2. Accelerator Physics

Based on the discussion in Chapter 1, our primary design goals are:

- Achieving a very low emittance beam of about 0.1 nm-rad at an energy of 4.5 GeV (not including the effect of intra-beam scattering)
- Providing adequate dynamic aperture to accept the electron beam from the existing PEP-II injector
- Storing high beam current up to 1.5 A with adequate lifetime and stability
- Providing at least 24 short-straight and dispersion-free regions in which to place the undulator insertion devices (ID) and maintaining flexibility to change its nearby optics
- Reusing the existing PEP-II tunnel, injector, and rf system

To achieve these challenging goals, we have introduced the following features into our design:

- Theoretical minimum emittance (TME) cells to achieve the very low emittance
- Double bend achromat (DBA) cells to provide spaces for IDs and to retain emittance
- 90-meter damping wigglers to further reduce emittance and damping time
- A powerful low emittance injector to continuously inject electrons into the small acceptance of the ring
- A large number of bunches (~3400) to mitigate the effects of intra-beam scattering, Touschek lifetime, and other single-bunch instabilities
- A large number of rf buckets enables us to have flexible bunch patterns to mitigate the effects due to fast-ion instability (FII)

A more detailed discussion of accelerator physics issues is contained in reference [10].

2.1 Lattice Design

In the PEP-X design, the HER FODO arcs are replaced with two DBA arcs and four TME arcs as shown in Fig. 1.3.1. In addition, a damping wiggler is added to a long straight section to help decrease the emittance. Each DBA arc consists of 16 cells with the optics shown in Fig. 2.1.1. The two DBA arcs provide 30 straight sections for 3 m IDs, where $\beta_x = 9.1$ m, $\beta_y = 8.1$ m. Each

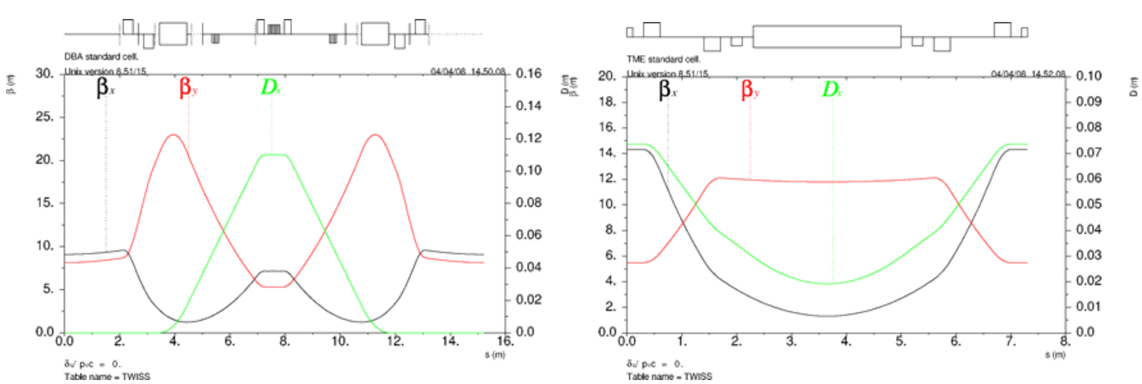

Figure 2.1.1: Optics functions in one DBA cell (left) and one TME cell (right).

TME arc contains 32 regular cells shown in Fig. 2.1.1 and 2 matching cells. In this design, the natural emittance for 6 arcs of TME cells is 0.1 nm at 4.5 GeV, but the combination of 4 TME and 2 DBA arcs results in a higher emittance of 0.37 nm. To reduce the emittance to the 0.1 nm level, the 89.3 m damping wiggler is included in a straight section 4. Depending on practical considerations, it can be also located in straights 2 and 6 without affecting the lattice parameters. The wiggler damping effect is maximized using 10 cm wiggler period and 1.5-T field.

The PEP-X straight sections will contain the injection system, the RF accelerating cavities, the damping wiggler and the tune adjustment system. In this design, 5 straight sections have identical FODO lattice, matched to the DBA or TME arcs and to the damping wiggler. Design of the injection section adopts a vertical injection into the PEP-X because of the larger vertical beam acceptance. The injection section uses the existing HER system, but adds 4 quadrupoles for improved optics match. The injected beam acceptance is maximized by using a high β_y function at the injection point and by moving the stored beam close to the injection septum with bump magnets and fast kickers.

The PEP-X optics functions are shown in Fig. 2.1.2 and the lattice parameters are listed in Table 2.1.1.

