Injector and Collider Rings of SuperKEKB B factory

– with some emphasis on the injector –

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3km SuperKEKB
Collider dual rings

Mt. Tsukuba

600m Injector Linac

Damping Ring

PF-AR

PF
KEKB and SuperKEKB overview

Daily performance improvements
Dual bunches in a pulse
Continuous injection
Simultaneous top-up injection
Upgrade towards SuperKEKB
Summary
KEKB Configuration (1999 – 2010)

Electron Positron Accelerator Complex at KEK

Linac delivered:
- for PF: 2.5 GeV e⁻
- for PF-AR: 3 GeV e⁻
- for KEKB: 8 GeV e⁻
- 3.5 GeV e⁺

Shared single injector between 4 storage rings
Shared beam transport line between HER & PF-AR
KEKB Design

- Maximum reuse of TRISTAN inheritance
- However, still many improvements applied, ex.
  - Many bunch collisions with dual ring collider
    - Energy asymmetry for the boost of center of mass of Bs
  - Full energy injection
    - Energy upgrade with SLED RF pulse compressor
      - from 2.5 GeV (400 m) → 8 GeV (600 m)
  - Injection aperture of 30 ps
    - Slight RF frequency modification to have an integer relation
      - Linac 2856 MHz : 10.386 MHz x 275
      - Ring (508.5 MHz →) 508.9 MHz : 10.386 MHz x 49
  - And so on
SuperKEKB Configuration (2018 – )

◆ Newer Electron Positron Accelerator Complex at KEK

Beam from Injector and Storage Current

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Electron Current</th>
<th>Positron Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperKEKB:</td>
<td>7 GeV e-</td>
<td>2600 mA</td>
</tr>
<tr>
<td></td>
<td>4 GeV e+</td>
<td>3600 mA</td>
</tr>
<tr>
<td>PF:</td>
<td>2.5 GeV e-</td>
<td>450 mA</td>
</tr>
<tr>
<td>PF-AR:</td>
<td>6.5 GeV e-</td>
<td>60 mA</td>
</tr>
</tbody>
</table>

SuperKEKB Design

◆ Maximum reuse of KEKB inheritance
◆ However, still many improvements applied, ex.

- Nanobeam collision scheme (with beam sizes of 50nm)
  - For 40-fold higher luminosity avoiding hourglass effect
- Precise superconducting focusing magnets
  - With many corrector coils
- RF system additions for twice higher beam current
- Many magnet additions/replacements for low emittance
- Damping ring construction
- PF-AR direct beam transport line construction
- Many improvements to inject even under nanobeam
  - At injector linac
Operator Shifts

◆ Operators for every 8-hour

- KEKB control room for SuperKEKB, PF-AR, Linac (Beam)
  - 3/2/2 Operators for SuperKEKB, PF-AR [A]
  - 1/1/1 Operators for Linac [B]
  - 1.5/1.5/1 Commissioning shifts for SuperKEKB and Linac [C]
  - 0.5/0.5/1 Safety shifts for SuperKEKB [D]

- Linac control room
  - 1/1/1 Operators for Linac (Hardware) [B]
  - 1/1/1 Safety shifts for Linac [E]

- Cryogenic control room

- PF control room

◆ Members

- Outsourcing: [A] x12, [B] x12
- SuperKEKB Staff: x55, Linac Staff: x30 (basically all staff)
- Staff: [C] x50, [D] x48, [E] x27 (overlapping)
**Injector Operation Statistics**

**Statistics**

Injector operation hours and failure rates

- **Failure**: device failures that prevent optimum performance
- **Beam loss**: time when beam injection was really impossible

---

**Operational balance**

**High demands**

**KEKB and light sources**

**SuperKEKB Light sources**

**Fiscal year**

**Hours**

**Rates (%)**

- Operation hours (hour)
- Failure rate (%)
- Beam loss rate (%)
KEKB and SuperKEKB overview

