Recent progress of KEKB

Y. Funakoshi
for the KEKB commissioning group
World-highest Peak Luminosity
- $2.11 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
- Twice as high as design value

World-highest Integrated Luminosity
- Total: $1010\text{fb}^{-1}$ as of Dec. 24 2009

Crab crossing
Skew-sextupole magnets
Finally two crab cavities were installed in KEKB one for each ring in January 2007

HER (e−, 8 GeV)  LER (e+, 3.5 GeV)

.....after 13 years’ R&D from 1994
KEKB was operated at Y(5S), Y(2S) and off-resonance (4S-60MeV).
# Machine parameters

<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></td>
<td>LER</td>
<td>HER</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>1.65</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>Bunches</strong></td>
<td>1389</td>
<td>1584</td>
</tr>
<tr>
<td><strong>Bunch current</strong></td>
<td>1.19</td>
<td>0.96</td>
</tr>
<tr>
<td><strong>spacing</strong></td>
<td>2.10</td>
<td>1.84</td>
</tr>
<tr>
<td><strong>emittance εₓ</strong></td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td><strong>βₓ</strong></td>
<td>59</td>
<td>56</td>
</tr>
<tr>
<td><strong>βᵧ</strong></td>
<td>6.5</td>
<td>5.9</td>
</tr>
<tr>
<td><strong>σₓ @IP</strong></td>
<td>103</td>
<td>107</td>
</tr>
<tr>
<td><strong>σᵧ @IP</strong></td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>νₓ</strong></td>
<td>45.505</td>
<td>43.534</td>
</tr>
<tr>
<td><strong>νᵧ</strong></td>
<td>44.509</td>
<td>41.565</td>
</tr>
<tr>
<td><strong>νₛ</strong></td>
<td>-0.0246</td>
<td>-0.0226</td>
</tr>
<tr>
<td><strong>beam-beam ξₓ</strong></td>
<td>0.117</td>
<td>0.070</td>
</tr>
<tr>
<td><strong>beam-beam ξᵧ</strong></td>
<td>0.108</td>
<td>0.058</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tuning with skew-sextupole magnets
Ohmi et al. showed that the linear chromaticity of x-y coupling parameters at IP could degrade the luminosity, if the residual values, which depend on machine errors, are large.

To control the chromaticity, skew sextupole magnets were installed during winter shutdown 2009.

The skew sextupoles are very effective to increase the luminosity at KEKB.

The gain of the luminosity by these magnets is ~15%.
D. Zhou, K. Ohmi, Y. Seimiya,

Figure 8: Scan of first order chromaticity of coupling parameters at IP (Top left: $\partial r_{1N}^*/\partial \delta$, Top right: $\partial r_{2N}^*/\partial \delta$, Bottom left: $\partial r_{3N}^*/\partial \delta$, Bottom right: $\partial r_{4N}^*/\partial \delta$)

\[
\begin{pmatrix}
r_{1N}^* \\
r_{2N}^* \\
r_{3N}^* \\
r_{4N}^*
\end{pmatrix}
= \begin{pmatrix}
R_1^* \sqrt{\beta_x^* / \beta_y^*} & R_2^* / \sqrt{\beta_x^* \beta_y^*} \\
R_3^* \sqrt{\beta_x^* \beta_y^*} & R_4^* \sqrt{\beta_y^* / \beta_x^*}
\end{pmatrix}
\]
Definition of x-y coupling parameters (SAD notation)

\[
\begin{pmatrix}
 u \\
 p_u \\
 v \\
 p_v
\end{pmatrix}
= T
\begin{pmatrix}
 x \\
 p_x \\
 y \\
 p_y
\end{pmatrix}
\]

\[
T(s) = \begin{pmatrix}
 \mu I & SR'S \\
 R & \mu I
\end{pmatrix}
= \begin{pmatrix}
 \mu & 0 & -R_4 & R_2 \\
 0 & \mu & R_3 & -R_1 \\
 R_1 & R_2 & \mu & 0 \\
 R_3 & R_4 & 0 & \mu
\end{pmatrix}
\]

\[
S = \begin{pmatrix}
 0 & 1 \\
 -1 & 0
\end{pmatrix}, \quad \mu^2 + \det R = 1
\]
Examples of scan of chromatic x-y coupling at IP
Measurement on chromaticity of x-y coupling at IP (HER)

