The Belle II Upgrade Program

Jerome Baudot for the Belle II collaboration

- Belle II/SuperKEKB current status & rationale for upgrades
- Overview of proposed technologies and R&Ds
**B,c,τ-factory: SuperKEKB + Belle II**

- **Initial physics program based on** $L_{\text{int}} = 50 \text{ ab}^{-1}$ at $\sqrt{s} = M_{Y(4S)}$
  ⇒ The Belle II physics book [PTEP 12 (2019) 123C01](#)

- **Belle II detector:**
  - Upgraded from Belle to match
    - Lower boost ⇒ improved vertex
    - Higher rates & radiations ⇒ faster det. & read-out

- **High luminosity collider:**
  - $L_{\text{peak}} \sim \text{multi } 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ range
  - High current / nano-beams / specific crossing features
  - Challenging background conditions
  ⇒ Snowmass contribution: [arXiv 2203.05731](#)

**Belle II collab**
~1000 researches / 26 countries

⇒ Started in 2018
The Belle II detector

**KLong and muon detector (KLM)**
- Resistive Plate Chambers (barrel outer layers)
- Scintillator + WLSF + SiPM’s (end-caps, inner 2 barrel layers)

**Particle Identification**
- TOP detector system (barrel)
- Prox. focusing Aerogel RICH (fwd)

**New/Upgraded Components**
- Beryllium beam pipe
- 2cm diameter

- EM Calorimeter (CDC)
- CsI(Tl), waveform sampling (barrel+ endcap)

- Final focusing magnets
- new

- SuperCond. Solenoid
- 1.5 T magnetic field

- Vertex Detector (VXD = PXD+SVD)
- 2 layers DEPFET pixels + 4 layers DSSD

- Central Drift Chamber
- He(50%):C2H6(50%), small cells, long lever arm, fast electronics

- C.Irmler, SVD
  - Tuesday AM poster

- U.Tamponi, PID
  - Monday PM talk

- R.Pestonik, ARICH
  - Monday PM poster
Luminosity & data taking timeline

- **TODAY**
  - 386 fb\(^{-1}\) accumulated
  - World record peak lumi 4.1 \(\times\) 10\(^{34}\) cm\(^{-2}\).s\(^{-1}\)

- **Long Shutdown Jul-2022 / Fall 2023**
  - Completeness & robustness of present Belle II
    - reach 2 \(\times\) 10\(^{35}\) cm\(^{-2}\).s\(^{-1}\)

- **Long Shutdown ~2026/27**
  - Higher luminosity SuperKEKB
    - Change collider interaction region
    - reach 6 \(\times\) 10\(^{35}\) cm\(^{-2}\).s\(^{-1}\)

- **Beyond 2032, ideas for**
  - Extended physics program
    - Polarized beams
      - reach 10\(^{36}\) cm\(^{-2}\).s\(^{-1}\)
Upgrade motivation

- Mitigate impact of beam-induced background
- Increase detector lifetime against radiation
- Improve performance: more physics/ab$^{-1}$

- **Long Shutdown Jul-2022 / Fall 2023**
  - Completeness & robustness of present Belle II
  - reach $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

- **Long Shutdown ~2026/27**
  - Higher luminosity SuperKEKB
  - Change collider interaction region
  - reach $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

- **Beyond 2032, ideas for**
  - Extended physics program
  - Polarized beams
  - reach $10^{36} \text{ cm}^{-2}\text{s}^{-1}$
Upgrade plans

**Short-term:**
- Vertex: complete 2\textsuperscript{nd} layer for pixel
- PID: replace PMTs used in TOP
- Data acquisition: replace boards (PCIe40)

**Medium-term:**
- Vertex detector
- Parts of main tracker
- PID with TOP & KLM

**Long-term:**
- Tracker
- PID with TOP, ARICH, KLM
- Calorimetry

**Long Shutdown Jul-2022 / Fall 2023**

- Completeness & robustness of present Belle II
  - reach $2 \times 10^{35}$ cm\(^{-2}\)s\(^{-1}\)

**Long Shutdown \sim2026/27**

- Higher luminosity SuperKEKB
  - Change collider interaction region
  - reach $6 \times 10^{35}$ cm\(^{-2}\)s\(^{-1}\)

**Beyond 2032, ideas for**

- Extended physics program
- Polarized beams
  - reach $10^{36}$ cm\(^{-2}\)s\(^{-1}\)

⇒ Snowmass contribution: [arXiv 2203.11349](http://arxiv.org/abs/2203.11349)

