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Doubling the PEP-II Luminosity in Simulations*

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Abstract

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Simulations show that luminosity of the PEP-II B-factory can be doubled from its present peak value of $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The particle simulation code BBI developed for studying beam-beam interaction was used to perform the simulations. It was first found that the parasitic collisions significantly degrade the simulated luminosity as the beam currents are increased from 3A and 1.7A to 4A and 2.2A in the low and high energy rings, respectively. The effect of changes in various accelerator parameters on luminosity was then studied in detail from a rough starting point based on analytic estimates and in the process we systematically optimized the luminosity and showed that a luminosity of over $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is achievable within feasible limits.

INTRODUCTION

The PEP-II asymmetric B-factory is an e+e- collider located at SLAC and has been in operation since 1999 delivering luminosity to the BaBar detector. The collider consists of two storage rings, namely the Low Energy Ring (LER) containing positrons at 3.1 GeV and the High Energy Ring (HER) containing electrons at 9 GeV. Luminosity is a representation of the performance of such colliders and PEP II has made steady progress over the years toward improving its luminosity. A peak luminosity of $1.09 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was reached recently and currently studies are underway for further improvement. This paper summarizes a systematic study conducted through simulations using the particle-in-cell code BBI [1],[2]. The code has been validated against various scenarios of measured luminosity including the current peak. Simulations results from BBI have been an important tool to determine the accelerator parameters for improving luminosity in the past.

For a given pair of number densities of ρ^+ and ρ^-, representing positrons and electrons respectively, luminosity may be expressed as follows,

$$L = n_b f_0 \int \rho^+(x,y,z;s)\rho^-(x,y,z';-s)dxdydzdz' \quad (1)$$

where n_b is the number of colliding bunches, $s = (z - z')/2$, f_0 is the revolution frequency.

Simulations become necessary to determine the charge densities, which tend to settle to an equilibrium after about two damping times. In the simulations, the beam distributions are evolved dynamically in a self consistent manner where the effects of the opposing beam are calculated for every turn. Parasitic interactions, which is an interaction between a bunch that has just undergone collision and a bunch of opposite charge heading toward the interaction point, becomes an important factor for higher bunch charge. The simulations take into account this phenomenon along with other single bunch effects.

In particle-in-cell simulations, care needs to be taken so that particles do not exit the computational grid. This is all the more important in this case because most particles that initially acquire high amplitudes later combine with the core of the beam due to radiation damping. In these simulations, the grid size was optimized so that the number of lost particles was a fraction of a percent. The computations were performed on a cluster of 32 processors with each processors evolving 10000 particles. Thus, there were 16000 computational particles representing each beam.

DETAILS OF THE SIMULATION RESULTS

Figure 1 shows the turn-by-turn evolution of luminosity for different current pairs. The number of turns corresponded to about twice the highest damping time in the ring. It is clear that the simulation was performed long enough to ensure that equilibrium in the beam distribution had reached.

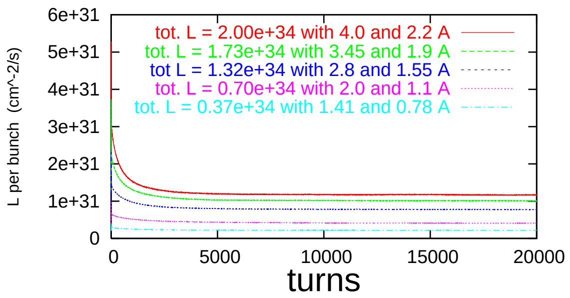

Figure 1: Turn-by-turn evolution of luminosity for different current pairs

Figure 2 shows the simulated luminosity for various pairs of currents with the highest one corresponding to the $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ case. The variation of luminosity is linear for lower currents which then begins to reach a saturation point showing that an indefinite increase in current will not produce increased luminosity. This is because of increased beam-beam interactions as well parasitic collisions caused by increased current.

