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# THE PEP STORAGE RING – CURRENT STATUS*

J. R. Rees

For the PEP Staff of SLAC, Stanford, California, and LBL, Berkeley, California.

## Introduction

The joint SLAC/LBL project group completed the construction of PEP at the beginning of April 1980. Commissioning of subsystems proceeded, concurrently with the completion of construction, and the storage ring was brought well enough under control to store the first long-lived circulating beam (electrons) on April 21. Positron beam storage, delayed by a recalcitrant injection kicker magnet, succeeded on May 3, and we achieved the first 8-GeV colliding beams in PEP the following day. Early in June, the injection kicker problem had been tamed sufficiently to operate comfortably at 11 GeV, an energy we deemed suitable for a month-long period of study and development, and by mid-June, with luminosities around $10^{30}cm^{-2}sec^{-1}$, we began delivering beam in brief intervals for checking out the experimental detectors.[1]

In July, a single stored electron beam was accelerated from 11 GeV to 15 GeV; however, we decided to concentrate our efforts thereafter at an energy of 14.5 GeV where the SLAC linac could supply a reliable positron beam and where the storage ring could tolerate a little misbehavior in the rf system without disastrous consequences.

The best performance achieved to date has produced a luminosity of $4 \times 10^{30}cm^{-2}sec^{-1}$ at each of the six interaction regions, and this luminosity has been used by the detectors. Sustained average luminosity has been quite another matter, however. PEP has delivered as much as 170 inverse nanobarns of integrated luminosity in a day and such days are only now becoming typical. Equipment failures and irreproducibility of injection conditions and rates still trouble us, and improvement of the delivery rate for high energy physics experimentation of course challenges us continuously.

At present, PEP typically operates with 18 milliamperes in the three bunches of each beam with a total circulating current of 36 milliamperes. Up to 24 milliamperes have been stored in a single three bunch electron beam and up to 10 milliamperes in a single bunch; there has been little incentive to strive for higher beam currents, since they cannot be used in colliding beams owing to the incoherent beam-beam limit of which we shall speak more later.

Six experimental detectors are in place, one in each interaction region, and five of these are regularly taking data.

In the following sections of this report I shall comment on the performance of the subsystems of PEP, discuss the beam dynamical behavior of the machine and compare it with our expectations and, finally, describe our plans for improving PEP. Earlier reports on the design and on initial performance may be found in Refs. 1-3.

## Subsystems of the Storage Ring

### Magnet Systems[4-6]

The magnets – dipole, quadrupole and sextupole – of the storage ring and the injection transport lines have performed well. They are connected in 18 circuits to their power supplies through current regulators, called choppers, which accomplish their function by switching on and off at a fixed frequency, typically 2000 Hz. The duration of the "on" pulse is modulated by a feedback circuit so as to maintain constant direct current in the magnet circuit. After passing through the usual period of infant disease, these choppers have proven quite reliable, and they have lived up to their promise of high bandwidth and good stability. The sources of raw DC power for the choppers, commercial voltage-regulated power supplies, have not, however, performed as reliably and have been responsible for a substantial fraction of PEP's unscheduled down time. No single mode of failure has dominated, but we feel we are making steady improvements in the reliability of these supplies. Although all of the chopper regulators are in a single location in adjacent racks, we have experienced few, if any, crosstalk problems.

We have not found it necessary to realign the storage ring magnet system since putting the ring in operation, although we have realigned selected magnets vertically, especially interaction-region quadrupoles. Using the liquid-level vertical reference system, we have been able to monitor the relative vertical motion of the tunnel.[6] Portions have sunk as much as 3 millimeters relative to reference locations in the earliest-tunneled section of the storage-ring housing; however, the settlement profile has, as expected, displayed characteristic wavelengths long compared to the betatron wavelengths, and only local corrections of short-wavelength disturbances have been needed.

Unexpected azimuthal variations in the vertical beta function at the interaction regions revealed themselves last fall, becoming more pronounced as we tried to lower the beta function. Measurement of beta is accomplished by varying the excitation of the interaction-region quadrupoles independently in each interaction region and measuring the consequent tune shift, and we measured azimuthal variations as large as two to one. By the same means we are able to correct the variation, so we were able to surmount the difficulty rather easily; however, we have not definitely identified the cause.