---

J. Baudot - The Belle 2 upgrade program - Pisa meeting on advanced detectors 2022
Vertex detector: VXD (PXD+SVD)

**Rationale**
- Be prepared for IR redesign (higher Background conditions)
- Improve performance / IP resolution, low $p_t$ tracks
- Be prepared to cover inner CDC (radii 135-240 mm)
- Triggering: possible contribution to L1
- Target *Medium-term*

**Requirements**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-6 layers over radii</td>
<td>14-135 mm</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>&lt; 15 µm</td>
</tr>
<tr>
<td>Total material budget</td>
<td>&lt; (2x0.2% + 4x0.7%) $X_0$</td>
</tr>
<tr>
<td>Hit rate</td>
<td>120 &lt; 1 MHz/cm$^2$</td>
</tr>
<tr>
<td>Total Ionizing Dose (inner)</td>
<td>100 kGy / year</td>
</tr>
<tr>
<td>NIEL fluence (inner)</td>
<td>$5 \times 10^{13}$ $n_{eq}$/cm$^2$</td>
</tr>
</tbody>
</table>

⇒ Higher granularity in time and/or space / current VXD

**Various proposals**

- *Thin and fine-pitch DSSD*
  - Sensor 140 µm thin & z-pitch < 80 µm
  - New ASIC for low noise

- *Upgraded DEPFET*
  - Higher radiation tolerance through higher gain
  - Faster read-out (few µs) with re-orientation and new ASICS

- *SOI pixels*
  - Lapis 200 nm process
  - Dual Time pixel sensor (DuTIP)
  - pitch 45 µm
  - 2x60 ns integration

- *CMOS-MAPS*
  - Tower 180 nm process
  - Extension of TJ-MONOPIX2 → OBELIX sensor
  - Pitch <40 µm with 100 ns integration
  - Fully pixelated VXD concept = VTX with all-Si modules or ALICE-ITS-like ladders
Vertex detector: VXD (PXD+SVD)

- **Rationale**
  - Be prepared for IR redesign (higher Background conditions) @ medium-term
  - Be prepared to cover inner CDC (radii 135-240 mm)
  - Improve performance / IP resolution, low $p_T$ tracks
  - Triggering: possible contribution to L1
  - Target **Medium-term**

- **Requirements**
  - 5-6 layers over radii: 14-135 mm
  - Spatial resolution: < 15 µm
  - Total material budget: < (2x0.2% + 4x0.7%) $X_0$
  - Hit rate: 120 $\ll$ 1 MHz/cm$^2$
  - Total Ionizing Dose (inner): 100 kGy/year
  - NIEL fluence (inner): 5x10$^{13}$ $n_{eq}$/cm$^2$
  - Higher granularity in:

- **Various proposals**
  - **Thin and fine-pitch DSSD**
    - Sensor 140 µm thin & pitch
    - New ASIC for low noise
  - **Upgraded DEPFET**
    - Higher radiation tolerance through higher gain
    - Faster read-out (few µs) with re-orientation and new ASICs
  - **SOI pixels**
    - Lapis 200 nm process
    - Dual Time pixel sensor (DuTiP)
    - Pitch 45 µm
    - 2x60 ns integration
  - **CMOS-MAPS**
    - Tower 180 nm process
    - Extension of TJ-MONOPIX2 → OBELIX sensor
    - Pitch <40 µm with 100 ns integration
    - Fully pixelated VXD concept = VTX with all-Si modules or ALICE-ITS-like ladders

Prototyping & tests on-going: C.Wessel, MAPS upgrade **Tuesday AM talk**
L.Massaccesi, VTX perf. simulation **Tuesday AM poster**
Main tracker: CDC

**Short-/Medium-term**
- Robustness against radiation-damage
- Mitigate cross-talk between read-out channels

**Replacement of read-out board**
- New ASIC
  - all-in-one ASD+ADC, lower cross-talk ($100 \downarrow 10$ mV/7pC)
- Components with higher radiation tolerance
  - Optical transceiver (sensitive to $\gamma$ and neutrons)
  - FPGA (sensitive to SEU)
  - Tests in 2022
  - Mass production 2023

**Long-term studies**
- Sustaining higher rates & backgrounds

**Exploration**
- Extended VTX
- TPC tracker with pixel read-out
  - Gridpix-like $200^2 \mu m^2$
Particle Identification: TOP & ARICH

- **Time Of Propagation (TOP)**
  - Maintain efficiency against ever higher background
    - Needed already at short/medium-term
  - Photon detection devices
    - 2022: move to Atomic Layer Deposited ALD-MCP-PMT
    - 2026: move to life extended ALD-MCP-PMT possibly to SiPM
  - Read-out electronics to accommodate SiPM
    - Better compactness using SiPM dedicated ASICs
    - Allows extra cooling required by SiPM

