Beam Dynamics in
Positron Injector Systems
for the Next Generation B Factories

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M. Kikuchi, K. Oide, and D. Zhou
for the SuperKEKB group
Next Generation B-factories

These projects aim to increase,

Peak luminosity $\sim 10^{36}$

For realizing the super-high luminosities, the injector improvements must be very important, especially in positrons.
S. Guiducci and A. Variola

**SuperB** and **SuperKEKB**

<table>
<thead>
<tr>
<th>Parameters of main (collider) ring</th>
<th>unit</th>
<th>SuperB</th>
<th>SuperKEKB</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>6.7</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Stored beam current</td>
<td>A</td>
<td>1.892</td>
<td>3.6</td>
<td>&lt; 1.8</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>978</td>
<td>2500</td>
<td>1580</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>1.2584</td>
<td>3.016</td>
<td>3</td>
</tr>
<tr>
<td>Beam lifetime at collision</td>
<td>sec.</td>
<td>254</td>
<td>340</td>
<td>&gt;6000</td>
</tr>
</tbody>
</table>

We need even higher charge considering the refill from scratch as high as possible. Beam-gas, Touschek, Radiative Bhabha.

<table>
<thead>
<tr>
<th>Parameters of injection beam</th>
<th>unit</th>
<th>SuperB</th>
<th>SuperKEKB</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge/bunch required from main ring</td>
<td>nC</td>
<td>0.65</td>
<td>2.1</td>
<td>0.15</td>
</tr>
<tr>
<td>Charge/bunch deliverable by injector</td>
<td>nC</td>
<td>0.5 – 2.0</td>
<td>4.0 (Max. 8.0)</td>
<td>1.0</td>
</tr>
<tr>
<td>bunch/pulse</td>
<td></td>
<td>1 (Max. 5)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum repetition rate</td>
<td>Hz</td>
<td>100</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Horizontal emittance (εx)</td>
<td>nm</td>
<td>4.1</td>
<td>12.5</td>
<td>300</td>
</tr>
<tr>
<td>Vertical emittance (εy)</td>
<td>nm</td>
<td>0.72 (κ = 1%)</td>
<td>0.26 (κ = 0%)</td>
<td>0.58 (κ = 5%)</td>
</tr>
</tbody>
</table>

Higher charge and Lower emittance are required for both B-factories to achieve their **Super-high luminosities**.

Narrow physical and dynamic apertures of the collider ring: higher charge and lower emittance.
Positron injector complex

The complexes are basically similar.
<table>
<thead>
<tr>
<th>Parameters of Positron Injector</th>
<th>Unit</th>
<th>SuperB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron gun</td>
<td></td>
<td>Thermionic</td>
<td>Thermionic</td>
</tr>
<tr>
<td>Primary electron charge/bunch</td>
<td>nC</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Primary electron energy</td>
<td>GeV</td>
<td>0.6</td>
<td>3.5</td>
</tr>
<tr>
<td>linac frequency before DR</td>
<td>MHz</td>
<td>L-band(TM020) 1428</td>
<td>S-band 2856</td>
</tr>
<tr>
<td>Energy compressor before DR</td>
<td></td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Energy of DR</td>
<td>GeV</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Bunch compressor after DR</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>linac frequency after DR</td>
<td>MHz</td>
<td>C-band</td>
<td>S-band</td>
</tr>
<tr>
<td>Energy of the colliding ring</td>
<td>GeV</td>
<td>6.7 (HER)</td>
<td>4.0 (LER)</td>
</tr>
<tr>
<td>Number of Pulse-to-pulse injection</td>
<td></td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Besides the primary electron energy, SuperB uses L-band accelerator before the DR, which make it possible to eliminate the ECS.
### Parameters of injection beam for damping ring

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>SuperB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (Maximum)</td>
<td>nC</td>
<td>2.0</td>
<td>8</td>
</tr>
<tr>
<td>Injected beam emittance</td>
<td>nm</td>
<td>1100</td>
<td>1400</td>
</tr>
<tr>
<td>Energy spread</td>
<td>%</td>
<td>1.5</td>
<td>5.0 → 1.5 (w ECS)</td>
</tr>
</tbody>
</table>

