The Belle II upgrade program

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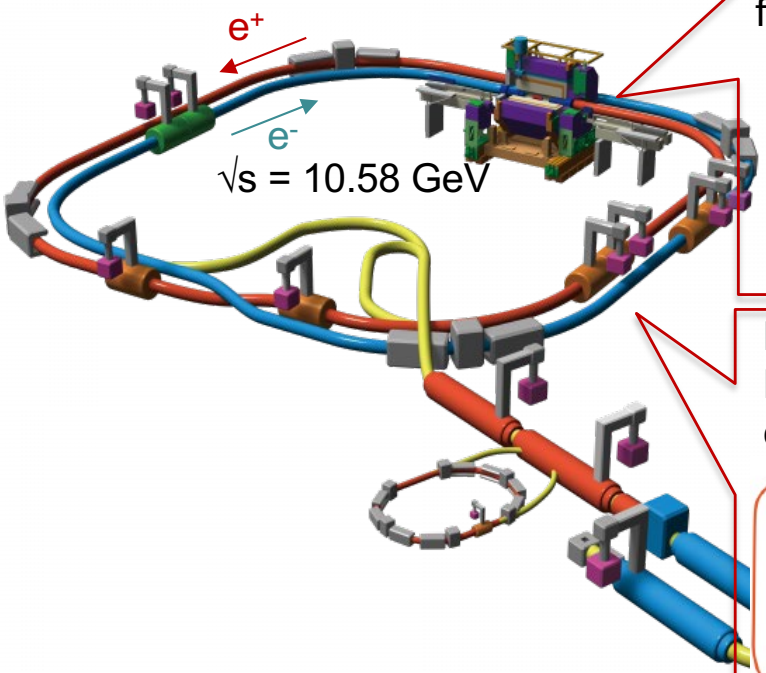
on behalf of the Belle II collaboration

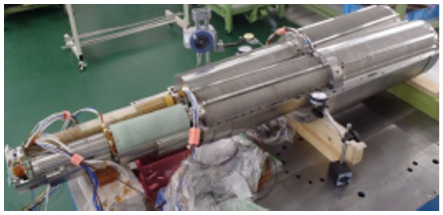
Outline

- SuperKEKB accelerator
- Belle II detector
- Achieved and target luminosities
- Long shutdown 1
- Run 2024
- 2025 plans
- SuperKEKB and Belle II near-term upgrades
- SuperKEKB and Belle II longer-term upgrades
- Summary

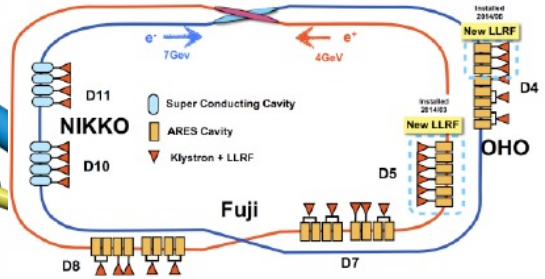
KEKB upgraded to SuperKEKB



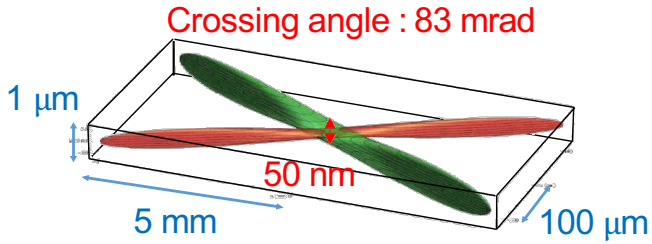
New QCS final focus magnets for nano-beam scheme



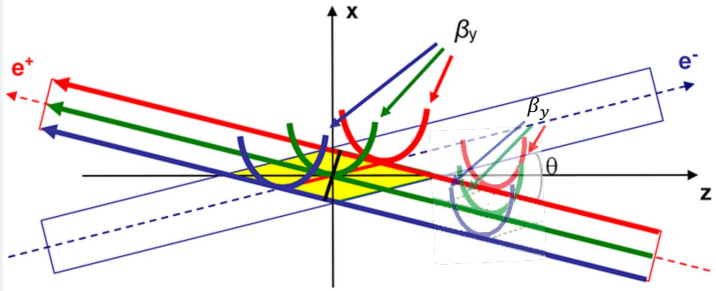
New RF cavities and modified RF system for high beam current operation



SuperKEKB



Crab waist scheme

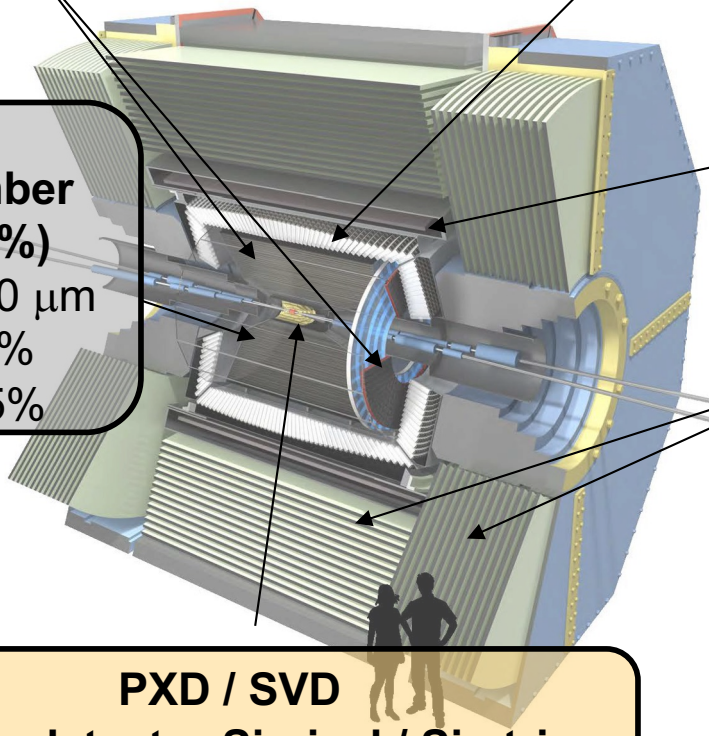


	KEKB	SuperKEKB 2024/12/27	SuperKEKB Target
Luminosity [$\times 10^{34}$ cm^{-2}s^{-1}]	2.1	5.1	60
Integrated luminosity (ab^{-1})	1.0	0.57	50
β_y^*	5.9	1.0	0.3
I_{LER} / I_{HER} (A)	1.64 / 1.19	1.63 / 1.26	3.6 / 2.6

Current Belle II detector

TOP / ARICH
Particle Identification
Barrel (quarz) / Forward (aerogel)
K ID-eff ~90% , π fake rate 10%

