BEAM-BEAM LIMIT, NUMBER OF IP'S AND ENERGY

Kazuhito Ohmi, KEK, Tsukuba, Ibaraki, Japan

Abstract

FCC-ee has been designed for factories of top (175 GeV), Higgs (120 GeV), W and Z (45 GeV). Number of IP is 4. CEPC has been designed for H with two IP. Limit of the beam-beam tune shift depends on the damping time. Number of IP affects the beam-beam performance, because the superperiodicity between is broken in real accelerators. We discuss beam-beam limit based on LEP experiences.

INTRODUCTION

Systematic study for energy/damping time and number of IP's are performed for LEP. LEP had been operated in several energy. The beam-beam tune shift limit is measured in each energy. The experiences should be helpful for FCC-ee design.

We study the beam-beam limit of LEP using simulations and compare the results with experimental results. LEP had operated with several energies. The number of IP is 4. Difference between LEP and FCC-ee is the fact that the bunch length (σ_z) is longer than vertical beta at IP (β_y^*). The effects of the difference will be discussed elsewhere.

Table 1 summarizes parameters of LEP. LEP had been operated at three stages with energy of 45.6, 60 and 100 GeV which are called LEP1, LEP1.5 and LEP2, respectively. The radiation damping time is faster for increasing the beam energy with cubic dependence. Luminosity and beam-beam tune shift limit increase for the energy increase.

SIMULATION RESULTS

We executed beam-beam simulation for LEP. Both of strong-strong and weak-strong simulations was performed using the code named BBSS [2, 3] and BBWS [3, 4]. Beam particles are tracked during 10 damping time under the beam-beam interaction. The number of macro-particles are 1,000,000 for the strong-strong and 65,536 for the weak-strong simulation. Though the bunch length is shorter than β_y, the bunch is sliced into 7 pieces. Because beam-beam induced head-tail instability is sometimes seen in the simulations.

Figure 1 shows the evolution of the luminosity for LEP2. The radiation damping time is 300 turns/IP. Equilibrium value is realized around 1-2 damping time Luminosity for several cases of bunch populations is plotted in the figure.

The beam-beam tune shift per IP is evaluated by the equilibrium luminosity per IP,

$$\xi_y = \frac{2r_e\beta_y L}{\gamma N_e f_0}. \quad (1)$$

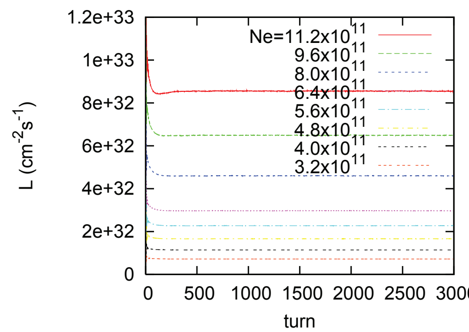

Figure 1: Evolution of luminosity for LEP2. The turn number is 4 times of actual turn number.

Figure 2 shows ξ_y per IP and vertical beam size evolution as function of the equilibrium bunch population. The vertical beam size evolutions are for (ν_x, ν_y)=(0.5775,0.0425)/IP. There are no remarkable signal related to luminosity degradation in x, σ_x. The beam-beam tune shift per IP is saturated at 0.12 for (ν_x, ν_y)=(0.5775,0.0425)/IP, while is not saturated over 0.18 at (0.51,0.57). The fractional tune operating point (0.5775,0.0425) is given by the tune in Table 1 divided by 4. LEP had been operated at the tune area (0.57,0.04) in every energy. CESR, KEKB, PEPII, BEPC-II had operated at the tune area (ν_x, ν_y)=(0.51,0.58). The electron positron colliders were successful by adopting the tune operating point.

At (ν_x, ν_y)=(0.5775,0.0425)/IP, beam-beam limit is seen ~ 0.12 at $N_e = 3 \times 10^{11}$. This value is very higher than experimental value 0.044 at $N_e = 1.2 \times 10^{11}$ in Table 1.

