BEAM-BEAM SIMULATIONS FOR KEKB AND SUPER-B FACTORIES

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Abstract

Recent progress of KEKB and nano beam scheme adopted in KEKB upgrade are discussed. For the present KEKB, chromatic x-y coupling, which was the key parameter to improve luminosity, is focussed. Beam-beam simulations with weak-strong and strong-strong models for nano beam scheme are presented. A weak-strong simulation was done in the presencee of the longitudinal microwave instability. Finally status of beam simulations in KEK supercomputers is presented.

INTRODUCTION

Crab cavity has been installed into KEKB to boostup the luminosity performance. Basically the crab cavity should give us potential to increase the beam-beam parameter more than 0.1. Actually various errors disturb to achieve the high beam-beam performace. For example linear x-y coupling at IP induces an emittance growth with couple to the beam-beam nonlinear interaction. Fast turn by turn fluctuation of the beam position also inducd an emittance growth with couple to the interaction. To achieve the high beam-beam parameter, errors should be removed as possible as we could. Tuning of colliders is just the work to remove errors. Tolerance for errors are estimated in simulations, but it is hard to know how much errors exist, how to correct the errors and how the errors were corrected in an accelerator.

Recently KEKB achieved the new luminosity record. The luminosity record increases 20%, from 1.76 to 2.1×10^{34} cm^{-2}s^{-1} in June 2009. It is twice of the design luminosity, 1×10^{34} cm^{-2}s^{-1}. Tuning of chromatic x-y coupling improved the luminosity remakably.

For KEKB upgrade, we turn to the strategy to boost-up the luminosity. Higher beam-beam parameter is hard to achieve against various errors. Increasing currnt is also problem for the operation cost. Nano-beam scheme, in which low emittance and low beta beams collide with a large crossing angle, is alternative way.

We discuss simulations of the crab crossing of the present KEKB and nano-beam scheme of the KEKB upgrade in Sec II and III, respectvely. In Sec. IV, the computer environment of KEK is reviewed.

RECENT PROGRESS OF KEKB

Chromatic x-y coupling

The existence of the chromatic x-y coupling was known by a measurement of the synchro-beta sideband in the beam size on the x-y tune space [1]. Simulations including the chromatic coupling has been performed using a symplectic integration method of the chromaticity [2]. Hamiltonian which expresses generalized chromaticity is given by

$$H_I(x,\bar{p}_x,y,\bar{p}_y,\bar{\delta}) \quad (1)$$
$$= \sum_{n=1}(a_n x^2 + 2b_n x\bar{p}_x + c_n\bar{p}_x^2 + 2d_n xy + 2e_n x\bar{p}_y$$
$$+2f_n y\bar{p}_x + 2g_n\bar{p}_x\bar{p}_y + u_n y^2 + 2v_n y\bar{p}_y + w_n\bar{p}_y^2)\bar{\delta}^n/2.$$

The coefficients $10 \times n$ are related to n-th order chromaticity of 10 Twiss parameters, $\alpha_{x,y}, \beta_{x,y}, \nu_{x,y}$ and $r_i, i = 1, 4$. Transfer map using H as a generating function guarantees the 6D symplectic condition.

Alternative way is the direct map for the betatron variables $\boldsymbol{x} = (x, p_x, y, p_y)^t$ and z as

$$\boldsymbol{x}(s+L) = M_4(\delta)\boldsymbol{x}(s). \quad (2)$$

$$z(s+L) = z(s) + \boldsymbol{x}^t M_4^t(\delta) S_4 \partial_\delta M_4(\delta)\boldsymbol{x}/2 \quad (3)$$

where $M_4(\delta)$, which is the revolution matrix at the interaction point, which contains 10 Twiss parameters and their chromaticity. The transformation for z guarantees the 6-D symplectic condition.

Twiss parameters at the interaction point is measured by turn by turn position monitors located at the both side of the interaction point [3, 4]. Their chromaticity is given by scanning RF frequcncy in the range of $\pm 200 \sim 300$ Hz.

