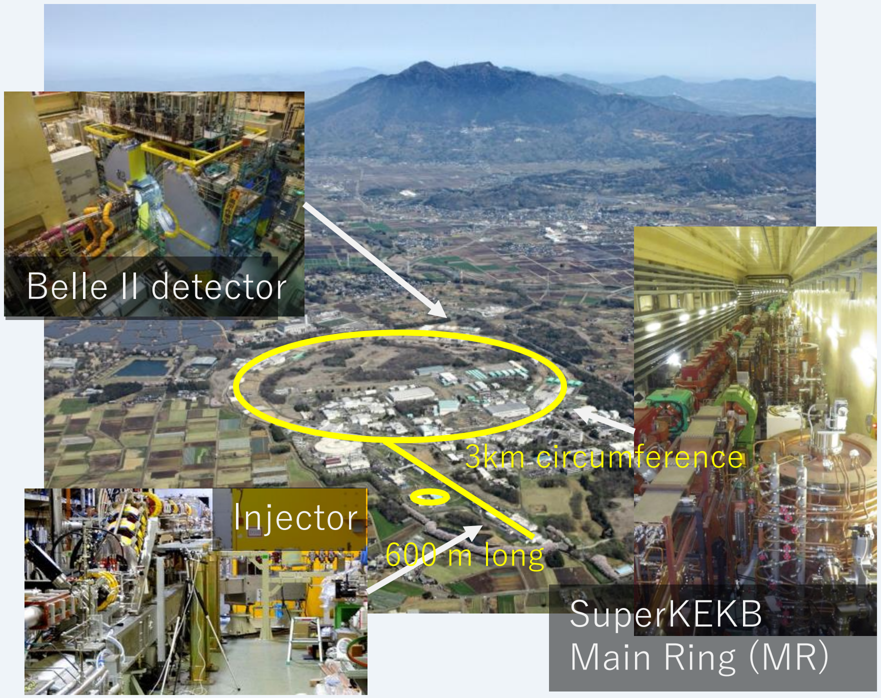
Status of the Belle II experiment

Yutaka Ushiroda (IPNS, KEK)
Belle II Project Manager

Joint workshop of FKPPL and TYL/FJPPL

May 18, 2022

Project Overview



SuperKEKB:
Largest scale e^+e^- collider in the world
World highest luminosity machine
$7\ \mathrm{GeV}e^- \times 4\ \mathrm{GeV}e^+,\ L \sim 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$\int L\,dt = 50\ \mathrm{ab}^{-1}$ at Υ(4S) and other collision energies

Construction: 2011-2018
Phase 1 Test Operation 2016.2 – 2016.6
Phase 2 Collision Tuning 2018.3-2018.7
Phase 3 **Physics Operation 2019.3.11-present**

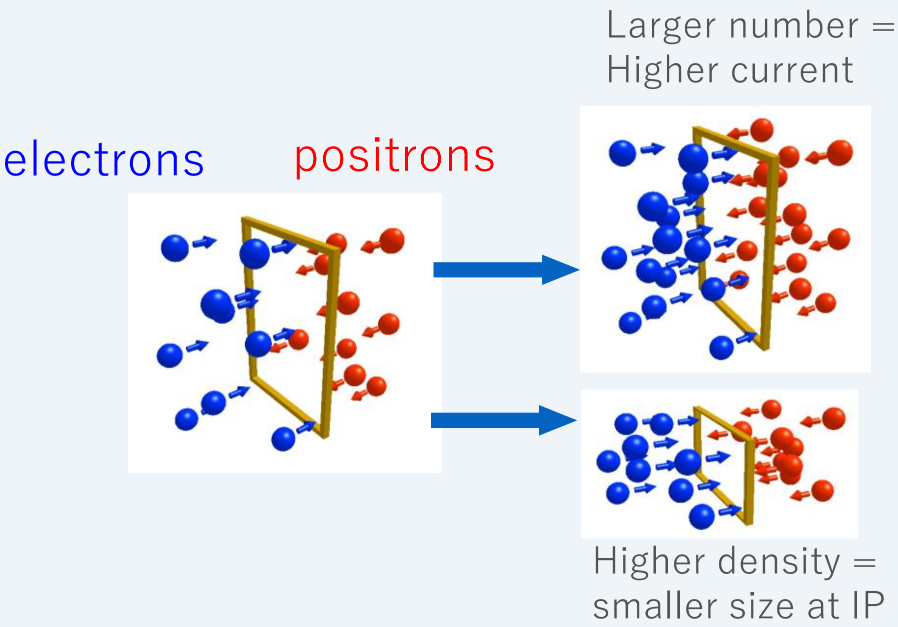
The main target:
- **Searches for NP through quantum effects** in b, c, and τ decays.

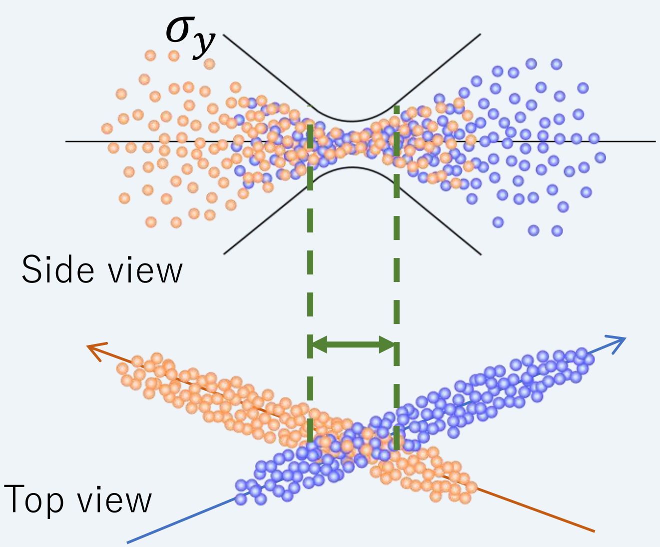
Unique studies:
- Searches for **Dark Sector** particles in clean e^+e^- collisions
- Studies of **exotic hadrons**

SuperKEKB "nano-beam" scheme

Idea by Dr. P. Raimondi for INFN SuperB

To get high luminosity:

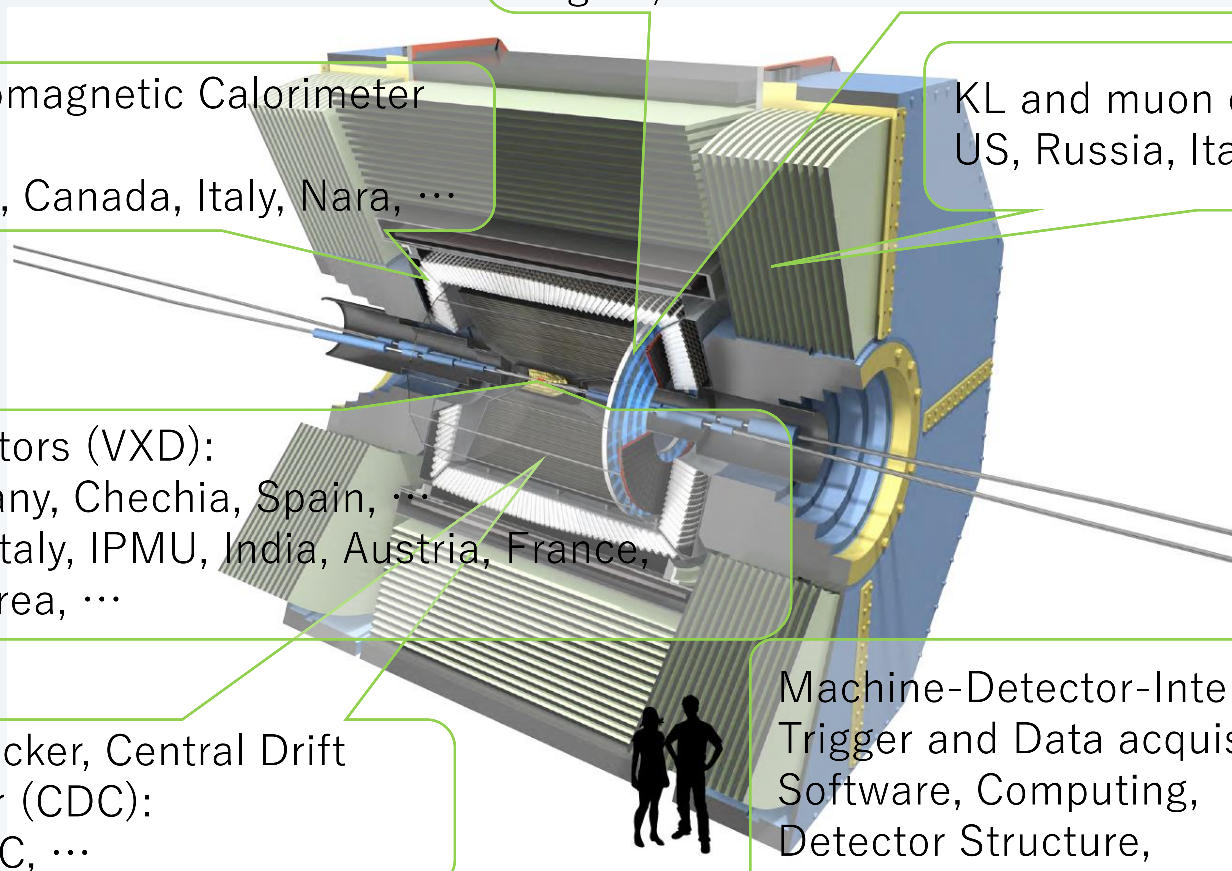




- Low emittance
- Squeeze vertical beam size to the size of virus ($\sigma \sim 50$ nm) @IP.
- Large crossing angle to avoid unwanted overlap of beams.
  Beams will collide only at the most squeezed part.

Principle verified, practically functioning well.