ECL
Electromagnetic Calorimeter
CsI(Tl) crystals
σ(E)/E 4%-1.6%



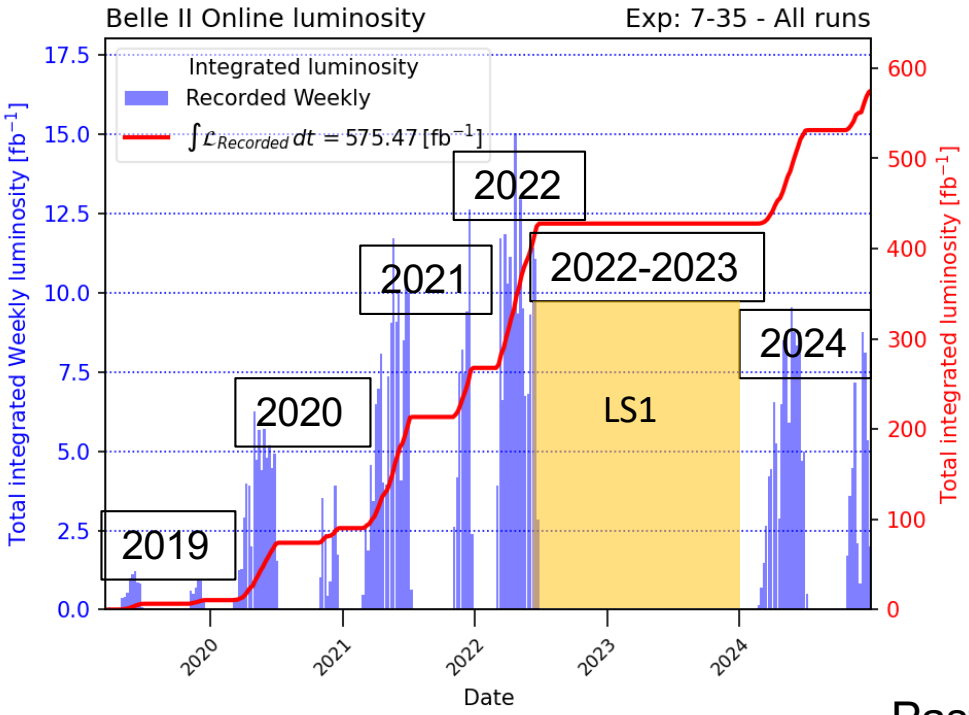
Supercond. solenoid
1.5 T

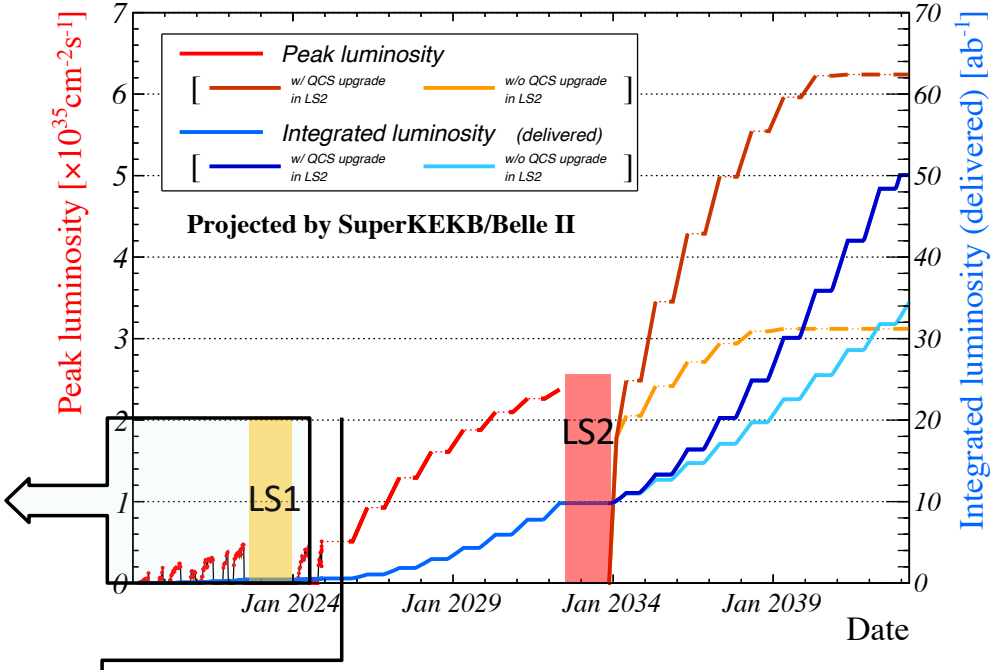
CDC
Central drift chamber
He(50%)-C_2H_6(50%)
spatial resolution 100 μm
p_T resolution 0.4 %
dE/dx resolution 5%

KLM
K_L and muon detector
Barrel (RPC – scintillators)
Endcap (scintillators)
μ ID-eff ~90%

PXD / SVD
Vertex detector Si-pixel / Si-strip
vertex resolution 15 μm

Achieved and target luminosities



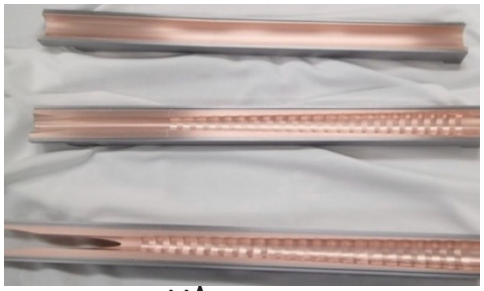


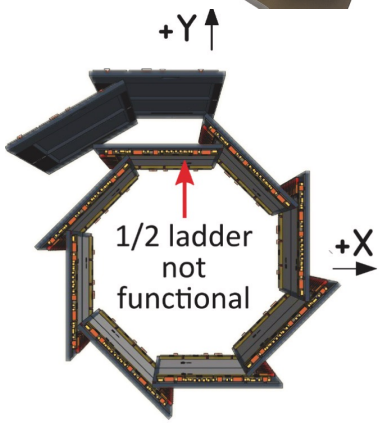
Past ← | → Future

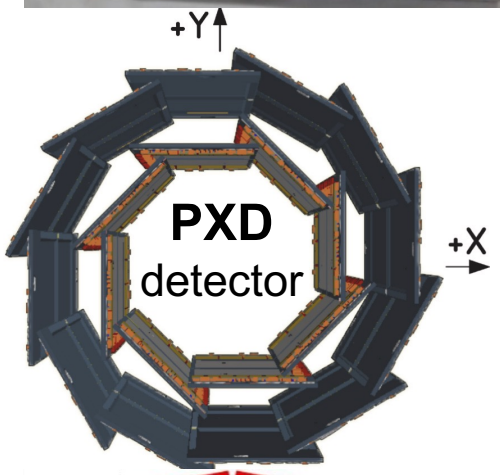
2019-2022	2022-2023	2024	PRESENT	2025-2032	2032-2033	2034-2042
Run 1	LS1	Run 2		Run 2	LS2	Run 3
4.7×10^{34} ($cm^{-2}s^{-1}$)		5.1×10^{34} ($cm^{-2}s^{-1}$)		2.4×10^{35} ($cm^{-2}s^{-1}$)		6.0×10^{35} ($cm^{-2}s^{-1}$)
0.43 (ab^{-1})		0.57 (ab^{-1})		10 (ab^{-1})		50 (ab^{-1})

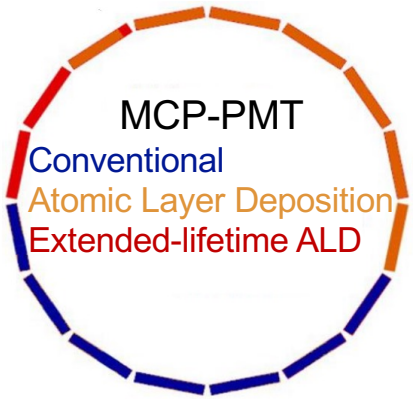
Long shutdown 1

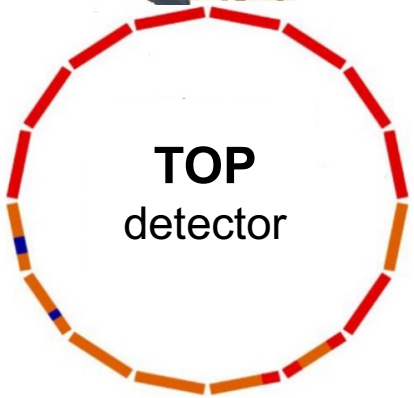
Before LS1 After LS1











Accelerator upgrade

- **IP Beam pipe replacement**
  New beam pipe design to reduce the synchrotron radiation from the accelerator near IP
- **Beam abort & monitoring**
  Additional diamonds to protect from beam loss
- **RF cavity, Collimator head, etc.**
  To improve beam lifetime and accelerator stability

