Belle II experiment

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(Virginia Tech/KEK)
_on behalf of the Belle II collaboration_

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July 30, 2016
Outline

- From $B$ to Super-$B$
- Accelerator
- Detector
- Physics
- Getting started

Kobayashi and Maskawa both worked in Kyoto university when writing their famous paper.
**B-factories**

- Combined BaBar and Belle luminosity is $\sim 1.5 \text{ ab}^{-1} \times (1.25 \times 10^9 \, \bar{B}B \text{ pairs})$.
- Main focus: $CP$-violation (published in 2001)
  - Also $B$-decays, CKM parameters, quarkonium(-like) states, charm- and $\tau$-physics etc.
  - (see talks by Miyabayashi-san, Kato-san and Y.J.Kwon)
- 500+ publications from BaBar, 400+ from Belle.
- But still no observation of the New physics (NP)!
Looking for New physics

- Flavor Frontier (indirect): Virtual production can probe scales to ~10 TeV or more, but effects are tiny (LHCb, Belle II).
- Virtual NP particles: asymmetries, rare decays, forbidden decays.
- No NP yet – upgrade Belle and KEKB.
Belle II and LHCb

Can Belle II compete with LHCb? Yes.

- Full solid angle detector and clean event environment and well defined initial state of $e^+e^-$ experiment:
  - Missing energy modes are a strength of Belle II and the $B$-factories; powerful constraints on the charged Higgs;
  - Modes with neutrals (although not impossible at LHCb) are another strength of Belle II;
  - Belle II does inclusive modes ($B \rightarrow X_s \gamma$, $B \rightarrow X_s \ell^+\ell^-$);
  - Belle II but not LHCb does modes with $K_s$ mesons including a significant fraction of the $b \rightarrow s$ penguin modes.
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Quest for high luminosity

- There are two ways to increase luminosity:
  - Increase beam currents
  - Decrease beam size
- SuperKEKB uses
  - ~2x increase in currents
  - "nano-beams"
- 40x luminosity

<table>
<thead>
<tr>
<th></th>
<th>E(GEV)</th>
<th>$\beta^*_y$ (mm)</th>
<th>$\beta^*_x$ (mm)</th>
<th>$2\varphi$ (mrad)</th>
<th>I(A)</th>
<th>L (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEKB</td>
<td>3.5/8.0</td>
<td>5.9/5.9</td>
<td>120/120</td>
<td>22</td>
<td>1.6/1.2</td>
<td>2.1x10$^{34}$</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>4.0/7.0</td>
<td>0.27/0.30</td>
<td>3.2/2.5</td>
<td>83</td>
<td>3.6/2.6</td>
<td>80x10$^{34}$</td>
</tr>
</tbody>
</table>
SuperKEKB accelerator

A lot of modifications all around the accelerator.

- Replace short dipoles with longer ones (LER)
- New TiN-coated beam pipe with antechambers
- Add / modify RF systems for higher beam current
- New interaction region
- Positron source: new target/capture section
- Inject low emittance positrons / electrons
- Damping ring
SuperKEKB status

- 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.
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Requirements for detector

- Higher beam-related and QED backgrounds;
- L1 trigger rate 30kHz vs 500Hz for Belle:
  - Stability to high background; fast readout;
  - Better performance (vertex resolution, tracking, PID, esp. improve $K/\pi$ separation);
  - Less material in front of ECL (for better performance).

Not a simulation, just a naive illustration
Belle II detector

Belle II is built on basis of Belle

- Main structure and magnet are reused;
- ECL and KLM are mostly reused;
- Vertex detector, drift chamber, PID, partially KLM are upgraded;
- All electronics are replaced.
Detector improvements

- Smaller beam pipe radius allows to place the innermost PXD layer closer to the Interaction point ($r = 1.4\text{cm}$)
  - Significantly improves the vertex resolution along $z$ direction.
- Pixel part of the vertex detector, larger SVD and CDC
  - Increases $K_s$ efficiency, improve vertex and timing resolution, better flavor tagging.
- PID: TOP and ARICH
  - Better $K/\pi$ separation covering the whole range momentum.
- ECL and KLM
  - Improvements in ECL and KLM to compensate for a larger beam background.
- Improved hermeticity.
- Improved trigger and DAQ.
VXD = PXD + SVD