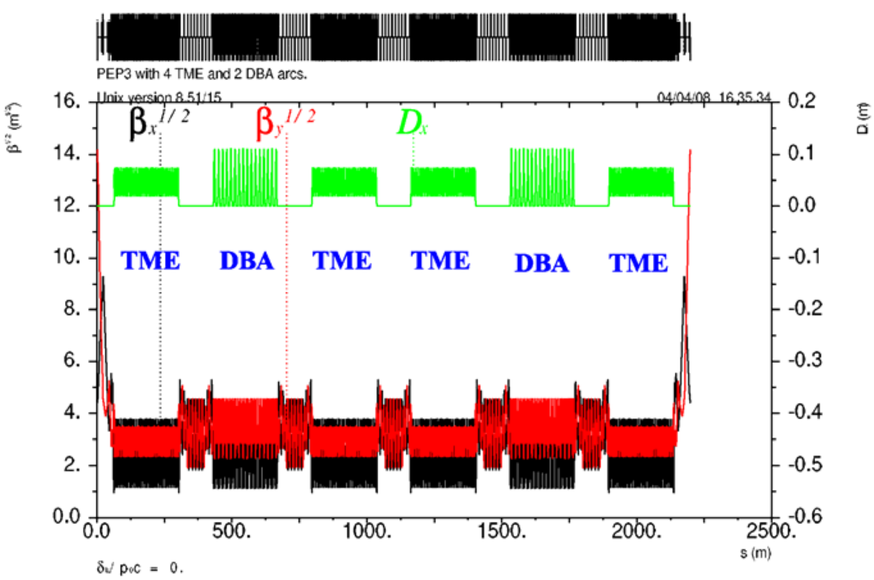

Figure 2.1.2: Optics functions in the complete PEP-X ring.

Table 2.1.1: PEP-X lattice parameters.

Energy, GeV	4.5
Circumference [m]	2199.32
Betatron tune, *x*/y	86.23 / 36.14
Synchrotron tune	0.00742
Momentum compaction	$4.72 \cdot 10^{-5}$
Emittance without IBS [nm]	0.094
RMS bunch length [mm]	2.50
RMS momentum spread	$1.12 \cdot 10^{-3}$
Damping time, *x*/*y*/s [ms]	19.7 / 20.2 / 10.2
Natural chromaticity, *x*/y	-132.7 / -72.8
Energy loss [MeV/turn]	3.27
RF voltage [MV]	10
Total damp wiggler length [m]	89.325
Damp wiggler period [m]	0.1
Damp wiggler field [T]	1.5
Regular ID straight length [m]	4.26
Number of regular ID straights	30
βx/*β*y at ID center [m]	9.09 / 8.14

2.2 Damping Wigglers

The ability of the damping wiggler to reduce emittance is determined by the period length of the wiggler, the peak magnetic field strength, and the total wiggler length. The emittance variation of the damping wiggler as a function of field strength for different wiggler period lengths based on the PEP-X lattice is shown in Fig. 2.2.1. The effects of emittance reduction versus total wiggler length for different wiggler periods are shown in Fig. 2.2.2.

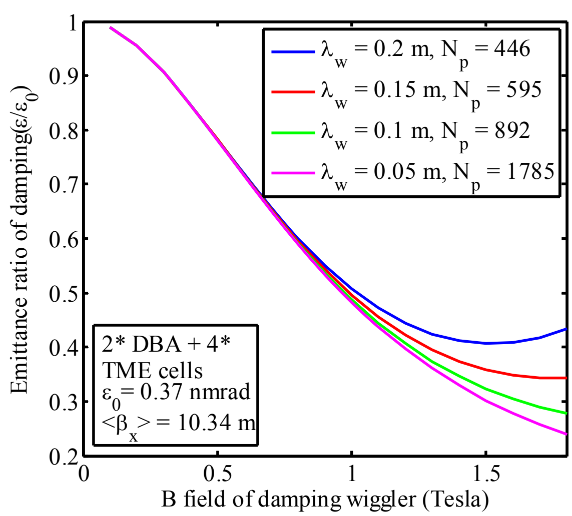

Figure 2.2.1: Emittance reduction of damping wiggler (~90 m) as function of wiggler field strength with different wiggler period length.

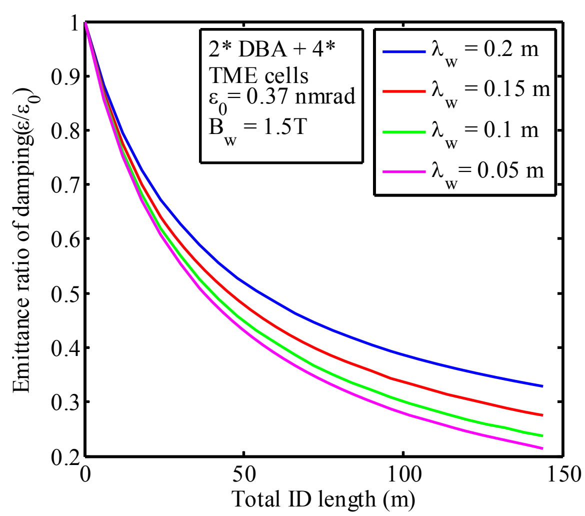

Figure 2.2.2: Effects of emittance reduction versus total wiggler length of different wiggler periods.

