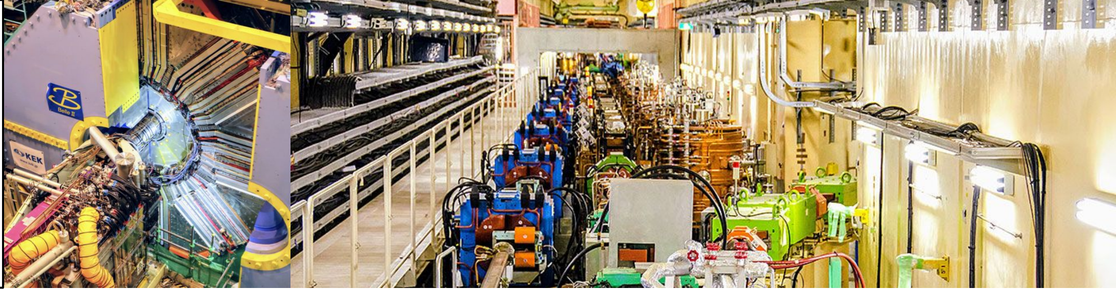
FUTURE CIRCULAR COLLIDER

The 5th FCC Physics workshop

February 7-12, 2022 Online Format



Beam background status of Belle II at SuperKEKB

On behalf of the Belle II beam background and MDI groups

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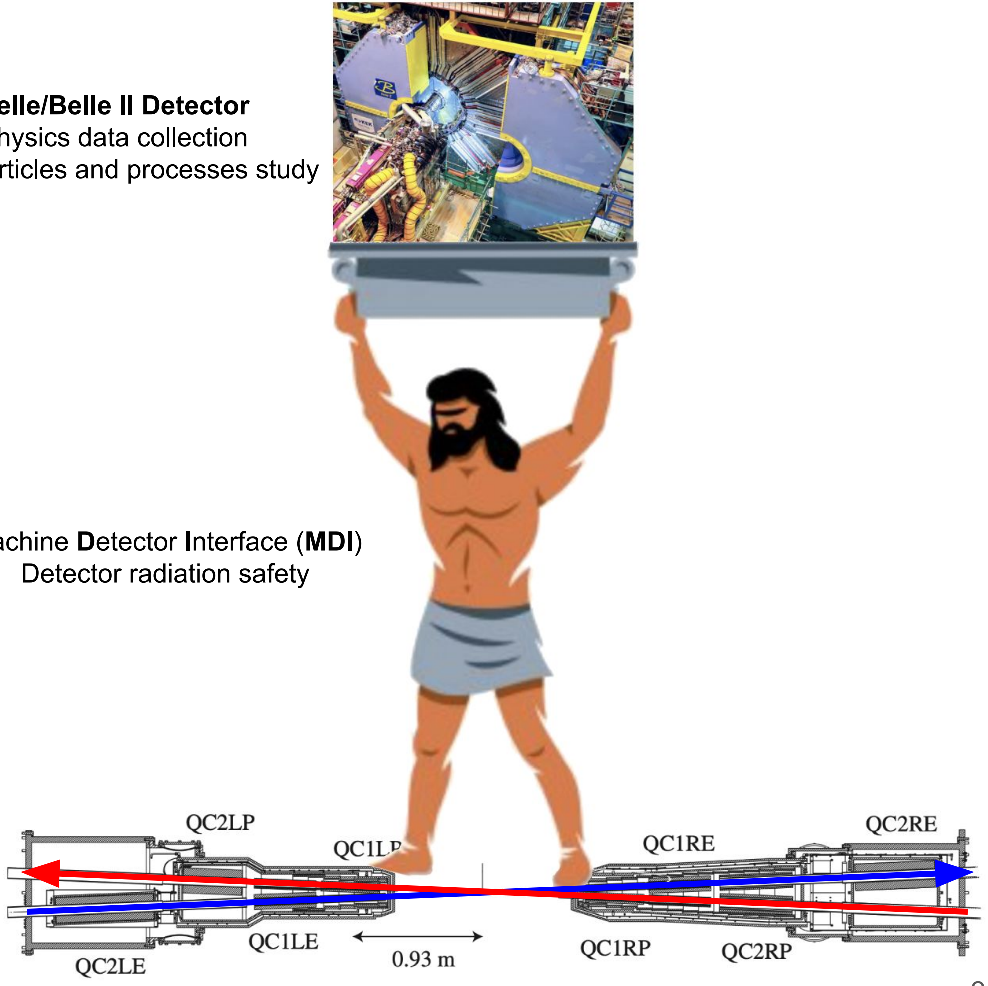
Outline

- Introduction
- KEKB to SuperKEKB
- Beam-induced backgrounds
- Collimation system
- Mitigations and plans
- Current status



Belle/Belle II Detector
Physics data collection
New particles and processes study

Machine **D**etector **I**nterface (**MDI**)
Detector radiation safety

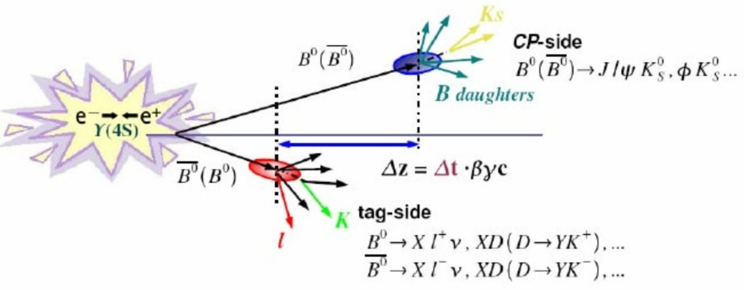
KEKB/SuperKEKB Collider
High rate of particles collisions
New particles production

Introduction: *B*-factories

1999-2010

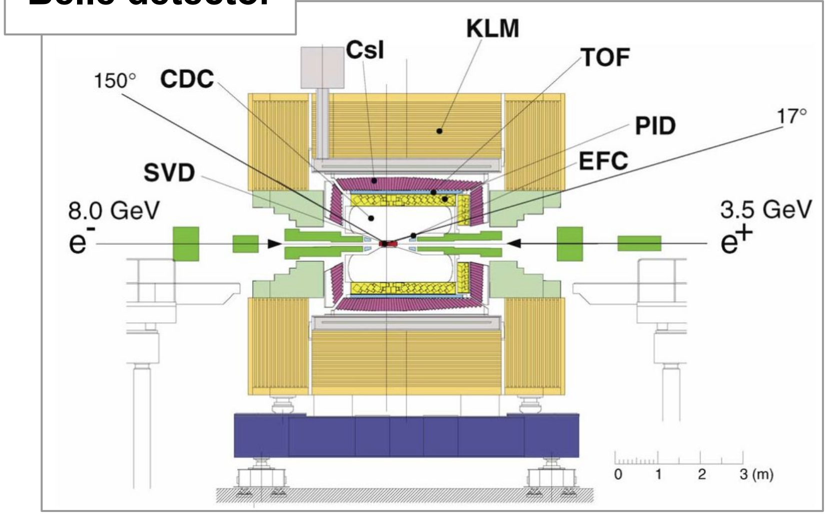
Since 2016

- Goals of **Belle** and **Belle II** experiments
  - Study the *CP*-symmetry violation in the *B*-meson system
  - Searching for New Physics beyond the Standard Model
- Requirements for **KEKB** and **SuperKEKB** colliders
  - Produce a large number of $B\overline{B}$-*pairs*
    - high collision luminosity
  - *B*-meson decay time difference (Δt) measurements
    - asymmetric collider
  - Precise measurements of the $B\overline{B}$-mixing rate
    - high quality spectrometer

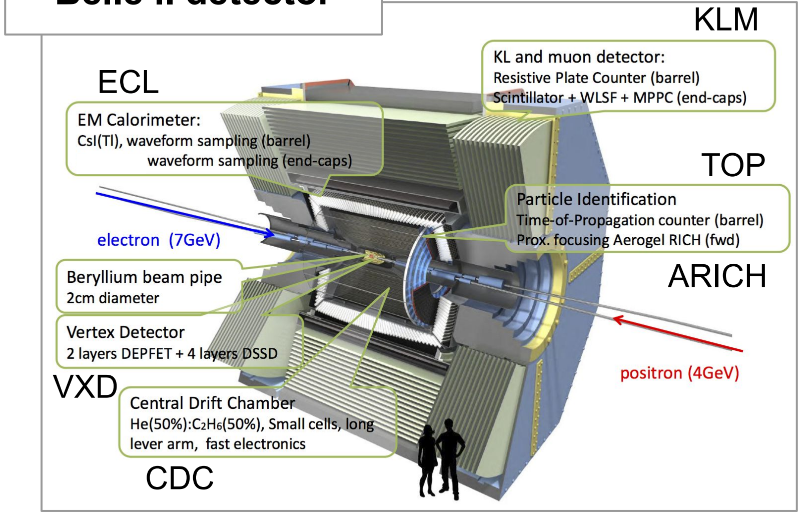


Introduction: Belle → Belle II upgrades

Belle detector



Belle II detector



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
waveform sampling (end-caps)

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

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

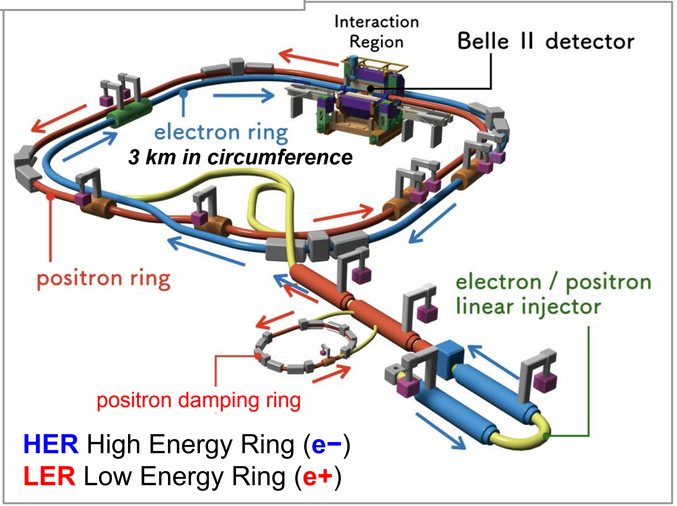
Designed and optimized for the observation of *CP*-violation in the *B*-meson system

- Collected **> 1 ab^{-1}** of data
- Observed large time-dependent *CP*-asymmetries
  - Recognized by the 2008 Physics Nobel Prize

- Newly designed VXD
- CDC with longer arms and smaller cells
- Completely new PID system
  - TOP detector in the barrel
  - ARICH detector on the forward side
- ECL with upgraded crystals and electronics
- Upgraded KLM
- Aims to collect **50 ab^{-1}** of data by 2031

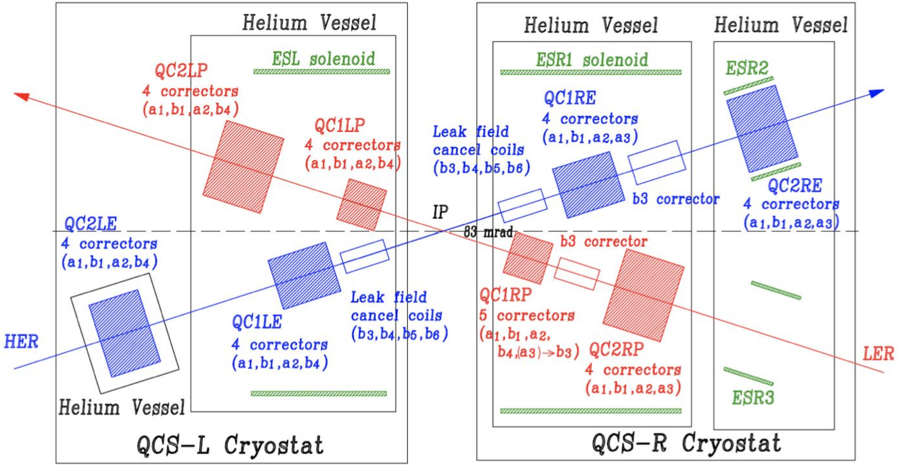
Introduction: KEKB → SuperKEKB upgrades

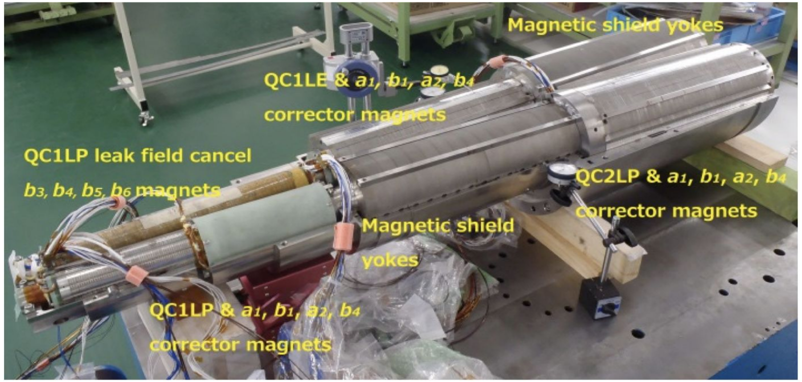
SuperKEKB collider



- Replaced short dipoles with longer ones (LER)
- Redesigned the lattices and IR (LER and HER)
- Installed antechambers (LER)
- Damping ring to reduce the emittance (LER)
- New superconducting final focusing quads (QCS) near the IP (LER and HER)
- Modified RF systems

SuperKEKB final focusing system (QCS)





KEKB → SuperKEKB: luminosity gain

Beam current

Beam-beam parameter

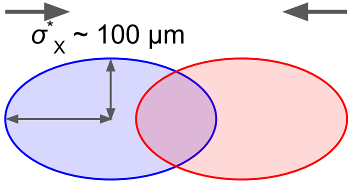
$$L = \frac{\gamma_\pm}{2er_e} \cdot \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \cdot \boxed{\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)} \cdot \left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Vertical beta-function at IP

	KEKB	**→ SuperKEKB**
β^*_Y (LER/HER)	: 5.9/5.0	→ 0.27/0.30 mm
I (LER/HER)	: 1.6/1.2	→ 2.8/2.0 A
ξ_Y (LER/HER)	: 0.13/0.09	→ 0.09/0.08
$E_{LER/HER}$	: 3.5/8.0	→ 4.0/7.0 GeV
$\mathbf{L_{peak}}$	**: 2.1×10^{34}**	**→ 6.3×10^{35} cm^{-2}s^{-1}**

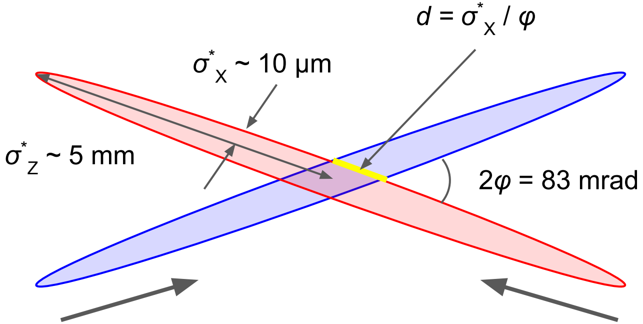
Factor of **30** increase in luminosity
based on the **nano-beam scheme**!