**Daily performance improvements**

- Dual bunches in a pulse
- Continuous injection
- Simultaneous top-up injection
- Upgrade towards SuperKEKB

Summary
PEP-II/SLAC and KEKB

- We exchanged ideas between PEP-II and KEKB
- Viewed each other from control rooms

**Friendly competition**
Daily Morning Meeting

- Every morning on weekdays and weekend from 9 a.m.
- Very often novel ideas are proposed for performance improvement of beams, devices and operation
- Bright new idea in the morning meeting could make the operation much advanced in the evening
  - Only some ideas are effective, so rapid prototyping is important
- EPICS control framework and Scripting languages
  - Especially, SADscript as a bridge btw. Accelerator simulation, Numeric manipulation, Graphic interface and EPICS controls
Operational Optimizations

- For example, run-length optimization

- Hundreds of tools were developed

- with graphical user interface for operators

- often automated

- Past examples follow from the next slide
KEKB and SuperKEKB overview
Daily performance improvements

Dual bunches in a pulse
Continuous injection
Simultaneous top-up injection
Upgrade towards SuperKEKB

Summary
Two bunches in a pulse

- As the stored beam current in MR increases, much more injection beam current was required
- Especially for the positron injection rate

Two bunches in a pulse acceleration in order to double the positron beam current planned

- Minimum bunch separation of 96 ns (10.386 MHz)
- Parallel dual grid pulsers for a single cathode
- Beam instrumentation with 96 ns separation
- Timing manipulation and bucket selection
- Energy equalization
Dual-bunch Energy Equalization, and Feedback

◆ Energy equalization is important for stable operation

Measurement at bunching section after energy equalization with RF pulse timing

First Bunch

Energy at A1_B8 : 15.637002-15.66293 MeV

\[
a = 1.25264 \pm 0.0071 \\
b = 0.8912 \pm 0.0147
\]

Second Bunch

Energy at A1_B8 : 15.708004-15.80365 MeV

\[
a = 1.3135 \pm 0.0079 \\
b = 0.6754 \pm 0.0100
\]

Beam loading compensation

Stabilization at bending section with SLED timing

Klystron

Beam

Beam Positions of 2-Bunches

- Beam Fluctuation

- Convert into Energy Difference

- Average (Integration)

- X Gain — Offset

Energy Difference Feedback

\[\text{Function} \quad \text{SP1.C5} = (a \times b)\]

\[\text{Function} \quad \text{SP1.C5} = (a \times b)\]

\[\text{Function} \quad \text{SP1.C5} = (a \times b)\]

\[\text{Function} \quad \text{SP1.C5} = (a \times b)\]
KEKB and SuperKEKB overview
Daily performance improvements
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Summary
Continuous Injection

- Detector data acquisition stopped during the injection and the detector high voltage (HV) preparation
- Especially for the positron injection rate

◆ Continuous Injection with detector HV applied was another major step forward

- For higher integrated luminosity
- by detector improvements, esp. CDC, TOF, DAQ
- with certain benefit from collision with crossing angle
  - without bending magnet at IP, for lower background
- Then, approximately 26% gain achieved
Continuous injection

2003, before continuous injection was applied
Data acquisition stopped during injection
(8-hour history of beam current, luminosity, etc.)

2004, after continuous injection was applied
Data acquisition continued during injection
(8-hour history of beam current, luminosity, etc.)
Beam mode switching improvements

♦ Continuous injection was applied in 2004

![Beam mode switching graph]

♦ Switched 360 times / day in 2008

♦ Simultaneous top-up injection was applied in 2009
  ❖ to enable switching every 20 ms (4 million times / day)
KEKB and SuperKEKB overview
Daily performance improvements
Dual bunches in a pulse
Continuous injection
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Upgrade towards SuperKEKB
Summary
Simultaneous Top-up Injections

