Status of SuperKEKB and Belle II

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On behalf of the Belle II Collaboration

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From Belle to Belle II

Belle achieves >500 Physics Journal Publications

Expected to gain 50ab\(^{-1}\) sample in next decade

**KEKB**

| Accelerator | KEKB |
|-------------|------|
| Beam Energy (GeV) | 3.5 x 8 \( (\gamma = 0.425) \) |
| CM energy | ...........Y(4S), ........... |
| Luminosity \( (cm^2 \cdot s^{-1}) \) | \( 2.1 \times 10^{34} \) |
| Total data \( (ab^{-1}) \) | 1 |

**SuperKEKB**

| | SuperKEKB |
|----------------|-----------|
| Beam Energy (GeV) | 4 x 7 \( (\gamma = 0.28) \) |
| CM energy | ...........Y(4S), ........... |
| Luminosity \( (cm^2 \cdot s^{-1}) \) | \( 8 \times 10^{35} \) |
| Total data \( (ab^{-1}) \) | 50 |
Flavour physics questions to be addressed by Belle II

- Are there new CP violating phases in the quark sector?
  - time-dependent CP violation in penguin transitions $b \rightarrow s$, $b \rightarrow d$ quarks, such as $B \rightarrow \phi K^0$ and $B \rightarrow \eta' K^0$
  - CP violation in the time integrated rates of charmless hadronic $B$ decays, such as $B \rightarrow K\pi$ and $B \rightarrow K\pi\pi$

- Multiple Higgs bosons?
  - Search charged Higgs in flavour transitions to $\tau$ leptons, including $B \rightarrow \tau\nu$ and $B \rightarrow D^{(*)}\tau\nu$.

- Left-right symmetry, and are there flavour-changing neutral currents beyond the SM?
  - forward-backward asymmetries
Flavour Physics @Belle II

- Lepton flavour violation (LFV)?

- Precise measurements of CKM matrix elements and their phases.

...
non-Flavour Physics @Belle II

• Is there a dark sector of particle physics at the same mass scale as ordinary matter?
  • Belle II has unique sensitivity to dark matter via missing energy decays.

• What is the nature of the strong force in binding hadrons?
  • States not predicted by the conventional hadron interpretation.
B-factories vs LHCb

- Advantages of LHCb
  - $b$ cross section: $\mathcal{O}(100\mu b)$ pp@13TeV vs $\mathcal{O}(nb)$ $e^+e^-@10.58$GeV
  - $O(10^4\mu m)$ vs $O(10^2\mu m)$ decay length
    - $10^2$ times larger

- Advantages of B factories
  - much higher luminosity (x$10^3$)
  - “missing mass” analyses can be performed to infer existence of **new particles** via energy/momentum conservation
  - **low background** allows for the reconstruction of final states containing photons from decays of $\pi^0$, $\rho^\pm$, $\eta$, $\eta'$ etc. and $K_L$ reconstruction
  - detection of decay products of one B allows **flavour** of the other B to be **tagged** (time dependent CP violation)
  - large samples of $\tau$ leptons allowing for measurements of **rare $\tau$ decays** and searches for **lepton flavour and lepton number violating $\tau$** decays
SuperKEKB

**Nano-Beam scheme** (P. Raimondi, DAΦNE):
Squeeze vertical beta function at the IP ($\beta_y^*$) and minimize longitudinal size of overlap region to avoid penalty from hourglass effect.

- **Overlap region (# bunch length)**
  - Strong focusing of beams down to vertical size of $\sim 50\text{nm}$ requires **low emittance beams**, very sophisticated **final focus** quadrupoles (QCS) and a large crossing angle.

$$L = \frac{\gamma \pm \xi_y}{2e\gamma} \left( 1 + a \right) \frac{R_L}{R_\xi} \left( \frac{I \pm \xi_y \pm \beta^*}{\phi_x \phi_y} \right)$$

- **Beam current** $\times 2$
- **Beam-beam param.** $\times 1$
- **Vertical beta function** $\times 20$

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**Table**

| LER / HER | KEKB | SuperKEKB | Factor |
|-----------|------|-----------|--------|
| Energy [GeV] | 3.5 / 8 | 4.0 / 7.0 |        |
| Crossing angle $2\phi_x$ [mrad] | 22 | 83 |        |
| $\beta_y^*$ [mm] | 5.9 / 5.9 | 0.27 / 0.30 | $\times 20$ |
| $\beta_x^*$ [mm] | 1200 | 32 / 25 |        |
| $I_\pm$ [A] | 1.64 / 1.19 | 3.6 / 2.6 | $\times 2$ |
| $\xi_y \sim (\beta_y^*/\xi_y)^{1/2}/\sigma^*_x$ | 0.129 / 0.09 | 0.09 / 0.09 | $\times 1$ |
| $\xi_x$ [nm] | 18 / 24 | 3.2 / 4.6 |        |
| # of bunches | 1584 | 2500 |        |
| Luminosity [$10^{34} \text{cm}^{-2} \text{s}^{-1}$] | 2.1 | 80 | $\times 40$ |
# SuperKEKB