Figure 1 shows the measured x-y coupling parameters as functions the momentum deviation. The parameters are fitted by polynomial of the momentum deviation, as follows,

$$\begin{aligned}
r_1(\delta(\%)) &= 0.00848 - 0.00435\delta + 0.00909\delta^2 + 0.151\delta^3 \\
r_2(\delta(\%)) &= 0.0137 + 0.00696\delta + 0.0222\delta^2 - 0.320\delta^3 \\
r_3(\delta(\%)) &= 0.189 - 0.304\delta + 2.45\delta^2 - 1.24\delta^3 \\
r_4(\delta(\%)) &= 0.0277 - 0.942\delta + -0.512\delta^2 - 0.301\delta^3
\end{aligned} \quad (4)$$

The coefficients, which are chromaticity, varies run by run, and differ from prediction of the optics design code like SAD. Therefore the accelerator model based on the measured chromaticity is important.

Using these transformation, synchro-beta resonances and their effects on the beam-beam interaction have been

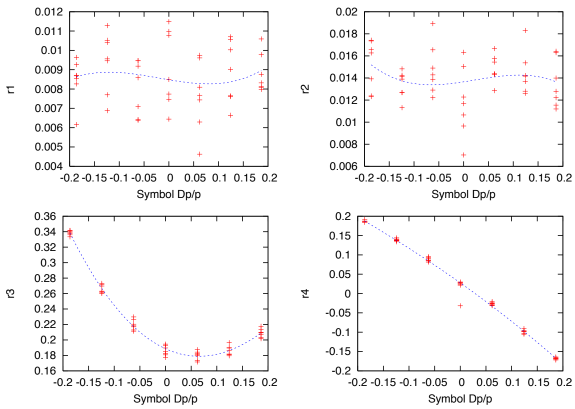

Figure 1: Measurement of the chromaticity for x-y coupling in KEKB-LER.

studied [5]. The transformation is implimented into both of the weak-strong (BBWS) and strong-strong (BBSS) codes for beam-beam interaction. Figure 2 shows the luminosity as a function of the chromaticity given by the weak-strong simulation. The chromaticity for r_4, $dr_4/d\delta$, can affect the luminosity: the luminosity degradation is 10-15 % for $dr_4/d\delta \sim 200$. Skew sextupole magnets are installed to correct the chromaticity. Luminosity increases 20% due to the chromaticity tuning as shown in Figure 3.

KEKB UPGRADE - NANO BEAM SCHEME

KEKB upgrade is progressing the design with the nano-beam scheme. In the nano-beam scheme, low emittance and low beta beams collide with a large crossing angle. Parameters as candidates of KEKB upgrade are summerized in Table 1.

Crab waist technique to fit the waist of the beam to the axis of colliding beam is taken into account in KEKB upgrade [6].

The ratio of the horizontal projection of the bunchlength and horizontal size, $\phi\sigma_z/\sigma_x$, which is called Piwinski angle, indicates the overlap area of two beam at collision. In the low emittance approach, the large retio $\phi\sigma_z/\sigma_x \approx 20$ means a large number of slice in the simulation.

Weak-strong simulation

Weak-strong simulation is convenient to survey feasibility of the design. Macro-particles, which represents weak beam, collide with a fixed chrage distribution as the strong beam. The strong beam is a fixed tri-Gaussian distribution for x, y, z with the size $\sigma_{x,y,z}$. The strong beam is sliced along z. The number of slices are 200. Since the overlap area is $\Delta z = \sigma_x/\phi \sim 20 \times \sigma_z$, the area, which mostly contribute the lluminosity, is sliced into 10 pieces in the average. Hourglass effect in the area is serious when the beta fuction is smaller than the overlap area, $\beta_y < \sigma_x/\phi$. The luminosity obtain by the weak-strong simulation is filled in