- **Aerogel RICH**
  - target long term
    - Current Hybrid-APD not adapted beyond $8 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$
  - 1st option: SiPM
    - On-going evaluation of various device
      - Single photon detection, Dark count rate,
        Neutron sensitivity ($5 \times 10^{12} \text{n_{eq}/cm}^2$), Cooling required
  - 2nd option: Large Area Picosecond photodetectors
  - Read-out
    - Upgrade of current ASIC
    - Or new ASIC

- **STOPGAP proposal**
  - target long term
  - Fill-in gaps between TOP quartz bar
  - CMOS-MAPS with 50 ps timing

J. Baudot - The Belle 2 upgrade program - Pisa meeting on advanced detectors 2022
Calorimetry: ECL

**Rationale**
- Target long-term
- Reduce pile-up from beam-induced background

**New preshower**
- BGO/LYSO + 1 mm² Si pixel
  - Angle = 0.08 rad expected @ normal incidence

**Read-out of current Csi(Tl)**
- From PiN diodes to APD

**Faster crystals**
- Full replacement: Csi(Tl) → pure Csi
  - From 1 µs to 30 ns light decay tile
- Photon detection: WLS + APD
Klong & Muon identification: KLM

• Target **medium to long term**

- **Complete replacement of RPCs with Scintillators**
  • Rationale: increased rate & robustness of read-out chain
  • New system = scint. bars + wave-length shifter fibers + SiPM
    - Already used in first layer & end-cap
  • More compact read-out
    - Allowing waveform sampling (time resol.) & improved data push to trigger

- **Investigating TOF-like performance**
  • Rationale: $K_L$ energy & background neutron rejection
  • Required time resolution ~30 ps
  • R&D on-going with large MPPC + new pre-amp
Rationale

• Keep high-efficiency on hadronic events
• Improve efficiency on low-multiplicity events ($\tau$, dark sector)
• Continuous improvements

Hardware

• Deployment of most recent UT4 boards
  - Xilinx Ultrascale with 200k gates, 25 Gbps, DDR4
  - Target 2026
• New UT5
  - Xilinx Ultrascale+ with 8000k gates, 32 Gbps, UltraRAM
  - Lower #boards needed
  - 2024-32

Firmware

<table>
<thead>
<tr>
<th>Component</th>
<th>Improvement</th>
<th>Time</th>
<th>#UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDC cluster finder</td>
<td>beamBG rejection</td>
<td>2026</td>
<td>10</td>
</tr>
<tr>
<td>CDC 2Dtrack finder</td>
<td>increase occupancy limit</td>
<td>2022</td>
<td>4</td>
</tr>
<tr>
<td>CDC 3Dtrack finder</td>
<td>enlarge $\theta$ angle acceptance</td>
<td>2022</td>
<td>4</td>
</tr>
<tr>
<td>CDC 3Dtrack fitter (1)</td>
<td>beamBG rejection</td>
<td>2025</td>
<td>4</td>
</tr>
<tr>
<td>CDC 3Dtrack fitter (2)</td>
<td>beamBG rejection</td>
<td>2025</td>
<td>4</td>
</tr>
<tr>
<td>Displaced vertex finder</td>
<td>LLP search</td>
<td>2025</td>
<td>1</td>
</tr>
<tr>
<td>ECL waveform fitter</td>
<td>resolution</td>
<td>2026</td>
<td>–</td>
</tr>
<tr>
<td>ECL cluster finder</td>
<td>beamBG rejection</td>
<td>2026</td>
<td>1</td>
</tr>
<tr>
<td>KLM track finder</td>
<td>beamBG rejection</td>
<td>2024</td>
<td>–</td>
</tr>
<tr>
<td>VXD trigger</td>
<td>BG rejection</td>
<td>2032</td>
<td>–</td>
</tr>
<tr>
<td>GRL event identification</td>
<td>signal efficiency</td>
<td>2025</td>
<td>1</td>
</tr>
<tr>
<td>GDL injection veto</td>
<td>DAQ efficiency</td>
<td>2024</td>
<td>–</td>
</tr>
</tbody>
</table>
• Belle II physics goals has steered and is steering a rich instrumental program

• Belle II operates efficiently at peak luminosities just below $10^{35} \text{ cm}^{-2}\text{s}^{-1}$

• Short-term: **consolidation of existing technologies**
  – entering the $L_{\text{inst}} = 1\text{-}2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ regime in the next years

• Medium- to Long-term: **introducing new technologies/concepts**
  – running safely at $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ after 2026 and beyond after 2032
  – with enhanced performances

• **To come**
  – International Task Force on SuperKEKB luminosity → conclusion THIS summer
  – Conceptual Design Report for medium-term upgrades → early 2023
Belle II @ Pisa meeting on advanced det.