### Parameters of damping ring

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<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
<td>51.1</td>
<td>135.5</td>
</tr>
<tr>
<td>Equilibrium $\varepsilon_x$</td>
<td>nm</td>
<td>23</td>
<td>42.0</td>
</tr>
<tr>
<td>Equilibrium $\varepsilon_y$</td>
<td>nm</td>
<td>0.2(k=0.01)</td>
<td>0.95(k=0)/2.10(k=0.05)</td>
</tr>
<tr>
<td>Betatron damping time</td>
<td>ms</td>
<td>7.3</td>
<td>10.87</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td></td>
<td>$5.7 \times 10^{-3}$</td>
<td>$1.41 \times 10^{-2}$</td>
</tr>
<tr>
<td>RF voltage</td>
<td>MV</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Bucket height</td>
<td>%</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Equilibrium energy spread</td>
<td></td>
<td>$6.2 \times 10^{-4}$</td>
<td>$5.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Bunch length (low current)</td>
<td>mm</td>
<td>4.8</td>
<td>6.57</td>
</tr>
</tbody>
</table>

S. Guiducci and A. Variola

Very huge!  
Very low!  
not very short!
### Parameters of injection beam for damping ring

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### Parameters of damping ring

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<tr>
<td>Circumference</td>
<td>m</td>
<td>51.1</td>
<td>135.5</td>
</tr>
<tr>
<td>Equilibrium ε&lt;sub&gt;x&lt;/sub&gt;</td>
<td>nm</td>
<td>23</td>
<td>42.0</td>
</tr>
<tr>
<td>Equilibrium ε&lt;sub&gt;y&lt;/sub&gt;</td>
<td>nm</td>
<td>0.2(k=0.01)</td>
<td>0.95(k=0)/2.10(k=0.05)</td>
</tr>
</tbody>
</table>

Our mission is to transport such high intensity beams without emittance growth and beam loss.

We can say that the issues are common for the two B-factories.
Common Issues

1. From e+ target to Damping ring
   - Large amount of charge
   - Huge emittances ($\epsilon_x, \epsilon_y, \epsilon_z$)
     • the huge positron beam causes the serious beam loss.

2. Damping ring
   - Microwave instabilities due to CSR will be a problem.
     • Because of the large beam pipe for capturing the large injection beam.

3. From Damping ring to Main ring
   - The beam should be transported keeping the low emittance.

For an example, the issues at SuperKEKB are presented today.
SuperKEKB

Positron Injector of SuperKEKB

1. e+ Target to Injection to DR

2. Damping Ring (1.1 GeV)

3. Extraction from DR to Injection to Main ring

We did the overall tracking simulation from the e+ generation to Main ring injection, assuming 8nC charge.
SuperKEKB has a very specific issue on,

**Beam loss**

- allowable only in the LINAC and SuperKEKB tunnels,
- severely restricted in the damping ring and the beam transport tunnels.

Tunnels are not deep enough.

Land elevation

Collider ring

BT

LINAC

primary e-

3.5GeV

e+

Beam loss
1. $e^+$ Target $\rightarrow$ Damping ring (DR)

Beam loss is a main problem.
e+ Capture section — Entrance of DR

• Capture section
  – Positrons are captured as much as possible by enlarging,
    • energy acceptance with adiabatic matching device (AMD) --- Flux concentrator
    • transverse acceptance with larger aperture,
      – L-band or
      – Large-aperture S-band

This is cut by the collimators and compressed by ECS.
e+ Capture section

There are two subjects to make decision:

1. The RF phase to the positron
   - Acceleration phase
   - Deceleration phase

2. Acceleration structure
   - L-band
   - Large-S-band

Our choice

- e- 3.5 GeV
  - Target
  - AMD
  - 35Φ or 30Φ Capture section
  - 120 MeV
  - LINAC Sector-2
  - 1.1 GeV

EGS4 + Tracking code by T.Kamitani

DR

σδ<1.5%

σδ<5.0%

L-band or Large-S-band?
Target – Capture section

Phase of the positron to the RF frequency

Accelerating phase

The positrons are decelerated to very low velocity, and the RF slips to the next acceleration phase.

