Operational report of the SuperKEKB Phase-2 commissioning

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on behalf of the KEKB group
1. Introduction of SuperKEKB
2. Brief results in Phase-1 commissioning
3. From Phase-1 to Phase-2
4. Phase-2 commissioning results
5. Summary
From KEKB to SuperKEKB

SuperKEKB/Belle II

x 40 Gain in Luminosity

To find New Physics beyond the Standard Model of particle physics by the extremely high luminosity colliding accelerator.

Belle/KEKB

Experimental verification of “Theory of Kobayashi-Maskawa”

The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa
From KEKB to SuperKEKB

Redesign the lattice to squeeze emittance (replace short dipoles with longer ones, increase wigglers cycles)

Upgrade Belle II detector

New superconducting final focusing magnets near the IP

SuperKEKB

- Nano-Beam scheme extremely small $\beta_y^*$, low emittance
- Beam current double

$$L = \frac{\gamma_{e\pm}}{2e\epsilon_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x} \left( \frac{1}{\beta_y^*} \right) \left( \frac{R_L}{R_y} \right) \right)$$

40 times higher luminosity
$2.1 \times 10^{34} \rightarrow 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

- Low emittance
- RF electron gun
- Upgrade positron capture section

Replace beam pipes with TiN-coated beam pipes with antechambers

New e+ Damping Ring

Reinforce RF systems for higher beam currents

From the presentation, Mar. 4, 2018 by Dr. K. Akai @ KEKB Review
SuperKEKB project schedule

From the presentation by Dr. K. Akai, Mar. 14, 2018@KEKB Review
Phase-1 commissioning major efforts

- Completion of the SuperKEKB Main Ring without the beam interaction region and the Injector Linac without the Dumping Ring.
- Vacuum scrubbing was done and beam background studies were performed by Beast detector.
- The optics correction was performed for getting a vertical low emittance.
  - The HER corrections went well.
  - In the LER corrections, the leakage magnetic field from the Lambertson septum magnets for beam abort turned out to have a harmful effect on the low emittance.
    - This problem was resolved by the skew quadrupole corrector and the permanent skew quadrupole magnet.
- The vertical beam size blowup was observed in LER. The cause was the electron clouds.
- Injector worked stably.
Phase-1 commissioning major efforts

Construction of MR: Installation of New Magnets

SuperKEKB Upgrade

- Completely new beam lines around the IP “Tsukuba straight section”
- New longer dipole magnets in the LER (~100)
- New: added 280 wigglers to the LER
- New vertical steering magnets (~220). Modification of horizontal steering magnets (~300)

Phase-1 interaction region

Mainly Tsukuba straight section magnets

HER New
HER Recycled
LER New
LER Recycled

36 wigglers added the HER.

Arc dipoles, wigglers

+ ~250 corrector magnets

Total number of water-cooled magnets ~ 1700

Courtesy of Dr. M. Masuzawa, KEK
Phase-1 commissioning major efforts

Construction of MR: Alignment of the magnets

Calibration of the lase trackers was done carefully.

(long) distance being compared with TS30

More than 1200 network control points in the tunnel
More than 4000 reference points for the magnets
More than 5000 points to be surveyed and analyzed.
More than 400 LT settings, with overlaps

Magnet Gp best guess form the survey and analysis was about 16.4 mm longer than the SuperKEKB design. This information was used when injecting LER beam to the ring on Feb. 9, 2016.

From the orbit measurement, the ring circumference:
- \(L_{ER}: C_{M} - C_{D} \approx 2.0 \text{ mm (Cir=3016m)}\)
- \(C_{LER} - C_{HER} \approx 0.2 \text{ mm (LER chicane can adjust +/- 3 mm)}\)
Phase-1 commissioning major efforts

Construction of MR: Installation of New Beam Pipes

- LER: Approximately 93% of beam pipes in length are renewed.
- HER: Approximately 82% are reused.

Sub systems, such as cooling water system, compressed air system, were basically reutilized, with necessary upgrades.

Control system was also reused, but the antique components are updated.

From the presentation, Jun. 13, 2016 by Dr. Y. Suetsugu @ KEKB Review
**Phase-1 commissioning major efforts**

**Beam operation: Vacuum scrubbing**

**LER**

\[
I_{\text{max}} = \sim 1010 \text{ mA} \\
\text{Beam dose}=775.0 \text{ Ah}
\]

The \(dP/dI\) value for arc section, where all of the beam pipes were newly fabricated, was \(\sim2 \times 10^{-6} \text{ Pa A}^{-1}\) at the beam dose of 500 Ah.