KEKB head-on (crab crossing)



Overlap region = bunch length
Hourglass requirement:
$\beta^*_Y \geq \sigma^*_Z$ ~5 mm

SuperKEKB nano-beam + crab waist scheme

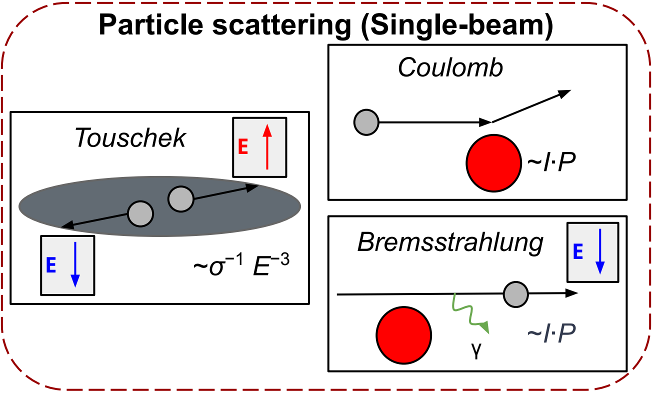


Overlap region << bunch length
Hourglass requirement:
$\beta^*_Y \geq \sigma^*_Z$ ~240 μm

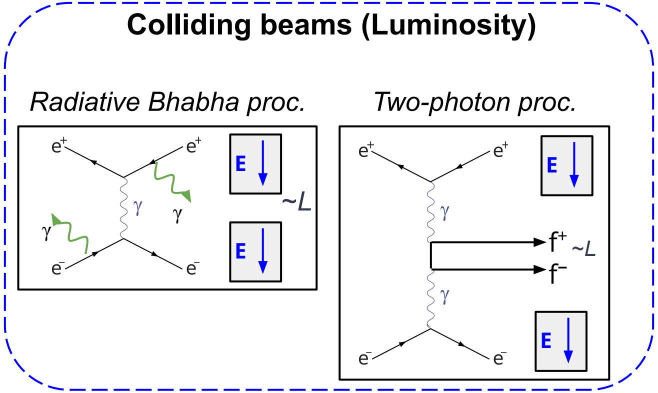
Beam-induced background: sources

SuperKEKB designed luminosity is x30 higher than at KEKB

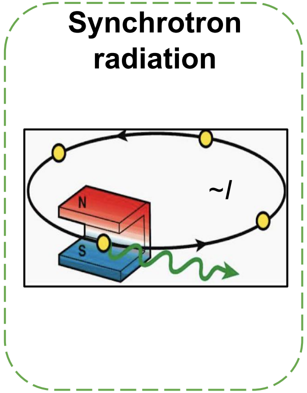
- ➢ Implies higher beam-induced backgrounds in the interaction region where Belle II is located
  - ■ affects operational stability, quality of data, and detector longevity



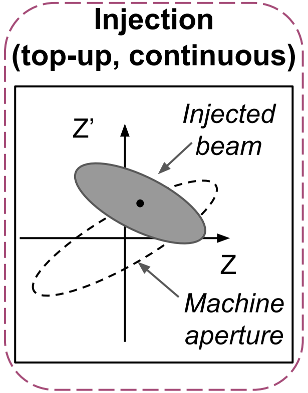
Particle scattering (Single-beam)



Colliding beams (Luminosity)



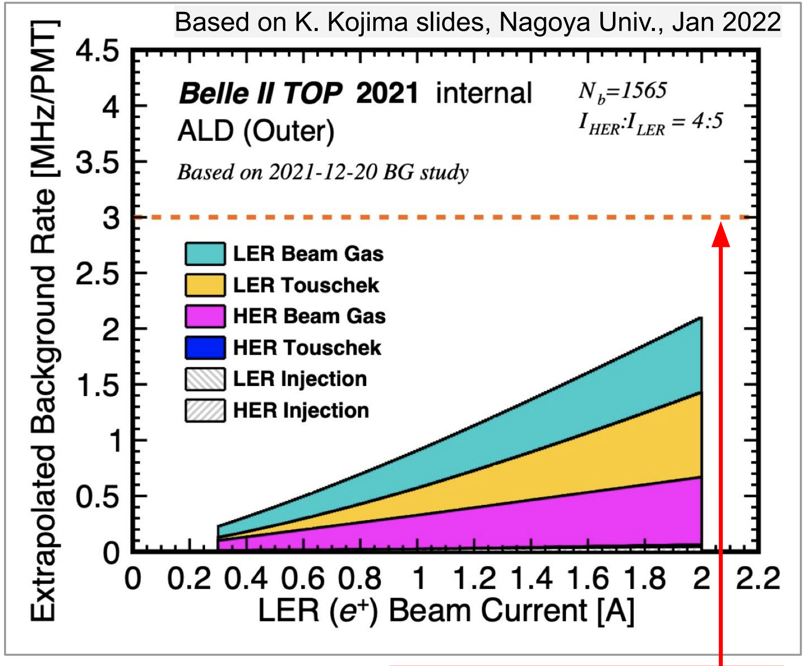
Synchrotron radiation



Injection (top-up, continuous)

- In 2010 [Belle II TDR], there was not enough understanding of beam-induced backgrounds at the nano-beam scheme in SuperKEKB except for naive extrapolation from KEKB
- Many aspects regarding detector protection were not properly foreseen at the early design stage
- Triggered a large campaign of developing a comprehensive set of countermeasures against each source

Background level in 2021



Based on K. Kojima slides, Nagoya Univ., Jan 2022

Current background limit for the TOP PMT rate

- Current background rates in Belle II are acceptable and well below limits
- Belle II did not limit beam currents in 2021
  - It will limit SuperKEKB eventually, without further background mitigation
- To reach the design luminosity a replacement of TOP short lifetime conventional PMTs is needed due to quantum efficiency degradation

Beam-induced background countermeasures

Beam-gas scattering

- It can be detrimental due to a smaller beam pipe aperture and a larger β-function in superconductive quadrupoles of the final focusing system (QCS)
- Simulation suggested to add vertical collimators at small β_Y to suppress this background in the interaction region
- Vacuum scrubbing reduces the residual gas pressure in the beam pipes

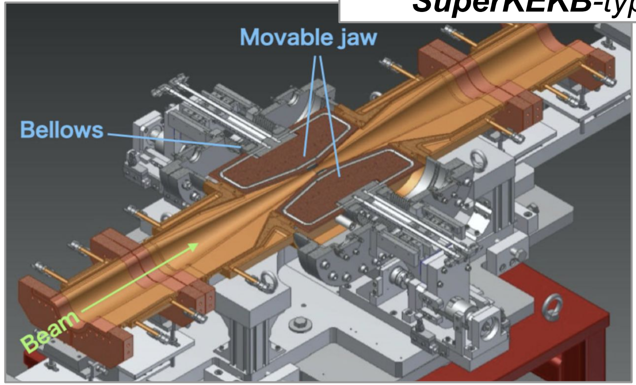
Touschek scattering

- The most dangerous background $\sim(\sigma_X\sigma_Y\sigma_Z)^{-1}$
- Simulation suggested to add horizontal collimators upstream the IP at large β_X
- Nowadays only ~1% of the total ring Touschek losses occur in the IR
- Beam lifetime is mainly defined by Touschek losses, τ ~10 (30) min for LER (HER)

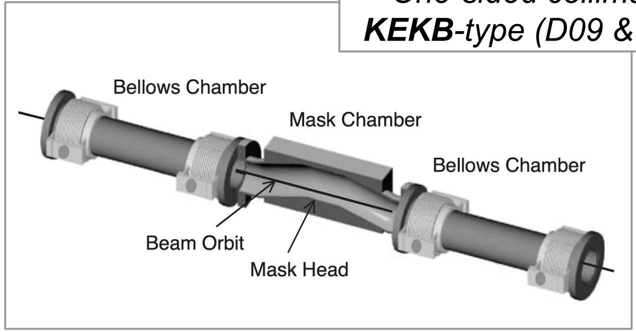
SuperKEKB collimation system

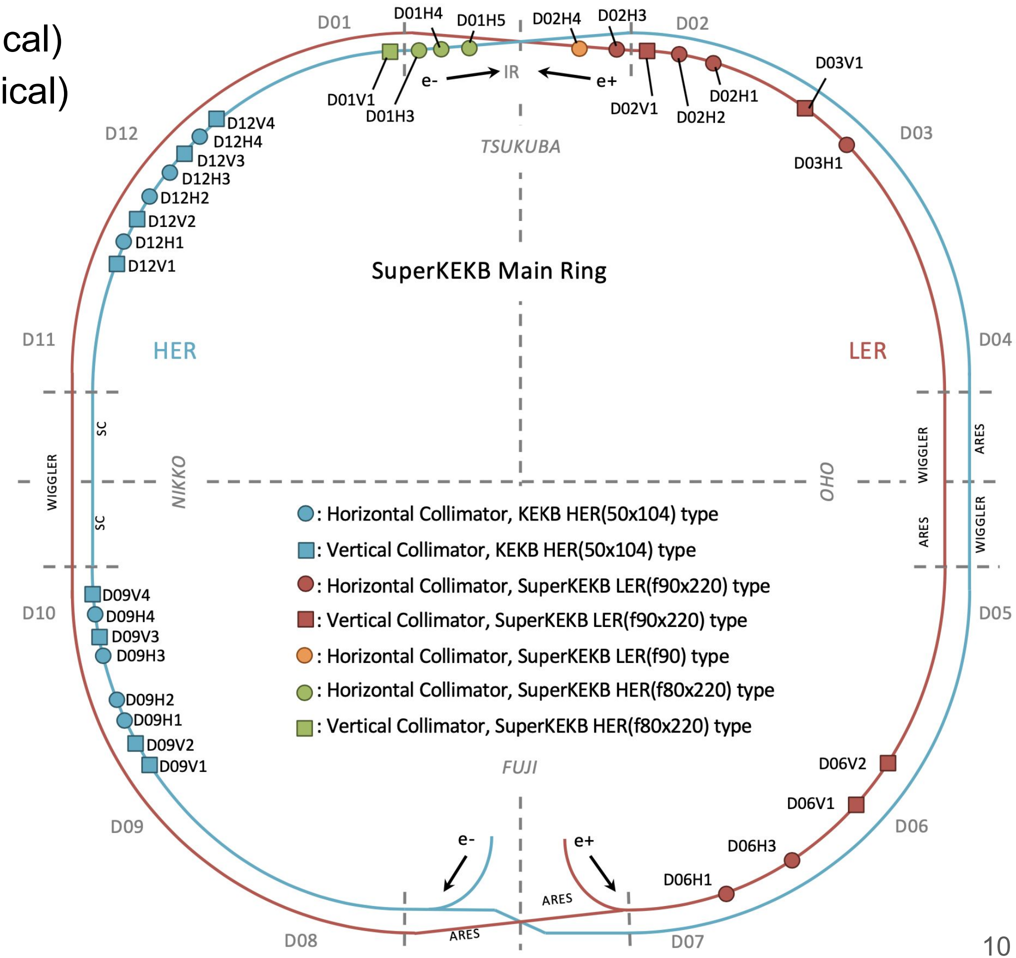
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)

Two-sided collimator
***SuperKEKB**-type*



One-sided collimator
***KEKB**-type (D09 & D12)*

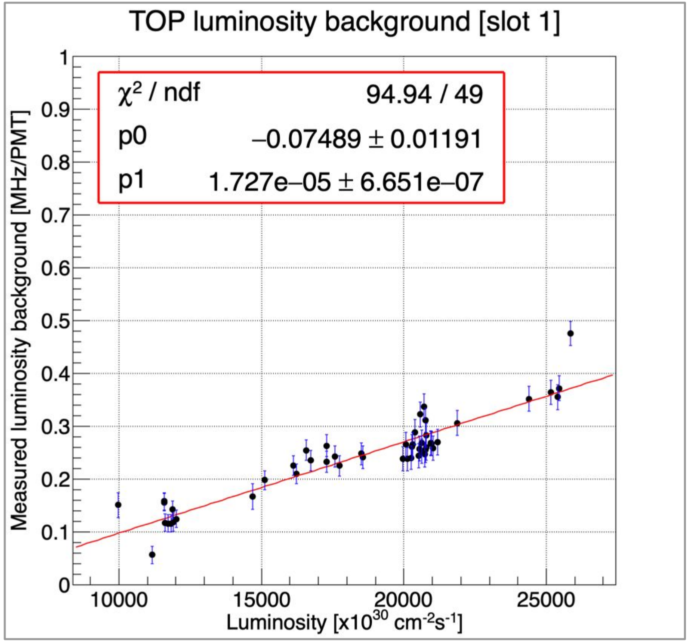




🔵: Horizontal Collimator, KEKB HER(50x104) type
🟦: Vertical Collimator, KEKB HER(50x104) type
🔴: Horizontal Collimator, SuperKEKB LER(f90x220) type
🟥: Vertical Collimator, SuperKEKB LER(f90x220) type
🟠: Horizontal Collimator, SuperKEKB LER(f90) type
🟢: Horizontal Collimator, SuperKEKB HER(f80x220) type
🟩: Vertical Collimator, SuperKEKB HER(f80x220) type

Beam-induced background countermeasures: colliding beams

- **At the early stage**
  - ○ Was assumed to be not dangerous
    - ■ KEKB
      - The two beams share one QCS → strong kick to the outgoing beam after the IP for off-energy particles, back-scattering showers towards Belle II
    - ■ SuperKEKB
      - Separate QCS for each beam → no kick from downstream quads
  - ○ However, a larger crossing angle introduces a non-negligible angular kick to off-energy particles which can then be lost around the IP
  - ○ **Dominant at design luminosities ~10^{35} cm^{-2}s^{-1}**
  - ○ Installed a heavy-metal shield outside the IR beam pipe for detector protection against EM showers



TOP [slot 1] single-beam backgrounds

LER (I_{LER} = 0.73 A):	1.2 MHz/PMT
HER (I_{HER} = 0.65 A):	0.2 MHz/PMT

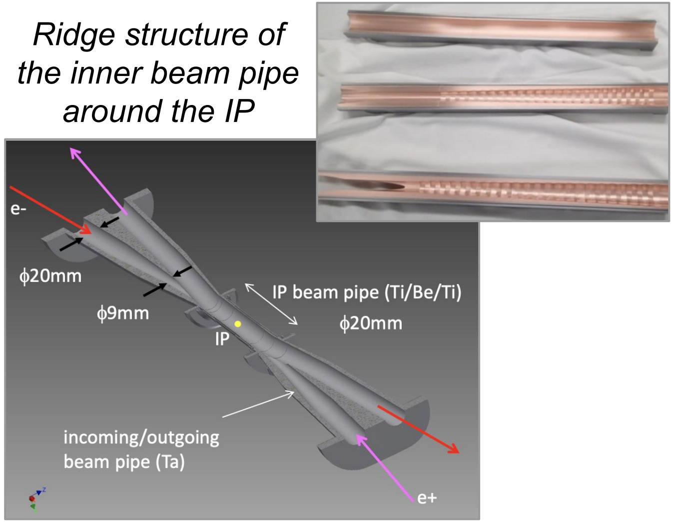
- **Nowadays**
  - ○ Luminosity BG is ≤ Single-beam BG, at the current luminosity ~10^{34} cm^{-2}s^{-1}

Beam-induced background countermeasures: synchrotron radiation and injection

- **Synchrotron radiation**
  - Beryllium beam pipe is coated with a 10μm thin gold layer
  - Incoming beam pipes collimate most of SR photons thanks to the design geometry ∅20mm → ∅9mm
  - Direct hits on the IP beam pipe are negligible
  - Ridge structure on the inner surface of the collimation part to avoid reflected SR hits at the detector
  - Building a new IP beam pipe with an additional gold layer and slightly modified geometry to reduce the amount of the backscattered SR

- **Beam losses during injection**
  - Damping ring for positrons to reduce the emittance
  - Use the injection trigger veto to do not trigger on high beam losses right after the injection (~ms)
  - Injection chain tuning for better optics matching

