KEKB/SuperKEKB Linac

(and S-, C-, L-, X-bands developments)

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KEK Electron Accelerator Complex

Present situation for SuperKEKB and light sources

- Beam from Injector and Storage Current
  - SuperKEKB: 7 GeV e- 2600 mA
  - 4 GeV e+ 3600 mA
  - PF: 2.5 GeV e- 450 mA
  - PF-AR: 6.5 / 5.0 GeV e- 60 mA

- Beam from Injector and Storage Current
  - SuperKEKB: 7 GeV e- 2600 mA
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  - PF: 2.5 GeV e- 450 mA
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Advances in KEK Injector Linac

Machine Performance Improvement

Challenges towards SuperKEKB

Upgraded Injector for SuperKEKB
Photon Factory Configuration (1982 –)

◆ Electron injector to dedicated light source

Linac delivered:
for PF: 2.5 GeV e⁻

PF 2.5 GeV/c

40 accelerator units were installed

Typical accelerator unit
2.5 GeV S-band Linac

Injectors for dedicated light source, Photon Factory

- World-second dedicated (2nd generation) source after Daresbury

Certain S-band experiences at universities in Japan

- Ex. 300-MeV 300-Hz linac for nuclear physics

Foreseen collider project TRISTAN

- 2.5-GeV 400-m linac without booster
- Quasi-constant gradient 2-m S-band structure
2.5 GeV S-band Structure

◆ Quasi-constant gradient
  - Disk 2a of 20 mm, 75 micron-step changing from entrance to exit
  - 5 sets of 2a to disperse transverse modes to avoid beam blow-up

◆ Electroplating technique to fabricate
  - No brazing, no need for tuning, and cost reduced
  - 160 structures 40 RF sources installed

◆ Long-pulse injection
  - up to 1 micro second, 8 MeV / m

◆ Several different injection modes during 37 years
  - Still serving 3000 users / year
  - Positron injection to cure ion instability under certain vacuum condition
  - Hybrid or shaft mode to serve single-bunch experiments as well
  - Simultaneous top-up injection to share the beams

Electron positron collider for Top quark

Linac delivered:
for PF: 2.5 GeV e⁻
for TRISTAN:
  2.5 GeV e⁻
  2.5 GeV e⁺

Shared single injector between particle physics and photon experiments
500-MeV Positron for TRISTAN

◆ Injection part
  ◢ High current thermionic gun
  ◢ 119 MHz sub-harmonic buncher for single bunch operation

◆ The same electroplating structure
  ◢ But combined 4-m structure for higher gradient

◆ Certain end-point experiments in-between injections
  ◢ Axion search
  ◢ Slow positron experiments for material science and particle physics
  ◢ Detector developments
KEKB Configuration (1999 – 2010)

Electron Positron Accelerator Complex at KEK

- **KEKB**
- **HER** 8 GeV/c
- **LER** 3.5 GeV/c
- **Belle**
- **PF-AR**
- **2.5 GeV/c**
- **6.5 GeV/c**

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

Injector Linac at KEK

KEKB Design

◆ Maximum re-use 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
Advances in KEK Injector Linac

Machine Performance Improvement

Challenges towards SuperKEKB

Upgraded Injector for SuperKEKB
PEP-II/SLAC and KEKB

◆ We shared ideas/experiences between PEP-II and KEKB control rooms

Friendly competition (above plots were on the same day in Oct.2005)
Performance improvements at KEKB

◆ Competition with SLAC PEP-II
  ❖ One of worries was the injector capability
    ▶ Injection beam quality
    ▶ Beam stability
    ▶ Beam current, especially positron
    ▶ Injection time to fill the both storage rings
    ▶ And, integrated luminosity

◆ Many improvements required, however
  ❖ Two serious damages in accelerator structure in 2001
    ▶ after the performance was pushed too hard
    ▶ We found our way with optimized performance
Operational Optimizations

- For example, run-length optimization

- One of 100 automations
Energy Stabilization Loops

- **BPMs - Energy knob**
  - Energy knob without energy spread

- **Simple P.I. Loop**

6 feedback loops along the linac depending on the modes.