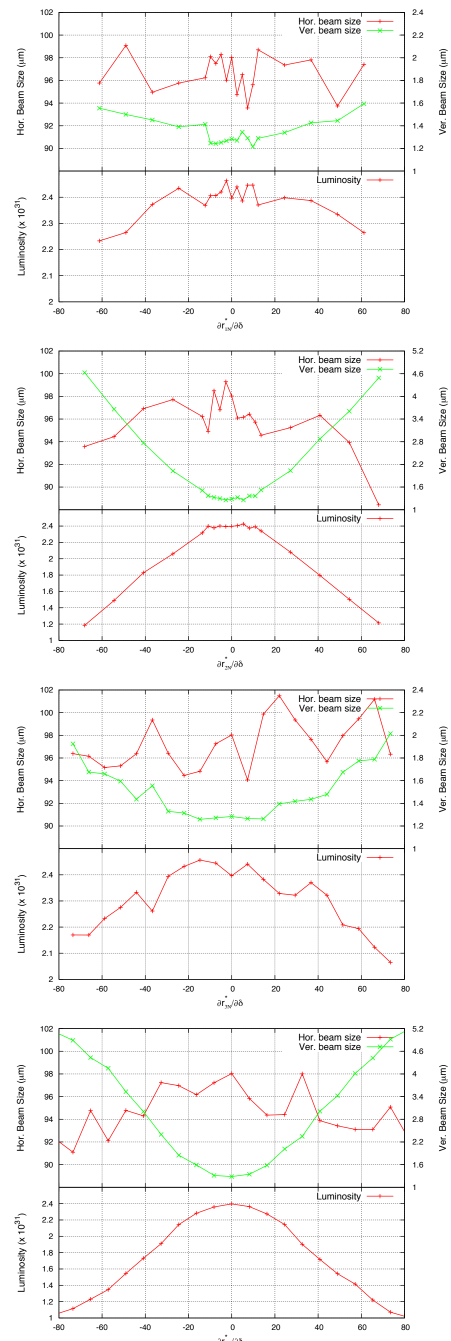

Figure 2: Simulated luminosity for the chromatic x-y coupling.

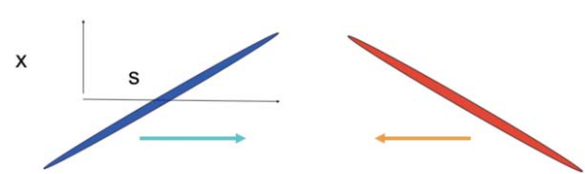

Figure 4: Schematic view of the low emittance approach for KEKB upgrade.

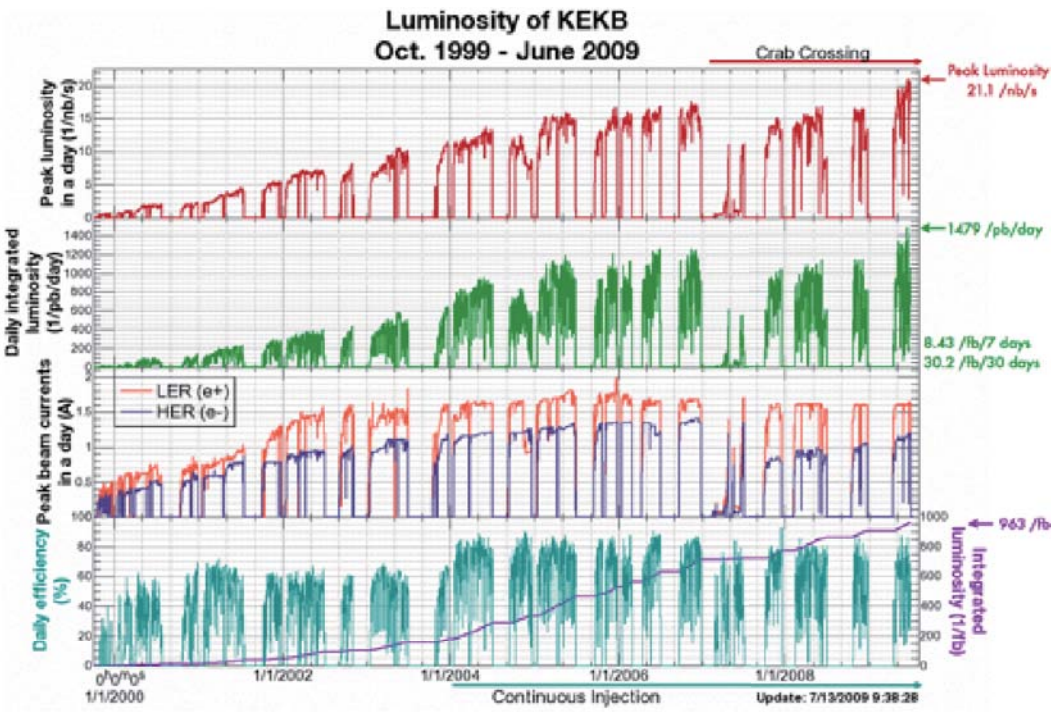

Figure 3: Luminosity trend of KEKB.