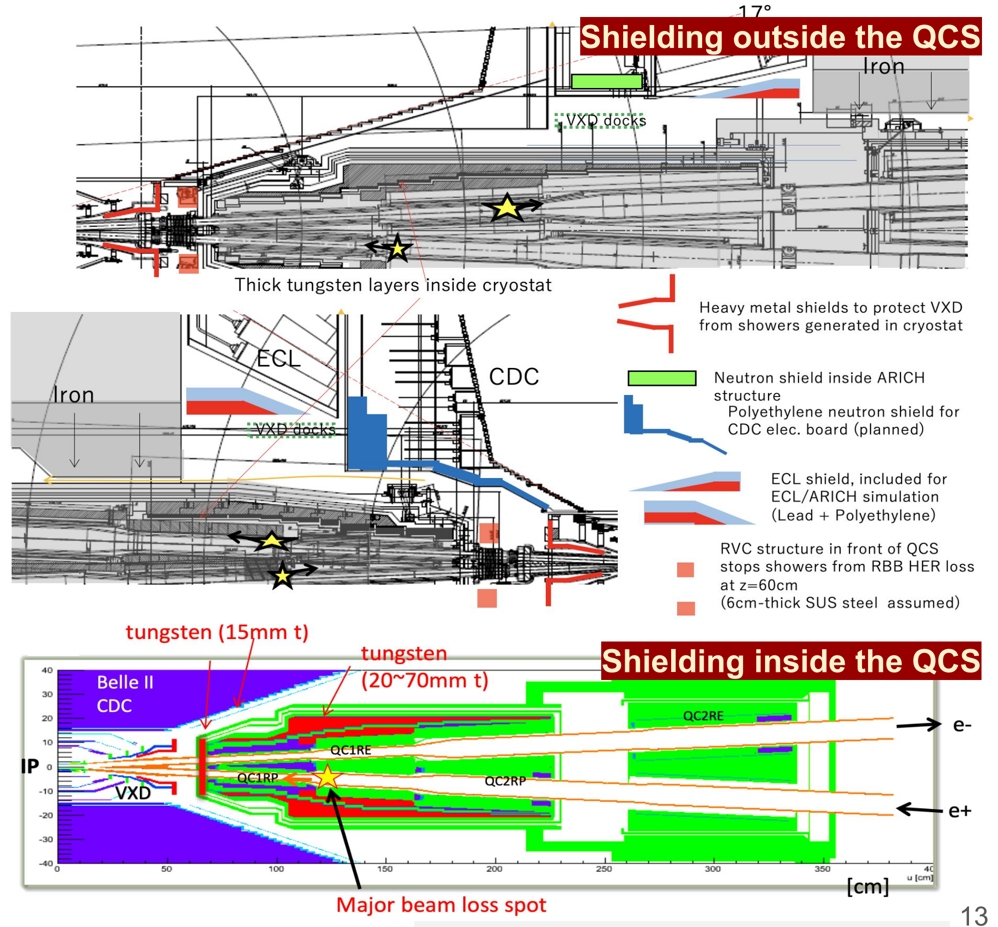
Ridge structure of the inner beam pipe around the IP



IP beam pipe geometry

Beam-induced background countermeasures: EM showers towards Belle II

- Most of IR beam losses occur inside the QCS
  - Partially considered in the TDR 2010
- Many detectors start to see single-event upsets (SEU) of FPGAs electronics boards
  - SEUs are presumably from neutrons created in the EM showers
  - Initially, no shielding was implemented
  - Still acceptable level
- Installed additional detector protection
  - Heavy metal shield inside VXD
  - Polyethylene+lead shield inside ECL, ARICH & CDC
- Planned detector protection
  - Additional bellows shield is under discussion
  - Extra neutron shields are being designed



Heavy metal shields to protect VXD from showers generated in cryostat

Neutron shield inside ARICH structure

Polyethylene neutron shield for CDC elec. board (planned)

ECL shield, included for ECL/ARICH simulation (Lead + Polyethylene)

RVC structure in front of QCS stops showers from RBB HER loss at z=60cm (6cm-thick SUS steel assumed)

Based on H. Nakayama slides, KEK, IPAC’21

Unexpected machine backgrounds: TMCI

Transverse mode coupling instability (TMCI)

- a result of the wake-field effect from bunches traveling through the collimator aperture
- leading to the onset of the bunch current head-tail instability
  - **Beam size blow up**
  - **Betatron tune shift**

Synchrotron frequency

Beam energy

$$I_{\text{thresh}} = \frac{8 f_s E/e}{\sum_j \beta_j k_j(\sigma_S, d)}$$

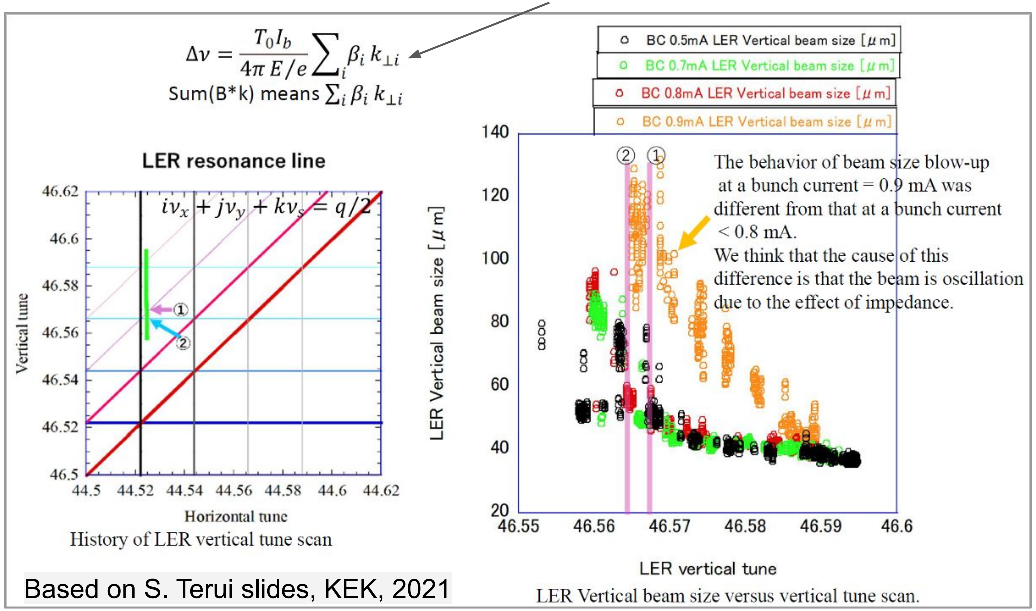
Maximum bunch current before reaching beam instabilities

Collimator beta-function

Collimator kick-factor

[A.Chao 1998, Handbook]

Tune shift due to wakefield effects



$$\Delta\nu = \frac{T_0 I_b}{4\pi E/e} \sum_i \beta_i k_{\perp i}$$

Sum(B*k) means $\sum_i \beta_i k_{\perp i}$

LER resonance line

History of LER vertical tune scan

The behavior of beam size blow-up at a bunch current = 0.9 mA was different from that at a bunch current < 0.8 mA. We think that the cause of this difference is that the beam is oscillation due to the effect of impedance.

LER Vertical beam size versus vertical tune scan.

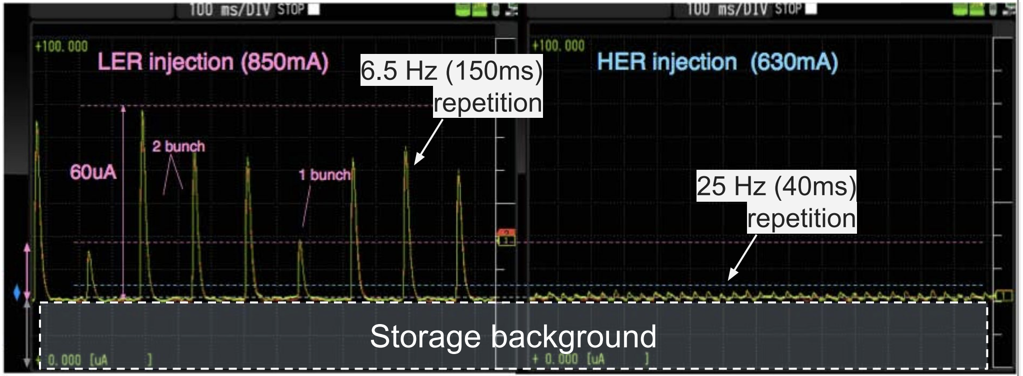
Based on S. Terui slides, KEK, 2021

In 2020-2021, TMCI could be one of the sources limiting bunch current increase even below I_{thresh} ~1.4 mA/bunch.

Unexpected machine backgrounds: injection background

- High beam losses during injection caused by
  - Injected charges with large amplitudes of oscillation due to injection kicker errors
  - Injection chain and main ring optics mismatch
- Up to 10 times higher instantaneous rates than the storaged beam background, see Figure
- Enlarges DAQ deadtime
- Reduces lifetime of the detector components, e.g. TOP PMTs

CDC leakage current during injection

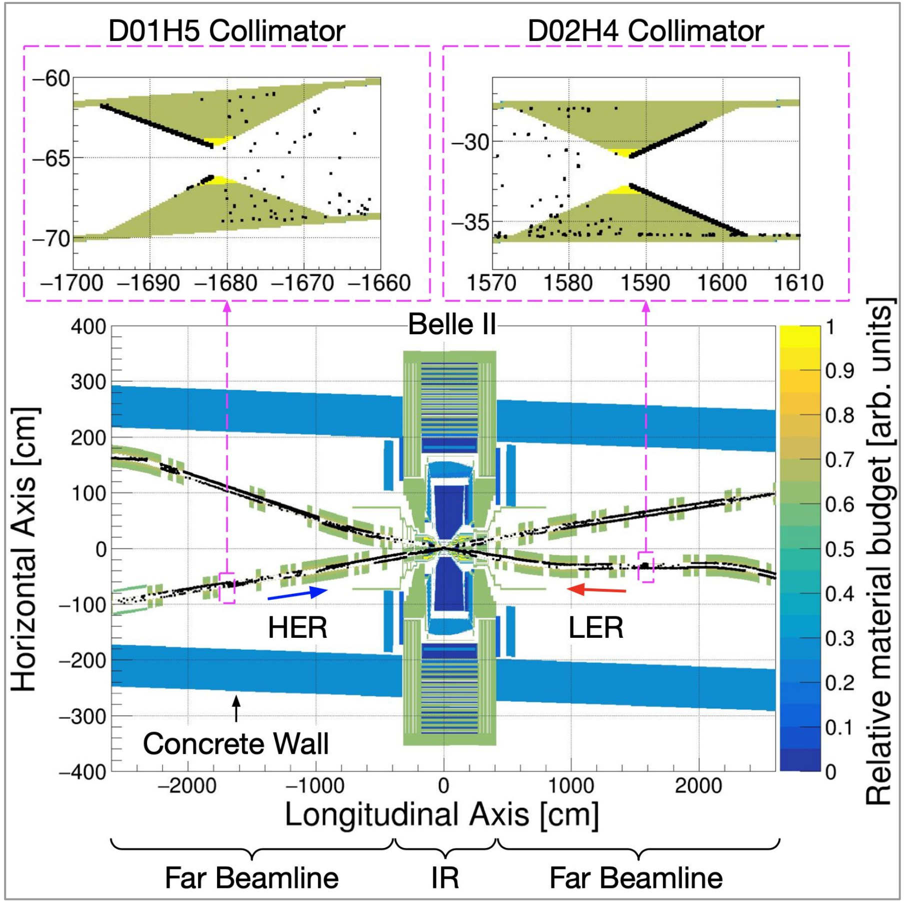


Based on S.Y. Ryu slides, RCNP/Osaka, 2021

Dedicated simulation and measurement efforts have been started to study this source of machine backgrounds looking for possibilities to improve the injection quality and reduce IR beam losses.

Beam-induced background: **simulation**

- **Single-beam background:**
  - Strategic Accelerator Design (SAD @KEK, multi-turn particle tracking)
    - Realistic collimator shape
    - Particle interaction with collimator materials
    - Measured residual gas pressure distribution around each ring
  - Geant4 (detector modeling)
    - Realistic detector model
    - Modeling of the detector surroundings, collider cavern
- **Luminosity background:**
  - Geant4 (single-turn effect, colliding beams)
- **Synchrotron radiation background:**
  - Geant4 (close to the Belle II detector)

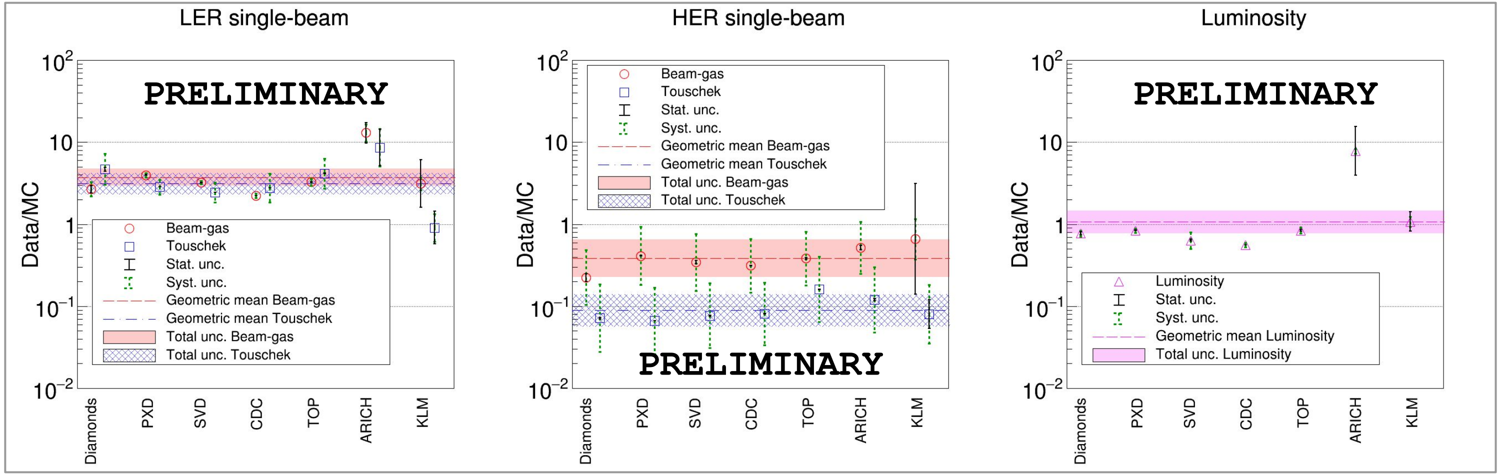


Current Geant4 model of Belle II and collider cavern. Black dots represent single-beam losses

Simulation accuracy: data/MC

Publication in preparation

Ratios of measured (**data**) to simulated (**MC**) backgrounds based on 2020-2021 dedicated studies



- **Phase 3** data and MC are within one order of magnitude
  - Improved compared to **Phase 1** (2016) & **Phase 2** (2018) background measurements

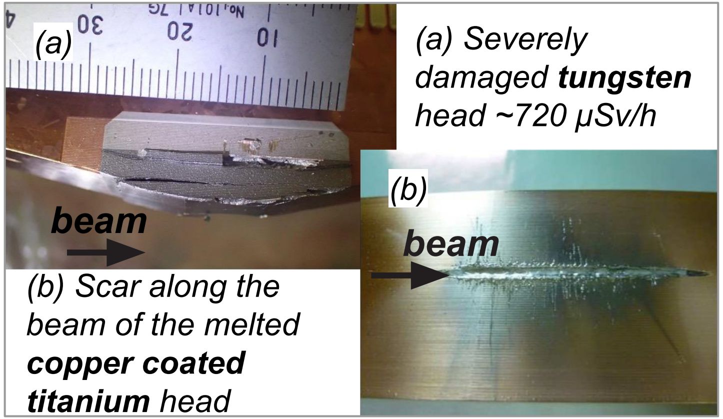
    [P.M.Lewis *et al.*, “First measurements of beam backgrounds at SuperKEKB”, NIMA 2019]