Figure 3 shows evolutions of $\langle y \rangle$ and $\langle yz \rangle$ at $N_e = 3 \times 10^{11}$. Coherent oscillation of π mode is seen in $\langle y \rangle$ motion (1st and 2nd pictures). $\langle yz \rangle$ (3rd) of two beams, which is related to head-tail motion, oscillate with an opposite phase.

Figure 4 shows the results for LEP15; beam-beam parameter (1st) as function of the bunch population and coherent motion in $\langle y \rangle$ (2nd) and $\langle yz \rangle$ (3rd).

Figure 5 show ξ_y as function of bunch population for LEP2 and LEP2.1. The tune shift is saturated at 0.3 for both cases. Coherent motion was not seen in LEP2 and 2.1. Fast radiation damping may suppress the coherent motion. Figure 6 shows evolution of the vertical beam sizes. Flip-flop of two beam sizes are reason of the beam-beam limit.

Weak-strong simulation is performed using LEP pa-

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Table 1: Parameter Table of LEP [1]

	LEP1	LEP15	LEP2	LEP2.1	unit
circumference	26658				m
number of IP	4				
energy	45.6	65	94.3	97.8	
bunch population	1.2	2	4	4	$\times 10^{11}$
emittance $\varepsilon_{x/y}$	19.3/0.23	24.3/0.16	21.5/0.31	21.1/0.215	nm
$\beta^*_{x/y}$	200/5	250/5	125/5	150/5	cm
damping time τ_y/IP	2888	1000	326	293	turns
natural bunch length	0.86	1.05	1.2	1.17	cm
natural energy spread	0.71	1.02	1.84	2.04	10^{-3}
horizontal tune	90.31	90.258	98.285	98.34	
vertical tune	76.17	76.166	96.155	96.18	
synchrotron tune	0.065	0.076	0.101	0.116	
luminosity	1.51	2.11	8.84	9.73	10^{31} cm^{-2}s^{-1}/IP
ξ_y per IP	0.044	0.051	0.073	0.0785	

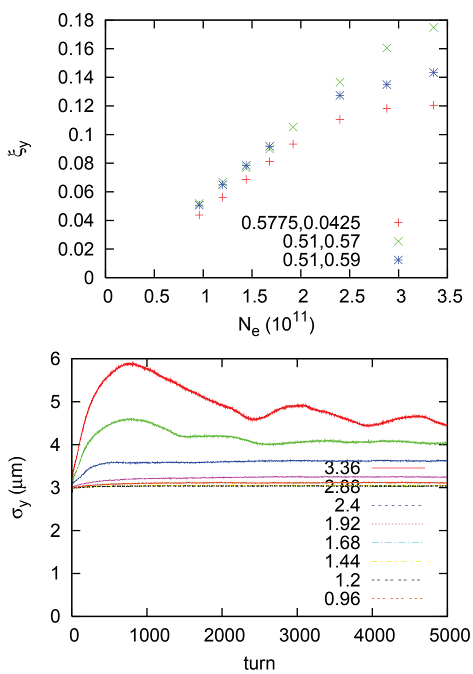

Figure 2: Beam-beam limit for LEP1. ξ in left picture is tune shift per IP. The vertical beam size for bunch populations for (0.5775,0.0425) are plotted in 2-nd picture.

