresponds to an energy uncertainty of 4 eV while an energy resolution of 1 meV requires a pulse length longer than 4 ps. PEP-X is therefore complementary to LCLS and its scientific program will be pushing toward the exploration of the combined minimum phase space boundary of 1nm, 1meV and 10ps through nanometer-spectroscopy techniques.

PEP-X would occupy the underground tunnel now occupied by the recently decommissioned PEP-II storage rings used to collide beams to study B-meson decays (Sec. 1.2). The extensive developments for high-current, stable operation in PEP-II that were driven by the high energy physics program, coupled with very low emittance storage ring implementation methods being used for new light source and damping ring designs, provide the possibility of delivering average x-ray brightness exceeding that available from the NSLS-II or PETRA-III by an order of magnitude. The 2.2-km circumference, which includes six 120-m straight sections, enables implementing a very low emittance lattice, limited by intrabeam scattering in the electron bunches, to the order of 0.1 nm-rad for 4.5-GeV electron energy. The vertical emittance can be reduced by lattice coupling adjustment to 8 pm-rad, the diffraction limited emittance for 1-Å photons. PEP-X would operate with a nominal beam current of 1.5 A, limited by the power handling capability of beam line optical components, making use of the powerful PEP-II rf system capable of sustaining beam currents in excess of 3 A at this energy. Studies indicate that with such a low emittance, FEL gain and brightness enhancement at soft x-ray wavelengths would be attained with the stored beam. Such a source would complement the LCLS science program and offer exciting and groundbreaking scientific opportunities, including:

- imaging with 1-nm or smaller spatial resolution with sufficient intensity
- combination of nm spatial and meV energy resolution: "nano-ARPES"
- combination of nm spatial with temporal resolution down to micro or nanoseconds: soft x-ray photon correlation spectroscopy
- spin polarized photoemission (now limited by 10^{-4} detection efficiency) with adequate intensity
- x-ray Raman spectroscopy or "x-ray-loss XAFS" of low-Z systems in small volumes and under extreme conditions

We envision PEP-X to replace SPEAR3 by about 2020, with the entire SSRL program migrating to PEP-X around that time. This timescale calls for a start of conceptual design funding by 2014 or earlier.

1.2. PEP-II Facility

The PEP-II accelerator facility consists of two storage rings: the 9-GeV, 2-A High Energy Ring (HER) and the 3.1-GeV, 3-A Low Energy Ring (LER) housed in a 2.2-km circumference tunnel having six 243-m arcs and six 120-m straight sections (Fig. 1.2.1). The LER is mounted ~0.9 m directly above the HER. Both lattices consist of 16 FODO cells per arc. There are only short (~0.5 m) empty straight sections in the HER arcs due to the long dipole magnets. The BaBar particle physics detector is located in Interaction Region 2 (IR-2) where special ring lattice and vacuum chamber features enable the beams from the two rings to collide. PEP-II operated as a B-factory for the US DOE High Energy Physics program from May 1999 until April 7, 2008.

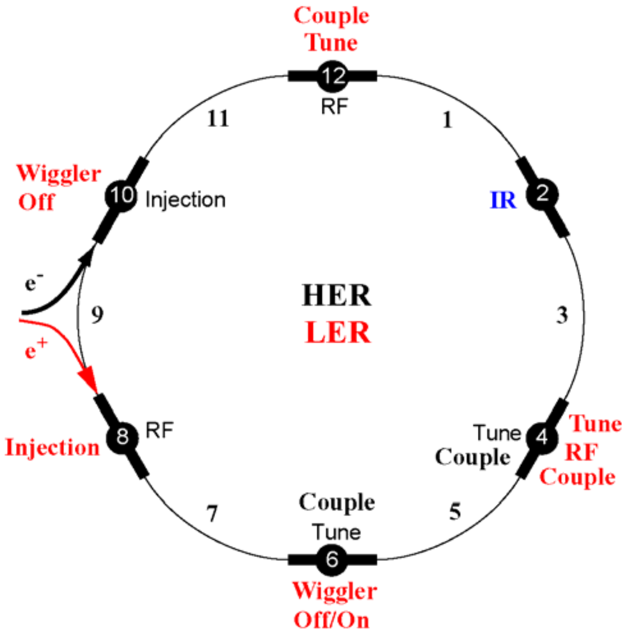

Figure 1.2.1: PEP-II with functions of the straight sections indicated in black for the 9-GeV electron HER and in red for the 3-GeV positron LER.