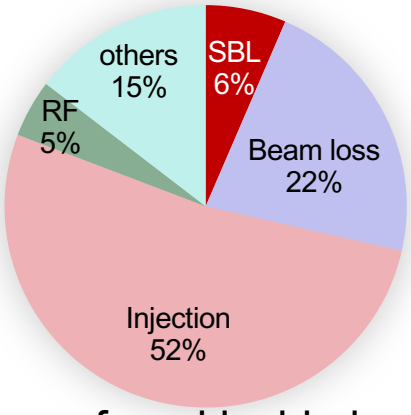
Detector upgrade

- **PXD detector**
  Full installation, 8 inner and 12 outer layers
- **TOP detector**
  Photodetectors with short lifetime replaced
- **All detectors**
  Repaired the not working electronics channels

Run2024

Peak luminosity record 5.1 x 10^{34} $cm^{-2}s^{-1}$: I_{LER} = 1.63 A, I_{HER} = 1.26 A, β_y^*=1, n_b = 2346

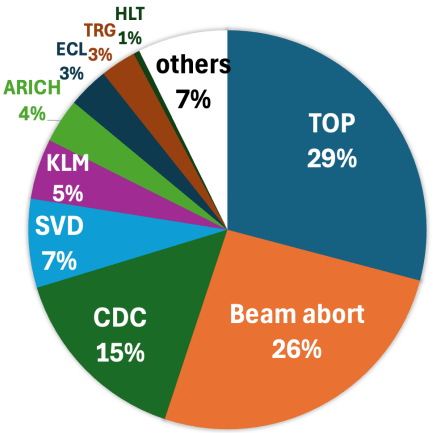
Beam aborts



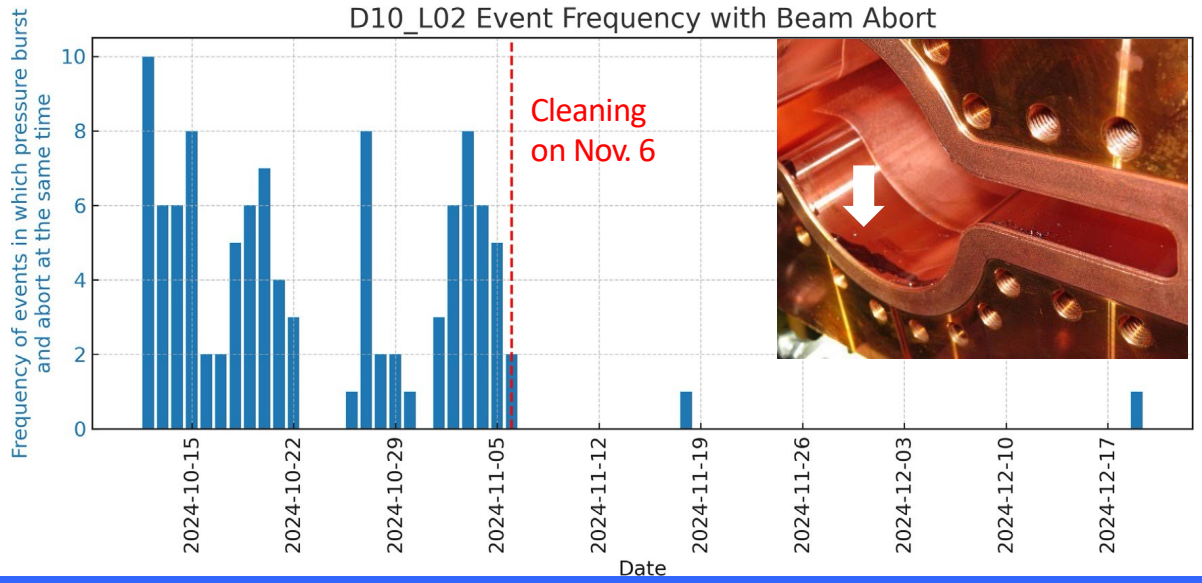
run2024 a/b/c

4257 beam aborts
in 5592 hours

Run stop



Black stains were found inside beam pipe flanges, probably caused by VACSEAL residual (high vacuum sealant).
Almost no SBL has been observed in the cleaned sectors.



PXD: 2% damaged by SBL, temporarily turned off.

TOP: update of firmware and software to reduce DAQ errors.

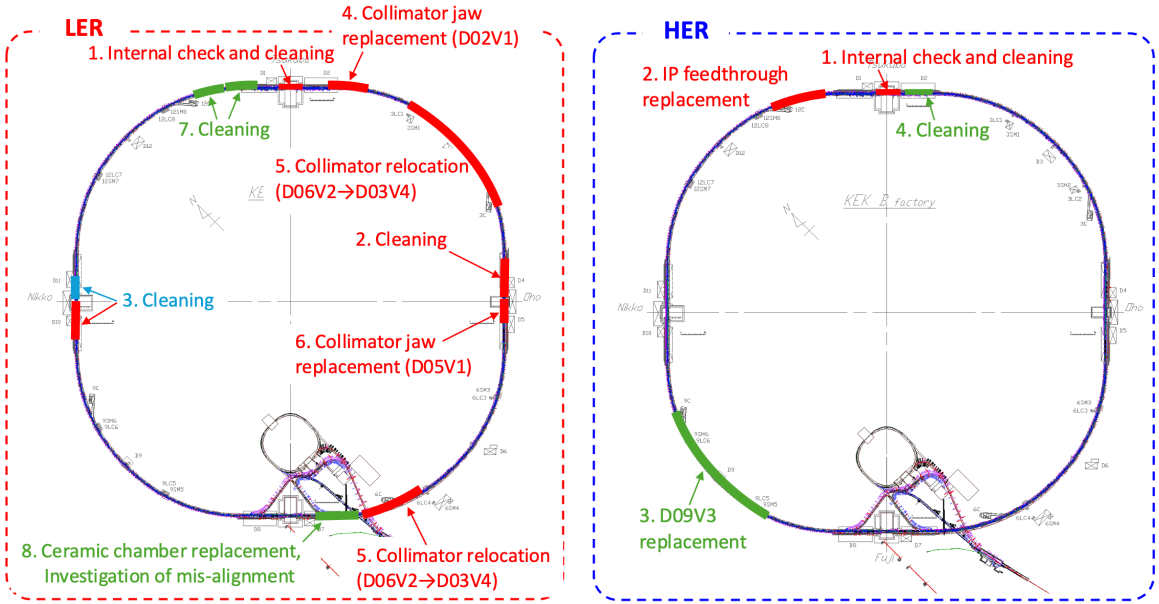
CDC: lower voltage, more precise O_2 and H_2O control.

2025 plans

Long break from January 2025 to October 2025, accelerator will restart in November 2025 (run2025c).

Accelerator

- beampipe cleaning
- collimator relocation
- faster aborts



Detector

- Firmware and software update (SVD, CDC, TOP, DAQ) to reduce downtime related to single-event upset (SEU)

Accelerator stability, SBL detection, beam abort speed-up need to be monitored before making plans for 2026.