The beam emittance for PEP-X without damping wigglers is 0.37nm-rad. Because of the small initial emittance, the optimal parameters of the damping wiggler tend towards short periods and high fields as shown in Fig. 2.2.1. With a period of 10 cm, a peak field of 1.5 Tesla and a total length of 89.3 m, the PEP-X damping wigglers reduce emittance from 0.37 to 0.1 nm-rad. This total damping wiggler length would be comprised of 18 wiggler sections, each 4.96-m long, installed in a long straight section having the FODO optics with a 10.3-m average horizontal beta shown in Figure 2.2.3. The total radiated power from the wiggler is 4 MW with a 1.5-A beam, which must be intercepted with a suitable photon absorber geometry (Sec. 4.1.3).

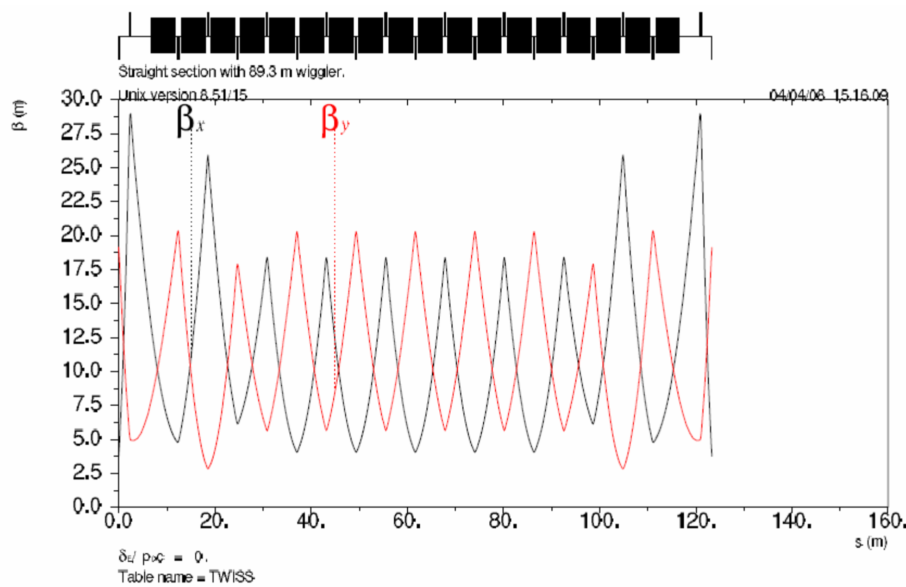

Figure 2.2.3: FODO optics for straight section containing 18 damping wiggler sections, each ~5-m long.

Table 2.2.1 summarizes parameters for different damping wiggler options, including a superconducting implementation that would take advantage of future technology and the possibility of providing a significant fraction of the damping function using a long soft x-ray FEL undulator (Sec. 3.3), reducing the total length of dedicated damping wigglers.

Table 2.2.1: Parameters of damping wiggler for PEP-X, $<\beta_x> = 10.34$ m, $J_x = 1$, $\varepsilon_0 = 0.37$ n mrad, total wiggler length is 89.3 m.

period (cm)	peak field (T)	full gap (mm)	wavelength* (Å)	wiggler parameter K	emittance ratio $\varepsilon/\varepsilon_0$
10	1.5	15.4	14.1	-	0.32
Option of partial lasing using damping wiggler					
5	1.27	5.93	60	5.93	0.36
5	0.5	2.33	12	2.33	0.78
Superconducting undulator					
1.4	1.5	1.96	2.6	1.96	0.30

*first harmonic

2.3 Dynamic Aperture

Sextupoles are located where the dispersion is large and the beta functions are well separated so that their strength and effect on dynamic aperture are minimized. The phase advance of the unit cell is also chosen to cancel out the first order terms. The horizontal and vertical phase advances per TME cell are 0.375 and 0.125 in units of 2π, respectively. The phase advances per DBA cell are 0.736 horizontally and 0.238 vertically. A dynamic aperture search by scan of the global tune, set by adjusting the strength of FODO quadrupoles in the long straight section, is shown in Fig. 2.3.1. The working tune of 86.23 and 36.14 are chosen. There are two families of sextupoles. One family, SD and SF, is in the TME cell, and the other, SD1 and SF1, is in the DBA cell. The linear chromaticity is set to zero. The dynamic aperture tracking results with systematic and random magnet errors are also shown in Fig. 2.3.2. The tracking point is set at the injection point. The 3-σ injected beam with injected beam emittance and beta function of storage ring is also shown in the figure. The vertical dynamic aperture is sufficient for the vertical injection.

