SIMULATION STUDY FOR LUMINOSITY REDUCTION IN KEKB

K. Ohmi, KEK, Tsukuba, Japan

Abstract

In commissioning of an $e^+ - e^-$ collider, a great deal of effort is put to search and to remove origin of the luminosity reduction. We have studied luminosity reduction mechanisms using computer simulations to help the jobs. We consider collision among an electron bunch and a positron bunch; that is, do not consider any multi-bunch effects. One turn map of beam particles consists of the beam-beam interaction and a transfer map by lattice. We first focus a linear map of lattice at the collision point. These effects are estimated by a strong-strong simulation.

1 INTRODUCTION

Luminosity in e^+e^- colliders is determined by steady distributions of two beams (ρ^+ and ρ^-) at a collision point as follows,

$$L = \int_0^c ds\delta_P(s' - (z - z')/2)dzdz' \int dxdy\rho^+(x, y, z, s')\rho^-(x, y, z', -s'), \quad (1)$$

where s which is used as the time like variable is a longitudinal coordinate along the positron beam orbit and c is the speed of light. $\delta_P(s) = \Sigma_{-\infty}^{\infty}\delta(s - nL)$, where L is the circumference of the ring. Here we assumed the both rings have the same circumference.

$\rho^\pm(x, y, z, s)$ is distribution function of the colliding $e^\pm$ beam. We have to understand the motion of each beam particle to evaluate the beam distributions at the collision point. The distribution does not depend on an initial condition due to the synchrotron radiation damping and quantum fluctuation. At a low particle density, the distribution is Gaussian in 6 dimensional phase space whose deviations are determined by emittance and Twiss parameters. As increasing bunch current, beam-beam interactions become important, beam blow up and coherent motion occur, and luminosity is reduced from the geometrical value.

Electrons or positrons in the beam moves be feeling various actions in an accelerator. The following actions are essential for studying the collision of two bunches.

- Lattice
- Synchrotron radiation
- Beam-beam interaction

In these actions only the lattice is controllable for us. We focus a map of lattice at collision point. The map includes information of closed orbit, tunes, linear optics functions (β,r, η, ζ[2]) and nonlinear parameters (chromaticity...) at the collision point. The map at the collision point determines the complex feature of the beam-beam effect. Closed orbit, optics functions at except for the collision point affect to the beam-beam effect only through emittances.

We present effects of the luminosity reduction caused by following sources.

- Error of closed Orbit
- Error of linear map
- Chromatic deformation of the linear map

We use a strong-strong simulation code to calculate the beam-beam force [4]. There is no assumption for both of the beam distributions. The distributions of beams may vary dynamically due to collision each other. They may be different from Gaussian distribution. The strong-strong simulation equips a 2-D poisson solver for an arbitrary charge distribution of beam. The effective coulomb potentials due to both beams are solved in every turn, and beam particles are kicked by the potential.

We discuss the beam-beam problem based on an analysis for KEKB. KEKB is an asymmetric multi-bunch e^+e^- collider. KEKB consists of two storage ring, HER and LER, which accumulate e^- at 8GeV and e^+ at 3.5GeV, respectively. Table 1 shows the design parameters of KEKB which is important for the beam-beam effect. β_x is relaxed to 1m from the design value of 0.33m.

Table 1: Basic parameters of KEKB

	HER	LER
Particle	e^-	e^+
E	$8GeV$	$3.5GeV$
I	$1.1A$	$2.6A$
$n_{e,p}$/bunch	1.4×10^{10}	3.3×10^{10}
N_{bunch}	~ 5000	
C	$3016m$	
β_x^*	$1m$	
β_y^*	$0.01m$	
ε_u	1.8×10^{-8}	
ε_v	3.6×10^{-10}	
ξ	~ 0.05	
ν_x/ν_y	$0.53/0.11$	
$T_0/\tau_{x,y,z}$	$2.5/2.5/5.0 \times 10^{-4}$	
θ_c	$2 \times 11mrad$	

2 ERROR OF CLOSED ORBIT

We first discuss error of the closed orbit $\boldsymbol{x}_0^\pm = (x, p_x, y, p_y, z, p_z)_0^\pm$ at the collision point. $x_0^\pm$ and $y_0^\pm$ are transverse orbit offset. Though $z_0^\pm$ is deviation of collision timing, we observe it as an error of β function discussed later. $p_{x,0}^\pm$ and $p_{y,0}^\pm$ means a crossing collision. In our case, since beams collide with a finite horizontal crossing angle $\theta_c = 22$mrad, small error of $p_x \ll \theta_c$ is negligible. We take no notice of $p_{z,0}^\pm$. We here investigate the effects of vertical offset and vertical crossing

