Crab crossing in KEKB and nano-beam scheme in SuperKEKB

K. Ohmi, D. Zhou (KEK)

EIC14, JLab

Mar. 17-21, 2014
Crab crossing at KEKB

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

KEKB crab crossing, 2008-2010

SuperKEKB nano-beam
Comparison of two approach

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

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

Overlap factor

\[ L \sim \frac{N^2}{\sqrt{e_x \beta_x e_y \beta_y}} \]

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

\[ \xi_y \sim N \sqrt{\frac{\beta_y}{e_x \beta_x e_y}} \]

\( \beta_y > \sigma_z \)

\( \theta \): half crossing angle

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

Keep $\varepsilon_x, \beta_x$ and $\sqrt{\frac{\beta_y}{\varepsilon_y}}$.

$\varepsilon_y \beta_y \to 0$

$L \to \infty$

$\beta_y > \sigma_z$ limits luminosity

- High current, Small coupling
- Choice of operating point

$\nu_x \to +0.5 \quad \xi_y \to \infty \quad N \to \infty$

$\theta = 0 \quad L \to \infty$
How $\xi_y$ 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.

$\nu_x = .508 \rightarrow \xi_y \approx 0.15$

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

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

### Machine parameters (before/after crab)

<table>
<thead>
<tr>
<th>Date</th>
<th>Nov. 15 2006 before crab</th>
<th>Jun. 17 2009 with crab</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER</td>
<td>1.65</td>
<td>1.64</td>
</tr>
<tr>
<td>HER</td>
<td>1.33</td>
<td>1.19</td>
</tr>
<tr>
<td>Current</td>
<td></td>
<td>1.64</td>
</tr>
<tr>
<td>Bunches</td>
<td>1389</td>
<td>1584</td>
</tr>
<tr>
<td>Bunch current</td>
<td>1.19</td>
<td>1.03</td>
</tr>
<tr>
<td>spacing</td>
<td>2.10</td>
<td>1.84</td>
</tr>
<tr>
<td>emittance $\varepsilon_x$</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>$\beta_x$</td>
<td>59</td>
<td>120</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>6.5</td>
<td>5.9</td>
</tr>
<tr>
<td>$\sigma_x@$IP</td>
<td>103</td>
<td>147</td>
</tr>
<tr>
<td>$\sigma_y@$IP</td>
<td>1.8</td>
<td>0.94</td>
</tr>
<tr>
<td>$\nu_x$</td>
<td>45.505</td>
<td>45.506</td>
</tr>
<tr>
<td>$\nu_y$</td>
<td>44.534</td>
<td>43.561</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>-0.0246</td>
<td>-0.0246</td>
</tr>
<tr>
<td>beam-beam $\xi_x$</td>
<td>0.117</td>
<td>0.127</td>
</tr>
<tr>
<td>beam-beam $\xi_y$</td>
<td>0.108</td>
<td>0.129</td>
</tr>
<tr>
<td>Luminosity</td>
<td>17.6</td>
<td>21.08</td>
</tr>
</tbody>
</table>

$10^{33} \text{cm}^{-2}\text{s}^{-1}$
Specific luminosity

Green: $\beta_x^* = 1.5\text{m (crab on)}$
Blue: $\beta_x^* = 1.5\text{m (crab off)}$
Geometrical loss: $\sim 11\%$

$\xi_y = 0.090$ (HER)

$\xi_y = 0.070$ (HER)

$\xi_y = 0.062$ (HER)

$\beta_x^* = 0.8\text{m}$
$\kappa = 1\%$

$\beta_x^* = 1.5\text{m}$
$\kappa = 1\%$

$\beta_x^* = 1.5\text{m}$
$\kappa = 1.3\%$

w/o crab
$\beta_x^* = 0.8\text{m}$
$\kappa = 1\%$
Summary for KEKB crab crossing

- Beam Crabbing was realized without problems.
- Strong Dynamic beta at crab cavity.
- Tuning knobs increase, optics parameters at crab cavity, in addition of those at IP. X-y coupling at crab cavity induces y-z tilt at IP.
- Correction of chromatic coupling at IP was efficient.
- Luminosity \(2.11 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\) was achieved. \(\xi_y \sim 0.09\).
- Expectation was \(3 \times 10^{34}, \xi_y > 0.1\).
- Chromatic aberration between crab cavity and IP may affect the luminosity performance.
Nano-beam scheme

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

KEKB crab crossing

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

Neglect parallel translation to $x$

SuperKEKB nano-beam
Low emittance approach

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

Super KEKB

\( \varepsilon_x = \frac{3}{5} \text{ nm}, \quad \varepsilon_y = \frac{3}{5} \text{ pm} \)

\( \beta_x = 32/25 \text{ mm}, \quad \beta_y = 0.3 \text{ mm} \)
# Machine Parameters

<table>
<thead>
<tr>
<th>Date</th>
<th>LER</th>
<th>HER</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011/July/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>4.000</td>
<td>7.007</td>
<td>GeV</td>
</tr>
<tr>
<td><strong>I</strong></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>
</tr>
<tr>
<td>Bunch Current</td>
<td>1.44</td>
<td>1.04</td>
<td>mA</td>
</tr>
<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</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>$\beta_x/\beta_y$</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td>mm</td>
</tr>
<tr>
<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>
<td></td>
</tr>
<tr>
<td>$\sigma_b$</td>
<td>8.08(7.73)x10^{-4}</td>
<td>6.37(6.31)x10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$\nu_c$</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>6.0(5.0)</td>
<td>5(4.9)</td>
<td>mm</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>-0.0247</td>
<td>-0.0280</td>
<td></td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>44.53/44.57</td>
<td>45.53/43.57</td>
<td></td>
</tr>
<tr>
<td>$\tau_{x,y}/\tau_s$</td>
<td>43.1/21.6</td>
<td>58.0/29.0</td>
<td>msec</td>
</tr>
<tr>
<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>
2. Beam-beam and luminosity: LER