SuperKEKB near-term upgrade

Belle II near-term and and longer-term upgrades are reported in the Conceptual Design Report (CDR) published in June 2024: [arXiv:2406.19421v2]

From 5x10^{34} to 1x10^{35}

beam currents +20% , β_y^* -20%

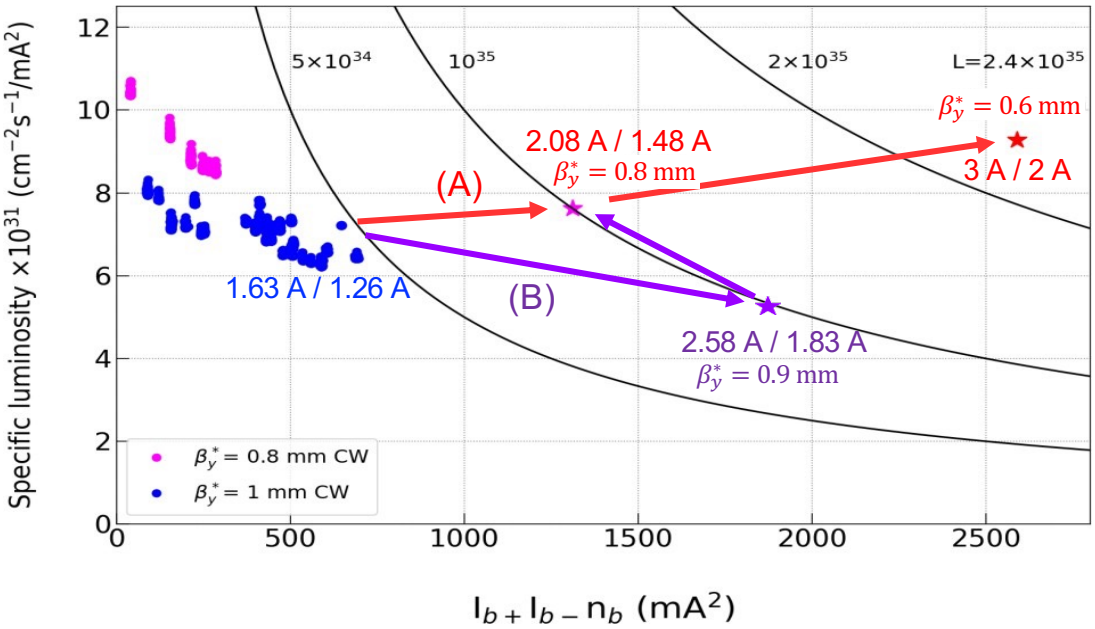
- Sextupole magnets optimization
- Off-momentum optics tuning

From 1x10^{35} to 2.4x10^{35}

beam currents +45% , β_y^* -20% additional

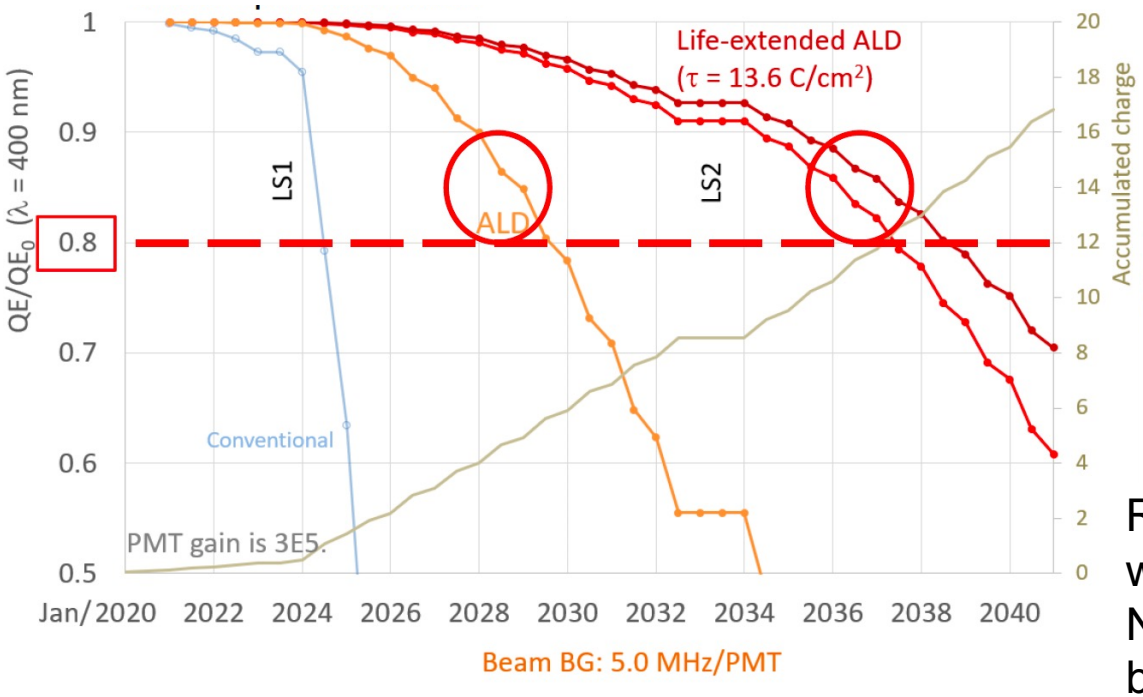
- Improve prediction accuracy of Beam-Beam simulation

