Novel Accelerator Methods and Technologies for KEKB Upgrade

J.W. Flanagan, KEK, for the SuperKEKB group

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DPF2011
Outline

- Machine Design Overview
- Particular Challenges
  - IR
  - Vacuum
  - Injector
  - Instrumentation
  - Alignment & Stabilization
- Construction & Commissioning
KEKB History

Luminosity of KEKB
Oct. 1999 - June 2010

since Feb. 2007
Crab Crossing

Peak luminosity 21.1 /nb/s
$10^{34}$ cm$^{-2}$s$^{-1}$
$=10$ /nb/s

1479 /pb/day
600 /pb/day
8.43 /fb/7 days
30.2 /fb/30 days

1039 /fb

Integrated luminosity (1/fb)
$\text{e}^+\text{-e}^- \text{ Colliders}$

Peak luminosity trends (e+e- colliders)

Luminosity

Year


Next-generation B-factories
Replace short dipoles with longer ones (LER)

Redesign the lattices of both rings to reduce the emittance

TiN-coated beam pipe with antechambers in LER

Add / modify RF systems for higher beam current

New superconducting final focusing quads near the IP

Low emittance positrons to inject

Positron source

New positron target / capture section

Low emittance electrons to inject

Low emittance gun

colliding bunches

$e^+ 4 \text{ GeV} 3.6 \text{ A}$

$e^- 7 \text{ GeV} 2.6 \text{ A}$

SuperKEKB

New beam pipe & bellows

Belle II

New IR

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x 40 Gain in Luminosity

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x 40 Gain in Luminosity
Design Concept of SuperKEKB

• Increase the luminosity by 40 times based on “Nano-Beam” scheme, which was first proposed for SuperB by P. Raimondi.

  • Vertical $\beta$ function at IP: $5.9 \rightarrow 0.27/0.30$ mm ($\times 20$)

  • Beam current: $1.7/1.4 \rightarrow 3.6/2.6$ A ($\times 2$)

  • Beam-beam parameter: $.09 \rightarrow .09$ ($\times 1$)

  \[
  L = \frac{\gamma \pm}{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{\pm \xi\pm y}}{\beta^*_y} \right) \left( \frac{R_L}{R_y} \right) = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}
  \]

  • Beam energy: $3.5/8.0 \rightarrow 4.0/7.0$ GeV

LER : Longer Touschek lifetime and mitigation of emittance growth due to the intra-beam scattering
HER : Lower emittance and lower SR power
Collision Scheme

**KEKB head-on (crab crossing)**

- $\sigma_x^*$ 100-150 $\mu$m
- $\sigma_z$ 6-7 mm

**Nano-Beam SuperKEKB**

- $\sigma_z$ 5-6 mm
- $\sigma_x^*$ 10-12 $\mu$m

Overlap region = bunch length

Overlap region $\ll$ bunch length

**Hourglass requirement**

- $\beta_y^* \geq \sigma_z \sim 6$ mm
- $\beta_y^* \geq \frac{\sigma_x^*}{\phi} \sim 300$ $\mu$m

Vertical beta function at IP can be squeezed to $\sim300$ $\mu$m. Need small horizontal beam size at IP.

$\rightarrow$ low emittance, small horizontal beta function at IP.

Y. Ohnishi et al.
## Comparison of Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KEKB Design</th>
<th>KEKB Achieved: with crab</th>
<th>SuperKEKB Nano-Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV) (LER/HER)</td>
<td>3.5/8.0</td>
<td>3.5/8.0</td>
<td>4.0/7.0</td>
</tr>
<tr>
<td>$\beta_y^*$ (mm)</td>
<td>10/10</td>
<td>5.9/5.9</td>
<td>0.27/0.30</td>
</tr>
<tr>
<td>$\beta_x^*$ (mm)</td>
<td>330/330</td>
<td>1200/1200</td>
<td>32/25</td>
</tr>
<tr>
<td>$\varepsilon_x$ (nm)</td>
<td>18/18</td>
<td>18/24</td>
<td>3.2/5.3</td>
</tr>
<tr>
<td>$\varepsilon_y / \varepsilon_x$ (%)</td>
<td>1</td>
<td>0.85/0.64</td>
<td>0.27/0.24</td>
</tr>
<tr>
<td>$\sigma_y$ (pm)</td>
<td>1.9</td>
<td>0.94</td>
<td>0.048/0.062</td>
</tr>
<tr>
<td>$\xi_y$</td>
<td>0.052</td>
<td>0.129/0.090</td>
<td>0.09/0.081</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>4</td>
<td>6 - 7</td>
<td>6/5</td>
</tr>
<tr>
<td>$I_{\text{beam}}$ (A)</td>
<td>2.6/1.1</td>
<td>1.64/1.19</td>
<td>3.6/2.6</td>
</tr>
<tr>
<td>$N_{\text{bunches}}$</td>
<td>5000</td>
<td>1584</td>
<td>2500</td>
</tr>
<tr>
<td>Luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$)</td>
<td>1</td>
<td>2.11</td>
<td>80</td>
</tr>
</tbody>
</table>

