4. PEP-X Implementation

4.1 Accelerator Systems

With the exception of the PEP-II rf system, much of the existing utility systems, and the majority of the PEP-II tunnel sections, the PEP-X accelerator systems will either be new or reworked from existing components (e.g. some magnets). PEP-X accelerator system implementations are summarized in the following sections.

4.1.1 Magnets and Supports

The PEP-X magnets will be a combination of newly constructed and reworked PEP-II magnets. Reworked magnets, comprising ~25% of all magnets for PEP-X result in considerable cost savings. The remaining magnets will be constructed from new materials using proven design expertise from SLAC with use of outside construction vendors. Very high field quality will be required for these magnets to maintain dynamic aperture in the ring.

Magnet support girders will be designed for maximum rigidity and stability in order to minimize orbit motion. The lowest magnet girder vibration mode frequency will be >25 Hz. Magnets and support girders will be thermally stabilized to the order of $0.1^{o}C$ to reduce thermally induced motion to the order of 1 μm vertically.

The complement of magnet types and associated power supplies are listed in Table 4.1.1. In addition, 360 to 500 horizontal correctors, and almost as many vertical correctors, are required. The exact number and locations of the correctors will be determined by future orbit correction studies. In many cases the horizontal and vertical correctors can share the same iron core. A subset of correctors will be used for fast orbit feedback, requiring ~1 kHz bandwidth.

4.1.2 Magnet Power Supplies

PEP-X will be equipped with new magnet power supplies. Some power supply components from PEP-II will be reused, but it is also expected the power supply technology will be superior and entirely digitally controlled in the future. In general, magnet power supplies will need to be very stable (1-30 ppm, depending on magnet type), have very low ripple to maximize high-frequency orbit stability, and have a high operational reliability and maintainability. The complement of lattice magnet power supplies are listed in Table 4.1.1.

Not included in Table 4.1.1 are the 750 to 900 bipolar orbit corrector power supplies, whose exact number will be determined by future orbit correction studies. Many of these supplies will be used for fast orbit feedback, requiring a bandwidth > 1 kHz. Corrector setpoint resolution must be sufficiently high to avoid generating orbit disturbances as a result of setpoint quantization noise. In modern light sources, 18-bit digital-to-analog converters are used in the power supply controllers for 1-mrad correctors to meet this requirement. In PEP-X, even higher setpoint resolution, or less corrector range, will be needed to reduce induced orbit noise well below 10% of the electron beam dimensions.

Also not included in Table 4.1.1 are many miscellaneous power supplies that will be used for quadrupole modulation, skew quadrupoles, and other special magnets.

Table 4.1.1: Lattice magnets and power supplies (PS) for PEP-X, not including orbit correctors injection magnets, and other special magnets.

	Magnet families	Number of magnets	Number of PS
DBA arc dipoles	BEND	64	2
TME arc dipoles	B, BM	136	4
	Total dipole:	200	6
DBA arc quadrupoles	QFCZ	64	2
	QFZ	60	60
	QDZ	60	60
	QFAZ	4	4
	QDAZ	4	4
TME arc quadrupoles	QF	256	4
	QD	256	4
	QFM1	8	4
	QDM1	8	4
Straight section quadrupoles	QDS1D	4	4
	QFS1D	4	4
	QDSE	20	2
	QFSE	16	2
	QDS1	4	1
	QFS1	4	1
	QDS2	8	1
	QFS2	8	1
	QDS3	8	1
	QFS3	8	1
	QDSEW	5	1
	QFSEW	4	1
	QDS1W	2	1
	QFS1W	2	1
	QDS2W	2	1
	QFS2W	2	1
	QDS3W	2	1
	QFS3W	2	1
	QDS1I	2	1
	QFS1I	2	1
	QDS2I	2	1
	QFOI	2	1
	QDOI	2	1
	QFI	2	1
	QDI	2	1
	Total quadrupole:	839	179
DBA arc sextupoles	SFI	32	2
	SDI	64	4
TME arc sextupoles	SF	128	8
	SD	256	16
	Total sextupole:	480	30

