3. Photon Sources and Beam Lines

3.1 Photon Source Properties

The PEP-X ring will contain two double-bend achromat (DBA) arcs each of which includes 15 straights suitable for installation of insertion device (ID) source magnets. Each DBA arc is preceded by a 120-m long straight which can accommodate an additional very long ID. Four theoretical minimum emittance arcs and associated 120m long straights comprise the remainder of the ring. These latter arcs, which minimize the overall ring emittance, are not designed to serve as photon beam line source points. The DBA ID straights are 4.26m long which provides sufficient space to accommodate 3.5-m IDs after accounting for bellows and taper masks. The electron beam characteristics at the center of each DBA straight are listed in Table 3.1.1.

Table 3.1.1: Electron beam characteristics at the center of the 4.26-m ID straights in the DBA straights.

ε_x (nm-rad)	ε_y (nm-rad)	δE/E (%)	β_x (m)	β_y (m)	σ_x (mm)	σ_y (mm)	σ_x' (mrad)	σ_y' (mrad)
0.144	0.0080	0.112	9.09	8.14	0.0362	0.0081	0.0040	0.0010

To illustrate the potential of PEP-X as a photon source, the calculated brightness and flux of several representative in-vacuum, hybrid, planar undulator magnets are presented in Figures 3.1.1 and 3.1.2, respectively. The magnetic parameters of these undulators, which are detailed in Table 3.1.2, are consistent with present commercially available magnet technology. Higher risk undulator designs utilizing cryogenically-cooled permanent magnets or superconducting magnets hold promise for higher performance but require some maturation of the associated technology. Thus the performance curves of Figures 3.1.1 and 3.1.2 offer conservative estimates of ID performance achievable with PEP-X. It should also be noted that the β_x and β_y values listed in Table 3.1.1 are not fully optimized for maximizing undulator brightness. Further refinement of the PEP-X lattice should result in more optimized β function values, yielding up to a two-fold increase in undulator brightness.

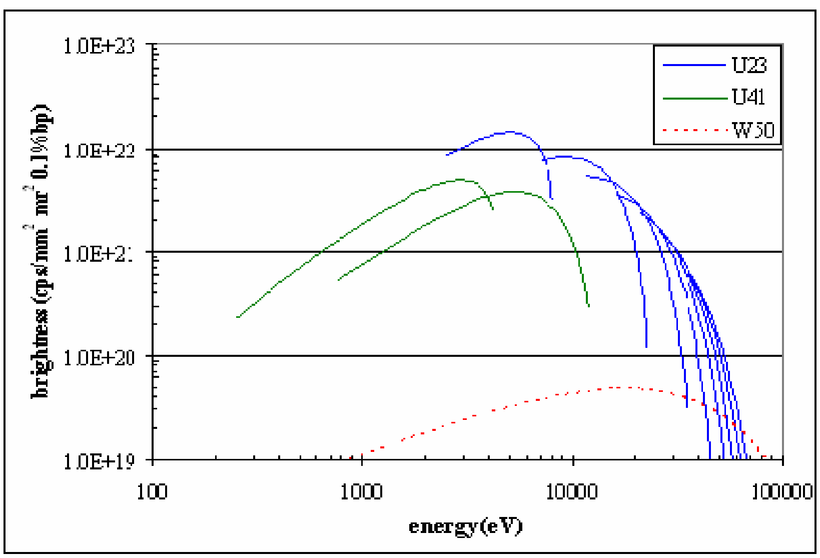

Figure 3.1.1: Calculated on-axis brightness of representative in vacuum insertion devices on PEP-X assuming the source and magnet parameters listed in Tables 3.1.1 and 3.1.2 and 1.5A stored current. Only the odd harmonic tuning curves are depicted for the two undulator sources U23 and U41. As noted in the text evolving magnet technologies and/or PEP-X lattice refinement could result in up to a two-fold brightness increase.