Y. Ohnishi et al.
Design Concept of SuperKEKB

- Re-use the KEKB tunnel.
  - We have no option for polarization at present.
    - Not demanded by Belle II.

- Re-use KEKB components as much as possible.
  - Preserve the present cells in HER.
  - Replace dipole magnets in LER, re-using other main magnets in the LER arcs.
Major Items to Upgrade

- Rebuild IR
- Optics improvements:
  - Tsukuba straight section
  - Arcs
  - Wiggler sections
- Magnets
  - Build or rearrange many magnets
  - Survey and alignment
- New LER beam pipes for electron-cloud suppression
- Beef-up RF system
  - Rearrange cavities
  - Increase number of klystrons: 1/2 kly/cav to 1/1 kly/cav
- Improve speed and resolution of beam monitor and control system:
  - Position: BPMs, digital Bunch-by-bunch feedback
  - Size: (SRM, X-ray)
  - Collision monitors: Large Angle Beamstrahlung Monitor (G. Bonvicini)
- Upgrade the injector linac and beam transport system
- Install a 1.1 GeV positron damping ring
- Increase capacity of cooling system for the magnets and vacuum system
RF

- Beam power requirements at SuperKEKB:
  - HER: 1.5 times
  - LER: 2.5 times higher

- Need to increase the beam power per cavity for both rings, and the number of RF stations where one klystron feeds one ARES cavity with RF power up to 800kW.

- Start with low beam current. At T=0 the maximum current is lower than the design value (maybe 60~70%). Increase to the design current will take two years or more.
  - Start by rearranging cavities
  - Add klystrons in stages as beam currents increase
Optics

LER Arc Cell Changes

KEKB LER

\[ \varepsilon_x = 32.0 \text{nm} \quad \alpha_c = 4.53 \times 10^{-4} \]
\[ U_0 = 27.1 \text{keV} \]

- Keep cell length and focusing structure
- \( 2.5\pi \) cell & non-interleave chromaticity correction
- Replace main bend (B2P) with 4.2m long bending magnet
- Optimize quadrupole strength to minimize emittance
- Increase beam energy from 3.5GeV to 4GeV to reduce intra-beam scattering effect

SuperKEKB LER

\[ \varepsilon_x = 2.48 \text{nm} \quad \alpha_c = 4.94 \times 10^{-4} \]
\[ U_0 = 10.6 \text{keV} \]

+Wiggler period shortened, new wigglers added
Optics

HER Arc Cell Changes

KEKB HER

- $\varepsilon_x = 24.7 \text{nm}$
- $\alpha_c = 3.75 \times 10^{-4}$
- $U_0 = 120 \text{keV}$

- Keep arc regular cell structure
- 2.5 $\pi$ cell & non-interleave chromaticity correction
- Optimize quadrupole strength to minimize emittance
- Decrease beam energy from 8GeV to 7GeV to keep $\gamma (4s)$ resonance

SuperKEKB HER

- $\varepsilon_x = 4.96 \text{nm}$
- $\alpha_c = 6.36 \times 10^{-4}$
- $U_0 = 70.7 \text{keV}$

+ Wigglers added

A. Morita
IR with local chromaticity correction

LER 2 Family Local Chromaticity Correction
Solenoid: V4

K. Oide

LCC sections needed for both rings

YCCS (-l)

XCCS (-l)

dNy = 1.75

dNy = 0.5

dNx = 1.25

IP
New final focusing system based on the nano-beam scheme has been designed.