4.1.3 Damping Wigglers

The ~90 m of damping wigglers (Sec. 2.2) will consist of 18 or more new magnets whose individual length will be 4-5 meters. The damping wigglers will be located in one or two long straight sections. The radiated power and power density for a 5-m wiggler with a 10-cm period and 1.5-T peak field are 220 kW and 500 kW/mrad^2, which must be accommodated by a suitable system of power absorbers. The accumulation of on-axis photon power for a series of in-line damping wiggler sections in a straight section presents a significant challenge for the design of the photon absorbing system. While this geometry has been adopted for the PETRA-III damping wigglers [16], the power levels are an order of magnitude large for PEP-X. Future R&D will be devoted to solving this problem for the in-line wigglers. If a workable solution is not found, it will be necessary to cant each wiggler section and the beam orbit by 3-4 mrad at the expense of increased emittance in order to direct the radiated power from each section to a specific photon absorber. The power density at each photon absorber must be reduced to ~5-10 W/mm^2, assuming present absorber technology is used, through a combination of inclination angle of the absorber with respect to the photon beam and its distance from the source. For example, the power from a 5-m wiggler section could be handled by an absorber having a 1.5-degree grazing angle of incidence, located 50 meters away. The length of this absorber exceeds 1 m to accommodate the photon beam footprint assuming reasonable (mis)steering envelope. As discussed in Section 3.1 shorter damping wiggler sections might also be located in DBA arc straight sections to serve as hard x-ray photon sources for beam lines.

Damping wigglers will most likely use permanent magnet rather than electromagnet technology to reduce operational power, although future superconducting technology may be considered. Radiation-damage resistant permanent magnet material will be used to maintain very high magnet field quality.

Fabricating the wiggler magnets could be an excellent project for international collaboration. For example, the damping wigglers for PETRA III were designed and built in the BINP laboratory in Novosibirsk, Russia [16], and were delivered on time and on a reduced budget compared to local industrial vendor bids for the DESY laboratory.

4.1.4 Vacuum System

All new vacuum chambers will be needed in the PEP-X arcs in order to accommodate the new magnet lattice and aperture requirements. It is likely that some PEP-II chambers could be reused for the straight sections.

The new vacuum chambers will be a combination of aluminum and copper depending on synchrotron radiation power handling requirements. Discrete absorbers, most likely fabricated from Glidcop™, or a material having similar properties, will be used in antechambers for high photon power densities. Special attention must be paid to maintaining a low vacuum chamber impedance by minimizing chamber discontinuities and component cavities that can trap higher order rf modes (HOMs) induced by the short electron bunches. The beam duct aperture dimensions will be an optimized trade-off between large size to reduce resistive wall impedance and small size to reduce magnet apertures (and thus reduce material and power costs) and the need for significantly tapered ID chamber transitions, which have relatively high impedance. The first estimate for the nominal magnet girder beam duct aperture is 75-mm wide by 25-mm tall.

PEP-X will be equipped with ~800 beam position monitor modules, with the actual number and locations dependent on future orbit correction analyses. BPM buttons, most likely having a diameter of 6-8 mm, and feed-throughs, as well as rf-shielded bellows, will be designed to minimize trapped HOMs and related heating. The chambers will have a sufficient water cooling system to minimize chamber motion due to beam heating at critical locations (e.g. BPM sites) that could affect beam orbit motion and photon beam stability. Highly stable BPM modules, possibly supported by thermally stable Invar, will be located upstream and downstream of insertion devices and will be used in a feedback system to maintain ultra-high photon beam stability. The vacuum chambers for PEP-II, whose accelerator rings operated with 2-3 A, were designed and built at SLAC, which has the expertise to design and build the PEP-X chambers and associated components.

Vacuum pumping will be provided by a combination of localized ion and TSP pumps together with the possibility of distributed NEG pumps. While it is expected that most of the PEP-II ion pumps can be reused, new ion, TSP and NEG pumps will be required. It is probable that small-gap ID vacuum chambers will be NEG-coated to provide sufficient pumping in those locations. A combination of new and reused vacuum pump power supplies will be used.

