The status of SuperKEKB commissioning

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Accelerator theory group, Accelerator laboratory, KEK, Japan

On behalf of SuperKEKB Commissioning Group

2nd international workshop on High Intensity Electron-Positron Accelerator at China
Mar. 21, 2018
Outline

➤ Introduction
➤ Phase I commissioning
➤ Plans for Phase II commissioning
➤ Beam dynamics issues in main rings
➤ Summary
1. Introduction

➤ “Nano-beam” scheme
- \( E \) (LER/HER): 3.5/8 \( \rightarrow \) 4/7 GeV
- \( \beta_y^* \) (LER/HER): 5.9/5.9 \( \rightarrow \) 0.27/0.3 mm
- \( I_{\text{beam}} \) (LER/HER): 1.7/1.4 \( \rightarrow \) 3.6/2.6 A
- \( \xi_y \): 0.09 \( \rightarrow \) 0.09
- Crab waist: optional
- \( \mathcal{L} \): 2.1 \( \rightarrow \) 80 \( \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \)

➤ Phase I
- w/o QCS and Belle-II
- Feb. - Jun., 2016

➤ Phase II
- w/ QCS and Belle-II
- w/o Vertex detector
- Feb. 2018 (~5 months)

➤ Phase III
- w/ Full Belle-II including VXD
- Feb. 2019 (plan)
1. Introduction

➤ Design parameters (ultimate) compared to a design of Tau/Charm factory

**SuperKEKB**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER</th>
<th>HER</th>
<th>Unit</th>
<th>2017/September/1</th>
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<td>7.007</td>
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<td>I</td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
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<td>Circumference</td>
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<td>$E_x/E_y$</td>
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<td>4.6(4.4)/12.9(1.5)</td>
<td>nm/pm</td>
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<td>Coupling</td>
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<td>$\beta_x''/\beta_y''$</td>
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<td>25/0.30</td>
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<td>Crossing angle</td>
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<td>3.20x10^{-4}</td>
<td>4.55x10^{-4}</td>
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<td>$\sigma_0$</td>
<td>7.92(7.53)x10^{-4}</td>
<td>6.37(6.30)x10^{-4}</td>
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<td>$\nu_c$</td>
<td>9.4</td>
<td>15.0</td>
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<td>$\sigma_2$</td>
<td>6(4.7)</td>
<td>5(4.9)</td>
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<td>-0.0280</td>
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<td>$\nu_x/\nu_y$</td>
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<td>$U_0$</td>
<td>1.76</td>
<td>2.43</td>
<td>MeV</td>
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<td>$T_{xy}/T_{xy}$</td>
<td>45.7/22.8</td>
<td>58.0/29.0</td>
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<td>$\xi_x/\xi_y$</td>
<td>0.0028/0.0881</td>
<td>0.0012/0.0807</td>
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<tr>
<td>Luminosity</td>
<td>8x10^{35}</td>
<td></td>
<td>cm^{-2}s^{-1}</td>
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http://www-superkekb.kek.jp/index.html

**Tau/Charm factory**

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<th>Parameter</th>
<th>Units</th>
<th>2017/September/1</th>
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<td>LUMINOSITY</td>
<td>10^{35} cm^{-2} s^{-1}</td>
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<td>cm Energy</td>
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<tr>
<td>Beam Energy</td>
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<td>X-Angle (full)</td>
<td>mrad</td>
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<td>Piwinski angle</td>
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<td>Hourglass reduction factor</td>
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<tr>
<td>Tune shift x</td>
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<tr>
<td>Tune shift y</td>
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<td>$\beta_x$ @ IP</td>
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<td>$\beta_y$ @ IP</td>
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<td>$\sigma_x$ @ IP</td>
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<td>$\sigma_y$ @ IP</td>
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<td>Coupling (full current)</td>
<td>%</td>
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<tr>
<td>Natural emittance x</td>
<td>nm</td>
<td>2.85</td>
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<td>Emittance x (with IBS)</td>
<td>nm</td>
<td>5.13</td>
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<tr>
<td>Emittance y (with IBS)</td>
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<tr>
<td>Natural bunch length</td>
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<tr>
<td>Bunch length (with IBS)</td>
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<td>Buckets distance</td>
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<td>Ion gap</td>
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<td>RF frequency</td>
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<td>Number of bunches</td>
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<td>N. Particle/bunch</td>
<td>#</td>
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<td>Beam power</td>
<td>MW</td>
<td>0.16</td>
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<tr>
<td>Transverse damping times (x/y)</td>
<td>msec</td>
<td>35/49</td>
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</table>