- Consists of 8 superconducting magnets
- Final focusing Q-magnets for each beam
- Crossing angle 83 mrad to bring the FF magnets closer to IP
- Need Belle rotation of 26 mrad
  - Need to fit to the existing tunnel.
## SuperKEKB IR
### SC Magnet Configuration

IRON YOKEs for QC1Es and QC2s, and IRON BOBBIN for ESL.

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Integral field gradient, (T/m) • m</th>
<th>Corrector</th>
<th>Leak field cancel coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC2RE</td>
<td>S.C. Quad. + Iron Yoke</td>
<td>12.91 [34.9 T/m × 0.37m]</td>
<td>$a_1, b_1, a_2, b_4$</td>
</tr>
<tr>
<td>QC2RP</td>
<td>S.C. Quad. + Iron Yoke</td>
<td>10.92 [30.3 × 0.36]</td>
<td>$a_1, b_1, a_2, b_4$</td>
</tr>
<tr>
<td>QC1RE</td>
<td>S.C. Quad. + Iron Yoke</td>
<td>26.22 [79.03×0.36]</td>
<td>$a_1, b_1, a_2, b_4$</td>
</tr>
<tr>
<td>QC1RP</td>
<td>S.C. Quad.</td>
<td>22.43 [66.52×0.337]</td>
<td>$a_1, b_1, a_2, b_4$, $b_3, b_4, b_5, b_6$</td>
</tr>
<tr>
<td>QC1LP</td>
<td>S.C. Quad.</td>
<td>22.91 [67.94×0.337]</td>
<td>$a_1, b_1, a_2, b_4$, $b_3, b_4, b_5, b_6$</td>
</tr>
<tr>
<td>QC1LE</td>
<td>S.C. Quad. + Iron Yoke</td>
<td>26.03 [82.75×0.36]</td>
<td>$a_1, b_1, a_2, b_4$</td>
</tr>
<tr>
<td>QC2LP</td>
<td>S.C. Quad. + Iron Yoke</td>
<td>10.96 [30.4 × 0.36]</td>
<td>$a_1, b_1, a_2, b_4$</td>
</tr>
<tr>
<td>QC2LE</td>
<td>S.C. Quad. + Iron Yoke</td>
<td>14.13 [20.2×0.70]</td>
<td>$a_1, b_1, a_2, b_4$</td>
</tr>
<tr>
<td>ESR</td>
<td>S.C. Solenoid</td>
<td>2.6 T [in the Belle solenoid field]</td>
<td></td>
</tr>
<tr>
<td>ESL</td>
<td>S.C. Solenoid + Iron Bobbin</td>
<td>3.0 T [in the Belle solenoid field]</td>
<td></td>
</tr>
</tbody>
</table>
Solenoid field profile with iron components in 2D

Iron yoke of QC1RE & QC2RP

Iron yoke of QC1LE

B$_z$ profile along the Belle axis

3D calculation model is now being constructed.

These solenoid coils have iron bobbin.

Additional solenoids are designed.
The leak field from QC1E is shielded with the iron yoke of QC1E and the iron pipe on the e-beam line.

QC1E magnet design parameter
- Field gradient = 70.68 T/m
- Maximum field in the coil = 2.69 T
- Design current = 1559 A
  - Current density in the coil = 599.6 A/mm²
- Operating point w.r.t the critical point = 67.2%

3D calculation model is now being constructed.
QC1P (No iron yoke)

QC1Ps are operated in the solenoid fields at the peak fields of 2.34 T and 2.29 T in the left and right sides of IP, respectively.

No iron components
The leak field of QC1P is canceled by the SC coils of $b_3$, $b_4$, $b_5$ and $b_6$

QC1P cross section

QC1P magnet design parameter
Field gradient $= 67.98$ T/m
Maximum field in the coil $= 3.93$ T
Design current $= 1609$A
Current density in the coil $= 819.6$ A/mm$^2$
Operating point w.r.t the critical point $= 79\%$

The 1$^{st}$ R&D QC1P magnet with correctors will be tested in October.
QC1P leak field cancellation coil

Typical coil design of the multipole SC coils

Cancelling the leak fields by SC multipole coils

- Corrector field
- Leak field
- After cancellation

Distance from IP (m)