![Diagram of SuperKEKB](image)

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| $\varepsilon_x$ [nm] | 18 / 24 | 3.2 / 4.6 |        |
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**SuperKEKB**

$\int L = 50$ ab$^{-1}$ by 2025 (50x KEKB)

$L_{\text{peak}} = 8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ (40x KEKB)

### Diagram:

- **Positron ring**
- **Electron ring**
- **Positron damping ring**
- **Electron-Positron linear accelerator**
- **Belle II detector**

### Table:

- **LER / HER**
- **KEKB**
- **SuperKEKB**
- **Factor**

- Energy [GeV] 3.5 / 8 4.0 / 7.0
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- $\varepsilon_x$ [nm] 18 / 24 3.2 / 4.6
- # of bunches 1584 2500
- Luminosity [$10^{34}$ cm$^{-2}$ s$^{-1}$] 2.1 80 x 40

### Graph:

- **SuperKEKB**
- **KEKB**
- **LHC**
- **PEP II**
- **PEP**
- **TRISTAN**
- **FERMATON**
- **BEPC2**
- **LHCb**
- **SPEAR**
- **SPS**
- **PETR**
- **DORIS**
- **LEP**
- **HERA**
- **BEP**

- Peak luminosity [cm$^{-2}$ s$^{-1}$]
- Goal of SuperKEKB/Belle II
- Integrated Luminosity [ab$^{-1}$]
- 9 months/year
- 20 days/month

### Calculations:

- **LEP / HER**
- **KEKB**
- **SuperKEKB**
- **Factor**

**Graph Notes:**

- SuperKEKB is predicted to achieve a luminosity of $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ by 2025, which is a significant increase from KEKB's $2.1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. This is achieved through improvements in the design and operation of the accelerator, allowing for higher beam intensities and better collision efficiency.

**Table Notes:**

- The table highlights key parameters that have been optimized for SuperKEKB, such as the increase in energy, crossing angle, and luminosity. The factor of 20 increase in beta radiation in the positron ring is particularly noteworthy, as it enables more efficient particle acceleration.

**Diagram Notes:**

- The diagram illustrates the complex interplay of components within the SuperKEKB system, including the positron and electron rings, the positron damping ring, and the electron-positron linear accelerator. The placement of the Belle II detector is also shown, indicating its strategic location for optimal data collection and analysis.

**Graph Details:**

- The graph illustrates the progression of integrated luminosity over time, with SuperKEKB projected to surpass KEKB's luminosity by a factor of 40 by 2025. This is achieved through advanced technologies and operational efficiencies, positioning SuperKEKB as a leading facility in particle physics research.
Belle II Detector

40x instantaneous luminosity is expected to represent **significantly higher background levels** in all Belle II subdetectors.

**K_L and muon detector (KLM):**
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**EM Calorimeter (ECL):**
- CsI(Tl), waveform sampling (barrel)
- Pure CsI, waveform sampling (endcaps)

**Vertex detector (VXD):**
- 2 layers DEPFET pixels
- 4 layers Double-sided silicon strip detectors

**Central Drift Chamber (CDC):**
- He(50%):C2H6(50%), Small cells, long lever arm, fast electronics.

**Particle Identification**
- Time-of-Propagation counter (barrel)
- Prox.focusing Aerogel RICH (fwd)

**Beryllium beam pipe:**
- 2cm diameter

**Readout (TRG, DAQ):**
- Max. 30kHz L1 trigger
- ~100% efficient for hadronic events.
- 1MB (PXD) + 100kB (others) per event over 30GB/sec to record
- Offline computing:
  - Distributed over the world via the GRID

**electron (7 GeV)**

**positron (4 GeV)**

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Belle II Detector

- Smaller beam pipe radius allows to place the innermost PXD layer closer to the Interaction point ($r = 1.4$ cm)
  - significantly improved vertex resolution
- VXD comprises the PXD of the ultra-low mass DEPFET pixels and larger SVD.
- PID: TOP and ARICH
  - better $K/\pi$ separation covering the whole momentum range
  - fake rate reduced by factor 2-5
- ECL and KLM consolidation
  - improvements in ECL and KLM to compensate for larger background
- Improved hermeticity
  - geometry and reduced boost
- Improved trigger and DAQ
  - 30 kHz L1 rate
  - 10 kHz HLT output rate (300 kB/evt)
  - need substantial computing resources
Belle II VXD

Challenges for vertex reconstruction:
• Higher backgrounds (lumi. increase, nano-beam) => higher occupancy
• Boost reduced from $\beta\gamma=0.42$ to $0.28$ => B-meson flight length of 125 $\mu$m