4.1.5 RF system

The present PEP-II RF system is one of the best in the world and is adequate to operate PEP-X with high current at 4.5 GeV. There are 15 full stations available, each station powering two or four single-cell, mode-damped cavities. Each station is equipped with a single 1.2-1.6 MW, 476-MHz CW klystron and associated high-voltage power supply and low-level rf controls [17]. Characteristics of the RF cavities are shown in Table 4.1.2.

Table 4.1.2: Properties of the PEP-II mode-damped rf cavity.

Frequency	476 MHz
Shunt impedence (R_s)	3.5 MΩ
Coupling factor without beam (β)	3.9
Unloaded Q	~30,000
Maximum power into cavity	500 kW

Eight or more PEP rf stations, each driving two rf cavities, will reliably provide power for any of the ring implementation scenarios outlined in Section 2.9 (PEP 2.1, 2.2, or X) operating at 1.5-A beam current. The klystron powers, cavity reflected energies, and electric fields at rf windows will all be well below their limits. Longitudinal stability should not be a problem, as cavity detuning, current, and beam impedance will all be less than for operation of PEP-II.

For PEP-X, two or three rf stations will need to be relocated from PEP Region 12 to Region 8, and waveguides in Region 4 will need to be modified. A new low level rf system will be needed for better control of rf parameters.

Operation of up to 3-A beam current is feasible, but it would be challenging. Twelve rf stations should provide enough power, but the cavity coupling boxes would need to be modified to efficiently couple this power to the cavities without causing arcs at the rf windows. Low-order longitudinal modes will tend to be unstable at these currents, likely requiring new longitudinal feedback filter designs. These problems should be soluble, but will require extensive simulations and cavity tests.

These cavities have been conditioned to ~750 kV, but tend to arc occasionally at these levels. To achieve high reliability for PEP-X, we plan to operate them at 600 kV maximum. A higher reliable operating voltage might be reached if studies can reveal the source and solution of the arcing problem.

4.1.6 Bunch-Lengthening Cavity System

In order to increase beam lifetime and to reduce the heat load on the vacuum system components, it is of benefit to keep the bunches in the ring relatively long. This requirement conflicts with the low-emittance PEP-X lattice design which has an inherently small momentum compaction and correspondingly short bunches for any rf voltage that is sufficiently high to give good longitudinal acceptance. This dilemma can be addressed by introducing higher-harmonic rf cavities phased in such a way as to lower the slope of the rf voltage at the synchronous phase—ideally to zero. In this way the bunch length can roughly be doubled for the same energy acceptance of the ring. This is optimally done at the 3^{rd} rf harmonic.

The 3^{rd} harmonic rf voltage does not deliver energy to the beam and can in fact be provided by passive cavities excited by the beam current. The cavities are detuned (positive, or inductive) for the induced rf voltage to have the desired phase. The amplitude is controlled by the amount of detuning (frequency offset). Superconducting cavities are ideal for this application since the phase of the voltage with respect to the beam is 90° practically independent of the amount of detuning, and, due to the high shunt impedance, the desired voltage can be reached even at small beam current. Examples are cavities built for SLS and ELETTRA (Super3HC) [18] and BESSY (based on a Cornell design) [19]. Room temperature cavities have been used for ALS [20].

For PEP-X, the optimal voltage of the 3^{rd} harmonic rf is about 30% of the fundamental rf voltage, about 3 MV. In fact, 2.5 MV are sufficient to double the bunch length; this could be provided by 3 cryomodules of the Super3HC-type 2-cell cavity or by 5 modules of the BESSY-type cavity. The cryogenic power needed is on the order of 200 W at 4.4 K, to be compared with about 1 kW of cryo power installed in the Research Yard at SLAC. Table 4.1.3 summarizes the parameters for a BESSY-type system.

Table 4.1.3: Parameters for a 3^{rd} harmonic bunch-lengthening cavity system.