$$L_{sp} = \frac{L}{(I_{b+})(I_{b-})(n_b)}$$

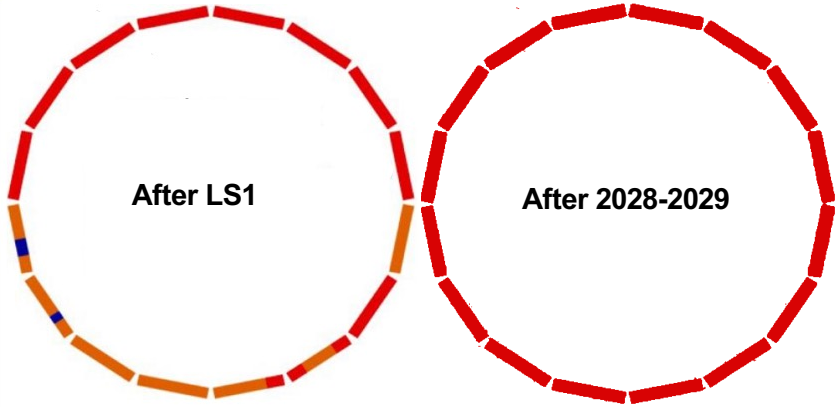


Belle II near-term upgrade

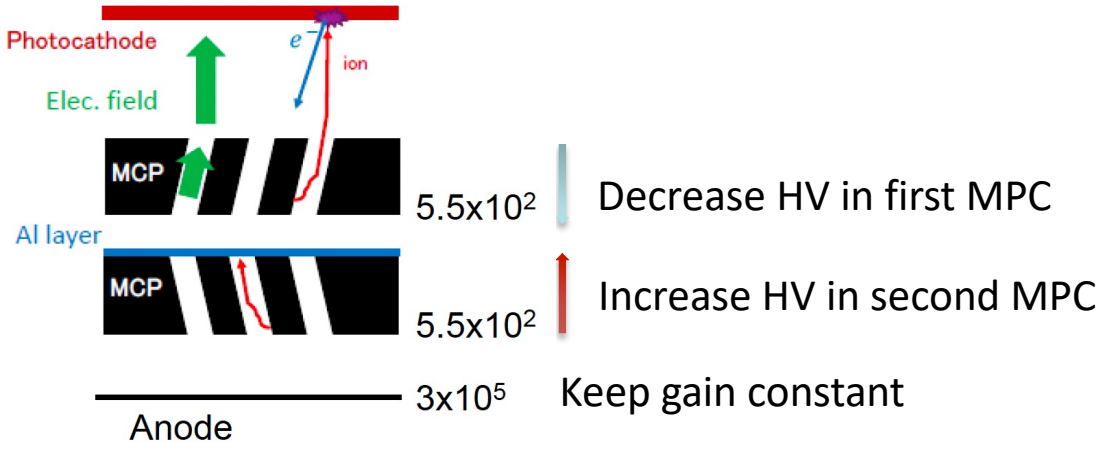
TOP MCP-PMT photodetectors lifetimes



MCP-PMT photodetectors upgrades



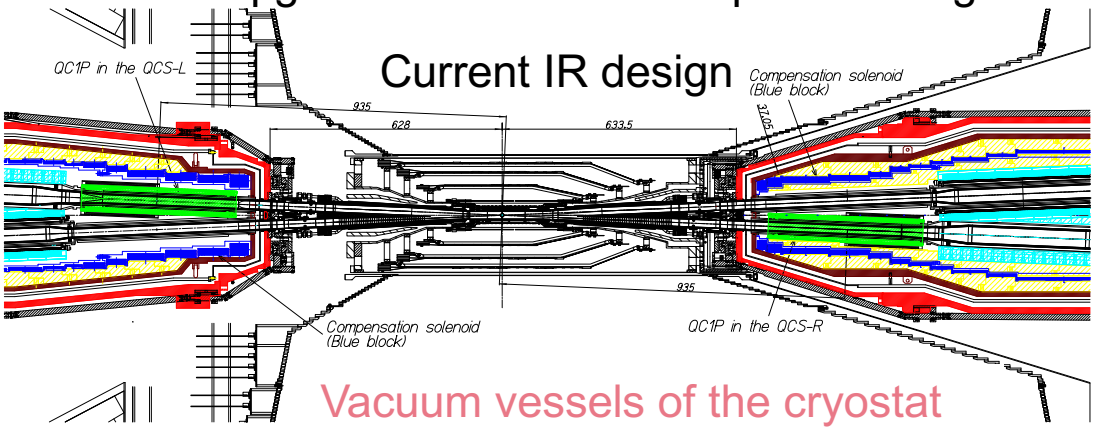
Replacement of short lifetime MCP-PMTs will be required in 2028-2029.
New 220 life-extended ALD MCP-PMT will be ready to be installed within 2026.



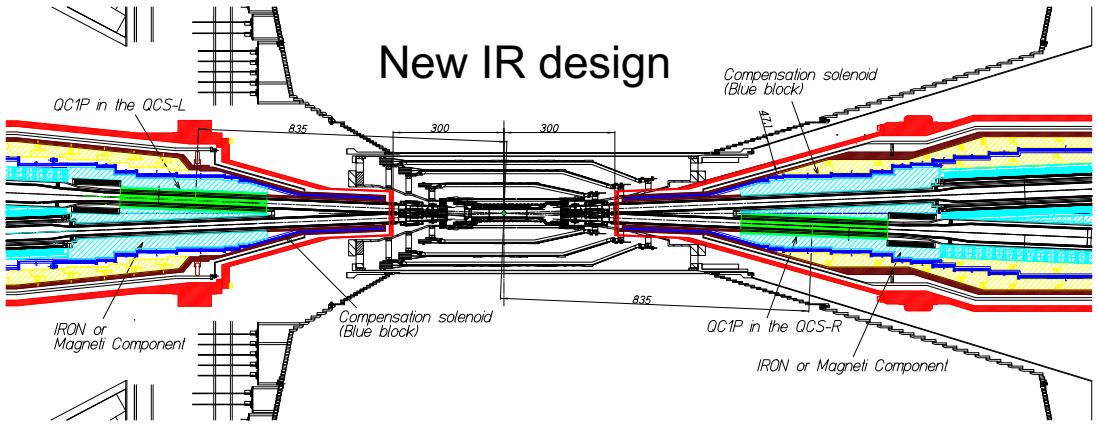
New asymmetric HV divider is under test
It should improve photodetectors lifetime.
The goal is to complete ongoing tests within 2026 and replace all HV divider boards during the next photodetectors upgrade.

SuperKEKB upgrade during LS2

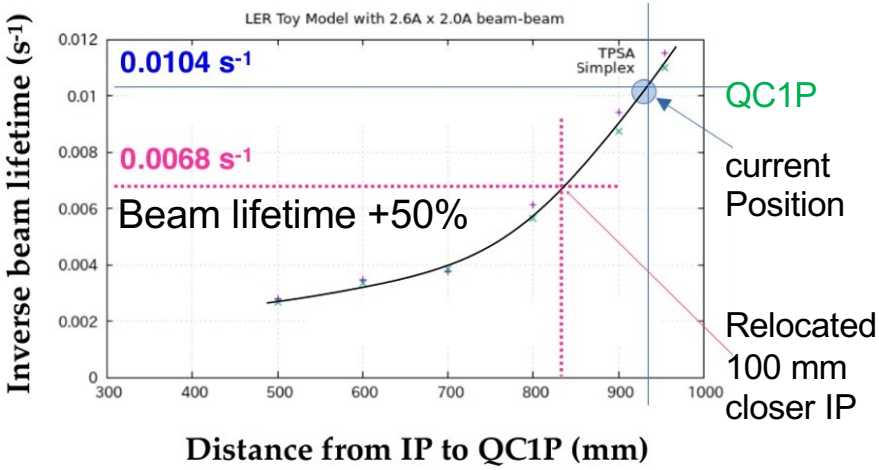
Goal LS2: upgrade the accelerator to reach luminosity of 6.0×10^{35} cm^{-2}s^{-1} with stable beams, upgrade the detector to improve background immunity and physics performance.

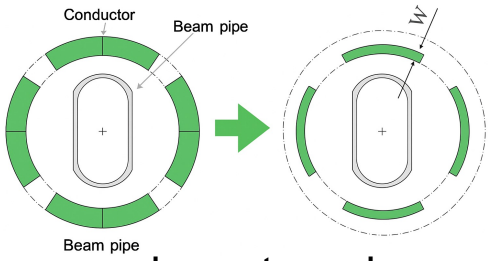


Vacuum vessels of the cryostat
Liquid helium vessels
Tungsten radiation shields
Anti-solenoid coils
Magnetic yokes/shields
QC1P magnets



New superconductive final-focus quadrupole magnets (QCS)





QC1P becomes closer to e^- beam pipe
⇒ need thinner conductors ⇒ J doubled
Study of the Nb3Sn cable having higher T_C and J_C w.r.t. NbTi

Belle II backgrounds

Before LS2

Expected backgrounds for L = 2.8 x 10^{35} $cm^{-2}s^{-1}$
(corrected for average Data2022/MC bkg)
have large safety factors (Limit/Expected ratio) :