### Vacuum System[7]

The vacuum system produces a total pumping speed of 94,000 liters per second in the arcs where the synchrotron radiation is emitted and 31,000 liters per second in the long straight sections. The average pressure with a total stored beam current of 36 milliamperes at a beam energy of 14.5 GeV is typically $6 \times 10^{-9}$ torr. At this pressure the calculated beam lifetime due to residual gas collisions is 5.2 hours, and the observed single-beam lifetimes are constant with that figure. When the beams are colliding at currents in the vicinity of the incoherent limit, the lifetimes are totally dominated by beam-beam disruption. We have not taken the time yet to measure the synchrotron-radiation-induced desorption rate.

In the design of the vacuum system a goal of "smoothness" was set to minimize higher-order-mode excitation by the beam bunches of discontinuities in the interior contours of the vacuum chamber. The goal was expressed at the outset of design as a "budget" of longitudinal impedance for each type of component coming to a total impedance throughout the ring of 126 megohms. We measured the impedance of each type of component in the laboratory during its design, and the total impedance actually achieved was 83 megohms, about 50 per cent below the budget. The stored currents usable to date – being far below those for which the components were designed – have not tested the heat dissipating

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capacity of the components, but the near freedom from longitudinal and transverse coherent beam instabilities and the absence of any notable bunch lengthening suggest that the effort to minimize impedance has been very profitable.

## Radiofrequency System[8]

The PEP radiofrequency system accelerates the beam in twenty-four 5-cell cavities driven by twelve klystrons. The designs of the system and the SLAC-built klystron were described in some detail in the 1977 occurrence of the Conference, and the system built closely follows those designs. In operation, the rf stations - each consisting of one klystron, two cavities and their associated power supply, waveguides and control equipment - have performed extremely well and reliably. They have been responsible for very little down time. When the storage ring was first commissioned, only four of the twelve stations were installed, a compromise adopted in the face of a shortage of electrician labor. We had to use all available labor to ensure that the other electrical systems would be completed on time. The cavities were in place, but the final installation of the klystrons, power supplies and control gear was delayed until after turn-on, during which time much of the work could proceed concurrently with operation.

We have been well pleased with the ease of operation of the rf stations. They can be switched on or off without disturbance to the station or the stored beam - provided, of course, that adequate total accelerating voltage is maintained.

The operating energy of PEP has never been curtailed specifically by a want of installed rf stations, having been always determined by some other consideration, such as injection. On the other hand, we have never yet succeeded in having twelve klystrons operating simultaneously in their sockets. The primary reason for this historical statistic was a delivery of imperfect stainless steel material to SLAC during the fabrication of the klystrons. Unfortunately, the material was not bad enough to reveal its faults before several tubes were completed, tested and stored. Then, it began to leak, evidently having become porous during brazing or welding. After one tube went soft on the shelf, and after the cause was found, we knew we had potential trouble with four others manufactured with the same material, but we elected to use them as long as we could. The last of these klystrons is expiring slowly now. We have not experienced any klystron failures from other causes; the total number of operating hours on the other klystrons was 26,000 hours at the end of January 1981.

The maximum conversion efficiency of the klystrons now in sockets averages about 63%. We believe this figure could be brought nearer the originally established goal of 70% by more sophisticated shaping of the magnetic focusing field; however, efficiency has not so far been an issue of enough importance to warrant the effort.

## Injection System[9]

The PEP injection system is straightforward: the two-mile linac produces the electrons and positrons at the desired energy, the transport lines carry the particles to the injection point, and the pulsed kicker magnet system introduces the new particles into one of the desired circulating bunches. The system has been described extensively in earlier conferences of this series. Predicted performance was predicated on the delivery by the linac of $10^8$ positrons per pulse and $10^9$ electrons per pulse, so filling times were expected to be - and are - dominated by the positron rates which were expected to reach 11 milliamperes per minute at 15 GeV when the linac repetition rate was 360 pulses per second. The SLAC linac has not recently run at 360 pps for fiscal reasons, and the highest repetition rate of the PEP injection beams has been 60 pps where the corresponding rate would be about 2 milliamperes per minute. The linac often delivers as much as, or more than, $10^8$ positrons per pulse at the injection point of the storage ring, and we have experienced positron filling rates briefly as high as 8 milliamperes per minute; however, rates as high as even 2 milliamperes per minute require precise timing of linac, transport line and storage ring, and such conditions are not yet easy to reproduce. Electron injection is almost always easy; however, sometimes even with a stored electron beam providing living proof that nothing drastic is wrong with the storage ring, the positrons will not go in. This fact will not surprise an experienced storage-ring person.