Parameter	Value	Unit
Voltage	2.5	MV
Frequency	1428	MHz
# cavities	5	(BESSY/Cornell type)
Shunt impedance	10^{10}	Ω
Q	$2x10^8$	
R/Q	50	Ω
P/cavity (dynamic)	12.5	W
P_{cryo}, total	≈125	W (static & dynamic)
Detuning	215	kHz

Beam dynamics issues associated with the use of 3^{rd} harmonic cavities included detuning to the Robinson-unstable side of the rf frequency, which, given the rather high beam current in PEP-X, could lead to beam stability issues. Because of the cancellation of the slopes of the fundamental and 3rd-harmonic rf voltages the bunch length may become very sensitive to phase transients induced by the ion-clearing gap [20]. It is conceivable that some of these issues could be addressed by a more complex active system. We plan to study these issues in detail analytically and in simulations.

4.1.7 Injection System

Precluding its use for other projects at SLAC, the electron injection system for PEP-X will be the same as that used for the PEP-II HER. The injector includes a damping ring, 12-GeV linac and transport line and is fully capable of injecting adequate beam into PEP-X with very few improvements, if any, needed for reliability. The injection charge capability is up to 5 x 10^{10} electrons (8 nC) per pulse at 120 Hz. As discussed in Section 2.6, the short PEP-X lifetime requires frequent top-off injection to maintain beam current constancy at the 1% level. It is expected that ~8 nC would need to be injected every 1-2 seconds (18-36 W injected beam power) for beam lifetimes of 30-60 minutes at 1.5 A, and that this charge would be distributed in ~12 buckets.

In order to minimize the impact of 1-Hz injection on user beam quality, the injection kicker bump will be compensated to a high degree to reduce the stored beam orbit transient and user data acquisition injection-gating and synchronizing techniques will be developed. The full width of the existing PEP half-sine kicker pulses is ~0.4 μs and therefore affects only ~6% of the stored bunches in PEP, so even kicker-induced stored beam orbit transients on the order of ten times the beam size (on the order of 100 μm rms) would have an effective integrated amplitude <10% of the beam size in if data is averaged over ~6 revolution periods (~45 μs) or more. Data gating would be required for experiments having shorter integration periods.

The present plan is to retain the PEP-II vertical injection scheme with its septum and kicker magnets. If it is determined that vertical injection is not acceptable, a horizontal injection scheme will be adopted. This will require new septum and kicker magnet designs, as well as a rerouting the injection transport line.

Use of the existing injector for PEP-X may conflict with future SLAC projects (e.g. FACET and/or LCLS-U3). In this case, a new 4.5-GeV linac for PEP-X would be constructed using available spare parts (including 3-m copper accelerating sections and klystrons). New controls and klystron modulators would be needed. Such an injector could be installed in IR-8 of PEP-X, making it independent of the other linac programs. With a new low-emittance rf gun, there would be no need for a damping ring to achieve the requisite injection beam properties. The linac would provide 10 to 20 bunches per pulse, with ~10^9 electrons in each bunch (0.16 nC, or 0.02 mA of beam current, per injected bunch) at up to 120-Hz repetition rate.

4.1.8 Instrumentation, Control and Feedback Systems

The PEP-II computer control system will need to be replaced for PEP-X. It is expected that a widely used control system standard, such as the EPICS control system toolbox, will be adopted along with many application and driver software packages that will have been developed by the controls community. State-of-the art hardware interface technology will be used. It is expected that controls will be distributed around the PEP-X ring in the support buildings associated with each of the six long straight sections. It is likely that, as much as possible, Ethernet LANs or the equivalent will be configured to communicate with distributed controllers embedded in individual processing and control components, thereby minimizing the control system cable plant. Device control and readback data rates will be sufficient to achieve desired component performance, ranging from rates on the order of 1 Hz for slow devices (e.g. temperature and pressure monitors) to many kHz (e.g. for hundreds of digitally controlled orbit feedback power supplies and BPM processors), and MHz for wideband devices. The technology that should be used to achieve these very high data rates in a distributed network will be investigated in future studies.