The PEP-II facility is equipped with mode-damped RF cavities (28 for the HER, 8 for the LER) powered by 15 klystron power stations, transverse and longitudinal multibunch feedback systems, injection components, vacuum system components, magnet power supplies, and a facilities infrastructure for cooling water, compressed gas and mains power. While PEP-II has a complete complement of instrumentation and control systems, it is likely that most of them will become obsolete or difficult to maintain in a future light source implementation and will need to be replaced.

Electrons for the HER and positrons for the LER are provided by the main SLAC linac and are transported to the rings via two transfer lines: the North Injection Transport (NIT) line for electrons circulating clockwise in the HER, and the South Injection Transport (SIT) line for positrons circulating counterclockwise in the LER. "Trickle charge" single-bunch injection at about 10 Hz (30 Hz possible) is provided for both rings to maintain a high degree of stored current constancy.

The nominal emittance for the HER is 48 nm-rad at 9 GeV respectively. By increasing the phase advance per HER lattice cell from 60° to 90° and reducing the ring energy to 4.5 GeV, the HER ring emittance can be reduced to 5 nm-rad; adding ~100 m of damping wiggler further reduces the emittance to 0.8 nm-rad. Increasing the phase advance per cell reduces the emittance even further, but the strong sextupoles that would be required reduce the dynamic aperture to an unacceptably small value. The drawback to this simple implementation is that there are no straight sections for insertion devices in the arcs. For this reason, new lattice configurations are being considered for PEP-X as discussed below.

The nominal emittance for the LER is 24 nm-rad at 3 GeV. Due to the short length of the LER dipole magnets, no appreciable reduction in emittance at energies between 3 GeV and the maximum of ~4 GeV is possible except that gained using damping wigglers. For this reason, use of the LER as a light source is not being considered.

1.3. PEP-X Implementation

The predominant goal for PEP-X is to serve as the next high-performance light source at SLAC for the diverse SSRL user community. The parameters and properties that define the performance capabilities of such a light source for providing scientific capabilities discussed in Section 1.1 include:

- high average brightness and flux
- moderate peak brightness and flux
- high coherent flux and photons per pulse
- spectral range and tunability
- photon energy resolution
- spatial measurement resolution
- photon beam size and bunch length
- photon polarization control
- beam line and optical component performance
- beam stability
- different operating modes as needed to accommodate various applications

1.3.1 Light Source Possibilities

The large circumference and six long straight sections provided by the PEP tunnel offer many interesting and potentially novel possibilities for implementing a light source that would achieve very high performance for some or all of the parameters listed above.

The predominant parameter characterizing source performance, brightness B, scales proportionally with photon flux $F(\Delta\lambda/\lambda)$ in a wavelength bandwidth $\Delta\lambda/\lambda$ and inversely with transverse beam emittance for that photon wavelength:

$$B(\Delta\lambda/\lambda) = \frac{F(\Delta\lambda/\lambda)}{4\pi^2(\varepsilon_x \oplus \varepsilon_r)(\varepsilon_y \oplus \varepsilon_r)}$$

where ε_x and ε_y are the horizontal and vertical electron beam emittances, ε_r is photon emittance from a point source, and $\oplus$ represents the quadrature sum. The two ways to reach high brightness are therefore to 1) reduce the transverse emittance of the electron beam towards the diffraction limit of the point-source photon beam at the wavelength of interest (given by $\lambda/4\pi$, or 8 pm-rad for 1-Å photons), and 2) increase the flux. Flux, and the radiated power that must be handled by beam line optics, increase with beam current and energy. Note that a very low-emittance source can have high brightness but low flux (such as an ERL), and a relatively high emittance source can be bright if the flux is large. In the early stages of the PEP-X design study, several implementation possibilities having different balances of flux and emittance were investigated, including:

