KEKB / SuperKEKB
The Luminosity Frontier

(number of events/unit time)
= (cross section) X (luminosity)

Katsunobu Oide (KEK)
Jan. 19, 2005 @ Kyoto Univ.
http://kekb.jp
KEKB = Asymmetric Double-Ring Collider for B-Physics
8 GeV Electron + 3.5 GeV Positron

1989: Design work started.
1994: Approval of the budget, construction started.
June 1995: KEKB Design Report
Sep. 1997: Commissioning of the injector Linac started.
Dec. 1998: First beam at HER.
Jan. 1999: First beam at LER.
May 1999: Belle roll-in.
June 1999: First event at Belle.
May 2003: Exceeded the design luminosity, 10 /nb/s.
… continues rewriting own records …
Continuous Injection™

Luminosity of KEKB

- Peak Luminosity: 13.92 /nb/s
- 944 /pb/day
- 6.01 /fb/7 days
- 24.00 /fb/30 days
- 340 /fb

Update: 1/19/2005 3:00:00
The best day 5/23/2004

>1000 /pb/day delivered
944 /pb/day recorded
Up to now, KEKB is taking the lead over PEP-II by about 50% margin.

But cannot relax. They have a very ambitious plan to $2.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$ by 2007.
Continuous Injection Mode (CIM)

- Belle takes data continuously, except for veto for 3.5 msec after each injection pulse.
- 30% higher average luminosity.
- More stable operation & higher operating currents.
The machine must be tuned up as ideal, to obtain the predicted luminosity….

- Four betatron tunes
- Emittances
- Global orbit/optics correction
  - Measure orbit responses at BPMs (450/ring)
  - $\Delta \beta / \beta \leq 7 \%$
  - $\Delta \eta_y \leq 7 \text{ mm}$
  - $X$-$y$ coupling
- Tuning of local parameters at the IP
  - relative orbit offsets (5) - better than $0.1 \sigma$, looking at beam-beam deflections, beam sizes, and Belle vertex
  - Vertical waists (2) $\pm 0.5 \text{ mm}$
  - vertical dispersions (4)
  - $x$-$y$ coupling parameters (8)
Collision with a finite crossing angle

- Easier beam separation.
- No bend for the incoming beam (less radiation).
- No separation bends (less background).
- Simplified IR.
- Room for solenoid compensation, smaller $\beta^*$.  

So, the merits were obvious, but was that safe enough?

- What about the synchrotron-betatron coupling?

$$H \approx f \left( x + \frac{x'z}{2} + \theta_x z, \ y + \frac{y'z}{2} \right) \delta(s - nC)$$

$z$: longitudinal position in a bunch, $\theta_x$: horizontal half crossing angle
Collision with a finite crossing angle

Synchrotron-betatron couplings are inevitable for a beam-beam interaction anyway, even with a head-on collision.

\[ f_y \approx \frac{4 \pi \xi_y}{\beta_y} \left( y + \frac{y'z}{2} \right)^2 \left( 1 - \frac{(x + \theta_x z)^2}{2 \sigma_x^2} \right) \delta(s - nC) + \text{higher orders} \]

The relative magnitude of the crossing angle term is about same as the original term.

Strong-weak simulations, KEKB Design Report, 1996

Crossing angle is manageable, if we choose the tunes.
Crab crossing in the near future

- Crab crossing will boost the beam-beam parameter up to 0.14!
  - (Strong-weak simulation)
  - Head-on (crab)
  - Crossing angle 22 mrad

- Superconducting crab cavities are under development, will be installed in KEKB in early 2006.
Fabrication & Processing 1

Niobium Sheet (Tokyo Denkai Co., Ltd.)
- Thickness = 5 mm, RRR=180

Half Cell Hydro-forming

Mechanical Polishing

Trimming of Half Cell

Beam Pipes

Electron Beam Welding

Grinding of Welded Part
  - Equator of Cell
    - ~100 μm

Barrel Polishing
  - ~100 μm

Electro-Polishing
  - HF+H₂SO₄ 1:10 in vol., ~100 μm

High Pressure Water Rinsing

Annealing
  - 700 °C, 3 hrs.

High Pressure Water Rinsing
  - 80 kg/cm², 60 min.

RF Cold Test
  - 4.2 K

Fabrication & Processing of Crab Cavity

Hydro-forming

Grinding of Welding Part

Barrel Polishing

Nb Half Cell
Fabrication & Processing 2

Electro-Polishing

Annealing at 700°C for 3 hours

High Pressure Water Rinsing by 80 bar Ultra-Pure water
1 /ab comes on the horizon!

Crab Cavity Beam Test

We are here

Initial goal

18 /fb/mo.