Tau/Charm Accelerator Report, M. Biagini et al., 2013
1. Introduction

➤ Master schedule
2. Phase I commissioning


- **Preparations**
  - Hardware tunings with beam
  - Operation software tests with beam
- **Vacuum scrubbing**
- **Low emittance tuning**
  - Machine imperfections and countermeasures
  - Target: vertical emittance <10 pm
- **Studies on intensity-dependent phenomena**
  - Beam background measurement with Beast detector
  - Electron cloud effects
  - Impedance measurements
  - ... ...
2. Phase I commissioning

2. Phase I commissioning

➤ Vacuum scrubbing

● LER (new vacuum chambers)
  ➢ Base pressure: \(~5 \times 10^{-8}\) Pa
  ➢ Ave. pressure: \(~1 \times 10^{-6}\) Pa
  ➢ \(I_{\text{beam}}\): \(~1.01\) A
  ➢ \(\tau_{\text{beam}}\): \(~70\) min

● HER (old KEKB chambers)
  ➢ Base pressure: \(~3 \times 10^{-8}\) Pa
  ➢ Ave. pressure: \(~1 \times 10^{-7}\) Pa
  ➢ \(I_{\text{beam}}\): \(~0.87\) A
  ➢ \(\tau_{\text{beam}}\): \(~400\) min

Courtesy of Y. Suetsugu
2. Phase I commissioning

- Low emittance tuning: Beta function correction: LER
  - Before correction

\[
\begin{align*}
\Delta \beta_x / \beta_x & \sim 19.5 \% \\
(\Delta \beta_y / \beta_y)_{\text{rms}} & \sim 20.5 \% \\
\Delta \nu_x & \sim -0.074 \\
\Delta \nu_y & \sim -0.141
\end{align*}
\]

Courtesy of H. Sugimoto
2. Phase I commissioning

- Low emittance tuning: Beta function correction: LER
  - After correction

\[ \frac{\Delta \beta_x}{\beta_x} \text{ [%]} \]

\[ \frac{\Delta \beta_y}{\beta_y} \text{ [%]} \]

\[ \phi_{x_{\text{meas}}} - \phi_{x_{\text{model}}} \text{ [rad]} \]

\[ \phi_{y_{\text{meas}}} - \phi_{y_{\text{model}}} \text{ [rad]} \]

\[ (\Delta \beta_x / \beta_x)_{\text{rms}} \sim 2.0 \% \quad \Delta \nu_x \sim 0.004 \]

\[ (\Delta \beta_y / \beta_y)_{\text{rms}} \sim 2.9 \% \quad \Delta \nu_y \sim 0.001 \]
2. Phase I commissioning

- Low emittance tuning: X-Y coupling correction: LER
  - Leakages in vert. orbits induced by 6 kinds of horizontal dipole correctors

Courtesy of Y. Ohnishi
2. Phase I commissioning

- Low emittance tuning: X-Y coupling correction: LER
  - History of global X-Y coupling

![Graph showing LER average (rms(DY)/rms(DX)) over time]

\[
\text{ave}(\text{rms}(\Delta y_i)_j) / \text{rms}(\Delta x_i)_j = 0.009
\]

Courtesy of Y. Ohnishi
2. Phase I commissioning

➤ Low emittance tuning: X-Y coupling correction: HER
  • History of global X-Y coupling

\[ \text{HER average}(\text{rms(DY)}/\text{rms(DX)}) \]

\[ \text{ave}(\text{rms}(\Delta y_i)/\text{rms}(\Delta x_i)) = 0.006 \]