- Christian Wessel, MAPS upgrade, Tuesday AM, https://agenda.infn.it/event/22092/contributions/167366/
- Umberto Tamponi, PID system, Monday PM, https://agenda.infn.it/event/22092/contributions/167677/
- Rok Pestonik, ARICH, Monday posters, https://agenda.infn.it/event/22092/contributions/167676/
- Ludovico Massacesi, MAPS simulation, Tuesday poster, https://agenda.infn.it/event/22092/contributions/166670/
- Chrstian Irmler, SVD, Tuesday poster, https://agenda.infn.it/event/22092/contributions/166726/
- Alice Gabriella, Diamond calibration, Tuesday poster, https://agenda.infn.it/event/22092/contributions/166769/
SuperKEKB collider

Recipe to high luminosity

- **High currents:** > 1 A
- **Nano-scale beam size:**
  \[ \sigma_x \times \sigma_y \sim 10 \mu m \times \sim 60 \text{ nm} \]
  \[ B_y < 1 \text{ mm} \]
- & specific beam crossing features
  - Crossing angle (83 mrad) + crab waist (80%)

Beam-induced backgrounds

- **Intra-beam scattering**
- **Beam-gas interaction**
- **Synchrotron radiation**
- **Luminosity driven**

Radiative Bhabha scattering
2-photon interaction
## Overview of the Upgrade program

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Function</th>
<th>upgrade idea</th>
<th>time scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>PXD</td>
<td>Vertex Detector</td>
<td>2 layer installation new DEPFET</td>
<td>short-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>medium-term</td>
</tr>
<tr>
<td>SVD</td>
<td>Vertex Detector</td>
<td>thin, double-sided strips, w/ new frontend</td>
<td>medium-term</td>
</tr>
<tr>
<td>PXD+SVD</td>
<td>Vertex Detector</td>
<td>all-pixels: SOI sensors all-pixels: DMAPS CMOS sensors</td>
<td>medium-term</td>
</tr>
<tr>
<td></td>
<td>Tracking</td>
<td>upgrade front end electronics replace inner part with silicon replace with TPC w/ MPGD readout</td>
<td>short/medium-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>medium/long term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>long-term</td>
</tr>
<tr>
<td>TOP</td>
<td>PID, barrel</td>
<td>Replace conventional MCP-PMTs Replace not-life-extended ALD MCP-PMTs STOPGAP TOF and timing detector</td>
<td>short-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>medium-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>long-term</td>
</tr>
<tr>
<td>ARICH</td>
<td>PID, forward</td>
<td>replace HAPD with Silicon PhotoMultipliers replace HAPD with Large Area Picosecond Photodetectors</td>
<td>long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>long-term</td>
</tr>
<tr>
<td>ECL</td>
<td>$\gamma, e$ ID</td>
<td>add pre-shower detector in front of ECL Replace ECL PiN diodes with APDs Replace CsI(Tl) with pure CsI crystals</td>
<td>long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>long-term</td>
</tr>
<tr>
<td>KLM</td>
<td>$K_L, \mu$ ID</td>
<td>replace 13 barrel layers of legacy RPCs with scintillators on-detector upgraded scintillator readout timing upgrade for K-long momentum measurement</td>
<td>medium/long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>medium/long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>medium/long-term</td>
</tr>
<tr>
<td>Trigger</td>
<td></td>
<td>firmware improvements</td>
<td>continuos</td>
</tr>
<tr>
<td>DAQ</td>
<td></td>
<td>PCIe40 readout upgrade add 1300-1900 cores to HLT</td>
<td>ongoing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>short/medium-term</td>
</tr>
</tbody>
</table>
Impact on performance & physics

=> Snowmass Belle II : arXiv 2203.11349

<table>
<thead>
<tr>
<th>Topic</th>
<th>VXD</th>
<th>CDC</th>
<th>PID</th>
<th>ECL</th>
<th>KLM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low momentum track finding</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Track p, M resolution</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP/Vertex resolution</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadron ID</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₀^0 ID</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Lepton ID</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π₀, γ</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topic</th>
<th>VXD</th>
<th>CDC (incl. Trigger)</th>
<th>PID</th>
<th>PID(Ω coverage)</th>
<th>ECL</th>
<th>KLM</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(B → τν, B → K⁽⁺⁾ν̄ν)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>B(B → X_uℓν)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>R, Polarisation(B → D⁽⁺⁾τν)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>FEI</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>S_CCP, C_CCP(B → π₀π₀, K⁺π₀)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>S_CCP, C_CCP(B → ργ)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>S_CCP, C_CCP(B → J/ψK⁺₅, η'K⁺₅)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Flavour tagger</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>τ LFV</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Dark sector searches</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Belle II, another view