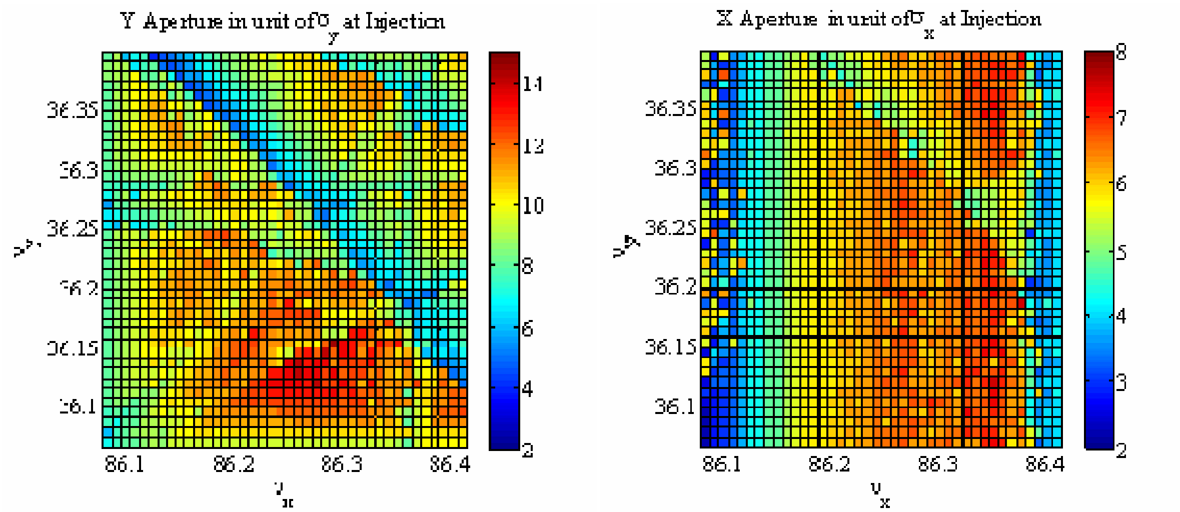

Figure 2.3.1: Scan of dynamic aperture at different working tunes.

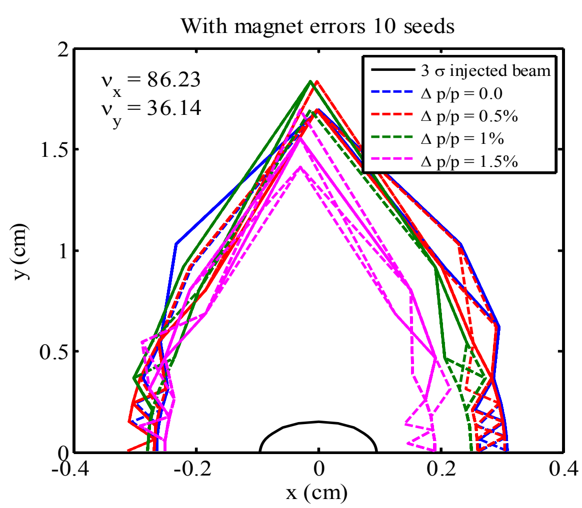

Figure 2.3.2: Dynamic aperture tracking with systematic and random magnetic errors based on the measurements of the PEP-II magnets.

2.4 Injection

At present it is planned to adapt the PEP-II vertical injection scheme for PEP-X. The stored beam will be bumped by four DC bump magnets then kicked by two identical pulsed kickers separated by 180° in vertical betatron phase. The injection aperture should be able to include at least a 6-sigma full width injected beam plus the effective septum width of 4 mm and a 4-sigma half-width stored beam. The beam parameters at the injection point are shown in Table 2.4.1. Injected beam parameters are based on those provided by the present linac and damping ring injector for PEP-II. The phase space diagram at injection point is shown in Fig. 2.4.1. The kick amplitude is 16.1 mm and the injected beam betatron amplitude is 6.23 mm as shown in the figure. The vertical aperture is adequate for these injection parameters. Future study will be determine if vertical injection can be accommodated by the small-gap insertion devices and chambers that create beam loss apertures. If this is a problem, a horizontal injection implementation will be pursued.

Table 2.4.1: Beam parameters at injection.