Courtesy of Y. Ohnishi
2. Phase I commissioning

➤ Low emittance tuning: Estimate of vert. emittance: LER

\[ \varepsilon_y = 7.2 \text{ pm} \]
2. Phase I commissioning

- Low emittance tuning: Estimate of vert. emittance: HER

![Graph showing wiggler and Lambertson septum with \( \varepsilon_y = 9.1 \) pm]
3. Plans for Phase II commissioning

➤ Main goals (Feb. — Jul., 2018)

- Nano-beam collision scheme to be verified: Low emittance, small $\beta^*$ and large Piwinski angle
- Luminosity $\geq 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ for Belle-II detector
- Beam background minimization for Belle-II detector

<table>
<thead>
<tr>
<th>Phase</th>
<th>LER</th>
<th>HER</th>
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<tr>
<td></td>
<td>$\beta_x^*$ [mm]</td>
<td>$\beta_y^*$ [mm]</td>
</tr>
<tr>
<td>2.0*</td>
<td>384</td>
<td>48.6</td>
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<tr>
<td>2.2</td>
<td>256</td>
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<td>2.3</td>
<td>128</td>
<td>2.16</td>
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<td>2.4</td>
<td>128</td>
<td>1.08</td>
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<tr>
<td>3.x</td>
<td>32</td>
<td>0.27</td>
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<table>
<thead>
<tr>
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<th>KEKB (2006)</th>
<th>Phase 2.2</th>
<th>Phase 2.3</th>
<th>Phase 2.4</th>
<th>Phase 3.x</th>
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<td>LER</td>
<td>HER</td>
<td>LER</td>
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<td>$\beta_x$ [mm]</td>
<td>590</td>
<td>560</td>
<td>256</td>
<td>200</td>
<td>128</td>
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<td>$\beta_y$ [mm]</td>
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<td>$\varepsilon_x$ [nm]</td>
<td>18</td>
<td>24</td>
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<td>4.6</td>
<td>2.1</td>
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<td>$\varepsilon_y/\varepsilon_x$ [%]</td>
<td>3</td>
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<tr>
<td>$\sigma_x^*$ [µm]</td>
<td>103</td>
<td>116</td>
<td>23.2</td>
<td>30.3</td>
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<td>$\sigma_y^*$ [nm]</td>
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<td>1900</td>
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<td>$\sigma_z$ [mm]</td>
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<td>$\phi_x$ [mrad]</td>
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<td>$\Phi$</td>
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<td>0.66</td>
<td>10.7</td>
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<td>Remark</td>
<td>$1.72 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$4 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$8 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
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3. Plans for Phase II commissioning

 расположенное здесь

- Detailed schedule (Feb. — Jul., 2018)

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<th>Jan.</th>
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</table>

- e- e+ HER LER

BT: Beam Transport line (Linac-MR)

First collision (beam-beam deflection) beta squeezing test down to the final collision tuning
4. Beam dynamics issues in main rings

➢ From KEKB to SuperKEKB

- A difficult journey with known limits to KEKB: Beam-beam, electron cloud, microwave instabilities, chromatic aberrations, ...
- A bright future if SuperKEKB is successful: FCC-ee, STCF/HIEPA, CEPC, ...

![Graph showing peak luminosity over time for various accelerators.]
4. Beam dynamics issues in main rings

- Interplay of various issues
  - Luminosity <= Emittance <= Beam-beam, Lattice nonlinearity, Space charge, Impedance, Electron cloud, Intra-beam scattering, etc.
  - Dynamic aperture and lifetime => Beam commissioning => Injection, Detector back ground, Alignments, etc. => Tolerances for hardwares => ...
4. Beam dynamics issues in main rings

➤ **Electron cloud:** Important in high-intensity positron/proton rings

- **SuperKEKB LER:** Several countermeasures against ECI

Tested in KEKB

Ref. Y. Suetsugu et al., NIMA 598 (2009)  
Ref. Y. Suetsugu et al., NIMA 604 (2009)
4. Beam dynamics issues in main rings