➤ Lum. tune scan for LER (by BBWS: weak strong with linear arc)

Choice of tune operating point $\nu_x$ near half integer, keep away from synchrobeta resonance $\nu_x, \nu_y=0.53,0.57$
2. Beam-beam and luminosity: HER

➤ Lum. tune scan for HER (by BBWS: weak strong with linear arc)
2. Beam-beam and luminosity: LER

➤ Lum. scan w/o and w/ crab waist for LER (by BBWS)

The crab waist is very powerful. Degradation of dynamic aperture is inevitable, because nonlinearity between IP and crab waist sextupole is not transparent. See later.
Characteristics of the collision

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

![Diagram with variables X, S, and Y showing neglecting parallel translation to x]
Dynamic aperture and Touschek life time

- Dynamic aperture with beam-beam is quite narrow.
- Touschek event-> betatron amplitude -> over the aperture

Transverse aperture is reduced significantly

Y. Ohnishi et al.
Crab waist

• Transformation of Effective Crab waist at IP.

\[ H_i^* = \pm \frac{1}{2\phi} x p_y^2 \]

\( \phi \): half crossing angle

+: before collision

-: after collision

• The nonlinearity is completely cancelled without beam-beam, when the transformation is applied at IP.

• Particles with a horizontal amplitude collide with another beam at their vertical waist.

• The aperture issue with beam-beam is recovered, but

\[ \bar{y} = y \pm \frac{x}{2\phi} p_y \quad \bar{p}_x = p_x \mp \frac{p_y^2}{2\phi} \]

\[ M_y^{-1} M_{BB} M_y \]

Waist shift: \( x/2\phi \)
Crab waist and IR nonlinearity

\[ M_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2} \]

- Severe dynamic aperture degradation is seen by crab sextupole installation in SAD (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 not base in Super KEKB.
Study with a simple model

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

\[ M_{IR} = e^{-H_{QF}} e^{-H_{L1}} e^{-H_{QD}} e^{-H_{L0}} e^{-H_{L0}} e^{-H_{QD}} e^{-H_{L1}} e^{-H_{QF}} \]

\[ M_{rev} = M_{IR} M_{arc} \]
Realistic crab waist

Crab-waist optics in LER

K_2 = 13.68 [1/m^2]

\[ \Delta \psi_x = 12.5 \times 2\pi \]
\[ \Delta \psi_y = 13.25 \times 2\pi \]

\[ \beta_x = 8.5 \text{ m} \]
\[ \beta_y = 200 \text{ m} \]
Dynamic aperture using SAD

- On momentum aperture

Ohnishi, SKEKB MAC14

Initial momentum deviation is zero.
(synchrotron motion is included.)
Dynamic aperture in realistic crab waist

- Crab waist sextupole reduces dynamic aperture significantly.
- The results is independent of (effective) crab sextupole location outside of IR (A. Morita).
Strategy for crab waist in SuperKEKB

• We understand efficiency of the crab waist on luminosity in simple model.
• However the side effect, which reduces dynamic aperture, is too severe in very low $\beta^*$ IP.
• Crab waist scheme is not adopted in SuperKEKB at present.
• Efforts to enlarge dynamic aperture with crab waist sextupole are continued. (BINP collaboration)
Luminosity simulation in realistic lattice

- Weak-strong beam-beam simulation using SAD.

- Crosscheck is began using other codes, Acceleraticum (Levichev, Piminov in BINP), BMAD (Sagan), SCTR (K. Ohmi).
Weak-strong Simulation for LER lattice

➤ Even low current, luminosity loss \(\sim\) 20% is seen.
➤ 30% loss at the design current.
➤ Chromatic effect cannot explain the lum. Loss.
Beam tail distribution LER, $A=J/\varepsilon$

- $N_e=6.53 \times 10^{10}$, SAD + weak-strong BB

\[ \frac{1}{2\theta_h} x p_y^2 \]
Other experiences on beam-beam in realistic lattice

KEKB crab, EPAC08

No crab

• No clear degradation due to lattice nonlinearity is seen in KEKB, except high beam-beam parameter.
BEPC-II

- SCTR code showed 15% loss at 6 & 8 mA.
- SAD does not show clear difference

![Graph showing SCTR and SAD results](image)
SuperKEKB

- Simplified IR model for SuperKEKB

IR solenoid is not taken into account
SCTR Including WS Beam-beam

- Note: bunch length 5.3mm (design 6mm)
Include Space charge

• No sol

Without IR solenoid
Space charge: LER

➤ Weak-strong model for space charge
➤ “Strong” beam: Emittance growth due to IBS included
➤ Remarkable luminosity loss is seen (65%).

With IR solenoid

SAD + weak-strong BB
Summary for SuperKEKB studies

- Touschek life time is severe when beam-beam interaction is taken into account.
- Crab waist degrade the dynamic aperture due to IR strong nonlinearity.
- Beam-beam effect in realistic Lattice has been studied using weak-strong & SAD.
- Clear luminosity loss (30%) has been seen.
- In KEKB, BEPC, the loss is small.
- Crosscheck is began using several codes. Understanding of mechanism will be performed.
- Solenoid and IR complex may degrade the luminosity. (preliminary)
- Further loss (60-70%) is seen in taking account of space charge. Crosscheck and understanding will be performed.