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# RECENT IMPROVEMENTS IN LUMINOSITY AT PEP†

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## Summary

We will describe improvements which have led to new records for peak and average luminosity at PEP. Comparison of recent results with several earlier lattice and optical modifications shows rather good correlation with the predictions of a beam-beam simulation program.

## Introduction

The PEP lattice has been modified from its original design (PEP1) by relocation of the final focus quadrupoles nearer to the interaction points. The purpose of this change was to allow operation with lower beta functions at the IPs, thereby increasing the luminosity. For a given chromatic aberration the value of $\beta^*$ (the * denotes value at the IP) scales approximately directly the distance of the final focus lens from the IP, and the maximum luminosity is expected to vary as the inverse of $\beta^*$. At PETRA and CESR the lattices were modified for lower $\beta^*$s and the expected luminosity improvements seem to have been observed.[1,2]

At PEP the changes were made in two stages. First (PEP2), in the summer of 1981 the nearest, vertically focusing quadrupole (Q1) was moved from its original distance of 11 m to 7.35 m from the IP, which is about the minimum required to accomodate the largest detectors. A current-limiting instability in PEP2 required use of a different focusing configuration. To avoid this problem the next, horizontally focusing quadrupole (Q2) was moved in the summer of 1982 from the original 15.2 m to 12.24 m (PEP3). Figures 1-4 show the lattice changes and typical beta functions in the insertion region. Table I lists optical parameters for several configurations. Operating experience in the original lattice and the two modifications and comparison with a beam-beam simulation study are summarized below.

Table I. Typical configurations: tunes, betas and dispersion function at the interaction point, and total emittance at 14.5 GeV.

| | PEP1 | PEP2a | PEP2b | PEP3a |
|---|---|---|---|---|
| $\nu_x$ | 21.28 | 21.28 | 25.275 | 21.25 |
| $\nu_y$ | 18.19 | 18.19 | 20.175 | 18.19 |
| $\beta_x^*$(m) | 4.27 | 3.0 | 2.95 | 3.0 |
| $\beta_y^*$(m) | 0.26 | 0.11 | 0.11 | 0.11 |
| $\eta_x^*$(m) | 0.0 | 0.0 | 0.0 | 0.0 |
| $\epsilon_{x0}$(mm-mr) | 0.125 | 0.112 | 0.099 | 0.117 |

## Operating Experience

Table II summarizes best results obtained in the three lattice modifications and several optical configurations.

PEP1. The original lattice was tried in several different optical configurations (tunes and $\beta^*$s). The PEP1 example in Tables I and II was eventually chosen for production running. Attempts were made to reduce $\beta_y^*$ but problems were encountered with increased background noise at the IRs and poor lifetimes with colliding beams. Eventually it was decided that the final-focus quadrupoles should be moved closer to the IPs in order to increase luminosity.

Table II. Performance and limiting parameters at 14.5 GeV.

| | PEP1 | PEP2b | PEP3a est. | PEP3a obs. |
|---|---|---|---|---|
| $I_{max}$(mA/beam) | 21 | 16.7 | 23 | 24.8 |
| $L_{max}(10^{30}cm^{-2}s^{-1})$ | 7.5 | 10 | 16 | 32.3 |
| $L_{av}(nb^{-1}/day)$ | | | | |
| typical | 220 | 300 | -- | 1000 |
| maximum | 300 | 450 | -- | 1534 |
| $\epsilon_{ymax}$(mm-mr) | .0098 | .0112 | .0105 | .0052 |
| $\Delta\nu_{xmax}$ | .031 | .030 | .033 | .050 |
| $\Delta\nu_{ymax}$ | .031 | .022 | .024 | .046 |

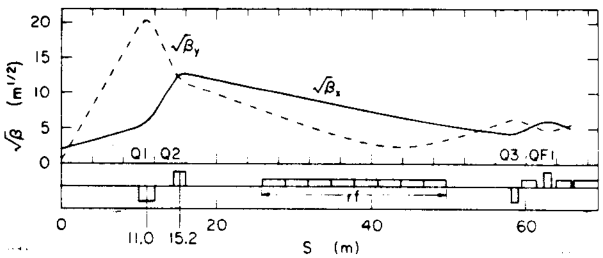


Fig. 1. PEP1: $\nu_x = 21.28$, $\nu_y = 18.19$, $\beta_x = 4.27$ m, $\beta_y = 0.26$ m, $\eta_x = 0.0$.

PEP2. Computer studies indicated that a worthwhile reduction of $\beta_y^*$ could be attained by moving only Q1 and that in this case the excitation of Q1 would remain almost constant, which would simplify the rebussing. If Q2 were not also moved, $\beta_x$ would become quite large at Q2, which would increase the sextupole strengths required for chromatic correction; however, computer tracking predicted single-particle stability at adequate betatron amplitudes.