Table 1: Parameters for KEKB upgrade and Frascati Super B factories.

variable	HighCurrent	NanoBeam-1	NanoBeam-2	Frascati
E_p/E_e (GeV)	3.5/8	3.5/8	3.5/8	4/7
ε_x (nm)(L/H)	24/18	2.8/2.0	2.8/2.0	2.8/1.6
ε_y (pm)	240/90	33.6/10.7	20.7/36.0	7/4
β_x (mm)	200/200	44/25	17.8/25	35/20
β_y (μm)	3/6	0.21/0.37	0.26/0.26	0.22/0.39
σ_x (μm)	69/60	11/7.07	7.06/7.07	9.9/5.66
σ_y (μm)	0.85/0.73	0.084/0.063	0.073/0.097	0.039/0.039
σ_z (μm)	5/3	5/5	5/5	5/5
ϕ (mrad)	0	30	30	24
$\phi\sigma_z/\sigma_x$	0	14/21	21/21	14/25
σ_x/ϕ (μm)	-	0.37/0.24	0.24/0.24	0.35/0.20
N_p/N_e (10^{11})	12/5.25	10.7/6.17	10.7/6.17	0.55/0.55
N_{bunch}/Cir(m)	5000/3016	2230/3016	2252/3016	1251/1800
ξ_y	0.3/0.5	0.081/0.081	0.079/0.079	0.147/0.150
L (cm^{-2}s^{-1})	5.3×10^{35}	$8(2.9) \times 10^{35}$	$8(8.5) \times 10^{35}$	$(11) \times 10^{35}$

table 1, where bracket and non bracket is those with and without the crab waist. In NanoBeam-1, luminosity without crab waist degrade 1/3 of that with crab waist, while no big difference for NanoBeam-2. Essential point whether such difference arises or not is the overlap area σ_x/ϕ is larger than β_y or not: that is, the hourglass effect is strong or not. If hourglass effect becomes serious ($\sigma_x/\phi > \beta_y$), luminosity degrades without crab waist. In $\sigma_x/\phi < \beta_y$, luminosity without crab waist does not degrade. Figure 5 shows luminosity and beam-beam parameter as a function of current in this condition. The gain of the crab waist is not remarkable for $\sigma_x/\phi < \beta_y$ in this current range. The gain is higher at higher current, and at further large current, corresponds to the beam-beam parameter > 0.1, the gain of the crab waist is remarkable even $\sigma_x/\phi < \beta_y$. Figure 6 shows luminosity in transverse tune space. Clear synchro-beta resonance line $2\nu_x + \nu_s$ = integer is seen in the both case of crab waist on and off.

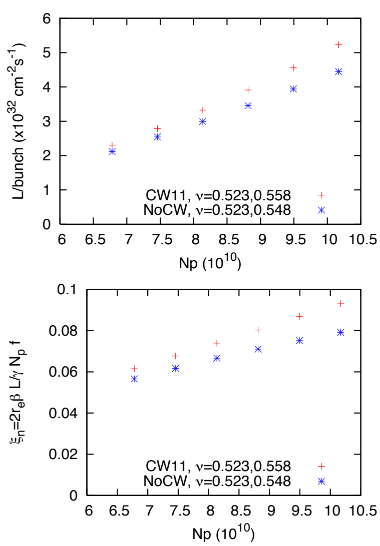

Figure 5: Luminosity and beam-beam parameter for NanoBeam-2 as function of the beam current.

Strong-strong simulation

For strong-strong simulation, both beams are represented by macro-particles. Both beams are sliced into many pieces, and collide slice by slice with solving Poisson equation during the interaction. Poisson equation has to be solved many times, square of the number of slice. Since the number of slice is 100-200, Poisson equation is solved 10^4 times per collision. The radiation damping time is 4000 turns for KEKB, therefore the collision has to be repreated 10^4 times, with the result that the total number is $10^8 - 10^9$ times. Note that the potential is calculated for two beams, and twice per slice to interplate potential along z [7]. KEK super computer HITACHI SR11000 computes one Potential solution in 10 ms. Simulation of the present KEKB in which Poisson equation is solve $10^2 \times 10^4$ turn=10^6 times, takes a few hours.