➤ Electron cloud: Vert. beam-size blowup (from XRM) in LER

- Threshold: depend on filling pattern and increase with vacuum scrubbing
- Varied conditions: # of trains, # of bunches in each train, # of buckets for bunch spacing

![Graph showing beam dynamics](image-url)
4. Beam dynamics issues in main rings

➤ Electron cloud: New countermeasures before Phase II
  ● Permanent magnets around bellows
4. Beam dynamics issues in main rings

➤ Electron cloud: New countermeasures before Phase II

- Permanent magnets with iron yokes around drifts of Al or Cu pipes with antechambers + TiN coating

Courtesy of Y. Suetsugu
4. Beam dynamics issues in main rings

➤ Electron cloud: New countermeasures before Phase II
  • Permanent magnets in Al cylinders around drifts of Al or Cu pipes with antechambers + TiN coating [Near main magnets (Q, SX, ST) to avoid interference]

Courtesy of Y. Suetsugu
4. Beam dynamics issues in main rings

➤ Electron cloud: New countermeasures before Phase II
  ● Reuse old solenoids for Al pipes recycled from KEKB

Courtesy of Y. Suetsugu
4. Beam dynamics issues in main rings

➤ Lattice nonlinearity

- Mainly attributed to the IR resulting from extremely small $\beta^{*}_{x,y}$
4. Beam dynamics issues in main rings

➤ Lattice nonlinearity

- OPERA-3D model of IR including all SC magnets and other magnetic components => “intrinsic” nonlinearity in lattice model
4. Beam dynamics issues in main rings

➤ Lattice nonlinearity

● Limit *Touschek lifetime* to \(~\)10 min for ideal lattice
● Require a strong injection (high charge and low emittance) for top-up injection to compensate fast beam loss
● Set strong constraints to *background* control in Belle-II detector
● Set small gaps to collimators, significantly increasing *impedance budget*

● Even worse, interplay with *beam-beam* ...
4. Beam dynamics issues in main rings

➤ Beam-beam effects

● Interplay with lattice nonlinearity => Loss in lum. and lifetime

Courtesy of Y. Ohnishi

D. Zhou et al., IPAC’15
4. Beam dynamics issues in main rings

➤ Beam-beam effects

- Limit dynamic aperture w/ crab-waist sext. => Loss in beam lifetime

Crab-waist sextupole reduces dynamic aperture under the influence of beam-beam effect.

![Graph showing beam dynamics issues](image)

- \( \frac{\Delta x_0}{\sigma_x} \)
- \( \frac{\Delta \delta_0}{\sigma_\delta} \)
- \( K_2 = 0 \)
- \( \frac{K_2}{K_2,\text{nominal}} = 50\% \)
- \( \frac{K_2}{K_2,\text{nominal}} = 75\% \)
- \( \frac{K_2}{K_2,\text{nominal}} = 100\% \)

Courtesy of Y. Ohnishi
4. Beam dynamics issues in main rings

➤ Beam-beam effects
- Drive beam tail and potentially increase detector background

- Ne=6.53x10^{10},

\[ H_I^* = \pm \frac{1}{2\theta_n} x p_y^2 \]
4. Beam dynamics issues in main rings

- Beam-beam effects: Not important in Phase II
  - Assume emittance coupling = 2%
  - Space-charge effect is not important
  - Lattice nonlinearity is not very important
  - $L=1\times10^{34}$ cm$^{-2}$s$^{-1}$ is promising
  - Even $L=10\times10^{34}$ cm$^{-2}$s$^{-1}$ is possible
5. Summary

➤ Phase I commissioning of SuperKEKB was very successful
  ● Hardware tuning
  ● Vacuum scrubbing
  ● Beam background
  ● Low emittance tuning

➤ Phase II commissioning underway
  ● Lum. $\geq 2\times10^{34}$ cm$^{-2}$s$^{-1}$ for Belle-II detector looks promising

➤ Challenges foreseen in Phase III commissioning
  ● Beam dynamics issues
  ● Powerful injector
  ● ... ... 

➤ Demonstrator for FCC-ee/CEPC/SCTF
  ● Call for international collaborations