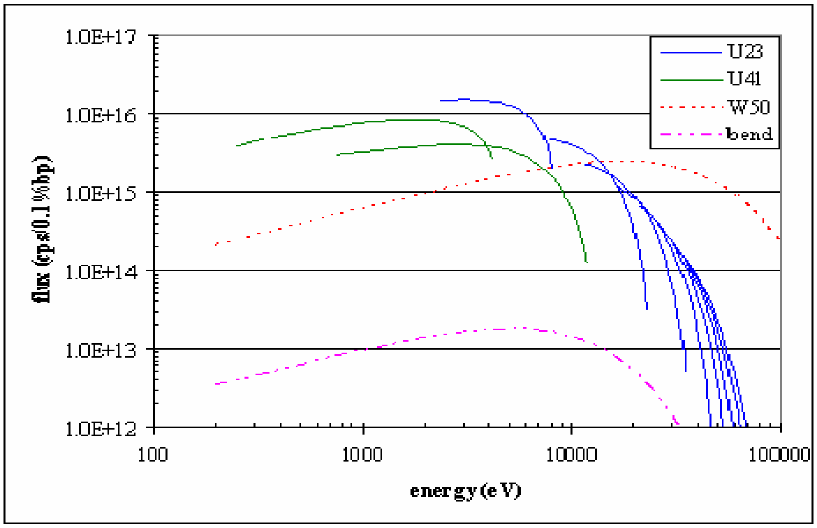

Figure 3.1.2: Calculated useful flux of representative sources on PEP-X assuming the source and magnet parameters listed in Tables 3.1.1 and 3.1.2 and 1.5 A stored current. The undulator curves represent the flux integrated over the central cone of the undulator emission spectra where only the odd harmonic tuning curves are depicted. The W50 wiggler and bend emission spectra are integrated over a 0.3-mrad horizontal by 0.1- mrad vertical acceptance.

Table 3.1.2: Representative source magnet characteristics. The minimum magnetic gap for the three in vacuum insertion devices is assumed to be 6.0 mm. Power values are for 4.5 GeV and 1.5 A.

	U23	U41	W50	bend
magnet	undulator	undulator	wiggler	dipole
period	23mm	41mm	50mm	n.a.
no. periods	150	85	70	n.a.
k_{max} or B	2.26	5.97	7.85	0.49T
Ecrit (keV)	14.2	21.0	22.6	6.6
power (kW)	74	166	191	0.29 kW/mrad
power dens (kW/mrad^2)	1038	884	784	1.6

The U23 undulator magnet characteristics are designed to provide continuous, odd harmonic tuning over a broad range of x-ray energies. The characteristics of this magnet are similar to several commercially produced in vacuum, hybrid, planar undulators recently installed on intermediate energy, third generation light sources worldwide including the BL12 undulator on SPEAR3. Demonstrated phase errors for such magnets are in the 1.5-2.0 degree range which results in nearly ideal brightness even when operating on high harmonic numbers.

U41 is a relatively long period, high-k undulator/wiggler as required to reach the carbon k-edge at 284 eV. Performance of an undulator operating in the softer x-ray regime can be enhanced by raising the minimum tunable energy (e.g. 1 keV) or degraded if the research program requires an elliptically polarized undulator. Since the characteristics of an undulator utilized for VUV or soft x-ray applications on PEP-X are likely to be tailored to meet the specific needs of the associated research program, the performance curves of the U41 undulator should be considered as only roughly indicative of VUV and soft x-ray undulator performance.

For applications which are not strictly brightness-limited and require photon energies in excess of approximately 20 keV, the pronounced roll off in U23 central-cone flux may pose an undesirable limitation. However, the PEP-X ring includes almost 100 m of damping wigglers with 20-keV critical energy. A portion of this wiggler could be used as a source of higher energy x-rays. Alternatively, some standard straights in the DBA arcs could be utilized for wigglers. Characteristics of a representative 50-mm period, in vacuum wiggler in a DBA straight are listed in Table 3.1.2 and its performance is depicted in Figures 3.1.1 and 3.1.2. The on-axis brightness of this wiggler falls well short of the U23, but the useful flux, defined here as the flux integrated over a 0.3-mrad horizontal by 0.1-mrad vertical acceptance, exceeds that of the U23 for energies in excess of 15 keV. As discussed in section 4.2, power deposited on the photon optics from such a source poses a significant engineering challenge.