Belle II detector



Particle Identification (PID):
(TOP) Nagoya Japan, US, Italy, Slovenia, …
(ARICH) KEK, Slovenia, Tokyo Metropolitan, Niigata, …

Electromagnetic Calorimeter (ECL):
Russia, Canada, Italy, Nara, …

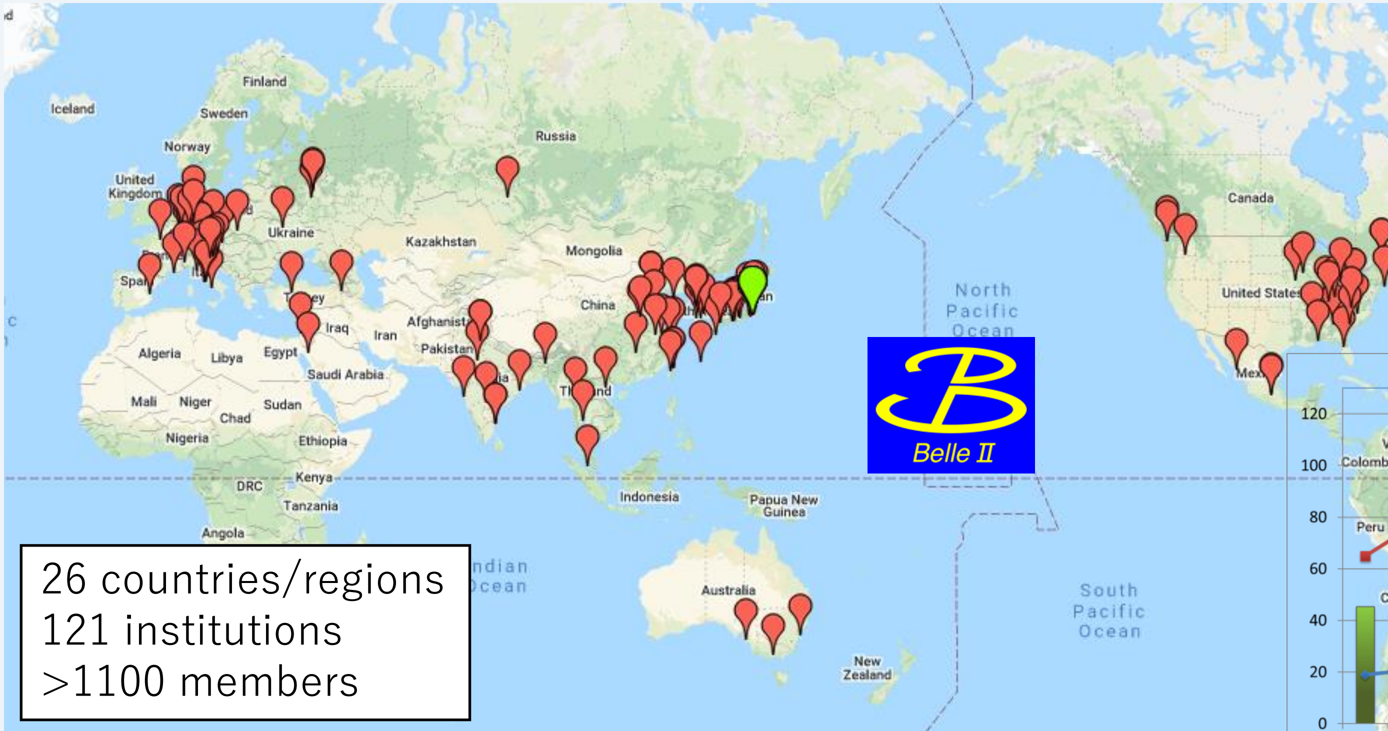
KL and muon detector (KLM):
US, Russia, Italy, China, …

Vertex Detectors (VXD):
(PXD) Germany, Chechia, Spain, …
(SVD) KEK, Italy, IPMU, India, Austria, France, Australia, Korea, …

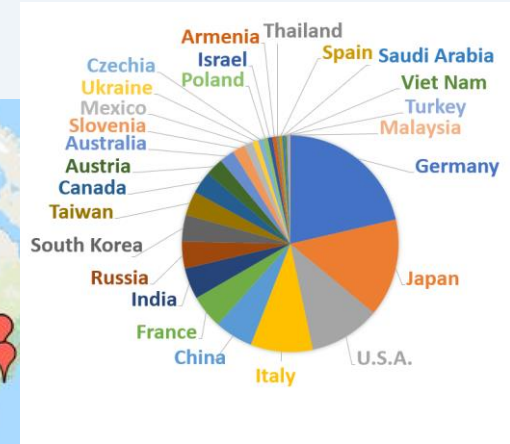
Main Tracker, Central Drift Chamber (CDC):
KEK, NPC, …

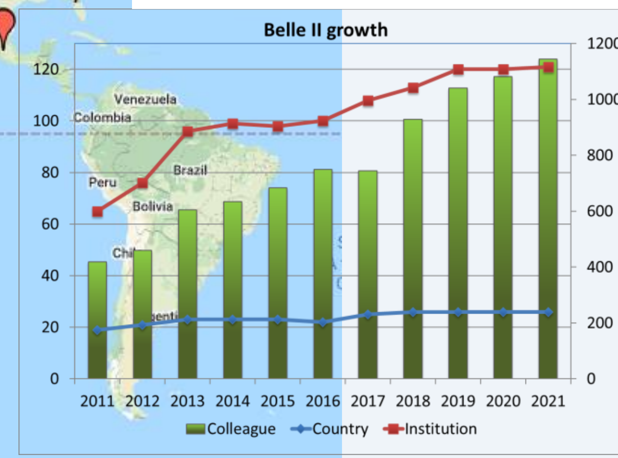
Machine-Detector-Interface,
Trigger and Data acquisition,
Software, Computing,
Detector Structure,
Electronics Hut, Experimental Hall, and services

Belle II collaboration



26 countries/regions
121 institutions
>1100 members





TYL support since 2013 was essential to establish official collaboration since 2017. Continued supports have also been beneficial to the collaboration to achieve key developments.

Project Development

1994	…	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

KEKB/Belle (1994-2010)
Construction 1994-1999
Experiment 1999-2010
Proof of KM theory
Still active

SuperKEKB/Belle II

Planning, Design

Construction

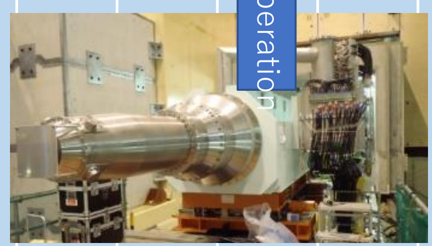
Inauguration of Belle II collaboration (2008)

