EVALUATION OF THE BEAM-BEAM EFFECT IN PEP USING MYER'S
SIMULATION PROGRAM*

SLAC-PEP-NOTE--375

DE89 006204

A. Hutton†
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The program BEAM BEAM written by Steve Myers for the LEP machine at CERN has given encouraging results in the simulation of the beam-beam effect in electron-positron storage rings.¹⁻⁷⁾ It therefore seemed worthwhile to apply the program to PEP with two main intentions. Firstly, to confirm the validity of the program by comparison with experimental data from previous PEP runs and secondly, to search for an improvement in the operating conditions of PEP. Clearly a successful prediction would also enhance the credibility of the program.

The program itself has been extensively described in the literature^{4,5)} and will not be repeated here, except for some comments of direct relevance to the present simulation.

Comments on the Program

The input data to the program requires various lattice parameters and the equilibrium single beam size. The vertical beam size was calculated assuming a ratio of the vertical to the horizontal emittance of 1%, a typical figure for PEP. This way of introducing the vertical beam size means that lattice coupling resonances cannot be seen by the program.

MASTER

† Visitor from CERN, 1211 Geneva 23, Switzerland.

* Work supported by the Department of Energy, Contract DE-AC03-76SF00515.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The machines simulated are not considered to be perfect and the magnitude of the various possible machine errors which affect the beam-beam effect are required as input data. Using these r.m.s. values each interaction region is assigned a specific value for each error, calculated using a gaussian random number generator. Not only does this value remain fixed during each simulation run, but since the random number generator is unseedable, these errors are the same in all runs.

Each beam is simulated by 50 macroparticles, a number chosen as a compromise between the statistical fluctuations and the computer time required⁸⁾. These particles are tracked through the RF cavities, the beam-beam interaction and the lattice.

The program assumes that there is one RF station per arc, which is not the case in PEP and, in addition, the cavities are not symmetrically distributed with respect to the interaction regions. The electrons and positrons therefore have slightly different energies which, coupled with the residual dispersion, gives a closed orbit difference which is included in Table 1. This effect is in addition to the 'microssing' caused by coupling of machine component misalignments with the orbit differences in the arcs due to synchrotron energy radiation.⁹⁾

The calculation of the beam-beam effect is performed by fitting a bigaussian curve to the distribution in one beam and finding the kick on each macroparticle in the other beam from a look-up table. The process is then reversed. This method has the advantage that the individual macroparticles keep their identity throughout the simulation. The kick is calculated for a thin-lens, the third dimension enters only in a modulation of the arrival time at the synchrotron frequency. PEP has three bunches per beam and in the simulation the three bunches of each beam are considered

to be strictly identical. In reality this is rarely the case and some effects are therefore excluded from the simulation.

The lattice calculation assumes a simple linear matrix transformation between crossing points using the input tune value. The tune values plotted in the graphs which follow are therefore the incoherent single beam tunes. Sextupole non-linearities, which are found experimentally to affect the beam-beam effect in PEP (including the core blow-up) can only be introduced by defining the dynamic aperture. Quantum effects are introduced by the addition of jump in three dimensions obtained from a fast gaussian random number generator. Since the generator is not seedable, the sequence is always the same and runs with an identical random number sequence show rather little statistical fluctuation. This will be seen in some of the data which follows. Radiation damping is introduced via a simple logarithmic decrement.

The maximum acceptable beam-beam effect in a real machine is usually given by the background in the experiments. With only 50 macroparticles per bunch, the information on the tails is rather sparse and while loss of particles would indicate serious problems the converse is probably not true. In the data which follows, emphasis is therefore put on the relative luminosity at the same current but some quantitative appreciation of the results will also be invoked and, hopefully, made plausible. In no case were macroparticles lost in the present simulation.

The program has run at SLAC on the IBM 3081 and the PEP control computer, a VAX 11/780 which is about 7 times slower. The tracking was continued for about one damping time which takes 4 minutes on the IBM and 30 minutes on the VAX. The majority of the data were obtained on the VAX during the summer shutdown of PEP when the control computer was very lightly loaded.