At beam energies of 8 GeV and 14.5 GeV and at injection repetition rates up to 60 pps we have seldom been troubled by injection-saturating effects up to the stored current we use.

## Instrumentation and Control System[10,11]

The PEP instrumentation and control system has recently been thoroughly described in Ref. 10. One of its primary functions is to present to the operator, via displays and touch panels, interfaces to the storage ring systems at different levels of abstraction. Thus, when things are going well, he communicates with the ring in terms of the luminosity, the circulating current, the optical functions, the measured orbits and the like. He may examine these quantities and control them. When things are going less well he may examine and control more primitive quantities, such as magnet currents, beam-position-monitor voltages and so forth, still through displays and touch panels. And, of course, the most primitive communication of all occurs when the main computer crashes, and he resorts to primal scream.

The computer control system has been steadily improved since commissioning, and now, with both Modcomp IV and VAX central computers working together, the system is extremely flexible and serviceable. The bulk of repetitive, rational procedures required to operate the storage ring are carried out routinely and automatically by the computers with advice or intervention by the operator only as required or desired. Betatron tunes, interaction-region beta functions, eta functions and chromaticities are requested as such by the operator, and the computers adjust the storage ring to produce them according to a mathematical model (of which more later) programmed in the computer. Closed-orbit-measurements and corrections are carried out on request as are special orbit adjustments at individual interaction regions. As we have become more familiar with the system, and as its bugs have been eradicated, we have grown to like it better and better.

# Performance

## Configurations

We have operated PEP with a variety of settings of the optical parameters which we normally control, viz., $\nu_x, \nu_y$ (the horizontal and vertical tunes), $\beta_x^*, \beta_y^*$ (the horizontal and vertical beta functions at the interaction points) and $\eta_x^*$ (the horizontal dispersion function at the interaction points.) Each distinct choice of these parameters - taken together with a set of appropriate closed-orbit corrections and certain necessary corrections to interaction region quadrupole strengths - is dubbed a "configuration" and saved as a data file on disk in the control computer. Figure 1 is a reproduction of a display presented to the operator showing the optical functions over one-twelfth of the

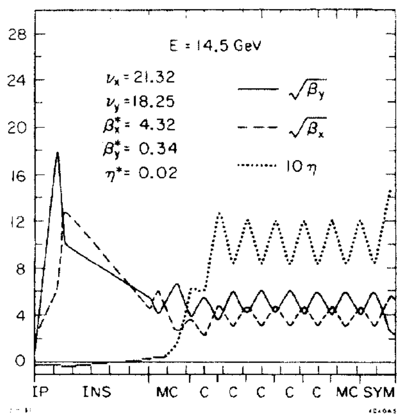


Fig. 1. Optical functions of PEP plotted over one-twelfth of the ring. IP signifies an interaction point. The vertical scale is in either $m^{1/2}$ or m, as appropriate.

ring. The model treats the machine as having sixfold symmetry. This display is of the configuration which was in use for most of the production runs to date.

We have explored configurations in the following ranges of parameters:

$$21.2 \le \nu_x \le 22.2$$
$$18.2 \le \nu_y \le 19.2$$
$$3.0\text{ m} \le \beta_x^* \le 4.9\text{ m}$$
$$0.15\text{ m} \le \beta_y^* \le 0.35\text{ m}$$

So far, all of our studies have been done with $\eta_x^*$ set for zero; however, owing to orbit distortions, the actual values of $\eta_x^*$ have not been exactly zero, and the $\eta_x$-function has been somewhat distorted everywhere. More importantly, perhaps, the $\eta_y$-function has not been zero everywhere as it would in an ideal machine. Since the vertical emittance is strongly influenced by the $\eta_y$-function in the bending magnets, the colliding beam behavior of the storage ring is also significantly influenced.

As I have mentioned earlier, the relationship between the optical parameters and the storage ring hardware is embodied in a mathematical model based on the measured properties of the magnets. The accuracy of the model is reflected in the actual parameters obtained when the computer sets the magnets. Typically, we find the actual tunes about 0.1 unit lower than those asked for, which represents a fractional error of about one part in two hundred. We are not sure of the cause of this disparity, but it may arise primarily in the setting of the interaction region quadrupoles to which the tunes are very sensitive. In the configuration of Fig. 1, the measured value of $\beta_y^*$ is 0.26 m rather than 0.34 m as shown. This parameter also is extremely sensitive to the exact strengths of the interaction region quadrupoles.