- Blue: without skew-sextuples
- Red: with skew-sextuples (after luminosity tuning)
- Dotted line: model optics without machine errors

Y. Ohnishi
Effectiveness of skew-sextupole magnets (crab on)

constant beam-beam parameter: $\xi_y$ (HER) = 0.08 ($I_{LER}/I_{HER}=8/5$)

- Simulation ($\beta_x^* = 0.8$ m)
- Simulation ($\beta_x^* = 1.5$ m)

No skew-sextupoles $\beta_x^* = 1.5$ m

With skew-sextupoles $\beta_x^* = 1.5$ m
Effectiveness of skew-sextupole magnets (crab off)
Effect of the crab cavities on the luminosity and the beam-beam parameter
Specific luminosity (crab on/off)

Luminosity improvement by crab cavities is about 20%. Geometrical loss due to the crossing angle is about 11%.
Beam-beam parameter (crab on/off)

<table>
<thead>
<tr>
<th></th>
<th>Crab on</th>
<th>Crab off</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_L$</td>
<td>0.828</td>
<td>0.763</td>
</tr>
<tr>
<td>$R_{\xi y}(\text{HER})$</td>
<td>1.15</td>
<td>0.993</td>
</tr>
</tbody>
</table>
Calculation of beam-beam parameter

• Reduction factor for beam-beam parameter

\[ \xi_y = R_{\xi_y} \xi_{y0} \quad \xi_{y0} = \frac{r_e}{2 \pi \gamma \sigma_y^* (\sigma_x^* + \sigma_y^*)} \]

– 2 sources of reduction
• hourglass effect and finite crossing angle

\[ R_{\xi_y} = \int_{-\infty}^{\infty} \sqrt{1 + \left( \frac{z/2}{\beta_y^*} \right)^2} f_y(x, \sigma_x, \sigma_y) \rho(z) dz \]

Montague’s factor

\[ f_y(x, \sigma_x, \sigma_y) = \frac{k}{k-1} \left[ 1 - e^{-\frac{x^2}{2\sigma_x^2}} \right] + \frac{i \sqrt{\pi x}}{\sigma_x \sqrt{2(1-k^2)}} \left\{ w \left( \frac{x}{\sigma_x \sqrt{2(1-k^2)}} \right) - e^{-\frac{x^2}{2\sigma_z^2}} \right\} \]

\[ k = \frac{\sigma_y}{\sigma_x} \]

\[ \rho(z) = \frac{1}{\sqrt{2\pi \sigma_z^2}} e^{-\frac{z^2}{2\sigma_z^2}} \]

Montague’s factor

\[ f_y(x, \sigma_x, \sigma_y) = \frac{k}{k-1} \left[ 1 - e^{-\frac{x^2}{2\sigma_x^2}} \right] + \frac{i \sqrt{\pi x}}{\sigma_x \sqrt{2(1-k^2)}} \left\{ w \left( \frac{x}{\sigma_x \sqrt{2(1-k^2)}} \right) - e^{-\frac{x^2}{2\sigma_z^2}} \right\} \]

\[ k = \frac{\sigma_y}{\sigma_x} \]

\[ \rho(z) = \frac{1}{\sqrt{2\pi \sigma_z^2}} e^{-\frac{z^2}{2\sigma_z^2}} \]
Calculation of beam-beam parameter [cont’d]

- Reduction factor for luminosity

\[ R_L \equiv \frac{L}{L_0} = \sqrt{\frac{2}{\pi}} a e^b K_0(b) \]

\[ a = \frac{\beta_y^*}{\sqrt{2}\sigma_z}, \quad b = a^2 \left[ 1 + \left( \frac{\sigma_z}{\sigma_x^*} \tan \phi \right)^2 \right] \]

