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PEP AS A SYNCHROTRON RADIATION SOURCE: STATUS AND REVIEW*

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ABSTRACT

The electron-positron collider, PEP, is a 15 GeV storage ring built and operated for high energy physics. As a synchrotron radiation source, it has some unique characteristics which give it extraordinary capabilities[1] which are now beginning to be exploited.

Two insertion device beam lines are operational, each illuminated by 2-m-long, 77-mm period undulator magnets. In parasitic operation on high energy physics runs, they provide photons above 10 KeV, with a peak brightness of 10^{16} photons/(s-mm^2-mrad^2) within a 0.1% band width. This record brightness in this spectral range has already opened up exciting new areas of research.

In tests of a low emittance mode of operation at 7.1 GeV, horizontal emittances of about 5 mm-rad were measured, which is about the same as that planned for the new third generation x-ray sources. At a current of 15 mA at 7.1 GeV, the present undulators deliver photon beams from 2.7 to 14 KeV with a peak brightness of about 10^{17}. Higher performance can be achieved with longer insertion devices optimized for these energies.

Future operation in both parasitic mode and dedicated low emittance mode is planned; this will not only provide new physics opportunities, but the ability to advance the technology of beamline components and instrumentation will be required for the high power, high brightness beams from the third generation x-ray sources. Further performance upgrades are being studied and planned. These will be discussed in this paper along with a description of the present status and a review of PEP's capabilities and limitations.

1. THE PEP FACILITY

The PEP storage ring was completed in 1980, and its design parameters can be found in the literature.[2] As shown in Fig. 1, it is a six-fold symmetric ring, with 117-m-long straights which have the low beta interaction regions, joined by six arcs composed of closely-packed FODO cells. In the center of each arc sextant is a symmetry straight section with about 4.5 m of free length. The two operational beam lines emanate from symmetry straight sections #1 and #5, which also contain 1.7-m-long, 2-T wiggler magnets designed for emittance control in colliding beam operation. The undulator magnets and beam lines have been described by Brown.[3]

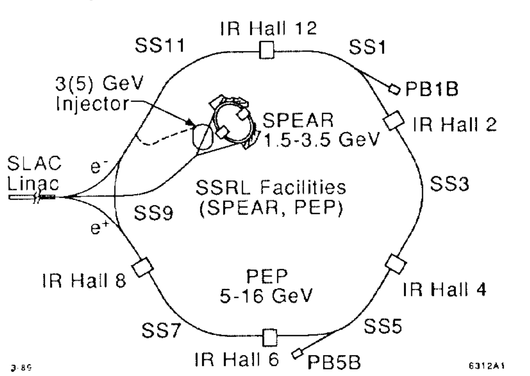

Fig. 1. PEP facility.

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Recently, there have been changes made in the PEP lattice and the high energy physics program which have significance for synchrotron radiation development. The lattice was modified with a mini-beta insertion in interaction region (IR) #2 and a more moderate low beta in the other five IR's. For colliding beam operation, the beams are now separated in these IR's and collide only in the TPC detector in region 2. This lattice modification was designed maintaining the variable tune optics capability which was part of PEP's initial design, and which allows the tuning of the lattice to the low emittance optics.

The other IR's are now available for other uses including beam lines, and the first of these new facilities is planned for region 12. These 100-m-long straights have zero dispersion and are ideal for insertion devices. The current plan for the IR12 beam line is to build a new facility along the exit line of this straight section and to equip it with a 12-m-long extended insertion device. This may be a single device with characteristics similar (except for length) to the existing undulators, or a series of undulators with different periods which could operate one at a time giving a broad spectral range, or a short-wavelength wiggler magnet. This latter device would produce a high brilliance source of x-rays in the 50–250 KeV range and would be an ideal source for Compton scattering research, coronary angiography, in-situ crystal growth studies, high-Z tomography and so forth. All of the above are being designed to be compatible with parasitic and dedicated operation.

PEP was designed to operate over a wide range of energy, 5 to 18 GeV; and the RF, magnet and vacuum systems were built accordingly. The large RF system, consisting of twelve 0.5-MW klystrons feeding 24 five-cell cavities, is capable of delivering 3 MW to the beam in replacing synchrotron radiation losses. This corresponds to 100 mA at 15 GeV or higher currents at lower energies. As will be discussed later in this paper, the size of this system gives us the flexibility of a large energy range at the price of dominating the total impedance seen by the beam. Therefore, it is the major player in determining single and multi-bunch instabilities.