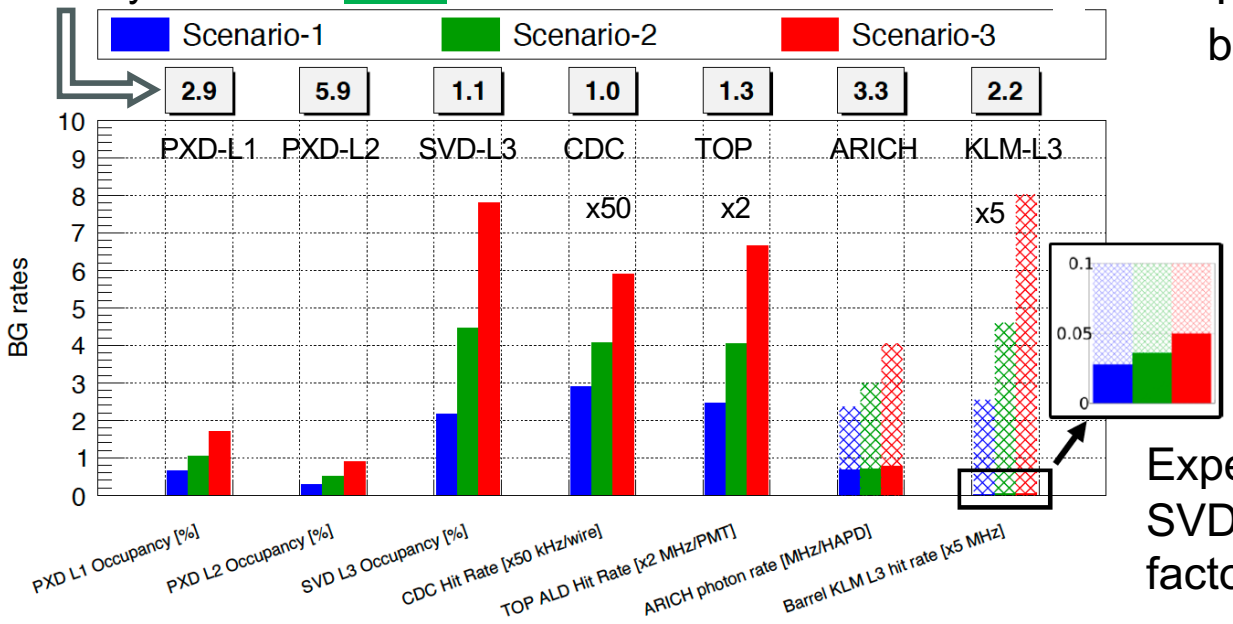
	Expected	Limit	Safety Factor
SVD L3 (occupancy %)	1.1	4.7	4.3
CDC (kHz/wire)	69	200	2.9

Background component	Average Data/MC
Beam-gas LER	3.46
Beam-gas HER	0.63
Touschek LER	3.44
Touschek HER	0.18
Luminosity	0.81

Safety factors for different sub-detectors from ~3 to ~20

After LS2

safety factors for Sc.-2.



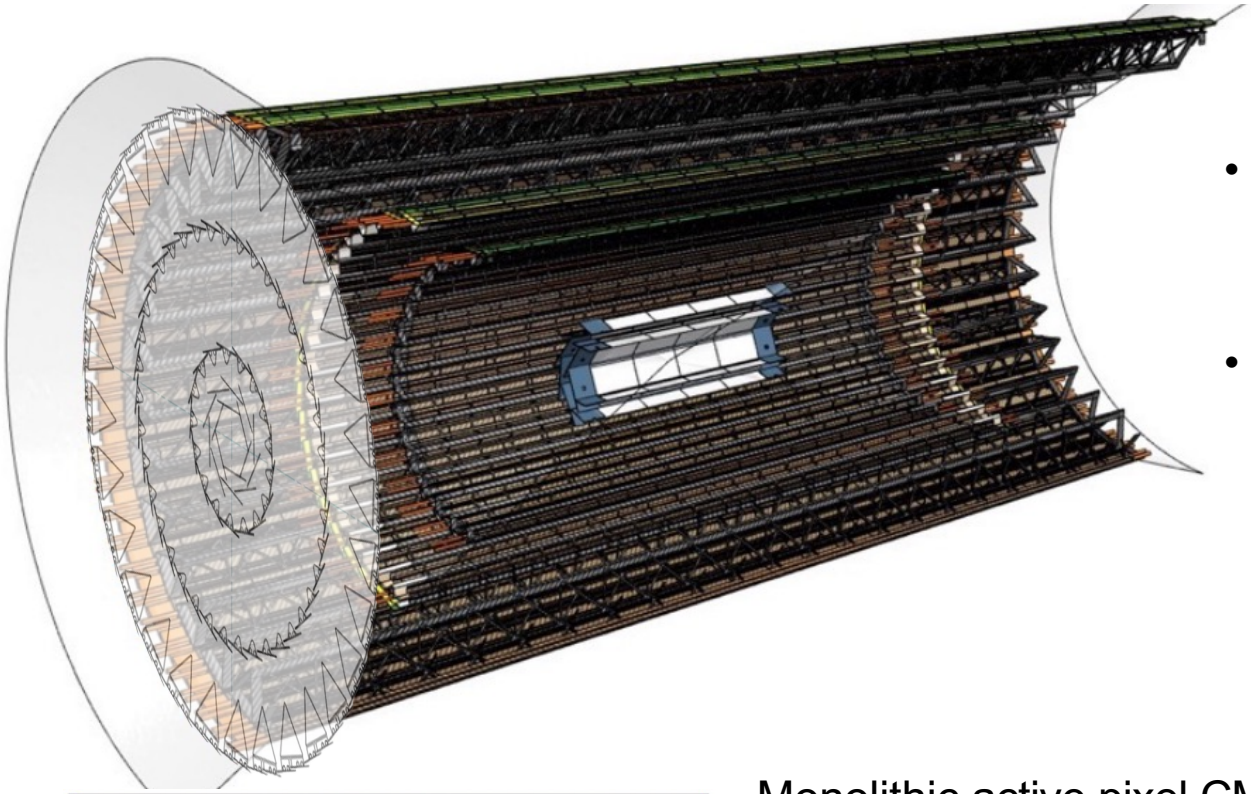
Three background scenarios have been considered after LS2:

Background component	Single-beam scaling Sc.-1	Sc.-2	Sc.-3
Beam-gas LER	2	5	10
Beam-gas HER	2	5	10
Touschek LER	2	5	10
Touschek HER	2	5	10
Luminosity	1	1	1

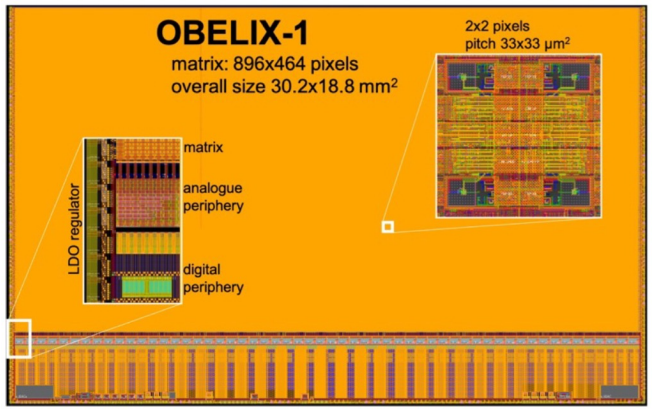
Expected backgrounds for not-upgraded SVD, CDC and TOP have limited safety factors @ L = 6.0 x 10^{35} $cm^{-2}s^{-1}$

Belle II vertex upgrade

PXD (pixel 2 layers) + **SVD** (double side silicon strip 4 layers) → **VTX** (pixel 5/6 layers)



- New geometry to accommodate new IR design.
- Higher max hit rate:
  120 MHz/cm^2 → 600 MHz/cm^2
  (short bursts 0.5 μs).