## The Wiggler Magnets[1,14]

A set of three wiggler magnets located symmetrically around the storage ring is used to enhance the horizontal emittance of the beams at energies below 15 GeV without varying the tunes or damping partitions from those used at 15 GeV. With the wigglers properly excited, the horizontal emittances at different energies (below 15 GeV) would be the same. Comparison of specific luminosity at low current at 11 GeV and that at 14.5 GeV shows them to be virtually identical for configurations with the same $\beta_x^*$ and $\beta_y^*$.

$$\mathscr{L}_{spec} = \frac{\mathscr{L}}{B\, I_B^2} = 0.1 \times 10^{30}\text{cm}^{-2}\text{sec}^{-1}\text{mA}^{-2} ,$$

where $\mathscr{L}$ is the luminosity, B the number of bunches in one beam and $I_B$ the current per bunch. Since the specific luminosity is simply a measure of the inverse of the effective cross-sectional area of the bunches, equality implies equal emittances, provided the beta functions at the interaction region are held constant. The wiggler magnets also provide enhanced damping rates at the lower energies and thus permit higher injection repetition rates.

## Colliding-Beam Performance

The colliding-beam performance of PEP has so far been totally dominated by the beam-beam incoherent limit. We have been able routinely to store single beam currents well in excess of those which we can use in the colliding-beam mode. Coherent instabilities have only intermittently troubled us. A coherent horizontal betatron mode sometimes has to be suppressed with the transverse feedback system. The storage ring is quite tolerant of variations in the betatron tunes. A stored beam can be carried over large variations in tune without being lost unless a half integer is crossed. Moreover, synchrobetatron resonances are not troublesome; indeed, they have been observed only through their effect on injection rates.

Generally speaking then, apart from equipment failure and positron injection problems, it is easy to store and collide beam currents up to the incoherent limit. That limiting current, however, is disappointingly low. Our experience, like that of the PETRA group, has been that usuable tune shifts are limited to $\Delta\nu_y \le 0.025$. In production running for experimental physics at 14.5 GeV, we seldom exceed $\Delta\nu_y = 0.02$ at the beginning of a fill.

When beams of currents near the limit are collided, one beam or both beams blow up vertically. At beam energies of 14.5 GeV - and with the asymmetric distribution of rf voltage enforced by the lack of a full complement of klystrons - the positron beam has almost always blown up preferentially if both opposing beams contained the same currents. We have found that increasing the positron current to be 20% to 30% greater than the electron current reduces the preferential blow-up of the positron beam, leads to similar blow-up of both beams and sometimes produces a greater luminosity. In most cases there are no coherent betatron oscillations attending collisions even at the largest currents used; although coherent beam-beam oscillations have occasionally set in. When they do, the mode of oscillation appears to be that mode in which all bunches oscillate together so that the luminosity is not degraded. As a rule these oscillations can be controlled by feedback.

We have not observed any significant disruption of the horizontal profile of the beams even though calculated horizontal tune shifts $\Delta\nu_x$ have been much larger than the prevailing value of $\Delta\nu_y$.

The preferential disruption of the positron beam is reminiscent of the "flip-flop" effect observed in SPEAR which has been shown to be determined by the sign of the (unwanted) horizontal dispersion at the interaction region and by the relative phase of rf cavity voltages on either side of the interaction region.[12] In the routine operation of SPEAR, the effect is controlled by adjusting the relative phase of the cavity voltages. Experiments are underway in PEP to determine whether the same parameters can control the preferential blow-up, and preliminary results display many of the same features as in SPEAR.

A particularly salient and intriguing feature of

PEP's colliding-beam performance is the ratio of the luminosity attained with three bunches in each beam and that with only one bunch in each beam. The 11-GeV data reported in Ref. 1 displayed a ratio of about three over the whole range of single-bunch currents which could be collided with three bunches in each beam, although it was possible to collide larger currents with only one bunch in each beam without intolerably short lifetimes. In both cases tune shifts $\Delta\nu_y$ in excess of 0.025 were reached.