- Layers 1-2: Pixel detectors (PXD)
  - DEPFET pixels
  - 50μm thick
  - r=14mm and 22mm (vs 20mm minimum for Belle)
- Layers 3-6: Strip detectors (SVD)
  - 4 layers of DSSD detectors, well tested at Belle
  - Largest radius 135mm (vs 88mm for Belle)
- Dedicated PXD preDAQ for data rate reduction from ~8M channels (matching against tracks from SVD+CDC)
VXD beam test in DESY

- Combined beam test of PXD and SVD
- Also test of DAQ, software, DB, CO₂ cooling, slow control, environmental sensors
- $e^-$ beam, momentum 2-5GeV
- B-field in PCMag: 0-1T
- Total of ~340 runs in 4 weeks

Overall the campaign was a great success for the VXD!
CDC

- Belle II Central Drift Chamber (CDC) is larger than that of Belle.
- Smaller drift cells with sense wires and more layers allow better charged track reconstruction and dE/dx measurement compared to Belle.
- Faster readout electronics

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of inner boundary (mm)</td>
<td>88</td>
<td>168</td>
</tr>
<tr>
<td>Radius of outer boundary (mm)</td>
<td>863</td>
<td>1111</td>
</tr>
<tr>
<td>Number of layers</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Number of sense wires</td>
<td>8400</td>
<td>14336</td>
</tr>
<tr>
<td>Gas</td>
<td>HeC₂H₆</td>
<td>HeC₂H₆</td>
</tr>
<tr>
<td>Diameter of a sense wire (μm)</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>
CDC status

- CDC construction is complete, CDC moved to the experimental hall next to Belle II detector.
- Cosmic ray test is ongoing, next is DAQ integration.
- The new CDC track finder is able to identify tracks on cosmic rays events with an efficiency close to 100% (i.e. each triggered event contains at least one track).
- A few interesting events with more than one particles are also correctly reconstructed. All the CDC hits are represented.
- The hits belonging to the same track are in same color.
PID: TOP+ARICH

Two Cherenkov detectors for particle identification (mainly $K$ and $\pi$)

- Barrel: Time of Propagation (TOP)
- Endcap: Aerogel Ring-Imaging Cherenkov (ARICH)

Much thinner than PID in Belle, less material in front of calorimeter.
TOP status

- All TOP modules installed in May.
- Commissioning with cosmic rays and DAQ tests are ongoing.

TOP: at 3GeV timing ~100ps is needed for K/π separation

Full internal reflection of laser beam inside TOP quartz module

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II (sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{eff}}$</td>
<td>88%</td>
<td>94%</td>
</tr>
<tr>
<td>π fake rate</td>
<td>9%</td>
<td>4%</td>
</tr>
</tbody>
</table>
ARICH status

- $K/\pi$ separation at 5$\sigma$
- Radiator: Aerogel $n=1.045-1.055$
- Transmission length >40mm
- Photon detection: Hybrid Avalanche Photo Detectors (HAPD)
- 420 units, 144 channels each
  Gain = $7\times10^5$, QE > 28%
- Production/assembly state, installation schedule under discussion.
Belle II electromagnetic calorimeter (ECL) reuses Belle CsI (TI) crystals and installs improved readout electronics with a waveform sampling to compensate for higher beam-related background.

R&D to replace in future endcap crystals with pure CsI with faster light emission and smaller light yield.

ECL readout electronics was installed and DAQ integration tests are going on.
The outermost detector for $K_L - \mu$ detection

- Endcap muon detection based on RPC will not work at design luminosity and higher background. The inner barrel layers efficiencies would also be small.

- Replace RPCs in the endcaps and two inner barrel layers with scintillator strips with WLS fibers and MPPC detectors.

- KLM installation was completed, $\sim \frac{1}{8}$ of the readout electronics were installed and DAQ integration tests are going on.
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Credit: Nature Methods, Le Maho, et. al.
Physics at Belle II

Since NP is not discovered yet, its manifestations are unknown. We should look everywhere. Our focus is on

- Precise CKM measurements,
- CPV in quarks and charged leptons,
- Missing energy studies:
  - $B \rightarrow \ell \nu$,
  - $B \rightarrow D^{(*)} \tau \nu$,
- Charged LFV: $\tau \rightarrow \ell \gamma$, $\tau \rightarrow \ell \ell \ell$, $\ell = e, \mu$,
- Quarkonium,
- Low multiplicity events.