For completeness, Table 3.1.2 lists the characteristics of a DBA dipole source while Figure 3.1.2 depicts the useful flux radiated by the dipole source. This relatively modest performance source is not envisioned to comprise a significant fraction of the PEP-X beam line capacity owing to competition with higher performance ID beam lines for experimental hall floor space.

3.2 Beam Line and Experimental Hall Layout

The extraordinary power density radiated by a PEP-X ID poses significant challenges for beam line component and optics design. Rather than rely upon speculative improvements in mask and optics power handling capabilities, the proof of principle layout of PEP-X beam lines discussed here assumes existing limitations on component thermal performance. Consequently, as detailed in Section 4.2, the preliminary beam line layouts employ long drift lengths to reduce power densities and aggressive beam aperturing and filtering to minimize total power deposited in key optical components. This conservative approach ensures the feasibility of the beam line design but it may tend to over estimate the cost and space requirements for the beam line components.

Limiting the power density intercepted by beam line front end components to manageable levels for existing technology results in placing front ends approximately 50-60 m from the source. Radiation shielding considerations demand that the front end and associated radiation stoppers be located inside the storage ring concrete shield wall. To accommodate these components and a low-pass filter mirror inside the storage ring shielding, the beam pipe penetration through the shield wall out to the experimental hall is located 70 m from the source (Figure 3.2.1). While this renders part of the beam line inaccessible during storage ring operations, it affords significant advantages from a radiation shielding perspective. In particular, locating the low-pass mirror inside the ring shielding substantially simplifies the shielding requirements for Compton scattered synchrotron radiation and laterally scattered gas Bremsstrahlung.

The beam exits the ring shielding into an 11-m-long first optics enclosure (FOE). The FOE provides sufficient length to accommodate all necessary grazing-incidence power masks and slits, the monochromator, experimental hutch stoppers, and Bremsstrahlung shielding. Focusing mirrors follow the FOE in the space upstream of experimental hutches. The layout of Figure 3.2.1 assumes tandem hutches each of which is 4m x 8m. Beam line control stations are envisioned to be located downstream of the experimental hutches.

The experimental hall layout of Figure 3.2.1 depicts a standard beam line length of 110 m to the back experimental station. This layout provides adequate room for typical focusing optics. Note, however, every fifth beam line is allocated 140 m to accommodate beam line configurations that require additional length such as highly demagnifying optics. Moreover, several beam lines situated towards the downstream end of the DBA arc could be extended substantially with the elimination of the downstream lab and office module. The most upstream beam line in each experimental hall utilizes an ID situated in the 120 m-long straight. Depending on where the ID is positioned in the long straight, the experimental hall as depicted in Figure 3.2.1 can accommodate up to 250 m of total beam line length. By extending the experimental hall along the axis of the 120m straight an ultra long beam line in excess of 500 m is feasible for the arc 1 hall (see Figure ES.1).