**HER**

\[
I_{\text{max}} = \sim 870 \text{ mA} \\
\text{Beam dose}=661.5 \text{ Ah}
\]

The \(dP/dI\) value at the arc section, where most of the beam pipes was reused from KEKB, was \(\sim5 \times 10^{-8} \text{ Pa A}^{-1}\) at the beam dose of 500 Ah.

From the presentation, Jun. 13, 2016 by Dr. Y. Suetsugu @ KEKB Review
Phase-1 to Phase-2

Construction of Interaction Region (IR)

Phase 1 IR without concrete shields

Installation of beam final focus superconducting magnet system (QCSR and QCSL) into IR:
The system will be presented in WG-7 this morning.

IR superconducting magnets:
- 8 main quadrupole magnets
- 43 corrector magnets
- 4 compensation solenoids

From the presentation by Dr. K. Akai, Mar. 14, 2018@KEKB Review

From the presentation, Jun. 13, 2016 by Dr. K. Kanazawa @ KEKB Review

QCSR was installed after delivery to KEK on Feb. 13, 2017

QCSR was installed in July 2016, and cool down test was done in Dec. 2016

Belle II detector before Roll-in.
Construction of Interaction Region (IR):

Connection between the detector IP chamber and QCS beam pipes by the remote vacuum connection

The connection works were completed at Jan. 15, 2018.

All magnets are re-installed and all beam pipes are connected. Cabling and other works finished.
Phase-1 to Phase-2

Construction of Dumping Ring Complex:

The DR damps the emittance of the e+ beam to inject into the LER. The positron beam from Flux Concentrator (FC) has a huge longitudinal distribution.

**LTR:** The energy spread (5%) should be reduced within the energy acceptance of the DR (1.5%) with the Energy Compression System (ECS) in the LTR.

**RTL:** The bunch length extracted from the DR (6.7mm) should be shortened (0.65mm) to fit the LINAC S-band system with the Bunch Compression System (BCS) in the RTL.

Targets in Phase-2 Commissioning

1. Verification of nano-beam scheme
   - Squeezing $\beta_y^*$ down to a few mm $< \sigma_z$.
   - Luminosity increases even though $\beta_y^*$ is smaller than $\sigma_z$.
   - Beam-Beam parameter, $\xi_y > 0.03$
   - $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 1[A] beam current in the LER

2. Understanding and reduction of Belle-II backgrounds

3. Establishment of the injection system

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
SuperKEKB Phase-2 Commissioning

- Beam operation of DR and SuperKEKB Phase-2
  - DR LTR beam tuning started on Jan. 23, 2018.
    - Major study items for LTR completed by Feb. 7
  - DR beam tuning started on Feb. 8.
  - DR RTL beam tuning started on Feb. 10.
  - BT beam tuning started on March 16.
  - SuperKEKB HER beam injection and tuning started on March 19.
    - HER captured beam and RF turn-on in March 20.
  - SuperKEKB LER beam injection and tuning started on March 27.
    - LER captured beam and RF turn-on in March 30.
  - Collision study with single bunches of e+ and e- started on April 20.
  - SuperKEKB completed the collision of the e+ and e- beams at 0:38 on April 26.

Hadronic events measured by Belle-II
SuperKEKB Phase-2 Commissioning

• First Beam Colliding

0:38 April 26, 2018

Hadronic Event

$e^+e^- \rightarrow q\bar{q}$

$q$ は、c, s, d, u などの軽いクォーク

Accelerator control room

Belle II control room
• History of Phase-2 Commissioning

Duration of the commissioning is 4 months (March 19 – July 2018)

- HER injection on March 19
- LER injection on March 27
- Beam collision on April 26

Max. \( I_{\text{HER}} \) = 800 mA
Max. \( I_{\text{LER}} \) = 860 mA
L_{\text{peak}} = 5.55 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
Beam scrubbing processes of LER and HER were going well. HER: Vacuum pressure was reduced to the almost same level at the end of Phase-1. LER: $dP/dI$ reached at $3 \times 10^{-7}$ Pa A$^{-1}$ ($\sim 2 \times 10^{-6}$ Pa A$^{-1}$ in Phase-1).

**LER:** Pressure increase per unit ampere ($dP/dI$) in Phase-2

**HER:** Pressure increase per unit ampere ($dP/dI$) in Phase-2

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
• Integrated Luminosity

**Daily Integrated Luminosity in Phase-2 (0 am- 9 am for 40 days)**

Delivered int. luminosity: **1853 pb⁻¹**

Recorded int. luminosity: **454 pb⁻¹**

Efficiency: **24.5 %**

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
Beta Squeezing at IP

The smallest $\beta_y^*$ in the world!