![Diagram showing energy stabilization loops and feedback controls](image_url)
Feedback Stabilizer monitor

- Robust operation is essential
  - Remote monitoring in summary panel
  - Several conditions, limits in loop variables
  - Beam-mode dependent operation
  - Status and variable logging, and their viewers

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Operation statistics and improvements

Statistics

Injector operation hours and failure rates

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

![Graph showing operation statistics and improvements](image_url)
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
Energy Equalization

- Beam loading compensation
  - For bunch separation of 96 ns
  - Or we sometimes utilize energy difference in order to equalize the beam orbits
Dual-bunch Energy Equalization, and Feedback

◆ Energy equalization is important for stable operation

Measurement at bunching section after energy equalization with RF pulse timing

Stabilization at bending section with SLED timing

Beam Fluctuation

Klystron Klystron

Beam Positions of 2-Bunches
- Beam Fluctuation
- Convert into Energy Difference
  - Average (Integration)
  - $x$ Gain
  - Offset

Energy Difference Feedback
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

◆ Switched 360 times / day in 2008

◆ Simultaneous top-up injection was applied in 2009
Simultaneous Top-up Injections

- Even faster beam mode switches
- Pulse-to-pulse modulation (PPM) at 50 Hz
  - PPM was first applied at PS/CERN (1977) at 1.2 second
  - ~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

Dual layer control concept

Event Generator

Central

KL_B5/B6
SB_B
SB_A
SH_A1

Cont-ABC
SB_C
SB_1
SB_2
SB_3
SB_4
SB_5

KL_51/52

Injection

Event Receivers

ARC

e− Gun

e+ Target

Cont-1
Cont-2
Cont-3
Cont-4
Cont-5

Dual Layer Controls

OPI

EPICS
Channel Access

IOCs

EVG

EVR

MRF Event Link

e− BT (PF: 2.5GeV, 0.1nC)
e+ BT (KEKB: 3.5GeV, 2nC)
e− BT (KEKB: 8GeV, 2nC, PFAR: 3.0GeV, 0.1nC)
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**
  - Primary e- (4GeV, 10nC)
  - e- BT (PF: 2.5GeV, 0.1nC)

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

- **KEKB-HER Injection**
  - Primary e- (4GeV, 10nC)
  - 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**
  - e− Gun
  - e− BT (PF: 2.5GeV, 0.1nC)

- **KEKB-LER Injection**
  - Primary e− (4GeV, 10nC)
  - e+ Target
  - e− BT (KEKB: 3.5GeV, 0.6nC)

- **KEKB-HER Injection**
  - e− Gun
  - e− BT (KEKB: 8GeV, 1.2nC)
KEKB Operation Improvement (base of SuperKEKB)

- **KEKB Operation Improvement (base of SuperKEKB)**
- **May.2000**
  - Dual Bunch e+
  - Continuous Injections
- **Feb.2005**
  - Crab Cavities and Simultaneous Injection
- **Dec.2008**
  - Crab Cavities and Simultaneous Injection

- **Purple**: Vacuum (e-, e+)
- **Yellow**: Luminosity
- **Green**: Integrated Luminosity
- **Red**: Beam Current (e-, e+)

Keeps world luminosity record

Belle/KEK

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Advances in KEK Injector Linac
Machine Performance Improvement
Challenges towards SuperKEKB
Upgraded Injector for SuperKEKB
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
C-band Developments for Energy Exchange

Electron cloud instability in the positron ring could be partially cured with higher energy in SuperKEKB

The same electroplating technique was applied for the 1-m structures, and succeeded doubling the gradient
Converting S-band unit into C-band units

- 2 units were actually installed and operated for injections during the KEKB project

- However, later scheme did not allow small apertures to avoid emittance growth, and removed for SuperKEKB
X-band Developments

◆ X-band deflector was developed
  ❖ For single-shot emittance measurement
  ❖ In collaboration with SLAC
  ❖ Medium power klystron and power modulators were developed
  ❖ Installation delayed for beamline design

◆ General purpose high-gradient acceleration study
  ❖ In collaboration with CERN, SLAC, Beijing, Shanghai, ⋯
  ❖ Especially CLIC collaboration and CLIC prototype structure tests
L-band Developments for Positron Yield