Simulation Conditions

In all four different configurations have been simulated, denoted here as PEP1, PEP2, PEP3 and PEP4. PEP was initially turned on with a low-beta configuration (PEP1). The machine energy was raised in steps to 14.5 GeV and this is the only energy that was used in the simulations. At this energy, there was little exploration of the tune diagram, the integers being multiples of 3 and the fractional parts close to those of SPEAR ($Q_H = 21.28$ $Q_V = 18.19$). By moving the inboard insertion quadrupoles a mini-beta configuration was produced but the tunes had to be raised to keep the beta values in the adjacent RF cavities small (PEP2). The fractional parts of the tune remained about the same ($Q_H = 25.275$, $Q_V = 20.175$). An attempt was made to reduce the tunes to their original values but keeping the mini-beta (PEP3) but this was abandoned without having the time to fully explore its capabilities since the initial results indicated that little, if any, improvement was obtainable.

In the present summer shutdown, the outboard mini-beta quadrupoles were moved, guaranteeing low beta values in the RF cavities independent of the tunes. The simulation program was therefore used to compare the relative merits of the two different integer choices and also to investigate the influence of the fractional part of the tune in a range which would not require a major effort to try on PEP. A possible modification of PEP3 was also investigated (PEP4) where the horizontal beta function was reduced. The relevant machine parameters are shown in Table 1. The r.m.s. values of the machine errors adopted are shown in Table 2 and are based on actual production runs in PEP¹⁰⁾.

The early operating conditions of PEP are described in two review papers^{11,12)} but the recent results are as yet unpublished. The information

given here has been gleaned from the log-book and discussions with those closely associated with the operation of PEP.

Simulation Results

The calculated luminosities for the PEP1 and PEP2 configurations are shown in Figures 1 and 2 as a function of the current per beam. The linear dependence above about 5 mA per beam is routinely observed in PEP under practically all operating conditions. In terms of absolute values, the maximum luminosity achieved is marked on the two graphs by a star and in both cases the simulation is in excellent agreement with the observed luminosity. Each point on the graphs was simulated with identical statistical conditions which accounts for the small scatter. The associated vertical beam blow-up is shown in Figures 3 and 4 where the values for each beam are given and the dashed line joins the average values. The usual behaviour is that one beam enlarges more than the other and since the maximum blow-up is smaller in the PEP1 configuration, the maximum collidable current should be higher and this is experimentally the case. The more or less linear dependence of the average vertical beam-size accounts for the linear luminosity dependence shown in Figures 1 and 2. Experimental data on vertical beam blow-up is sparse since the measurements are difficult. The simulation is in good agreement with the qualitative observations of the synchrotron light monitor and in good quantitative agreement with the only well measured data¹³⁾ which is shown on Figure 4 by a star.

A preliminary scan of the vertical tune is shown in Figures 5 and 6. The most salient feature is the similarity in shape of the two curves which have different integer parts of the tune. If the tune between interactions were the relevant parameter, as is often believed, then the two curves should be very different. The points were all simulated with identical random

numbers so that statistical fluctuation are not the cause of the similarity. The luminosity plotted is the value obtained after one transverse damping time (1250 turns in PEP at 14.5 GeV). In order to confirm the validity of this choice, the bunches were tracked for four damping times (5000 turns) at three different vertical tunes corresponding to the nominal value in Figure 6, the minimum and one of the peak values. The results are shown in Figure 7 and demonstrate that one damping time is sufficient to give a good estimate and all of the rest of the simulations have been done for one damping time only.

The relative importance of the various machine errors on PEP2 was examined by successively removing one error after the other, all other parameters (and the random numbers) being identical. The results are shown in Table 3. The most important single effect is the vertical position error which is not surprising since the r.m.s. error is equal to the unperturbed vertical beam height. The improvement due to removal of all the errors is a factor of two and this is therefore the gain that might be expected by tweaking the machine operating conditions over a period of running. This is in fact the sort of improvement that the operators do obtain on PEP.

Comparison of Future PEP Options

Three possibilities were considered (PEP2, PEP3 and PEP4). PEP2 is the latest, most well-understood operating condition, PEP3 and PEP4 have the original tunes but differ in the horizontal beta values at the crossing point. All the data in this section were obtained on the VAX, the statistical conditions being different from point to point.