Leak field (T)
R&D : Cryostat vibration

- High vibration dumping material test

<table>
<thead>
<tr>
<th>Mn</th>
<th>Cu</th>
<th>Ni</th>
<th>Fo</th>
<th>単位/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bal.</td>
<td>22.4</td>
<td>5.2</td>
<td>2.0</td>
<td>wt%</td>
</tr>
<tr>
<td>Bal.</td>
<td>20.0</td>
<td>5.0</td>
<td>2.0</td>
<td>at%</td>
</tr>
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</table>

N. Ohuchi
• Dynamic apertures of both rings are limited by nonlinear leakage fields of IR magnets for counter-rotating beams. More serious in LER.
• Recent tuning of IR compensation fields
  • => **Beam lifetimes > 600 sec**
  • More than sufficient to maintain maximum beam currents
    • Maximum injection rates:
      • LER: 4 nC/bunch, 2 bunches/pulse, 25 Hz
      • HER: 5 nC/bunch, 2 bunches/pulse, 25 Hz
1/10σ_y vertical offset causes ~ 2% luminosity loss.
The offset mainly comes from the mechanical vibration of IR quadrupoles.
Simulation of vibration of QC1 is going on based on data of floor vibration at Tsukuba. Main component appears near 50Hz.

The vertical orbit change at IP due to simulated QC1 vibration is estimated to be ~5σ_y*. Faster IP orbit feedback than used at KEKB is needed.
Simulation study of the IP orbit feedback has just started to determine specification of the feedback system.
Measures to reduce the vibration of IR quadrupoles such as improved support structures will be studied further.
Vacuum System

- To cope with the electron cloud issues and heating problems, **ante-chamber type beam pipes** will be adopted in the LER with a combination of TiN coatings, grooved shape surfaces, and clearing electrodes.
- Upgrade of vacuum system for SuperKEKB is underway.
- Most design and R&D for key components is finished.
- Further studies are required for movable masks.
  - May borrow PEP-II design
- Baking and TiN coating facilities will be ready this year.
- Manufacturing of beam pipes and bellows chambers for LER wiggler sections started last year.
- For LER arc and straight sections, they will start this year.
- Remaining parts of LER and HER will follow.
Beam pipes:

- Antechambers for reduced photoelectron density, low beam impedance, low SR power density
- Aluminum alloy for LER arc section. Copper is required for wiggler section (and HER).
- Fabricate by cold-drawing technique (copper) or extrusion technique (aluminum)
- Copper beam pipes have been tested in KEKB.

**Concept**

- Gate valve
- Bellows chamber
- Electrode: Suppress electrons inside the beam pipe
- Grooves: Suppress secondary electron emission
- BPM
- NEG strip
- Beam SR
- Gate valve

Y. Suetsugu
High charge positron source and low-emittance RF electron gun are designed to improve the rate and quality of injected beams to deliver the required beams with increased injection efficiencies.

### Table: Beam Parameters

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<tr>
<th></th>
<th>KEKB obtained (e+/e-)</th>
<th>SuperKEKB required (e+/e-)</th>
</tr>
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<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>3.5 GeV / 8.0 GeV</td>
<td>4.0 GeV / 7.0 GeV</td>
</tr>
<tr>
<td><strong>Bunch charge</strong></td>
<td>e- → e+ / e- 10 → 1.0 nC / 1.0 nC</td>
<td>e- → e+ / e- 10 → 4.0 nC / 5.0 nC</td>
</tr>
<tr>
<td><strong>Beam emittance</strong></td>
<td>2100 μm / 300 μm</td>
<td>6 μm / 20 μm</td>
</tr>
</tbody>
</table>

- **e-**
  - High Charge
  - Low emittance ⇒ Photo RF gun

- **e+**
  - High Charge ⇒ Adiabatic matching device + Large aperture accel.
  - Low emittance ⇒ Damping Ring

- Emittance preservation ⇒ Alignment, dispersion, wake, CSR
- Simultaneous injection
  - Pulse-to-pulse optics ⇒ Pulse magnet
**Nominal acceleration**
- S-band 160MeV / RF unit
- C-band 8m at 4-4

*For HER*
- 7.0 GeV
- 5nC x 2

*For LER*
- 4.0 GeV
- 4nC x 2

*For AR*
- e− or e+?