    [Z.J.Liptak *et al.*, “Measurements of Beam Backgrounds in SuperKEKB Phase 2”, arXiv:2112.14537]
  - Confirms our good understanding of beam loss processes in SuperKEKB
- These ratios are used to extrapolate detector backgrounds towards design luminosity
  - Belle II background level is expected to be acceptable at L_{peak} = 6.3x10^{35} cm^{-2}s^{-1} assuming TOP PMTs replacement and low injection beam losses

Further background mitigation: collimators and beam abort system

Issues

- Still high residual gas pressure in LER ~40nPa
- Unstable injection with high beam losses
- Unexplained and uncontrolled beam losses
    - Detector and collimators damage
- Vertical collimators should be closed to a very narrow aperture ±2mm = 60% of the QCS aperture
    - Limits the bunch current due to TMCI
    - Collimator head is very close to the main beam core
        - High radiation dose on collimators
        - High risk of collimator damage

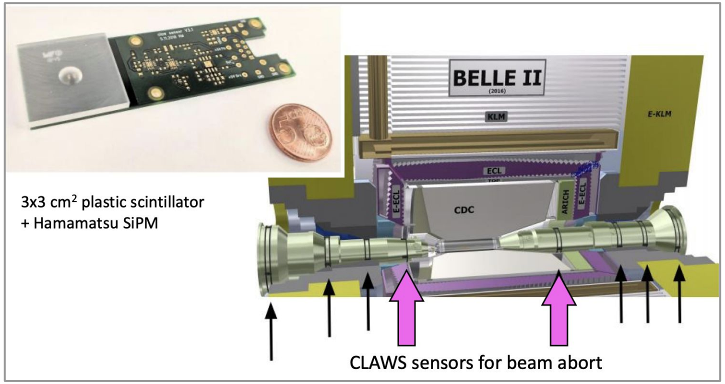


*(a) Severely damaged **tungsten** head ~720 µSv/h*

*(b) Scar along the beam of the melted **copper coated titanium** head*

Solutions

- Continue vacuum scrubbing, P_{LER} ~10nPa by 2026
- Injection chain (LINAC, beam-transport lines) upgrade
- Injection optics mismatch measurements
- Low-impedance collimators with composite materials
- New CLAWS system installation → now the beam abort kicker can be fired faster by ~4.4µs on average
- Abort timing analysis to pin-down the initial beam loss location along the ring



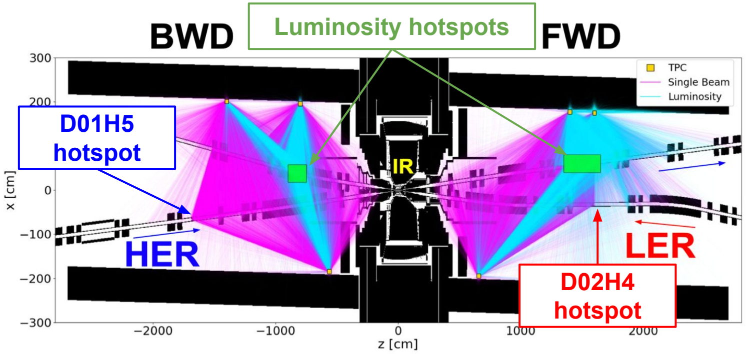
3x3 cm^2 plastic scintillator + Hamamatsu SiPM

CLAWS sensors for beam abort

Further background mitigation: neutron shielding

- Neutron shielding around Belle II is not ideal and there is neutrons leakage
    - Detector performance degradation
- Monte-Carlo simulation predicts neutrons due to single-beam and collision (luminosity) beam losses.

Neutron hotspot regions predicted by MC



Hotspot regions

BWD:
-9.0m ≤ z ≤ -7.5m
|y| ≤ 20cm
18cm ≤ x ≤ 60cm

FWD:
+13.5m ≤ z ≤ +16.5m
|y| ≤ 20cm
40cm ≤ x ≤ 80cm

- Above shows MC neutrons that pass through each TPC, traced back to their production point along the beam line from the 05-09-2020 FarBeamLine MC sample
- In both tunnels, the majority of luminosity background induced neutron production comes from localized regions (shaded green regions) -> call them RBB hotspots

Based on J. Schueler slides, UH

Neutrons from collimator hotspots

- The highest beam losses are at the nearest collimators to the IR (D02H4 - LER, D01H5 - HER), ~16m from IP
- Move hotspots away from Belle II
    - Reduce losses at these collimators by closing far upstream collimators

Neutrons from luminosity hotspots

- Time Projection Chamber (TPC) measurements suggest localized regions along the beamline where neutrons originating from
    - Leading background in the forward cavern
    - Can be mitigated only via shielding, design is ongoing

Summary

- SuperKEKB and Belle II have successfully rolled in as a new generation of *B*-factories
  - World-record luminosity 3.81x10^{34} $cm^{-2}s^{-1}$
  - > 0.2 ab^{-1} of collected data
  - Clean environment of the primary e^+e^- interaction compared to hadron machines
  - Wide-ranging physics program
- A naive extrapolation from KEKB machine studies did not work well for the new nano-beam scheme
  - Installation of not planned additional shielding to protect the detector
  - TMCI has to be considered as one of the major sources limiting the machine
- Improved beam-induced background simulation helps to predict beam losses at various machine conditions

  [A. Natochii *et al.*, "Improved simulation of beam backgrounds and collimation at SuperKEKB", PRAB 2021]
  - Several new types of collimators are designing
  - Some collimators relocation is scheduled
- To reach the design luminosity, several further machine and detector upgrades are under consideration

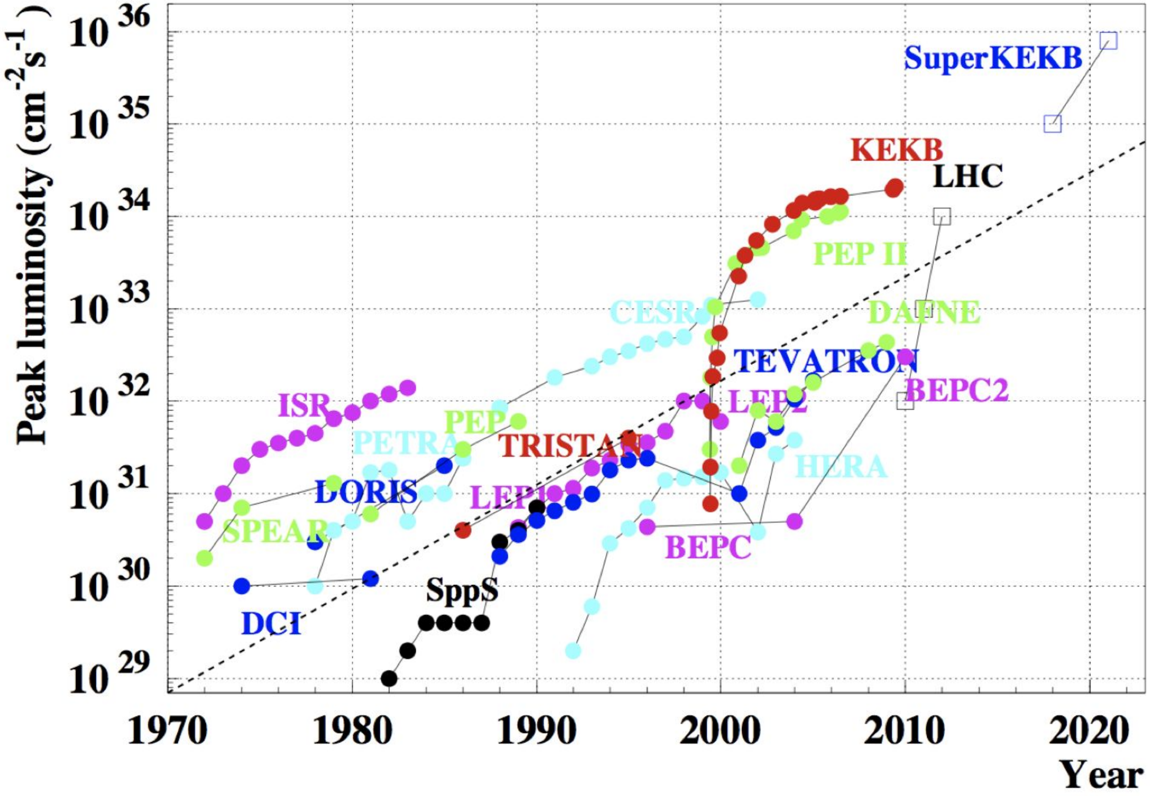
An important lesson learned from the KEKB to SuperKEKB upgrade, **the MDI group advice:**

It's critically important to reserve enough space at the early stage of the design for shielding between the final focusing and detector!

Backup

Introduction: pushing the intensity frontier

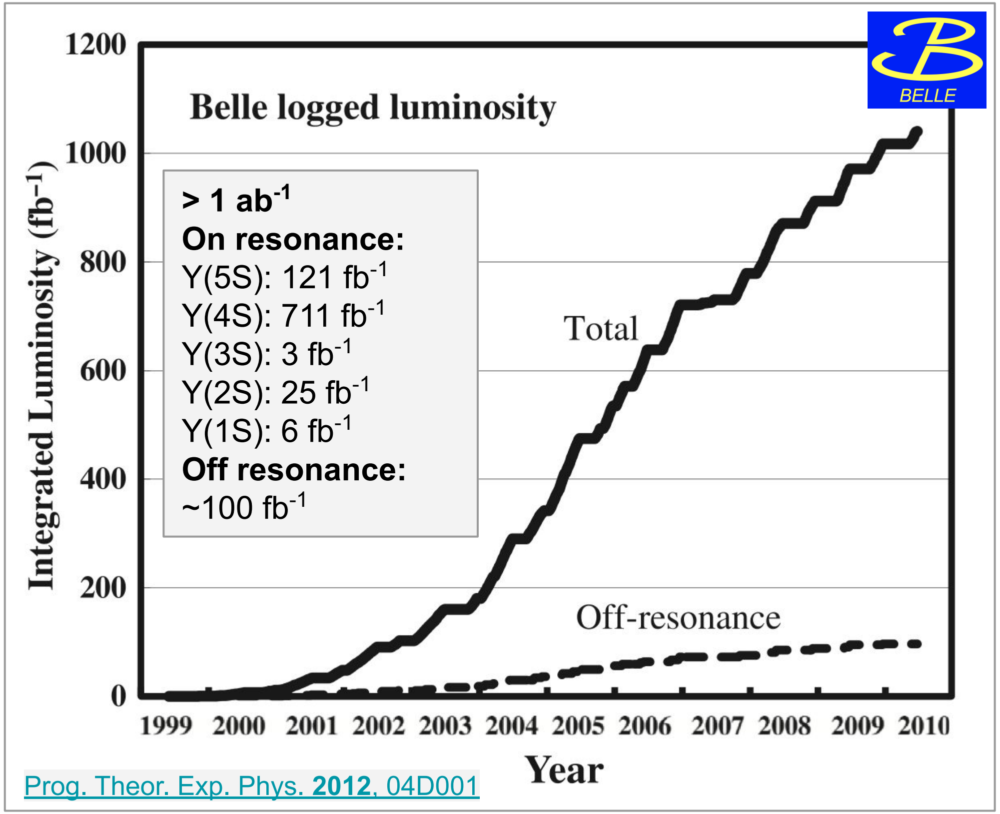
By design **SuperKEKB/Belle II** will reach the record luminosity of **6.3 x 10^{35} cm^{-2}s^{-1}** (x30 **KEKB/Belle**)
corresponding to ~1 kHz of Y(4S) (σ ~1.1 nb)



Belle and KEKB (1999-2010): achievements

- Observation of large time-dependent *CP*-asymmetries
    - 2008 Physics Nobel Prize

- Measurements of the unitarity triangle and CKM matrix elements
- Established the existence of highly suppressed processes
    - $b \to d\gamma$ and $b \to s l^+ l^-$
- Search for the lepton-flavor-violation in τ decays
- Spectroscopy and interactions of $c\bar{c}$ charmonium mesons
- Discovery of new *X*(3872), *Y*(3940), *Z*(3930) particles



> 1 ab^{-1}
On resonance:
Y(5S): 121 fb^{-1}
Y(4S): 711 fb^{-1}
Y(3S): 3 fb^{-1}
Y(2S): 25 fb^{-1}
Y(1S): 6 fb^{-1}
Off resonance:
~100 fb^{-1}

Prog. Theor. Exp. Phys. **2012**, 04D001

Motivation for Super *B*-factories

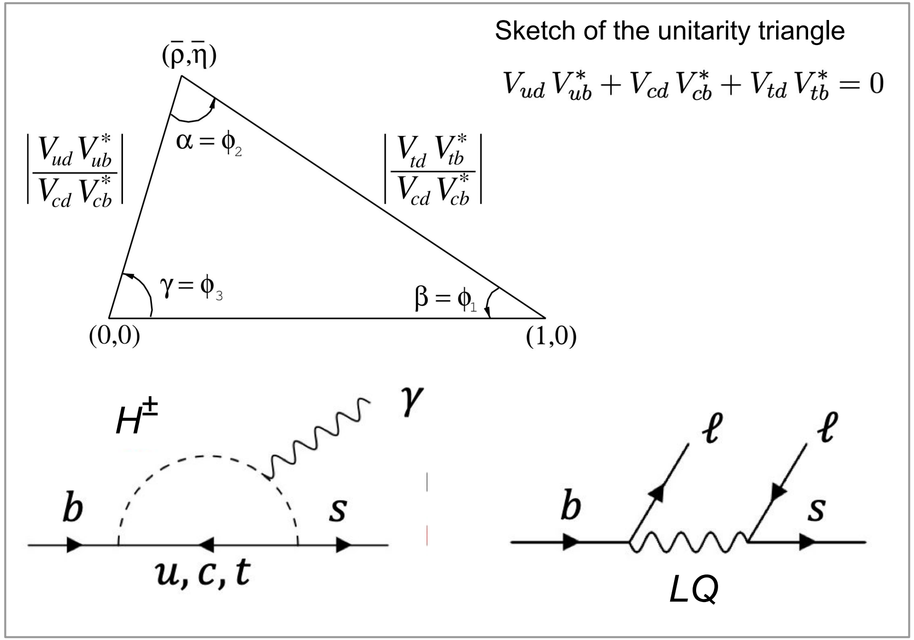
Complementary approaches to search for NP beyond the SM

- **Energy frontiers** → ATLAS & CMS/LHC
  - new particles production through *p-p* collisions
- **Rare/precision frontiers** → LHCb/LHC, BESIII/BEPCII, **Belle II/SuperKEKB**
  - flavor physics reactions, deviation from the SM prediction

Challenges for New/Super *B*-factories

- Precise measurement of unitarity triangle parameters
- Charged Higgs ($H^{\pm}$) and Leptoquarks (*LQ*)
- New sources of *CP*-violation
- Lepton number/flavor violation
- Search for Dark Matter, etc..