At 14.5 GeV, where we have concentrated most of our development work, the behavior of the storage ring is different. Figure 2 displays typical performance

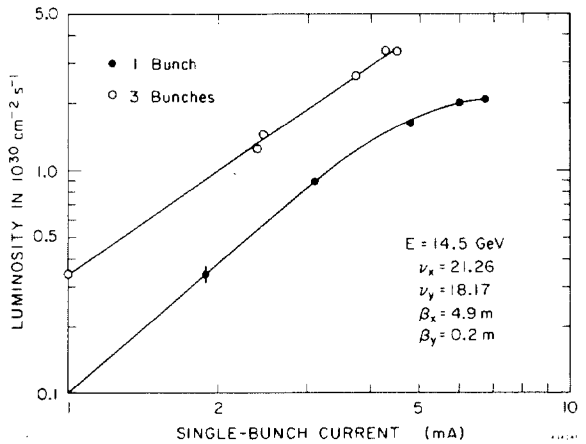


Fig. 2. Luminosity per interaction region as function of single-bunch current in milliamperes.

of PEP at that energy. The single-bunch luminosity rises quadratically with bunch current at low currents and saturates in the vicinity of 5 milliamperes per bunch. Figure 3 shows the same data characterized in

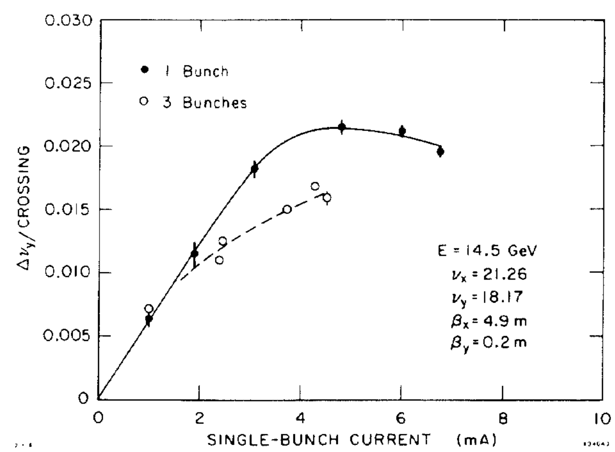


Fig. 3. Vertical beam-beam tune shift per interaction as a function of single-bunch current in milliamperes.

terms of the vertical tune shift. The three-bunch luminosity is, as it should be, a factor of three higher than the one-bunch luminosity at small currents, but as the bunch current increases, it rises less rapdily than quadratically. (For these data it varies as $I_B^{1.6}$.) At the largest usable currents it is only about twice as high as the single-bunch luminosity, and the allowable tune shift is correspondingly lower as well.

In varying the configuration over the range of tunes and betatron functions described above, we found that the single-bunch performance was usually comparable to that of Fig. 2 and Fig. 3, but we found that the three-bunch performance varied wildly in comparison to the single-bunch performance. An example is provided by a configuration in which the only parameter changed intentionally from those which pertain to the typical configuration discussed above was $\beta_x^*$. That parameter was reduced to 3.3 m, a substantial reduction. Although the one-bunch performance of this configuration was similar to that of the typical configuration, the three-bunch performance was greatly inferior. Figures 4 and 5 show the performance of this configuration.

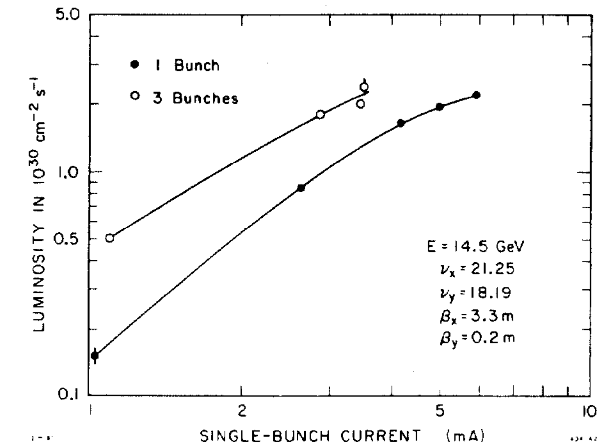


Fig. 4. Luminosity per interaction region as a function of single-bunch current in milliamperes.

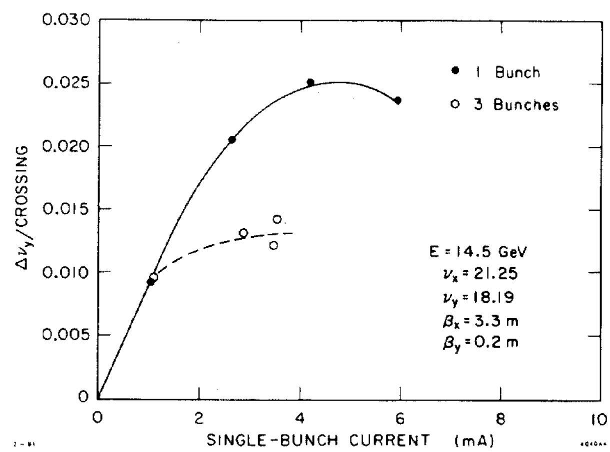


Fig. 5. Vertical beam-beam tune shift per interaction as a function of single-bunch current in milliamperes.

