Status of KEKB and upgrade plan to SuperKEKB

Mitsuhiro Yoshida, Haruyo Koiso, on behalf of KEKB accelerator group.

KEK, Ibaraki, Japan
Place and Layout of KEKB
KEKB = Asymmetric Double-Ring Collider for B-Physics
8 GeV Electron + 3.5 GeV Positron

Crab cavity was installed.
Superconducting cavities (HER)
ARES copper cavities (LER)
TRISTAN tunnel
8 GeV e- 3.5 GeV e+ Linac
e+ target

Collision point has horizontal crossing angle of 22 mrad to separate 2 beams easily.
e+ 7.8×10^{10}/bunch
Hight = 2.1 μm
Width = 110 μm
7 mm
100 kHz
1389 bunches

(Bo or B0 ?)

8.0 GeV e+ e- collision at E_{cm} = 10.58 GeV (4s)

1) KEKB is operating for asymmetric e+ e- collision at E_{cm} = 10.58 GeV (4s)
2) Generated B-meson pair have enough momentum to measure the decay time.
3) B-meson decay time is approximately 1 ps.
4) The dihedral angle of the B-mesons is approximately...
Progress of KEKB for 7 years

1989: Design work started
1994: Approval of the budget, construction started.
1995/6: KEKB Design Report
1997/9: Commissioning of the injector Linac started.
1998/12: First beam at HER.
1999/1: First beam at LER.
1999/5: Belle roll-in.
1999/6: First event at Belle.
2001/4: World record of the luminosity, 3.4 /nb/s.
2002/10: World record of the integrated luminosity, 100 /fb.
2003/05: Exceeded the design luminosity, 10 /nb/s.

... continues rewriting own records ...

Achieved >700 /fb in 7 years. Continuous injection modes (CIM)
### Parameters to decide Luminosity

Luminosity:

- **Design**: \(1.0 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\)
- **Achieved**: \(1.712 \times 10^{34} \text{ cm}^{2}\text{s}\)

\[
L = \frac{\gamma \pm \sigma_y^*}{2e\epsilon_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \frac{I \pm \xi}{\beta_y^*} \left(\frac{R_L}{R_y}\right)
\]

- **Beam-beam parameter**: \(0.052 \text{ (Design)} \rightarrow 0.056 \text{ (Achieved)}\)
- **Stored current (HER/LER)**: \(1.1/2.6 \text{ A (Design)} \rightarrow 1.35/1.75 \text{ A (Achieved)}\)
- **Vertical \(\beta\) at the IP**: \(10/10 \text{ mm (Design)} \rightarrow 5.9/6.5 \text{ mm (Achieved)}\)

Horizontal size at IP:

- Design: 77 \(\mu\)m

Vertical size at IP:

- **Design**: 5.9/6.5 mm
- **Achieved**: 5.9/6.5 mm

#### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design LER</th>
<th>Design HER</th>
<th>Dec. 2006 LER</th>
<th>Dec. 2006 HER</th>
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<tr>
<td>Circumference [m]</td>
<td>3016</td>
<td>3016</td>
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<tr>
<td>RF Frequency [MHz]</td>
<td>508.88</td>
<td>508.88</td>
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<td>Emittance (e_x) [nm]</td>
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<td>18</td>
<td>18</td>
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<tr>
<td>Beam current [A]</td>
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<td>1.1</td>
<td>1.662</td>
<td>1.340</td>
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<td>Number of bunches</td>
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<td>1388</td>
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<td>Bunch current [mA]</td>
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<td>0.22</td>
<td>1.200</td>
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<td>Hor. Size@IP [\mu m]</td>
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<td></td>
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<tr>
<td>Ver. Size@IP [\mu m]</td>
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<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
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<tr>
<td>(\xi_x)</td>
<td>0.039</td>
<td>0.039</td>
<td>0.117</td>
<td>0.070</td>
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<tr>
<td>(\xi_y)</td>
<td>0.052</td>
<td>0.052</td>
<td>0.105</td>
<td>0.056</td>
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<td>Beam lifetime [min.@mA]</td>
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<td>180@1340</td>
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<tr>
<td>Luminosity [/nb/s]</td>
<td>10</td>
<td></td>
<td>17.12\times10^{33}/\text{cm}^2/\text{s}</td>
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<tr>
<td>(\int \text{Lum/day} [/fb])</td>
<td>(\sim0.6)</td>
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<td>1.232</td>
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<td>(\int \text{Lum/7 days} [/fb])</td>
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<td>(\int \text{Lum/30 days} [/fb])</td>
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<td></td>
<td>30.21</td>
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Vertical \(\beta\) at the IP is much less than the designed parameter, therefore we can obtain higher luminosity.
Features of KEKB