PEP-X will require electron and photon beam monitoring instrumentation that surpasses the present state of the art for storage ring light sources. Instrumentation requirements include BPM processors that can achieve sub-micron resolution in a few hundred Hertz bandwidth as well as first-turn and turn-by-turn orbit measurements (perhaps of individual bunches or localized bunch trains), a quadrupole modulation system that can be used to establish BPM electrical centers with respect to quadrupole magnetic centers, beam loss monitors to maximize injection capture efficiency, transverse profile monitors that can resolve the micron-level electron beam size, a high-resolution bunch current monitor (which will aid automated top-off injection), a bunch purity monitor for photon timing mode experiments, a precision total current monitor (DCCT), a high resolution tune monitoring system, and other diagnostics. Many systems having performance specifications at or near the PEP-X requirements are already available. Laser wire technology, such as that being implemented at PETRA III [21], might be employed to measure the very small electron beam transverse dimensions in place of a synchrotron radiation monitor, which is likely to have insufficient, diffraction-limited beam size resolution. Photon BPMs in the beam lines will be used to improve photon beam stability before and after optical components.

As discussed in Section 2.5, advanced orbit and beam line feedback systems will be needed to achieve the requisite level of electron and photon beam stability (<10% of photon beam dimensions) in PEP-X. An integrated effort from the accelerator and beam line designers will be needed to maintain stability integrity in all aspects of hardware and control system design. It is likely that high-resolution (~100 nm or better) mechanical motion/position survey sensors will be needed for critical components in the accelerator (e.g. user BPMs) and beam line (e.g. optical components, small apertures and collimators, etc). Some of these devices may require cutting-edge technology (e.g. "telescope technology" such as the laser-Doppler stabilization system used for atomic force microscopes and the X-ray Nanoprobe at the APS [22]). Maintaining the beam pointing and position stability at user experimental stations located >100 m from the photon source will is an engineering challenge. BPMs will be located near sextupoles, as well as quadrupoles, in order to maintain precise orbit centering in them to maximize dynamic aperture.

High frequency electron bunch motion, driven by accelerator transverse and longitudinal impedances will be controlled with bunch-bunch feedback systems. Feedback kicker bandwidth must be at least half of the 476-MHz rf frequency to affect bunches separated by 2.1 ns. Longitudinal instability caused by rf voltage phase and amplitude noise, including that caused by ripple in the high voltage power supply at harmonics of 60 Hz, must be controlled with a combination of the low-level rf and longitudinal multibunch feedback systems. It is expected that the action of a third harmonic bunch lengthening cavity may complicate fast rf and longitudinal feedback system performance, requiring further development of those systems.

4.1.9 Machine and Personnel Protection Systems

Protection interlocks for accelerator vacuum and magnets will be configured using robust programmable logic controller (PLC) technology, a technology that is bound to evolve significantly in the next decade. The usual array of vacuum pressure sensors, component temperature monitors, water flow sensors, component position detectors, etc., will be incorporated in the machine protection interlock to guard against component and system damage. A fast orbit interlock, which protects parts of the vacuum chamber and beam line components from mis-steered high-power photon beams, will be required to maintain the electron beam orbit within a tight channel when beam current exceeds an inherently safe level for mis-steering. Beam loss monitors around the ring may be interlocked to protect against excessive injection losses that could damage permanent magnet IDs and other sensitive components.

Personnel protection systems include those for accessing the ring tunnel and beam line experimental stations. These fully redundant interlocks will be configured using highly reliable and secure PLC systems designed for such use. A beam containment system will also be configured in this way, employing safety-rated beam loss monitors, linac and transport line current monitors, beam shut-off ion chambers, and other devices designed to maintain radiation levels within safe limits determined by the radiation shielding implementation.

4.1.10 RF Beam Manipulation Components

PEP-X may contain special accelerator components, such as transverse crab cavities or other rf components, together with their high-power rf power sources, for bunch phase space manipulation [8,9]. In one novel implementation, rf deflecting cavities might be used to exchange longitudinal and vertical electron beam emittances to produce very short bunches (<100 fs) at the expense of large vertical beam size (several millimeters) [23].

