Performance of KEKB with Crab Cavities

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KEK
Outline

• Overview of KEKB
• Crab cavity and crab crossing scheme
• Performance of KEKB with crab crossing
• Some experience of crab cavity operation with beams
• Summary and future plans
Overview of KEKB

• Circumference:
  • 3016m

• Beam energy
  • 3.5 GeV (e+; LER)
  • 8.0 GeV (e-; HER)
  • $E_{cm} = 10.58\text{GeV} (\Pi(4S))$

• Beam Currents*
  • 1.8A [1.62A] (2.6A) (LER)
  • 1.34A [0.95A] (1.1A) (HER)

• Number of Bunches: 1585/ring (~5000)

• Horizontal crossing Angle:
  • 22mrad or crab crossing

• Peak Luminosity
  • $1.0 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ on May 09 2003
  • $1.71 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (record w/o crab)
  • $1.61 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (record w/ crab)

• Physics:
  • B physics (Asymmetric) (Belle)

• Integrated Luminosity:
  • Total: >850 fb$^{-1}$
  • ~ 1fb$^{-1}$/day (record: 1.23 fb$^{-1}$/day)

*Beam currents: [ ]: w/ crab, ( ): design
Luminosity of KEKB
Oct. 1999 - June 2008

Peak luminosity

Daily integrated luminosity

Peak luminosity in a day (1/nb/s)

Daily integrated luminosity (1/pb/day)

Peak beam currents in a day (A)

Daily efficiency

Peak luminosity
17.12 /nb/s

1232 /pb/day

7.82 /fb/7 days
30.21 /fb/30 days

850 /fb
Crab cavity and crab crossing scheme
Crabcrossing scheme: some history

- The crab crossing scheme was proposed in 1988 by R. Palmer.
  - Idea to recover the head-on collision with the crossing angle for linear colliders.
- Also in ring colliders
  - Oide and Yokoya showed that the synchro-betatron coupling terms associated with the crossing angle are canceled by the crab crossing (1989).
- KEKB adopted a horizontal crossing angle of 22mrad.
- The crab cavities were considered as backup devices in KEKB design.
- The KEKB crab cavity was first designed by K. Akai at Cornel (1991-1992)
- R&D of crab cavity started at KEKB in 1994.

K. Hosoyama: Development of the KEK-B Superconducting Crab Cavity
Thursday26  Morning Session in the Maestrale Auditorium
**Horizontal crossing angle**

- KEKB adopted 22mrad horizontal crossing angle.
  - Easier beam separation
  - Less SR background
  - Less Luminosity-dependent background
  - Space for solenoid compensation
  - Less parasitic collision

- Possible demerit
  - Synchro-betatron resonance
    -> We continued development of crab cavity as a backup device.

- Observation
  - No serious effects of s-b resonance
  - We got $\gamma$ of 0.056 w/o crab cavity.
Crab crossing at KEKB

- Crab Crossing can boost the beam-beam parameter higher than 0.15! (K. Ohmi)

**Head-on (crab)**

Strong-strong beam-beam simulation

22mrad crossing angle

\[
\xi_y \approx 0.15
\]

\[
\nu_x = 0.508
\]

After this simulation appeared, the development of crab cavities was revitalized.

First proposed by R. B. Palmer in 1988 for linear colliders.
Structure of crab cavity

-crab mode: TM110: $B_y$ on beam axis
-lower mode: TM010: dumped through coaxial coupler
Finally two crab cavities were installed in KEKB, one for each ring in February 2007!

HER (e-, 8 GeV)  
LER (e+, 3.5 GeV)

.....after 13 years’ R&D from 1994
Single crab cavity scheme

- Beam tilts all around the ring.
- $z$-dependent horizontal closed orbit.
- Tilt at the IP:

$$\theta_x = \frac{\sqrt{\beta_x^C \beta_x^*} \cos(\psi_x^C - \mu_x/2) V_C \omega_{rf}}{2 \sin(\mu_x/2) E_c}$$

1 crab cavity per ring.
- Saves the cost of the cavity and cryogenics.
- Avoids synchrotron radiation hitting the cavity.
Beam was indeed tilted!

