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ABSTRACT

The design and construction of the PEP project is briefly reviewed. The initial testing of the storage ring system and its present performance is described. The short-range plans for continuing development are discussed.

INTRODUCTION

PEP is an 18-GeV positron-electron storage ring constructed at the Stanford Linear Accelerator Center as a joint venture of SLAC and the Lawrence Berkeley Laboratory, and sponsored by the U.S. Department of Energy. The official beginning of the project was in March 1976, with formal ground-breaking actually taking place in June 1977. The official completion date originally established by SLAC and DOE was April 1980. However, it appeared to us in 1976 that with some good luck we should be able to complete the construction six months earlier than that, and we set our internal schedule for completion as October 1979. We didn't have that good luck! Nevertheless, we did make the originally established date of April 1980, and also noteworthy is the fact that the project was completed within its initial cost estimate of 78 million dollars.

The schedule for installation of technical components and control systems was arranged in such a way as to allow some testing of subsystems before the entire ring was complete. In November and December of 1979, tests were carried out (on weekends in order not to interfere with the rest of the installation) which accomplished the transport of a positron beam from the linear accelerator through one-twelfth of the storage ring. These tests, although limited, were very beneficial, helping us understand the inter-relationships of the various technical systems. By the end of March 1980, all technical systems required to store a beam were complete and installed. We then started trying to get all of the systems operating properly, and together this took some two weeks' time — beam was first stored on April 16.

At that time, we limited the injection energy to 8 GeV because we were having problems with an injection component — the kicker magnet. (See below). During the remainder of April and May, hectic activity continued on completing and testing various technical systems, completing the installation of the first round of experiments in the interaction regions and testing the colliding-beam performance of the storage ring. In early June, the kicker

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magnet problem had been solved, and the injection and operating energy was raised to 11 GeV. Rapid progress was then made on all fronts. By the middle of June, the colliding beam performance reached a level where it became prudent to begin physics runs to allow the experiment groups time to check out their apparatus and to begin data acquisition at 11 GeV per beam.

REVIEW OF THE PEP DESIGN

The design of the Positron-Electron Project, PEP, has been described at prior conferences.[1,2] The more important parameters are listed in Table 1.

Table 1

Storage Ring Parameters

Characteristic	Value
Nominal Maximum Energy	18 GeV
Nominal Minimum Energy	4 GeV
Maximum Current per Beam at 15 GeV	55 mA
Number of Particles per Beam at 15 GeV	2.5×10^{12}
Number of Bunches	3
Design Luminosity per Interaction Region at 15 GeV and below at 18 GeV	 10^{32} (E/15) cm^{-2} sec^{-1} 1×10^{31} cm^{-2} sec^{-1}
Number of Interaction Regions	6
Available Free Length for Experiments	19 m
Circumference	2200 m
Symmetry	6
RF Power Installed	5.5 MW
Number of Accelerating Sections	22
Number of 0.5 MW Klystrons	11
RF Frequency	353.2 MHz
Harmonic Number	2592

The lattice design has six-fold symmetry, with approximately 100-meter-long straight insertions (including 19-meter-long low-β insertions) which alternate with strong focusing arcs having short 5-meter straight sections at their midpoints. These latter sections are used for wiggler magnets (in three symmetric locations), transverse and longitudinal feedback equipment, optical monitoring and laser polarimeter systems. The radiofrequency

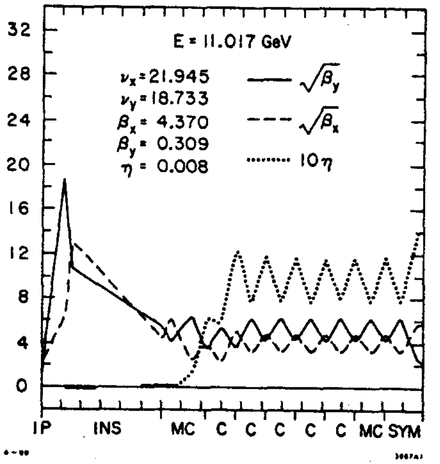

Figure 1

accelerating systems are distributed around circumference in three of the long straight sections. The lattice is flexible with the betatron functions and dispersion functions at the interaction points being tunable over a large range. Figure 1 shows the optical functions in one-twelfth of the lattice in a configuration which has been used in much of the early testing of the storage ring.

The chromatic corrections of the lattice parameters are achieved using up to nine separate families, or circuits, of sextupoles.3) To date, we have operated over a range of betatron function at the interaction points from 0.5 m to .2 m in the vertical plane and from 5.0 m to 3.3 m in the horizontal. Several distributions of sextupole families have been used over this range. The mathematical lattice model of the storage ring in the control computer, which translate the optical parameters requested by the operator into hardware set-points, has proved quite accurate; in the lattice shown in Fig. 1, the measured betatron functions agree within 10% with what is computed from the model, and the betatron tunes agree to better than 0.1.