24 /fb/mo.

44 /fb/mo.

Projection of KEKB Luminosity
SuperKEKB, the next step
Three factors to determine luminosity:

 Stored current:
  1.2/1.65 A (KEKB)
  \[ \rightarrow 4.1/9.4 \text{ A (SuperKEKB)} \]

 Beam-beam parameter:
  0.057 (KEKB)
  \[ \rightarrow 0.14 \text{ (SuperKEKB)} \]

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

 Vertical \( \beta \) at the IP:
  5.2/6.5 mm (KEKB)
  \[ \rightarrow 3.0/3.0 \text{ mm (SuperKEKB)} \]
Colliding Bunches at KEKB / SuperKEKB

Hor. Crossing Angle 22 / 30 mrad

World’s smallest beam size in ring colliders

Height: 2.1 / 1.4 μm
Width: 110 / 59 μm
Length: 7 / 3 mm

7.8 / 11.8 × 10^{10} positrons/bunch
5.8 / 5.1 × 10^{10} electrons/bunch

Revolution period: 10 μsec
1293 / 5018 bunches / beam
6 - 8 / 2 ns bunch spacing
8GeV Positron beam 4.1 Å
3.5GeV Electron beam 9.4 Å

Super B Factory at KEK
$\text{HOM} \propto \frac{N \pm I \pm}{\sigma_z}$

$I_\pm = N_\pm N_b f_{\text{rev}}$

$L \approx \frac{\gamma \pm I \pm \xi \pm y}{2e r_e \beta_y^*}$

$\sigma_z \leq \beta_y^*$

Complicated Object

High-power RF

Beam Instabilities

Electron cloud Fast ion

precise control of linear optics

shorter lifetime

smaller aperture

Heating, discharge, destruction...

Impedance of components

Belle background

higher chromaticity

Strong injector

Orbit drift

Beam Instabilities

Strong injector
ARES Cavity

- Passive stabilization with huge stored energy.
- Eliminates unnecessary modes by a coupling of 3 cavities.
- Higher order mode dampers and absorbers.
- No need for longitudinal bunch-by-bunch feedback.
- No transverse instability arises from the cavities.

Superconducting Cavity

- World’s highest current, 1.2 A.
- Input coupler has been operated up to 380 kW.
- Ferrite HOM absorber working at 10 kW.
ARES upgrade for SuperKEKB

◆ Larger detuning
  ⇒ Change energy ratio : Us/Ua = 9 → 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/π
mode instability )

◆ Higher HOM power
  Upgrade of HOM damper

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

Talks by Kageyama, Abe
Superconducting Cavity

SuperKEKB challenges:
The expected power load to the HOM absorber is 50 kW/cavity at 4.1 A, (even) with a larger beam pipe of 220 mm φ.

HOM damper upgrade may be needed.
Electron cloud

Blow-up of the vertical beam size in LER has been suppressed by more solenoid windings. The covered length of solenoids reached 2,300 m, raised the threshold to 1.8 A.

Specific luminosity vs. LER current. Solenoids are just so effective.
Winding more solenoids in the LER
Vacuum components: Antechamber-type copper duct

Smaller SR Power Density
Lower Impedance
Lower photoelectron production

Prototype ducts were installed in the LER (Jan.2004)

Talk by Suetsugu
Fight for High Current

- High luminosity always requires high stored current.
- 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
  Damage on Belle detectors
- 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.
Vacuum components:
Bellows chamber with comb type RF-shield

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

Comb-type bellows were installed in the LER (2004).

Talk by Suetsugu
C-Band Klystrons

Prototype C-band structure installed and tested at linac using actual beam (2003). Measured field gradient of 41 MV at 43 MW agrees with expectation.