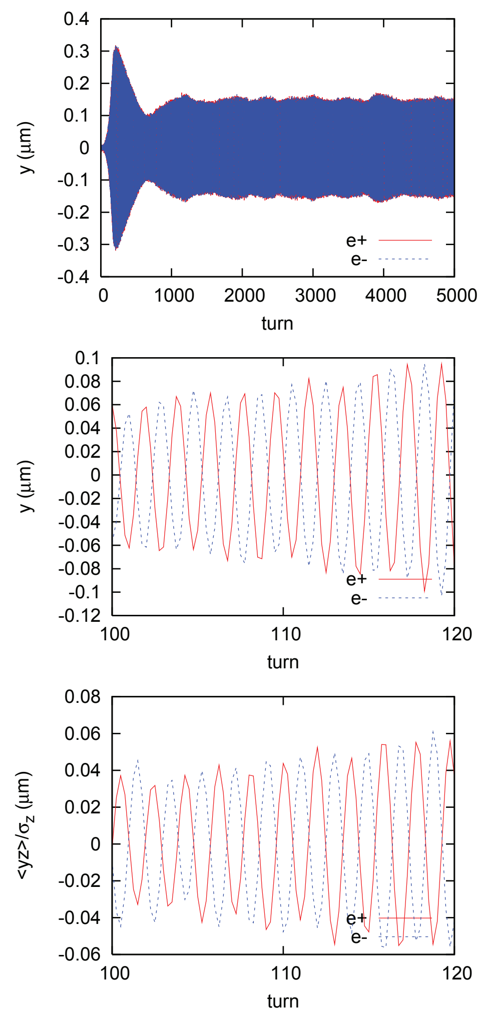

Figure 3: Coherent motion seen in LEP1 simulation at $N_e = 3 \times 10^{11}$. 1st and 2nd pictures show $\langle y \rangle$ motion. 3rd picture shows $\langle yz \rangle$ motion.

rameters. Coherent phenomena like coherent motion or flip/flop seen in the strong-strong simulation are basically suppressed in the weak-strong. Purely incoherent emittance growth due to nonlinear beam-beam resonances is seen. Figure 7 shows ξ_y and σ_y as function of bunch population. The tune shift limit per IP is 0.2, 0.3, 0.3 and 0.35 for LEP1-LEP2.1, respectively at tune (0.57,0.04)/IP area. There is no limit in this tune shift level for (0.51,0.57)/IP. The tune shift limit per IP exceed 0.5 for LEP2 and 2.1.

The tune shift limit is summarized in Figure 8 for the

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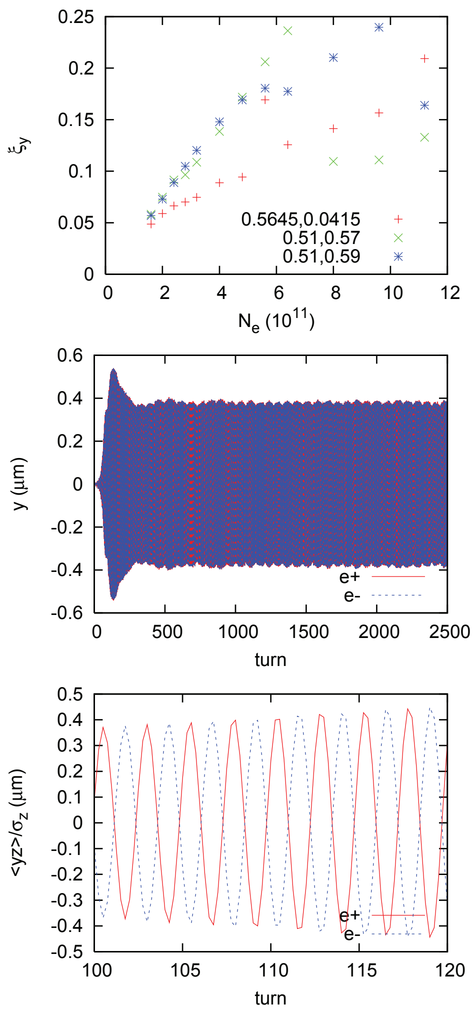

Figure 4: Beam-beam limit for LEP1.5.