Observation with Streak Cameras (H. Ikeda et al)
Performance of KEKB with crab crossing
Specific luminosity with crab crossing

- Crab crossing (physics run)
- Crab crossing (beam study)
- 22 mrad crossing
- Beam-beam simulation (strong-strong)
- SuperKEKB (1.53mA²)
  - \(I_{\text{bunch}}\) (LER) = 1.87 mA
  - \(I_{\text{bunch}}\) (HER) = 0.82 mA
## Machine parameters

<table>
<thead>
<tr>
<th></th>
<th>Nov. 2006 (w/o crab)</th>
<th>Mar. 2008 (with crab)</th>
<th>Units</th>
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<tbody>
<tr>
<td><strong>Circumference</strong></td>
<td></td>
<td>3016</td>
<td>m</td>
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<tr>
<td><strong>Hor. emittance</strong></td>
<td>18</td>
<td>24</td>
<td>15</td>
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<tr>
<td><strong>Beam current</strong></td>
<td>1662</td>
<td>1340</td>
<td>1605</td>
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<tr>
<td><strong># of bunches</strong></td>
<td>1388+1</td>
<td>1584 + 1</td>
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<tr>
<td><strong>RF frequency</strong></td>
<td></td>
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<td>MHz</td>
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<td><strong>RF Voltage</strong></td>
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<td>15.0</td>
<td>8.0</td>
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<tr>
<td>$\nu_s$</td>
<td>-0.0246</td>
<td>-0.0226</td>
<td>-0.0240</td>
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<tr>
<td>$\nu_x / \nu_y$</td>
<td>45.505/43.534</td>
<td>44.509/41.565</td>
<td>45.505/43.567</td>
</tr>
<tr>
<td>$\beta_x^* / \beta_y^*$</td>
<td>59/0.65</td>
<td>56/0.59</td>
<td>90/0.59</td>
</tr>
<tr>
<td>$\langle (mom. compact.) \rangle$</td>
<td>3.31 x 10⁻⁴</td>
<td>3.38 x 10⁻⁴</td>
<td>3.17 x 10⁻⁴</td>
</tr>
<tr>
<td>$\xi_x / \xi_y$</td>
<td>0.117/0.105</td>
<td>0.070/0.056</td>
<td>0.099/0.097</td>
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<tr>
<td><strong>Beam life</strong></td>
<td>110@1600</td>
<td>180@1340</td>
<td>94@1605</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>1.712</td>
<td>1.610</td>
<td>$10^{34}$cm⁻²s⁻¹</td>
</tr>
</tbody>
</table>
Beam-beam parameter

\[ \xi_y \sim 0.093 \text{ (HER) (April 3 2007)} \]

\[ \xi_y : \text{experiments} \]
Specific Luminosity and beam-beam parameter

\[ y = -16.35x + 26.54 \]  
Green Ratio = 100%

Crab crossing
- 49-spβ \( x^* = 80, 84 \text{ cm} \)
- \( \varepsilon x = 18, 24 \text{ nm} \)
- 3.5-sp β \( x^* = 80 \text{ cm} \)
- 3.06-spβ \( x^* = 80 \text{ cm} \)
- 3.06-spβ \( x^* = 90 \text{ cm} \)

\( \xi_y \approx 0.093 \) (HER) (April 3 2007)

Green line

\( l_{\text{bunch HER}} \times l_{\text{bunch LER}} [\text{mA}^2] \)
Why the specific luminosity drops faster than expected?

• Speculations:
  ✨ Too many tuning parameters to find out an optimum set?
  ✨ Short beam lifetime prevents us from approaching a better parameter set?
    ✨ Dynamic-$\beta$ and dynamic emittance effects due to beam-beam?
    ✨ Beam lifetime decrease dependent on horizontal orbit offset at IP
  ✨ Synchro-betatron resonance near 1/2 integer?
  ✨ Some unknown fast noise?
  ✨ Crosstalk between beam-beam and lattice non-linearity?
  ✨ Vertical crab at IP?
  ✨ and more….
Too many tuning parameters?

- Many tuning knobs are tuned by scans only on the luminosity and the beam sizes and the beam lifetime.
- Each scan takes a long time, typically ~30min.
- During beam operation, the operators are almost always doing some scan.
- Is it possible to reach an optimum set of parameters with this method?
- We still suspect this possibility.
Dynamic-β and dynamic emittance by beam-beam (calculation)

The focusing force of the beam-beam interaction not only squeezes the beam at the interaction point, but increases the emittance drastically.
Deformation of $\beta$-function all around the ring due to beam-beam effect ("dynamic beta")
Beam size calculation with dynamic beam-beam effects