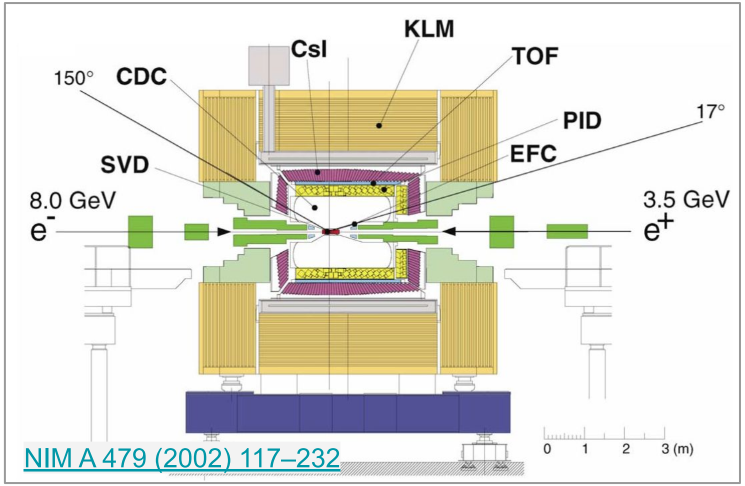
Tasks for Belle II/SuperKEKB


Sketch of the unitarity triangle

$$V_{ud}\,V_{ub}^{*} + V_{cd}\,V_{cb}^{*} + V_{td}\,V_{tb}^{*} = 0$$

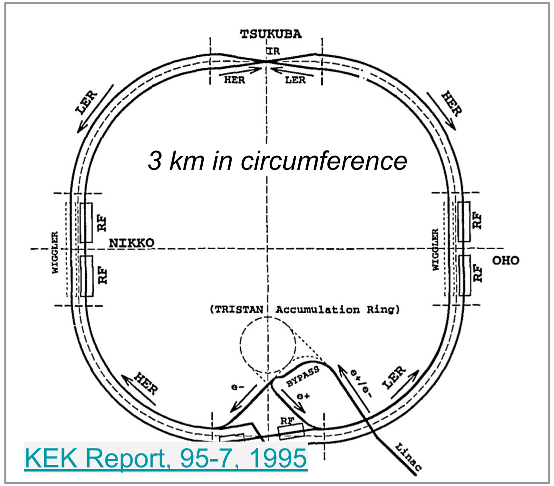
Belle and KEKB (1999-2010)

Belle detector



NIM A 479 (2002) 117–232

KEKB collider



KEK Report, 95-7, 1995

HER High Energy Ring

LER Low Energy Ring

CM-energy is at Υ(4*S*) resonance = 10.58 GeV for efficient $B\bar{B}$-pair production

- Designed and optimized for the observation of *CP*-violation in the *B*-meson system.
- Collected > 1 ab^{-1} of data for Υ(1*S*), Υ(2*S*), Υ(4*S*) and Υ(5*S*) resonances

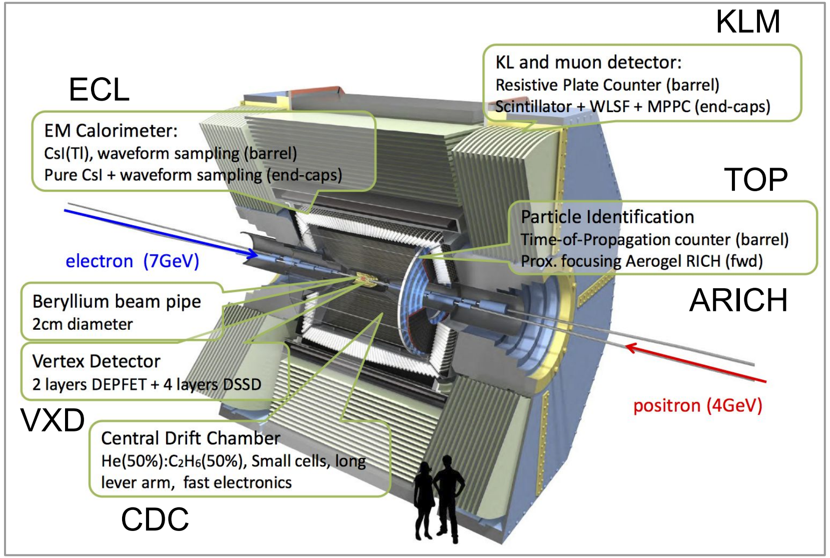
Beam energy		(GeV)	8.0 (e^-), 3.5 (e^+)
Beam current		(A)	1.2 (e^-), 1.6 (e^+)
Beam size at IP	x	(μm)	80
	y	(μm)	1
	z	(mm)	5
Luminosity		($\text{cm}^{-2}\,\text{s}^{-1}$)	2.1×10^{34}
Number of beam bunches			1584
Bunch spacing		(m)	1.84
Beam crossing angle		(mrad)	± 11 (crab-crossing)

More than twice the original design goal

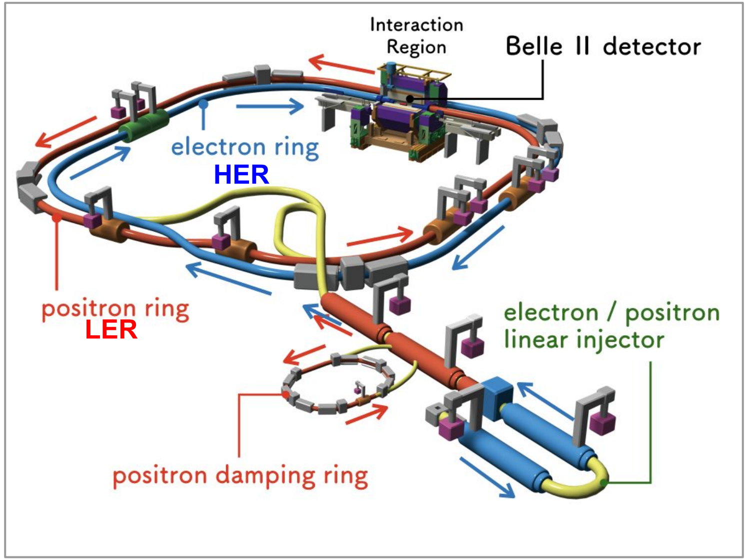
World's first operational set of superconducting crab cavities

Next generation *B*-factory: Belle II and SuperKEKB (since 2016)

Belle II detector



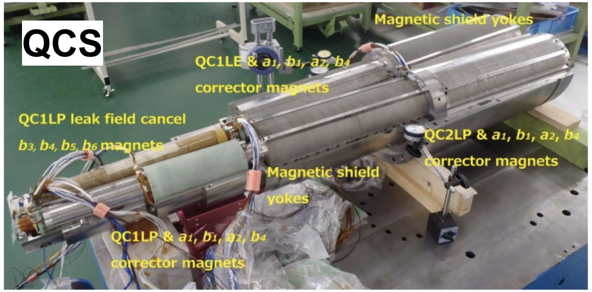
SuperKEKB collider

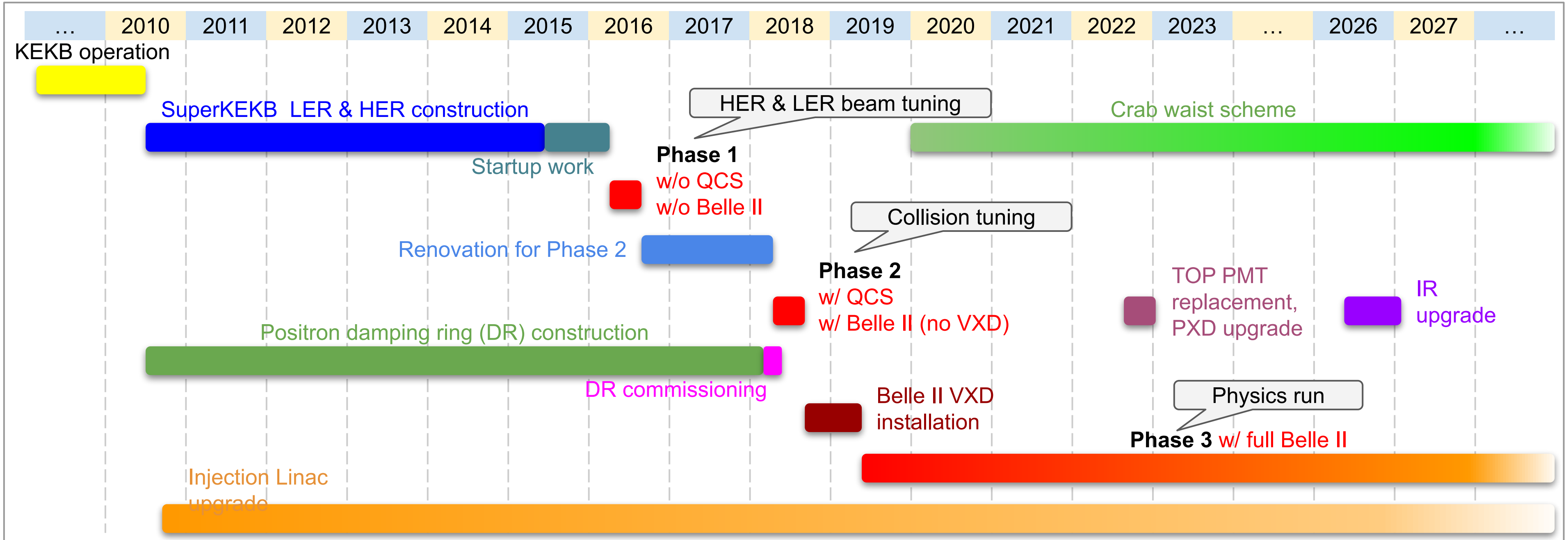


- Precise study of b, c, τ to search for New Physics in clean experimental environment
- Access to the Hidden/Dark sector
- L_{int} = 50 ab^{-1} (50 x KEKB) by 2031
- L_{peak} = 6.3 x 10^{35} cm^{-2}s^{-1} (30 x KEKB) by 2029

Timeline for machine upgrades

- **Phase 1** (2016) → Accelerator commissioning
- **Phase 2** (2018) → First collisions; partial detector; background study; physics possible
- **Phase 3** (2019) → Nominal Belle II start





… 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 … 2026 2027 …

KEKB operation

SuperKEKB LER & HER construction

Startup work

HER & LER beam tuning

Phase 1 w/o QCS w/o Belle II

Crab waist scheme

Renovation for Phase 2

Collision tuning

Phase 2 w/ QCS w/ Belle II (no VXD)

TOP PMT replacement, PXD upgrade

IR upgrade

Positron damping ring (DR) construction

DR commissioning

Belle II VXD installation

Physics run

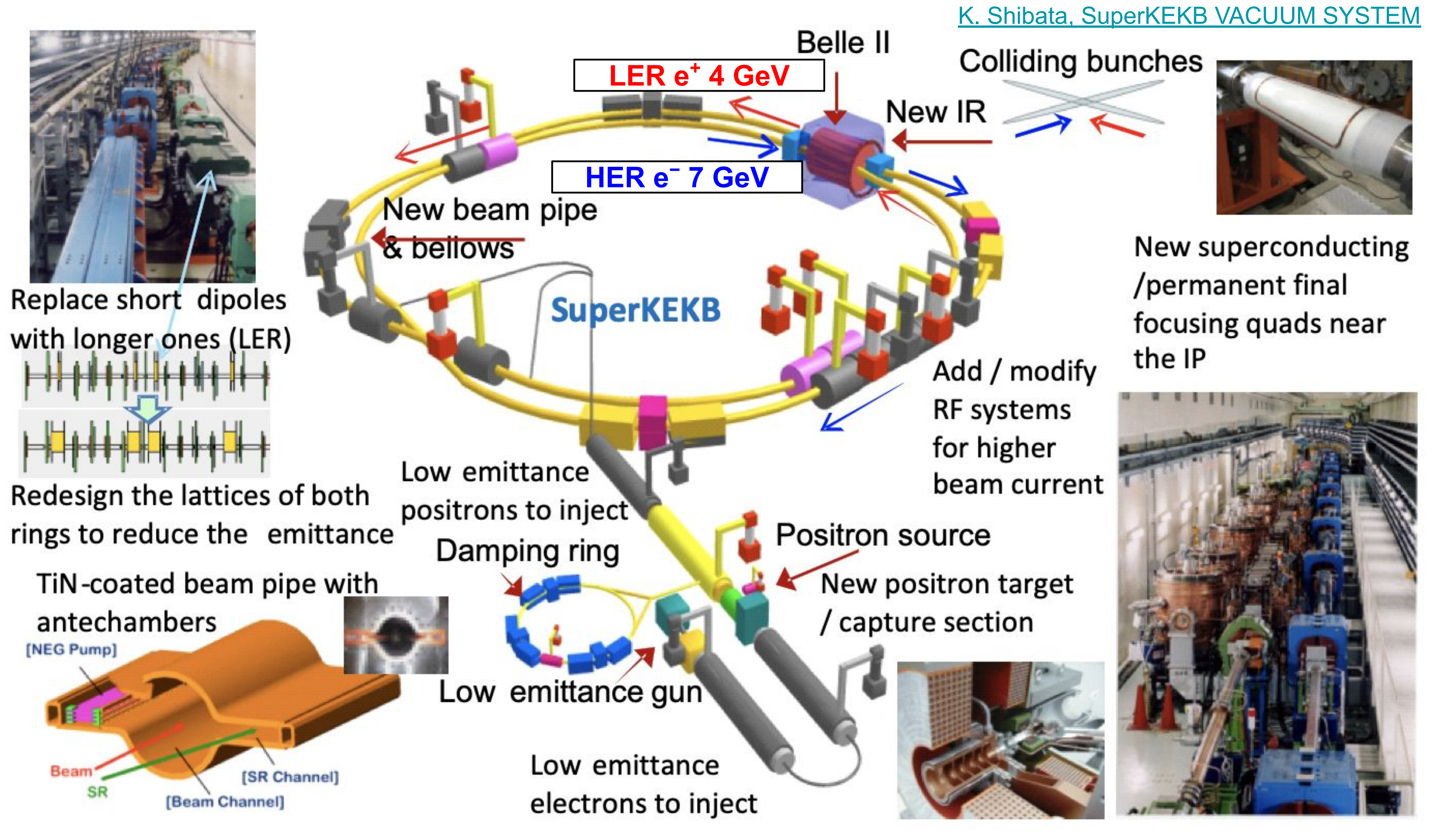
Phase 3 w/ full Belle II

Injection Linac upgrade

Based on M. Tobiyama slides, KEK, EIC workshop 2020

KEKB → SuperKEKB: machine modifications

K. Shibata, SuperKEKB VACUUM SYSTEM



New beam pipe & bellows

Replace short dipoles with longer ones (LER)

Redesign the lattices of both rings to reduce the emittance

TiN-coated beam pipe with antechambers

Low emittance positrons to inject

Damping ring

Low emittance gun

Low emittance electrons to inject

Positron source

New positron target / capture section

Add / modify RF systems for higher beam current

New superconducting /permanent final focusing quads near the IP

KEKB → SuperKEKB: luminosity degradation & crab waist scheme

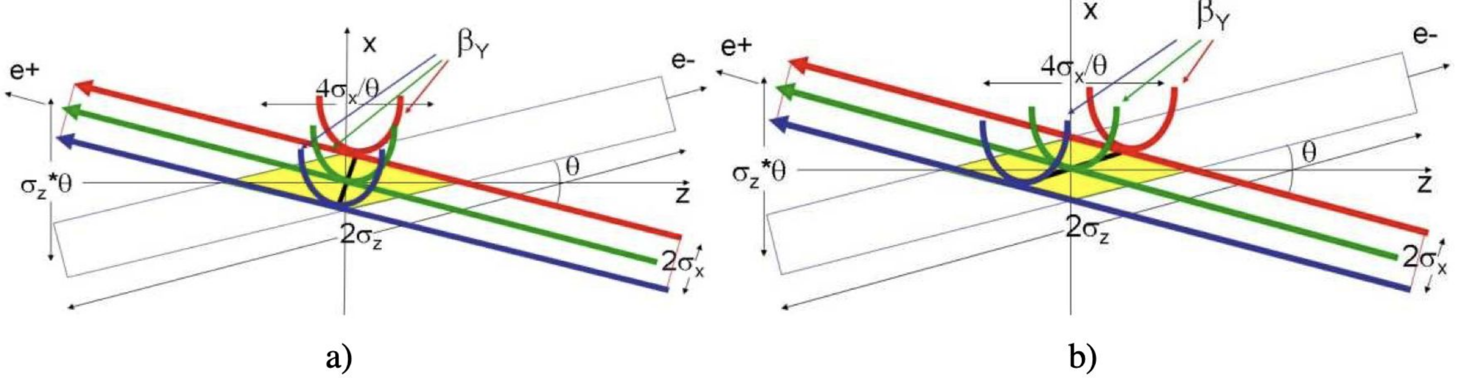
- **Initially**
  - Was hard to operate the SuperKEKB near the working point of the betatron tune (.57,.61)