2.1 Orbit offset

In the case of flat beam, tuning of vertical offset is more difficult than that of horizontal. We here present effects of only vertical offset. When two beams collide with an offset, the geometrical luminosity is reduced as follows, without effects of crossing angle and hour glass.

$$L \propto \exp(\Delta y^2/4\sigma_y^2) \tag{2}$$

Actually beam blow-up occurs and the luminosity reduced more. Fig.1 shows the beam size, geometrical and simulated luminosity. The geometrical luminosity includes the effects of crossing angle and hour glass. The figure and Eq.(2) show that the geometrical luminosity is reduce to be 77% for the offset of σ_y. The figure shows dynamical luminosity reduction due to beam-beam blow-up. The beam blow-up occurs both beam and the luminosity is reduced to be 55%.

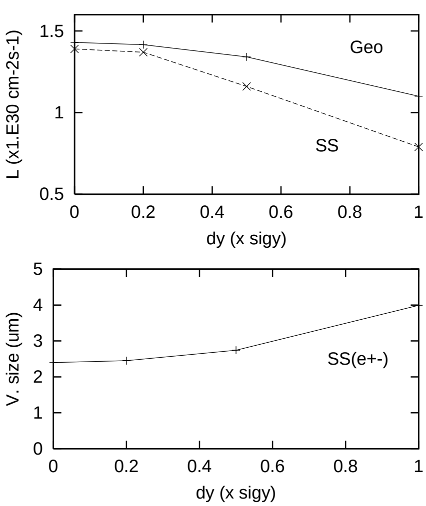

Figure 1: Luminosity reduction due to vertical offset.

2.2 Vertical crossing angle

The aspect ratio of vertical size for the bunch length is $\sigma_y/\sigma_z = 5 \times 10^{-4}$. Vertical crossing angle of the order of 0.5mrad affects the luminosity geometrically. Figure 2 shows the luminosity reduction due to the vertical crossing angle. Dynamical reduction is not so strong.

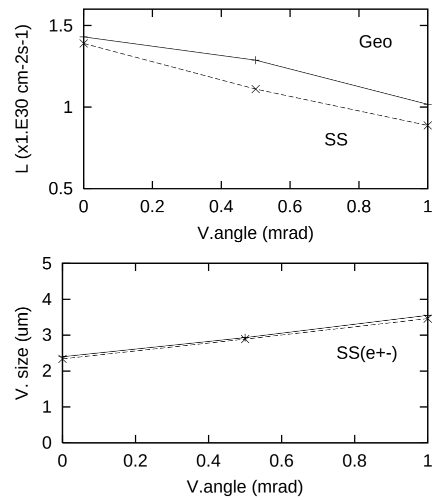

Figure 2: Luminosity reduction due to vertical crossing angle.

3 ERROR OF LINEAR MAP

We next consider error of the linear map at the collision point. The transformation is expressed by 6×6 matrix M,

$$\boldsymbol{x}(s + C) = M\boldsymbol{x}(s), \tag{3}$$

M is 6 dimensional symplectic matrix, which has 21 independent parameters. M is factorized using a block diagonalize matrix U and a matrix V written by Twiss-dispersion functions,

$$M = VUV^{-1} \tag{4}$$

$$U = \begin{pmatrix} U_X & 0 & 0 \\ 0 & U_Y & 0 \\ 0 & 0 & U_Z \end{pmatrix} \tag{5}$$

$$U_i = \begin{pmatrix} \cos\mu_i & \sin\mu_i \\ -\sin\mu_i & \cos\mu_i \end{pmatrix} \tag{6}$$

$$\mu_i = 2\pi\nu_i \qquad \nu_{X,Y,Z} : \text{Tune} \tag{7}$$

They are 3 tunes ($\nu_{x,y,z}$) and 18 Twiss-dispersion parameters. The factorization of parameters is written in Ref.[2]. Tune dependence has already been studied using weak-strong simulation [1], and is being studied using the strong-strong simulation[5]. We here discuss the luminosity reduction due to error of Twiss-dispersion parameters at the collision point.