@crab (aperture < 5\(\sigma_x\))
Trial of higher $\beta_x^*$

- $\beta_x^*$: 0.9 -> 1.5m
- $\beta_x$@crab: 199 -> 109m (LER)
- $\beta_x$@crab: 160 -> 97m (HER)

$\beta_x^* = 0.8m$
$\beta_x^* = 1.5m$
$\kappa = 1\%$
$\beta_x^* = 1.5m$
$\kappa = 1.3\%$

w/o crab
$\beta_x^* = 0.8m$

Machine study
$\beta_x^* = 1.5m$
Mysterious lifetime asymmetry with respect to sign of hor. offset

- The (HER) beam current seems to be limited by the short lifetime of the LER beam.
- The (LER) beam lifetime is very asymmetric with respect to H offset.

Collision center given by the beam-beam kick
- Luminosity boost by crab crossing disappears with 2 mrad crossing angle.
- Luminosity boost by crab crossing disappears with ~40 μm horizontal offset.
- Typical value of horizontal offset in physics experiment is ~15 μm, which is obtained by offset scan.
- This kind of horizontal offset depending on beam current can degrade the specific luminosity.
- Some luminosity boost by the crab crossing is actually observed by crab Vc scan.
Synchro-betatron resonance

- The horizontal tune is set nearby the half integer resonance and its synchrotron side bands.
- On the resonances, some harmful effects are observed.
  - Single-beam beam size blowup
  - Tow-beam beam size blowup
  - Beam lifetime reduction (or beam loss)
- The resonance is stronger in HER where no local chromaticity correction is installed.
- Strength of the resonance is strongly dependent on a choice of sextupole setting. The luminosity also changes by changing the sextupole setting.
- Even in the off resonance tunes, it affects the luminosity due to the tune footprint by the beam-beam?
- We still suspect this resonance.
Negative-\(\alpha\)Optics

• Motivation
  – To weaken the synchro-betatron resonance particularly in HER

\[
\begin{align*}
2
v_x + v_s &= \text{integer} \\
2v_x + 2v_s &= \text{integer}
\end{align*}
\]

\(v_x: .5112, .5224\)

with given \(v_s \sim -.0224\)

– To shorten the bunch length

• Results
  – We have succeeded to weaken the synchro-betatron resonance line in HER. We could operate the machine with \(v_x\) below the resonance lines.

  – We have successfully shorten the bunch length of both beam.
    • ~6mm -> ~4.5mm

  – However, we found unexpectedly large synchrotron oscillation in LER due to the microwave instability and gave up the trial of the negative-\(\alpha\)optics.

  – Recently, we succeeded in suppressing the instability by increasing the absolute value of \(\alpha\).
LER Optics (cell)

Positive $\alpha$

Negative $\alpha$

H. Koiso
### Positive $\alpha$ (now)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\varepsilon_x$ (m)</td>
<td>2.405366E-8</td>
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<td>$\varepsilon_y$ (m)</td>
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<td>$\varepsilon_z$ (m)</td>
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<td>$f$ (Hz)</td>
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<td>$\Delta f$ (Hz)</td>
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<td>$v_s$</td>
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<tr>
<td>$\text{Crabing}_{ip}$ (mrad)</td>
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### Negative $\alpha$

<table>
<thead>
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<th>Value</th>
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<td>0.0215</td>
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<tr>
<td>$\text{Crabing}_{ip}$ (mrad)</td>
<td>0.0000</td>
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</table>
We once found that the luminosity increased by lowering the gain of bunch-by-bunch feedback system (LER vertical) in case of 22mrad crossing angle. It seemed that some noise from the FB system affected the luminosity. At present, no remarkable effect of FB gain is observed.
Latest beam-beam simulation

Preliminary!!

K. Ohmi
Some experience of crab cavity operation with beams
Phase stability of crab cavities

- Two measurements with different signals (cavity pick up signal and signal from phase detector of PLL) give a consistent result.
- Phase fluctuation faster than 1 kHz is less than ±0.01°, and slow fluctuation from ten to several hundreds Hz is about ±0.1°.
- They are much less than the allowed phase error obtained from the beam-beam simulations for the crabbing beams in KEKB.