Figure 8 shows the variation of luminosity as a function of vertical tune for two different values of the current with the same configuration as

Figure 6 but with the points much more closely spaced. The main features are repeated at the lower current (2×10 mA per beam) and are accentuated at the higher current (2×20 mA per beam). The luminosity drops slightly up to about 20.34 and then increases by about 30% to a relatively flat region above that.

The variation of the luminosity with horizontal tune is shown in Figure 9 both for the nominal vertical tune (20.175) and a higher value (20.40) corresponding to the plateau in Figure 8. The most striking thing about Figure 9 is the difference in fluctuations between the two curves which cannot be attributed purely to statistical variations. I believe that this is due to the amplification of the statistical fluctuations by the non-linear beam-beam forces indicating that the beams are more sensitive with the lower vertical tune. This variability will be used as one of the criteria for judging a working point. The next observation is that there is no evidence for a beam-beam coupling resonance which would depress the luminosity for values of the horizontal tune just below the vertical tune¹⁴⁾ and this is clearly not the case in Figure 9. It may be, however, that the gaussian kick used for the beam-beam effect in the simulation program depresses the octopole driving term for this resonance. Finally the luminosity attainable is greater for the higher fractional part of the vertical tune for all values of the horizontal tune between 25.24 - 25.45.

This conclusion is reinforced by Figure 10 where the luminosity as a function of current is plotted for the two values of the vertical tune and the nominal horizontal tune. Comparing with Figure 2, the statistical fluctuations are greater because of the random number generator but the results are quantitatively the same. The higher vertical tune clearly gives a higher luminosity over the whole current range examined. The linear

dependence is seen in both cases.

Turning now to PEP3 and PEP4, the variation of the luminosity as a function of the vertical tune is shown in Figure 11. The two curves are almost identical even though the initial luminosity in PEP4 is 36% greater than for PEP3 (Table 1). However the vertical kick due to the beam-beam effect is also greater in PEP4 and this increases the vertical dimensions to almost exactly cancel the expected gain. While this effect will always occur, the exact cancellation is fortuitous, other cases have been simulated in which the luminosity did improve when the horizontal beta value was reduced.

Perhaps more surprising is the similarity of the two cases at low beam currents as shown in Figure 12. This underlines the importance of vertical beam blow-up under all operating conditions and this is also the operating experience at PEP. The effect is practically all in the vertical plane but there is in all the simulations a slight horizontal blow-up ($\sim 10\%$) which is in agreement with the experimental observations.¹³⁾ The similarity between PEP3 and PEP4 argues against an influence of the horizontal beam-beam effect in luminosity limitations. Clearly at a given current PEP3 has less vertical blow-up than PEP4 so PEP3 would be the preferred configuration of the two.

The cause of the drastic drop in luminosity in the vertical tune range 18.26-18.35 has not been explained. It is neither a beam-beam coupling resonance nor a lattice coupling resonance (not seen by the program). Initial ideas that it could be a third order resonance driven by the vertical orbit separation were disproved by repeating the simulation of PEP4 with zero vertical error and this is shown in Figure 13. There is no qualitative change in the luminosity curve but there is an increase in luminosity as would be expected. This increase is smaller when the beams are strongly

blown up since the separation is then a smaller fraction of the beam-size.

Comparing Figures 8 and 11 it can be seen that at the nominal fractional part of the tune (.175) PEP3 gives the same luminosity as PEP2 while PEP4 gives about 20% greater. The similarity between PEP2 and PEP3 is supported by the experimental evidence cited above where this comparison was made and rough equivalence found. At a higher fractional part of the tune (.4) the three cases all give roughly the same luminosity. Since the PEP2 configuration is rather well understood there therefore seems little reason to change. A last set of simulations were therefore done to quantitatively compare the two vertical tune values (20.175, 20.4) in the PEP2 configuration.