Phase 1 "Test" Operation

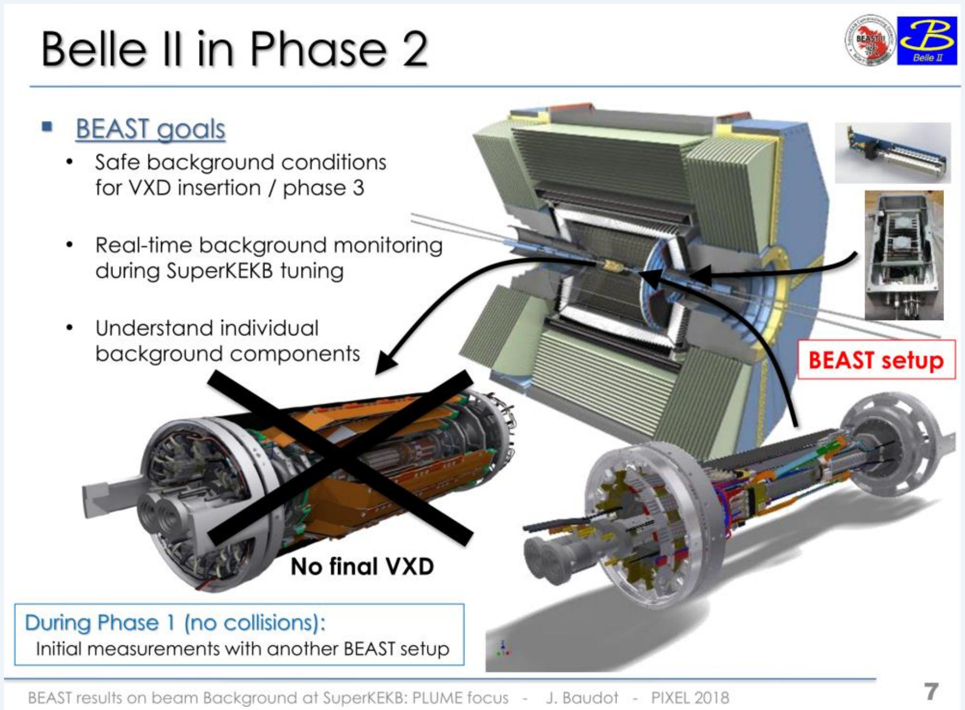
Phase 2 Operation for collision Tuning

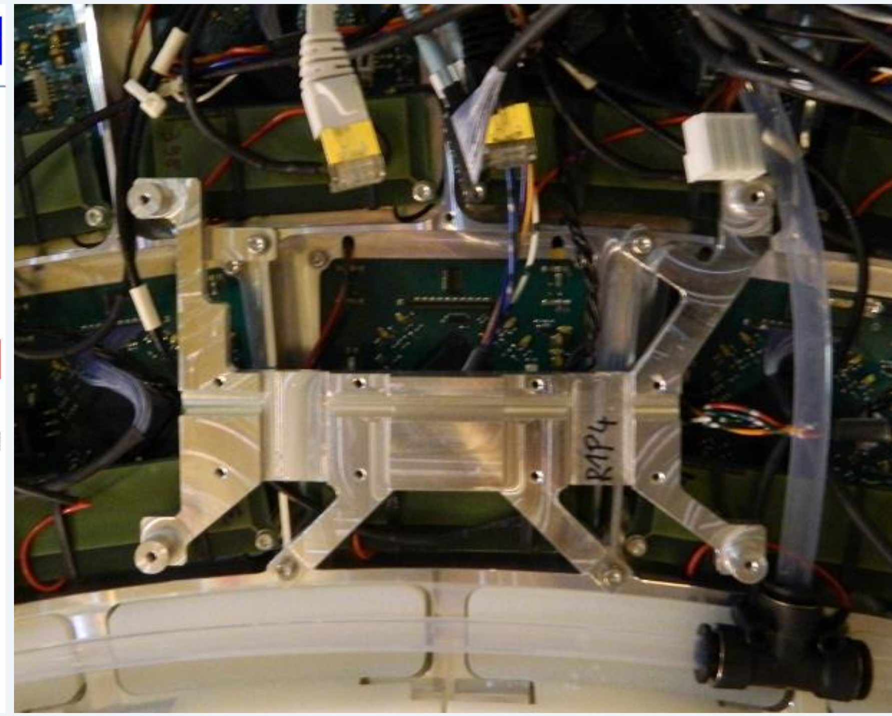
Phase 3 Physics Runs

LS1



Example commissioning activities

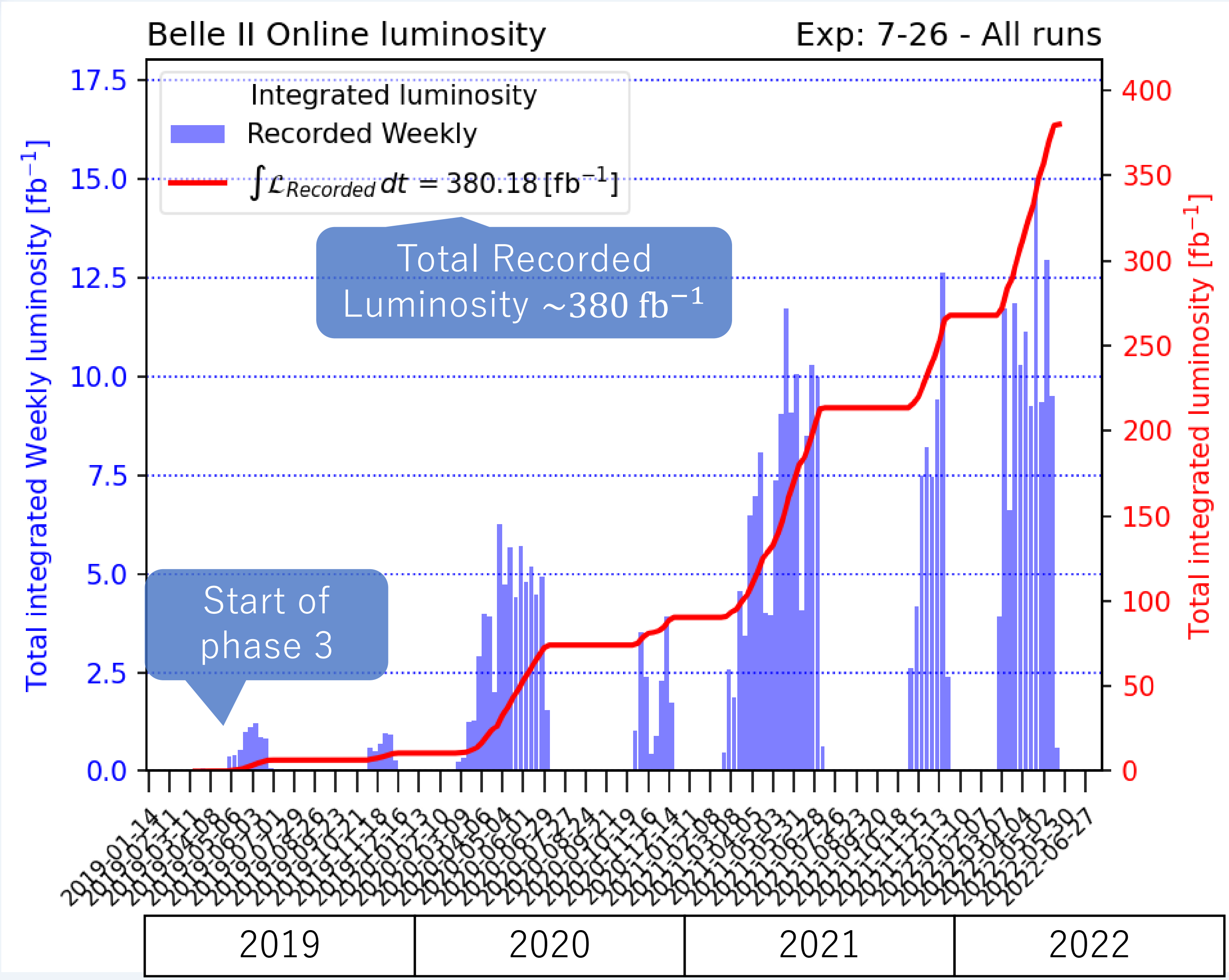




Phase 2:
“BEAST” background monitor complex instead of the real VXD to understand beam background. (IPHC)

Phase 2 to 3:
New cooling of ARICH
Temperature of FPGAs
50 - 70 ℃ → < 40℃
(LAL/IJCLab)

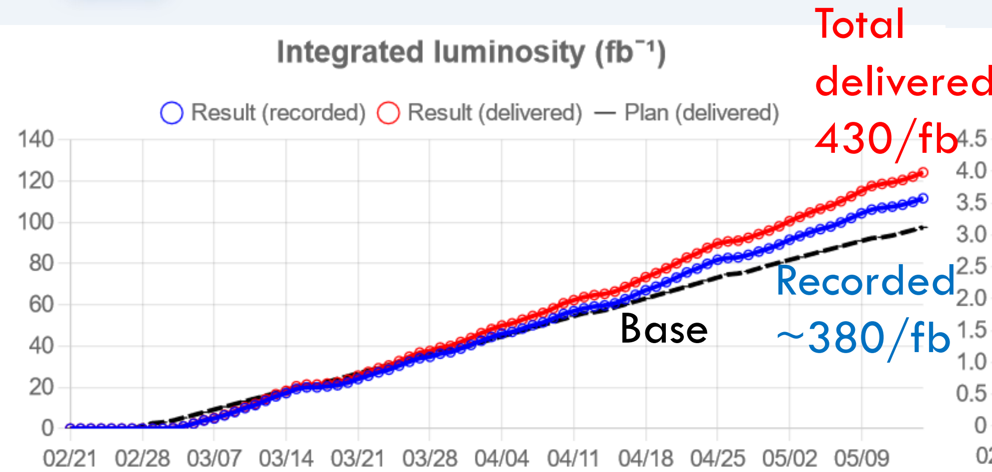
Operation Status



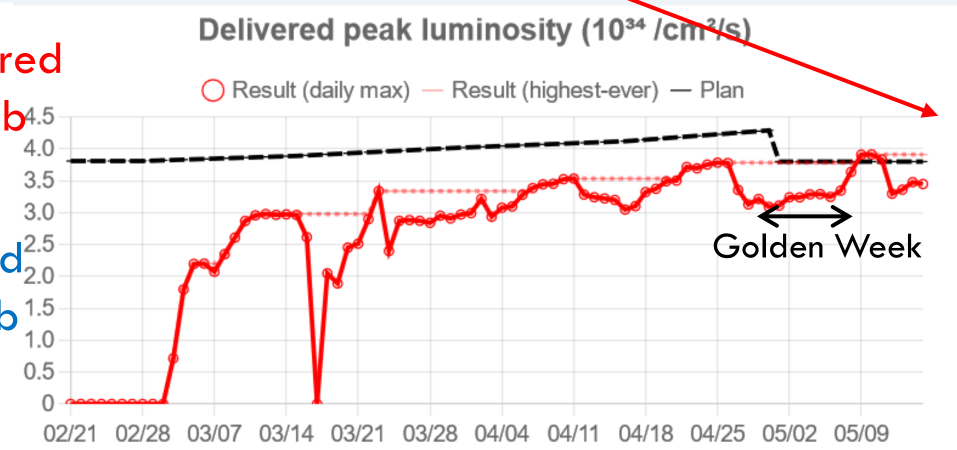
Constantly improving the performance despite pandemic.

Recent runs

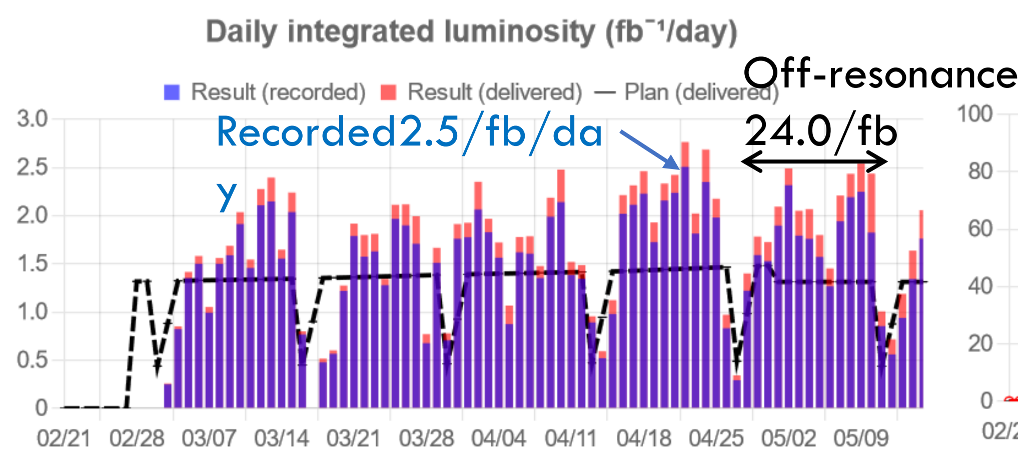
$L = 4.1\ \sout{3.9} \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$,
New World Record (May 17, 2022)



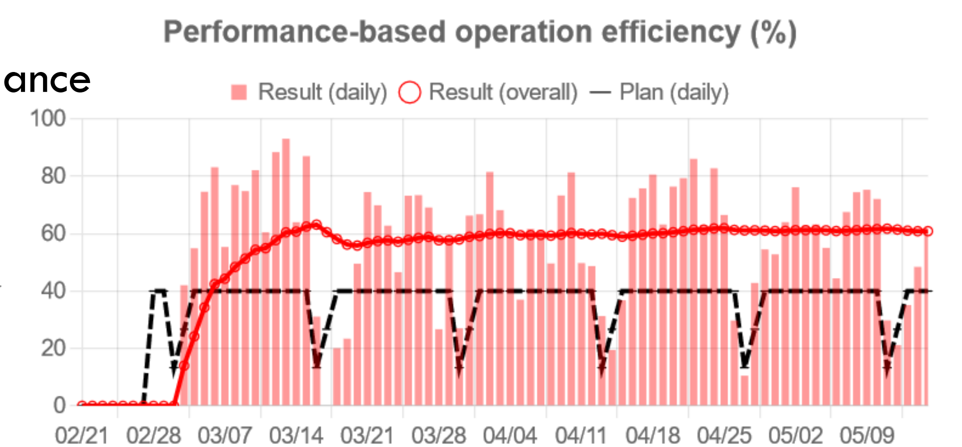
[Delivered ∫L(plan)] = ∑ [Daily delivered ∫L(plan)]