Decelerating phase (Our choice)

RF phase slips.

The high energy tail is remained.

The high energy tail is not remained.

Watch the movies at: [http://research.kek.jp/people/iida/THYA01_talk_movie.ppt](http://research.kek.jp/people/iida/THYA01_talk_movie.ppt)
e+ acceleration 0.12 to 1.1 GeV

Phase of the positron to the RF frequency

Accelerating phase

Decelerating phase (Our choice)

Particles at the low energy tail are eliminated by the energy acceptance
Energy Spread Compression

Phase of the positron to the RF frequency

Accelerating phase

Decelerating phase (Our choice)

Subsequently ECS rotates the beam to compress the energy spread.

There are collimators to cut the energy tail.

Watch the movies at: [http://research.kek.jp/people/iida/THYA01_talk_movie.ppt](http://research.kek.jp/people/iida/THYA01_talk_movie.ppt)

Collimator

σ<5.0%
Comparison of Acceleration and Deceleration phases in the longitudinal phase space

The entrance of DR

There are still long high-energy tail

"Acceleration phase"

"Deceleration phase"

We chose “Deceleration phase”

Charge: 6.59 nC

Charge: 6.75 nC
e+ Capture section — Entrance of DR

1. RF Phase of the capture section
   Acceleration phase or Deceleration phase?

2. Accelerating structure
   L-band or S-band?

- Our choice
- existing S-bands

In SuperKEKB,

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L-band</td>
<td>1298 MHz</td>
<td></td>
</tr>
<tr>
<td>S-band</td>
<td>2856 MHz</td>
<td></td>
</tr>
</tbody>
</table>

\[ f_L : f_S = 5:11 \]

Coprime ratio

The important thing is that the L-band is not just the half of S-band, but 5/11 of the S-band frequency. As we have to use the existing S-band linac as much as possible, the downstream accelerating structures must be S-band, anyway.
Satellite bunch elimination

a) Satellite bunches (delayed particles) generated in the capture section make beam loss in the DR injection.

b) Choosing a coprime (5:11) frequency ratio of L-band (1298 MHz) and downstream S-band (2856 MHz), most of the L-band satellites are eliminated by the S-band acceleration in LINAC.

- a) only S-band case (loss = 0.40%)
- b) L + S-band combination case (loss = 0.05%)

Particles outside the separatrix are lost at DR.
2. Damping ring (DR)

Microwave instability due to CSR

• One of the most serious common issue to e+ damping rings with high bunch charge.
  • That is because we need high bunch charge, which has
    ➢ Large injection emittance from e+ production, which needs
    ➢ Large beam pipe in the ring, which increase
    ➢ Large CSR, causing
    ➢ Microwave instability, resulting
    ➢ $\sigma_\delta, \sigma_z$ blowup

It may be very relevant to the positron damping rings, including SuperB, ILC, CLIC, etc…
- The usual wake potentials of the various components of the DR are not serious.
- The wake potential due to CSR is two-orders larger than the others.

Shape of the chamber
Vertical aperture: ±12mm

Antechamber is necessary to suppress the electron cloud.
Enlargements of $\sigma_\delta$ and $\sigma_z$ due to CSR in DR

- Tracking simulation with 5M macro particles -

Initial beam:

a) Damped beam in DR with Gaussian shape

- The resulted bunch length and energy spread are somewhat different.
- The quasi-equilibrium states depend on the initial beam distribution!

b) Beam from Linac

Next to these enlargements of bunch length and energy spread are within acceptable range for the injection.

\[ \frac{\sigma_z}{\sigma_{z0}} \]

\[ \frac{\sigma_\delta}{\sigma_{\delta0}} \]

A quadrupole oscillation appears around $2.5 \times 10^{10}$ to make the damping slower.
DR of SuperKEKB

- Reversed-bend FODO cell
  - Low momentum compaction factor
  - Wide momentum aperture
- Large Coherent Synchrotron Radiation (CSR) effects
  - This issue has been mitigated by the following changes:
    - Higher beam energy
      - 1.0GeV → 1.1GeV
    - Larger momentum compaction factor
      - 0.0019 → 0.0141
    - Higher cavity voltage for higher synchrotron tune
      - 0.261MV → 1.4MV
    - Reduce the vertical aperture of chamber
      - 34mm → 24mm
3. Damping ring (DR) → Main Ring (LER)