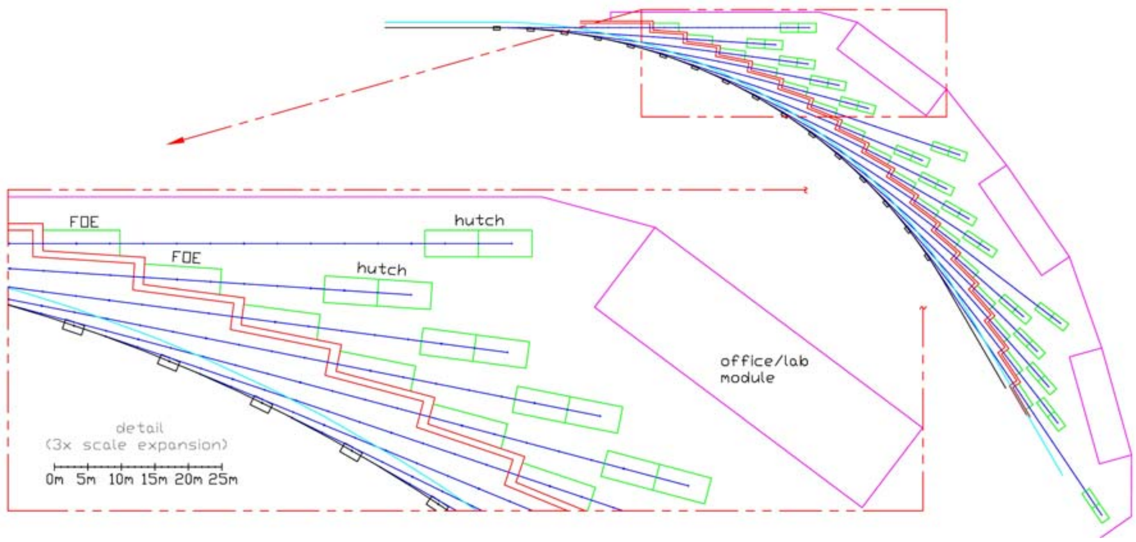

Figure 3.2.1: The preliminary layout of one of the two experimental halls. The detailed inset at the lower left provides a 3x scale expansion of approximately one third of the hall including one 140m beam line, four 110m beam lines, and one 15m x 50m office/lab module. The ring concrete shield wall is the red saw tooth structure. The ~3.5m x 11m FOE are depicted in green as are tandem 4m x 8m experimental hutches located at the end of each beam line.

Co-located with each cluster of five beam lines is an approximately 8000 square foot lab and office module. Each module provides space for two 600 square foot labs as well as offices and small conference rooms for approximately 40 light source and beam line staff. Each experimental hall includes three such modules. The experimental floor of each hall comprises approximately 100,000 square feet of column-free high bay while the storage ring shielding encloses another 25,000 square feet per arc resulting in a total building area of approximately 150,000 square feet.

3.3 Soft X-ray FELs

Studies indicate that the radiation from a 50-100 m undulator whose first harmonic is tuned to < ~400 eV would be enhanced by one to two orders of magnitude by the SASE FEL process acting with the stored beam[12]. For the 3.3-nm (379 eV) case shown in Figure 3.3.1, the peak bunch current must be 270 Apk (~1 mA in a 10-ps rms bunch) and the electron beam must be fully coupled to minimize emittance growth from intrabeam scattering (Sec. 2.6). The SASE process does not reach saturation; instead a partial lasing equilibrium is reached between the SASE-induced energy spread and bunch lengthening (which reduces peak current) and the FEL gain (Fig. 3.3.1). Such an FEL undulator would provide a significant fraction of the damping needed to reach low emittance, reducing the total length of other dedicated damping wigglers.