Delivered peak luminosity during physics runs

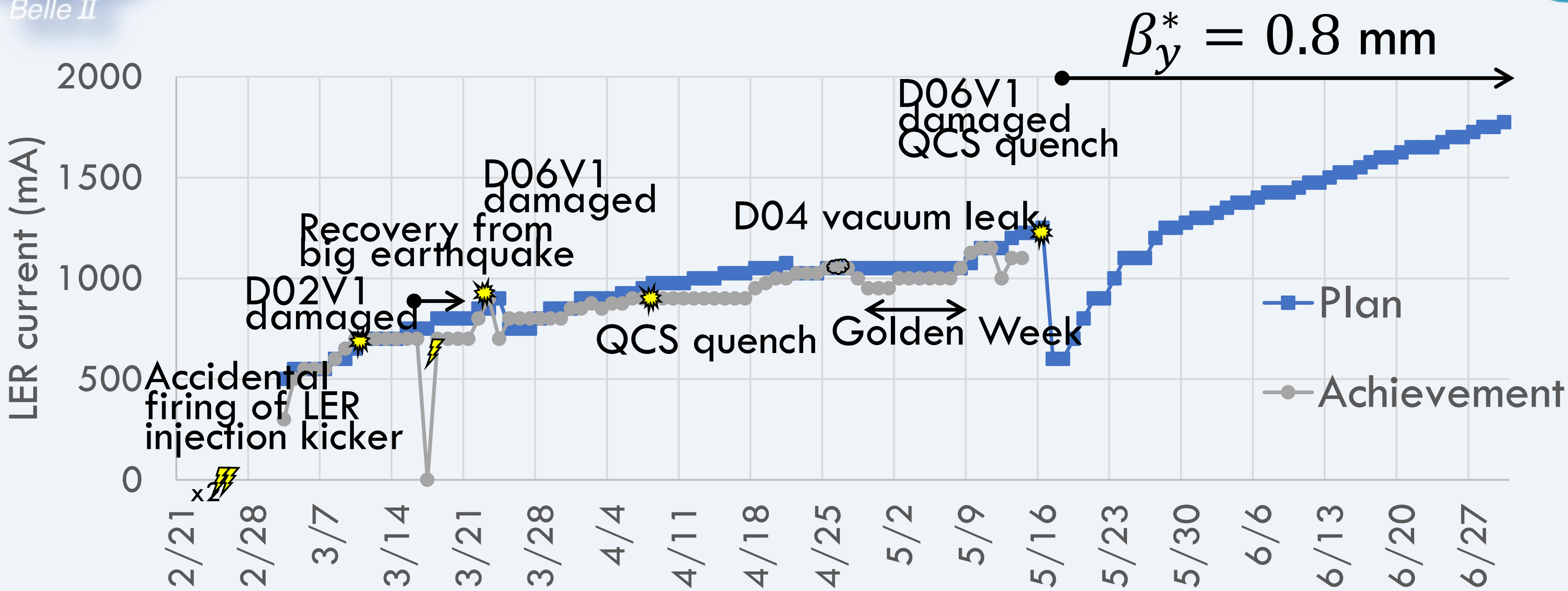


[Daily delivered ∫L(plan)] = [Delivered L_{peak}(plan)] × [86400 sec] × [Daily efficiency (plan)]



[Daily efficiency] = [Daily delivered ∫L] / [Highest-ever delivered L_{peak} at the time] / [86400 sec]
Highest-ever delivered L_{peak} is reset to 0 at the beginning of each run period.
Start-up period and scheduled maintenance days are excluded in the overall efficiency calculation.

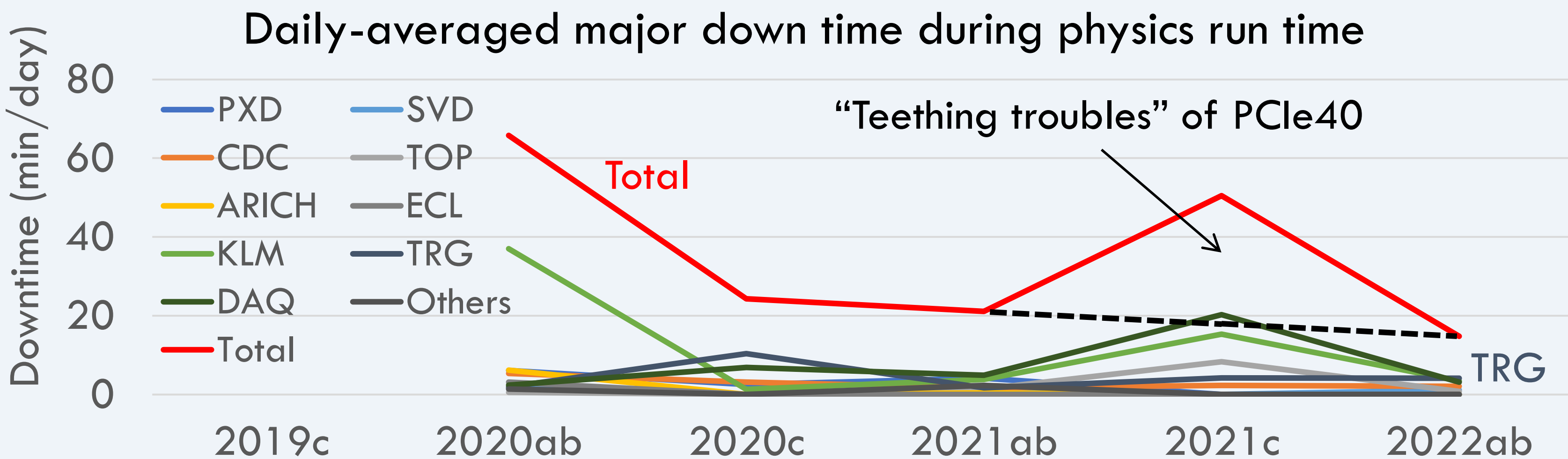
Recent machine issues



- Injection performance sometimes unstable and limits the beam current
  - 2-bunch injection need to be polished further.
- LER injection kicker (K1-3) accidental firing
  - Old thyratrons…
- LER large beam loss and damage of the collimator heads
  - Cause yet to be identified
- Earthquakes
  - Good performance ruined by earthquakes. Especially the impact due to Mar 16th earthquake still remains.

Major downtime of Belle II (> 30 min)

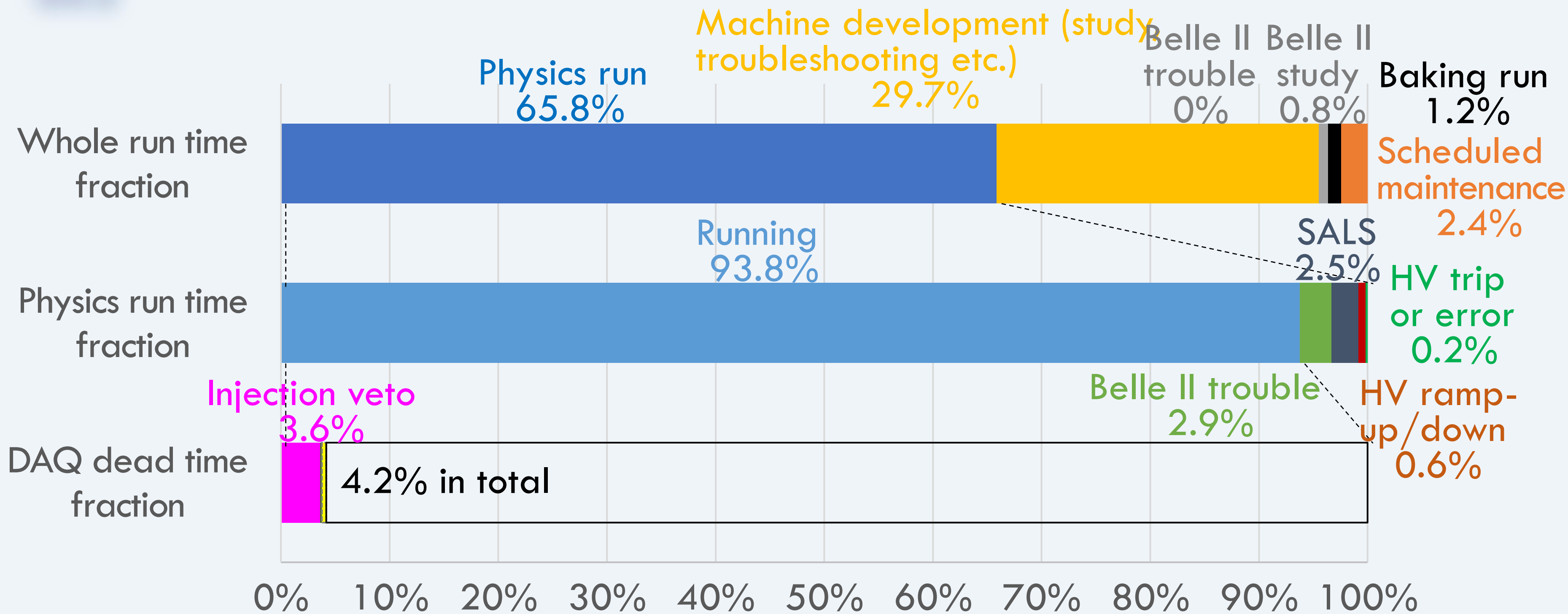
= Objective of Jira ticket
(track till solved)

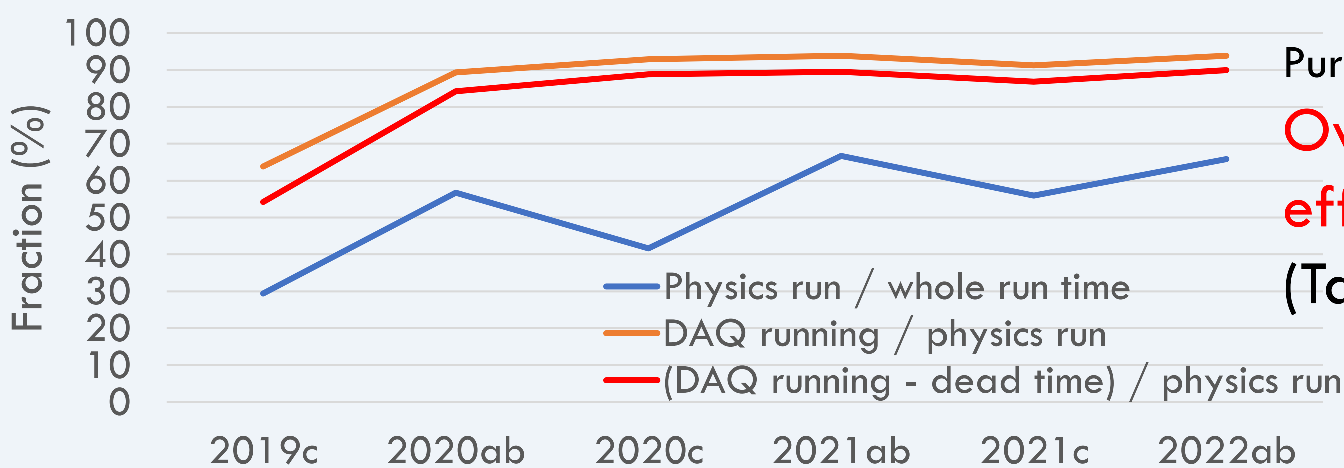


There were "teething troubles" after upgrading the backend readout system to PCIe40 (to be explained), but otherwise major down time is decreasing thanks to careful tracking of issues and hardworking of operation teams.

