The SuperBelle Project

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(for the “SuperBelle” collaboration)

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Outline
- Motivation
- Requirements
- Design
- Summary
The KEKB Collider

8 x 3.5 GeV
22 mrad crossing angle

World record:

\[ L = 1.7 \times 10^{34}/\text{cm}^2/\text{sec} \]
B factory main task: measure CP violation in the system of B mesons

specifically: various measurements of complex elements of Cabbibo-Kobayashi-Maskawa matrix

Transitions between members of the same family more probable (=thicker lines) than others

→ CKM: unitary matrix
→ CKM: almost a diagonal matrix, but not completely
→ CKM: almost real, but not completely...

deviations could signal processes not included in SM
Belle spectrometer at KEK-B

- **Aerogel Cherenkov Counter** (n=1.015-1.030)
- **Electromag. Cal.** (CsI crystals, 16X₀)
- **ToF counter**
- **1.5T SC solenoid**
- **Silicon Vertex Detector** (4 layers DSSD)
- **Central Drift Chamber** (small cells, He/C₂H₆)
- **µ and K_L detection system** (14/15 layers RPC+Fe)
- **3.5 GeV e⁺**
- **8 GeV e⁻**

+ an extremely well operating KEK-B collider
CP violation in the decays of B:

\[ B \rightarrow f_{CP} \quad \bar{B} \rightarrow f_{CP} \]

Time dependence of the decays

Asymmetry = \( \frac{(\bar{N}-N)}{(\bar{N}+N)} \)

CP is violated, violation in excellent agreement with the Kobayashi-Maskawa theory \( \Rightarrow \) Nobel prize 2008
B factories: a success story

- Measurements of **CKM** matrix elements and **angles** of the unitarity triangle
- Observation of **direct** CP violation in B decays
- Measurements of rare decay modes (e.g., \(B \to \tau \nu\), \(D \to \tau \nu\)) by fully reconstructing the other B meson
- Observation of D mixing
- CP violation in \(b \to s\) transitions: probe for new sources if CPV
- Forward-backward asymmetry (\(A_{FB}\)) in \(b \to s l^+ l^-\) has become a powerful tool to search for physics beyond SM.
- Observation of new hadrons
Physics at a Super B Factory

- Next step: precision measurements
- **Much larger sample needed** $\Rightarrow$ SuperB factory
- There is a good chance to see new phenomena;
  - CPV in B decays from the new physics (non KM).
  - Lepton flavor violations in $\tau$ decays.
- They will help to diagnose (if found) or constraint (if not found) new physics models.
- Even in the worst case scenario (such as MFV), $B \rightarrow \tau \nu$, $D_{\tau \nu}$ can probe the charged Higgs in large tan$\beta$ region.
- **Physics motivation is independent of LHC.**
  - If LHC finds NP, precision flavour physics is compulsory.
  - If LHC finds no NP, high statistics $B/\tau$ decays would be an unique way to search for the TeV scale physics.
Luminosity of different accelerators vs. time

Super-B factory
KEKB upgrade plan: Super-B Factory at KEK

- Asymmetric energy $e^+e^-$ collider at $E_{CM} = m(Y(4S))$ to be realized by upgrading the existing KEKB collider.
- **Initial target:** $10 \times$ higher luminosity $\cong 2 \times 10^{35}$/cm$^2$/sec after 3 year shutdown
  $\rightarrow 2 \times 10^9 \ BB \ and \ \tau^+\tau^-$ per yr.
- **Final goal:** $L = 8 \times 10^{35}$/cm$^2$/sec and $\int L \ dt = 50 \ ab^{-1}$

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- **Crab cavity**
- **New IR with crab crossing and smaller $\beta_y^*$**
- **New beam-pipes with ante-chamber**
- **More RF for higher beam current**
- **Damping ring for $e^*$**
- **Si vertex detector with very short strips**
- **Faster calorimeter with waveform sampling and pure CsI**
- **Background tolerant small cell drift chamber**
Crab cavity commissioning