Table 11.3: Accelerating section characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S-band</th>
<th>1-st prototype</th>
<th>C-band</th>
<th>2m-structure</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>KEKB</td>
<td>1.082</td>
<td>2.0</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>total length</td>
<td>2.072</td>
<td>108</td>
<td></td>
<td></td>
<td>MM</td>
</tr>
<tr>
<td>number of regular cells</td>
<td>54</td>
<td>54</td>
<td>108</td>
<td></td>
<td></td>
</tr>
<tr>
<td>regular cell length (d)</td>
<td>35.0</td>
<td>17.5</td>
<td>17.5</td>
<td></td>
<td>MM</td>
</tr>
<tr>
<td>disk thickness (t)</td>
<td>5.0</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
<td>MM</td>
</tr>
<tr>
<td>disk iris diameter (2a)</td>
<td>24.95</td>
<td>12.48 - 10.45</td>
<td>14.03</td>
<td>10.54</td>
<td>MM</td>
</tr>
<tr>
<td>cavity diameter (2b)</td>
<td>83.0</td>
<td>41.5 - 41.0</td>
<td>42.0</td>
<td>41.0</td>
<td>MM</td>
</tr>
<tr>
<td>group velocity (v_y/c)</td>
<td>1.4</td>
<td>1.9 - 1.0</td>
<td>2.8</td>
<td>1.0</td>
<td>%</td>
</tr>
<tr>
<td>shunt impedance</td>
<td>57</td>
<td>75 - 85</td>
<td>67</td>
<td>85</td>
<td>MΩ/m</td>
</tr>
<tr>
<td>Q factor</td>
<td>13700</td>
<td>9690</td>
<td>9700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF power in cells</td>
<td>30</td>
<td>34 - 15</td>
<td>59</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Field gradient</td>
<td>21</td>
<td>41.2 - 39.0</td>
<td>42.5</td>
<td>38.1</td>
<td></td>
</tr>
<tr>
<td>Filling time</td>
<td>462</td>
<td>234</td>
<td>376</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attenuation constant</td>
<td>0.302</td>
<td>0.434</td>
<td>0.696</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 11.7: C-band 1m-long accelerating section (1-st prototy

Talk by Kamitani
• Positron emittance needs to be damped, to pass reduced aperture of C-Band section and to meet IR dynamic aperture restrictions.
  – Electron DR may be considered later to reduce injection backgrounds in physics detector, but for now only positron DR considered.

• Damping ring located downstream of positron target, before C-Band accelerating section.
How long should we run?

Projection of KEKB Luminosity

- Data doubling period > 4 yrs = unhealthy
- How long should we run?
How much do we need?

SuperKEKB 年次計画 (2005.1.11)

総額: 465.8 Oku-yen
We may invite another detector.

... if you like it.
Summary

• KEKB has been the front runner on the luminosity frontier.
• 1 /ab will be reached around 2007.
• A technically feasible design of SuperKEKB for $2.5 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$ has been done.
Luminosity*:

\[ L = \frac{N_+ + N_- f}{4 \pi \sigma^*_x \sigma^*_y} R_L \]

Beam-beam tune shift parameter*:

\[ \xi_{\pm x, y} = \frac{r_e}{2 \pi \gamma_{\pm}} \frac{N_+ \beta^*_{x,y}}{\sigma^*_{x,y} (\sigma^*_x + \sigma^*_y)} R_{x,y} \]

Beam current:

\[ I_{\pm} = N_{\pm} e f \]

Luminosity rewritten:

\[ L = \frac{\gamma_{\pm}}{2 e r_e} \left( 1 + \frac{\sigma^*_y}{\sigma^*_x} \right) I_{\pm} \xi_{\pm y} \left( \frac{R_L}{R_y} \right) \]

\[ L \approx \frac{\gamma_{\pm} I_{\pm} \xi_{\pm y}}{2 e r_e \beta^*_y} \]

*Assume both beams have the same sizes and \( \beta^* \)'s.
The magnetic shield is made by 3mm thick permalloy sheet by spinning and forming. The cell and beam pipe parts can divide into two pieces and assemble around the crab cavity.
## Parameters for SuperKEKB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>bare lattice</th>
<th>with beam-beam</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current (LER/HER)</td>
<td>I</td>
<td>9.4/4.1</td>
<td>9.4/4.1</td>
</tr>
<tr>
<td>Beam energy (LER/HER)</td>
<td>E</td>
<td>3.5/8.0</td>
<td>3.5/8.0</td>
</tr>
<tr>
<td>Emittance</td>
<td>$\varepsilon_x$</td>
<td>24</td>
<td>77</td>
</tr>
<tr>
<td>Horizontal beta at IP</td>
<td>$\beta_x^*$</td>
<td>20</td>
<td>4.5</td>
</tr>
<tr>
<td>Vertical beta at IP</td>
<td>$\beta_y^*$</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>Horizontal beam size</td>
<td>$\sigma_x^*$</td>
<td>69</td>
<td>59</td>
</tr>
<tr>
<td>Vertical beam size</td>
<td>$\sigma_y^*$</td>
<td>0.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Beam size ratio</td>
<td>$r = \sigma_y^<em>/\sigma_x^</em>$</td>
<td>1</td>
<td>2.4</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>$\theta_x$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Luminosity reduction</td>
<td>$R_L$</td>
<td>0.86</td>
<td>0.81</td>
</tr>
<tr>
<td>$\xi_x$ reduction</td>
<td>$R_{\xi_x}$</td>
<td>0.99</td>
<td>0.97</td>
</tr>
<tr>
<td>$\xi_y$ reduction</td>
<td>$R_{\xi_y}$</td>
<td>1.11</td>
<td>1.17</td>
</tr>
<tr>
<td>Horizontal beam-beam</td>
<td>$\xi_x$</td>
<td>0.137</td>
<td>0.041</td>
</tr>
<tr>
<td>Vertical beam-beam</td>
<td>$\xi_y$</td>
<td>0.218</td>
<td>0.108</td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>$R_L/R_{\xi_y}$</td>
<td>0.78</td>
<td>0.70</td>
</tr>
<tr>
<td>Luminosity</td>
<td>L</td>
<td>$4 \times 10^{35}$</td>
<td>$2.4 \times 10^{35}$</td>
</tr>
</tbody>
</table>
Table 1: Machine parameters of KEK, comparing to the design values.