Data taking efficiency

Feb 21 - May 14, 2022



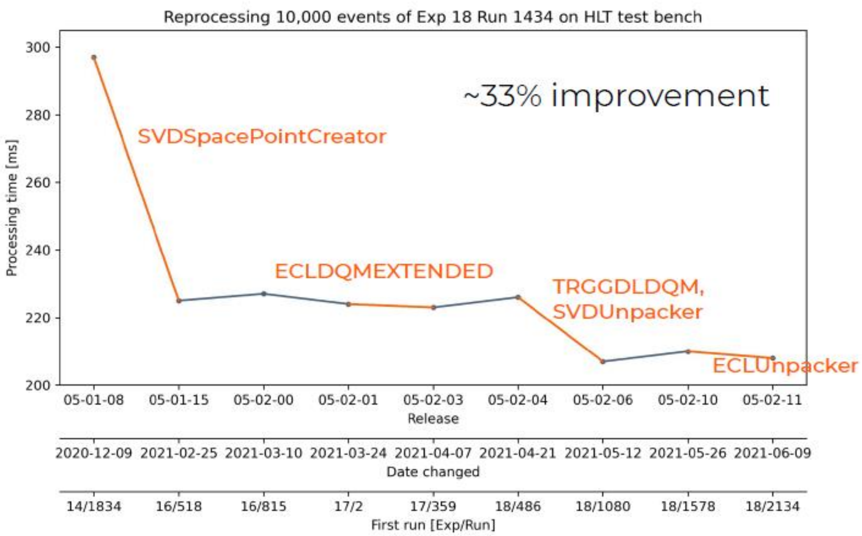


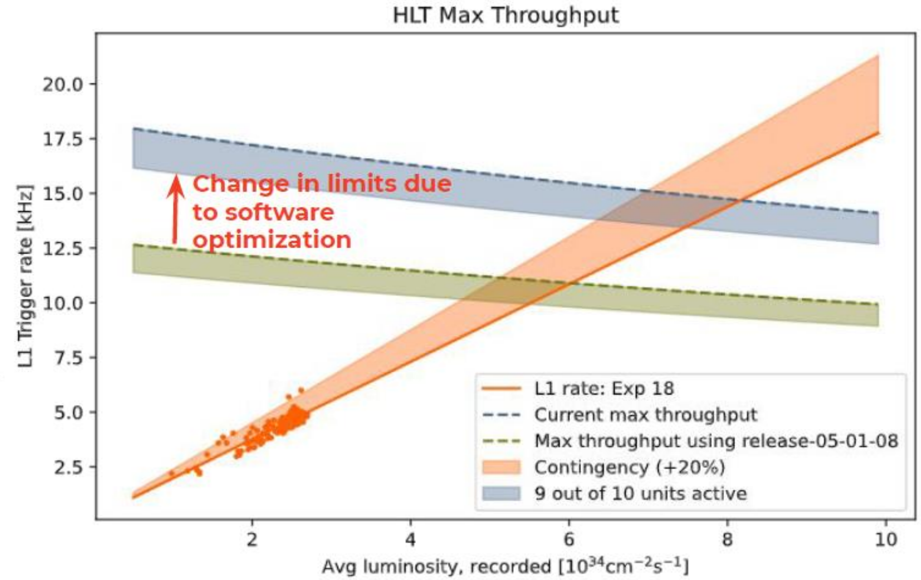
Pure DAQ deadtime: 0.6%

Overall data taking efficiency = 89.9%

(Target 90%)

Trigger Improvement





~9 kHz → ~13 kHz max.
Should now be able to operate HLT smoothly till LS1 ! 😌

IJCLab

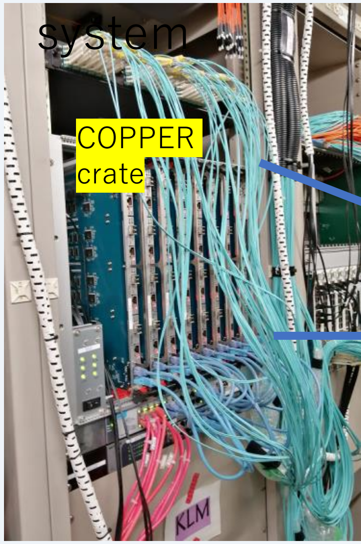
9

High Level Trigger (HLT) has been improved.
DAQ limit has been pushed up from 9kHz to 13kHz so that we can keep the current (loose) L1 trigger condition for the time being.

Further improvements both in HLT and in L1 are needed, which will be essential to continue low-multiplicity physics like dark sector physics.

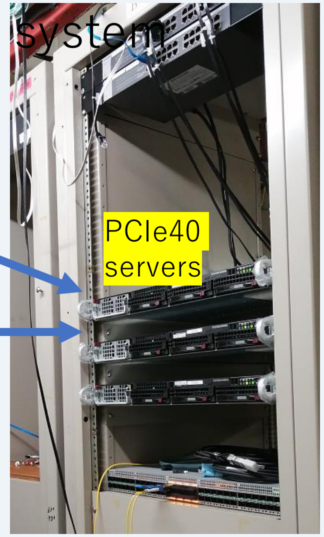
Upgrade of readout (2017-2023)

COPPER system



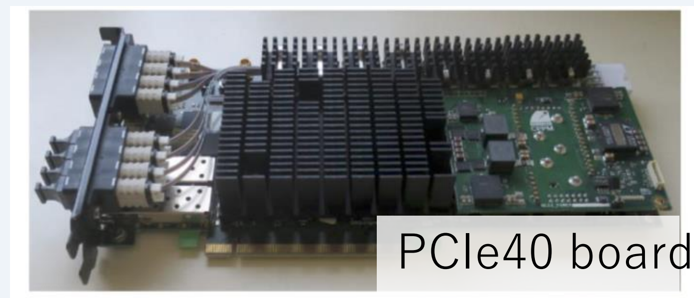
211 boards+43 PCs
Used since Belle era
Parts are discontinued

PCIe40 system



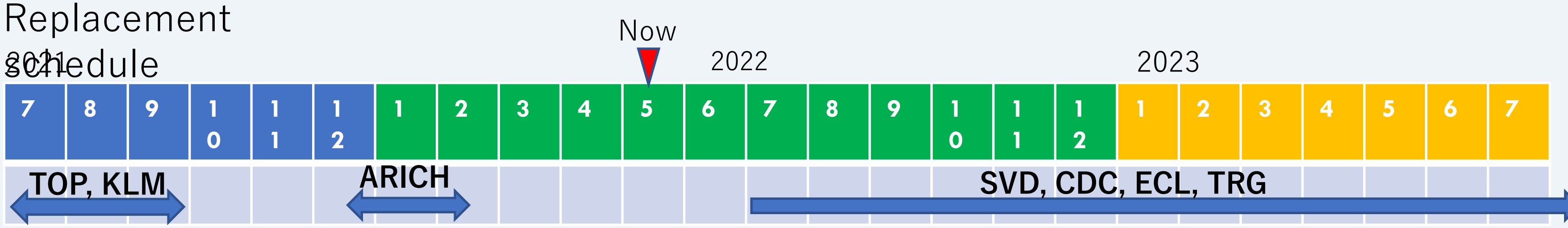
21 boards on 21 PCs
630MB/s/server
(a few times better)

DAQ upgrade activities started from 2017.
PCIe40 (used by ALICE and LHCb, proposed by IJCLab) has been selected in 2019.
Replacement work ongoing since 2021.



Upgrade for TOP, KLM and ARICH sub-systems have been completed successfully.
SVD, CDC, ECL and TRG will follow soon during LS1.

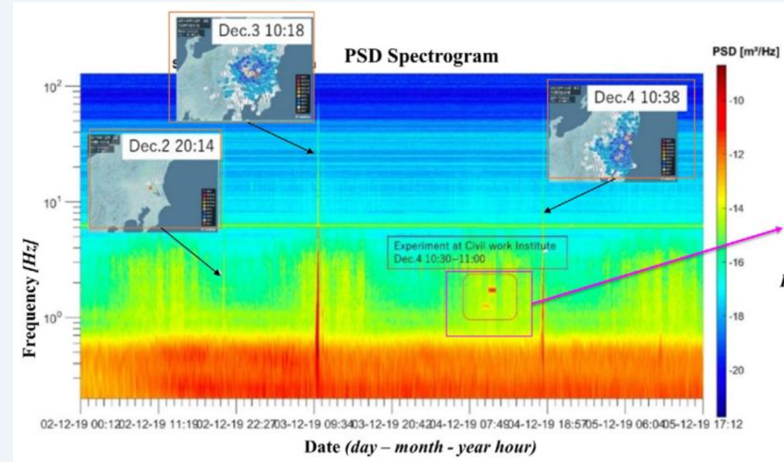
Replacement schedule



Vibration Monitoring

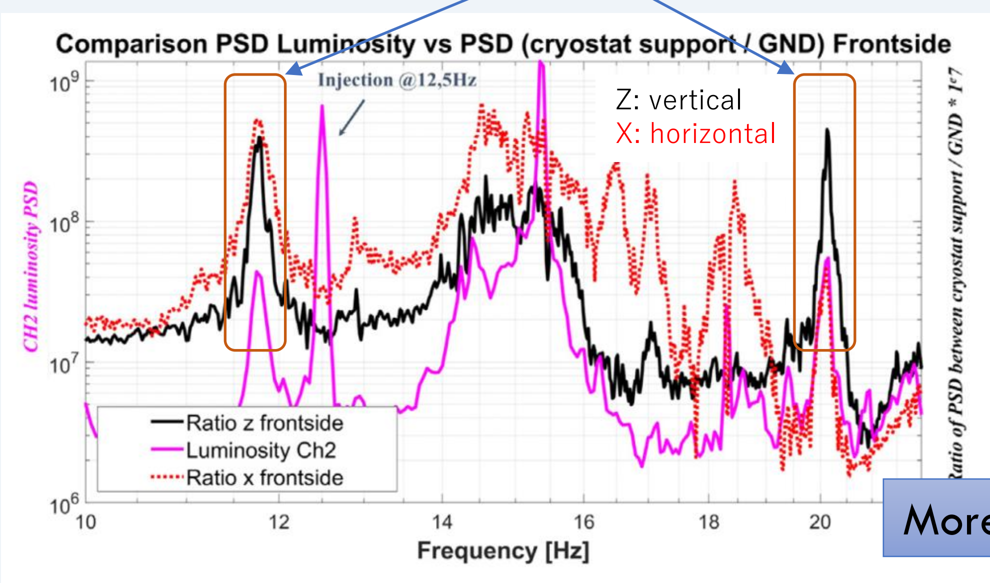
The LAPP Vibration Monitoring system detects

- earthquakes
- the effects of the experiment at the Civil Work Institute close to KEK
- people's activities (traffic for instance)



With the fast luminosity monitors,
we can associate vibration with luminosity degradation.