Vertical injection						
Beam parameters	Energy(GeV)	β_y (m)	α_y	D_y (m)	ε_y(nm rad)	σ_y(mm)
Injected beam	4.5	40	0	0	1.3	0.23
stored beam	4.5	200	0	0	0.185	0.19

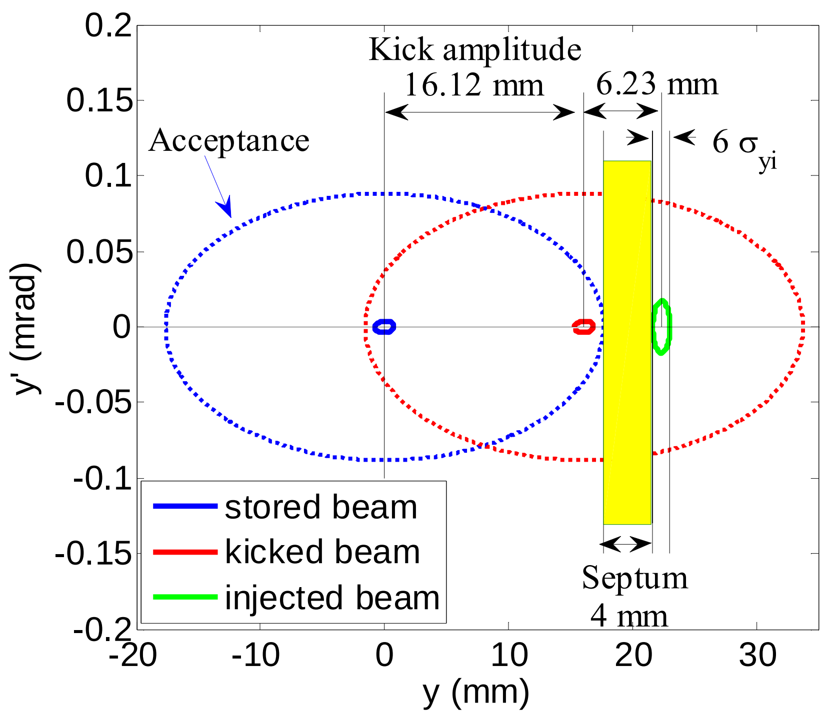

Figure 2.4.1: Phase space diagram of injection acceptance. In this scheme the kick amplitude is the maximum and the injected beam betatron amplitude 6.23 mm is the smallest. The stored beam center is on the closed orbit of a DC bump.

2.5 Stability Requirements

The demanding beam stability requirements for synchrotron light sources include maintaining sufficiently constant photon beam position, angle, size, energy, and, in some cases, photon pulse time-of-arrival, for users to achieve the spatial, temporal and spectral resolution needed for their experiments. Typical specifications for beam pointing stability are 10% of photon beam transverse dimensions, while the longitudinal phase stability requirement may be a small fraction of 1^o in order to meet the energy resolution needs ($<5 \times 10^{-5}$) or time-of-arrival jitter needs (<1ps) for demanding experiments. Stability requirements are a function of bandwidth, dependent on experiment data integration times, and component specifications must reflect this.

Transverse stability requirements may be modified depending on 1) whether the beam is focused or not; 2) the size of limiting apertures upstream of the experiment (including small slits and collimators); 3) the presence and nature of diffracting and other optical components; 4) whether acquired data are normalized to the instantaneous incident beam intensity. For example, energy-dependent sample absorption measurements may require <0.1% noise in the data to resolve fine structure in the spectral scans. Without proper intensity normalization, meeting this noise criterion would require a more demanding pointing stability requirements of <5% of the beam dimensions, and a transverse beam size stability of <0.1%, averaged over the data point acquisition period. In another example, imperfections in a vertically focusing mirror may make it impossible to produce the few-micron vertical spot size of a perfect 1-to-1 imaging system, relaxing the need to stabilize beam position at the source to a small fraction of a micron.

Given the very small photon beam size and divergence of a typical undulator source in PEP-X, extraordinary measures will need to be taken in both the accelerator and beam lines to achieve beam pointing and intensity stability, especially in the vertical plane. These measures include:

- stable design of experimental floor and building
- stable support of magnets and vacuum chambers with nm-level vibration amplitudes and sub-micron-level diurnal stability
- temperature stability on the order of 0.1^oC for critical accelerator and beam line components
- highly stable (order 10 ppm or less) and very low ripple main magnet power supplies
- very high performance beam position monitor (BPM) and orbit feedback systems (beyond the present state of the art) using ultra-stable electron BPMs flanking each insertion device photon source and x-ray BPMs in the beam line
- optical component feedback systems and photon beam intensity monitors in the beam lines to maintain pointing stability and to normalize acquired data to incident intensity
- real-time tune and coupling compensation for scanning insertion devices

Achieving these stringent requirements will require an integrated effort from the accelerator and beam line designers to maintain stability integrity in all aspects of hardware and control system design. It may be necessary to implement high-resolution (~100 nm) mechanical motion/position survey sensors for critical components in the accelerator (e.g. ID BPMs) and beam line (e.g. optical components, small apertures and collimators, etc).