- Even faster beam mode switches
- Pulse-to-pulse modulation (PPM) at 50 Hz
  - PPM was applied at PS/CERN (1977?) at 1.2 s
  - ~150 parameters were switched every 20 ms for 3 beams
- Many Hardware improvements as well as controls
  - PF top-up injection for higher quality experiments
  - Sensitive luminosity tuning with Crab cavities

- Many more parameters in SuperKEKB for 4 beams
Fast Global Synchronous Controls

- Event-based controls (MRF)
- 114.24MHz event rate, 50Hz fiducials
- Timing precision < 10ps
KEKB Operation Improvement (base of SuperKEKB)

- May.2000: Dual Bunch $e^+$
- Apr.2003: Continuous Injections
- Feb.2005: Crab Cavities and Simultaneous Injection
- Dec.2008: Crab Cavities and Simultaneous Injection

Graphs and data showing beam currents, luminosities, and integrated luminosities with colors indicating different parameters:
- Red: beam current ($e^-$, $e^+$)
- Purple: vacuum ($e^-$, $e^+$)
- Yellow: luminosity
- Green: integrated luminosity

Keeps world luminosity record

Belle/KEK

©2008 STUDIO R
KEKB and SuperKEKB overview
Daily performance improvements
Dual bunches in a pulse
Continuous injection
Simultaneous top-up injection
Upgrade towards SuperKEKB
Summary
Mission of Electron/positron Injector in SuperKEKB

- For 40-times higher luminosity in SuperKEKB collider
- Low emittance & low energy spread injection beams with 4 times higher beam current
  - New high-current photo-cathode RF gun
  - New positron capture section
  - Positron damping ring injection/extraction
  - Optimized beam optics and correction
  - Precise beam orbit control with long-baseline alignment
  - Simultaneous top-up injection to DR/HER/LER/PF/PFAR
- Balanced injection for the both photon science and elementary particle physics experiments
SuperKEKB Schedule

SuperKEKB/Belle II schedule

<table>
<thead>
<tr>
<th>Calendar year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<td>SuperKEKB LER &amp; HER upgrade construction</td>
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<td>Positron damping ring (DR) construction</td>
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<tr>
<td>Injector Linac upgrade construction &amp; operation</td>
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<td>VXD installation w/ full Belle II</td>
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<tr>
<td>Operation for years</td>
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</tbody>
</table>

Injector Linac and SuperKEKB at KEK

## Required injector beam parameters

<table>
<thead>
<tr>
<th>Stage</th>
<th>KEKB (final)</th>
<th>Phase-I</th>
<th>Phase-II</th>
<th>SuperKEKB (final)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
</tr>
<tr>
<td>Energy</td>
<td>3.5 GeV, 8.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
</tr>
<tr>
<td>Stored current</td>
<td>1.6 A, 1.1 A</td>
<td>1 A, 1 A</td>
<td>1.8 A, 1.3 A</td>
<td>3.6 A, 2.6 A</td>
</tr>
<tr>
<td>Life time (min.)</td>
<td>150, 200</td>
<td>100, 100</td>
<td>–, –</td>
<td>6, 6</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>primary e⁻ 10 → 1</td>
<td>primary e⁻ 8 → 0.4</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Norm. Emittance (γβε) (µrad)</td>
<td>1400, 310</td>
<td>1000, 130</td>
<td>200/40 (Hor./Ver.)</td>
<td>150 100/15 (Hor./Ver.)</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.125%, 0.125%</td>
<td>0.5%, 0.5%</td>
<td>0.16%, 0.1%</td>
<td>0.16%, 0.07%</td>
</tr>
<tr>
<td>Bunch / Pulse</td>
<td>2, 2</td>
<td>2, 2</td>
<td>2, 2</td>
<td>2, 2</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
<td>25 Hz</td>
<td>25 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Simultaneous top-up injection (PPM)</td>
<td>3 rings (LER, HER, PF)</td>
<td>No top-up</td>
<td>Eventually</td>
<td>4+1 rings (LER, HER, DR, PF, PF-AR)</td>
</tr>
</tbody>
</table>
Subjects to Consider at Injector