Just noise? Look closer!
Unitary triangle

- Unitary triangle changed dramatically in $B$-factories era.
- But is it really a triangle? Current $\alpha + \beta + \gamma = (175 \pm 9)^\circ$ (PDG), Belle II expects to improve the precision to $\alpha \sim 0.3^\circ$, $\beta \sim 1.0^\circ$, $\gamma \sim 1.5^\circ$.
- Improvement in precision should help to resolve the tension between inclusive and exclusive measurements of $|V_{ub}|$ and $|V_{cb}|$.
Reconstruction with tagging

- At Belle (II) events are clean are well separated from each other; we reconstruct the whole event:

\[ e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B_{tag} B_{sig} \]

- Purity
- Efficiency

**Inclusive**
- \( B \rightarrow \text{anything} \)
- \( \varepsilon = O(2\%) \)

High background

**Semileptonic**
- \( B \rightarrow D^{(*)}\ell \nu \)
- \( \varepsilon = O(0.2\%) \)

**Hadronic**
- \( B \rightarrow \text{hadrons} \)
- \( \varepsilon = O(0.1\%) \)

Low background

**Example:**
\[ B \rightarrow D^{(*)}\tau \nu \]

Now 4σ deviation from the SM

\[ \Delta \chi^2 = 1.0 \]
Physics at 50 ab$^{-1}$

Parameterize NP contributions to the $B_{d,s}$ mixing amplitudes as

$$M_{d,s}^{12} = (M_{d,s}^{12})_{\text{CM}} x (1 + h_{d,s} \exp(2i\sigma_{d,s}))$$


Mattew Barrett
PoS(FPCP2015)049

Extrapolating to 50ab$^{-1}$ assuming no change in central values
### Physics at 50 ab$^{-1}$

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle or LHCb$^*$ (2014)</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
<th>LHCb 8 fb$^{-1}$ (2018)</th>
<th>LHCb 50 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT angles</td>
<td>0.667 ± 0.023 ± 0.012(1.4°)</td>
<td>0.7°</td>
<td>0.4°</td>
<td>1.6°</td>
<td>0.6°</td>
</tr>
<tr>
<td>$\alpha$ [$^\circ$]</td>
<td>85 ± 4 (Belle+BaBar)</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$ [$^\circ$] ($B \rightarrow D(\ast)K(\ast)$)</td>
<td>68 ± 14</td>
<td>6</td>
<td>1.5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$2\beta_s (B_s \rightarrow J/\psi \phi)$ [rad]</td>
<td>0.07 ± 0.09 ± 0.01*</td>
<td>0.025</td>
<td>0.009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S(B \rightarrow \phi K^0)$</td>
<td>0.90 $^{+0.09}_{-0.19}$</td>
<td>0.053</td>
<td>0.018</td>
<td>0.2</td>
<td>0.04</td>
</tr>
<tr>
<td>$S(B \rightarrow \eta' K^0)$</td>
<td>0.68 ± 0.07 ± 0.03</td>
<td>0.028</td>
<td>0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S(B \rightarrow K_S^0 K_S^0 K_S^0)$</td>
<td>0.30 ± 0.32 ± 0.08</td>
<td>0.100</td>
<td>0.033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_s^{eff} (B_s \rightarrow \phi \phi)$ [rad]</td>
<td>$-0.17 \pm 0.15 \pm 0.03^*$</td>
<td>0.12</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_s^{eff} (B_s \rightarrow K^{*0} K^{*0})$ [rad]</td>
<td>$-0.13$</td>
<td>0.13</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct CP in hadronic Decays $A(B \rightarrow K^0\pi^0)$</td>
<td>$-0.05 \pm 0.14 \pm 0.05$</td>
<td>0.07</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UT sides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ incl.</td>
<td>$4.16 \cdot 10^{-3}(1 \pm 2.4%)$</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ excl.</td>
<td>$3.75 \cdot 10^{-3}(1 \pm 3.0%<em>{ext} \pm 2.7%</em>{th})$</td>
<td>1.8%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$</td>
<td>V_{ud}</td>
<td>$ incl.</td>
<td>$4.47 \cdot 10^{-3}(1 \pm 6.0%<em>{ext} \pm 2.5%</em>{th})$</td>
<td>3.4%</td>
<td>3.0%</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ excl. (had. tag.)</td>
<td>$3.52 \cdot 10^{-3}(1 \pm 10.8%)$</td>
<td>4.7%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Leptonic and Semi-tauonic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B \rightarrow \tau\nu)$ [$10^{-6}$]</td>
<td>$96(1 \pm 26%)$</td>
<td>10%</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B \rightarrow \mu\nu)$ [$10^{-6}$]</td>
<td>$&lt; 1.7$</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(B \rightarrow D\tau\nu)$</td>
<td>$0.440(1 \pm 16.5%)^{\dagger}$</td>
<td>5.6%</td>
<td>3.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(B \rightarrow D^{*}\tau\nu)$</td>
<td>$0.332(1 \pm 9.0%)^{\dagger}$</td>
<td>3.2%</td>
<td>2.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B \rightarrow X_s \gamma)$</td>
<td>$3.45 \cdot 10^{-4}(1 \pm 4.3% \pm 11.6%)$</td>
<td>7%</td>
<td>6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{A}_{CP}(B \rightarrow X_s \gamma)$</td>
<td>$2.2 \pm 4.0 \pm 0.8$</td>
<td>1</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S(B \rightarrow K_S^0 \pi^0 \gamma)$</td>
<td>$-0.10 \pm 0.31 \pm 0.07$</td>
<td>0.11</td>
<td>0.035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2\beta_s^{eff} (B_s \rightarrow \phi \gamma)$</td>
<td>$-0.83 \pm 0.65 \pm 0.18$</td>
<td>0.23</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B_s \rightarrow \gamma\gamma)$</td>
<td>$&lt; 8.7$</td>
<td>0.3</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B \rightarrow K^{*+}\nu\bar{\nu})$ [$10^{-6}$]</td>
<td>$&lt; 40$</td>
<td>$&lt; 15$</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B \rightarrow K^-\nu\bar{\nu})$ [$10^{-6}$]</td>
<td>$&lt; 55$</td>
<td>$&lt; 21$</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{9}/C_{9}' (B \rightarrow X_s \ell\bar{\nu})$</td>
<td>$\sim 20%$</td>
<td>10%</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B_s \rightarrow \tau\tau)$ [$10^{-3}$]</td>
<td>–</td>
<td>$&lt; 2$</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B_s \rightarrow \mu\mu)$ [$10^{-9}$]</td>
<td>$2.9^{+1.3}_{-1.0}$</td>
<td>0.5</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Theoretical workshops