Besides mechanical and electrical stability of the magnets, BPM and beam line components, there are a number of high frequency effects which can drive transverse and longitudinal bunch motion. These include rf phase and amplitude noise, rf cavity and vacuum chamber impedances, and coherent synchrotron radiation impedances. Mitigations for these effects include high performance low-level rf controls, longitudinal and transverse multibunch feedback systems and low impedance vacuum chamber designs. While it is expected that a third harmonic bunch lengthening cavity will provide Landau damping for coupled oscillations, the bunch lengthened mode may complicate fast rf feedback performance, requiring further rf controls development.

Because of the short beam lifetime, frequent top-off injection will be required for PEP-X (Sec. 2.6). The stored beam orbit transient associated with each injection pulse could degrade beam quality for a user if the orbit transient amplitude (averaged over the user data acquisition integration period) is not reduced to 10% of the very small electron beam dimensions, or unless user data acquisition can be successfully gated with each injection pulse. The interval between injection pulses can be increased by increasing lifetime, reducing current constancy (e.g. 10%, at the expense of requiring multiple 120-Hz injection shots to refill), or by increasing the injected charge per shot. This issue is discussed further in Section 4.1.7.

2.6 Intrabeam Scattering and Touschek Lifetime

Intrabeam scattering (IBS) describes multiple Coulomb scattering that leads to an increase in all beam dimensions and in energy spread, whereas the Touschek effect concerns large single Coulomb scattering events that lead to immediate particle loss. In low emittance machines, such as PEP-X, both effects are important.

We assume PEP-X is coupling-dominated and the vertical emittance is proportional to the horizontal emittance, $\varepsilon_y = \kappa\varepsilon_x$, where κ is the coupling parameter. In Table 2.6.1 we give steady-state emittances due to IBS for I = 1.5 A for bunch lengths $\sigma_z = 2.5$ mm and $\sigma_z = 5.0$ mm and for two couplings κ. At full coupling $\kappa = 1$, ε_x is minimized and is significantly less than 0.1 nm. The other couplings were chosen to give diffraction limited ε_y at 1-Å wavelength, $\varepsilon_y = 8$ pm. For these cases ε_x is somewhat larger than 0.1 nm. Note that the beam energy spread and bunch length for PEP-X parameters grow little under the influence of IBS. The last column in the table gives the Touschek lifetime T_l, calculated using the simulated dynamical momentum and horizontal apertures as well as the lattice functions in the entire ring. These calculations are based on the IBS determined, steady-state beam sizes. In the fully coupled cases, $T_l \sim 1.5$-2 hours; in the diffraction limited cases $T_l \sim 0.5$ hour. Finally, note that since both IBS and the Touschek effect depend on N and σ_z only as their ratio N/σ_z, I = 3.0 A, $\sigma_z = 5.0$ mm, emittances and lifetimes are identical to the ones when I = 1.5 A, $\sigma_z = 2.5$ mm.

Table 2.6.1: Steady-state emittance and Touschek lifetime at 1.5 A for two values of bunch length σ_z. In each case a full coupling result k = 1 and one which yields $\varepsilon_y = 8$ pm are given.

σ_z [mm]	κ	ε_x [nm-rad]	ε_y [nm-rad]	T_l [min]
2.5	1	0.082	0.082	81
2.5	0.045	0.18	0.0082	33
5.0	1	0.068	0.068	110
5.0	0.055	0.14	0.0079	42

Due to the very short lifetime, PEP-X will require a 3rd-harmonic rf cavity to lengthening the bunch to 5 mm. As discussed in Section 4.1.6, such a cavity introduces beam dynamics issues that require further study.

Even with a 5-mm bunch length, the beam lifetime at 1.5 A may need to be increased by increasing the vertical coupling. Frequent top-off injection will be required to maintain beam current constancy at the 1% level desired to maintain a constant power load on beam line optics in order to improve beam quality at user end stations. For example, assuming a 1-h lifetime at 1.5 A, 15 mA of beam current, or 110 nC of electron charge, would need to be replaced every 36 seconds. With the present limit of 8 nC per pulse from the present linac injector (Sec. 4.1.7), beam would need to be injected every 2 seconds to maintain 1% current constancy in this case (the time between injection pulses is proportional to the lifetime for this level of current constancy).

IBS and Touschek lifetime have been explored for 3.5- and 4-GeV beam energy [11]. The conclusion is that the emittance growth due to IBS for 1.5-A beam current essentially cancels the E^{-2} emittance reduction that would be expected by reducing the energy E for non-IBS-limited beams, and the net photon emission and brightness is reduced at these lower energies.