Superconducting cavity:
- Accumulating beam current of 1.35 A

IP:
- Finite crossing angle.
- QCS
- Belle detector

Vacuum Components
- High current
- SR

Electron cloud is reduced by a solenoid magnetic field

Kicker/Separator and J-LINAC:
- It provides direct injection energy for continuous injection.

ARES cavity
(Normal conducting cavity with energy storage cavity):
- Stable acceleration of high current by huge accumulation energy.

Feedback system:
- Contributes to the suppression of other instability by feedback of every bunch
2006 April - July

Peak Luminosity: 16.31E+[mb/sec] @06/30 00:55
Integrated Luminosity: 64926.8[pb]
1350mA → 1300mA
4/11/2006 0:00 - 7/2/2006 0:00 JST

HER BY*: 6.2 → 5.9 mm
QKCLP (LER skewQ) setting problem was solved.
After that, the Luminosity becomes reproducibly since optics correction becomes better.

Y(5S) + 21.7/fb

Integ. Lumi. [fb]
Dead Time [s]
2006 September - December

Beam-beam simulation predicts higher luminosity in the lower horizontal emittance.

<table>
<thead>
<tr>
<th>εx (nm)</th>
<th>H\L</th>
<th>10</th>
<th>15</th>
<th>18</th>
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<tr>
<td>24</td>
<td>1.469</td>
<td>1.077</td>
<td>1.414</td>
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<td>18</td>
<td>1.621</td>
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<td>1.505</td>
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<td>15</td>
<td>1.643</td>
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<td>10</td>
<td>1.595</td>
<td>1.194</td>
<td>1.433</td>
<td>1.249</td>
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</table>

3.5 $\rightarrow$ 3.27 spacing

LER lower emittance
Lower HER $\nu_x$
$\beta_x^* \rightarrow 50$cm

Off-resonance
Crab Crossing is ready

- Crab crossing will boost the beam-beam parameter up to 0.19!

Crab Crossing will boost the beam-beam parameter up to 0.19!

Next Milestone

54 /fb/mo

27 /fb/mo.

Crab Cavity Beam Test
Crab Cavities were installed

Presented by Morita (MOOPMA04)

Crab cavities were already installed.
Super KEKB Overview

8 GeV positron beam
4.1 A

3.5 GeV electron beam
9.4 A

New collision point design
Upgrade of measuring instrument
SuperBelle
New IR

Crab cavities
New beam pipe & bellows
More RF sources
More RF cavities
Energy exchange C-band
Damping ring
Positron source

Super B Factory at KEK
**Parameters for Super KEKB**

<table>
<thead>
<tr>
<th>Super KEKB</th>
<th>KEKB</th>
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<th></th>
<th>Super KEKB</th>
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<td></td>
<td>LER</td>
<td>HER</td>
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<td>HER</td>
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<tr>
<td>Current [A]</td>
<td>1.616</td>
<td>1.210</td>
<td>9.4</td>
<td>4.1</td>
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<tr>
<td>Bunches</td>
<td>1388</td>
<td>5018</td>
<td></td>
<td></td>
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<tr>
<td>Spacing [m]</td>
<td>1.8 or 2.4</td>
<td>0.6</td>
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<td></td>
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<tr>
<td>Emittance εx [nm]</td>
<td>18</td>
<td>24</td>
<td>24</td>
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<tr>
<td>βx* [cm]</td>
<td>59</td>
<td>56</td>
<td>20</td>
<td></td>
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<tr>
<td>βy* [cm]</td>
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<td>Hor. Size@IP [μm]</td>
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<td>69</td>
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<td>Ver. Size@IP [μm]</td>
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<td>0.73</td>
<td>0.73</td>
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<tr>
<td>ξx</td>
<td>.106</td>
<td>.068</td>
<td>.152</td>
<td>.152</td>
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<tr>
<td>ξy</td>
<td>.105</td>
<td>.060</td>
<td>.215</td>
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<td>Bunch length [mm]</td>
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<tr>
<td>RF voltage [MV]</td>
<td>8</td>
<td>15</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