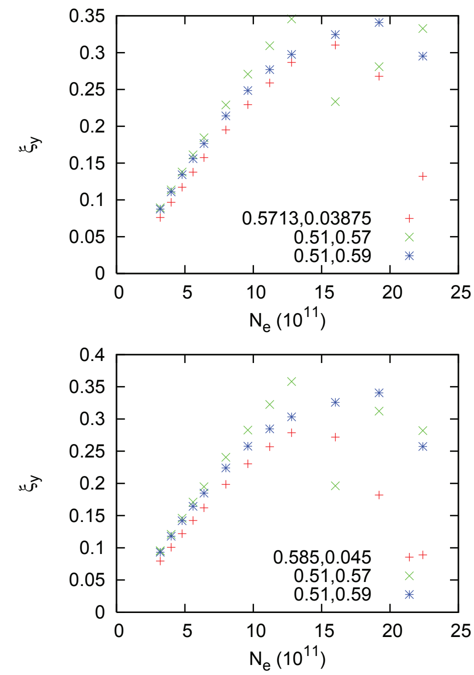

Figure 5: Beam-beam limit for LEP2 (1st) and LEP2.1 (2nd).

damping time. ξ_y in experiments are plotted in 1st picture. The line is a scaling formula $0.5\tau^{-0.4}$ [5]. The formula agrees with ξ_y of LEP, but deviates for those in other machines with lower energy. Simulation and experimental results are plotted in right picture. Simulations especially weak-strong give much higher ξ_y than experiments. Strong-strong simulations at $(\nu_x, \nu_y) = (0.57, 0.04)$/IP and experimental data for low energy colliders scales $1.6\tau^{-0.4}$.

NUMBER OF IP'S

When superperiodicity between IP's is perfect, the beam-beam system is equivalent to a single IP collider with circumference divided by the number of IP's.

When betatron phase advances between IP's are different, or β^*, x-y coupling and dispersion at IP are different IP by IP, the superperiodicity is broken. Such errors degrade luminosity performance.

We now assume the phase variation of IP-by-IP (1) $\Delta(\phi_{y,12}, \phi_{y,23}, \phi_{y,34})/2\pi = (0.01, 0.02, 0.01)$, where $\Delta\phi_{y,41} = -\sum_{i=1}^{3} \phi_{y,i,i+1}$. We also tried

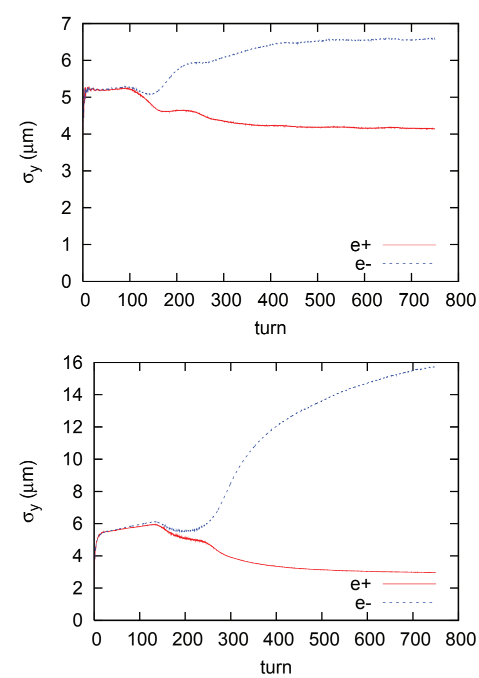

Figure 6: Beam size evolution at $N_e = 20 \times 10^{11}$ for LEP2(1st) and LEP2.1(2nd).

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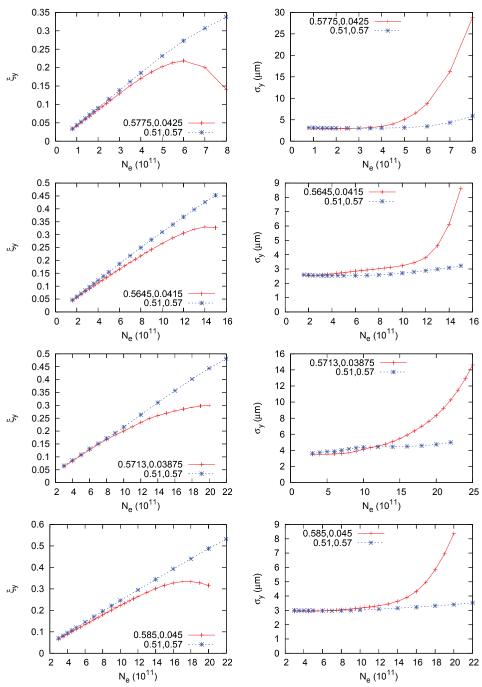

Figure 7: Beam-beam limit for LEP in weak-strong simulations. Tune shift per IP ξ_y is plotted in odd pictures and vertical beam size is ploeed even pictures. LEP1 1st-2nd, LEP1.5 3rd-4-th, LEP2 5-6-th, LEP2.5 7-8-th.