EXPERIENCE WITH TECHNICAL SYSTEMS

Transport and injection system4)

Two beam transport lines take the positron and electron beams from the linear accelerator to the injection points in the storage ring. Beams can be injected at any operating energy of the storage ring between 4 and 15 GeV. The injection equipment includes four DC beam-bump magnets and three pulsed kicker magnets for each of the two beams. As mentioned earlier, we experienced electrical breakdown problems across ceramic supports within the vacuum tanks of two of the six kicker magnets. This problem limited the injection energy to 8 GeV during April and May. It is now corrected.

The rest of the transport and injection system has been reasonably trouble free and performs as designed. The one-nanosecond pulses transmitted through ±0.3% energy-defining slits contain at best approximately 10^9 electrons per pulse and 10^8 positrons per pulse. The injection repetition rate can be varied up to 180 pps, although, to date, less than 60 pps have generally been required to give filling times of a few minutes when the equipment was working properly. Positron injection is often difficult for reasons not yet understood.

The magnet and power supply systems[5)]

The PEP main magnet system consists of approximately 200 each of bend magnets, quadrupoles and sextupoles which are powered in 19 separate circuits. There are nine sextupole curcuits, nine quadrupole circuits and one circuit which includes all the bends and the interaction-region quadrupoles. Each circuit is driven by thyristor-chopper power supplies running from common 600 VDC busses. In addition to the chopper supplies, there are about 120 bipolar transistor actuators for various trim and steering magnet circuits.

As a consequence of PEP's delayed and compressed installation schedule, the power supplies and their magnet circuits were not completed as systems until just before beam turn-on so that little time was available for testing, and system debugging was carried out simultaneously with beam tests throughout April and May.

Vacuum system[6)]

So far, PEP has had only limited high-current, high-energy operation, and, therefore, there has been little testing of the vacuum system under heavy gas load, however, the system appears to be very good; the beam lifetime is several hours at the highest currents and energies at which we have run. On two occasions the RF sections have been vented to atmospheric pressure due to RF window failures. After purging with dry nitrogen and pumpdown, there has been no requirement for in situ bakeout.

Radiofrequency system[7)]

The PEP 353-MHz radiofrequency accelerating system is comprised of 12 stations. Each station consists of a 500-KW klystron which feeds a pair of 5-cell accelerating cavities.

The SLAC-designed 500-KW klystrons have performed well, although the peak efficiency is a few percent less than the hoped for 70%. Some of the early tubes went soft while awaiting completion of installation after high power testing. This problem was traced to porosity developing in some stainless steel weldments due to faulty material. The tubes have been rebuilt and are back in service.

Only a fraction of the system is required for beam storage at low or medium energies; this was one of the items where contractors were able to defer a portion of their installation work until after beam start-up. As of July, eleven stations were operating, and the twelfth station is being installed in August.

Survey and alignment[8)]

The PEP laser survey system proved to be rapid and reliable. The goal was to have residual alignment errors of less than 0.1 mm, and the orbit measurements would indicate that this goal was met. Typically, the orbit correction program can reduce the RMS orbit deviation to less than 2mm using less than 30 correctors with the maximum distortion being less than 4mm.

Instrumentation and control[9)]

A description of the PEP control system and a discussion of its performance can be found elsewhere in these proceedings. The MODCOMP-IV has been supplemented with a VAX-11 in order to handle better the message traffic from the seven remote MODCOMP-II's and the desired multi-task service of interfacing with the operators.

BEAM PERFORMANCE

As mentioned earlier, the initial injection energy was 8 GeV. During the first injection tests, the lattice was set to a configuration with $\beta_y^* = 0.45$ metre and $\beta_x^* = 5.0$ metre. After beam was stored, the lattice functions were measured and found to be very severely mismatched around the ring. This was shown to be due to a reversed trim winding on an interaction region quadrupole, and when it was corrected, the ring proved to be quite symmetric.

Other than the expected head-tail instability, which occurs with negative chromaticity, no instabilities have been observed, with the following qualification: single-bunch currents greater than 5 or 6 mA have not been used. Both horizontal and vertical head-tail instabilities had threshold between 0.05 and 0.1 mA when the chromaticity of the respective degree of motion was negative. The coherent tune shift with current, which has been measured in the configurations used to date, to be of the order of $\Delta\nu_x \approx \Delta\nu_y \approx .0025$/mA, can affect the beam during injection, giving the impression of instability if the betatron tunes are near some lattice resonance.

Before studying colliding beams at 8 GeV, the vertical betatron function was lowered to $\beta_y^* = 0.35$ metre, and the wiggler magnet system was energized to a level equal to 70% of the design excitation at 8 GeV. The maximum linear beam-beam tune shift, computed from the maximum luminosity and current, always lay between $\Delta\nu_y = .02$ to $.03$. (The early luminosity measurements had large systematic errors while the measurement system was debugged.)

Figure 2 shows the luminosity versus current for two cases: a) no excitation by the wiggler magnet system and b) the wiggler system powered to a level where the calculated emmittance of the beam had been increased by the wiggler by a factor of 2.4 . To within the accuracy of the measurements at that time, the beam behavior was in good agreement with the predictions.