The damped emittance should be preserved to the entrance of the main ring.
**e+ beam from DR:**

Transverse emittance is small.
Bunch length is not so short yet.

\[ \varepsilon_x = 40.2 \text{ nm} \]
\[ \varepsilon_y = 0.25 \text{ nm} \]

\[ \sigma_z = 8.39 \text{ mm} \]
\[ \sigma_z = 0.90 \text{ mm} \]

The transport line has a number of horizontal and vertical bends to produce higher-order dispersions in both planes as well as synchrotron radiation.

The main linac has two frequencies: S-band and C-band. After compressed in the ECS at the end of LINAC, the beam is transported to the main ring.

The bunch length is one-order reduced by the BCS to match the S-band frequency of the linac. We should use an L-band accelerating structure for longitudinal focusing such a long bunch.
Various sources of Emittance growth after the Damping Ring

- Longitudinal bunch gymnastics
  - Adjusting RF-phases to compensate the beam loading by the RF-curvature.

- Transverse emittance blows up at least by:
  1. Misalignments of accelerating structures and quadrupoles
  2. Second-order dispersion in the transport line
  3. Synchrotron radiation at the beam transport line
  4. Beam-beam effect after the injection to the colliding ring

8 nC
Minimization of Energy spread

In our simulation, the wake effects are calculated using K. Yokoya’s approximated formula.

- We should adjust the three parts of the RF phases:
  a) L-bands of the BCS
  b) S-band and C-band of the LINAC
  c) S-band of the ECS

8 nC

Vc = 88 MV (S-band)
R_{56} = -0.24 m
Compression 1/4
## Optimization of acceleration phase for minimization of the energy spread

<table>
<thead>
<tr>
<th>Tuning knob</th>
<th>a) L-band of BCS</th>
<th>b) S,C-band in LINAC</th>
<th>c) S-band of ECS</th>
<th>Entrance of Main eing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Place</td>
<td>Entrance of LINAC</td>
<td>End of LINAC</td>
<td>Exit of ECS</td>
<td>Entrance of Main eing</td>
</tr>
<tr>
<td>$\sigma_z$ [mm]</td>
<td>±0.896</td>
<td>±2.15 (99% incl.)</td>
<td>±10.87 (99% incl.)</td>
<td>±21.93 (99% incl.)</td>
</tr>
<tr>
<td>$\sigma_\delta$ [%]</td>
<td>±0.825</td>
<td>±1.13 (99% incl.)</td>
<td>±0.271 (99% incl.)</td>
<td>±0.271 (99% incl.)</td>
</tr>
</tbody>
</table>

Transmission: 100%

By these careful adjustments
Optimization of acceleration for minimization of the energy spread

<table>
<thead>
<tr>
<th>Tuning knob</th>
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<tbody>
<tr>
<td>Place</td>
<td>Entrance of LINAC</td>
<td>End of LINAC</td>
<td>Entrance of Main entrance</td>
</tr>
<tr>
<td>$\sigma z$ [mm]</td>
<td>$\pm 0.896$</td>
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<td>$\pm 21.93$ (99% incl.)</td>
</tr>
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<td>$\sigma \delta$ [%]</td>
<td>$\pm 0.825$</td>
<td>$\pm 1.13$</td>
<td>$\pm 0.271$ (99% incl.)</td>
</tr>
</tbody>
</table>

The scanning shape is not parabola at the bottoms, which are for their strange distribution, not Gaussian shape.

Transmission: 100%

By these careful adjustments

8nC
Various sources of Emittance growth after the Damping Ring

- Longitudinal bunch gymnastics
  - Adjusting RF-phases to compensate the beam loading.
- Transverse emittance blows up at least by:
  1. Misalignments of accelerating structures and quadrupoles
  2. Second-order dispersion in the transport line
  3. Synchrotron radiation at the beam transport line
  4. Beam-beam effect after the injection to the colliding ring

8 nC
Transverse emittance growth

1. Caused by misalignments

Misalignments in the tracking simulation were done by the following steps:
- Accelerating structures and quadrupoles are misaligned independently.
- Amplitudes of the misalignments are given by Gaussian distribution.
- The orbit distortion due to quadrupole misalignments are corrected by steering magnets.