The beam size at low particle density is expressed by emittance and Twiss-dispersion functions at the collision point. The emittance is determined by the global characteristics of the lattice, while Twiss-dispersion functions is local parameters at the collision point. The beam size $\Sigma_{ij} = \langle x_i x_j \rangle$ is expressed by

$$\Sigma = V\Sigma_n V^t. \tag{8}$$

where Σ_n is a diagonal 6×6 matrix represented by emittances,

$$\Sigma_n = diag[\varepsilon_X, \varepsilon_X, \varepsilon_Y, \varepsilon_Y, \varepsilon_Z, \varepsilon_Z]. \tag{9}$$

The transverse beam size is expressed by $\langle xx \rangle = \beta^*_x \varepsilon_x$ and $\langle yy \rangle = \beta^*_y \varepsilon_y$, if there is no waist error, no x-y coupling and no dispersion function at the collision point. V is a diagonal matrix in this case,

$$V = diag\left[\sqrt{\beta^*_x}, 1/\sqrt{\beta^*_x}, \sqrt{\beta^*_y}, 1/\sqrt{\beta^*_y}, \sqrt{\beta^*_z}, 1/\sqrt{\beta^*_z}\right]. \tag{10}$$

Error of V enlarges the beam size at the collision point and reduces the luminosity. We call this as geometrical effect.

The Twiss-dispersion functions affect the luminosity dynamically. For example, a relaxation of focused β enlarge the beam-beam tune shift. X-Y coupling causes a coupling of the beam-beam tune shift. The luminosity and vertical beam size were evaluated by the strong-strong simulation for the Twiss-dispersion error. Figures 3, 4 and 5 show the luminosity and beam size blow-up due to the waist error, vertical dispersion error, x-y coupling, respectively.

Figure 3 is result for waist error. The beam blow up is much larger than geometrical one. In Figure 4, the dynamical effect of the vertical dispersion function can not be also neglected, though it is smaller than the case of waist error. In Figure 5, we make 9 model lattices (1 st – 9 th trial) with $\varepsilon_y = 0.02\varepsilon_x$ using random error of skew quadrupoles [3], and performed the simulation. The 0-th trial is for no x-y coupling. Simulation results by a weak-strong method is overwritten in the figure.

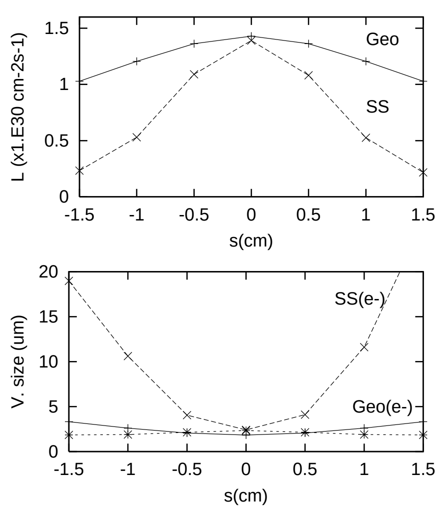

Figure 3: Luminosity reduction due to waist error.

4 SUMMARY

We performed simulations for beam-beam interactions to study the luminosity reduction. A strong-strong simulation[4] is used for the evaluation of the luminosity and beam size. We knew various sources which cause the luminosity reduction. To recover them, we have to tune up the parameters patiently. If we can measure or guess the Twiss-dispersion functions at the collision point, it will be helpful for the luminosity tuning[6].

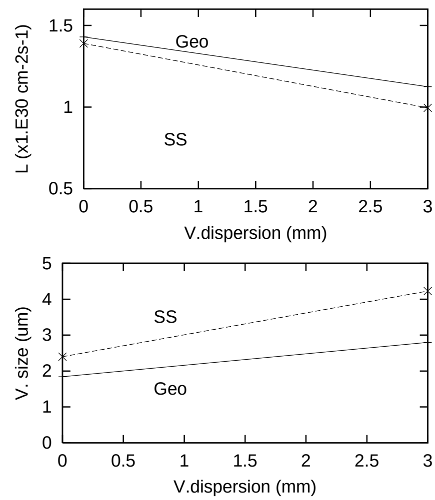

Figure 4: Luminosity reduction due to vertical dispersion function at the collision point.

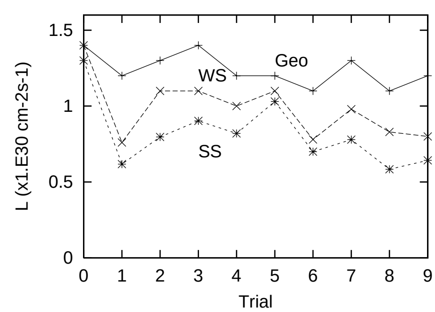

Figure 5: Luminosity reduction due to x-y coupling at the collision point.

The author thanks members of KEKB commisioning team.

5 REFERENCES

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