At the present, it is foreseen that high energy physics will operate at energies between 10 and 15 GeV per beam, while dedicated, single beam operation for SSRL will be between 6 and 10 GeV. However, in this rapidly changing field, synchrotron radiation use at higher energies is not ruled out. For the high energy electrons and positrons, PEP requires the SLC as an injector; and the necessary timing and synchronization of PEP, the linac and the damping rings was proven in the fall run of 1988.[4] Single electron beams can be provided in the same way or from the Nuclear Physics Injector, NPI, which uses the last five out of thirty sectors of the linac, and with the new high power klystrons can deliver beam up to 10 GeV. Options for independent injectors for PEP are discussed later in this paper.

2. RECENT PERFORMANCE IN PARASITIC MODE

In the Fall of 1988, PEP ran a high energy physics program for six weeks. This was the first shake down run with colliding beams for the one interaction region mini-beta system. The beam energy was 13.7 GeV; and up to 20 mA per beam, distributed in three bunches, were used in the colliding beam runs. This limit was not the beam-beam limit but an artificial one imposed due to higher order mode heating of the vacuum chamber inside the TPC detector; a problem which is presently being corrected. Some of the lattice parameters are shown in

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Table 1. After the ring was commissioned with colliding beams, the two undulator beam lines were brought on line. The automatic feedback steering systems, which maintain the photon beam stable down the 50-m lines, were commissioned; and after a very brief time, the operators were tuning the machine parameters, breaking luminosity records and simultaneously providing stable photon beams. GeV and KeV users were both happy. PEP, with a single collision point in which to maximize luminosity and minimize background, is much more tolerant, and easier to operate than when there were six.

To complement earlier measurements on multi-bunch stability limits at 7.1 GeV in the low emittance mode, a brief test was done with electrons only and with a variety of bunch parameters, such as peak intensity and spacing. With a small number of bunches—less than twenty—the maximum current was limited at approximately 60 mA by the then state of conditioning of the RF and vacuum systems. With 50–100 bunches, the maximum stable current was limited to lower levels by multi-bunch instabilities. This is consistent with expectations[5] and will be further discussed later in this paper.

Table 1. Parameters for colliding beam and low emittance lattices.

		LOW ϵ	COLLIDING
At Energy	GeV	7.1	13.7
Emittance	π nm-rad	6.4	104
Tunes	ν_x	29.28	21.28
	ν_y	13.20	18.22
Phase Advance in Arcs	ψ_x	100° per cell	56° per cell
	ψ_y	33° per cell	34° per cell
Lattice Functions in Arcs	β_x m	$4 \rightarrow 21$	$10 \rightarrow 23$
	β_y m	$14 \rightarrow 44$	$17 \rightarrow 37$
	η m	$0.25 \rightarrow 0.5$	$0.8 \rightarrow 1.2$
Momentum Compaction	α	0.00097	0.0025
Typical Synchrotron Tune	ν_s	0.03	0.045
Bunch Length		0.5 cm	1.5 cms
Energy Spread		0.047%	0.091%
Damping Time	τ_x, τ_y, $2 * \tau_s$	77 msec	10.7 msec
Interaction Region 2	β_x	57.2m	1.00 m
	β_y	137.1 m	0.04 m
	η	0	0
Other IR's	β_x	79.3 m	4.5 m
	β_y	96.6 m	0.18 m
	η	0	0

The experimental program on PEP made use of the unprecedented spectral brilliance afforded by the undulator beam lines in the x-ray part of the spectrum. In the commonly-accepted units, the beam lines delivered 1.0×10^{15} photons/second/mm^2/mrad^2/0.1% bandwidth at 14 keV. By way of comparison, the 27-period wiggler on Beam Line 6 at SPEAR, when operated at 12 kG, 3.3 GeV, and 80 mA, yields a brilliance (in the same units) of 2.3×10^{14} at 14 keV. This has made possible experiments that require photon beams that are very highly defined in their angular and/or spatial distribution.

Four experiments were performed during the late-November to mid-December run. The first experiment to be completed, involving a collaboration between SSRL and AT&T Bell Laboratories, utilized the technique of glancing incidence x-ray diffraction to study the growth kinetics of artificial crystals grown by molecular beam epitaxy. This particular class of experiment requires a small beam cross section to efficiently intercept a crystal oriented at an angle of incidence of less than one degree, which is required to obtain information about the kinetics of in-plane crystal structure.

