Luminosity with more bunches in PEP

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Abstract

The near term accelerator physics program for PEP includes experiments in a collider mode with up to 9 bunches in each beam. In this memo, luminosity data from the 3x3 configuration is first used to calculate vertical beam size, emittance and tune shift as a function of current. The data is then used to extrapolate to the case with either 6x6 or 9x9 bunches colliding in PEP. Vertical emittance growth from the separated bunch optics and dispersion at the IP are included in the calculations. The conclusion is that given a 90mA current drive limitation in PEP, operating with 6x6 bunches yields the maximum luminosity.

JAN 10 1991

*Work supported by U.S. Department of Energy Contract No. DE-AC03-76SF00515

Introduction

Preparations for operating PEP in a collider mode with either 6x6 or 9x9 bunches are nearing completion^[1-6] and first experiments are expected to begin soon. The basic configuration consists of circulating 6 or 9 bunches in each counter-propagating beam with a single collision point in IR2. Six bunch operation is a subset of nine bunch operation utilizing the same beam separation scheme with every third bunch missing. In each case, the e⁻/e⁺ beams are vertically separated at the 2 parasitic crossing points between each IR with electrostatic plates already existing in PEP. The vertical orbit separation also generates vertical emittance, however, and residual vertical dispersion where the beams collide^[6].

The luminosity increase obtained by colliding more bunches comes only at the price of higher total currents. The trade-off between bunch number and total beam current is reminiscent of that encountered in B-factory design, where the main objectives are to remain below the beam-beam tune shift limit and below the single-bunch stability limit. But more total current puts more stress on the storage ring systems. Indeed, some of the factors limiting more bunches in PEP are RF drive^[3], multi-bunch instabilities^[4] and vacuum considerations^[5].

In this memo, luminosity data from PEP colliding in the 3x3 bunch mode is used to predict luminosity with either 6 or 9 bunches in each beam. The main difficulty arises from a difference in the natural vertical beam size between the 3x3 and 6x6 (9x9) bunch schemes^[6]. Beam-beam effects are incorporated into the 6x6 (9x9) luminosity estimates by extrapolating the vertical beam blow-up as a function of the vertical tune-shift parameter from the 3x3 mode of operation. It is found that since PEP is limited to total currents below 90mA^[2,3], the luminosity performance is optimized by colliding 6x6 bunches.

Beam Parameters for 3x3

In the nomenclature of Sands^[7], luminosity is given by

$$L = \frac{I_b^2}{4e^2 f A_{int}} \quad (1)$$

where

I_b = single beam current (Amp)

$e = 1.6 \times 10^{-19} \text{C}$

$f = 136.25 \text{kHz}$ (PEP)

$A_{int} = \frac{\pi}{4} \cdot B \cdot (2\sigma_x^* \cdot 2\sigma_y^*)$

$B = \# \text{ bunches/beam}$

At low intensity, the luminosity increases quadratically with current. In practice, for 3x3 bunches in PEP, beam-beam space charge forces cause the beams to blow up vertically above about 2.5mA/bunch, and the luminosity increase is only linear with current. Above

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5mA per bunch, the beams blow-up even more rapidly (vertical tune shift parameter saturates) and a second break point is encountered in the luminosity curve. This behavior is illustrated in Fig. 1[1] for the case of a good luminosity run with 3x3 bunches colliding at IR2.

The data in Fig. 1 can be broken down into roughly three regions. In the region A-B (0 to 16mA), we assume that the vertical emittance is constant so that ξ_y increases linearly with current and the luminosity increases with I^2 :

$$L_{3 \times 3} (x 10^{30} \text{cm}^{-2} \text{s}^{-1}) = 0.058 \cdot I_t^2 \quad 0 < I_t < 16 \text{mA}$$

I_t is the total current circulating in PEP. Assuming constant horizontal beam size of $\sigma_x^*(I_t) = 382 \mu\text{m}$ (synchrotron integral calculation, $\epsilon_x = 106 \pi \text{nm-rad}$, $\beta_x^* = 1.375 \text{m}$), we find $\sigma_y^* = 8.5 \mu\text{m}$ below 16mA. The vertical emittance due to x-y coupling and orbit errors is therefore about $1.3 \pi \text{nm-rad}$ (excluding beam-beam effects) for a β_y^* of 5.5cm. The same result can be obtained directly from a plot of vertical tune shift as a function of beam current at low intensities.