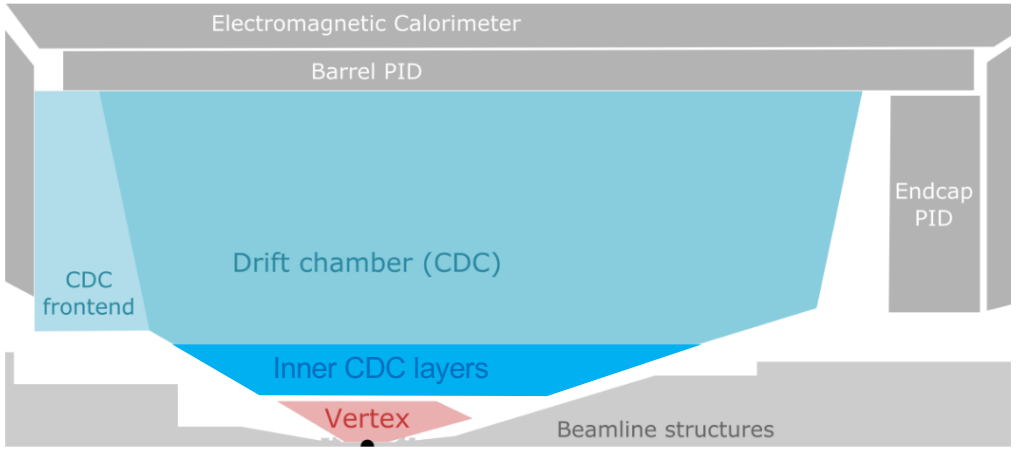
Monolithic active pixel CMOS **OBELIX** sensor:

Optimized **BEL**LE II monolithic active p**ix**el sensor based on TJ-Monopix2, developed for the ATLAS Inner Tracker (ITk) upgrade, 33 μm^2 pitch , 15 μm resolution.

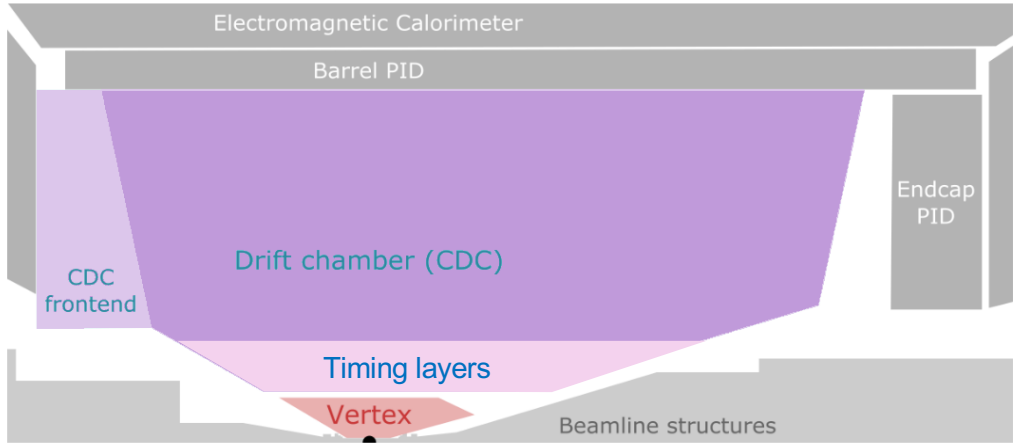
The goal is to produce OBELIX-1 prototype within Q2 2026, to be tested within Q1 2028.

Belle II tracking upgrade

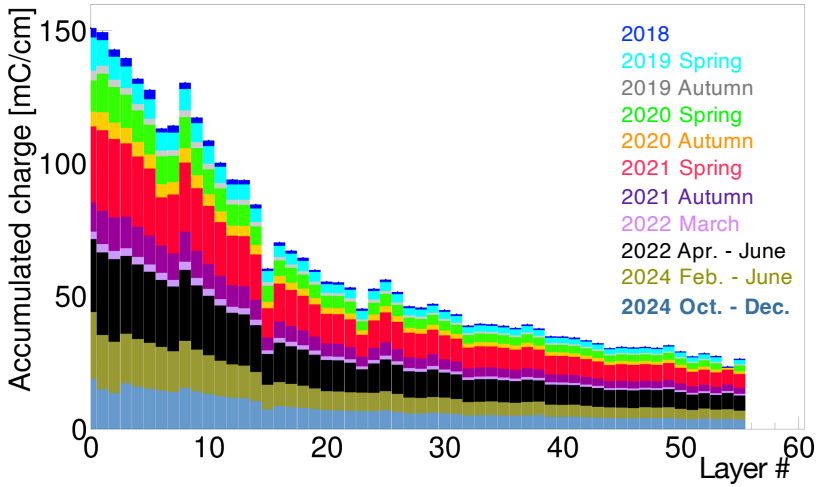
CDC present



CDC upgrade

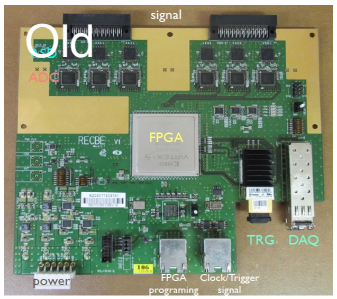


Option 1: keep current CDC, compensating aging degradation with lower HV and different gas mixture.
Option 2: replace CDC with a new drift chamber, possible use of timing layers in the inner region.



Inner layers accumulated ~ 0.15 C/cm.
Expected 6% gain decrease at 1 C/cm.

Electronics upgrade

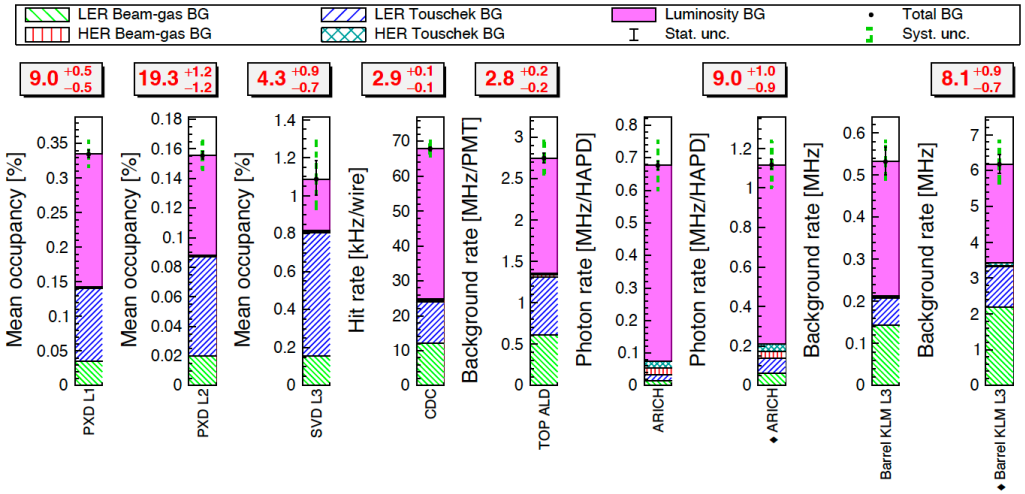


New CDC readout more radiation tolerant has been developed. The goals:
- ASIC evaluation module within 2025;
- start FE modules production within 2026.