Installed in the tunnel (Feb. 2007)
Under commissioning
Requirements for the Super B detector

Critical issues at $L = 8 \times 10^{35}$/cm$^2$/sec

- **Higher background (×20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM

- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing

- **Require special features**
  - low $p, \mu$ identification $\rightarrow s_{\mu\mu}$ recon. eff.
  - hermeticity $\rightarrow \nu$ “reconstruction”

Possible solution:
- Replace inner layers of the vertex detector with a silicon striplet or pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace endcap calorimeter by pure CsI.
- Faster readout electronics and computing system.
Belle Upgrade for Super-B

SC solenoid
1.5T

Csl(Tl) 16X₀ → pure CsI (endcap)

μ / Kₐ detection
14/15 lyr. RPC+Fe → tile scintillator

Aerogel Cherenkov counter + TOF counter
→ “TOP” or fDIRC + Aerogel RICH

Tracking + dE/dx
small cell + He/C₂H₆
→ remove inner lyr.
fast gas+Si r<20 cm

Si vtx. det.
4 lyr. DSSD → 2 pixel/striplet lyr.
+ 4 lyr. DSSD

New readout and computing systems
**SVD Upgrade**

- **Readout chip:** VA1TA → APV25
  - Reduction of occupancy coming from beam background.
  - Pipeline readout to reduce dead time.

- **Sensors of the innermost layer:**
  Normal double sided Si detector (DSSD) → Pixel sensors

- **Configuration:** 4 layers → 6 layers (outer radius = 8cm → 4cm)
  - More robust tracking
  - Higher Ks vertex reconstruction efficiency

- **Inner radius:** 1.5cm → 1.0cm
  - Better vertex resolution. Not on day 1.
CDC Upgrade

- Larger outer radius: 752mm → 978mm
  - Longer lever arm → better $P_t$ reso.
  - More samplings → better dE/dx reso.
- Smaller cell size:
  12mm, 64cells → 8mm, 160cells
  - Improved background tolerance
- New ASD with fast shaping

20nsec
Time Of Propagation (TOP) counter

- Cherenkov ring imaging with precise time measurement:
- Reconstruct angle from one coordinate and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
  - Good time resolution < ~ 40 ps
  - Single photon sensitive under 1.5 T
Aerogel RICH

- Proximity focusing RICH with aerogel radiator

Highly transparent aerogel: $\Lambda_t > 40\text{mm} (\lambda=400\text{nm})$

Multi-pixel photodetector to measure single photon positions in $B=1.5T$
- Hybrid Avalanche PhotoDiode
- Micro Channel Plate - PMT
- Geiger mode Avalanche PhotoDiode
Multiple layer radiator

How to increase number of photons w/o degrading resolution?
Use of radiator with increasing refractive ind. – focusing radiator

- both layers with the same $n$ - “normal” configuration
- rings overlap from different layers - “focusing” configuration
Aerogel RICH – test results

4cm aerogel single index

\[ \chi^2 / \text{ndf} = 2467. / 116 \]
\[ P1 = 5495. \]
\[ P2 = 0.2965 \]
\[ P3 = 0.2072 \times 10^{-1} \]
\[ P4 = 85.32 \]
\[ P5 = 796.0 \]

\[ n_f = 7.69 \]
\[ n_b = 1.09 \]

\[
\begin{array}{c}
\text{theta cerenkov} \\
\theta_\text{(rad)}
\end{array}
\]

\[
\begin{array}{c}
\text{ring in cerenkov space} \\
\text{tx(rad)}
\end{array}
\]

2+2cm aerogel

\[ \chi^2 / \text{ndf} = 1095. / 116 \]
\[ P1 = 7289. \]
\[ P2 = 0.3074 \]
\[ P3 = 0.1428 \times 10^{-1} \]
\[ P4 = 74.49 \]
\[ P5 = 884.4 \]

\[ n_f = 7.46 \]
\[ n_b = 0.83 \]

\[
\begin{array}{c}
\text{theta cerenkov} \\
\theta_\text{(rad)}
\end{array}
\]

\[
\begin{array}{c}
\text{ring in cerenkov space} \\
\text{tx(rad)}
\end{array}
\]
ECL Upgrade