**Parameters to decide Luminosity**

 Stored current: 1.36/1.75 A (KEKB) → 4.1/9.4 A (SuperKEKB)

 Beam-beam parameter: 0.059 (KEKB) → 0.19 (SuperKEKB)

\[
L = \frac{\gamma \pm \frac{\sigma_y^*}{2er_e}}{\beta^*} I \pm \xi \pm y \left( \frac{R_L}{R_y} \right)
\]

Luminosity:
- 0.16 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} (KEKB)
- 4 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} (SuperKEKB)

Higher current and low \( \beta \) and higher beam parameter will provide 400 /nb/s.

Vertical \( \beta \) at the IP:
- 6.5/5.9 mm (KEKB) → 3.0/3.0 mm (SuperKEKB)

Lorentz factor

Classical electron radius

Beam size ratio

Geometrical reduction factors due to crossing angle and hour-glass effect
Beam-Beam Simulation

Tune scan

- Bunch luminosity v.s. tune
- Total luminosity = 5000 x bunch luminosity
- Green line sketches the progress of KEKB.

$L_{\text{total}} = 4 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
Expected Luminosity

\[ 10 \text{ ab}^{-1} = 10^{10} \text{ BB} + 10^{10} \tau \tau \]

**SuperKEKB**

- **50/ab**: Discoveries of \( B \rightarrow K\nu\nu \)
- **15/ab**: Discovery of new CP violation in \( B^0 \rightarrow \phi K_s \)
- **1/ab**: Discoveries of \( B^0 \rightarrow D\tau\nu, \tau\nu \)

We are here!
Accomplishment of higher luminosity

- **For Higher beam currents**
  - Large number of RF cavities and stations to obtain RF power
  - Cure of HOM power
  - Handling of SR power
  - Cure of electron cloud instability and ion instability
  - Bunch-by-bunch feedback system (transverse and longitudinal)
  - Powerful injector

- **For Smaller beta function at IP**
  - New QCS+special magnets at IR
  - Need short bunch length (Cure of CSR should be necessary.)

- **For Higher beam-beam parameter**
RF Upgrade for High Current

ARES upgrade for SuperKEKB

- For Larger detuning
  
  Change energy ratio: $\frac{U_s}{U_a} = 9 \rightarrow 15$
  
  Small modification on the window size of A-cav
  
  -1 mode growth time: $0.3$ ms to $1.6$ ms.
  
  Then the -1 (and -2) modes related to the fundamental mode will be suppressed by a FB system in the RF control system.
  
  (need bunch-by-bunch FB to suppress ARES HOM & $0/\pi$ mode instability )

- For Higher HOM power
  
  Upgrade of HOM damper

- For Higher input RF power
  
  $400$ kW/cavity -> $800$ kW/cavity
  
  R&D of input coupler using new test-stand.

Superconducting Cavity

Storing world’s highest beam current of $1.4$A. Input coupler has been operated up to $380$ kW. Ferrite Higher Order Mode (HOM) absorber working at $10$ kW (has achieved $12$ kW at $1.2$ A).

SuperKEKB challenges: The expected power load to the HOM absorber becomes $50$ kW/cavity at $4.1$ A, (even) with a larger beam pipe of $220$ mmφ. HOM damper upgrade may be needed.
Vacuum Components for High Current

- High luminosity requires high stored current in Super KEKB.

- The history of KEK was a history of fight against high current, which caused
  Heating of components, by synchrotron light and higher order modes
  Discharge and melt down
  Vacuum leak
  Displacement due to thermal expansion

- Endless upgrades of components have been done on vacuum chambers/movable masks/bellows/pumps/abort windows, etc.

- Machine protection system with fast beam abort has been developed to reduce the possible damage.