- A very low-emittance, high-current storage ring with damping wigglers in place of the HER having an emittance between 1 and 0.1 nm-rad, depending on how much of the PEP-

II HER is replaced, at an energy between 3 and 5 GeV. Vertical emittance would be ~8 pm-rad, at the diffraction limit for 1-Å, 12-keV photons, reached by reducing the horizontal-vertical emittance coupling. This implementation option was ultimately chosen for the base machine proposal (Sec. 1.3.2).

- An ultra-low emittance storage ring (emittance <0.05 nm-rad) in place of the HER, most likely requiring on-axis injection due to a very small dynamic aperture. On-axis injection would necessitate complete bunch or multi-bunch replacement during each injection cycle from either a high-performance linac injector or from an accumulator ring, possibly configured from the LER. Current and flux would be limited by lifetime issues.
- An ultra-low emittance, low-current energy recovery linac (ERL, ~0.01 nm-rad, the diffraction limit for 10-keV photons), possibly co-located in the ring tunnel.
- Soft x-ray FEL lasing capabilities providing high flux on rings having <0.1 nm-rad emittance using a very long (~100 m) undulator (Sec.3.3) Unsaturated SASE from the stored electron beam would enhance the radiated power at the resonant wavelength by a factor of ~100, resulting in an average brightness of $\sim 10^{24}$. Saturated lasing at these wavelengths, perhaps in shorter undulators, might be reached with a laser seed source, although sufficiently powerful sources do not yet exist for wavelengths <~10 nm.

Many of these implementation options have been considered by earlier investigators: conversion of PEP-I into a light source was first considered in the mid-1980s to early 1990s [1, 2, 3, 4], a 2-km "ultimate light source" (~0.13 nm-rad @ 7 GeV with 280 m of damping wigglers) was investigated in 2000 [5], multi-GeV ERL light sources are under experimental development at Cornell [6] and elsewhere, and FEL lasing of a 60-m long undulator at 4 nm wavelength in a switched bypass on the converted PEP-I light source was investigated in 1992 [7].

For all ring implementation options, space is available to implement rf electron bunch manipulation components, whether for fast kicking or for bunch phase space manipulation [8, 9]. For example, pulsed and CW rf crab cavities are already being considered for use as localized bunch-length compressors, and 3rd-harmonic rf cavities are used to lengthen bunches in many storage rings in order to increase beam lifetime and to avoid disruptive high-frequency beam instabilities. PEP-X could employ these devices, and potentially other technologies yet to be developed, to enhance light source performance.

1.3.2 PEP-X Base Implementation

Of the implementation options mentioned above, the one that is best matched to meeting future SSRL needs at reasonable cost and risk, in an era where the LCLS provides high peak brightness and short-bunch FEL capability at SLAC, is the first: a very low emittance storage ring having high current and flux and >~24 insertion device (ID) straight sections for x-ray beam lines. While a very low-emittance ERL promises to provide very high

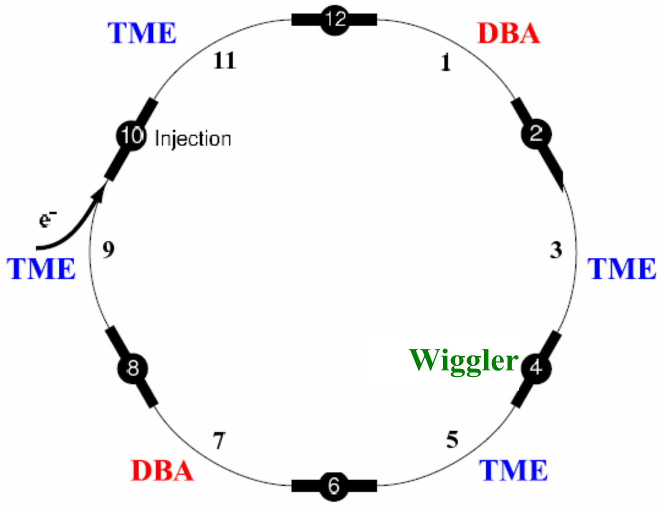

Figure 1.3.1: PEP-X with 2 DBA arcs and 4 TME arcs. Damping wiggler location might change and/or be distributed in two long straight sections.

brightness with less current and total photon power, the technology is highly experimental at this stage and the cost for the high-energy superconducting linac could be prohibitive.

