Beam-beam predictions for SuperKEKB and Large Crossing angle

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Beam-beam workshop at CERN
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Thanks: KEKB/SuperKEKB term, E. Levichev, P. Piminov, E. Perevedentsev, P. Raimondi, D. Shatilov, F. Zimmermann, M. Zobov
Two approach toward high luminosity

- High current, high beam-beam parameter.
- Low emittance, low beta, low current, so-called super bunch collision
Comparison of two approach

High current: \( \frac{\sqrt{\epsilon_x \beta_x}}{\theta \sigma_z} > 1 \) or \( \theta = 0 \)

Low emittance: \( \frac{\sqrt{\epsilon_x \beta_x}}{\theta \sigma_z} < 1 \)

Overlap factor

\[ L \sim \frac{N^2}{\sqrt{\epsilon_x \beta_x \epsilon_y \beta_y}} \]
\[ \xi_x \sim \frac{N}{\epsilon_x} \]
\[ \xi_y \sim N \sqrt{\frac{\beta_y}{\epsilon_x \beta_x \epsilon_y \beta_y}} \]
\[ \beta_y > \sigma_z \]

\[ \theta: \text{half crossing angle} \]

\( \xi_x \) is smaller due to cancellation of tune shift along bunch length
High current approach

\[ L \sim \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}} \]

\[ \xi_x \sim \frac{N}{\varepsilon_x} \]

\[ \xi_y \sim N \sqrt{\frac{\beta_y}{\varepsilon_x \beta_x \varepsilon_y}} \]

\[ \beta_y > \sigma_z \text{ limits luminosity} \]

- High current, Small coupling
- Choice of operating point

\[ \nu_x \rightarrow +0.5 \quad \xi_y \rightarrow \infty \quad N \rightarrow \infty \]

\[ \theta = 0 \quad L \rightarrow \infty \]
Why $\xi_y$ can be large

- $\nu_x \to 0.5$, the horizontal motion is integrated independent of $y$, because horizontal beam-beam force weakly depends on $y$.

- $z$ independent for $\theta_c = 0$.
- Nonlinear $y$ motion (1 dim) is slowly modulated by $x$ motion (externally).

Figure 3: Phase space plot in $x - p_x$. $y_0 = 2\mu m \approx 3\sigma_y$. plots (a), (b), (c) and (d) is given for $\nu_x = 0.503, 0.51, 0.52$ and 0.54, respectively.

Head-on (crab) Strong-strong beam-beam simulation

22 mrad crossing angle

Head-on $\nu_x = 0.58 \implies \xi_y \sim 0.15$

Weak-strong: $\xi = 0.3$
Limitation of crab and $v_x \rightarrow 0.5$ scheme

- Dynamic beta in horizontal works demerit.
- Aperture issue appears other place of IR, especially at the crab cavity.
- Low crab $\beta_x$ requires high crab voltage, while high IR $\beta_x$ degrades luminosity.
- Crossing angle relaxes the dynamic beta ironically, $\sigma_x = (\varepsilon_x \beta_x + \theta \sigma_z^2)^{1/2}$.
- We had to find the middle ground.
• The crab crossing works fairly well, though it is not perfect.

<table>
<thead>
<tr>
<th>Machine parameters (before/after crab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
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<tr>
<td>------</td>
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<tr>
<td>Current</td>
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<tr>
<td>Bunches</td>
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<td>Bunch current</td>
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<tr>
<td>emittance $\varepsilon$</td>
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<tr>
<td>$\beta_x$</td>
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<tr>
<td>$\beta_y$</td>
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<tr>
<td>$\sigma_x$ @IP</td>
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<tr>
<td>$\sigma_y$ @IP</td>
</tr>
<tr>
<td>$\nu_x$</td>
</tr>
<tr>
<td>$\nu_y$</td>
</tr>
<tr>
<td>$\nu_6$</td>
</tr>
<tr>
<td>beam-beam $\xi_x$</td>
</tr>
<tr>
<td>beam-beam $\xi_y$</td>
</tr>
<tr>
<td>Luminosity</td>
</tr>
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</table>
Nano-beam scheme

• KEKB with crab cavity targeted a high beam-beam parameter >0.1.