These rf components and systems will require an extensive R&D and design effort.

4.1.11 Cable Plant

It is expected that much of the aging PEP-II cable plant will need to be replaced for PEP-X.

4.1.12 Utilities

The AC power, water cooling, and support buildings exist for PEP-X, but will most likely require refurbishment in the future. The air-handling in the tunnel may need to be reworked and upgraded to handle tighter tolerances on air temperature stability needed.

4.1.13 Accelerator Tunnel and Shielding

The PEP-II accelerator tunnel must be modified in two arcs to accommodate the DBA lattice and associated photon beam lines (Figs. ES.1 and 3.2.1). The tunnel in these two arcs must be rebuilt to provide the ratchet wall shielding geometry needed for photon beam line penetrations as well as to provide an aisle on the inner side of the accelerator wide enough (>~1.5 m) for equipment access and installation in the DBA straight sections. On the order of 2×10^5 yds^3 of earth must be excavated in the arc 1 area to expose the accelerator tunnel and provide the area needed for the experimental hall described in Section 3.2. Far less excavation is required in arc 7.

Ratchet wall shielding thickness will be determined by the calculated neutron and gamma radiation doses caused by both the stored and electron beams. It is likely that the 20-40 W injected beam will be the predominant factor in this determination. It is estimated the lateral shielding walls will be ~1-m thick, and the transverse walls will be ~1.5-m thick. Polyethylene will be used to shield neutrons, and additional lead and/or steel will be used for localized shielding as needed. An alternative shielding implementation that will be considered in the future is to replace some of the excavated earth to provide some fraction of radiation shielding. Earth has a density that is ~70% that of heavy concrete, so ~7 ft of earth would provide the equivalent of 5 ft of concrete shielding. Much further analysis is required from the Radiation Physics Department to establish actual shielding requirements.

Further analysis is needed to determine if the concrete tunnel floor in the DBA arcs needs to be rebuilt for additional stability. A significant engineering task is to determine how or if the accelerator floor will connect with the experimental hall floor to achieve maximum stability of each beam line with respect to the electron orbit in the associated photon source magnet.

The accelerator tunnel in the four TME arcs may require refurbishment to control water seepage and other imperfections.

4.1.14 Facility Preservation

The successful reuse of equipment from PEP-II will depend on proper maintenance over the next decade. Vacuum chambers will be vented to dry nitrogen, water cooling channels for vacuum chambers and magnet conductors will be drained and blown dry, and a program of preventive maintenance and/or safe storage will be instigated for all components of value, including power supplies, instrumentation and control components, utility infrastructure and other accelerator components.

4.2 Photon Beam Line Systems

The preservation of photon beam emittance, coherence and stability in the presence of the unprecedented beam power of PEP-X poses a significant challenge for beam line design. While it is reasonable to assume improvements relative to the current state of the art of beam line component and optics technology, this report outlines a conservative, proof of principle beam line design respecting the constraints imposed by existing technology. Consequently, preliminary beam line layouts utilize long drift lengths to reduce power densities to manageable levels and aggressive beam aperturing and filtering to minimize the power deposited in key optical components. Nonetheless, optics designs based on current technology cannot preserve fully the extraordinary emittance of the PEP-X source. Emittance preservation is likely to be enhanced as x-ray optics technology evolves.

4.2.1 High Power Beam Lines

As detailed in Table 3.1.2, the U23 undulator develops the greatest power density of the representative ID sources. Power density represents a key constraint in beam line design as it defines the minimum distance between source and first power masks. As demonstrated shortly, once properly apertured and filtered, the optics can manage the remaining thermal load with relatively modest power-induced degradation of the beam emittance. The higher total power though lower power density of the longer period ID, such as W50, alter the beam line design problem. These inherently lower-brightness ID beam lines reduce the emphasis on emittance preservation, but the optics must cope with greater total power to extract the maximum performance from the source. Since these sources represent a minority application on a low emittance ring such as PEP-X and a successful undulator beam line design solution can be