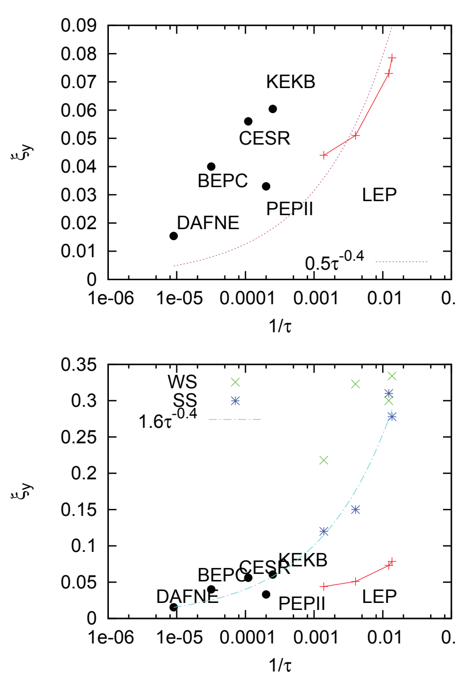

Figure 8: Beam-beam limit as function of vertical damping time. 1st picture depict tune shift in experiments. Simulation results are added in 2nd picture.

(2) (0.02,0.04,0.01)
(3) 0.04,-0.02,-0.01.

The third parameter is given by a measurement in LEP.

Strong-strong simulations are performed with taking into account the phase errors. Figure 9 shows beam-beam tune shift/IP as function of the bunch population for LEP2 containing the phase errors. Red line is no error as reference. Green and magenta lines are given for the phase errors for the cases (1) and (3), respectively. The limit values are 0.2 and 0.15 for the errors, respectively. Vertical beam size are plotted in 2nd picture as function of N_e. Coherent quadrupole motion is seen at the stage of the beam-beam limit. 3rd picture depicts evolution of σ_y of two beams at $N_e = 8 \times 10^{11}$.

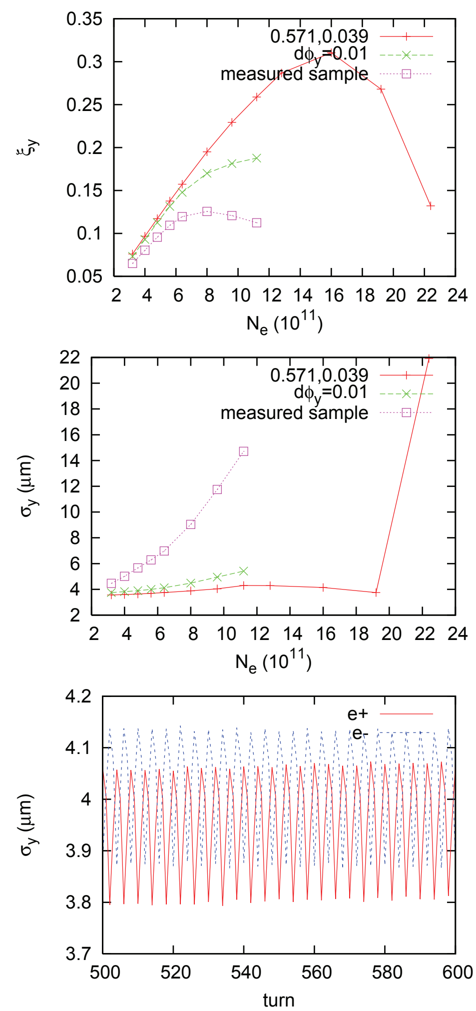

Figure 9: Beam-beam limit for LEP2 with vertical betatron phase errors. Tune shift beam size as function of the bunch population are seen in 1st and 2nd pictures, respectively. 3rd picture depicts coherent quadrupole motion onset of beam-beam instability.