Pixel Detector (PXD)
• 2 layers of 40 DEPFET modules @r=14/22 mm
• 250 x 768 pixels per module
• Pixel size: 50 x 55-85 $\mu$m²
• Occupancy: 0.4 hits/$\mu$m²/s (3% max)
• Integration time: 20 $\mu$s (rolling shutter)
• Thickness: 75 $\mu$m, 0.21% $X_0$ per layer

Silicon Vertex Detector (SVD)
• 4 layers of 172 double-sided silicon strip detectors (DSSDs) @r=3.8/8.0/11.5/14cm;
• 768 strips in p-side, 768(512)strips in n-side.
• Slant shapes in FWD region for the material budget reduction.
• material budget: 0.7% $X_0$ per layer

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SuperKEKB&Belle II Commissioning

BEASTII Phase 1
w/o QCS/Belle II

BEASTII Phase 2
Collision + partial Belle II

Physics run

Goal of SuperKEKB/Belle II

9 months/year
20 days/month
To measure the beam background relevant in Physics data taking.

**Beam Background**
- Touschek
- Beam-gas Coulomb
- Beam-gas Bremsstrahlung
- Injection BG
- Beam dust
  + Radiative Bhabha
  + QED 2-photon
  + Synchrotron Radiation

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June 28, 2016  (LER beam current at 1000 mA, HER at 870 mA)
Most beam backgrounds appear safe for Belle II when extrapolating to Phase 3, but the safety factors are small, we must proceed cautiously.

Touschek has larger impact on Belle II, and agrees with simulation.

Measured Touschek-subtracted electron beam-induced background as a function of delivered current.
SuperKEKB&Belle II Commissioning

\[ K/\pi \text{ different } \theta_c \rightarrow \text{different path length } \rightarrow \text{different time of propagation.} \]

\[ \theta_c \text{ is reconstructed from: hit position (x,y) in the photo detector plane and time of propagation} \]

- 16 quartz bars: 2x1.25 m x 0.45 m x 2 cm
- 32 (segmented anode 4x4) Micro-channel plate PMTs
  Hamamatsu SL-10 MCP PMT

50 ps time resolution!
Belle II CDC: 56 layers, 14336 sense wires, Gas: He:C₂H₆ 1:1
Smaller azimuthal cell size at same radius compared with the Belle CDC.
Final focus magnets are installed

In total 55 independent SC magnets in two cryostats
SuperKEKB&Belle II Commissioning

Belle II rolled in on Apr. 11, 2017

Belle II roll in: 1400 tons, 8mx8m, moved 13m horizontally
It is desirable to have as thick aerogel layer as possible, as this increases the number of emitted photons, but thicker aerogel also increases the uncertainty in the photon emission point.

Two aerogel layers with different refraction indices, $n_1 = 1.045$ and $n_2 = 1.055$, are chosen so that the two rings overlap on the detector plane.

**Expected Performance**

Detailed simulation performed in the Belle II software framework.

Results from release -00-00-00:

- ccbar events with nominal background
- Excellent K identification efficiency (small $S$ misidentification probability) over wide momentum range.

Belle II

- $o = 93\% (4\%)$
- $o = 88\% (9\%)$ for Belle
Motivation for BEAST II Phase II:
- Machine commissioning
- Radiation safe environment for the full VXD.
- Target luminosity is $1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$.

2 PXD and 4 SVD layers in $+x$ sector where the highest backgrounds are expected.

Dedicated radiation monitors:
- FANGS, FE-I4 based hybrid pixel to investigate the Synchrotron Radiation (SR) background.
- CLAWS, scintillators with SiPM to measure the time evolution of the injection background.
- PLUME, double-sided high granularity MIMOSA pixels
SuperKEKB&Belle II Commissioning

Early physics prospects
- Efficiency losses for low $P_t$ particles,
- No appreciable losses in photon efficiency.
- Estimate of integrated luminosity ($20\pm20$ fb$^{-1}$)

Dark sector research
- Axion-like particles (ALPs) produced in ALP-strahlung, then decays into DM or into two photons.

The $\Upsilon(3S)$ offers greatest access to lower bottomonium states
- $\eta_b(1S,2S)$, $h_b(1P)$ and $\Upsilon(n^3D_1)$ Studies
- Hadronic/Radiative transitions.

Expected sensitivity of Belle II. [arxiv: 1709.00009]
SuperKEKB&Belle II Commissioning

1st Phase 3 PXD ladder is successfully assembled

SVD L3 mount complete

VXD integration and commissioning

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SuperKEKB&Belle II Commissioning

Goal of SuperKEKB/Belle II: $50 \text{ ab}^{-1}$ by 2025

Physics run

9 months/year
20 days/month
Summary

- Belle II has a rich physics program.
- SuperKEKB upgrades are on-target, Belle II detector construction is ongoing.
- BEAST2 Phase2 will start in Feb. 2018, to further investigate the beam background, and probably first data for physics studies.
- Physics data taking will start in the beginning of 2019!

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