The second experiment involved the diffraction of 14.4 keV x-rays from the Fe^{57} *nuclei* in an enriched crystal of yttrium-iron garnet. With the high spectral brilliance available to the experimenters, the rich time and angular structure of the diffracted photon beam could be studied, yielding insights into the phenomena of nuclear superradiance. The by-product of this experiment was a 500-photon/second beam collimated to roughly 8 arc-seconds and monochromatic to 10^{-8} eV!

The third experiment, utilizing the high angular collimation of the beam, investigated the time-dependence of the structure of membrane-bound bacteriorhodopsin upon irradiation by visible photons. This protein plays a key role in the conversion of visible light into nerve impulses in the human eye, and the structural changes upon irradiation are crucial to the function of this molecule. This work was a collaboration between scientists at SSRL and the University of California, San Francisco.

The fourth experiment, a collaboration among the University of Oregon, Los Alamos National Laboratories, and SSRL, was a gas-phase photoemission experiment, designed to elucidate the relaxation processes undertaken by a krypton atom after suffering a K-shell photoionization. This experiment is a crucial link in the calibration of tritium beta-decay experiments that are being performed to measure the mass of the neutrino. Although the data are not yet fully analyzed, it is expected that the current upper limit of 27 eV may be revised downward substantially as a result of this experiment.

3. LOW EMITTANCE PERFORMANCE

PEP was designed for variable tune operation at high energy to optimize luminosity at constant RF power. Studies of higher tune configurations of PEP, at lower energies, to obtain reduced emittance for synchrotron radiation purposes were carried out in 1984[6] and 1985[7]. By raising the focusing strength in arcs, the horizontal phase advance can be increased from 56° to 100° per cell, reducing the dispersion function by more than a factor of two. This lattice reduces the emittance by a factor of four compared with the regular colliding beam lattice at the same energy. At lower energy, the emittance in the colliding beam lattice is already small; and it was the intent to use the emittance wigglers to "increase" this value for optimum luminosity.

To keep the strength of the sextupoles and their effect on the dynamic aperture small, the natural chromaticity of the total ring was reduced by having parallel focusing (rather than low-beta insertions) in the interaction region straight sections. The vertical beta functions for one-sixth of the ring, from the mini-beta region 2 to IR4, are shown in Fig. 2. This lattice change reduces the vertical chromaticity by a factor of two; in the horizontal, the chromaticity is almost unchanged, with the change in the insertions cancelling the increased focusing in the arcs. The natural chromaticities of the low-emittance lattice ($\Delta\nu/\Delta p/p$) are approximately −35, and the dynamic aperture is large compared to the vacuum chamber aperture.

The first brief test of this lattice was in a one-day run in March 1986.[8] After the mini-beta upgrade, a more complete test occurred in a twelve-day run in December 1987. The lattice parameters were carefully measured and corrected. The emittance was measured[9] using the synchrotron radiation from the

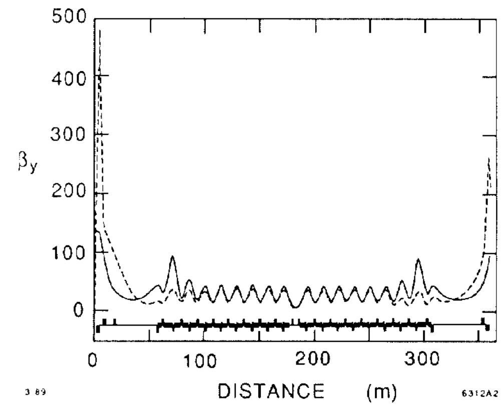

Fig. 2. Low emittance and colliding beam optics.

undulator in beam line #1 by analyzing the "angular" and "spatial" profile of the photon beam with pinhole optics and scanners. The result was a measured horizontal emittance of 5.3 ± 0.8 nm-rad, in good agreement with the theoretical value shown in Table 1. At the same time, the emittance ratio between the vertical and horizontal planes was measured to be 0.04 ± 0.02.

The photon energy spectrum, as seen through the pinhole and uncorrected for the absorption in the beryllium exit window, is shown in Fig. 3. The sharp features of the harmonics in the spectra, and the side lobes on the third and fifth harmonics, are in excellent agreement with theoretical predictions. An independent analysis of this brightness spectra[10] yields an emittance similar to those measured with scanners. A schematic of the beam line apparatus used in these measurements is shown in Fig. 4.