    ← due to luminosity degradation caused by beam-beam resonances
- **Since early 2020**
  - Used a set of dedicated sextupoles for the crab waist scheme

    ← does not affect the dynamic aperture

    ← beam-beam resonances are suppressed

https://arxiv.org/pdf/1608.06150.pdf



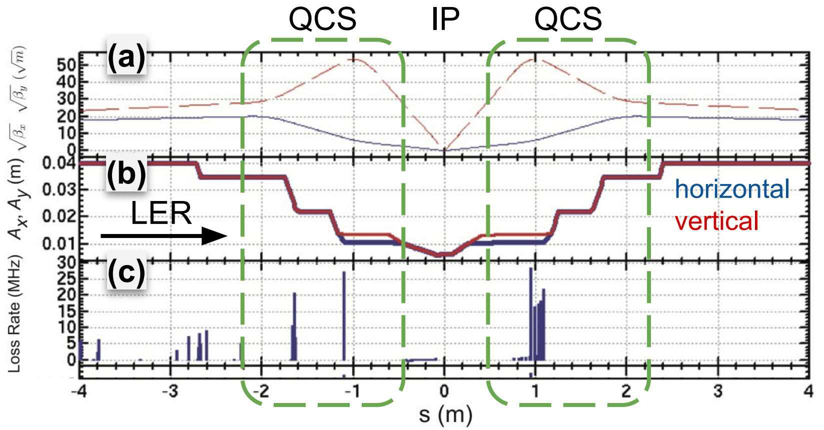
*Differently from the crab crossing scheme (**KEKB**) where bunches are tilted by the crab cavities with respect to the beam longitudinal axis, CW (**SuperKEKB**) rotates the optics function β_Y.*

Crab Waist collision scheme: a) crab sextupoles OFF; b) crab sextupoles ON

Beam-induced background countermeasures: beam-gas scattering (1)

	KEKB	SuperKEKB
A_Y , mm	35	13.5
β^{max}_Y , m	600	2900

- Initially, the beam-gas background was assumed to not be dangerous, based on KEKB experience
- However, it can be detrimental due to a smaller beam pipe aperture A_Y and a larger β^{max}_Y in superconductive quadrupoles of the final focusing system (QCS)
- Simulation suggested to add vertical collimators at small β_Y to suppress this background in the interaction region

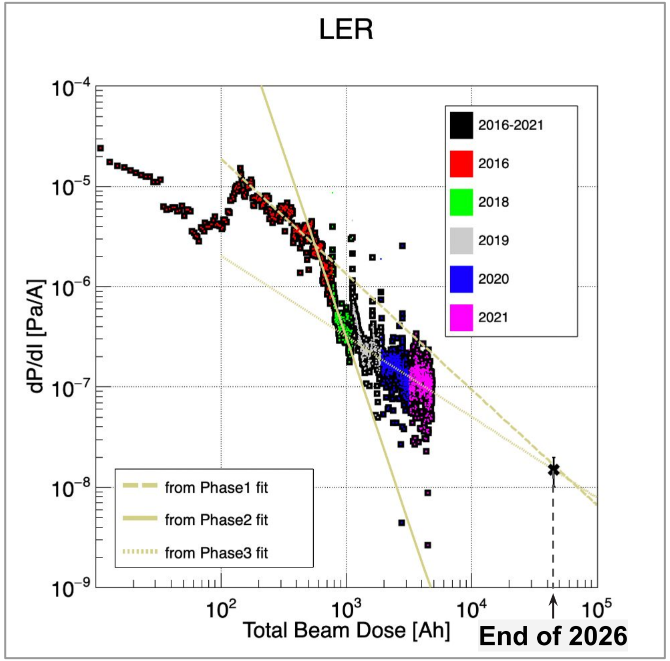


SuperKEKB interaction region (a) beta-function, (b) aperture, and (c) beam losses

Beam-induced background countermeasures: beam-gas scattering (2)

- Vacuum scrubbing reduces the residual gas pressure in the beam pipes
    - At much higher beam doses we may reach the hardware limit of 10 nPa for most of cold cathode gauges (CCG)
- The large values of dP/dI around 2016-2018 were the result of the electron cloud effect
    - Was cured by applying permanent magnets and solenoids around the beam pipe
- The beam-gas lifetime in SuperKEKB $\lesssim$1 hour, while in KEKB >10 hours

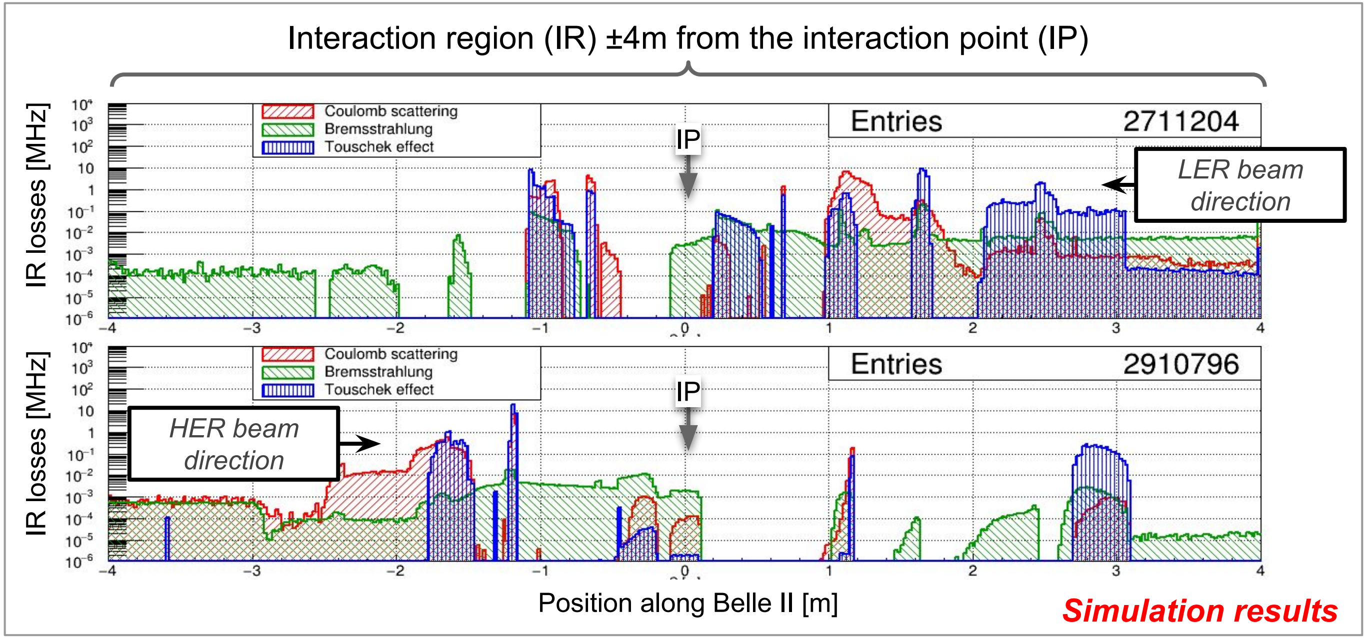
$$
\begin{aligned}
P &= P_{\text{dynamic}} + P_{\text{base}} \\
P_{\text{dynamic}} &= I \times dP/dI \\
P_{\text{base}} &= P(0\ \text{A}) \approx 10\ \text{nPa}
\end{aligned}
$$



An example of the LER dynamic pressure reduction due to vacuum scrubbing

Beam-induced background countermeasures: Touschek scattering

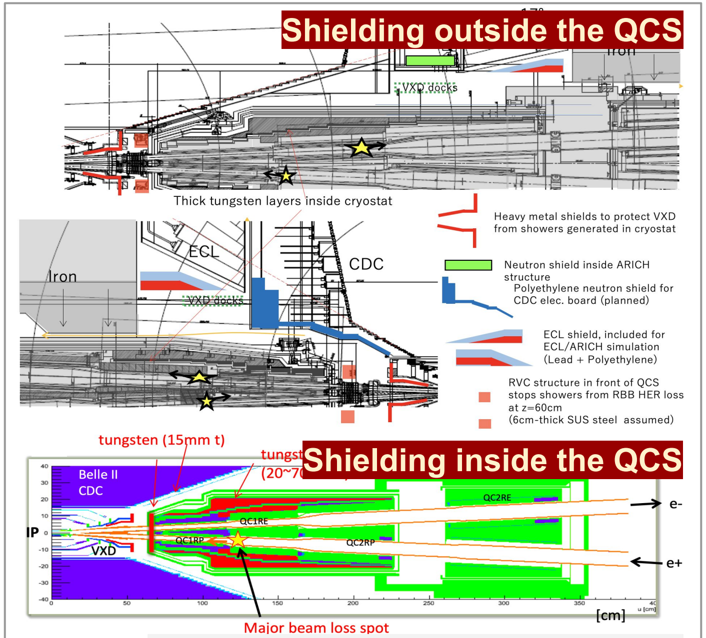
- **Initially**
  - Was assumed to be the most dangerous background ~$(\sigma_X \sigma_Y \sigma_Z)^{-1}$
  - Simulation suggested to add horizontal collimators upstream the IP at large β_X
- **Nowadays**
  - Only ~1% of the total ring Touschek losses occur in the IR
  - Beam lifetime is mainly defined by Touschek losses, τ ~10 (30) min for LER (HER)



Simulation results

Beam-induced background countermeasures: EM showers towards Belle II

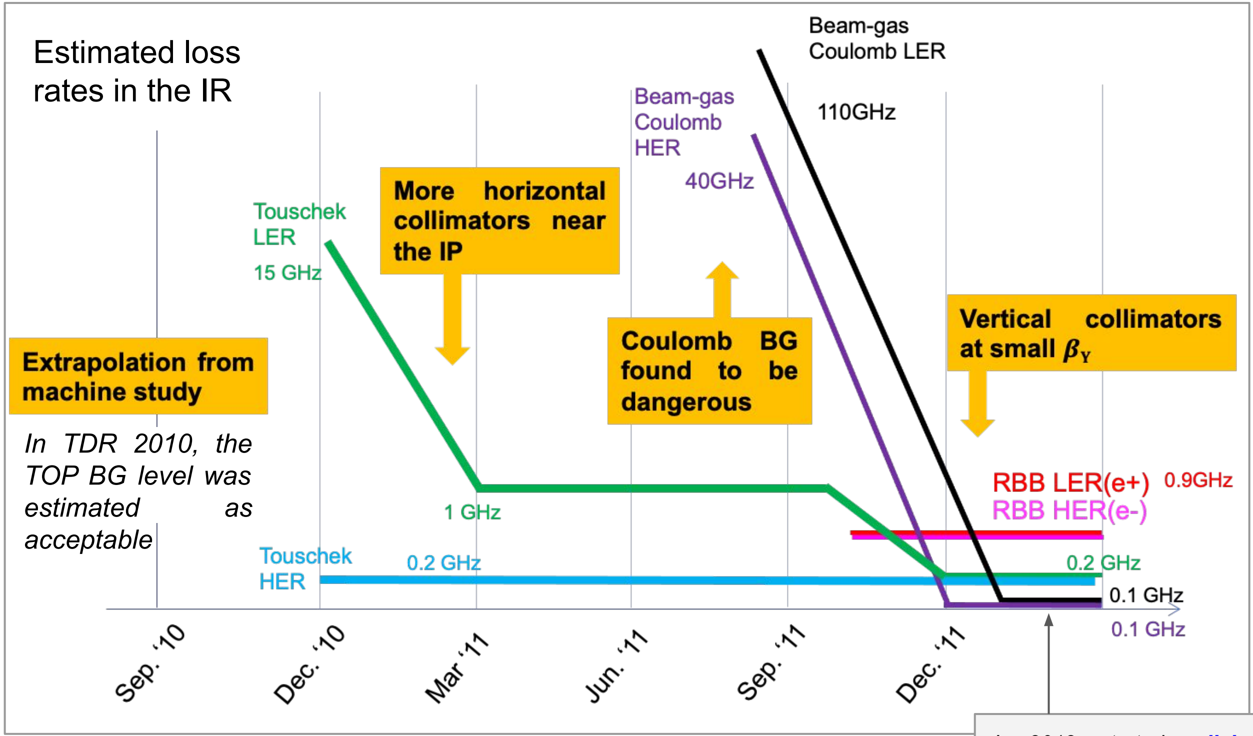
- Most of IR beam losses occur inside the QCS
    - Partially considered in 2010 [Belle II TDR]
    - Heavy metal shield inside QCS ← redesign was needed
    - Required a lot of time and negotiation with the QCS group
- Inner detectors protection
    - Heavy metal shield inside the vertex detector volume
    - Took years to find the optimal configuration due to space limitation and different material properties
- ECL cryostat/diode shielding
    - Polyethylene+lead shield inside ECL
    - Simulation campaign to find the best configuration
    - Preparation and design of the shield made in Canada
- ARICH HAPD protection from neutrons
    - Boron-doped polyethylene shield instead of the inner layer of the sub-detector
- TOP protection, the most dangerous level of the background
    - Installation of the additional bellows shield
        - Rejected in 2015, not enough space due to cables
        - Revisited in 2020, better understanding of backgrounds and new design approach
    - Under discussion to be installed for significant background reduction
- Single-event upsets (SEU) of FPGAs on CDC electronics boards
    - No additional shielding was implemented
    - **Now we start to see CDC SEUs**, still acceptable level