The same simulations are performed using weak-strong simulation. Figure 10 shows ξ_y as function of the bunch population with phase error between IP's.

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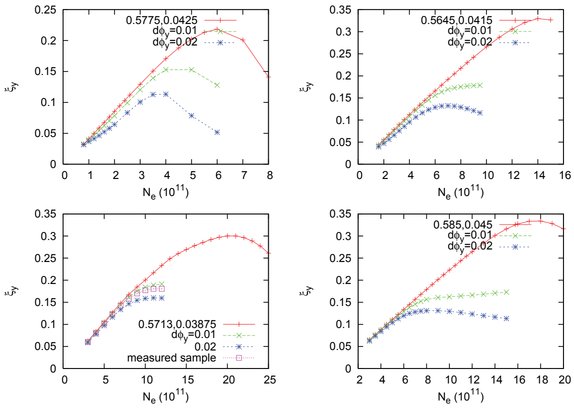

Figure 10: Beam-beam limit for LEP in weak-strong simulations. Tune shift of LEP1, LEP15, LEP2 and LEP2.1 are plotted in 1st, 2nd, 3rd and 4-th pictures.

x-y coupling and collision offset are different in IP-by-IP. We studied cases $r_2 = 0.0024, -0.0024, 0.0048, -0.0024$ and offset $\Delta y/\sigma_y = (0, 0.25, 0.5, -0.25)$ for each IP. Strong-strong simulation was performed with the errors in x-y coupling and collision offset for LEP2. Figure 11 shows ξ_y with x-y coupling and offset at IP's. Red is without error as reference. Green and blue lines are given for the errors of r_2 and Δy, respectively. No clear degradation for the reference is seen.

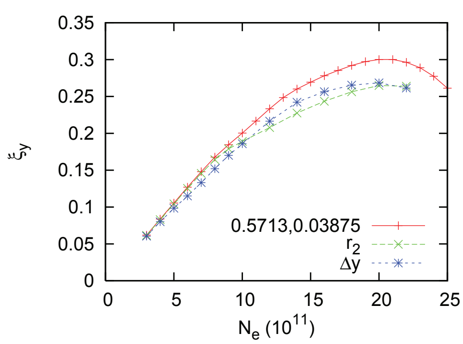

Figure 11: Beam-beam tune shift per IP as function of bunch population with errors in x-y coupling and offset.

SUMMARY

Beam-beam limit in LEP is studied using strong-strong and weak-strong simulations. Equilibrium luminosity is calculated for various currents and energies. Tune shift is calculated by equilibrium luminosity for each current and energy in simulations. Tune shift limits in strong-strong simulations are smaller than those of weak-strong simulations. Coherent instability appears in LEP operating point (0.57,0.04)/IP for LEP1 and 1.5 in the strong-strong simulations. Flip-flop of the beam sizes appears in LEP2 and 2.1.

The tune shift limit is compared with experimental results. Maximum tune shift is much higher than measured ones. The tune shift per IP measured in LEP is satisfied a scaling for the damping time per IP in unit of turn $0.5\tau^{-0.4}$. The tune shift of KEKB, CESR, BEPC is higher than the scaling. Tune shifts of the strong-strong simulation and the three colliders scale as $1.6\tau^{-0.4}$.

Superperiodicity is broken when betatron phase, IP optics parameters and collision offset are different in IP-by-IP. Luminosity degradation due to the errors. The betatron phase errors $\sim 0.02 \times 2\pi$ affect luminosity performance. x-y coupling ($r_2 \sim 0.0024$) and collision offset ($0.25 - 0.5\sigma_y$) IP-by-IP do not affect clearly.

Difference between LEP and FCC-ee is the fact that the bunch length (σ_z) is longer than vertical beta at IP (β_y^*). The same study should be performed using FCC parameter.

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