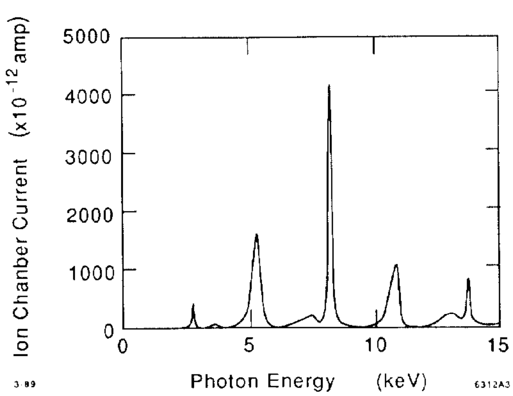

Fig. 3. Pinhole energy spectrum (44.45-mm gap).

One can further reduce the transverse emittance of an electron beam in a storage ring by a redistribution of the damping partition functions, trading longitudinal and transverse damping. This was tested during the run. After considerable effort by M. Donald to correct the lattice and orbit which was offset by several millimeters, the following results were obtained: Increasing the RF frequency by 4 KHz changes the energy by 1.25%, and J_x from 1 to 2.1 as J_s goes from 2 to 0.9. Beam was stored in this lattice, and the emittances measured as before. The horizontal emittance was measured to be 3.8 ± 0.5 nm-rad compared to a prediction of 3.7, and the ratio ϵ_y/ϵ_x was 0.015 ± 0.008. A vertical emittance of 0.005 nm-rad!

There appeared to be no problems in achieving the theoretically-predicted emittances in PEP, and the experimental program turned towards studies of beam intensity limits where

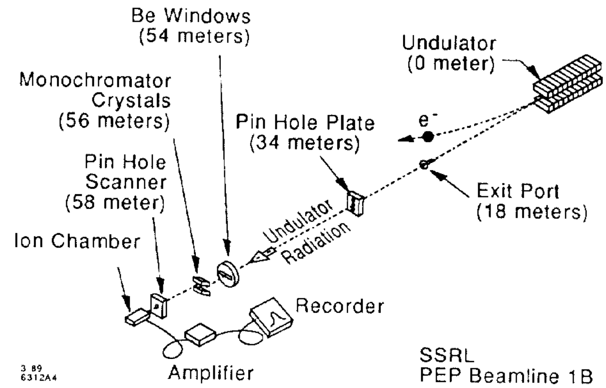

Fig. 4. SSRL PEP beamline 1B.

the theoretical predictions were less favorable. As with the emittance measurements,[9] much more detailed information on beam intensity limitations can be found elsewhere in these proceedings.[5]

The "fast head tail" or "transverse mode coupling" instability has been extensively studied in PEP.[11] An impedance model represented by a broad band, Q = 1, resonator at a frequency of 1 GHz, with a $Z/n = 2.5\Omega$, has been successful in fitting bunch lengthening data between 4.5 and 14.5 GeV. The corresponding transverse impedance in the same model was estimated to be $Z_T = 0.5\ M\Omega/m$, and this model has been accurate in predicting the threshold of the mode-coupling instability over the same energy range and for different colliding beam lattices. When applied to the low emittance lattice, this model predicted instability thresholds which were a factor two higher than those experimentally observed. Perhaps this is not so surprising as there are two significant differences in these lattices which can affect the calculations; the momentum compaction and the bunch length are considerably smaller in the low emittance lattice, and the beta functions in the insertion straights are considerably larger. These insertions contain the RF systems, separator plate tanks and many synchrotron radiation masks, which make up at least 66% of the total impedance. A much more detailed model of their impedance versus frequency would be required for exact calculations. An experiment was performed where a relatively minor change in the beta functions in the insertion straights changed the mode coupling limit from the horizontal to the vertical plane, and increased the current by 50%. Many other measurements are presented in Ref. 5.

A single bunch current of over 2 mA at 7.1 GeV is not an impediment to high current operation, assuming one can operate with many bunches. A study of multi-bunch instability limits was undertaken over a period of several days. This is a complex issue, and many bunch patterns and RF conditions were studied and are reported in Ref. 5. Under certain conditions, up to 30 mA could be accumulated, but not in a reproducible manner, and the maximum current that was stable was of the order of 15 mA. Calculations have been performed using various levels of modest de-Qing of the higher order modes in the 120-cell RF system. This is to simulate that the cells are not identical, and the frequency and Q of these modes are dependent of the system's operating conditions. They predict growth times for longitudinal coupled-bunch modes of a few millisecs with transverse coupled modes having growth times five to ten times longer. This is consistent with the observed behavior and continues to be a subject of intensive study.