- Luminosity

\[ L = \frac{1}{4\pi} \frac{N^+ N^-}{\sigma_x^* \sigma_y^*} f_{col} R_L \]

- We use calculated values for \( \sigma_x^* \) and calculate \( \sigma_y^* \) and \( \xi_{y0} \) from observed luminosity.
Crab Crossing can boost the beam-beam parameter higher than 0.15! (K. Ohmi)

$\beta_x^* = 0.8m$

Strong-strong beam-beam simulation

22mrad crossing angle

$\xi_y \sim 0.15$

$v_x = 0.508$

Head-on collision

RF deflector (crab cavity)
Summary of crab cavity operation

• The crab cavities at KEKB did work and brought the luminosity increase by ~20%.
• The highest luminosity with crab is $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.
  – Skew-sextupoles
  – Increase of HER beam current by solving the physical aperture problem
• There still exists a large discrepancy between the luminosity achieved and the beam-beam simulation.
  – The simulation predicted that the luminosity would be doubled.
  – Side effects of large tuning knobs to compensate the machine errors?
  – Horizontal dipole oscillation of the beams in collision?
**e+/e- simultaneous injection**

**Fast beam mode switching**

- **e+/e-/PF(e-) simultaneous injection was finally realized in April 2009.**

- **e+/e-/PF(e-) simultaneous injection**
  - Switch beam mode fast (in principle pulse-to-pulse for 50Hz linac pulses)
  - Magnet settings in the linac are unchanged among the modes. We use some pulse steering/bending magnets.
  - Many timing signals and klystron phases are switched pulse-to-pulse.

- **Benefits of the simultaneous injection**
  - The beam condition became more stable.
  - Much faster beam tuning became possible.
  - The luminosity decrease during the PF injection and the PF machine study can be avoided.
Fast beam mode switch scheme is strongly required.

Schematic view of the beam-mode switches. The block pulses show beam gate timings.
Slow switching

After achievement of pulse-to-pulse switching injection

~50mA

~33μA

< ~1mA

AR injection

AR has not participated in the simultaneous injection yet.

HER: 12.5Hz
LER: 12.5Hz
PF: 0.5Hz
KEKB operation in 2010

• The KEKB operation was resumed on May 13th.
• The KEKB operation will be terminated at the end of June.
  – Physics operation: energy scan (3 weeks)
  – Machine study: (2 weeks)

Fine grained scan around Y(5S) and Y(6S)

A tetra-quark state?
Machine studies

• SuperKEKB
  – Vacuum R&D
    • Counter-measures for ECI (previous talk by Y. Suetsugu)
    • Movable mask, radiation from vacuum chamber etc.
  – RF system
    • High power operation of klystron
    • SCC reverse phase operation
  – Beam monitor system
    • Bunch-by-bunch feedback system
    • BPM signal detection circuit
  – Beam transport
    • Beam abort window
Machine studies [cont’d]

• SuperKEKB (cont’d)
  – Beam behavior, beam dynamics
    • Stability of beam orbit, effects of electron clouds
  – Physics Detector
    • Background study

• KEKB performance
  – e-/e+/PF simultaneous injection
  – Side effect of large tuning knobs
  – effect of compensation solenoid
  – Measurement of x-y coupling at IP and its chromaticity
  – Horizontal oscillation in physics run

• Others
  – Study for LHC crab cavity, Positron target for ILC
Summary and future prospects

- A new luminosity record was made by using skew-sextupole magnets.
- The crab cavities did work and brought the luminosity improvement by about 20%.
- This improvement is still lower than the beam-beam simulation.
- e+/e- simultaneous injection was realized.
- KEKB/Belle has accumulated the integrated luminosity of 1000 fb⁻¹.
- KEKB is being used also as an R&D machine.

- The KEKB operation will be terminated at the end of coming June. We plan to start the construction of SuperKEKB.
- The design luminosity of SuperKEKB is 8 x 10^{35} \text{ cm}^{-2}\text{s}^{-1} (x40 of KEKB).
  
  (Talk by M. Masuzawa: FRXBMH01)