- Increase of dark currents due to neutron flux
- Fake clusters & pile-up noise

**Barrel:**
- 0.5\(\mu\)s shaping + 2MHz w.f. sampling.

**Endcap:**
- Pure CsI + photopentods
- 30ns shaping + 43MHz w.f. sampling

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**Barrel**

- \(\times 1/1.5\)

**BW endcap**

- \(\times 1/5\)

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Pure CsI & photopentods
Scintillator-based KLM (endcap)

- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%

Mirror 3M (above groove & at fiber end)

Optical glue increase the light yield ~ 1.2-1.4

WLS: Kurarai Y11 Ø1.2 mm

Diffusion reflector \((\text{TiO}_2)\)  Strips: polystyrene with 1.5% PTP & 0.01% POPOP
• B factories have proven to be an excellent tool for flavour physics
• Reliable long term operation, constant improvement of the performance.
• Major upgrade in 2009-12 → Super B factory, L x10 -> x40
• Essentially a new project, all components have to be replaced, plans exist (LoI), nothing is frozen...
• Expect a new, exciting era of discoveries, complementary to LHC
Super B factory: an important part of a broad unbiased approach to New Physics

ν experiments, $g_{\mu} - 2$, $\mu \rightarrow e$, etc.

LHC, ILC

Mass spectrum, interactions

ν mass and mixing, CPV, and LFV

New physics

Quark sector

Lepton sector

Energy frontier

τ LFV, CPV

Flavor mixing, CP phases

Super B factory, LHCb, $K$ experiments...
Comparison with LHCb

<table>
<thead>
<tr>
<th>$e^+e^-$ has advantages in...</th>
<th>LHCb has advantages in...</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPV in $B \rightarrow \phi K_S$, $\eta' K_S$,...</td>
<td>CPV in $B \rightarrow J/\psi K_S$</td>
</tr>
<tr>
<td>CPV in $B \rightarrow K_S \pi^0 \gamma$</td>
<td>Most of $B$ decays not including $\nu$ or $\gamma$</td>
</tr>
<tr>
<td>$B \rightarrow K \nu\nu$, $\tau \nu$, $D^*(\tau)\nu$</td>
<td>Time dependent measurements of $B_S$</td>
</tr>
<tr>
<td>Inclusive $b \rightarrow s \mu\mu$, see</td>
<td>$B_{(s,d)} \rightarrow \mu\mu$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma$ and other LFV</td>
<td>$B_c$ and bottomed baryons</td>
</tr>
<tr>
<td>$D^0\bar{D}^0$ mixing</td>
<td>Complementary!!</td>
</tr>
</tbody>
</table>
How to achieve the super-high luminosity

**Stored current:**
1.34 / 1.8 A (KEKB)  
→ 4.1 / 9.4 A (SuperKEKB)

**Beam–beam parameter:**
0.057 (KEKB)  
→ 0.19 (SuperKEKB)

**Luminosity:**
0.15 × 10^{35} \, \text{cm}^{-2}\text{s}^{-1} \, \text{(KEKB)}
4 × 10^{35} \, \text{cm}^{-2}\text{s}^{-1} \, \text{(SuperKEKB)}

**Bunch length** \((\sigma_s)\)
7 ~ 9 mm \,-\, 3 \, \text{mm}

**Vertical \(\beta\) at the IP:**
5.2/6.5 mm (KEKB)
→ 3.0/3.0 mm (SuperKEKB)

**Crab cavity**

\[
L = \frac{\gamma_{\pm}}{2e} \frac{1 + \frac{\sigma_y^*}{\sigma_x^*}}{\beta_y^*} \frac{I_{\pm} e^{-\xi_{\pm} y}}{R_L} \frac{R_y}{R_L}
\]