*Emittance preservation through whole linac*

*Capture and acceleration*
- 3.5 GeV
- 10nC x 2

*DR*
- 1.1 GeV @ DR

*Target @ 1-4*
- 3.5 GeV
- 10nC x 2

*Photocathode RF gun*

*RF gun*

*e− bypass line for DC separation bend*

*Target bypass bump orbit*

*T.Higo*
**DAW + LaB$_6$ (or Ir$_5$Ce)**

- **Low-maintenance, long-life**
  
  LaB$_6$ hot cathode DAW RF-Gun demonstrated in 2008 at Rika U.
  Simulations show 6 mm-mrad emittance at 5 nC bunch charge

  - Cavity: Lower Electric Field
  - Stable operation
  - Short Aging Time

  **Stable cathode:** LaB$_6$ or Ir$_5$Ce
  
  - Inactive, Solid (no thin film), High Melting Temperature: life time $>>$ Cs$_2$Te
  - Work function $\phi = 2.8$ eV(LaB$_6$), 2.57 eV(Ir$_5$Ce)

  : laser power $<<$ metal
Requirements:
- Injection aperture of LER = 0.7 μm
  - \( \Rightarrow \) emittance of injected beam < 14.5 nm
- Lifetime of LER = 600 sec
  - \( \Rightarrow \) intensity of injected beam = 4 nC/bunch (30% injection efficiency)
- Lattice parameters optimized to suppress microwave instability due to CSR.
- Electron cloud density is below instability threshold.
- Chamber design employing antechamber has been proposed. Fabrication of chambers is scheduled for FY2012.
Beam Instrumentation

- BPM and feedback systems for higher currents and resolution.
- Photonic instrumentation:
  - SR monitors
    - Interferometer (transverse size)
    - Streak camera (bunch length)
  - X-ray monitors
    - Bunch-by-bunch vertical size
  - Beamstrahlung monitor
    - Beam collision monitoring
SRM Extraction Mirror

- Heat load on extraction mirrors a problem at high currents
  - Causes deformation of mirror, and change in apparent beam size.

<table>
<thead>
<tr>
<th></th>
<th>LER (BSWFRP)</th>
<th>HER (BSWOLE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SuperKEKB</td>
<td>KEKB</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Current (A)</td>
<td>3.6</td>
<td>2</td>
</tr>
<tr>
<td>Bending radius (m)</td>
<td>177.4</td>
<td>85.7</td>
</tr>
<tr>
<td>Power (W/mrad)</td>
<td>72</td>
<td>48</td>
</tr>
<tr>
<td>Distance to mirror (m)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Mirror width (mm)</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Total incident power (W)</td>
<td>161</td>
<td>109</td>
</tr>
</tbody>
</table>
SRM: Diamond Mirrors

- Monocrystalline diamond
  - Thickness 500 μm
    - 10 mm x 20 mm mirror prototype made
    - 20 mm x 20 mm needed, now possible
  - 3 micron Au surface coating
  - Monocrystalline diamond makes for good surface flatness (<~λ/50)
  - Better heat transfer and thermal expansion coefficients than the beryllium used at KEKB:
    - Beryllium: δmagnification = 43% @ HER full current
    - Diamond: δmagnification = ~7% @ HER full current

Mirror surface distortion due to 200W of SR power at center of Be mirror

Mirror surface distortion due to 228W of SR power at center of Au+Dia mirror

Diamond mirror temperature distribution w/ 228W of SR

Diamond mirror surface distortion w/ 228W of SR

ANSYS simulations: M. Arinaga
Resolution fundamentally limited by measurement wavelength and opening angle between slits from beam (D/F).

Max. slit separation determined by beam spread and mechanical considerations.

Vertical beam size measurement is possible with interferometers, though is near the limit of the interferometer resolution.

Measurement wavelength needs to be lowered to fit beam size into dynamic range.

Also need to be able to measure 99% visibility. (Very difficult!)

Limitation on slit separation is due to antechamber height (14 mm).

 Extraction mirror will be in antechamber for reduced impedance.