In November 1988, a workshop on "Accelerator Physics Issues Relating to the Use of PEP as a Synchrotron Radiation Source" was held at SLAC.[12] The control of multi-bunch instabilities was a major issue at the workshop. Many approaches were explored, including the reduction of the number of RF systems, damping of the higher order modes to very low Q values, etc. It was the general consensus that in order to maintain the maximum flexibility in the future use of PEP at different energies and in different operating conditions, the preferred approach was the use of general purpose longitudinal and transverse feedback systems. As will be seen below, this is also necessary for future developments in the use of PEP for high energy physics.

4. POSSIBLE DEVELOPMENTS IN THE JOINT USE OF PEP

In the near term, the direction of development of PEP for high energy physics is towards increased luminosity in one interaction region. An extension of the present mini-beta system, where three counter-rotating bunches of electrons and positrons are allowed to collide in only one IR, is being studied. It seems plausible that using new electrostatic separators, nine bunches per beam could be used at the same current per bunch, increasing the total current and the luminosity by a factor of three. This raises the same issues regarding multi-bunch stability and the limitations on the handling of synchrotron radiation power that need to be addressed for the development of PEP as a synchrotron radiation source.

An even more demanding idea which is being studied, is the conversion of PEP to a B-Meson Factory.[13] Here a lower energy ring is built to collide with PEP in one IR. To obtain the desired luminosity, PEP would have to operate between 8 and 12 GeV, with a single beam comprised of many bunches at the maximum achievable current. It is obvious that the development of PEP has very similar goals for HEP and SR applications.

A proposal has been submitted to begin a high energy-nuclear physics program on electron (positron) nuclear interactions at PEP. One interaction region would be equipped with a gas jet target and a special purpose detector. The target densities required are sufficiently small that in a ring 2.2 km in diameter, the beam lifetime can be very little affected, and this experiment could operate in both colliding beam and dedicated synchrotron radiation modes of operation. It should be noted that high current, spread over many bunches, improves the duty cycle for this type of research and allows even less dense gas jet targets.

5. THE DEVELOPMENT OF PEP AS A SYNCHROTRON RADIATION SOURCE

The review presented so far on the performance to date of PEP as a synchrotron radiation source, both in parasitic and dedicated operation, shows its tremendous potential as a research tool in exploiting new areas of physics and technology. Many reports and studies in the literature have explored options for the further development of PEP,[1] and they cannot all be covered in this paper.

We will assume that after further joint study by all interested parties, the requirements for feedback systems regarding bandwidth (bunch spacing) and gain (operating scenarios) will be specified and that such systems will be built. The performance characteristics of the ring will then be comparable to the design goals of the third generation of x-ray sources, and the beam lines will be much in demand for research and technology development.

More beam lines will be required, and several options are possible. As mentioned in Sec. 1, a new line will be developed along the exit line of straight section #12. Chicanes, as shown in Fig. 5, can produce four additional insertion device beam lines in any suitable IR straight section, and the path length increase (accommodated by a small change in RF frequency) is no longer a serious problem in maintaining exact six-fold symmetry for six collision points. Additional insertion device beam line facilities can be built in other symmetry or IR straight sections, and

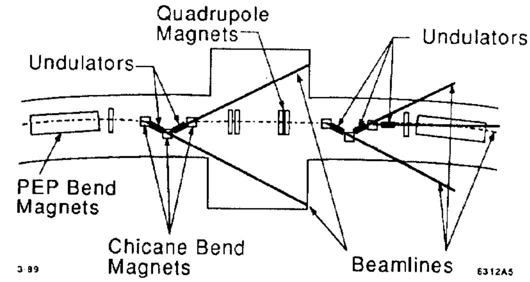

Fig. 5. Schematic layout of five insertion device beamlines in one PEP interaction region.

designs exist for bending magnet lines from neighboring magnets that would lead into the same experimental facilities.