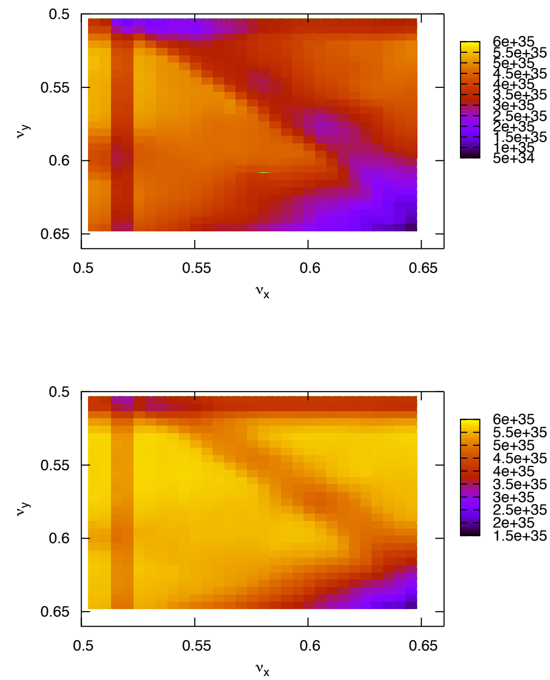

Figure 6: Luminosity on the transverse tune space. Top and bottom are without and with crab waist, respectively.

Soft Gaussian approximation reduces the simulation time extremely. Therefore we adopt a mixed method of the PIC solver and soft Gaussian approximation. When colliding two beam (slice) separation is closer than $5\sigma_x$, PIC solver is used, otherwise soft Gaussian approximation is used. Figure 7 shows the luminosity given by the strong-strong simulation. The luminosity somewhat degrade from the design value. The beam-beam parameter obtained by the luminosity is 0.08. No coherent motion was seen. The horizontal size did not change, while vertical size was enlarged. This result means that there is no serious problem for beam-beam dynamics point of view.

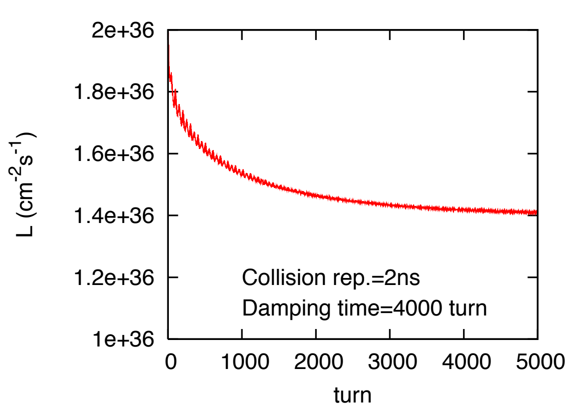

Figure 7: Luminosity evolution given by the strong-strong simulation.

Effect of the micro-wave instability

Bunch current in KEKB upgrade is higher than the present current of KEKB. Bunch lengthening and micro wave instability have been observed even in KEKB. Though the chmaber is more carefully designed, resial impedance or CSR contribution may cause micro-wave instability. Actually missing impedance exist in the prsent KEKB [8]. The horizontal beam-beam force integrated along the bunch length is Bassetti-Erskine type for tri-Gaussian distribution in x-y-z plane. When the micro-wave instability arises, the transverse beam-beam force is distorted and fluctuated in the nano-beam scheme as shown in Figure 8.

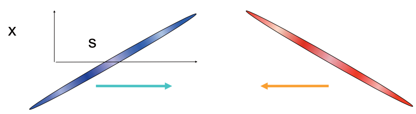

Figure 8: Collision of beams with a longitudinal density modulation.