<table>
<thead>
<tr>
<th>SR Source Bend Parameter</th>
<th>S-LER1 (BSWFRP)</th>
<th>S-HER (BSWOLE)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_x$</td>
<td>3.20E-09</td>
<td>4.60E-09</td>
<td>m</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.27%</td>
<td>0.24%</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_y$</td>
<td>8.64E-12</td>
<td>1.10E-11</td>
<td>m</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>29.98</td>
<td>32.49</td>
<td>m</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>16.1</td>
<td>18.9</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>4</td>
<td>7</td>
<td>GeV</td>
</tr>
<tr>
<td>Bend effective length</td>
<td>0.89</td>
<td>2.90</td>
<td>m</td>
</tr>
<tr>
<td>Bend angle</td>
<td>5.04</td>
<td>5.00</td>
<td>mrad</td>
</tr>
<tr>
<td>Bend radius $\rho$</td>
<td>179.0</td>
<td>580.0</td>
<td>m</td>
</tr>
<tr>
<td>Observation wavelength $\lambda$</td>
<td>4.00E-07</td>
<td>4.00E-07</td>
<td>m</td>
</tr>
<tr>
<td>SR Opening angle $\theta_c (\lambda)$</td>
<td>1.0</td>
<td>0.7</td>
<td>mrad</td>
</tr>
<tr>
<td>Slits opening angle D/F</td>
<td>0.7</td>
<td>0.7</td>
<td>mrad</td>
</tr>
<tr>
<td>Max. Visibility (fringe depth) $\gamma_{\text{max}}$</td>
<td>99%</td>
<td>99%</td>
<td></td>
</tr>
<tr>
<td>Min. measurable beam size $\sigma_{y\min}$</td>
<td>12.8</td>
<td>13.5</td>
<td>$\mu$m</td>
</tr>
</tbody>
</table>
X-ray monitor using Coded Aperture Imaging

Technique developed by x-ray astronomers using a mask to modulate incoming light. Resulting image must be deconvolved through mask response (including diffraction and spectral width) to reconstruct object. Open aperture of 50% gives high flux throughput for bunch-by-bunch measurements. Heat-sensitive and flux-limiting monochromator not needed.

We need such a wide aperture, wide spectrum technique for shot-by-shot (single bunch, single turn) measurements.

Source distribution:

\[
\begin{bmatrix}
A_{\sigma} \\
A_{\pi}
\end{bmatrix} = \frac{\sqrt{3}}{2\pi} \frac{\gamma}{\omega_c} (1 + X^2) (-i) \left[ \frac{K_{2/3}(\eta)}{\sqrt{1 + X^2}} K_{1/3}(\eta) \right],
\]

where

\[
X = \gamma \psi,
\]

\[
\eta = \frac{1}{2} \frac{\omega}{\omega_c} (1 + X^2)^{3/2},
\]

Kirchhoff integral over mask (+ detector response)

\[
A_{\sigma,\pi}(y_d) = \frac{iA_{\sigma,\pi}(\text{source})}{\lambda} \int_{\text{mask}} \frac{t(y_m)}{r_1 r_2} e^{i2\pi (r_1 + r_2)} \left( \cos \theta_1 + \cos \theta_2 \right) dy_m,
\]

Detected pattern: Measured slow-scan detector image (red) at CesrTA, used to validate simulation (blue)
XRM: Coded Aperture tests at CesrTA

Example of turn-by-turn size and position data (one bunch out of

Example of bunch-by-bunch data (electron-cloud blow-up study data) Single-shot data average for each bunch

Single-shot resolution (simulation + measured spread)
SuperKEKB x-ray monitor

Uniformly Redundant Array (URA) for x-ray imaging to be used at SuperKEKB

<table>
<thead>
<tr>
<th>X-ray Source Bend Par.</th>
<th>S-LER (BS2FRP.1)</th>
<th>S-HER (BS2E.82)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_x$</td>
<td>3.20E-09</td>
<td>4.60E-09</td>
<td>m</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.27%</td>
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<td>$\varepsilon_y$</td>
<td>8.64E-12</td>
<td>1.10E-11</td>
<td>m</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>50.0</td>
<td>11.5</td>
<td>m</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>20.8</td>
<td>11.3</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>4</td>
<td>7</td>
<td>GeV</td>
</tr>
<tr>
<td>Effective length</td>
<td>0.89</td>
<td>5.9</td>
<td>m</td>
</tr>
<tr>
<td>Bend angle</td>
<td>28.0</td>
<td>55.7</td>
<td>mrad</td>
</tr>
<tr>
<td>$\rho$</td>
<td>31.7</td>
<td>105.9</td>
<td>m</td>
</tr>
<tr>
<td>Critical Energy</td>
<td>4.4</td>
<td>7.1</td>
<td>keV</td>
</tr>
</tbody>
</table>