The results are shown in Figures 14 and 15 where two squares in the tune diagram were covered, centered on the two working points and spaced at intervals of 0.01. Three dimensional plots tend to be rather confusing so the data is presented in the form of circles whose diameter increases with increasing luminosity. There is clearly a marked improvement in increasing the vertical tune from 20.175 to 20.4. A somewhat smaller gain could also be obtained by reducing the horizontal tune to around 25.24. In order to quantify the results, an average was taken of the 25 points surrounding the suggested working points and the rms error was also calculated. The results are given in Table 4 and confirm the results of Figure 9. The luminosity with a vertical tune of 20.4 is 30% greater than the nominal configuration and the variability is halved. Looking at Figure 15, a working point in the lower right hand corner would appear to be even better than in the center. However, this is very close to a lattice coupling resonance which is not shown up by the program and which would render machine operation difficult. If the beam-beam coupling resonance proves to be a problem, the separation of the fractional parts of the tune should be increased by about

0.05 (i.e. move to the upper left corner in Figure 15).

This then is the clear prediction of the simulation program.

Increase the vertical tune by about 0.25 and obtain 30% more luminosity and a machine that is less sensitive to small variations in the machine. This will be tried out in the next operating period and hopefully will confirm the prediction.

Acknowledgements

The program BEAM BEAM was written by Steve Myers who has also provided a wealth of advice and suggestions over the phone. The present study was done during a six month's sabbatical leave and I would not have achieved anything if it had not been for the active support and encouragement of Burt Richter, John Rees and the whole PEP team. In particular Tom Knight, Martin Donald and Tony Gromme did the lions share of getting the program running here at SLAC and Marie Barnes typed the manuscript. It is a pleasure for me to take this opportunity to thank everyone who made my stay at SLAC so pleasant.

TABLE 1
PEP SIMULATION CONDITIONS

	PEP 1	PEP 2	PEP 3	PEP 4	
β_v	0.26	0.11	0.11	0.11	m
β_H	4.27	2.95	3.00	1.80	m
Q_v	18.190	20.175	18.175	18.175	
Q_H	21.280	25.275	21.275	21.275	
σ_v natural	1.81×10^{-5}	1.03×10^{-5}	1.15×10^{-5}	1.12×10^{-5}	m
σ_H natural	7.36×10^{-4}	5.32×10^{-4}	6.03×10^{-4}	4.54×10^{-4}	m
$\sigma_v \sigma_H$ natural	13.32×10^{-9}	5.46×10^{-9}	6.96×10^{-9}	5.10×10^{-9}	m ²
INITIAL CONDITIONS 2 x 10 mA per beam					
Luminosity	5.68×10^{30}	13.89×10^{30}	10.90×10^{30}	14.87×10^{30}	cm ⁻² s ⁻¹
ΔQ_v	0.046	0.048	0.037	0.051	
ΔQ_H	0.019	0.025	0.020	0.021	
INITIAL CONDITIONS 2 x 20 mA per beam					
Luminosity	22.72×10^{30}	55.55×10^{30}	43.59×10^{30}	59.48×10^{30}	cm ⁻² s ⁻¹
ΔQ_v	0.092	0.095	0.075	0.102	
ΔQ_H	0.037	0.049	0.039	0.041	

TABLE 2

R. M. S. ERRORS ADOPTED FOR THE SIMULATION

Horizontal tune error	0.04	
Vertical tune error	0.04	
Horizontal orbit difference e^+/e^{-*}	1.0×10^{-5}	m
Vertical orbit difference e^+/e^{-*}	1.0×10^{-5}	m
Horizontal dispersion [*]	0.05	m
Vertical dispersion [*]	0.005	m

* Values at the interaction points.

TABLE 3

EFFECT OF MACHINE ERRORS ON PEP2

<u>Standard Conditions</u>		
$B_V = 0.11$ m	$Q_V = 20 \cdot 18$	
$B_H = 2.95$ m	$Q_H = 25 \cdot 28$	
2×10 mA per beam	Errors as in Table 2	
<u>Calculated Luminosity</u>		
All errors	5.3×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No horizontal tune error	5.5×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No vertical tune error	5.7×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No horizontal orbit difference	5.5×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No vertical orbit difference	7.1×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No horizontal dispersion	5.8×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No vertical dispersion	5.4×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$
No errors	10.7×10^{30}	$\text{cm}^{-2} \text{s}^{-1}$