The study of simulating the specified luminosity involved examining the effects of a number of accelerator parameters besides just increase in current. Care was taken

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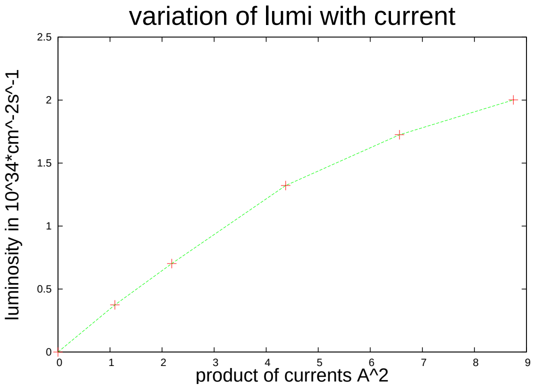

Figure 2: Variation of luminosity with product of currents

to ensure that all parameters were altered in the simulation within experimentally realizable limits. The starting point comprised of a set of parameters at interaction point that were based on an analytic estimate for doubling the current peak luminosity. However, since analytic estimates do not take into account all realistic effects, simulations showed that these parameters yielded a luminosity of only $1.55 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. Following this, a number of parameters were altered one at a time and the corresponding change in luminosity was examined. Different combinations of these changes were then used as a guide to find a final set of parameters leading to value twice the current peak luminosity.

Figure 3 shows the results for different sets of parameters. The horizontal line shows the luminosity of an initial set of parameters to which changes were made. Table 1 provides the details of the changes made. Wherever applicable, all values correspond to the location of the interaction point. Thus, in order to reach the desired luminosity in the simulation, we had to decrease the LER y emittance, decrease the LER horizontal tune, decrease the LER horizontal beta function as well as decrease the LER damping time. Decreasing the y emittance is in general beneficial to luminosity but can be realized only within experimental limits. Decreasing the horizontal tune results in moving closer to the half integer. This proves to be beneficial because it compensates for the tune spread resulting from beam-beam effects. Reducing the damping time, which can be realized through a wiggler causes the beam to settle to an equilibrium more rapidly.

A COMPARISON WITH PRESENT MACHINE CONDITIONS

Tables 2 and 3 show a comparison between the parameters that yielded the current peak luminosity of $1 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ and the simulated luminosity of $2 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ for the HER and the LER respectively. Reducing the beta function, especially the vertical beta function contributes to luminosity because of stronger focusing. However, a limit is reached after which the hour glass effect becomes more prominent. This effect is then mitigated by decreasing the bunch length.

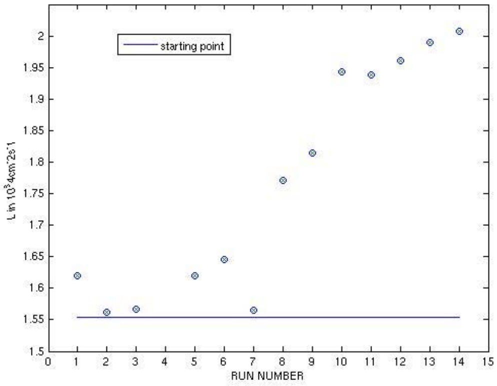

Figure 3: Luminosity obtained for different runs where the horizontal line represents the starting point.

	parameter changed	quantity of change
1	LER damping time	by -40 %
2	LER y emittance	1.2nm to 1nm
3	LER x emittance	36nm to 30nm
4	LER current	3520mA to 4A
5	LER beta x	20 to 30cm
6	LER x emittance further	to 25 nm
7	horizontal parasitic separation	by +10%
8	changes 1 + 5 + 7	.
9	8 + 4	.
10	9 + LER y tune	0.55 to 0.50
11	9 + HER x emittance	50 to 40 nm
12	11 + 3	.
13	1 + 4 + 5 + 6 + 7 + HER emitx	50 to 40 nm

Table 1: Table showing details of changes made in accelerator parameters that are illustrated in Fig 3.

Some of the changes indicated in the tables can be realized more easily while others require hardware upgrades. For example, changing the beta function, emittance and transverse tunes may achieved by altering the lattice. Changing the longitudinal tune and bunch length requires adding more RF stations, a hardware upgrade. Decreasing the damping time of the Low Energy Ring may be accomplished by turning on the already installed wiggler.