• SuperKEKB goes toward Low emittance, low beta, moderate beam-beam parameter <0.1

Neglect parallel translation to x
Low emittance approach

- Bunch length is free.
- Small beta and small emittance are required.

Keep \( \sqrt{\frac{\beta_y}{\epsilon_y}} \) and \( \sigma_x/\beta_y \)

Then take limit \( \epsilon_y/\beta_y \to 0 \)

\[ L \to \infty \]

- Super KEKB
  \( \epsilon_x = \frac{3}{5} \) nm, \( \epsilon_y = \frac{3}{5} \) pm
  \( \beta_x = \frac{32}{25} \) mm, \( \beta_y = 0.3 \) mm
### Machine Parameters

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<th>HER</th>
<th>unit</th>
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<td>E</td>
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<td>7.007</td>
<td>GeV</td>
</tr>
<tr>
<td>I</td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2,500</td>
<td></td>
<td></td>
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<tr>
<td>Bunch Current</td>
<td>1.44</td>
<td>1.04</td>
<td>mA</td>
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<tr>
<td>Circumference</td>
<td>3,016.315</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>$\varepsilon_x/\varepsilon_y$</td>
<td>3.2(1.9)/8.64(2.8)</td>
<td>4.6(4.4)/11.5(1.5)</td>
<td>nm/pm 0:zero current</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
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<tr>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td>mm</td>
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<td>Crossing angle</td>
<td>83</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>3.25x10^{-4}</td>
<td>4.55x10^{-4}</td>
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<td>$\sigma_8$</td>
<td>8.08(7.73)x10^{-4}</td>
<td>6.37(6.31)x10^{-4}</td>
<td>0:zero current</td>
</tr>
<tr>
<td>$V_c$</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>6.0(5.0)</td>
<td>5(4.9)</td>
<td>mm 0:zero current</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>-0.0247</td>
<td>-0.0280</td>
<td></td>
</tr>
<tr>
<td>$\nu_x/\nu_y$</td>
<td>44.53/44.57</td>
<td>45.53/43.57</td>
<td></td>
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<td>$U_0$</td>
<td>1.87</td>
<td>2.43</td>
<td>MeV</td>
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<td>$\tau_{x,y}/\tau_z$</td>
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<td>58.0/29.0</td>
<td>msec</td>
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<td>$\xi_x/\xi_y$</td>
<td>0.0028/0.0881</td>
<td>0.0012/0.0807</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>8x10^{35}</td>
<td></td>
<td>cm^{-2}s^{-1}</td>
</tr>
</tbody>
</table>
Current dependence of $L$ and $\xi$ given by a weak-strong simulation

- Nano beam collision is reliable for small $\xi<0.1$ without Crab Waist.
- The gain of CW remarkably appear higher beam-beam parameter.

\[
\frac{\nu_s}{\nu} = 0.012
\]

Strong-strong was performed.
No serious difference.

Crab waist is base line of SuperB.
Beam particles collide with the other beam at their waist using sextupole magnets both side of IP.
Crab waist and IR nonlinearity

- Strong dynamic aperture degradation is seen by crab sextupole installation (H. Koiso).
- We do not know how to handle the nonlinear terms of Q’s and Solenoid located at very high $\beta$.
- Crab waist is an option in (the) future for Super KEKB.