<table>
<thead>
<tr>
<th>Date</th>
<th>6/7/2004</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER</td>
<td>HER</td>
</tr>
<tr>
<td>Current</td>
<td>1.58</td>
<td>1.19</td>
</tr>
<tr>
<td>Bunches</td>
<td>1289</td>
<td>5000</td>
</tr>
<tr>
<td>Bunch current</td>
<td>1.2</td>
<td>0.92</td>
</tr>
<tr>
<td>Spacing</td>
<td>1.8-2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Emittance $\varepsilon_x$</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>$\beta_x^*$</td>
<td>59</td>
<td>56</td>
</tr>
<tr>
<td>$\beta_y^*$</td>
<td>0.52</td>
<td>0.65</td>
</tr>
<tr>
<td>Hor. Size @ IP</td>
<td>103</td>
<td>116</td>
</tr>
<tr>
<td>Ver. Size @ IP</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Bunch length</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Beam-beam $\xi_x$</td>
<td>.107</td>
<td>.075</td>
</tr>
<tr>
<td>Beam-beam $\xi_y$</td>
<td>.070</td>
<td>.057</td>
</tr>
<tr>
<td>Ave. pressure</td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td>Lifetime</td>
<td>160</td>
<td>220</td>
</tr>
<tr>
<td>Luminosity</td>
<td>13.92</td>
<td>10</td>
</tr>
<tr>
<td>$\int L\text{um}/\text{day}$</td>
<td>944</td>
<td>~600</td>
</tr>
<tr>
<td>$\int L\text{um}/7\text{ days}$</td>
<td>5.94</td>
<td>–</td>
</tr>
<tr>
<td>$\int L\text{um}/30\text{ days}$</td>
<td>24.00</td>
<td>–</td>
</tr>
<tr>
<td>$\int L\text{um}, \text{total}$</td>
<td>271/5 years</td>
<td>100/3 years</td>
</tr>
</tbody>
</table>

Units: A (Amperes), mA (Milliampere), m (Meters), mm (Millimeters), nm (Nanometers), μm (Micrometers), nPa (NanoPascals), min. (Minutes), /nb/s (Events per second).
## Machine parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LER/HER</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>$E$</td>
<td>3.5/8.0 GeV</td>
</tr>
<tr>
<td><strong>Beam current</strong></td>
<td>$I$</td>
<td>9.4/4.1 A</td>
</tr>
<tr>
<td><strong>Particles/bunch</strong></td>
<td>$N$</td>
<td>$1.18 \times 10^{11}/5.13 \times 10^{10}$</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>$n_b$</td>
<td>5018</td>
</tr>
<tr>
<td><strong>Circumference</strong></td>
<td>$C$</td>
<td>3016.26 m</td>
</tr>
<tr>
<td><strong>Bunch spacing</strong></td>
<td>$\sigma_b$</td>
<td>0.6 m</td>
</tr>
<tr>
<td><strong>Horizontal $\beta$ at IP</strong></td>
<td>$\beta_x$</td>
<td>200 mm</td>
</tr>
<tr>
<td><strong>Vertical $\beta$ at IP</strong></td>
<td>$\beta_y$</td>
<td>3 mm</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
<td>$\sigma_z$</td>
<td>3 mm</td>
</tr>
<tr>
<td><strong>Radiation loss</strong></td>
<td>$U_0$</td>
<td>1.23/3.48 MeV/m</td>
</tr>
<tr>
<td><strong>Horizontal beam-beam</strong></td>
<td>$\xi_x$</td>
<td>0.137</td>
</tr>
<tr>
<td><strong>Vertical beam-beam</strong></td>
<td>$\xi_y$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Talk by Ohnishi
Reducing LER $\nu_x$ from 0.510 to 0.506 increased the luminosity by 20% in 2003, as the simulation predicted.

20% more luminosity is expected by reducing HER $\nu_x$ from 0.513 to 0.507.