To reach the highest performance and a brightness that is ten times higher than state-of-the art facilities now in construction, the base design for PEP-X replaces almost all of the PEP-II HER lattice and vacuum chamber components. On the other hand, many valuable components from PEP-II including the tunnel, high-performance rf systems, multi-bunch feedback components and facility infrastructure would be reused where possible.

The present magnet lattice for PEP-X consists of two arcs having 16 double-bend achromat (DBA) cells per arc and four arcs having 32 theoretical minimum emittance (TME) cells and 2 matching cells per arc to minimize ring emittance (Fig. 1.3.1). While the arcs with TME cells would have no straight sections for IDs, each of the two DBA arcs would provide 15 straight sections, 4.3 m in length, and an experimental hall for each arc would contain ~16 beam lines nominally 110-140 m long, including one having an ID source located in the upstream long straight section (Fig. ES.1). The beam line for this ID could be up to 250 m long while still contained in the experimental hall by placing the source ID far upstream in the 120-m straight section. There is room in the arc 1 area for longer beam lines, up to ~600 m, that extend beyond the experimental hall (Fig. ES.1). Very long undulators or multiple undulators (in special chicane or gentle arc lattice sections) for beam lines could be located in IR-12 and IR-6 and would provide significant emittance damping.

The 4.5-GeV operating energy for PEP-X has been chosen at this point in the design study as a first-order optimization of the trade-off between brightness at photon energies <~10 keV and the dynamical properties of the electron beam. In principle, the photon brightness below 10 keV would be enhanced as the ring energy E is reduced towards 4 GeV and below provided the beam current I can be increased from that at 4.5 GeV to maintain a constant photon power density on accelerator and beam line components ($I \propto E^{-4}$ for constant power density). In reality, the intrabeam scattering (IBS) increases beam emittance for a given beam current as electron energy is reduced (Sec. 2.6), and this effect negates the potential brightness gain. For PEP-X, the brightness below 10 keV is less at 4 GeV and below than at 4.5 GeV. Lower ring energy also reduces the thresholds for electron bunch instabilities. A more detailed optimization of operating energy will be made in the future, with beam power issues limiting the upper energy reach.

While the accelerator rf and vacuum chamber systems can operate with a current of 3 A at 4.5 GeV, the operating beam current of 1.5 A was chosen for stable multibunch operation and to limit the angular power density from undulator sources to 1 $MW/mrad^2$, a value that can be handled by present-day beam line optical components situated midway along a 140-m beam line. This power handling capability could conceivably increase in the future as new high-power optics technology is developed, enabling higher current operation in PEP-X (at the expense of increasing emittance from intrabeam scattering within each electron bunch). Due to the short beam lifetime at these currents and small coupling, frequent top-off injection, on the order of every second(s), is necessary to maintain percent-level current constancy. The natural electron bunch length of 2.5 mm rms would be lengthened to 5 mm rms using a 3rd harmonic rf cavity to improve lifetime. Lifetime can be increased further by increasing the vertical coupling.

Machine parameters are summarized in Tables ES.1 and 2.1.1. Nominal photon spectral brightness and flux are shown in Fig. ES.2 for typical 3.5-m IDs in the arcs. Photon source properties are discussed more completely in Section 3. While the horizontal and vertical betatron amplitudes for the ID straight sections do not provide optimal source properties at the time of this report, it is expected that they will be optimized as lattice studies continue.

The chosen PEP-X implementation is described in more detail in the following sections. These sections summarize the present status of the PEP-X design study; all performance parameters and engineering concepts presented in the report are preliminary and subject to change and further optimization.