- **Lorentz factor**
- **Classical electron radius**
- **Beam size ratio**
- **Geometrical reduction factors due to crossing angle and hour-glass effect**
<table>
<thead>
<tr>
<th>Item</th>
<th>Gain</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam pipe</td>
<td>x 1.5</td>
<td>high current, short bunch, electron cloud</td>
</tr>
<tr>
<td>IR($\beta_x^* = 20\text{cm}/3\text{mm}$)</td>
<td>x 1.5</td>
<td>small beam size at IP</td>
</tr>
<tr>
<td>low emittance(12 nm)</td>
<td>x 1.3</td>
<td>mitigate nonlinear effects with beam-beam</td>
</tr>
<tr>
<td>$v_x \to 0.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>crab crossing</td>
<td>x 2</td>
<td>mitigate nonlinear effects with beam-beam</td>
</tr>
<tr>
<td>RF/infrastructure</td>
<td>x 3</td>
<td>high current</td>
</tr>
<tr>
<td>DR/e+ source</td>
<td>x 1.5</td>
<td>low $\beta^*$ injection, improve $e^+$ injection</td>
</tr>
<tr>
<td>charge switch</td>
<td>x ?</td>
<td>electron cloud, lower $e^+$ current</td>
</tr>
</tbody>
</table>
KEKB’s Track Record

~ 1.3 Billion $\bar{B}B$ pairs

$\sim 1274/\text{fb}$!

$L_{\text{peak}}$ (KEKB) = $1.7 \times 10^{34}$/cm$^2$/sec (design 1.0)
Luminosity Prospects

Results from Super-Belle w/ ~10ab-1 LHC(b)
Situation of LC...

10ab⁻¹ (initial target) ~ 2016
3 year shutdown for upgrade

L ~ 2 x 10³⁵ cm⁻² s⁻¹

50ab⁻¹ by ~ 2020

L ~ 8 x 10³⁵ cm⁻² s⁻¹
Crab cavity commissioning

Crab Crossing

- 49 sp. $\beta x^* = 80, 84 \text{cm}$
- $\beta x^* = 80 \text{ cm}$
- $\beta x^* = 90 \text{ cm}$
- $\beta x^* = 68 \text{ cm}$
- $\beta x^* = 100 \text{ cm}$
- 3.06 bucket spacing
- 22 mrad crossing

Simulation head-on
Simulation 22 mrad

Specific Luminosity/bunch $[10^{30} \text{ cm}^{-2} \text{s}^{-1} \text{mA}^{-2}]$

Total Bunch Current $I_{\text{bunch \ HER}} \times I_{\text{bunch \ LER}} [\text{mA}^2]$
Ante-chamber / solenoid for reduction of electron clouds

Ante-chamber with solenoid field
Conservative, robust detector should handle up to 20 times more background

Rad-Bhabha mask around QCS magnet
IR chamber design

Results based on GEANT sims validated by Belle/KEKB experience.
Main challenge: R+D of a photon detector for operation in high magnetic fields (1.5T)

Candidates:
• MCP PMT: excellent timing, could be also used as a TOF counter
• HAPD: proximity focusing mode, problems with the stability
• SiPMs: easy to handle, but never before used for single photon detection (high dark count rate with single photon pulse height) → use a narrow time window and light concentrators

First Cherenkov photons observed with SiPMs!
Detector module for beam tests at KEK

SiPMs: array of 8x8 SMD mount Hamamatsu S10362-11-100P with 0.3mm protective layer

Light guides

SiPMs

SiPMs + light guides

2cm
Rare decays - prospects

- Radiative, electroweak and tauonic B decays are of great importance to probe new physics.

- We are starting to measure $B \to \tau\nu, K\nu\nu, D\tau\nu, A_{FB}(K^{*}\Pi), A_{CP}(K\pi^{0}\gamma)$ etc. at the current B factories.

  → Hot topics in the coming years!

- For precise measurements, we need a Super-B factory!