Summary

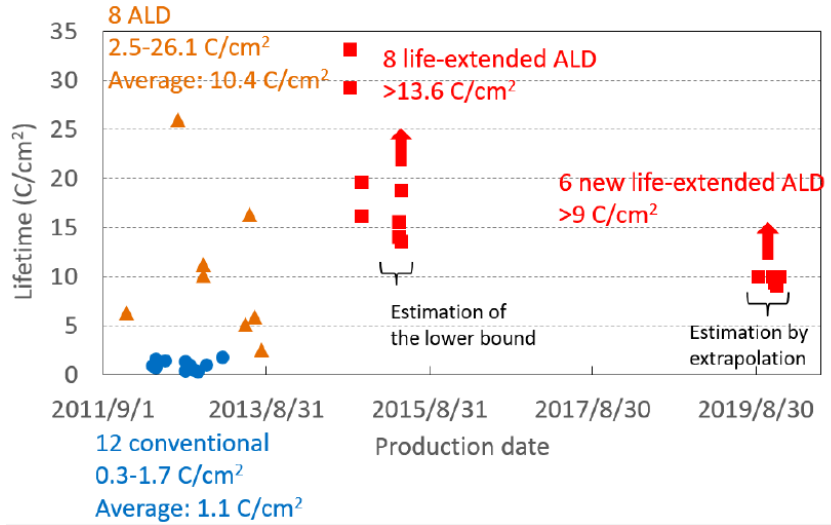
- SuperKEKB accelerator and Belle II sub-detectors have been upgraded in LS1 and during 2025 break:
  - ✓ increase beam lifetime and reduce instabilities;
  - ✓ PXD installation completed;
  - ✓ TOP photodetector with short lifetime replaced;
  - ✓ many other activities to improve sub-detectors performances.
- Key future upgrades:
  - ✓ interaction Region (IR): need modification for high luminosity;
  - ✓ new Vertex Detector (VTX) with MAPS technology to accommodate new geometry and to sustain higher hit rate;
  - ✓ CDC new electronics and new drift chamber;
  - ✓ TOP: complete photodetectors replacement,
    new HV divider to increase photodetectors lifetime,
    second replacement of all photodetectors;
  - ✓ TRIG, ECL, KLM: electronic and software upgrades to improve performances in high radiation environment.

Belle II detector sub-systems limits



Detector	BG rate limit	Measured BG
Diamonds	1–2 rad/s	< 132 mrad/s
PXD	3 %	0.1 %
SVD L3, L4, L5, L6	4.7 %, 2.4 %, 1.8 %, 1.2 %	< 0.22 %
CDC	200 kHz/wire	22.3 kHz/wire
ARICH	10 MHz/HAPD	0.5 MHz/HAPD
Barrel KLM L3	50 MHz	4 MHz
	non-luminosity BG	
	Before LS1 / After LS1	
TOP ALD	3 MHz/PMT / 5 MHz/PMT	1.8 MHz/PMT
	+ luminosity BG	

MCP-PMT photodetectors lifetimes measured in laboratory

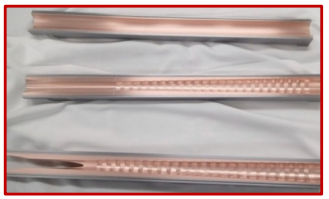


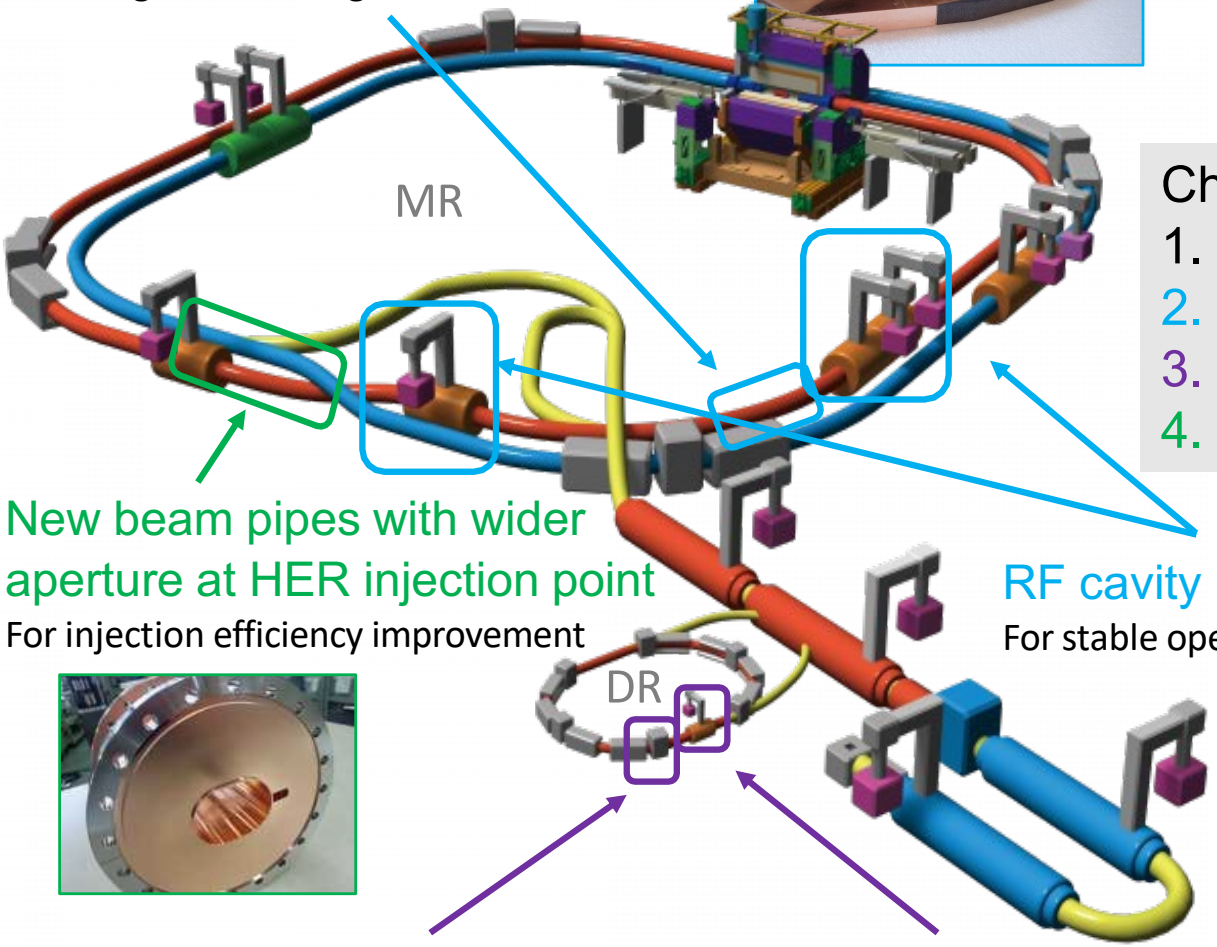
Long shutdown 1

Carbon collimator head (LER)

As countermeasure against kicker-pulser misfiring and resulting destruction of collimator

Radiation shield enhancement at IR





Challenges with high lumi. machine

1. Short beam lifetime
2. Beam instabilities
3. Low machine stability
4. Low injection efficiency

New beam pipes with wider aperture at HER injection point

For injection efficiency improvement

RF cavity modification and replacement (LER)

For stable operation with larger beam current

DR Extraction kicker power supply modification and repair (DR)

For stable operation

Vacuum seal replacement at RF section (DR)

For pressure reduction