COMPUTATION OF FREQUENCY SPREAD

Figures 4 and 5 show the frequency spectrum of the motion of the centroid of the beam for the LER. This corresponds to the case of $2 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ luminosity. For the sake of brevity, we shall discuss only the LER and state that the spectra of the HER are very similar. The spectrum was evaluated for the final 1024 turns of the 2,000 turns computed. The single particle tunes for the LER are 0.5162

parameters	$L = 10^{34}$	$L = 2 \times 10^{34}$
$\beta_{x/y}$(beta)	35/1.08 cm	30/0.8 cm
$\epsilon_{x/y}$(emittance)	55/1.30 nm	40/1.8 nm
ν_x (x tune)	0.5160	0.5203
ν_y (y tune)	0.6223	0.6103
ν_s (s tune)	0.0490	0.04
σ_z (bunch length)	1.15 cm	0.9 cm
$\tau_{x,y/s}$ (damping time)	5030/2573	5030/2573
current	1.732A	2.2A

Table 2: IP parameters corresponding to the current measured peak luminosity and the simulated peak for the HER.

parameters	$L = 10^{34}$	$L = 2 \times 10^{34}$
$\beta_{x/y}$(beta)	40/1.08 cm	30/0.85 cm
$\epsilon_{x/y}$(emittance)	33/1.50 nm	30/1.20 nm
ν_x (x tune)	0.5250	0.5162
ν_y (y tune)	0.5790	0.5509
ν_s (s tune)	0.0320	0.04
σ_z (bunch length)	1.25 cm	0.95 cm
$\tau_{x,y/s}$ (damping time)	9800/4800	8424/4128
current	2.94A	4.0A

Table 3: IP parameters corresponding to the current measured peak luminosity and the simulated peak for the LER.

(horizontal) and 0.5509 (vertical), while for the HER, the tunes are 0.5203 (horizontal) and 0.6103 (vertical). The two peaks in fig 4 represent the so called pi and sigma modes. These modes represent the relative motion of the two beams. These modes are clearly visible in the x motion because the single particle tune of the two beams are very close to each other, which is not the case with the vertical motion motion tunes. The frequency spectrum spread represents the extent of the beam-beam force. It is important that this spread must remain confined within the operating regime of the machine in tune space.

SUMMARY

In this paper we have presented simulation results for the beam-beam interaction for the PEP II B-factory. The results of these simulations indicate that the current peak luminosity achieved in the machine can be doubled by making feasible machine parameter changes. A detailed process was employed in this study which showed how each parameter affected the change in luminosity. The study was based on an initial set of parameters that were determined through analytical results which predicted a doubling of the current peak measured luminosity. However, simulations showed that the analytical results overestimated the luminosity by about 30%. This could be attributed to the fact that analytic estimates neglect various phenomena that become significant at high currents. One example of this being parasitic interactions. Various changes were made to this initial set of parameters and the luminosity obtained from simulations was examined along with other output parameters such as beam sizes and dynamic beta functions. The changes were initially made one parameter at a time and this was followed by studying the effect of a combination of parameter changes. It was important to note that these changes did not add up when combined which is characteristic of any highly nonlinear system. This study will provide a guide in changing the machine parameters in the future for optimum luminosity delivered to the BaBar detector. The results also indicate that there is room for further optimization, which will be examined through continuing this study.

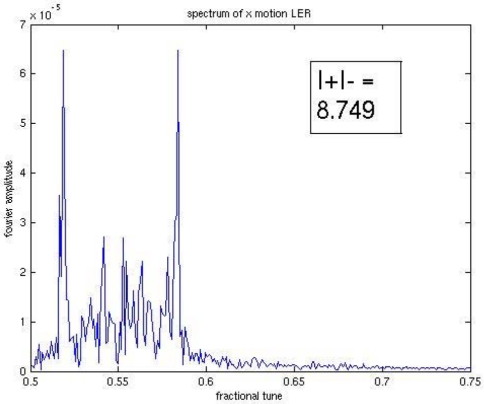

Figure 4: Frequency spectrum of the x motion for the LER.

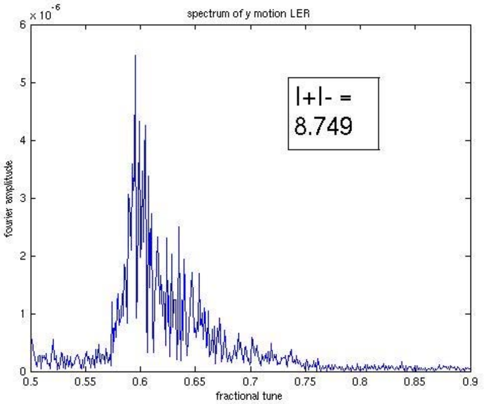

Figure 5: Frequency spectrum of the y motion for the LER.

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