Collaboration with BINP
Study with a simple model

- Strong nonlinearity in drift space, chromatic effects.
- Quadrupole edge at very high $\beta$

$$M_{IR} = e^{-H_{QF}} e^{-H_{L1}} e^{-H_{QD}} e^{-H_{L0}} e^{-H_{L0}} e^{-H_{QD}} e^{-H_{L1}} e^{-H_{QF}}$$

$$M_{rev} = M_{IR} M_{arc}$$

- Dynamic aperture is strongly degraded by installation of crab waist sextupoles.
- More nonlinear components in IR actually.
Characteristics of the collision

- $\beta y$ is small only interaction area
  - Beam particles with a large horizontal amplitude collide high beta region
  - Issues on injection, collision offset, Touschek ....
  - Crab waist recovers the issues, but

![Graph showing characteristics of the collision](https://via.placeholder.com/150)

Neglect parallel translation to $x$
Error tolerance

- Collision offset
- $x$-$y$ coupling at the collision point
- Dispersion at the collision point
- Their chromaticity

- Correction of these errors was essential to achieve the high performance in KEKB. It should be important also in SuperKEKB.
Tolerance of collision condition
Horizontal collision offset and waist

• Horizontal offset and waist are related to each other.
• The cross point of the waist is only one in x-z plane for the crab waist scheme.
X-Y coupling w/ crab waist

- D. Zhou & K. Ohmi
Beam noise

• Turn by turn noise

\[ L (10^{35} \text{ cm}^{-2} \text{s}^{-1}) \]

\[ \sigma_x = 6-10 \mu m \]

\[ \sigma_y \text{ does not change} \]

\[ \delta x (\mu m) \]

\[ \delta y (\text{nm}) \]

\[ \delta x = 0, 0.2, 0.4, 0.6, 0.8, 1 \]

\[ \delta y = 40, 60, 80, 100, 120, 140, 160 \]

static offset

\[ L (10^{35} \text{ cm}^{-2} \text{s}^{-1}) \]

\[ \sigma_y = 60 \text{nm} \]

\[ \sigma_x \text{ does not change} \]

\[ \delta y (\text{nm}) \]

\[ \delta y = 0, 2, 4, 6, 8, 10 \]
Summary – tolerance for parameters with 20% luminosity degradation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>w/ crab waist</th>
<th>w/o crab waist</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1^*$ (mrad)</td>
<td>±5.3</td>
<td>±3.5</td>
</tr>
<tr>
<td>$r_2^*$ (mm)</td>
<td>±0.18</td>
<td>±0.13</td>
</tr>
<tr>
<td>$r_3^*$ (m$^{-1}$)</td>
<td>±44</td>
<td>±15</td>
</tr>
<tr>
<td>$r_4^*$ (rad)</td>
<td>±1.4</td>
<td>±0.4</td>
</tr>
<tr>
<td>$\partial r_1^*/\partial \delta$ (rad)</td>
<td>±2.4</td>
<td>±2.1</td>
</tr>
<tr>
<td>$\partial r_2^*/\partial \delta$ (m)</td>
<td>±0.086</td>
<td>±0.074</td>
</tr>
<tr>
<td>$\partial r_3^*/\partial \delta$ (m$^{-1}$)</td>
<td>±1.0×10$^4$</td>
<td>±8400</td>
</tr>
<tr>
<td>$\partial r_4^*/\partial \delta$ (rad)</td>
<td>±400</td>
<td>±290</td>
</tr>
<tr>
<td>$\eta_y^*$ (µm)</td>
<td>±62</td>
<td>±31</td>
</tr>
<tr>
<td>$\eta_y'$ *</td>
<td>±0.73</td>
<td>±0.23</td>
</tr>
<tr>
<td>$\Delta x$ (µm) collision offset</td>
<td>10</td>
<td>10</td>
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<tr>
<td>$\Delta s$ (µm) waist error</td>
<td>100</td>
<td>100</td>
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<tr>
<td>$\Delta y,\Delta y'$ (µm,µrad) collision offset</td>
<td>0.02 (100)</td>
<td></td>
</tr>
<tr>
<td>$\delta x$ (µm) turn by turn noise</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\delta y$ (nm)</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

The degradation is roughly quadratic

$\sigma_x=6-10µm$  \ $\sigma_y=50$ nm
Weak-strong beam-beam simulation considering lattice

2. Beam-beam: Lattice nonlinearities

- BB(weak-strong) + LN
  - Direct vert. emit. growth
  - Current dependent
  - Mechanism not well understood

LER: specific lum.