Based on H. Nakayama slides, KEK, IPAC’21

Timeline for machine background mitigation

TDR - - - Factor 1000 of the BG reduction! - - → **Commissioning**



Extrapolation from machine study

In TDR 2010, the TOP BG level was estimated as acceptable

More horizontal collimators near the IP

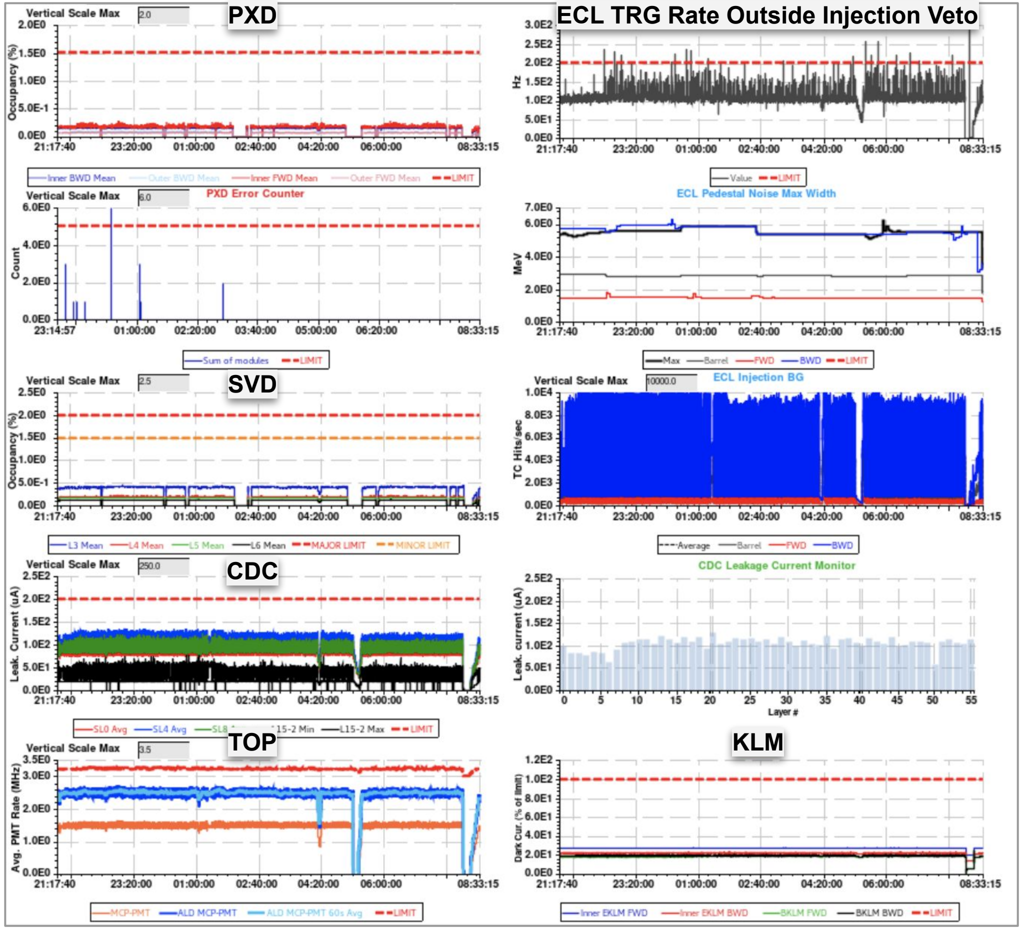
Coulomb BG found to be dangerous

Vertical collimators at small β_Y

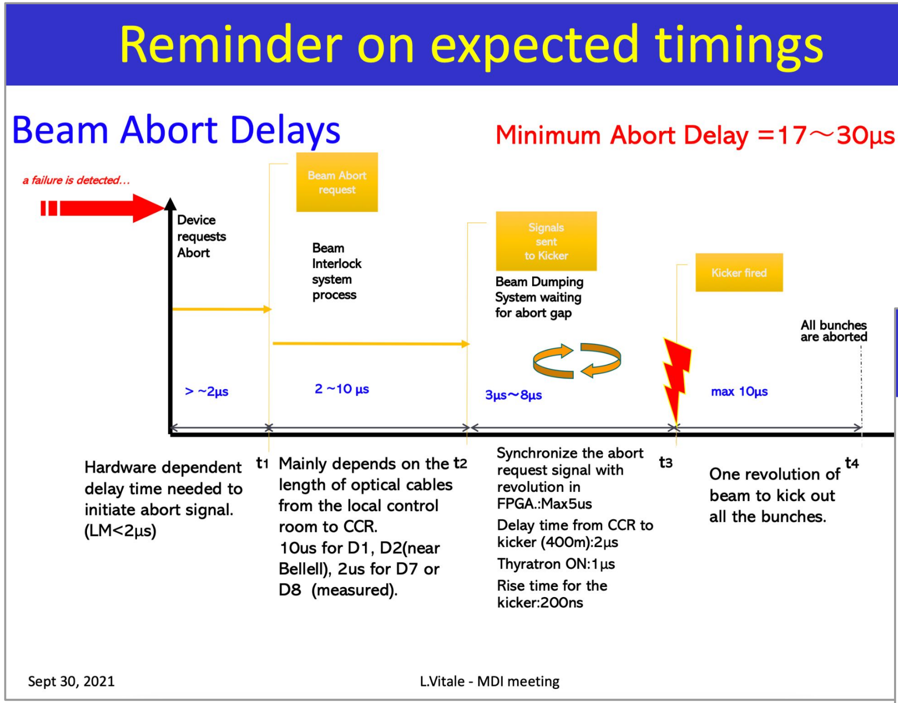
In 2012, started ***collaboration with the Italian SuperB group****. It was very beneficial and helped us a lot.*

Background level in 2021

- Current background rates in Belle II are acceptable and well below limits
- TOP is the most susceptible Belle II sub-detector to beam-induced backgrounds
    - Current accumulated charge allowed to rise the TOP PMT hit rate limit from 1.2 MHz/PMT to 3.0 MHz/PMT
    - TOP PMT replacement works are planned in 2022 due to quantum efficiency degradation of PMTs
- In 2021 Belle II did not limit beam currents



Screenshot of the beam commissioning group (BCG) display during SuperKEKB/Belle II operation in July 2021. Red, dashed line (---) is a limit



Reminder on expected timings

Beam Abort Delays

Minimum Abort Delay =17～30μs

a failure is detected…

Device requests Abort

Beam Abort request

Beam Interlock system process

Signals sent to Kicker

Beam Dumping System waiting for abort gap

Kicker fired

All bunches are aborted

> ~2μs

2 ~10 μs

3μs~8μs

max 10μs

Hardware dependent delay time needed to initiate abort signal. (LM<2μs)

t1

Mainly depends on the length of optical cables from the local control room to CCR.
10us for D1, D2(near Bellell), 2us for D7 or D8 (measured).

t2

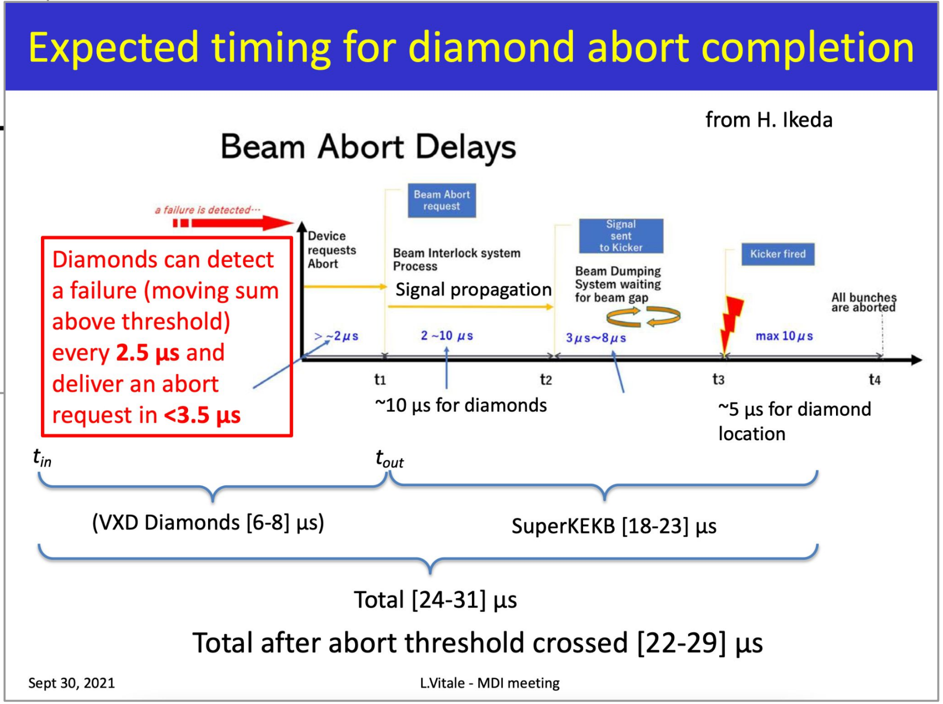
Synchronize the abort request signal with revolution in FPGA.:Max5us
Delay time from CCR to kicker (400m):2μs
Thyratron ON:1μs
Rise time for the kicker:200ns

t3

One revolution of beam to kick out all the bunches.

t4

Sept 30, 2021 L.Vitale - MDI meeting



Expected timing for diamond abort completion

from H. Ikeda

Beam Abort Delays

a failure is detected…

Device requests Abort

Beam Abort request

Beam Interlock system Process

Signal propagation

Signal sent to Kicker

Beam Dumping System waiting for beam gap

Kicker fired

All bunches are aborted

> ~2 μs

2 ~10 μs

3 μs~8 μs

max 10 μs

t1 t2 t3 t4

Diamonds can detect a failure (moving sum above threshold) every **2.5 μs** and deliver an abort request in **<3.5 μs**

~10 μs for diamonds

~5 μs for diamond location

t_{in} t_{out}

(VXD Diamonds [6-8] μs)

SuperKEKB [18-23] μs

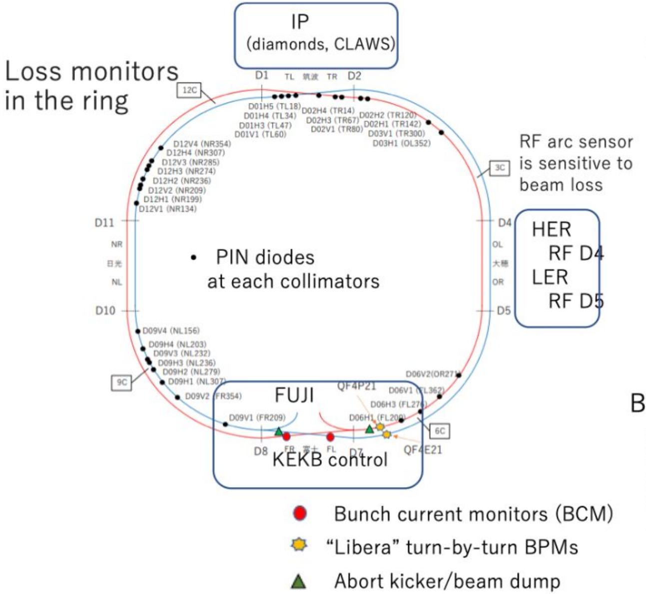
Total [24-31] μs

Total after abort threshold crossed [22-29] μs

Sept 30, 2021 L.Vitale - MDI meeting

H.Nakayama , KEK/MDI, 2021

Abort analysis


Loss monitors in the ring

IP (diamonds, CLAWS)

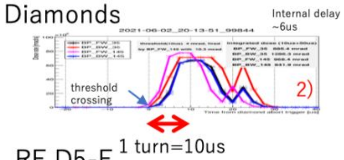
RF arc sensor is sensitive to beam loss

- PIN diodes at each collimators

HER RF D4
LER RF D5

FUJI
KEKB control

● Bunch current monitors (BCM)
✹ "Libera" turn-by-turn BPMs
▲ Abort kicker/beam dump

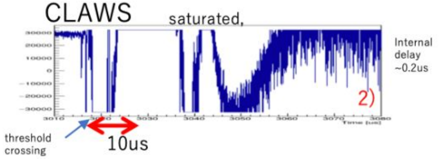

Diamonds

Internal delay ~6us

threshold crossing

2)

1 turn=10us


CLAWS

saturated,

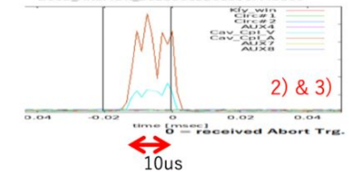
Internal delay ~0.2us

threshold crossing

2)

10us

Timing between sensors are synchronized by 1) abort kicker trigger signal, 2) abort request signal, or 3) "all beam kicked out" timing


RF D5-E

2) & 3)

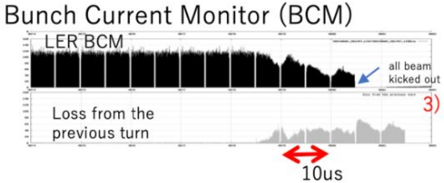
10us


PIN diodes on collimators

Long integration time

1us

1)


Bunch Current Monitor (BCM)

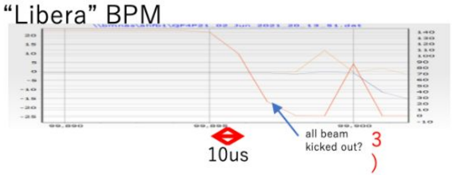
LER BCM

all beam kicked out

3)

Loss from the previous turn

10us


"Libera" BPM

all beam kicked out?

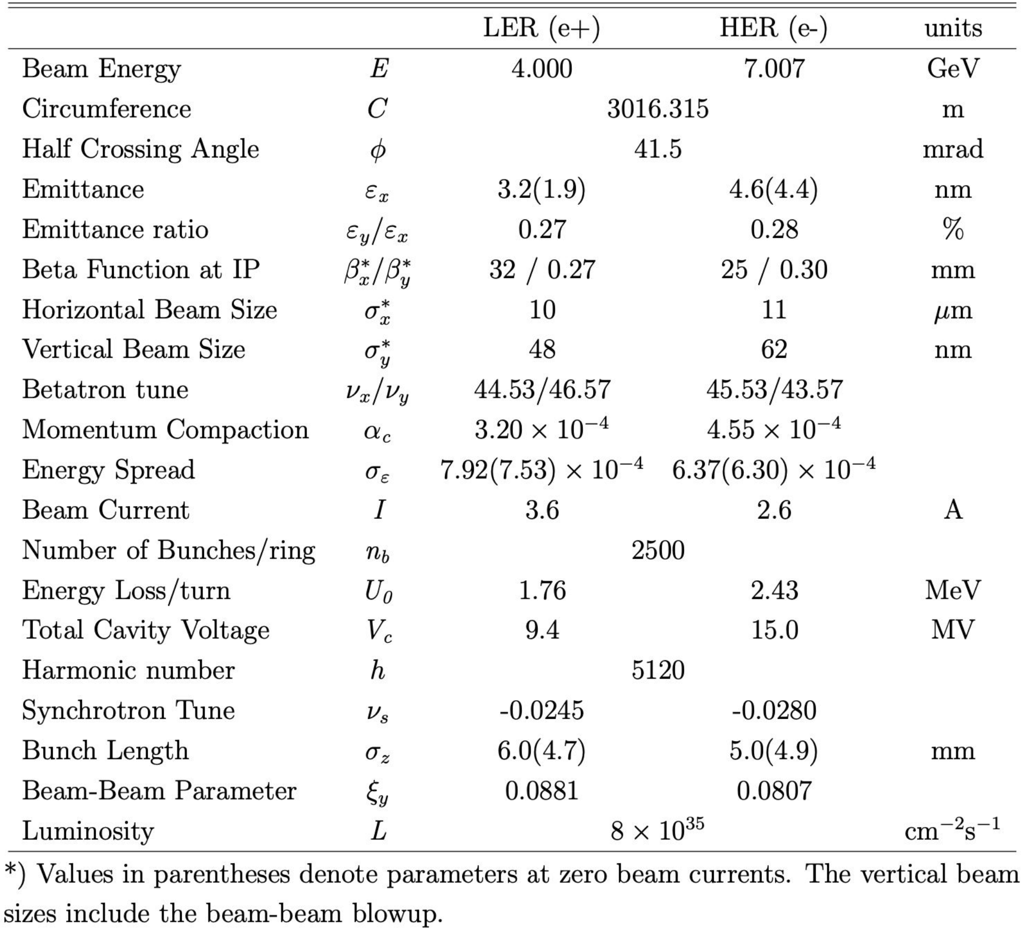
3)

10us

- By comparing beam loss timing among several sensors along the ring, we can find the possible area of initial beam loss.

- If we can add new beam loss sensors at some important collimators, it will help us pin-down the initial beam loss position of dangerous aborts.