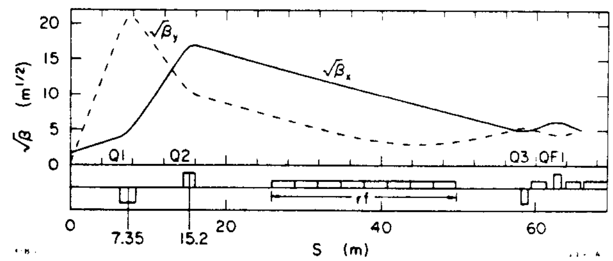


Fig. 2. PEP2a: $\nu_x = 21.28$, $\nu_y = 18.19$, $\beta_x = 3.00$ m, $\beta_y = 0.11$ m, $\eta_x = 0.0$.

This change (Q1) moved was made in the summer of 1981. On resuming operation we first tried a configuration (PEP2a, Table I) similar to the PEP1 production configuration. Unfortunately an instability appeared, characterized by sudden horizontal blowup at a threshhold of about 3.5 mA per bunch, about half of what was expected to be required to reach the beam-beam limit. The blowup was diagnosed as the "fast head-tail" instability, arising from short-range wake fields excited mainly in the RF cavities. Theoretically the threshhold for the instability should be inversely proportional to the average β function in the RF cavities, which as may be seen in Figures 1 and 2 is much larger (in the horizontal) in PEP2a than in PEP1.

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A quick fix for this problem was provided by refocusing to produce a small waist in the RF region, e.g., the PEP2b configuration in Fig. 3. In order to further increase the threshhold two of the cavities in each RF region were later moved (Jan. 1982) from a high-$\beta$ point to a lower-$\beta$ point. It was then possible to store beam currents of above 19 mA per bunch; the beam-beam limit was about 5.5 mA per bunch. During the last seven weeks of the 1981-1982 cycle an intensive collaboration among machine physicists, operators and maintenance crews produced an accumulated luminosity of 13,000 $nb^{-1}$(inverse nanobarns), i.e., an average > 300 $nb^{-1}$ $day^{-1}$. Peak luminosity was $1.0 \times 10^{31}$ $cm^{-2}$ $s^{-1}$ and the best daily average was $\simeq$ 450 $nb^{-1}$ $day^{-1}$ at 14.5 GeV.

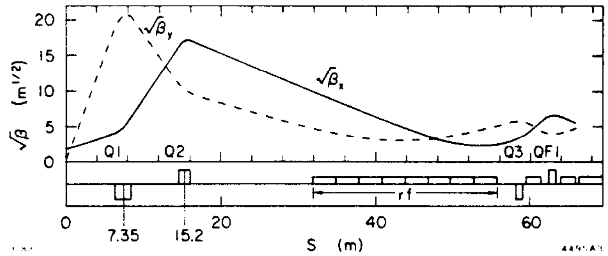


Fig. 3. PEP2b: $\nu_x = 21.275$, $\nu_y = 18.175$, $\beta_x = 2.95$ m, $\beta_y = 0.11$ m, $\eta_x = 0.0$. Note that the RF cavities have been moved.

PEP3. In spite of the respectable success of the PEP2 modification there were theoretical grounds to also move the second final focus quadrupole Q2. This would decrease the maximum $\beta_x$ and reduce the sextupole strengths required for chromatic correction, giving a more linear lattice. Also, in a configuration analogous to PEP1 and PEP 2a, the $\beta$s in the RF region would be lowered enough so that the estimated fast head-tail threshold would be around 10 mA per bunch.

After the Q2s were moved in the summer of 1982, we first used configuration PEP3b with the same tunes and $\beta^*$s as PEP2b which had been so successful in the previous cycle. The results were disappointing — after two months of operation luminosities were no better than had been obtained with the PEP2 lattice. It was then

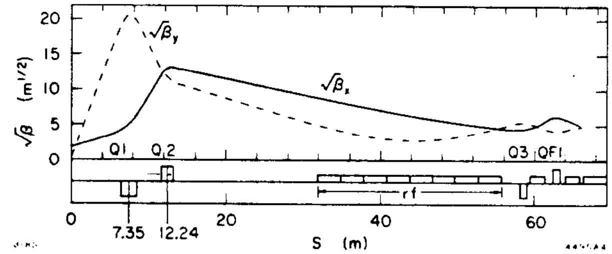


Fig. 4. PEP3a: $\nu_x = 21.25$, $\nu_y = 18.19$, $\beta_x = 3.00$ m, $\beta_y = 0.11$ m, $\eta_x = 0.0$.

decided that the PEP3a configuration should be tried, a decision which was guided by at least two theoretical considerations. First, the beam emittance would be larger which should permit higher colliding currents at the beam-beam limit. Second, a study by A. Hutton[3] using the beam-beam simulation program developed by S. Meyers[4] had also predicted higher luminosity for PEP3a than for PEP3b.

The change to the PEP3a optics was made in early January 1983 and the predicted improvements were seen within the first week of operation. The present luminosity record is $3.2 \times 10^{31}$ $cm^{-2}$ $s^{-1}$ and the best average luminosity is > 1500 $nb^{-1}$ $day^{-1}$ at 14.5 GeV. (See Table II and Fig. 5.)

Other Factors Contributing to Improvements

In addition to the lattice and optics changes described above, at least three other factors have contributed to improvements in PEP's productivity.