• **Mask:**
  • 59-element, 10 $\mu$m/element URA
  • High-power design
    • 10 $\mu$m Au mask
  • Substrate:
    • 625 $\mu$m Si
    • 300 $\mu$m diamond
  • Test at CesrTA

• **Detector:**
  • 64-channel, 50 $\mu$m pitch

Simulated detector response for various beam sizes at SuperKEKB LER
SuperKEKB Estimated single-shot resolutions (SuperKEKB full current)

- **Red points:** using 64-pixel detector of same type as at CesrTA
- **Green points:** using detector with improved photon detection efficiency at higher x-ray energies
  - Deep pixel designs being pursued.
LABM: Large Angle Beamstrahlung Monitor

- The radiation of the particles of one beam due to the bending force of the EM field of the other beam
- Beamstrahlung POLARIZATION at specific azimuthal points provides unique information about the beam-beam geometry.
LABM: Beam pipe insert

- View port location at $\pm 90$ degrees minimizes backgrounds, polarization measurement errors, and provides redundancy against beam orbit errors.
- Located 4.8 m downstream of IP in HER, 3.7 m downstream in LER.
- Mirror and window sizes: 2.83X2 mm$^2$ and 2.1X2.1 mm$^2$. 

G. Bonvicini
Magnets

- A large number of magnets need to be rearranged, replaced, and added to reduce the horizontal emittance of both beams to one-fifth to one-tenth of their present values.
- LER magnets largely removed from KEKB tunnel.
- HER magnets and vacuum chambers left in place.
- Earthquake has highlighted alignment and stabilization issues.
KEKB Tunnel

Floor sections at expansion joints pulled apart in some places, pushed together at others

Some level shifts also detected, especially around Oho area. Tunnel around Oho experimental hall has sunk relative to Oho.

Signs of subsidence can also be seen outside Oho. Crack in driveway in front of D4 loading dock door:
Damage centered around expansion joints
Evidence that magnets moved up to 10 mm at interface between experimental halls and arc sections
⇒ Tunnel movement requires quantitative measurement

Masuzawa
BL3LP.5
Movement of magnet footing
Expansion joint movement

- Joint had already opened up on 3/11
- Bolt hole designed to slide to accommodate thermal expansion/contraction

Photo: Ohsawa
4/16 aftershock (Shindo 4 in Tsukuba)
No bedrock even 100 m down

N value around 10 in Tristan/KEKB/SuperKEKB tunnel

Sugawara, Yoshioka
KEK Report 2003-12, Feb. 2004 A
Magnet positions on either side of IP:
Horizontal shifts between 11/2010 and 5/2011

8mm
Just under 2mm
Magnet positions in arc sections:
Horizontal shifts between 2/2010 and 6/2011

Up to 3 mm shifts seen in X and Y

Directions of movement change at expansion joints (red arrows):
tunnel sections moving relative to each other
Movement of expansion joints measured by Hydrostatic Leveling System

Small variations due to temperature fluctuations

Spikes due to earthquakes (after-shocks)

Permanent level shifts observed at each after-shock, up to 0.7 mm over the span of two months.

Behavior prior to measurement unknown.

Continuous monitoring will be needed.
Machine commissioning start

- Main Ring and Damping Ring commissioning planned to start in the second half of FY2014.
- Linac is in operation for PF and PF-AR during the construction period. Test operation for the upgrade will be performed in parallel. Commissioning of Linac for SuperKEKB will start in FY2014.

Detector

- The detector people prefer that machine operation start without Belle II.
- Initial commissioning will be in “BEAST” mode:
  - No SVD
  - Belle solenoid may or may not be rolled in at the time
    - Under discussion.
<table>
<thead>
<tr>
<th></th>
<th>FY2010</th>
<th>FY2011</th>
<th>FY2012</th>
<th>FY2013</th>
<th>FY2014</th>
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</thead>
<tbody>
<tr>
<td><strong>Beam pipes and vacuum components</strong></td>
<td>Dismantle KEKB</td>
<td>Fabrication</td>
<td>Baking, TiN coating</td>
<td>Install, system check</td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>Magnets and power supplies</strong></td>
<td></td>
<td></td>
<td>Fabrication</td>
<td>Install, alignment, system check</td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>RF system</strong></td>
<td></td>
<td></td>
<td>Reinforce and rearrange</td>
<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>Monitor &amp; control, Beam transport</strong></td>
<td></td>
<td></td>
<td>R&amp;D</td>
<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>QCS and IR hardware</strong></td>
<td></td>
<td></td>
<td>Fabrication</td>
<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>Damping Ring</strong></td>
<td></td>
<td></td>
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<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>e±- Injector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>RF system</strong></td>
<td></td>
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<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
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<tr>
<td><strong>QCS and IR hardware</strong></td>
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<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>Damping Ring</strong></td>
<td></td>
<td></td>
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<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
<tr>
<td><strong>e±- Injector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>SuperKEKB commissioning</strong></td>
</tr>
</tbody>
</table>