The combined effect of the beam-beam and micro-wave instability is studied with the weak-strong simulation. The weak-beam is represented by maco-particles on 6-dimentional phase space as is done generally. The strong-beam is represented by macro-particles on the longitudinal phase space, where the transverse distributuion is fixed and determined by the design σ_x and σ_y. Longitudinal wake field is introduced for the strong beam. When the strong beam is unstable in longitudinal, the weak beam experiences fluctuating beam-beam force from the strong beam. Figure 9 shows the longitudinal profile of the strong beam, and luminosity and weak beam size evolution. The impedance (wake) is the resonator model used by Y. Cai [9],

$$Z(\omega) = \frac{R_S}{1 + iQ\left(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right)} \quad (5)$$

where $R_S = 2.5 \times 10^{-6}$ s/m, $\omega_R = 2\pi \times 31.3GHz$ and $Q = 1$. The luminsity is smaller than the design value in the simulation, $8 \rightarrow 6 \times 10^{35}$ cm^{-2}s^{-1}. Bunch lengthening is the reason of the luminosity degradation, but no other complex effects is seen. There is not blow-up in the transverse beam size. Since the longitudinal profile is lengthening but is stable, the beam-beam force does not fluctuate. The resonator impedance may be mild for the micro wave instability. Actual impedance is more complex, thus the beam profile may fluctuate. The simulation shoule be performed with a realistic impedance.

COMPUTING AT KEK

Common memory or distributed memory

Two super computers are used in KEK. One is a common memory type of parallel computer, HITACHI SR11000. It consists of 16 nodes, where each node equips 16 CPU's

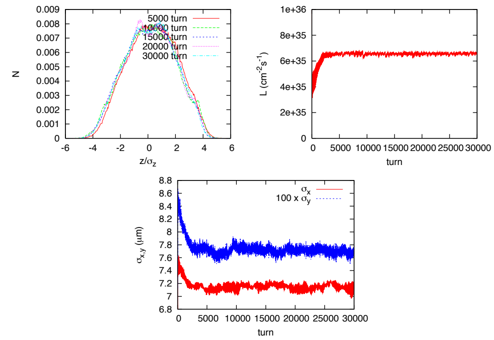

Figure 9: Longitudinal profile fo the strong beam. Luminosity and transverse beam size of the weak beam.

(POWER 5) with a common memory (24 GB). The total power is 2 TFlops.

Another is the distributed memory type of computer, Blue Gene. It consist 10,000 nodes, which contain 2 PowerPC440 in each, and the total power is 57 TFlops.

Simulations for accelerators have been carried out mainly using SR11000, even though the total CPU power is lower.

The potential solver is called 10^2 times per collision for the present KEKB. It is called 10^4 or more for the upgrade of KEKB. The total numbers of Poisson solve is 10^6 and $10^8 - 10^9$ for the present KEKB and KEKB upgrade, respectively. It is similar number for JPARC-MR. A potential calculation including the distribution to all CPU's should be finished less than 1 ms to complete these simulations in a reasonable computation time, < 100 hours.

HITACHI SR11000m in which communication between CPU is via memory, solves potential in 10 ms. For Blue Gene, the overhead of network communication should be cared.

PIC simulation is carried out as follows,

1. Particle loops are paralleled.
2. Count distribution $\rho(x_i, x_j)$ and take summation for all nodes.
3. Potential $\varphi(x_i, y_j)$ is calculated by solving 2D Poisson equation with parallel for the mesh.
4. $\varphi(x_i, y_j)$ is distributed to all nodes, and is used to track particles.

When the mesh is 128×128 with 8 Byte memory, 128 kB data has to be communicated in the process of (2) and (4) per one potential calculation. This communication is performed via memory for SR11000, but via network for Blue Gene. The network overhead is estimated by the help of Dr. Doi (IBM-Japan). `MPI_Allreduce` for 32 node spend 15 sec for 10^4 times: that is 1.5 ms . Since the deta communication is performed along "tree" structure, it is twice for 1024 node: i.e., $\log_2 1024/\log_2 32 = 2$. Anyway the communication time has already over the required time 1 ms per one potential calculation.

The common memory type of supercomputer SR11000 is still useful for particle in cell simulations of circular accelerators. However computing power of super parallel computers based on the distributed memory increases more and more. Super parallel computers are trend of the computing. KEK super computers are replaced by new one with 1 PFlops in 2011. RIKEN computer center with 10 PFlops starts at 2012. We have to keep up the trend in spite of the network overhead in our simulation scheme.

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