Instrumentation and software improvements. Rapid, semi-automated programs have been incorporated into the control system for tasks such as measuring and correcting errors in orbits, dispersion functions, and $\beta^*$s. Displays of luminosity, vertical beam size, and background noise at several of the six IRs have been very helpful to the operators.

The green-thumb effect. The PEP operators are superbly adept at empirically adjusting many parameters such as orbit corrections, tunes, and sextupole strengths in

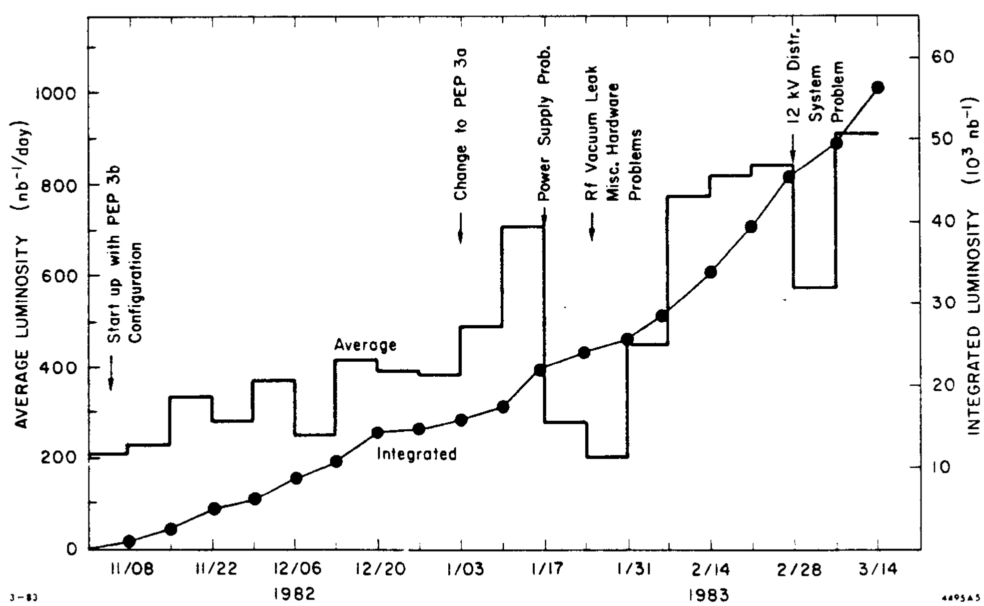


Fig. 5. Average luminosity and total integrated luminosity during the 1982-83 cycle. The average is over scheduled experimental time for each week.

order to improve beam lifetimes, increase luminosity, and decrease background noise. These efforts continually increase productivity with a time-constant of many weeks.

"Golden orbits." Once a good configuration has been established, it is always found that the orbit which works best is not the "best" orbit as indicated by the position monitors. Evidently the inspired green-thumbing by the operators eventually compensates for effects such as position monitor errors, local phase and β errors, dispersion functions, and x-y coupling. A very useful feature of the orbit correction program is the ability to save the "golden orbit" and subsequently correct to it rather than to the "best" orbit.

## Beam-Beam Simulation Studies

The studies of beam-beam effects by A. Hutton[3] using a program by S. Meyers,[4] have been extended somewhat and an attempt has been made to test the predictive powers of this type of simulation.[5] Some effects predicted by the simulation are listed in Table II for the three configurations which have been used the most. Here the limiting currents and luminosities for PEP1 and PEP2b are experimental values — i.e., they represent some kind of a beam-beam limit. It was noted that the simulated beams blow up to similar vertical emittances ($\simeq$ .01 mm-mr) in both PEP1 and PEP2b, and this value was used as a criterion for estimating the limiting values for PEP3a. This estimate was confirmed by actual results early in PEP3a operation. Later improvements to some 100% above the prediction are thought to mean that the operators have managed to reduce the machine errors relative to the errors which had been adopted in the Hutton computations.

The simulation also predicts that PEP3b should be essentially the same as PEP2b — also in agreement with experimental results.

Another prediction suggested by Hutton's work was that the luminosity would increase if the vertical tune were increased from $\simeq$18.19 to $\simeq$18.40. A 30% increase in luminosity was predicted on the criterion of a vertical emittance limit of .01 mm-mr. However, when this was tried in the real machine it didn't work; the limiting colliding currents and peak luminosities were far lower at the higher tune than at the lower tune. In this case vertical emittance evidently was not a limitation.[7] There was evidence of a type of coherent beam-beam effect which has been described by Keil.[6] Also, resonances associated with skew sextupole errors — namely, $3\nu_y = 55$, $2\nu_x+\nu_y = 61$ and $2\nu_x-\nu_y = 24$ — were observed near the tunes 21.27/18.40. These could be excited by median-plane tilts arising from vertical orbit errors in sextupoles.

We conclude that the beam-beam simulation can be a valuable guide in investigating new lattice and optics modifications but that some caution must be used in selection of appropriate limiting criteria.

## Acknowledgments

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## References

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7. It should be noted that emittances quoted here are based on unperturbed $\beta^*$ values. The dynamic β effect may be rather large at the large $\Delta\nu$s we are dealing with.