Starting with a lattice optimized for low emittance and with adequate dynamic aperture, further reductions in emittance can be achieved through the use of damping wigglers.[14,15] If there are free straight sections where the dispersion is zero and the beta functions small, damping wigglers can increase radiation damping with a small increase in quantum excitation. In the low emittance lattice, approximately 20 m of length at either end of each of the six straight sections have these desirable characteristics, and three to five of these locations could accommodate damping wigglers. Three such wigglers (60 m in total length) in a well-corrected lattice, would reduce the emittance from 5 to 1 nm-rad. The effect of the intrinsic non-linear fields of such devices have been studied and are reported in Ref. 14. In themselves, these wigglers would be impressive radiation sources, producing tens of kilowatts of hard radiation.

Gradient or "Robinson" wigglers installed in straight sections with nonzero dispersion, such as the symmetry straights, could be used to modify the damping partition functions as an alternative to offsetting the closed orbit by changing the RF frequency. Several examples of such insertions have been studied.[16] Either approach towards decreasing the transverse emittance by trading off longitudinal damping, and therefore increasing the energy spread, requires careful evaluation as there are several negative effects on other desirable features, such as total current and effective beam size in undulators.

In experiments using time resolution to follow the decay of excited states, the bunch length and the spacing between bunches are important parameters. All existing and planned sources face the same problem, which is that to produce very short bunches, one will have to keep the single bunch intensity low to avoid the "microwave instability" which causes bunch lengthening. However, with the known impedance of PEP, and using the full RF system at 40 MV, it should be possible to operate in the low emittance mode at say 8 GeV, with fifty 10-psec bunches, at a total current of 10 to 20 mA. The bunches are spaced by 150 nsec, and this is consistent with the parameters of the multi-bunch feedback systems discussed above.

In contemplating the future use of PEP as a synchrotron radiation source, one must consider the question of a dedicated injector. This question arises even when one considers the high energy physics study of PEP as a B-Factory. The SLC is technically an excellent injector for any program on PEP. However, it is in itself an R&D vehicle in accelerator technology as well as a HEP research facility, and its operating schedule could interfere with and limit the development of PEP. The 3 GeV linac-booster synchrotron injector, which is presently being built by SSRL as a dedicated injector for SPEAR, has the reserve capacity in its design to be upgraded to 5 GeV. It is proposed[17] that with this upgrade and an injection line connection to PEP, as shown in Fig. 6, one could have an injector available "on demand." This

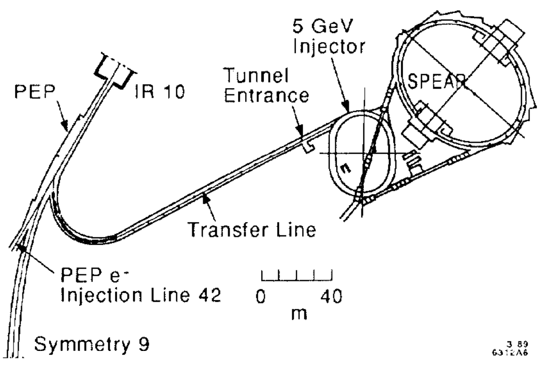

Fig. 6. PEP 5 GeV injector.

would not be an "on energy" injector which is so desirable, but few synchrotron radiation sources to date have that luxury.

Our research program at SLAC towards very high energy linear colliders, suggests an interesting possible alternative. One near term goal in this program is to demonstrate an accelerating gradient of 200 MeV/m in a high frequency linear accelerator structure. Several possible RF power sources with the requisite peak power[18] are in the R&D stage. It is possible that in a few years, a 50–75-m-long, 10–12 GeV linac injector could be constructed inside the PEP tunnel in one of the 100-m-long straight sections.

6. CONCLUSIONS

The already-demonstrated performance of PEP, in both parasitic and dedicated modes of operation, show it can be an important synchrotron radiation resource. It is a national asset in entering the fields of science and technology which will be the heart of the programs on the future third generation x-ray sources. In the near term, increased performance and operating time will have a major impact on these fields.

Different fields of research have common interests which benefit from R&D directed towards the achievement of stable, high current, multi-bunch operation in PEP. The accelerator physics and engineering development issues are of importance in many diverse areas of accelerator technology. The ability to produce photon beams with unprecedented power densities will be of importance to technology development, especially for synchrotron radiation applications.

Only a few of the possible longer term possibilities, using PEP's unique capability, have been mentioned in this paper, more can be found in the literature. Many of the ideas conflict with one another in technical compatibility, but we are far from being in a position at this time to judge which developments will be the most important for science in the next decade.

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