2.7 Collective Effects

The impedance of the rf cavities and vacuum chamber can drive single bunch and coupled-bunch instabilities in the ring. In this preliminary study we used some plausible assumptions regarding the impedance of the machine and considered the longitudinal microwave instability of the beam, an instability driven by coherent synchrotron radiation (CSR), and the transverse multibunch instability excited by a long-range resistive wall wakefield.

If the bunch rms length is chosen to be 2.5 mm, the threshold for the microwave instability is 2.5 A of total beam current. For a 5-mm rms bunch length, the threshold of the instability increases to about 8 A (Fig. 2.7.1).

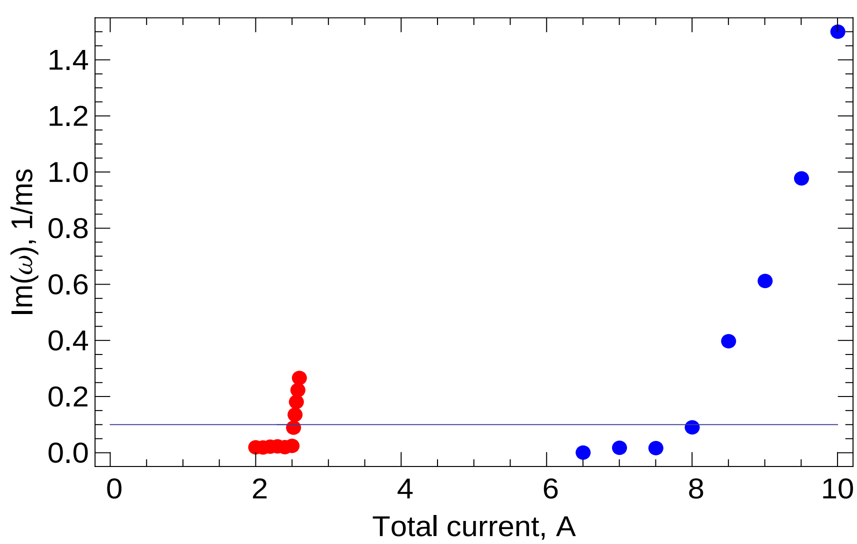

Figure 2.7.1: Thresholds for microwave instability for 2.5 (red dots) and 5 mm (blue dots) rms bunch length versus the total current in the ring. The horizontal line gives the value of the inverse synchrotron time 0.1 ms^{-1}.

We estimated the threshold peak current for the CSR-driven instability to be 154 A, corresponding to a total current of 1.5 A, assuming Gaussian bunches with a 2.5-mm rms bunch. We also found that the growth time of the transverse multibunch instability is equal to 0.38 ms (corresponding approximately to 50 revolutions) for this current and bunch length. This value does not change much for a 5-mm bunch length. Studies of this topic are on-going.

2.8 Fast Ion Instability

The ionization of residual gas by the electron beam generates positive that can be trapped by the electron beam and resonantly couple to the beam. Mutually driven transverse oscillations of an electron beam and ions can result in a fast transverse instability, called Fast Ion Instability (FII). The coupling force between the electron bunches and ions is inversely proportional to the cube of the transverse beam size. The estimated coupling force in PEP-X is about three orders of magnitude larger than that in B-factories (KEKB and PEP-II) due to PEP-X's ultra small beam emittance.

On the other hand, the ultra small beam size can drive partial ions unstable by overfocusing them. Therefore, fewer ions can be trapped with a smaller beam emittance. The trapped ions oscillate under the beam space charge force with a frequency depending on the local beam size. Since the beam size varies long the ring, the ion frequency spread along the ring provides additional landau damping.

The beam instability is simulated with a particle-in-cell program. The residual gas in the vacuum chamber is composed of monocular hydrogen (75%), carbon monoxide (14%), carbon dioxide (7%) and methane (less than 4%). We assume a constant pressure of 1 nTorr along the whole ring. The simulated growth time is shown in Table 2.8.1. A multi-bunch-train beam filling can reduce the number of trapped ions. Therefore, various beam filling patterns have been investigated. There is a faster instability in full coupling case because more ions can be trapped. With 8 bunch trains, there is a similar vertical growth time of 50 μs for 100%, 10% and 5% coupling due to the balanced effects of the coupling force, trapping condition and landau damping.

Table 2.8.1: Simulated beam growth rate with different coupling and beam filling patterns (bunch-train number×number of bunch per train). The total vacuum pressure is 1nTorr and the total beam current is 3.0 A.