- First collision
- $\beta_y^* < \sigma_z$
- Detuned optics
- Vacuum scrubbing
- $\beta_y^* = 3\, \text{mm}$

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
SuperKEKB Phase-2 Commissioning

- Travel Guide for Luminosity

Luminosity contour

\[ L_{sp} = \frac{L}{n_b I_+ I_-} \]

High bunch current
\( n_b=395 \)
\( I_{peak} = 2.29 \times 10^{33} \) @ 
\( LER = 270 \text{ mA} \)

Extrapolation
\( \times 4 \quad L = 9 \times 10^{33} @ 1.08 \text{ [A]} \)

\( \approx 10^{34} \)

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
SuperKEKB Phase-2 Commissioning

- Machine Parameters in Phase-2 and Phase-3 final

<table>
<thead>
<tr>
<th></th>
<th>High bunch current</th>
<th>High current</th>
<th>Phase 3 (final)</th>
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<td></td>
<td>LER</td>
<td>HER</td>
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<td>$I @ L_{peak}$</td>
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<td>$L$</td>
<td>$2.29 \times 10^{33}$</td>
<td>$5.55 \times 10^{33}$</td>
<td>$8 \times 10^{35}$</td>
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</tr>
</tbody>
</table>

Test of luminosity performance  
*$\varepsilon_y$ enhancement in LER

From the presentation by Dr. Y. Ohnishi, Dec. 5, 2018
@Joint Workshop of future tau-charm factory at LAL
Quench of final focus superconducting magnets

25 quenches occurred around the QC1 and the corrector magnets.

- In April, beam injection was not stable and the collimators were not adjusted (full opened).
- In the end of April, the collimators were adjusted and quenches became less frequent.
- No quench occurred from May 25 to June 25.
- Two collimators, D2V1 (LER) and D1V1 (HER), were damaged in June 25 and July 9.
- After the collimators were damaged, the beam operation became unstable and the frequency of quench increased.
Experiences in Phase-2 Commissioning

- Quench of final focus superconducting magnets

(): quench number after tuning the collimators
Experiences in Phase-2 Commissioning

- Countermeasure of the superconducting magnet Quench
  - To make a relation between the magnet quench and the beam operation clear.

![Diagram of QCS group and Monitor group](image)

- Coil voltages of all QCS magnets are monitored by the QCS data logger.
- We can compare the magnet voltage of QCS group with the beam loss of monitor group by using the same signals of abort kicker and beam current.
• Two collimator heads were damaged.
  • LER D02_V1 (Bottom)
  • HER D01_V1 (Top)
  • 4 new heads (V:3, H:1) are under manufacturing, and will be delivered in March. (Phase-3 commissioning will start in March 11.)

Two collimators were replaced with the new ones.
The collimator system will be improved for Phase-3.

- Following 5 collimators were newly installed into the tunnel.
  - LER D02_H1, D02_H2, D03_H1, D06_V2
  - HER D01_H3
- LER D06_H4 was relocated to D06_H1.
- One more vertical-type collimator will be ready by the summer in 2019.

Horizontal type collimator (D02_H1) installed in the LER.
Experiences in Phase-2 Commissioning

- **LER Electron Cloud Effect (ECE).**

  **Phase-1**
  - ECE was observed from 900 mA.
  - It was considered to be due to the electron cloud in the drift beam pipes.
    - The beam pipes had the ante-chamber and the TiN coating.

  **Phase-2**
  - New beam pipes: assembling the permanent magnet (60 G~100 G).
  - Beam pipes from KEKB: setting the solenoids (~50 G).
    - In total, the axial magnetic field over 20 G covered the 86% of the drift parts (~2000 m).

  **Pressure/Beam current**
  (In case of outgas by SR, \( \frac{dP}{dI} \) is constant.)

  **Increase of vertical beam size**

  No vertical beam size increment up to 0.8 mA/bunch
Summary

• Verification of nano-beam scheme
  – Luminosity tuning at $\beta_y^*=3\text{mm}$ ($\times 10$ final value)
  – $2.26 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ at $I_{\text{LER}}=270$ mA ($n_b=395$) -> $10^{34} \text{cm}^{-2}\text{s}^{-1}$ at $I_{\text{LER}}=1080$ mA ($n_b=1576$)
  – Beam-Beam parameter reaches 0.02.
  – Peak luminosity is $5.55 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ at $I_{\text{LER}}=790$ mA

• Max. beam current is 860 mA in LER and 800 mA in HER.
• QCS quench issue (unexpected).
  – Movable collimators can avoid most of quenches,
• The additional collimators are installed until Phase-3 operation to control beam loss and/or background.
• ECE was successfully reduced by adding the permanent magnets and solenoids.
• Phase-3 commissioning will start at March 11 to attain $L=8 \times 10^{35}$. 