  → Observe $K^{(*)}\nu\nu$, zero crossing in $A_{FB}, D^{(*)}\tau\nu$

  → Expected precision ($5\text{ab}^{-1} \to 50\text{ab}^{-1}$);

    - $\text{Br}(\tau\nu)$: 13% → 7%
    - $\text{Br}(D^{(*)}\tau\nu)$: 7.9% → 2.5%
    - $q_{0}^{2}$ of $A_{FB}(K^{*}\Pi)$: 11% → 5%
    - $A_{CP}(K\pi^{0}\gamma)$ tCPV: 0.14 → 0.04
## SuperB vs SuperKEKB

### Notes:
- SuperB length w/o spin rotators.
- SuperKEKB luminosity assumes x2 gain from crab cavities.

SuperB luminosity arises from small emittance & small $\beta^*$ compared to SuperKEKB.

<table>
<thead>
<tr>
<th></th>
<th>SuperB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>1800</td>
<td>3016</td>
</tr>
<tr>
<td>Energy (GeV) (LER/HER)</td>
<td>4/7</td>
<td>3.5/8</td>
</tr>
<tr>
<td>Current (A)/beam</td>
<td>1.85</td>
<td>9.4/4.1</td>
</tr>
<tr>
<td>No. bunches</td>
<td>1251</td>
<td>5018</td>
</tr>
<tr>
<td>No. part/bunches</td>
<td>5.5x10¹⁰</td>
<td>12/5x10¹⁰</td>
</tr>
<tr>
<td>$\theta$ (rad)</td>
<td>2x24</td>
<td>2x15</td>
</tr>
<tr>
<td>$\varepsilon_x$ (nm-rad) (LER/HER)</td>
<td>2.8/1.6</td>
<td>24</td>
</tr>
<tr>
<td>$\varepsilon_y$ (pm-rad) (LER/HER)</td>
<td>7/4</td>
<td>180</td>
</tr>
<tr>
<td>$\beta_y^*$ (mm) (LER/HER)</td>
<td>0.22/0.39</td>
<td>3</td>
</tr>
<tr>
<td>$\beta_x^*$ (mm) (LER/HER)</td>
<td>35/20</td>
<td>200</td>
</tr>
<tr>
<td>$\sigma_y^*$ (µm) (LER/HER)</td>
<td>0.039</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_x^*$ (µm) (LER/HER)</td>
<td>10/6</td>
<td>50</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>$L$ (cm⁻²s⁻¹)</td>
<td>1x10³⁶</td>
<td>4x10³⁵</td>
</tr>
</tbody>
</table>
## Comparison between SuperB and SuperKEKB

<table>
<thead>
<tr>
<th></th>
<th>SuperB (Nominal)</th>
<th>SuperKEKB (2006)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance</td>
<td>$\varepsilon_x$</td>
<td>1.6</td>
<td>9 nm</td>
</tr>
<tr>
<td>Horizontal beta</td>
<td>$\beta_x^*$</td>
<td>20</td>
<td>200 mm</td>
</tr>
<tr>
<td>Vertical beta</td>
<td>$\beta_y^*$</td>
<td>0.3</td>
<td>3 mm</td>
</tr>
<tr>
<td>Horizontal beam size</td>
<td>$\sigma_x^*$</td>
<td>5.7</td>
<td>42 µm</td>
</tr>
<tr>
<td>Vertical beam size</td>
<td>$\sigma_y^*$</td>
<td>35</td>
<td>367 nm</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$</td>
<td>6</td>
<td>3 mm</td>
</tr>
<tr>
<td>Half crossing angle</td>
<td>$\phi_x$</td>
<td>17</td>
<td>15 mrad</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>$\varphi$</td>
<td>18</td>
<td>1 rad</td>
</tr>
<tr>
<td>Current (LER/HER)</td>
<td>$I_b$</td>
<td>2.28/1.30</td>
<td>9.4/4.1 A</td>
</tr>
<tr>
<td>Luminosity ($\times 10^{35}$)</td>
<td>$L$</td>
<td>10</td>
<td>8 cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>AC Plug Power</td>
<td>$P$</td>
<td>34</td>
<td>83 MW</td>
</tr>
</tbody>
</table>

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AC power for KEKB is already 40 MW. Max site power is 100 MW at KEK.