Characteristic vibrations of cryostat support table



- Important to understand vibrations to achieve higher luminosity, especially with smaller β_y^*.
- The data will be a useful input to the design of new IR and QCS

More ideas to improve our machine are welcome!

Operation Plan

- Our priority is to operate as many months as possible.
- On the other hand, we have scheduled long shutdowns in addition to annual short shutdowns.
  - Annual (typical): 3 months in summer, 1-2 months in winter; winter shutdown to be shortened (under discussion).
  - Long Shutdown 1 (LS1) from summer 2022 to fall 2023 (15 months)
    - Mainly to replace PXD (1 layer → 2 layers)
    - Also replace IP beam pipe, other aged detector components, …
    - Several improvements in machine components will also be made.
  - Long Shutdown 2 (LS2) from 2026 or later
    - Mainly to upgrade machine to improve instantaneous luminosity.
      - Main task of the International Task Force (since summer 2021).
    - Also to upgrade detectors.

Preparation for LS1

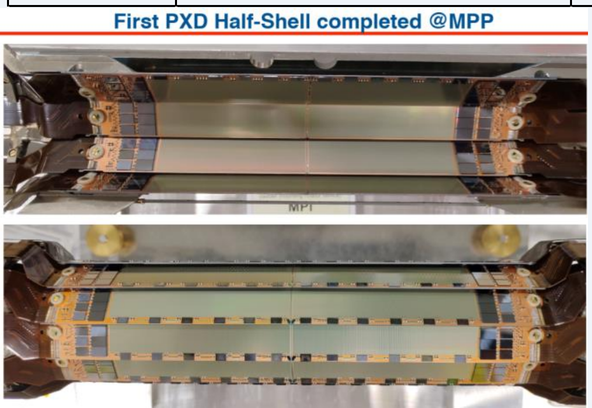
- **Mainly to replace PXD (1 layer → 2 layer)**
- **Modify IP beam pipe to reduce SR hits**

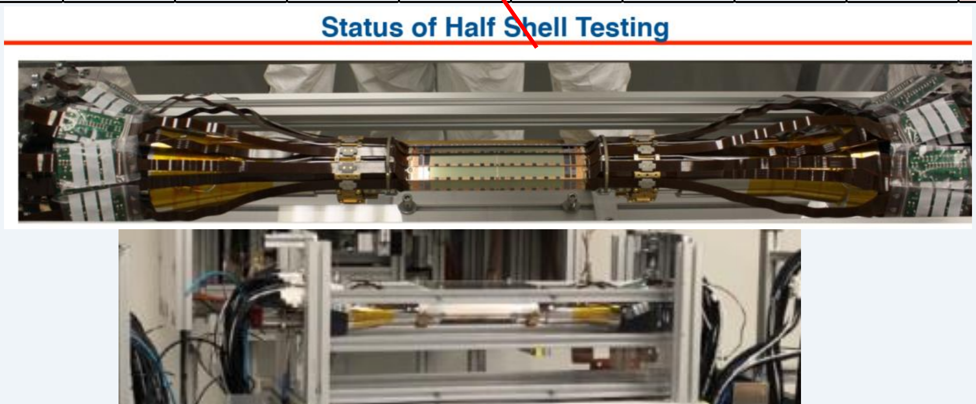
preparation on schedule.

Passed the test of gold sputtering (difficult step)

The last step of IP part "gold sputtering" ongoing this week.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IP beam pipe production	IP part production												
	IP part +crotch part												
	Beam pipe + HM shields												
PXD production	1st Half shell integration												
	1st Half shell test												
	2nd Half shell integration												
	2nd Half shell test												
	Ship to KEK(+contingency)												
	Diamond sensor mount												
	PXD mount on the IP pipe and test												

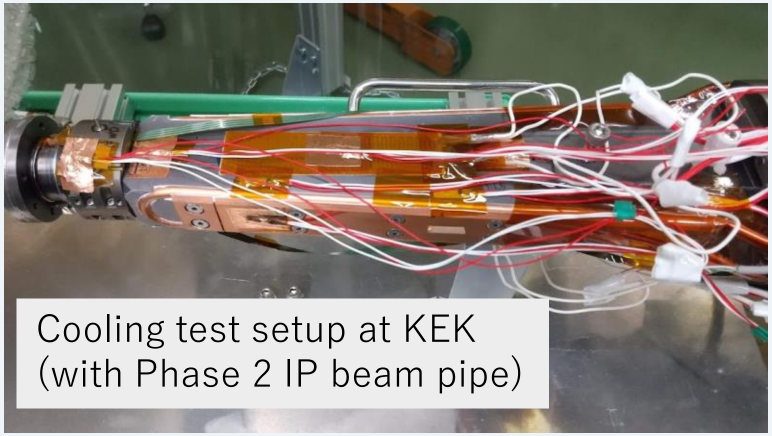


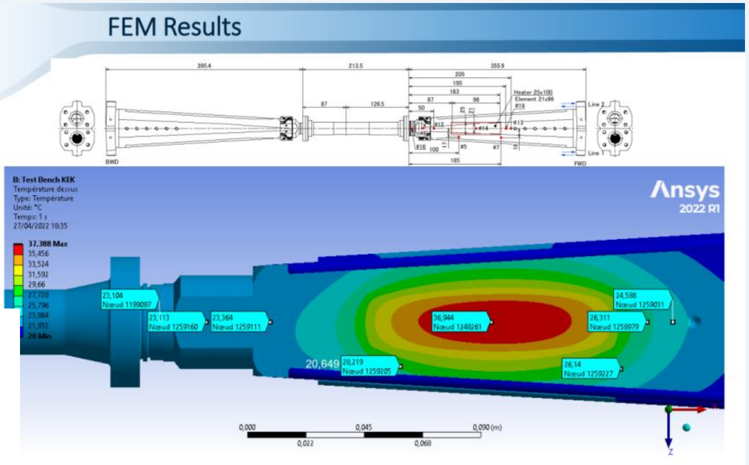


Another key development for LS1

Temperature rise ($\sim 38\,^{\circ}\mathrm{C}@1\,\mathrm{A}$) near the IP beam pipe has been a bit of concern.

- Wall current? SR? HOM heating?
- Design improvements to avoid SR fan
- A better cooling of beam pipe

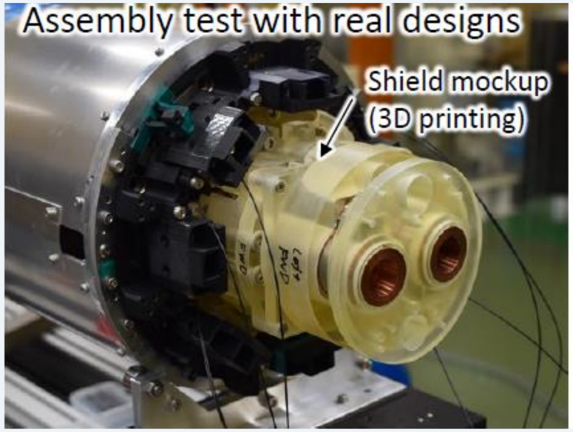





new thermal paste

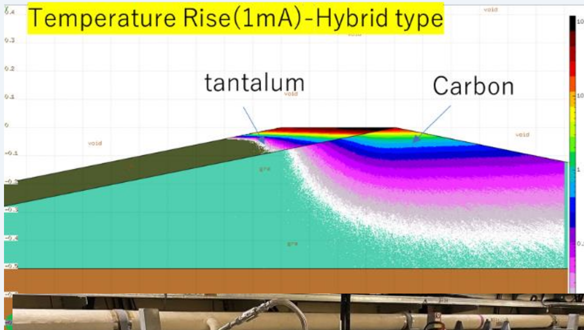
Remote collaboration so far.
On-site activity should start soon during LS1.

Machine modifications during LS1



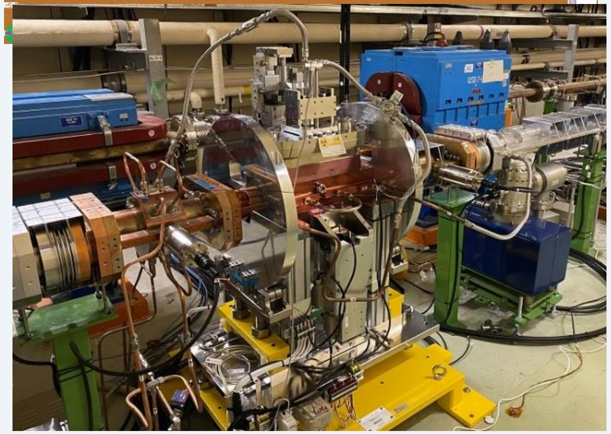
Modifications in hardware:

- Additional shields,
- New collimator head, robust against beam hits
- New collimation scheme “Non-linear collimator”, more free from beam instabilities (under discussion),
- More beam-loss monitors for better diagnostics,
- Enlarge physical aperture at injection point
- Better pulse-by-pulse beam control



Improvements in operation:

- Longer beam lifetime,
- Higher injection efficiency,
- Higher beam currents,
- Higher luminosity,
- Stable and safer operations



(We are still operating now but)
we are looking forward to resuming operation of improved machine.

Longer-term upgrade R&D

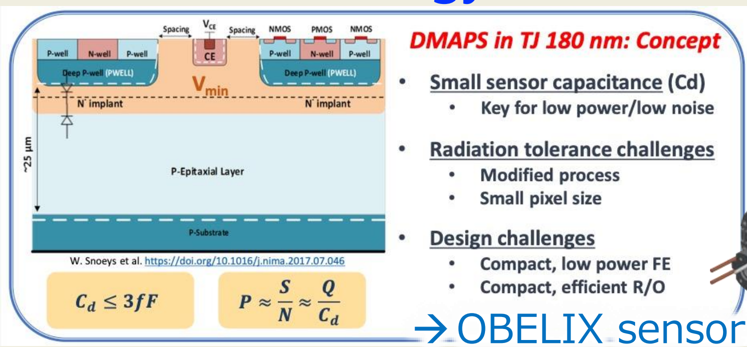
There will be another long shutdown (LS2, 2026 or later) for machine upgrade.
We are preparing for possible detector upgrade taking this opportunity.