- (As of 2014)
- Have to consider too many subjects!
- Phronesis needed (Greek: Practical wisdom, Ability to understand the Universal Truth)
New positron capture section after target with Flux concentrator (FC) and large-aperture S-band structure (LAS) Satellite bunch (beam loss) elimination with velocity bunching Pinhole (2mm) for passing electrons beside target (3.5mm) Recently, facing discharge difficulties at maximum field
Development of Photo-cathode RF Gun

- **Succeeded in injection** during SuperKEKB Phase 1 and 2 commissioning
- **Employs** Yb-doped-fiber and Nd/Yb:YAG laser, Ir\(_5\)Ce cathode, QTWSC or cut disk cavities
- **Stability improving**
- **Beam instrumentation improvements and comparison with simulation codes underway**

- **Secondary RF gun was constructed as a backup**
- **Incorporate suggestions by review committee for availability and so on**

**One of Key Component: Photo Cathode RF Gun**

- Quasi traveling wave side couple cavity
- Primary RF gun
- Secondary RF gun
- Thermionic gun
- Electron Guns
- **Injector Linac and SuperKEKB at KEK**
Development and installation of pulsed magnets

- 100 Pulsed magnets and power supplies are installed in 2017 - 2019
- 30 quads, 36 steerings, 2 bends, 13 girders were fabricated and installed in 2017
- Quads with advanced design in-house for 1 mH, 330 A, 340 V, 1 ms
- Small form factor of 19 inch width and 3U height each, with energy recovery up to 75%
- Steering power supplies were also developed in-house
- Essential for SuperKEKB low emittance injection and for simultaneous injection
- 4+1 ring simultaneous injections with virtual accelerator concept

- **Long term tests at a stand**
- **Satisfies specification, 0.01%**
- **Control synchronization**

- **Beam test with two quads**
- **Successful fast beam switches**
- **Switching features are confirmed**
- **Now all in operation**

- **Girders are tested as well**
- **In-house drawings to save rsc.**
- **1μm alignment precision**
- **Ready for Phase-3 upgrade**

Enomoto, Natsui et al
**Pulse-to-pulse modulation**

- **Simultaneous injection**
- **Four PPM virtual accelerators for SuperKEKB project**

Based on Dual-tier controls with EPICS and event-system

**Independent parameter sets**
- for each VA (20ms)
- >250 parameters for equipment controls
- many more for beam controls

**maybe with additional PPM VA of stealth beam**
- for measurement and optimization

**Event-based Control System**

- Every 20 ms

**Simultaneous injection**

- **PF Injection**
  - DC Injection

**SuperKEKB-LER Injection**

- PF-AR Injection
  - Damping ring

**SuperKEKB-HER Injection**

- F.B

**PF Injection**

- e⁻ (2.5GeV, 0.2nC)

**SuperKEKB-LER Injection**

- e⁻ (3.5GeV, 10nC)

**SuperKEKB-HER Injection**

- e⁻ (7GeV, 5nC)

**PF-AR Injection**

- e⁻ (6.5GeV, 5nC)

**F.B**
KEKB and SuperKEKB overview
Daily performance improvements
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Upgrade towards SuperKEKB

Summary
Summary

◆ We learned a lot during KEKB operation
◆ It contributed to achieve the world highest luminosity
◆ SuperKEKB is another challenge with higher beam charge and lower transverse/longitudinal emittance
◆ Steady progress is made towards designed beam in steps
◆ We may need to improve the injection further
  ❖ ex. stealth beam measurement / optimization, etc
◆ With some Phronesis we may enjoy beam commissioning
Thank you

Conference papers at <http://www-linac.kek.jp/linac/>
One Machine, Multiple Virtual Accelerators (VAs)