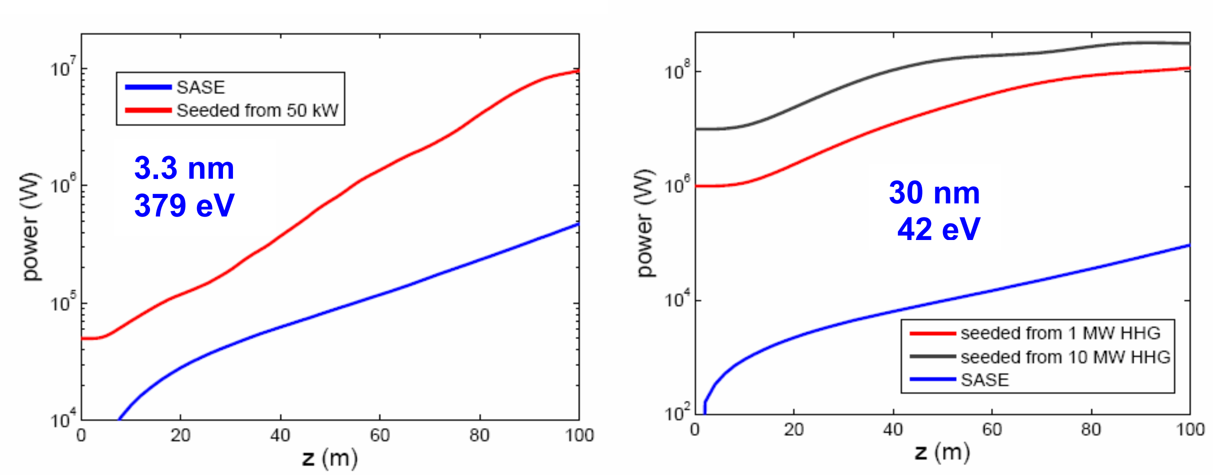

Figure 3.3.1: Simulations of the power evolution of a 3.3-nm SASE FEL (left) and 30-nm FEL (right) using an equilibrium energy spread (1.26 x 10^{-3}) and 270-Apk current in PEP-X having an emittance of 0.07 nm-rad (blue). The undulator for the 3.2-nm case has a 5-cm period and a 1-T peak field. Seeded-FEL simulations are shown in red and black.

The drawback to the partial lasing ID is the very large spontaneous radiation power that would emitted with a 1.5-A stored beam (~4 MW, ~26 MW/mrad^2). This power density would result in ~20 kW into a 30 µrad x 30 µrad beam line acceptance aperture, over a factor of 10 higher than present monochromator technology permits. The total beam current, and the average brightness for other users, would therefore have to be reduced to ~150 mA in ~150 bunches for operating in this mode. An alternative is to periodically switch some fraction of the electron beam into an FEL bypass with a duty cycle that is tolerable for both the FEL beam line optics and other users. Laser seeding at the radiated wavelength could also be used to induce periodic lasing in a shorter undulator with a seeding repetition rate in the kHz range (Figs 3.3.1 and 3.3.2). At present, laser seeding sources having sufficient power only exist for wavelengths >~10 nm.

Using an injector with a high brightness gun, similar to that used for the LCLS FELs, high peak power saturated-FEL pulses over the wavelength range of 1.5 to 50 nm, having full transverse coherence and pulse lengths between 50 and 1000 fs, could be produced in a 50 to 100-m undulator [13]. Such a high-brightness electron bunch could be injected in a gap between the stored electron bunches using a very fast on-axis injection kicker [8]. The repetition rate would be the same as that of the injector. The high-brightness, ultra-short electron bunch would have to be transported to the undulator through a suitable isochronous lattice. Studies show that coherent synchrotron radiation (CSR) effects will disrupt bunch quality if the transport optics contains too many bending magnets, as would be the case if attempting to inject such a bunch from the LCLS injector located in the main SLAC linac vault [14].

While it is as yet unclear whether these or other FEL ideas are practical for PEP-X operation, they will continue to be considered in future PEP-X studies.

3.4 RF Undulators

PEP-X could benefit from the use of rf undulators, presently under development at SLAC [15]. These devices enable fast polarization switching (with kHz repetition rates), variable undulator period control, and the possibility of fast on-off switching for SASE FELs that would greatly reduce the total radiated power from the stored beam, as discussed in Section 3.3. These devices use high power rf in a waveguide to produce a periodic field using technology based on the recent development of a 500 MW X-band rf source for the Next Linear Collider at SLAC combined with advances in over-moded rf components.

Two rf undulator configurations presently being investigated have a K of ~1 in the soft x-ray regime: 1) a "pearl string resonator", consisting of a series of spherical cavities, and 2) a cylindrical waveguide resonator. Each operate at S-band rf frequencies, but could support shorter period lengths if operated at X-band or W-band frequencies. The rf power repetition rate is expected to be in the kHz range.