Above point B, the beams begin to blow up vertically and the luminosity follows the approximate scaling law:

$$L_{3 \times 3} (x 10^{30} \text{cm}^{-2} \text{s}^{-1}) = 1.87 \cdot I_t (\text{mA}) - 15 \quad 16 < I_t < 30 \text{mA}$$

The upper part of the luminosity curve, points C-D, can be fit with a linear scaling law

$$L_{3 \times 3} (x 10^{30} \text{cm}^{-2} \text{s}^{-1}) = 1.38 \cdot I_t (\text{mA}) \quad 30 < I_t < 42 \text{mA}$$

This current dependence slightly over-estimates the luminosity at high currents, but keeps the tune shift parameter constant in the range C-D. For $\sigma_x^* \gg \sigma_y^*$,

$$\xi_y = \frac{\beta_y^* N_{\text{bfc}}}{2\pi \sigma_y^* \sigma_x^*} = \frac{9.2 \cdot \beta_y^*}{E(\text{GeV})} \cdot \frac{L(I)}{I} = 0.05. \quad (2)$$

Technically, the vertical tune shift decreases somewhat at high currents. A hard luminosity limit is reached at $I_t = 42 \text{mA}$ when $\xi_x \rightarrow 0.05$ and the beams disrupt.

With the luminosity curve broken down into three discrete ranges, the vertical beam size, emittance, and tune shift parameter can be plotted as a function of current as shown in Figs. 2-4. The curves corresponding to the PEP luminosity data (Fig. 1) are labeled '3x3'. In each case, the horizontal beam size is assumed constant, $\sigma_x^*(I_t) = 382 \mu\text{m}$, the dispersion functions are zero at IR2, and $\beta_y^* = 5.5 \text{cm}$. A constant horizontal beam size over the full range of currents correlates well with observations in PEP. Although beams in collision tend to develop non-Gaussian tails[8], we stick to Eqn. 1 so that

$$\sigma_y^*(I_t) = \frac{I_t^2}{16\pi \sigma_x^* e^2 f_B \cdot L(I_t)} \quad (3)$$

$$\text{and} \quad \epsilon_y(I_t) = \frac{(\sigma_y^*(I_t))^2}{\beta_y^*} \quad (4)$$

The vertical tune shift parameter is given by Eqn. 2, and from $\xi_x = \text{const} \cdot \frac{N_b}{\epsilon_x}$, we find the

horizontal tune shift scales linearly with current. The increase in vertical emittance (beam size) with current is attributed to the beam-beam interaction.

Beam Parameters for 6x6 (9x9)

To complete the analysis, the increased natural beam size at the collision point (generated by the optics for bunch separation in the arcs) must be included. There are two primary differences with this optics, namely, vertical emittance growth from quantum emission in regions of vertical dispersion, and vertical dispersion at the collision point. At the design value for the beam separation distance,

$$\begin{aligned} \sigma_x^* &= 382 \mu\text{m} && \text{(same as 3x3 optics)} \\ \epsilon_y(\text{natural}) &= 3.35 \pi \text{nm-rad}^{[6]} && \text{(no x-y coupling or orbit errors)} \\ \epsilon_y(\text{total}) &= 3.35 + 1.3 = 4.65 \pi \text{nm-rad} && \text{(includes coupling)} \\ \eta_y &= 8 \text{mm}^{[6]} \\ \frac{\Delta p}{p} &= 0.09\% \\ \beta_y^* &= 5.5 \text{cm} \end{aligned}$$

$$\text{so} \quad \sigma_y^* = \sqrt{\epsilon_y \beta_y^* + (\eta_y \frac{\Delta p}{p})^2} = 17.6 \mu\text{m} \text{ at IR2.} \quad (3)$$

Since the natural beam size for the 6x6 (9x9) optics is larger than for the 3x3 optics, it is not possible to simply scale the luminosity directly by accounting for the number of bunches. Instead, we can use the 3x3 bunch luminosity data to plot the vertical beam size as a function of the vertical tune shift parameter. This will be the basis for scaling to the case where the 6x6 (9x9) beams have a larger natural spot size. Eliminating current as the independent variable in Figs. 2 and 4, the result is shown in Fig. 5. Physically, this plot gives us a measure of "spot size increase vs. current density" for σ_x^* fixed.