- Series of experimental-theoretical workshops for development of Belle II physics program “Belle II Theory Interface Platform” (B2TiP).

- It is a joint effort of both theorists and experimentalists to have a close communication.

- Aim at delivering a full report in spring 2017.

- The last workshop was held in Pittsburgh in May 23-26.

- 9 working groups: semileptonic and leptonic $B$ decays, radiative and EWP $B$ decays, time dependent CPV, Phi 3, hadronic $B$ decays, charm, quarkonium, low multiplicity, new physics.
Software and MC

- Belle II analysis software framework (basf2) is being actively developed.
- 5 MC (6th has started) campaigns to estimate, measure, mitigate, and protect against beam backgrounds.
- Sample MC analyses with the new software.
- Belle II uses GRID for computing. ~40 computing sites in 18 countries (Australia, Austria, Canada, China, Czeck R., France, Germany, India, Italy, Japan, Korea, Poland, Russia, Slovenia, Taiwan, Turkey, Mexico, USA).
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SuperKEKB phase 1

SuperKEKB first started in February and worked until June (Phase 1).

- Startup of each hardware system
- Establish beam operation software tools
- Preparation for installation of Belle-II detector
  - Enough vacuum scrubbing
    - Request from Belle II group: ~1 month vacuum scrubbing with beam current of 0.5~1A (360~720Ah).
  - Beam background study with test detector (named BEAST)
- High beam current operation
  - Find and solve problems associated with high beam current operation
- Optics study w/o IR (no detector solenoid)
  - Low emittance tuning
- Other machine studies
SuperKEKB phase 1 history

No collisions. Achieved currents:

**HER:** 870 mA, $5.7 \times 10^{-8}$ Pa, ~200 min. (6/17)

**LER:** 1010 mA, $4.7 \times 10^{-7}$ Pa, ~60 min. (6/22)
SuperKEKB phase 1 results

- Faster startup than KEKB...
  - KEKB beam currents achieved after first 3 months
    LER: ~300mA, HER: ~200mA
  - SuperKEKB beam currents achieved after first 3 months
    LER: ~650mA, HER: ~590mA

- Compared with KEKB...
  - Each hardware component has been upgraded with experiences at KEK and has worked fine (RF, Magnet, Vacuum...)
  - The bunch-by-bunch feedback system has more effectively suppressed instabilities.
  - Operational tools (such as closed orbit correction system) has worked fine based on experiences at KEKB.
  - Less machine troubles than KEKB so far.
BEAST II

- Due to high beam currents, small beam size and higher luminosity, predicted SuperKEKB Beam background is 40 times higher than at KEKB.