In another, even more striking case using tunes one integer higher ($\nu_x = 22.27$, $\nu_y = 19.21$) the single-bunch luminosity reached $2.5 \times 10^{30}$ cm$^{-2}$sec$^{-1}$ corresponding to a tune shift $\Delta\nu_y = 0.035$, but the three-bunch luminosity could be made no better than the same figure with a corresponding tune shift $\Delta\nu_y = 0.016$.

Since we have been anxious to begin experimental physics as early as possible, we have concentrated on improving the configuration which consistently gives the best three-bunch performance. Although our explorations of the effects of varying the beta functions and the tunes have not been as thorough and systematic as we would like, we are convinced by now that the three-bunch behavior of the storage ring is profoundly influenced by details of the configuration to which the one-bunch performance is much less sensitive. This opinion seems to be in consonance with recent simulation studies made at PETRA.[13] In particular, the dispersion functions $\eta_x^*$ and $\eta_y^*$ at the interaction regions are intended to be zero in the configurations we have been using. In fact, they are not zero owing to the combined effects of misalignments and orbit corrections to counteract the misalignments, and the three-bunch behavior of the ring may be quite sensitive to these functions. We have been steadily improving our methods of controlling and minimizing them.[11]

To sum up, the colliding-beam performance of PEP at 14.5 GeV is about one twenty fifth of the goal set in its design.

$$\mathscr{L} = 4 \times 10^{30} \mathrm{cm}^{-2} \mathrm{sec}^{-1} = 0.04\ \mathscr{L}_{\mathrm{design}}$$

The multiplier 0.04 may be interpreted as the product of three factors in the formula for the luminosity in the beam-beam-interaction limited regime.

$$\mathscr{L} = \frac{fB\gamma^2}{4r_e^2} \left(\Delta\nu_y^2\right) \left(\frac{1}{\beta_y^{*2}}\right) \left(A^*\right)$$

where f is the orbital frequency, B the number of bunches in each beam, $\gamma$ the beam energy, $r_e$ the classical electron radius, $\Delta\nu_y$ the vertical beam-beam tune shift, $\beta_y^*$ the vertical betatron function at the interaction point and $A^*$ is the effective lateral collision area. The multiplier is accounted for as follows:

1) The dominant factor is the permissable tune shift $\Delta\nu_y$ which is currently limited to about one third of the design value of 0.06 with a concomitant reduction of luminosity by 1/9.

2) The next factor is $\beta_y^{*-2}$. We are currently operating with $\beta_y^*$ values about twice as large as the 11 cm value assumed in the design, so the reduction of luminosity due to this factor is about 1/4.

3) The final factor is the effective area $A^*$ which depends on several parameters. The present values of the $\beta$-functions increase $A^*$ relative to the design values; the current value of $\eta_x^*$ (zero) decreases $A^*$; and the beam-beam blow-up increases $A^*$. The net result is that $A^*$ is about $\sqrt{2}$ times as large as the design value.

The factors (1), (2) and (3) come to 0.04.

We are striving to make gains in all these factors. In particular, we are trying to develop usable configurations with lower values of $\beta_y^*$; we have found the going rather difficult so far, but it grows easier as we gain better mastery over the orbit distortions and error-induced $\eta$-functions. A more dramatic step toward lower $\beta$'s has been the installation of a pair of quadrupoles at 4.5 meters from the interaction point in one interaction region preparatory to a so-called mini-beta experiment. We hope to be able to lower the beta function at that interaction region well below 11 cm and measure its effects. At the same time, engineering is proceeding for the introduction of two additional mini-beta insertions to create a threefold symmetric ring with three mini-beta insertions, and we eagerly watch the progress of the mini-beta program at PETRA.


## Acknowledgements

The status of PEP is the cumulative result of the dedicated efforts of large groups of people at the Stanford Linear Accelerator Center and the Lawrence Berkeley Laboratory and a few people from Europe, Japan and China. In giving this report, the author is acting as their spokesman and wishes to acknowledge that fact. The close LBL/SLAC collaboration in the design and construction of PEP was, in my view, a real and unprecedented success and is one of PEP's signal virtues.


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