D. Zhou
Hadron collider (LHC)

- LHC $\beta^* > \sigma_z$
- $\beta^* = 55\text{cm (design)}$ 15cm(HL-LHC), $\sigma_z = 7.5\text{cm}$
- Hourglass effect does not matter.
- Crossing angle can be used control of the luminosity and beam-beam tune shift.
- Maximum beam-beam tune shift is realized at zero crossing angle in simulations.
- Highest bunch luminosity is limited by event pileup.
Two approach toward high luminosity

• High current, high beam-beam parameter.

• Low beta, Higher bunch current with long bunch, so-called super bunch collision
Simulation of luminosity evolution

- Weak-strong model to avoid statistical noise.
- Gaussian beam distribution in transverse and longitudinal directions.
- 2 IP simulation. Horizontal/Vertical crossing.
Luminosity degradation in the simulations

- Very high potential for headon ($\theta_c=0$).
- Especially $\xi>0.2-0.3 \, v_x=v_y$, 1dim motion!

$1 \text{ day}^{-1}=10^{-9}$
Effect of crossing angle and offset

- Zero crossing angle, symmetry, less resonances.
- More resonances appear in collision with crossing angle and with collision offset.
- Tune modulation due to synchrotron motion in the crossing collision.

\[ \xi_{tot} > 0.2 \]
\[ \xi_{tot} \leq 0.035 \]
FMA analysis for $F=1$ ($\theta_c=0$) and $F=0.8$ ($\theta_c=285\mu\text{rad}$)
Crossing collision and offset collision

• Similar transverse behavior, but $\Delta L(\text{crossing}) \gg \Delta L(\text{offset})$. 

1 day$^{-1} = 10^{-9}$
Resonance crossing

• No Crossing, integrable

\[ \nu_s = 0 \]

• Crossing, non-integrable

\[ \nu_s = 0 \]
Tune scan

- Nominal parameters but high current, $\theta_c=285 \, \mu rad$, Keeping $\nu_y-\nu_x=0.01$.

- The present working point is good, but not the best.
Two approach toward high luminosity

• High bunch current, high beam-beam parameter.

• Low beta, Higher bunch current with long bunch, so-called super bunch collision
Large crossing angle collision in LHC

HL-LHC

- Luminosity leveling using crab cavity

Parameter table given by O. Bruning and F. Zimmermann (IPAC12)

$L [10^{34} \text{ cm}^{-2}\text{s}^{-1}]$

\[ F = \left( 1 + \left( \frac{\sigma_z \theta_c}{2 \sigma_\perp} \right)^2 \right)^{-1/z} \]

\[ \sigma_z = 7.55 \text{ cm} \]
Luminosity degradation in HL-LHC

\[ \xi_{\text{tot}} < 0.03 - 0.035, \]
similar as nominal crossing collision.
Summary

• Crab crossing and nano-beam (LPA) in KEKB/SuperKEKB.

• Crab crossing works fairly well. We go to nano-beam for SuperKEKB.

• Dynamic aperture, error tolerance of IR optics are critical issues.

• Crab crossing or LPA in LHC.

• Crab crossing ($\theta_c=0$) showed very high beam-beam parameter as seen in KEKB.

• There are no serious problem for single bunch collision in LPA. In this simple model.
• The difference between $\theta_c=0$ or finite is occurrence of 7-th order resonance. The resonance appear even in offset collision.

• The 7-th order resonance is seen in Tevatron. Small crossing angle or offset?
World wide trials toward high luminosity in lepton colliders

Luminosity $[10^{28} \text{ cm}^{-2} \text{ s}^{-1}]$

\[ \xi_{\text{lumi}} = \frac{N \epsilon_r \beta_{\text{nom}}^*}{4\pi\gamma\sigma_{\text{lumi}}^2} \]

M. Zobov, this workshop

D. Shwartz, this workshop

Y. Zhang, this workshop
Thank you for your attention