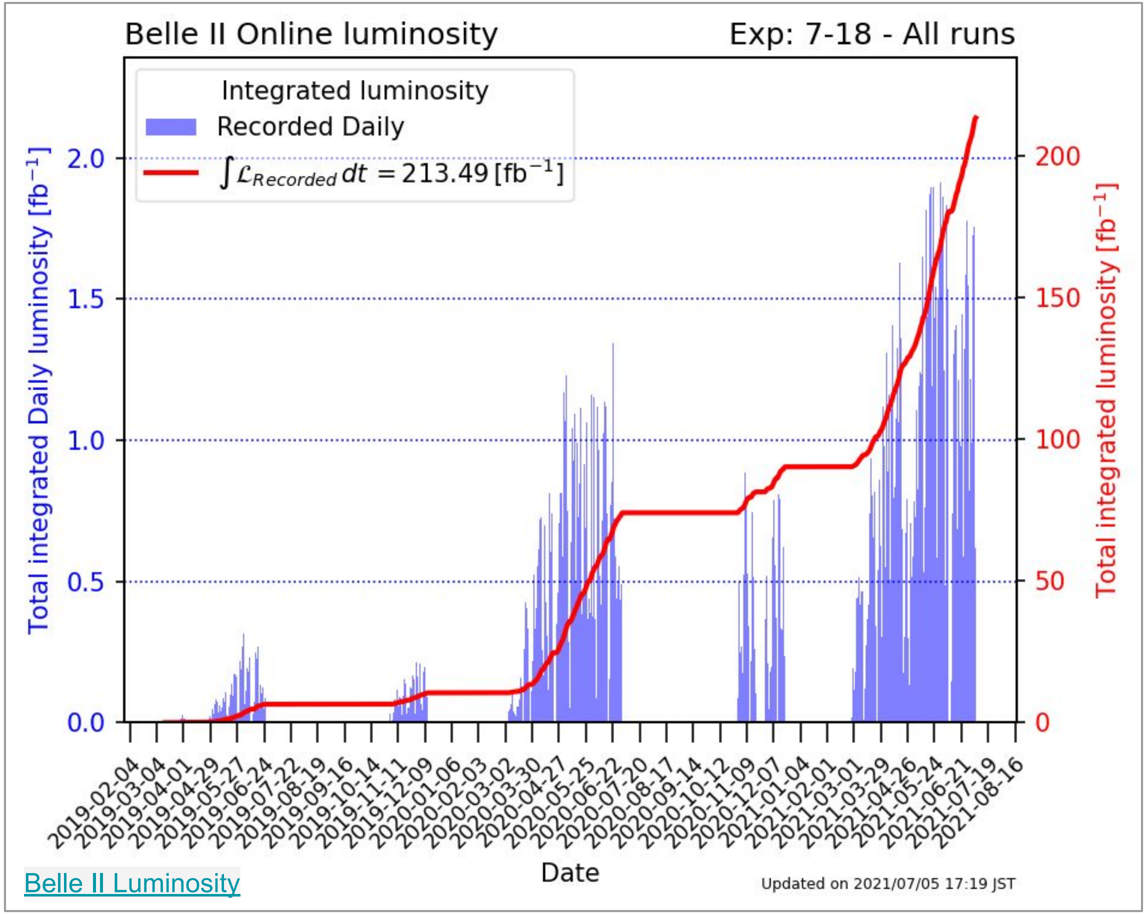
SuperKEKB design parameters



		LER (e+)	HER (e-)	units
Beam Energy	E	4.000	7.007	GeV
Circumference	C	3016.315		m
Half Crossing Angle	ϕ	41.5		mrad
Emittance	ε_x	3.2(1.9)	4.6(4.4)	nm
Emittance ratio	$\varepsilon_y/\varepsilon_x$	0.27	0.28	%
Beta Function at IP	β_x^*/β_y^*	32 / 0.27	25 / 0.30	mm
Horizontal Beam Size	σ_x^*	10	11	μm
Vertical Beam Size	σ_y^*	48	62	nm
Betatron tune	ν_x/ν_y	44.53/46.57	45.53/43.57	
Momentum Compaction	α_c	3.20×10^{-4}	4.55×10^{-4}	
Energy Spread	σ_ε	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$	
Beam Current	I	3.6	2.6	A
Number of Bunches/ring	n_b	2500		
Energy Loss/turn	U_0	1.76	2.43	MeV
Total Cavity Voltage	V_c	9.4	15.0	MV
Harmonic number	h	5120		
Synchrotron Tune	ν_s	-0.0245	-0.0280	
Bunch Length	σ_z	6.0(4.7)	5.0(4.9)	mm
Beam-Beam Parameter	ξ_y	0.0881	0.0807	
Luminosity	L	8×10^{35}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

*) Values in parentheses denote parameters at zero beam currents. The vertical beam sizes include the beam-beam blowup.

Phase3 integrated luminosity



Belle II Luminosity

Analysis procedure. Single-beam background fit

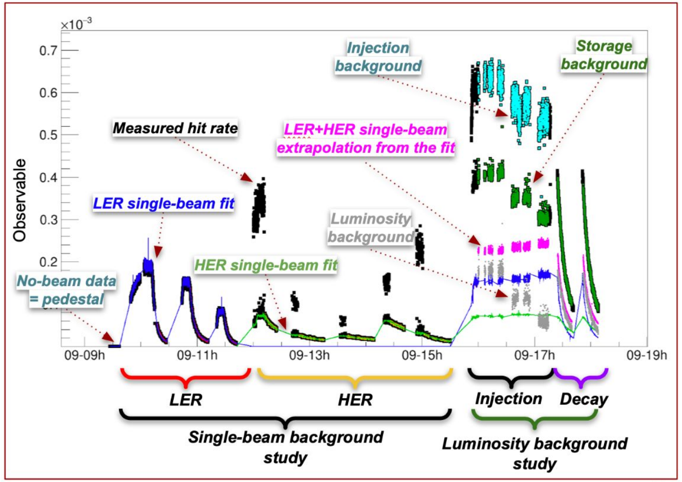
1. No-beam data is used for statistical error estimation and pedestal measurements
2. Subtract the pedestal (only Diamonds, PXD and SVD)
3. Fit observables for LER and HER background studies (only beam decay)
4. Extrapolate single-beam backgrounds to the collision (luminosity) background study
5. Extract the luminosity component
   difference between collision data and extrapolated single-beam backgrounds scaled by the Touschek lifetime correction factor
6. Linear fit of the luminosity background
7. Extrapolate single-beam and luminosity backgrounds to the simulated beam parameters
8. Calculate data/MC ratios

Diamonds, PXD & SVD

$$O = T\frac{I^2}{\sigma_X\sigma_Y\sigma_S n_b} + B_2PI - B_3I$$

CDC, TOP, ARICH, KLM

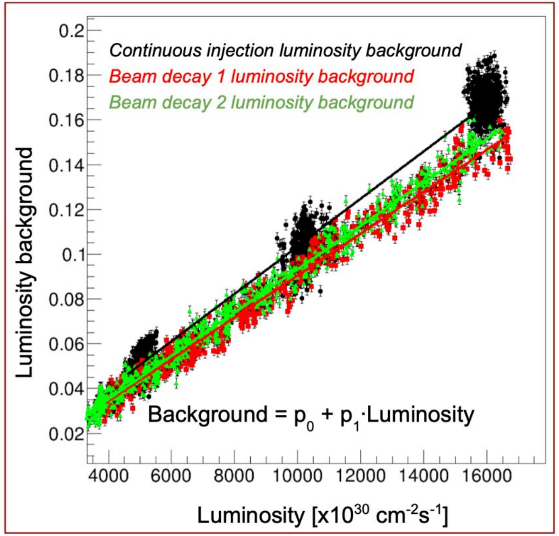
$$O = T\frac{I^2}{\sigma_X\sigma_Y\sigma_S n_b} + B_2PI - B_3I + D$$



round fit

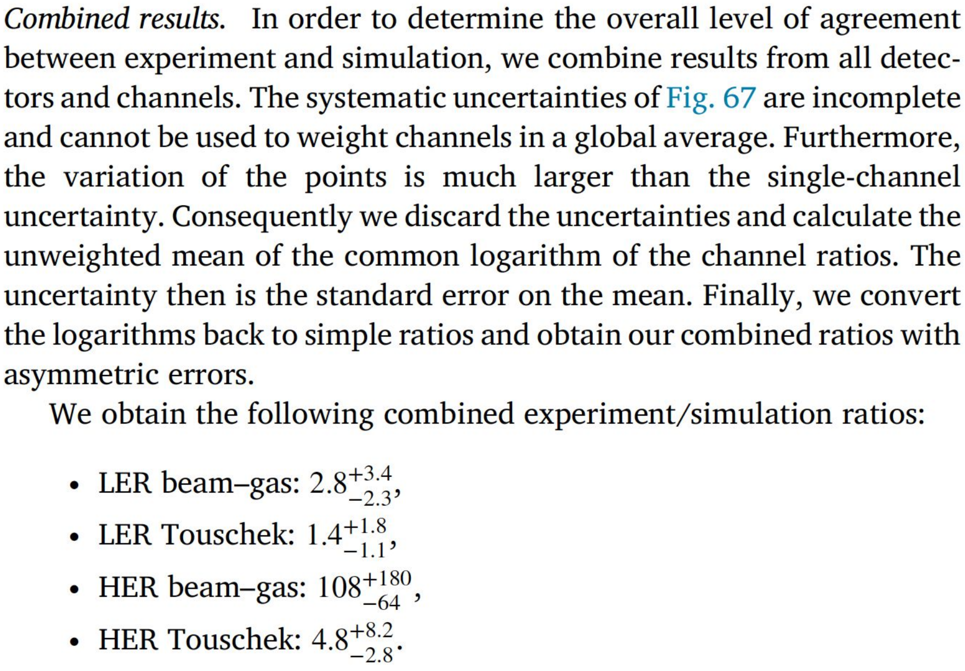
by the Touschek lifetime correction factor

6. Linear fit of the luminosity background
7. Extrapolate single-beam and luminosity backgrounds to the simulated beam parameters
8. Calculate data/MC ratios



Phase 1 data/MC ratios

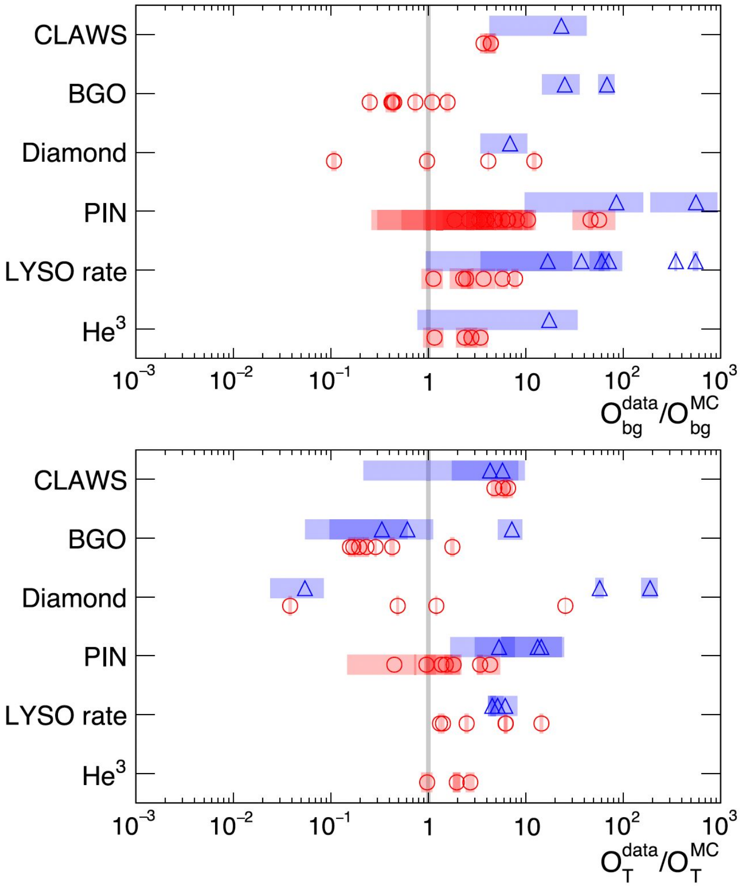
[P.M.Lewis *et al.*, “First measurements of beam backgrounds at SuperKEKB”, NIMA 2019]



Combined results. In order to determine the overall level of agreement between experiment and simulation, we combine results from all detectors and channels. The systematic uncertainties of Fig. 67 are incomplete and cannot be used to weight channels in a global average. Furthermore, the variation of the points is much larger than the single-channel uncertainty. Consequently we discard the uncertainties and calculate the unweighted mean of the common logarithm of the channel ratios. The uncertainty then is the standard error on the mean. Finally, we convert the logarithms back to simple ratios and obtain our combined ratios with asymmetric errors.

We obtain the following combined experiment/simulation ratios:

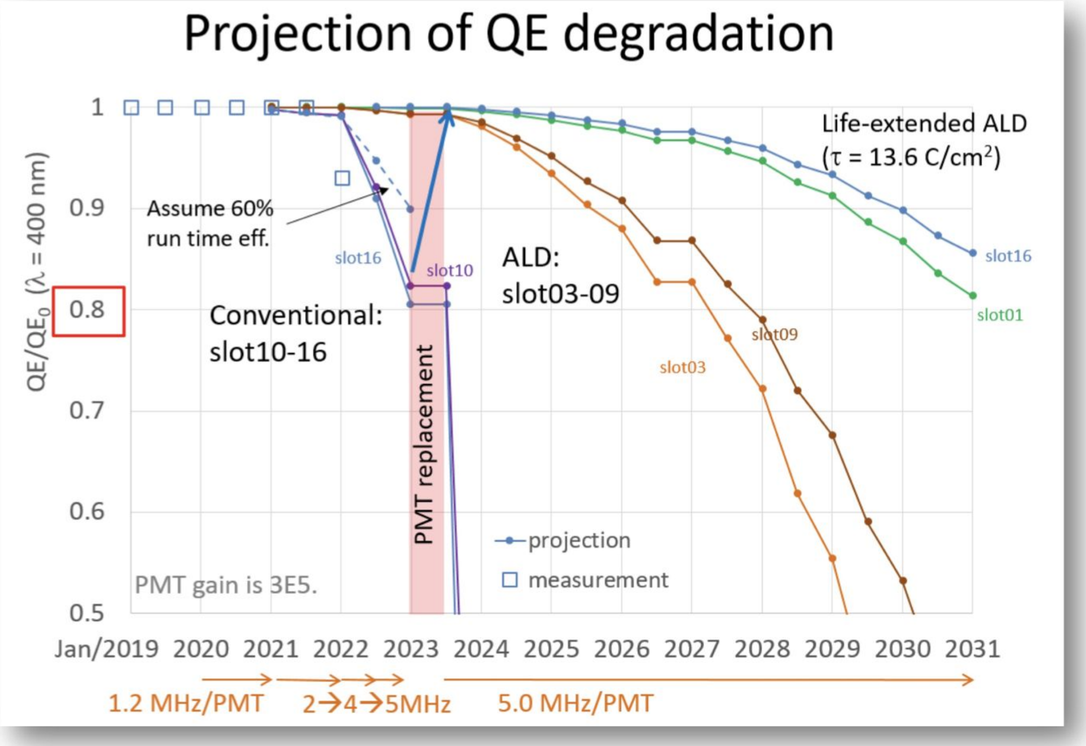
- LER beam–gas: $2.8^{+3.4}_{-2.3}$,
- LER Touschek: $1.4^{+1.8}_{-1.1}$,
- HER beam–gas: 108^{+180}_{-64},
- HER Touschek: $4.8^{+8.2}_{-2.8}$.



MCP-PMT QE Projection & Hit Rate Limit

"Status and plan for MCP-PMT replacement" by K. Inami at 41st B2GM TOP session

The hit rate limit for beam-induced backgrounds can be increased gradually **up to 5 MHz/PMT.**



K. Kojima, et al. / 41st B2GM Background Session