TABLE 4
LUMINOSITY AVERAGED OVER 25 POINTS

$B_V = 0.11 \text{ m}$	$B_H = 2.95 \text{ m}$
2 x 20 mA per beam	
<u>Tunes</u>	<u>Luminosity</u>
$Q_H = 25.275$	$10.57 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
$Q_V = 20.175$	$\pm 15\%$
$Q_H = 25.235$	$11.85 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
$Q_V = 20.175$	$\pm 12\%$
$Q_H = 25.275$	$13.88 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
$Q_V = 20.400$	$\pm 7.5\%$

REFERENCES

1. S. Myers, LEP Note 188 (1979).
2. S. Myers, LEP Note 310 (1980).
3. S. Myers, LEP Note 327 (1981).
4. S. Myers, IEEE Trans. Nucl. Sci. NS-28, 2503 (1981).
5. S. Myers, CERN-ISR/RF/82-06 (1982).
6. S. Myers, LEP Note 373 (1982).
7. S. Myers, LEP Note 400 (1982).
8. S. Myers, Private Communication. In connection with the present study, S. Myers carried out a series of simulations with up to 300 particles and demonstrated that 50 particles was sufficient to describe the behaviour of the beam.
9. M. Bassetti, Proc. 11th Internat. Conf. on High Energy Accelerators, Geneva 7-11 July 1980, pp 650-655 (1980).
10. M. Donald, Private Communication.
11. J. M. Paterson, Proc. 11th Internat. Conf. on High Energy Accelerators, Geneva 7-11 July 1980, pp 7-15 (1980).
12. J. R. Rees, IEEE Trans. Nucl. Sci. NS-28, 1989 (1981).
13. A. W. Chao, P. Morton, P. Wilson, PEP-Note in preparation.
14. B. W. Montague, Proc. 11th Internat. Conf. on High Energy Accelerators, Geneva 7-11 July 1980, pp. 731-735 (1980).

LUMINOSITY AS A FUNCTION OF CURRENT

$\theta_V = 0.26$ M, $\theta_H = 4.27$ M. $Q_H = 21.280$, $Q_V = 18.190$

Fig. 1

LUMINOSITY AS A FUNCTION OF CURRENT
 $\theta_V = 0.11 \text{ M.}$ $\theta_H = 2.95 \text{ M.}$ $Q_H = 25.275.$ $Q_V = 20.175$

Fig. 2

BEAM BLOW-UP AS A FUNCTION OF CURRENT
 $\theta_V = 0.26 \text{ M}$, $\theta_H = 4.27 \text{ M}$, $Q_H = 21.280$, $Q_V = 18.190$

Fig. 3

BEAM BLOW-UP AS A FUNCTION OF CURRENT
 $\theta_V = 0.11 \text{ M}$, $\theta_H = 2.95 \text{ M}$, $\theta_H = 25.275$, $\theta_V = 20.175$

Fig. 4

Fig. 5

LUMINOSITY VERSUS VERTICAL TUNE

$\theta_V = 0.11 \text{ M}$, $\theta_H = 2.95 \text{ M}$, $Q_H = 25.275$

Fig. 6

TIME EVOLUTION OF LUMINOSITY $\theta_V = 0.11$ M, $\theta_H = 2.95$ M, $Q_H = 25.275$

Fig. 7

Fig. 8

LUMINOSITY VERSUS HORIZONTAL TUNE

$\theta_v = 0.11 \text{ M}$, $\theta_H = 2.95 \text{ M}$, $2 \times 20 \text{ mA}$

Fig. 9

LUMINOSITY AS A FUNCTION OF CURRENT

$\beta_V = 0.11 \text{ M}$, $\beta_H = 2.95 \text{ M}$, $Q_H = 25.275$

Fig. 10

LUMINOSITY WITH DIFFERENT θ_H

$$\theta_V = 0.11 \text{ M}, Q_H = 21.275$$

Fig. 11

LUMINOSITY AS A FUNCTION OF CURRENT

$$\theta_V = 0.11 \text{ M}, Q_V = 18.175, Q_H = 21.275$$

Fig. 12

Fig. 13

LUMINOSITY VERSUS BOTH TUNES

$\theta_V = 0.11$ M, $\theta_H = 2.95$ M, 2×20 mA

Fig. 14

LUMINOSITY VERSUS BOTH TUNES

$\beta_V = 0.11 \text{ M}$, $\beta_H = 2.95 \text{ M}$, $2 \times 20 \text{ mA}$

Fig. 15