- Control/Monitor are carried dependent on a VA
  - Mostly independent between VAs
- Independent parameter set for each VA, one of the VAs is controlled at a time
  - VAs for Injections (HER (e-), LER (e+), PF, PF-AR) and Linac-only in SuperKEKB project

Event-based Control System

**PF Injection**
- e^- Gun
- e^- BT (PF: 2.5GeV, 0.1nC)

**KEKB-LER Injection**
- Primary e^- (4GeV, 10nC)
- e^- Gun
- e^- BT (KEKB: 3.5GeV, 0.6nC)

**KEKB-HER Injection**
- e^- Gun
- e^- BT (KEKB: 8GeV, 1.2nC)
Multiple Closed Loop Controls Overlapped

- Closed loops were installed on each VA independently

Event-based Control System

- PF Injection
- KEKB-LER Injection
- KEKB-HER Injection

- ARC
- e^− Gun
- e^+ Target
- e^− Gun
- Primary e^− (4GeV, 10nC)
- e^− BT (PF: 2.5GeV, 0.1nC)
- e^− BT (KEKB: 3.5GeV, 0.6nC)
- e^− BT (KEKB: 8GeV, 1.2nC)

Injecto Linac and SuperKEKB at KEK

SuperKEKB at 2002

◆ Some consideration on upgrade for SuperKEKB was presented already in 2002
◆ Much different from present form, but this shows a project needs a long lead time

Later,

Energy exchange was rejected

Nano-beam scheme was employed

Linac / Ring Upgrade for SuperKEKB

◆ for Precise Measurement of B-meson System Parameters and Search for New Physics (ex. SUSY)
  SuperKEKB : Luminosity of $10^{35}$ cm$^{-2}$ s$^{-1}$
  with Major Upgrade of Linac and Ring
◆ Luminosity Increase
  (1) Squeezing Beta at Interaction Region (by factor of 3.3)
  (2) Increasing $e^-$ and $e^+$ Beam Current (by factor of 3.3)
  (3) Exchanging Energies of $e^-$ and $e^+$ (to cure $e^-$ cloud issues)
◆ for Linac
  (3) is the Major Challenge, as well as (2)
  Two Schemes are Considered
    (a) Higher Gradient with C-band Structures
    (b) Recirculation of Positron
### Linac Schedule Overview 2018

**RF-Gun**
- **e- beam commissioning** at A, B-sector

**e- commiss.** at A, B, R, C, 1

**e+ commiss.** at 1, 2 sector (FC, DCS, Qe- 50%)

**Non damped e+ commiss.** at 1, 2, 3, 4, 5 sector

**damped e+ commiss.** at 1, 2, 3, 4, 5 sector (Qe+ = 1~4nC)

**e- commiss.** at A, 2, 5 sectors (Qe- = 1~4nC)

#### Phase 1: high emittance beam for vacuum scrub

- Phase 2, 3: low emittance beam for collision

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**Time**

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<th>Year</th>
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<th>2016</th>
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**Location**

- low intensity e+
- 2nd stage (e-/e+)
- non-damped e+
- 3rd stage
- damped e+
- 4th stage
- with VXD
- 5th stage

**Location:**
- A1-RF gun
- AB-sec
- J-arc
- C1-sec
- Target + FC
- 12-sec
- SY2
- DR
- 345-sec
- HER
- LER
- 3T/32gun
- PF
- Pfar

**Beam Licenses in steps**

**Low Emittance Beams**

**Low Emittance Injections**

**4+1 Ring Injections**

**Without Top-up**

**Direct PF-AR BT**

**Improved RF gun**

**With Top-up**

**1 nC** Phase 1

**1 - 2 nC** Phase 2

**1 - 4 nC** Phase 3

*Electron: **

*Positron: **

*Low current electron: **

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*Injection Linac and SuperKEKB at KEK*