EOI	Upgrade ideas scope and technology	Time scale
RMBA	Improved diamond readout electronics. Integration with SKB abort system	< 2026
DEPFETs	Adiabatically improved replacement of existing system	2026
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	2026
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	2026
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	2026
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< 2026
TOP	Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option	2026 and later
ECL	Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.	> 2026
KLM	Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF	2026
STOPGAP	Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger	> 2026

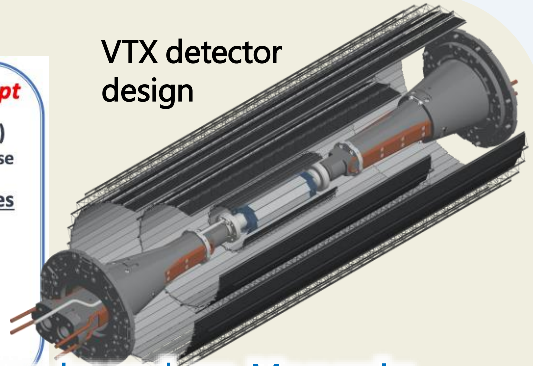
Belle II VXD upgrade project

VXD upgrade for better beam BG capability and better physics performance
R&Ds for the sensor technologies are ongoing
French contributions to CMOS and SOI development

CMOS technology

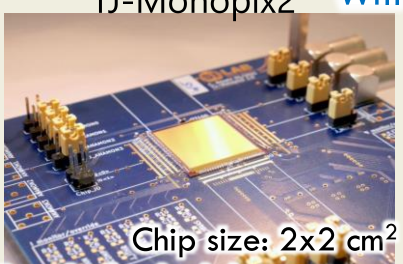


VTX detector design



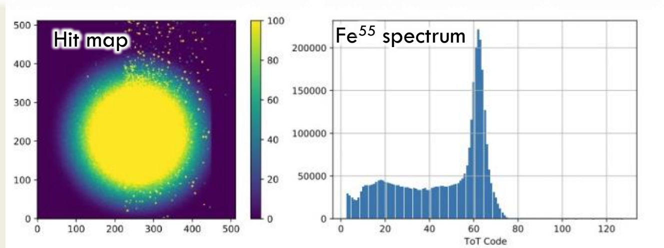
→ OBELIX sensor based on Monopix will be fabricated for VTX in mid-2022

TJ-Monopix2



Chip size: 2x2 cm^2

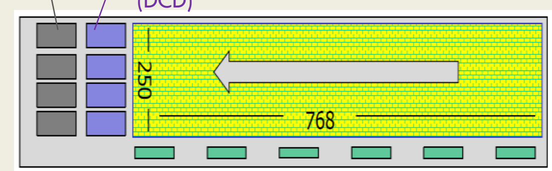
Proof-of-principle prototype



Analysis of beam test data ongoing

IPHC, CMMP-Marseille, IJCLab,
HEPHY, Bonn, Dortmund, Goettingen, KIT,
Bergamo, Pavia, Pisa,
IFIC, …

DEPFET technology



- Gain increase with shorter FET length L

$$g = \frac{dI_{drain}}{dQ} \propto \sqrt{\frac{t_{ox}}{L^3}}$$

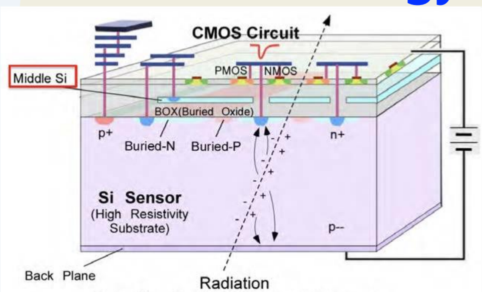
higher amplification in pixel → thinner oxide
→ improved radiation tolerance

- Improve ASIC for a faster integration speed

MPI, KIT

Belle II VXD upgrade project

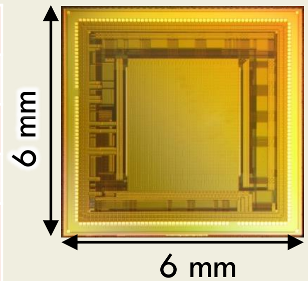
SOI technology



DuTiP 1st prototype sensor

Chip size	6x6 mm^2
Pixel size	45x45 μm^2
Thickness	50 $\mu m^{(*)}$
Clock	15.9 MHz (63ns)
Expected noise	about 86 e^-

(*) chip to be thinned to 50um in future

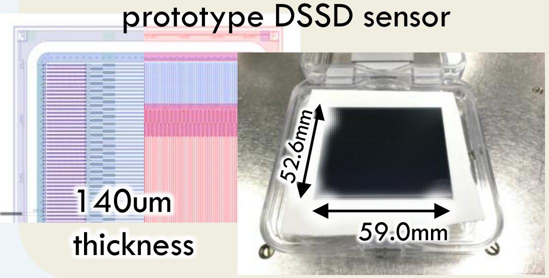


In the prototype, an analog circuit and a primary in-pixel digital circuit are implemented.
Prototype performance evaluation is ongoing.

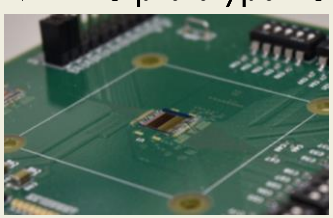
KEK, U-Tokyo, IPHC, …

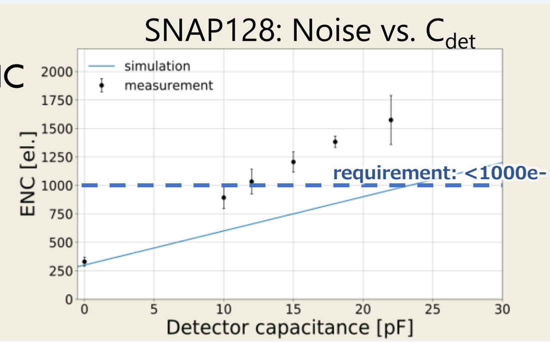
Thin DSSD technology

prototype DSSD sensor



SNAP128 prototype ASIC

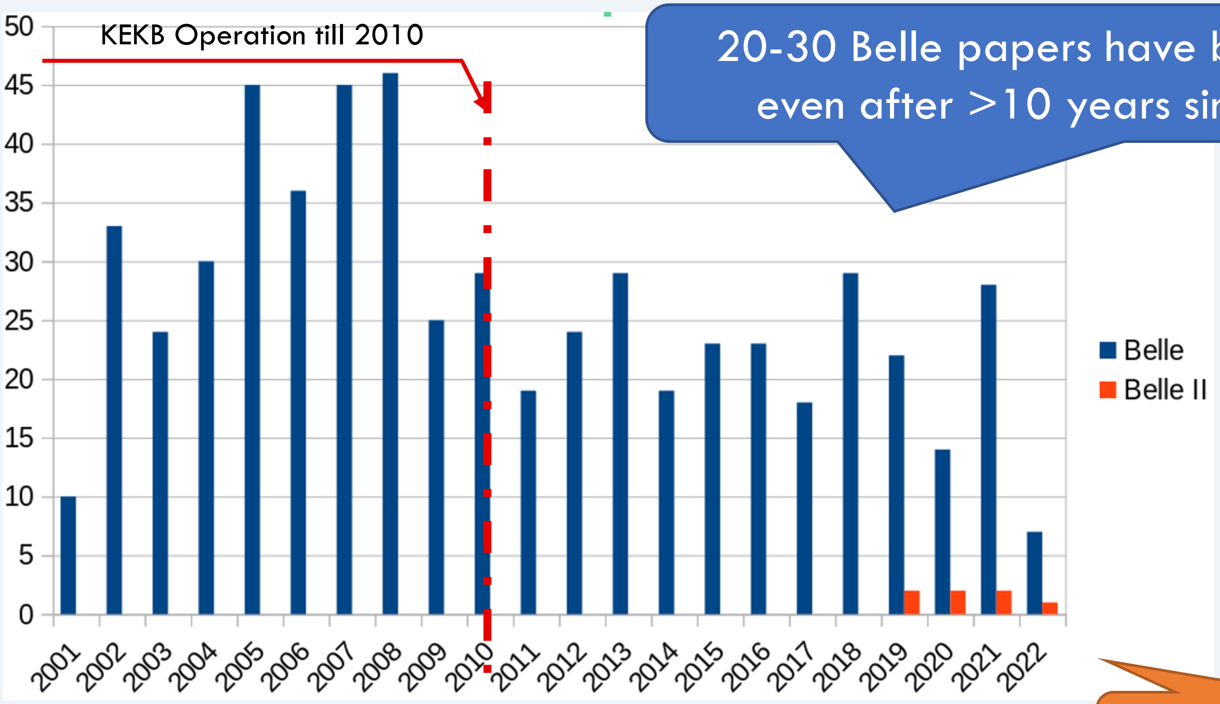




Prototype sensor and ASIC were produced. Reasonable sensor characteristics are confirmed. ASIC design is being optimized for better performance.

KEK, IPMU, U-Tokyo, TIFR, …

Physics analyses



20-30 Belle papers have been published every year even after >10 years since the end of operation

Belle II

Publications from Belle II

VOLUME 86, NUMBER 12 PHYSICAL REVIEW LETTERS 19 MARCH 2001

Measurement of the CP Violation Parameter $\sin 2\phi_1$ in B_d^0 Meson Decays

We present a measurement of the standard model CP violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a 10.5 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. One neutral B meson is reconstructed in the $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, or $J/\psi \pi^0$ CP-eigenstate decay channel and the flavor of the accompanying B meson is identified from its charged particle decay products. From the asymmetry in the distribution of the time interval between the two B-meson decay points, we determine $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$.

The systematic errors are dominated by the uncertainties in w_l ($^{+0.05}_{-0.07}$) and the $J/\psi K_L$ background (± 0.05). Separate fits to the $\xi_f = -1$ and $\xi_f = +1$ event samples give $0.82^{+0.36}_{-0.41}$ and $0.10^{+0.57}_{-0.60}$, respectively [12]. Figure 3(a) shows $-2\ln(L/L_{\max})$ as a function of $\sin 2\phi_1$ for the $\xi_f = -1$ and $\xi_f = +1$ modes separately and for both modes combined. Figure 3(b) shows the asymmetry obtained by performing the fit to events in Δt bins separately, to-

From the asymmetry in the distribution of the time
determine $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$.