By normalizing $\sigma_y^*(\xi_y)$ to the low current value, $\sigma_y^*(\xi_y=0)$, the fractional beam blow-up as a function of tune shift parameter is found. In principle, if we assume that the magnetic properties of PEP are similar for higher amplitude betatron oscillations, then the normalized plot can be applied to beams with arbitrary vertical spot size providing the machine optics has the same β_x^* , β_y^* , and σ_x^* . Since the data leading to Fig. 5 is taken directly from PEP, the self consistency problem whereby spot size affects current density and current density affects spot size (via the beam-beam force) is inherently solved. Although the natural spot size of the 6x6 (9x9) beam ($\sigma_y^* = 17.6 \mu\text{m}$) is larger than the

natural spot size of the 3x3 beam ($\sigma_y^* = 8.5\mu\text{m}$), the fractional blow-up of the vertical beam size as a function of current density can be inferred from the plot.

From Fig. 5, we find the low current or 'natural' vertical beam dimension in the 3x3 configuration is about $8.5\mu\text{m}$. The beam-beam interaction does not lead to beam blow-up until the tune shift parameter reaches $\xi_y \sim 0.035$, and by the time ξ_y first reaches 0.05 the beam has blown up by a factor of 1.75. These values, of course, will vary on a given day of machine operation. For currents above the saturation level, the beam blows up rapidly until the horizontal tune shift hits $\xi_x \sim 0.05$ and the beams are lost.

For the 6x6 (9x9) bunch beams, Fig. 5 predicts that the beams will again begin to blow-up vertically at $\xi_y \sim 0.035$, and that for a given tune shift $\xi_{y0} < 0.05$, we have

$$\frac{\sigma_{y6x6}^*(\xi_{y0})}{\sigma_{y6x6}^*(\xi_y=0)} = \frac{\sigma_{y3x3}^*(\xi_{y0})}{\sigma_{y3x3}^*(\xi_y=0)} \quad (5)$$

A $\sigma_y^* = 17.6\mu\text{m}$ bunch, of course, contains about twice the total current of a $\sigma_y^* = 8.5\mu\text{m}$ bunch for equal σ_x^* and equal charge density

To complete the scaling for the 6x6 (9x9) collider, we simply read off the fractional increase in the vertical beam size as a function of vertical tune shift (Fig. 5), and then calculate the corresponding bunch current.

$$I_b = \frac{2\pi\gamma\sigma_y^*\sigma_x^*\xi_y}{\beta_y^*r_c} \cdot \frac{ec}{L} \quad (6)$$

where σ_y^* is found from Eqn. 5. Horizontal beam size is assumed constant at all current levels. This technique gives the parameter set $\{B, \sigma_y^*, \sigma_x^*, I_b\}$, and therefore luminosity.

Using this procedure, the projected beam size, vertical emittance and tune shift have been superimposed on Figs. 2-4 for the case with 6x6 or 9x9 bunches in PEP. In each case, the total beam current has been cut-off at the point where the horizontal tune shift reaches $\xi_x = 0.05$. Since the initial vertical beam size is almost a factor of two larger for the 6x6 (9x9) bunch case, ξ_y never reaches saturation before $\xi_x \rightarrow 0.05$.