- Background is reduced by installing moveable collimators and adding shielding near the final focus magnets.

- **Beam Exorcism for a Stable Experiments II** (BEAST II): measure and characterize beam background for safe roll-in of Belle II.

- Provide feedback to SuperKEKB.

- First comparison of simulation with experimental data.

- Seven independent BEAST II sub-detectors to measure beam loss backgrounds

<table>
<thead>
<tr>
<th>System</th>
<th>Number of detectors</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;CLAWS&quot; scintillator</td>
<td>8</td>
<td>Injection background</td>
</tr>
<tr>
<td>Diamonds</td>
<td>4</td>
<td>Ionizing radiation dose</td>
</tr>
<tr>
<td>PIN Diodes</td>
<td>64</td>
<td>Neutral vs charged ionizing dose</td>
</tr>
<tr>
<td>BGO</td>
<td>8</td>
<td>Luminosity</td>
</tr>
<tr>
<td>Crystals</td>
<td>6 CsI(Tl) 6 CsI 6 LYSO</td>
<td>EM energy spectrum</td>
</tr>
<tr>
<td>He-3 tubes</td>
<td>4</td>
<td>Thermal neutron flux</td>
</tr>
<tr>
<td>Micro TPCs</td>
<td>2</td>
<td>Fast neutron flux</td>
</tr>
</tbody>
</table>
BEAST II results

- Early stage: LER/HER first turns seen by BEAST sensors.
- Vacuum scrubbing progress seen by BEAST sensors.
- “Vacuum burst” (dust capture) events seen by BEAST sensors.
- Provide “live” display of injection BG.
- Collimators are proven to reduce BEAST BG (incl. injection BG).
- Analysis of the results and comparison with simulation is ongoing.

BEAST II Online monitor display

HER baking

LER Touschek study
Schedule

- July 2016 – May 2017
  - QCS installation, cooling etc
- October 2016 – June 2017
  - CDC, ARICH installation
- December 2016
  - Belle II roll in
- November 2017 – March 2018
  - Phase 2 operation
  - Beta function squeezing, collision tuning
  - Belle II w/o VXD physics run
- April – June 2018
  - VXD installation
- October 2018 – ...
  - Full Belle II detector physics run

Expected running time:
9 months/year
20 days/month

Goal of Belle II/SuperKEKB

Phase 1 (BEASTII)
Phase 2 (Belle II w/o VXD)
Phase 3 (Full Belle II)
Summary

- TOP, ECL, KLM are installed. CDC is ready for installation. DAQ tests of individual systems with cosmic rays and their integration are ongoing.

- PXD, SVD, ARICH are in production/assembly state.

- Accelerator Phase 1 completed. SuperKEKB has been successfully switched on. It reached 1.01A current in the LER and 0.87A in the HER. Getting ready for Phase 2 with partial Belle II detector (w/o VXD) in 2017.

- Physics run is scheduled to start on 2018.

- Reach and promising physics program is further refined and extended in collaboration with theorists.
Belle II collaboration

https://www.belle2.org

Formed in 2008 on basis of the Belle collaboration.

631 collaborators, 100 institutions, 23 countries/regions.
BEAST Phase 1 sensors at IP

- BGO crystals
- Diamonds
- PIN diodes
- CLAWS scintillators
- LYSO/Csl crystals
- He3 tubes (thermal neutrons)
- Micro TPCs (fast neutrons)

sCVD, ZDLM at >10m downstream

Various measurements (fast charged particle, high-energy photons, thermal/MeV neutron, dosimetry, etc..) to validate beam loss simulation
BEASTII run monitor

Good time resolution injection BG monitors

Directional neutron detection
KLM tracks

As of June 21, we now see cosmic-ray tracks 😊

Run 16100 event 81  y vs x

Run 16101 event 36  y vs x

y vs z

y vs z
PXD module size