Presented by Y. Suetsugu (MOOPMA05)

Bellows chamber with comb type RF-shield

Heavy groove on the surface of a copper movable mask in HER.

Thermal deformation of the fingers for rf shield of bellows.

- High thermal strength
- Low impedance
- No sliding contact on the surface facing the beam

Comb-type bellows were installed in the LER.
For KEKB: Solenoids are so effective to reduce electron cloud.

Vertical beam size @ IP vs. LER current

Blow-up of the vertical beam size in LER has been suppressed by solenoid windings.

The covered length of solenoids reached 2,300 m raised the threshold to 1.8 A.

For SuperKEKB: Much higher current, and bunch spacing should be reduced.

Specific luminosity vs. LER current.

Solenoids are just so effective.
Ante Chamber

Smaller SR Power Density
Lower photoelectron production

Prototype ducts were installed in the LER
Energy Switch

8 GeV $e^- / 3.5$ GeV $e^+ \Rightarrow 8$ GeV $e^+ / 3.5$ GeV $e^-$

- S-band (2856 MHz) $\Rightarrow$ C-band (5712 MHz)
- Higher stored energy density in the acceleration structure $\Rightarrow$ higher acceleration field
C-band Acceleration Units

Present S-band accelerator module

Wave guide

S-band SLED

Pulse Modulator

S-band Klystron

C-band accelerating sections

41 MW 4 μs

New C-band accelerator module

Wave guide

C-band compressor

Pulse Modulator

C-band Klystron

C-band accelerating sections

40 MW 2 μs

Accel. field gradient = 21 MV/m

100kW C-band multi beam klystron is under development (WEPMA140)

Accel. field gradient = 42 MV/m

Energy Gain by C-band unit

Field gradient = 41.2 MV/m (= 39.66 MeV/0.962 m)

48 C-band klystrons
Fast Beam Mode Switch

Phase-I (2005):  
- New PF-BT line bypassed energy compression system for e^+

Phase-II (2006):  
- Multi-energy optics  
- Fast phase switch for SB Klystron

Phase-III (2007):  
- Bypass line or e^+ target with hole  
- Pulse bend

(A) Present Continuous injection mode  

KEKB e^-  KEKB e^+  

20-ms (50-Hz) RF pulse cycle  

mode switch (30 sec)

(B) High-speed beam mode switch  

KEKB e^-  KEKB e^+  KEKB e^-  KEKB e^+  PF e^-  PF-AR e^-  PF e^-  KEKB

20-ms (50-Hz) RF pulse cycle

Schematic Diagram of the RF System
Multi-Bunch Acceleration

Present 2–bunch acceleration

First Bunch

Second Bunch

SLED output

Accelerating Voltage

5–bunch acceleration

Beam Loading Compensation

5 bunches

SLED output

3-bunch acceleration with 5-bunch ready waveform was successfully tested in April 2006.

(Presented@LINAC06)

IQ circuit using FPGA will be installed
Another Idea for Super B

Long bunch approach was proposed by P. Raimondi et al, for $L = 1 \times 10^{36}$ using ILC damping ring concept.

**Short Bunch**

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

$$\xi_x \sim \frac{N}{\varepsilon_x}$$

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

$$\beta_y > \sigma_z$$

**Long Bunch**

$$L \sim \frac{N^2}{\theta \sigma_z \sqrt{\varepsilon_y \beta_y}}$$

$$\xi_x \sim \frac{N}{\theta \sigma_z} \sqrt{\beta_x}$$

$$\xi_y \sim \frac{N}{\theta \sigma_z} \sqrt{\beta_y}$$

$$\beta_y > \frac{\sqrt{\varepsilon_x \beta_x}}{\theta}$$

Overlap factor

Crab waist or traveling focus makes less emittance blow up.

Bunch length must be less than $\beta_y$. Operating point closed to half integer.

Small beta and emittance are required

Adopting this idea to KEKB is under consideration.
Summary

- Peak luminosity is increasing even after the design luminosity (10/nb/s) was obtained up to May 2005. The present peak luminosity is 17.12/nb/s.
- Present integrated luminosity is 710/fb.
- Crab cavities were installed and machine study will begin soon.
- SuperKEKB project is proposed. Designed peak luminosity is 400/nb/s.