The maximum luminosity achieved at 8 GeV was 3.5×10^{29} cm^{-2} sec^{-1}. This was achieved both with one bunch per beam and with 3 bunches per beam. Experiments with lower β_y^* and with stronger wiggler magnet settings were curtailed when operation at higher energies became possible.

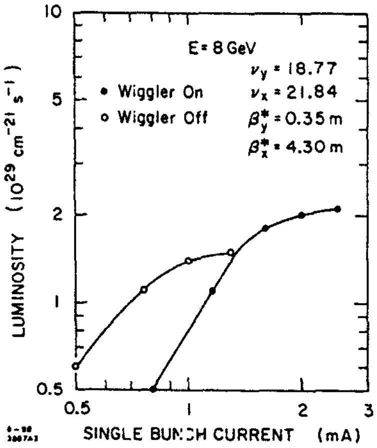

Figure 2

By the time operation at 11 GeV had settled down, many improvements in instrumentation and machine control had been implemented, and storage ring operation was reproducible. The betatron function was lowered to a $\beta_y^* = 0.30$ metres, and the sextupole correction system was changed to one where there were nine families instead of the two families used at the outset.

The maximum luminosity measured with the lattice configuration shown in Fig. 1 was 8×10^{29} cm^{-2} sec^{-1} with one bunch per beam, and 1.5×10^{30} cm^{-2} sec^{-1} with 3 bunches per beam.

The wiggler magnet system was set at a level where the calculated emittance was increased by 50% over that without the wiggler, and where it was 80% of the emittance assumed in the design at this energy. Typical curves of luminosity versus single bunch current are shown in Fig. 3.

The three-bunch data shown were taken during early physics runs in which the detector magnets of the Mark II, MAC and DELCO were operating. Over a wide range of current, the luminosity varies as $L \approx I^2$, indicating a constant emittance, and the luminosity per interaction region scales with the number of bunches.

Figure 4 shows the computed linear beam-beam tune-shift from this data. The $\Delta\nu_y$ per crossing increases linearly with current to values between 0.025 and .03 . In the single-bunch mode, higher bunch currents were successfully collided with a visible increase in vertical beam size and the luminosity saturated. A limit on luminosity and current is reached when the lifetime

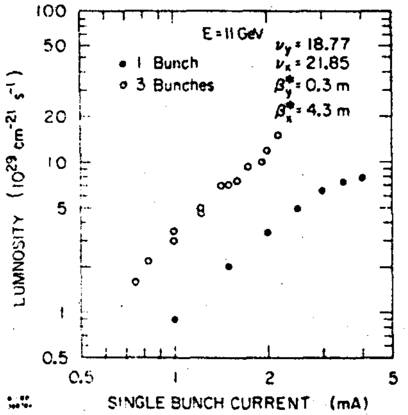

Figure 3

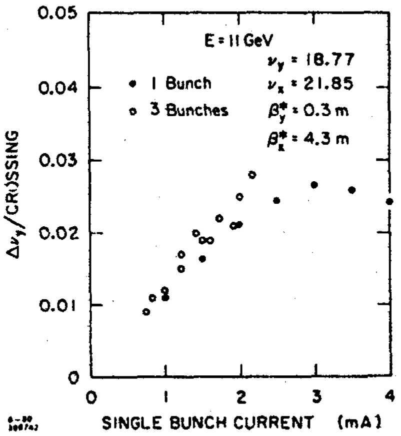

Figure 4

of one or both beams is significantly reduced. The three-bunch data have not, at this time, been extended into this regime.

SUMMARY AND FUTURE PLANS

After approximately three months of shakedown of the many engineering systems which make up the storage ring, the total system is beginning to operate as designed. Comparing present performance with the design assumptions indicates that the maximum beam-beam tune shift achieved, to date, is one half of the assumed 0.06 . For the present lattice, all other parameters appear to reproduce the design values, and, after one allows for the lower maximum tune-shift, the luminosity is in agreement with the predicted value for this lattice.

In the design of PEP, much flexibility was allowed for in the lattice, and we must now begin gradually to explore the alternatives available. In the "standard configuration" of the design, the betatron and dispersion functions at the interaction points were: $\beta_y^* = 0.11$ m, $\beta_x^* = 2.8$ m and $\eta_y^* = -0.5$ m.

We will explore lower β^* values and non-zero dispersion to find the optimum operating conditions and to understand the scaling of the beam-beam limit as a function of these parameters. We will also explore alternate betatron tunes both to refine operating points and to study the use of smaller emittances. Higher energy operation is being pursued during this Conference, and our goal is to achieve 15-GeV operation this month.

ACKNOWLEDGEMENTS

As this is the first report on the operating performance of PEP since the completion of construction, I would like to thank all of the staff at the Stanford Linear Accelerator Center and the Lawrence Berkeley Laboratory who contributed to the design and construction of this project. Although this report is very preliminary, it is not without the encouraging indication that everyone's efforts are bearing and will continue to bear fruit.

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