According to beam-beam simulation by K. Ohmi, allowed phase error for N-turn correlation is 0.1×√N (degree). The measured phase errors are much smaller than the allowed values given by beam-beam simulation.
Beam operation with crab cavities

Crab detuned

Peak Luminosity: 1.940 x 10^36 nb/sec @ 03/24/07:12
Integrated Luminosity: 64,952.8 [pb^-1]

1/1/2007 0:00 - 5/1/2008 0:00 IST

HER current
LER current
Luminosity
Trip rate of crab cavities

RF Trip of Crab Cavity (13/02/2007~30/06/2008)

- Period 1: 13/02/2007~30/06/2007
- Period 2: 05/10/2007~17/12/2007
- Period 3: 12/02/2008~30/06/2008

- HER
- LER

# of trips / week

- Crab detuned for high current
- LER Crab Vc suddenly dropped
- RF conditioning HER Crab Vc lowered using large beta function
- Temporary warm-up due to the power line accident
Summary

• 20 years after they were initially proposed, in February 2007 crab cavities are for the first time installed in an operating collider, KEKB.
• The crab cavities at KEKB have been working much more stably than the initial expectation.
  – They are presently being used in usual physics run (high beam current!!).
• The success of the development of the crab cavities is important, since they can be applied to other machines such as SR facilities or an upgrade of LHC.
• With crab crossing, the vertical beam-beam parameter of 0.093 was obtained. This indicates superiority of crab crossing scheme.
• However, the crab cavity at KEKB has not yet fully realized its potential capability in the sense that the specific luminosity is much lower than the beam-beam simulation at the high bunch currents.
• Finding the cause of this problem is very important for KEKB, since the design of SuperKEKB already counts the luminosity gain by the crab cavities.
Future plans

• We will continue the investigation on the low specific luminosity at high bunch currents.
• More beam-beam simulation (Ohmi)
• In the autumn run this year, the e+ and e- simultaneous injection may be realized at KEKB. It is expected that the beam operation with shorter beam lifetime will be possible. Some luminosity gain is expected with this.
• KEKB maybe continue its operation also in the next fiscal year (Apr. 2009~).
Spare slides
Downhill Simplex Method

Method of Minimization

- \{1, 2, 3\} \quad 1\text{(best)}<2\text{(next-to-the worst)}<3\text{(worst)}
- Evaluate \(3_R\)
- If \(3_R<1\),
  - If \(3_E<3_R\), \{1, 2, 3_E\} : \text{Expand} , if not,\{1, 2, 3_R\} : \text{Reflect}
- If \(1<3_R<2\), \{1, 2, 3_R\} : \text{Reflect}
- If \(2<3_R<3\), \text{Reflect 2} \quad \text{proposed by A. Hutton}
  - If \(3_{C+}<3_R\), \{1, 2, 3_{C+}\} : \text{Contract+} , if not,\{1, 2, 3_R\} : \text{Reflect}
- If \(3<3_R\), \text{Reflect 2}
  - If \(3_{C-}<3\), \{1, 2, 3_{C-}\} : \text{Contract-} , if not, \{1, 2_S, 3_S\} : \text{Shrink/Reflect2}
Machine study

Peak Luminosity 14.964 [nb/sec] @ 03/03 05:20
Integrated Luminosity 18715.0 [pb]
2/3/2008 9:00 - 3/17/2008 9:00 JST

Beam Current [A]

LER

Pressure [Pa] h

Integ. Lumin. [fb]

2/25/2008

®x* = 0.9m

LER Nikko new optics

®x* = 1.5m

®x* =
Before 2/21 (maintenance)
βx max 199 m
(vx, vy) = (45.505, 43.59)

After 2/21 (maintenance)
βx max 91 m
(vx, vy) = (44.505, 43.59)
Large β distortion in wiggler section
Bunchlength measurement

\[ \alpha = -2.55 \times 10^{-4} \]

\[ \langle \rangle = +3.31 \times 10^{-4} \]

\[ \langle \rangle = -3.41 \times 10^{-4} \]

H. Ikeda
Synchro-betatron resonance in HER

- **Positive-**
  - We could NOT operate under the resonance \(2\nu_x + s = \text{integer}\)

- **Negative-**
  - We could operate under the resonance \(2\nu_x - s = \text{integer}\)
The luminosity depends on the sextupole setting

- We often observed the horizontal size changed dependent on sextuple setting.
- The luminosity is also improved with the chromaticity tuning.
Calculation of beam-beam parameter

• Reduction factor for beam-beam parameter

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

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

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

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

Montague’s factor
Calculation of beam-beam parameter [cont’d]

• Reduction factor for luminosity

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

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

– Luminosity

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

– We use calculated values for \( \int_x^* \) and calculate \( \int_y^* \) and \( y_0 \) from observed luminosity.