Belle II

BELLE2-NOTE-PL-2020-011
DRAFT Version 1.0
July 27, 2020

Prompt measurements of time-dependent CP-violation and mixing

The Belle II Collaboration

Abstract

This document presents the approved plots corresponding to the prompt mixing and time dependent CP violation measurements using 34.6 fb^{-1} of data collected in 2019 and 2020. For more detail, see B2-NOTE-PH-2020-038 and B2-NOTE-PH-2020-027.

The wrong tag fraction extracted from the mixing fit is used as an input for this fit. Fro the fit, the value obtained for the time-dependent CP-violation parameter $S_f \approx \sin 2\phi_1$ is

$$S_f = 0.55 \pm 0.21\ (\text{stat.}) \pm 0.04\ (\text{syst.}),$$

which is in agreement with the world average $S_f \approx 0.691 \pm 0.017$ and is 2.71 standar deviations away from 0 (accounting for the statistical uncertainty only).

Doing better analyses than early Belle, but threshold is much higher to publish to journal.

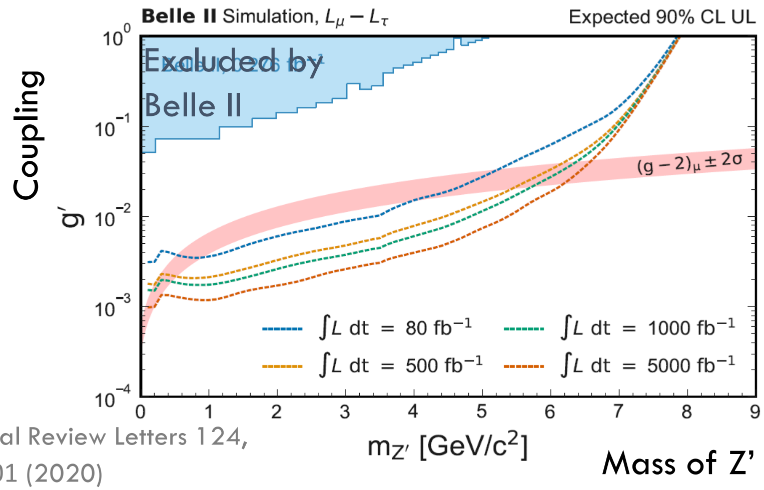
Several new results have been published

- thanks to better trigger and detector performance
- thanks to better analysis methods and
- by combining Belle and Belle II data

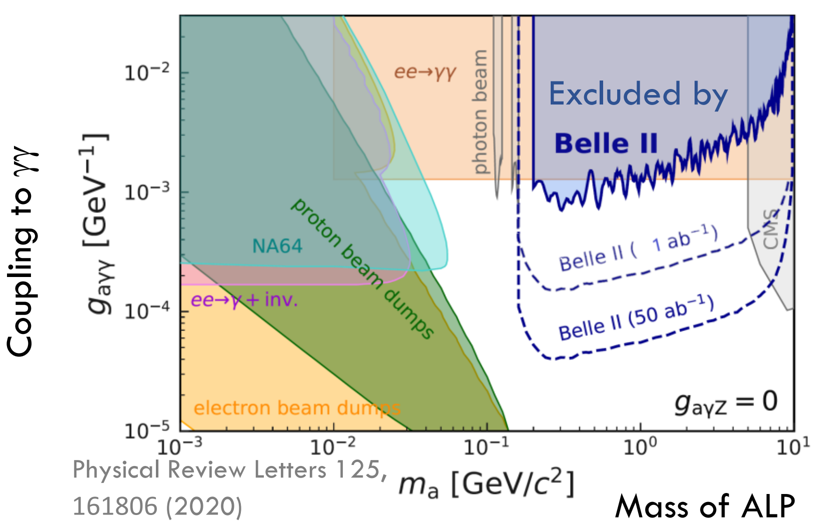
Good trigger and good detector

Searches in Dark Sector

Belle II L1 trigger is capable to take low-multiplicity events.



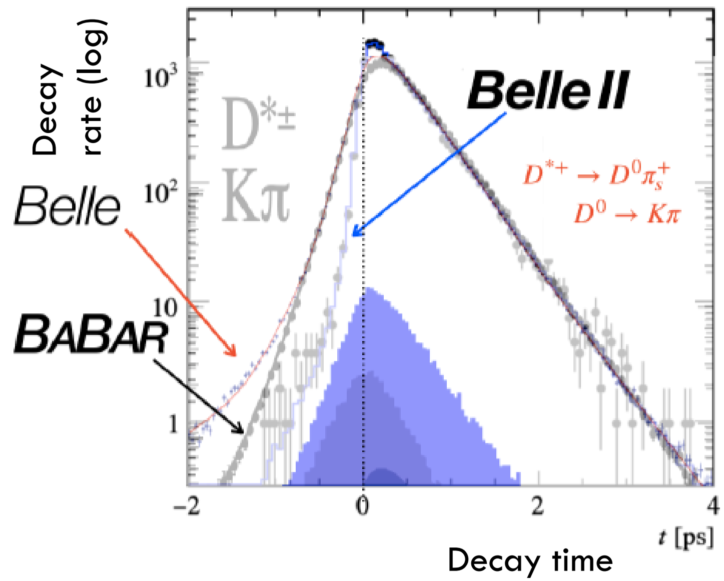
Physical Review Letters 124, 141801 (2020)



Physical Review Letters 125, 161806 (2020)

Excellent Vertex Resolution

Pixel sensors at only 14mm away from IP, well aligned, give high precision measurement of particle decay positions.



Physical Review Letters 127, 211801 (2021)

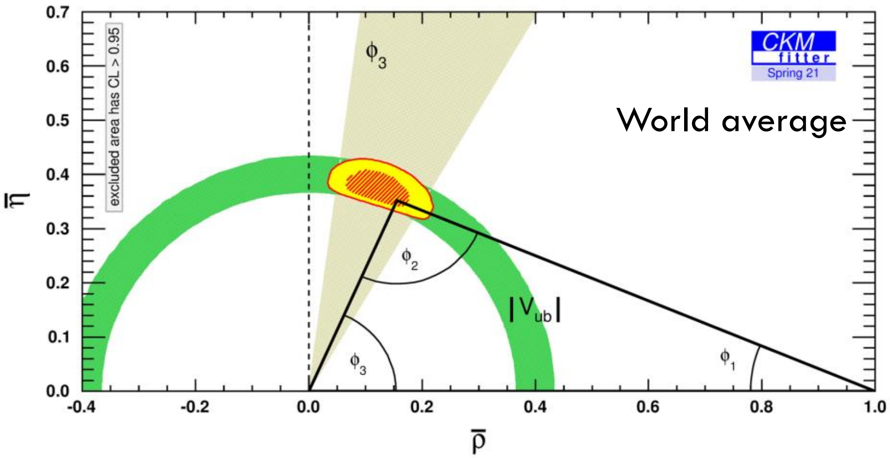
New analysis methods

Angle measurement

Combined analysis of Belle (711/fb) and Belle II (128/fb) gives much better result than simple increase in data size. (~35% better signal efficiency)

$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$

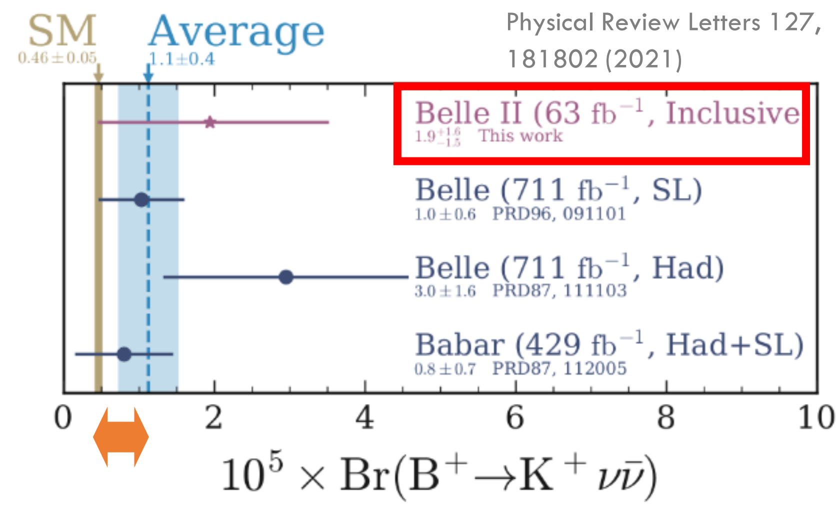
(was $\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$)



Journal of High Energy Physics 2022, 63 (2022)

NP search

Physical Review Letters 127, 181802 (2021)

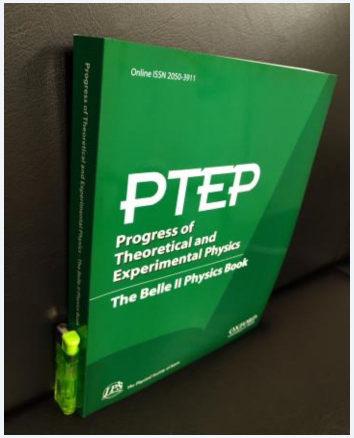


Belle II (63/fb) is already comparable to Belle (711/fb, hadronic tag) result

More to come with more data!

Physics potential summarized in ~700 pages of Physics Book

https://arxiv.org/abs/1808.10567 (E. Kou et al.)



Summary

- SuperKEKB and Belle II has started "phase 3" physics operations since 2019. Eagerly taking data despite COVID-19 pandemic.
- New "nano-beam" collision scheme is working well. $L \sim 4.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been achieved (with lower beam current), a new W.R.
- New results have been published thanks to good detectors, good trigger, and good analysis methods. More to come with more data.
- We appreciate TYL for the support to establish and develop collaborations between French and Japanese researchers. More in-person, on-site collaborations are wanted.

Related TYL Projects

TYL projects related to Belle II
http://fjppl.in2p3.fr/cgi-bin/twiki.source/bin/view/FJPPL/FJPPLprojects

- FLAV_03: E. Kou and T. Kaneko (theoretical aspects of B measurements, at LHCb and Belle II).
- FLAV_05: J. Baudot and K. Miyabayashi (TDCPV measurements in Belle II, focus on B->K0S nπ γ)*

- D_RD_24: J. Baudot and T. Tsuboyama (Monolithic pixel R&D for an upgraded Belle II inner tracker)
- D_RD_26: J. Bonis and S. Tanaka (Mechanics of the Belle II IP region)

- A_RD_13: I. Chaikovska and Y. Enomoto (high intensity positron sources for circular colliders, SuperKEKB and beyond, FCC-ee) *
- A_RD_14: L. Brunetti and M. Mazusawa (influence of vibrations on the SuperKEKB collider performance)

* Till 2021