Coupling	Number of bunches	Beam filling pattern	τ_x (μs)	τ_y (μs)
100%	3440	1×3440	42	12
	3440	8×430	105	40
10%	3440	1×3440	112	18
	3440	8×430	130	50
	3237	83×39	3300	294
	2988	83×36	3400	394
5%	3440	1×3440	116	24
	3440	8×430	133	58

The feedback response time of the present PEP-II feedback system is 500 μs. The growth time of 50 μs with a nominal bunch number 3440 is ten times faster than the feedback. A good vacuum of 0.1 nTorr is required for a 500 μs of FII growth time if the beam filling pattern of 8×430 is chosen. A compromise is to reduce the number of bunches to 3237 (83×39). This bunch-train filling pattern can significantly reduce the number of trapped ions and a growth time of 300 μs with 1 nTorr is achievable. In this case, a pressure of 0.5 nTorr would meet the feedback specifications.

2.9 Lattice Migration from PEP-II to PEP-X

The final PEP-X configuration could be reached in a series of four migration stages from PEP-II:

PEP-II: 1) the existing machine is setup for 4.5 GeV beam; 2) phase advance in four arcs 5, 7, 9, 11 is increased from 60º to 90º for a lower emittance.

PEP-2.1: 1) the IR low β straight is replaced with a FODO straight; 2) phase advance in arcs 1, 3 is increased from 60º to 90º and the special IR bending adjustment is removed; 3) 40 more sextupoles are installed in these arcs; 4) 90 m wiggler is installed in straight sections 2 and 6.

PEP-2.2: 1) DBA lattice is installed in arcs 1, 7; 2) photon beamlines are installed; 3) the HER RF cavities are relocated from straight 12 to straight 4.

PEP-X: 1) TME lattice is installed in arcs 3, 5, 9, 11; 2) lattice in straight sections is adjusted for better match to the TME arcs; 3) injection system is adjusted for maximum injection efficiency.

Parameters for the migration stages are listed in Table 2.9.1 shown for the beam energy of 4.5 GeV, rf voltage of 10 MV and the 90-m damping wiggler.

Table 2.9.1: Parameters for the lattice migration stages.

Migration stage	**PEP-II**	**PEP-2.1**	**PEP-2.2**	**PEP-X**
Betatron tune, *x*/y	28.529 / 29.61	31.19 / 32.23	47.105 / 32.13	86.23 / 36.14
Synchrotron tune	0.0458	0.0398	0.0324	0.0074
Momentum compaction	$1.69 \cdot 10^{-3}$	$1.33 \cdot 10^{-3}$	$8.95 \cdot 10^{-4}$	$4.72 \cdot 10^{-5}$
Emittance without IBS [nm]	7.4	0.41	0.32	0.094
RMS bunch length [mm]	3.9	13.8	11.0	2.5
RMS momentum spread	$3.0 \cdot 10^{-4}$	$1.18 \cdot 10^{-3}$	$1.14 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$
Damping time, *x*/*y*/s [ms]	295 / 297 / 151	23 / 23 / 12	20 / 21 / 11	20 / 20 / 10
Natural chromaticity, *x*/y	-55.6 / -72.8	-46.1 / -41.0	-62.3 / -57.9	-132.7 / -72.8
Energy loss [MeV/turn]	0.22	2.84	3.16	3.27
Number of photon beamlines	2	2	32	32

2.10 Conclusion

The selection of topics studied in the chapter is based on the experience we have accumulated over many years working with SPEAR3, PEP-II, and ILC damping rings. The study shows that there is no show-stopper and the goals discussed at the beginning of this chapter are realistic and achievable. A summary of the main PEP-X parameters is shown in Table 2.10.1.

Many results of this study should be considered preliminary. For example, the broad-band wakefield, based on the LER of PEP-II, serves only as a rough approximation of the impedance model for the new machine. More investigations are necessary to firm up these calculations and to optimize the design.

Table: 2.10.1: PEP-X main parameters. Note that the emittances include the contribution from the intra-beam scattering assuming 5.5% coupling.

Energy [GeV]	4.5
Circumference [m]	2199.32
Horizontal emittance with IBS [nm-rad]	0.14
Vertical emittance with IBS [nm-rad]	0.0079
RMS bunch length [mm]	5.0
Total current [A]	1.5
Number of bunches	3200
Beam lifetime [minutes]	42

Our study does not yet show any evidence to exclude a possibility of storing 3-A beam current in the ring. Clearly, this current requirement will make the implementation of many technical systems more challenging and costly.

The study also provides us with many suggestions of how to improve the design:

- Introduce a third-harmonic cavity system to lengthen the bunch and therefore to further reduce the effect of intra-beam scattering and to mitigate the microwave instability
- A faster feedback system in the transverse planes may be necessary to control the fast-ion stability and multi-bunch instability due to the resistive-wall impedance
- Increase the momentum compaction factor to mitigate the microwave instability
- Increase the off-momentum dynamic aperture to increase lifetime