The projected peak luminosity as a function of total current for 6x6 and 9x9 bunches is plotted in Fig. 6. Since PEP is theoretically current limited to $I_t < 90\text{mA}$ it appears that colliding 6x6 bunches at $\sim 82\text{mA}$ produces the optimum luminosity. At this current level, the vertical size of the 6x6 beam has increased by less than 10%, the vertical tune shift is $\xi_y \sim 0.041$, and the luminosity is $9.2 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$. The limiting factor is the horizontal tune shift, $\xi_x = 0.05$. If we had started with only the 'natural' emittance of $\epsilon_y(\text{natural}) = 7.35\pi\text{-nm-rad}$, the corresponding peak luminosity estimate would have been $1 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$. It will be interesting to compare the luminosity curves in Fig. 6 with numerical simulations of PEP^[9] which can include the long-range forces at the bunch crossings in the arcs.

Finally, it is worth stressing that the approach to the horizontal tune shift limit might cause a faster vertical blow-up of the beam than predicted here, so the luminosity estimates should be considered as an upper limit.

Conclusions

In this paper, a plot of the luminosity as a function of beam current with PEP colliding 3x3 bunches is first broken down into three regions: (1) luminosity scaling with I^2 (2) linear luminosity increase with current and (3) a high current region with saturated vertical tune shift. For a constant horizontal emittance and $\beta_y^* = 5.5\text{cm}$, the luminosity data is used to extract estimates for the vertical beam size, emittance, and tune shift parameter as a function of current.

The natural emittance for the 3x3 bunch data used here is $\epsilon_y \sim 1.3\pi\text{-nm-rad}$, and the beam-beam interaction does not generate appreciable emittance growth until $\xi_y = 0.035$. Both of these values will depend on machine conditions including orbit errors and residual dispersion at the interaction region.

Scaling the 3x3 data to the case with more bunches colliding is not straightforward because the 6x6 (9x9) beams have a larger natural emittance and have vertical dispersion at IR2. Since it is not possible to scale the luminosity directly, we have plotted the vertical beam size as a function of the vertical tune-shift (transverse current density), as derived from the 3x3 luminosity curve. Then, for a given value of vertical tune-shift, the corresponding fractional blow-up in the vertical beam size due to the beam-beam interaction is found and used to calculate the beam size in the 6x6 (9x9) collider. Finally, the tune shift and transverse beam dimensions are used to solve for the bunch current and luminosity. The effects of x-y coupling and the impact of the horizontal tune shift near $\xi_x = 0.05$ are unknown and could lead to further beam blow-up.

In conclusion, the scaling arguments applied in this paper indicate that colliding 6x6 bunches should lead to the highest luminosity in PEP given an upper limit on the beam current of $I_t < 90\text{mA}$. The peak luminosity of $6 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$ obtained with 42mA in the 3x3 mode should be possible with about 60mA in the 6x6 mode or 75mA with 9x9. If total beam currents of 90mA become possible, the projected luminosity for 6x6 bunches is about $9.0 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ at 82mA . Since the horizontal tune shift limits beam stability at $\xi_x = 0.05$, higher luminosities are not accessible unless the beta-functions are lowered at the collision point.

Additional benefits of colliding 6x6 as opposed to the full complement of 9x9 bunches include faster filling times, less load on the RF system, reduced load on the vacuum system and longer growth times for coupled bunch instabilities. At 85mA , the single bunch current

for 6x6 is well below the mode-coupling limit and near the threshold for turbulent bunch lengthening.

Acknowledgements

Thanks to Max Cornacchia, Martin Donald, Heinz-Dieter Nuhn and Jeff Tennyson for discussions on the processes of beam blow-up at high currents.

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List of Figures

1. PEP luminosity data colliding 3x3 bunches.
2. 3x3 vertical beam size extrapolated from luminosity data (Fig. 1) and projected beam size for 6x6 and 9x9 bunch operation.
3. Vertical emittance extrapolated from luminosity data (Fig. 1) and projected emittance for 6x6 and 9x9 bunch operation.
4. Vertical tune shift extrapolated from luminosity data (Fig. 1) and projected tune shift for 6x6 and 9x9 bunch operation.
5. Vertical emittance vs. tune shift extrapolated from luminosity data (Fig. 1).
6. Projected luminosity curves for 6x6 and 9x9 bunch operation.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

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01 / 18 / 91