The transverse wake is calculated using K.Yokoya’s approximated formula.
Transverse emittance growth (Cont’d)
1. Caused by misalignments

Examples of the particle distributions at the end of LINAC

Vertical emittance alignment is more important than the horizontal

Emittance growth at the entrance of LER

The green line is Max. Allowable $\varepsilon_{yR}$ for injection for MR. Only 60µm misalignment is allowed.

Severe!

X 1.6 with 100µm misalignment
Emittance minimization by changing the initial offset

The emittance growth due to the misalignments can be suppressed by choosing the initial offset and angle of the beam at the entrance of LINAC at some level.

**Measurement**

L. Zang, M. Yoshida

Initial: $\gamma_e = 10(\mu\text{m.rad})$

$\gamma_e = 270(\mu\text{m.rad})$ -> $160(\mu\text{m.rad})$ x 1.5

$\gamma_e = 110(\mu\text{m.rad})$

$\gamma_e = 110(\mu\text{m.rad})$

$\gamma_e = 168(\mu\text{m.rad})$ -> $11.5(\mu\text{m.rad})$ x 1.15

**Simulation**

M. Satoh

$\gamma_e = 270(\mu\text{m.rad})$

$\gamma_e = 110(\mu\text{m.rad})$
Transverse Emittance growth

2. Caused by the second order dispersion

We install the two pairs of horizontal and vertical sextupoles.
Corrections of Second-Order Dispersion using Sextupoles

(a) w/o Sextupoles

Correction of second order dispersion by sextupoles

(b) w Sextupoles

Emittance growth is suppressed by sextupoles.
Transverse emittance growth

3. due to
Emission of Synchrotron Radiation (SR)
in the beam transport line

<table>
<thead>
<tr>
<th>LER</th>
<th>w/o SR</th>
<th>w SR</th>
<th>Growth factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_x$ (nm)</td>
<td>10.8</td>
<td>12.2</td>
<td><strong>1.13</strong></td>
</tr>
<tr>
<td>$\varepsilon_y$ (nm)</td>
<td>0.247</td>
<td>0.256</td>
<td><strong>1.04</strong></td>
</tr>
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</table>

The growth factor is not so large.
Injection into the Main ring (LER)

For larger vertical amplitude of the injected beam, the dynamic aperture shrinks.

\( \frac{J_y}{J_x} \): Ratio of the vertical to horizontal amplitude of the injected beam.

If \( \frac{J_y}{J_x} < 2\% \), the beam is safely injected in the Main ring. In this case, \( \varepsilon_y \) of injected beam is 2.3 nm. \( \varepsilon_y \) from DR assuming no-coupling is 0.25 nm. -> enough margin
4. $\epsilon_y$ growth due to Beam-Beam effect after the injection

Y.Ohnishi

Strong(Stored beam) – Weak(Injected beam) model

The particles oscillating horizontally collide with the other beam at the position which is shifted from the waist point. Due to this effect, 5.5% beam particles are lost.

Beam loss will arise by the b-b effect anyway. Insensitive to the $\epsilon y$ of the injected beam ??? Needs more study.

- Vertical emittance growth of injected beam: 16 times larger than that w/o Beam-Beam effect.

- Vertical coherent oscillation

This is especially strong in the nano-beam scheme which is very small waist at the IP.
Summary

1. From e+ target to Damping ring
   - Beam loss mitigated by
     • choosing proper accelerations in capture section

2. Damping ring
   - Microwave Instabilities due to CSR mitigated by
     • narrower beam pipes
     • larger momentum compaction factor
     • higher synchrotron tune.

3. From Damping ring to Main ring
   - Emittance growth mitigated by
     • adjusting RF-phase
     • offset the initial position of the beam
     • positioning of sextupoles.

The performance of LINAC and beam transport are very important for the next generation B-factories.

I believe proper tunings and patient effort will surely lead us to success!
Gracias por su atención