- L-band structure was developed to enhance the positron yield
  - After the positron target for large-aperture capturing
  - After the damping ring for bunching
- Kantal coaxial RF load to fit inside of solenoids
- Synergy expected with 1.3 GHz RF ILC development
  - $2856 \times 5 \div 11$
    - "11" is needed anyway for the ring synchronization
  - S-band satellite bunches can be filtered with this frequency
- Klystron was developed as well
  - High power test succeeded
- Now this is a backup plan
Large Aperture S-band Development

- L-band system may consume large resources
- Beam simulation suggests S-band may suffice
  - With velocity bunching
  - For capturing, bunching, and satellite elimination
- Larger aperture S-band structure was designed
  - 20 mm → 30 mm aperture, double feed, fitting into solenoids
  - Electroplating → brazing because of small productions
Advances in KEK Injector Linac
Machine Performance Improvement
Challenges towards SuperKEKB

Upgraded Injector for SuperKEKB
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

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The single injector would behave as multiple injectors to multiple storage rings by the concept of virtual accelerator
SuperKEKB Schedule

SuperKEKB/Belle II schedule

|---------------|------|------|------|------|------|------|------|------|------|------|---------|

- **Phase 1**: SuperKEKB LER & HER upgrade construction
  - Start-up
  - w/o QCS
  - w/o Belle II

- **Phase 2**: Belle II upgrade construction
  - Belle II roll-in
  - w/ QCS
  - w/ Belle II (no VXD)

- **Phase 3**: Positron damping ring (DR) construction
  - DR commissioning
  - VXD installation
  - w/ full Belle II
  - operation for years

- **KEKB operation**: SuperKEKB LER & HER upgrade construction
- **Injector Linac upgrade construction & operation**
### Required injector beam parameters

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Positron generation for SuperKEKB

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, Ir5Ce 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

M. Yoshida et al.

Injector Linac at KEK

K. Furukawa, KEK, FCC week, Jun. 2019
Development and installation of pulsed magnets

- Pulsed magnets and power supplies were installed in 2017
- >30 quads, >40 steerings, 2 bends, 14 girders are operational
- Quads with advanced design at 1 mH, 330 A, 340 V, 1 ms with energy recovery up to 75%
- Small form-factor of 19 inch width and 3U height each
- 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

- Successful fast beam switches
- 0.01% reproducibility and stability
- Girders with In-house drawings to save resources
- 0.1mm alignment precision

- Long term tests at a stand
- Satisfies specifications
- Control synchronization

Enomoto, Natsui et al
Pulse-to-pulse modulation

◆ Four PPM virtual accelerators for SuperKEKB project

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

Independent parameter sets for each VA (20ms)
>200 parameters for equipment controls
many more for beam controls

maybe with additional PPM VA of stealth beam for measurement
Residual Dispersion Function in Linac

- Large residual dispersion was generated from the J–ARC.
- With dispersion correction by tuning the magnetic field of quadrupole magnets, residual dispersion became small enough.

Y. Seimiya et al.
Simultaneous 4 + 1 Ring Top-up Injection

◆ Realized for the first time
  ✐ SuperKEKB HER 7 GeV e–
  ✐ SuperKEKB LER 4 GeV e+
  ✐ Photon Factory 2.5 GeV e–
  ✐ PF-AR 5.0 / 6.5 GeV e–

❖ 4 beams are modulated at 20 ms PPM
❖ More than 200 pulsed devices were constructed for SuperKEKB, as well as beam and RF monitors
❖ Injection noise (background) were well studied and routinely adopted from the 3rd week of May (after a severe fire)
Summary
Summary

◆ We learned a lot during injector development and operation for 4 decades

◆ It contributed to achieve the world highest luminosity

◆ Injection into SuperKEKB is another challenge with higher beam charge and lower transverse/longitudinal emittance

◆ Trial and error for a new accelerator may be necessary depending on many parameters along the accelerator chain

◆ With some Phronesis we can enjoy accelerators
  ◆ Phronesis [Greek]: Practical wisdom, Ability to understand the Universal Truth

**Injector Linac at KEK**

**Thank you**

Mt. Tsukuba

SuperKEKB dual rings

PF-AB

PF

700m Injector Linac

Conference papers at http://www-linac.kek.jp/linac/