Revised on July 23, 2011

K. Akai
SuperKEKB construction has started. Dismantling of KEKB is well underway. Mass fabrication of magnets, beam pipes, etc. has commenced.

R&D advancing on new components.

Commissioning scheduled to start in the second half of FY2014.
Earthquakes over mag. 4.5

frequency [ /day]

Jan/1 Mar/1 May/1 Jul/1 Sep/1

average in 10 days
Want to know, what is chance that a beam of a certain size is misfit as one of a different size?

Tend to be photon statistics limited. (Thus coded aperture.)

So:

- Calculate simulated detector images for beams of different sizes
- “Fit” images pairwise against each other:
  - One image represents true beam size, one the measured beam size
  - Calculate $\chi^2/\nu$ residuals differences between images:

$$
\frac{\chi^2}{\nu} = \frac{1}{N-n-1} \sum_{i=1}^{N} \frac{(s'_i - s_i)^2}{\sigma_i^2},
$$

- Weighting function for channel $i$:
  $$
  \sigma_i = \sqrt{S_i}.
  $$

- Value of $\chi^2/\nu$ that corresponds to a confidence interval of 68% is chosen to represent the 1-s confidence interval
### RF gun VS DC gun

<table>
<thead>
<tr>
<th></th>
<th>RF gun</th>
<th>DC gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Field</td>
<td>~ 100 MV/m</td>
<td>~ 10 MV/m</td>
</tr>
<tr>
<td>Voltage</td>
<td>Several MV</td>
<td>100 kV ~ 500 kV</td>
</tr>
<tr>
<td>Bunching</td>
<td>Shaped internally</td>
<td>Buncher needed</td>
</tr>
<tr>
<td>Electron density</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

### Pillbox or Disk and Washer (DAW) type

- **Pillbox type**
  - Electromagnetic node overlaps beam hole
  - No electromagnet nodes on beam axis, so **DAW type has more design freedom in cavity**

- **DAW type**
  - Electromagnetic node
  - Beam hole
Spares
The KEKB B factory is being upgraded to search for physics beyond the Standard Model, with a target luminosity of $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$, a factor of 40 times greater than the world record luminosity achieved at KEKB. To achieve this target luminosity the upgraded machine, SuperKEKB, will require the use of new advances in accelerator technology, among them the development of a low-emittance, high-bunch-charge injector system, a high-beam-current vacuum system incorporating the latest electron-cloud mitigation techniques, an interaction region design that provides a low beta function at the collision point while minimizing emittance growth due to fringe fields and maximizing the dynamic aperture, and beam diagnostics and feedback for monitoring and controlling low-emittance beams and their collisions. This talk will discuss the design challenges facing SuperKEKB, and the technologies that are being developed to meet them.
Collaborations

- Discussions have been held with some US institutions regarding possible participation on the accelerator side. Some possible areas identified:
  - Low-emittance RF gun, mask design, linac alignment and damping ring commissioning (SLAC)
  - Electron-cloud related issues (Fermilab)
  - Large Angle Beamstrahlung Monitor (Wayne State, PNNL)
    - Wayne already a member of Belle
  - Outside the US, BINP (flux concentrator) + INFN (FB, beam dynamics, crab waist sims.)
Ground subsidence
IR

Prototype Q-magnet (collared)

Prototype Q-magnet

7.8cm diameter

Very compact superconducting magnets for final focusing system

N. Ohuchi
Linac

Linac

K. Suzuki, K. Furukawa
• Belle broke free of its anchor and moved on its rails ~20 cm, coming to rest 6 cm from initial position.
• Many snapped cable ties, no other obvious damage visible from outside.
• Awaiting detailed inspection of internal detector components.