HEP Journal Club Seminar

Beam Background Expectations for Belle II at SuperKEKB

by Andrii Natochii (University of Hawaii at Manoa)

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AF5: Accelerators for PBC and Rare Processes

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Paper contents

Cornell University

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High Energy Physics – Experiment

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The Belle II experiment at the SuperKEKB electron-positron collider aims to collect an unprecedented data set of $50\ \mathrm{ab}^{-1}$ to study CP-violation in the B-meson system and to search for Physics beyond the Standard Model (BSM). SuperKEKB is already the world's highest-luminosity collider. In order to collect the planned data set within approximately one decade, the target is to reach a peak luminosity of $6.3\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ by further increasing the beam currents and reducing the beam-size at the interaction point by squeezing the betatron function down to $\beta^*_{\mathrm{y}} = 0.3$ mm. Beam backgrounds are a key challenge in this context. We estimate the expected background evolution in the next ten years and discuss potential challenges and background mitigation strategies. We find that backgrounds will remain high but acceptable until a luminosity of at least $2.8\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ is reached at $\beta^*_{\mathrm{y}} = 0.6$ mm. Beyond this luminosity, predictions are highly uncertain, owing to a planned redesign of the interaction region. Improved background estimates with reduced uncertainties for the final, maximum-luminosity operation will require completion of this redesign.

Comments: Contribution to Snowmass 2021. 25 pages, 9 figures, 2 tables. For the update v1 -> v2, we put the corrected Snowmass topical group number AF06 -> AF05

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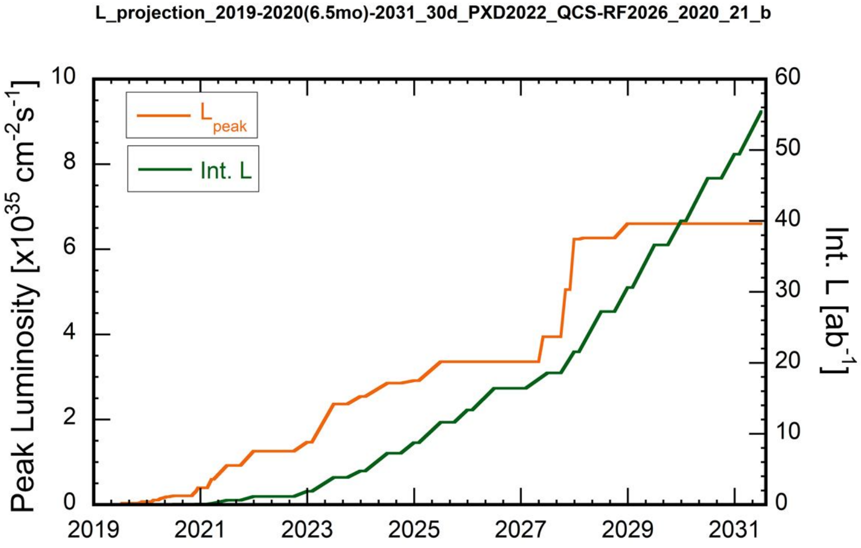
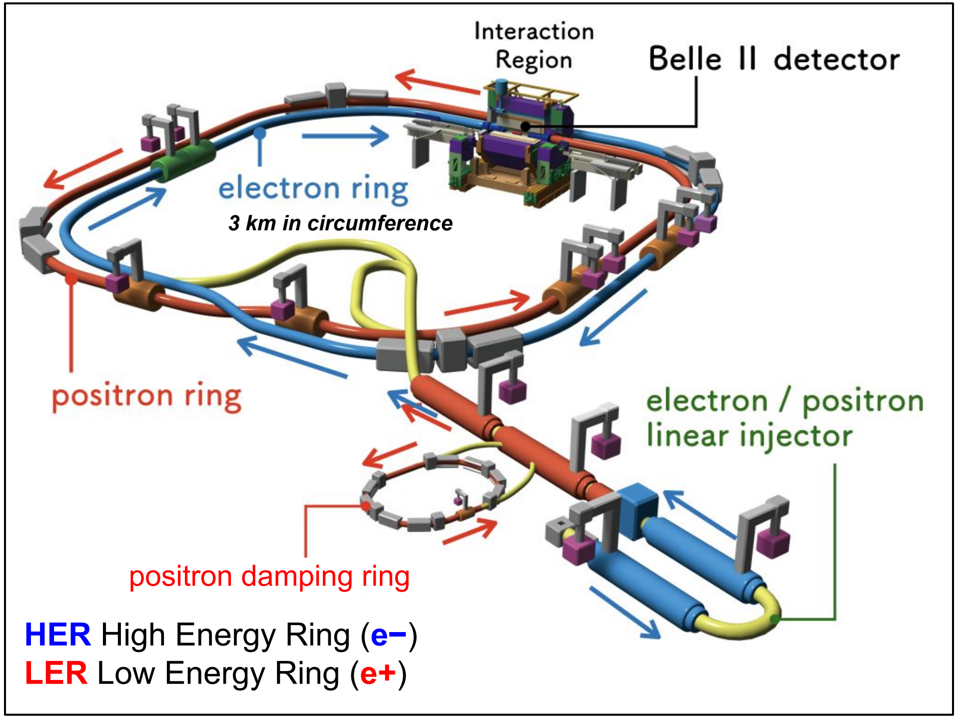
Overview

- Belle II goal
  - Collect 50 ab^{-1} of data by 2030s to study *CP*-violation in the *B*-meson system
- SuperKEKB target peak luminosity
  - $L = 6.3 \times 10^{35}\ cm^{-2}s^{-1}$
    - Squeezing beam sizes at the IP
    - Increasing beam currents
- Challenges
  - Stable machine operation
  - Acceptable beam-induced backgrounds
- Results of the background prediction study
  - Expected backgrounds in Belle II are below detector limits until $L = 2.8 \times 10^{35}\ cm^{-2}s^{-1}$
  - Beyond this value the prediction is very uncertain
    - Redesign of the interaction region is needed
    - The target machine lattice review is ongoing



Luminosity projection

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

Luminosity gain

Beam current

Beam-beam parameter

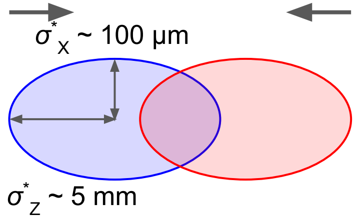
$$L = \frac{\gamma_\pm}{2er_e} \cdot \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \cdot \boxed{\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)} \cdot \left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

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
L_{peak}	**: 2.1×10^{34}**	**→ 6.3×10^{35} cm^{-2}s^{-1}**

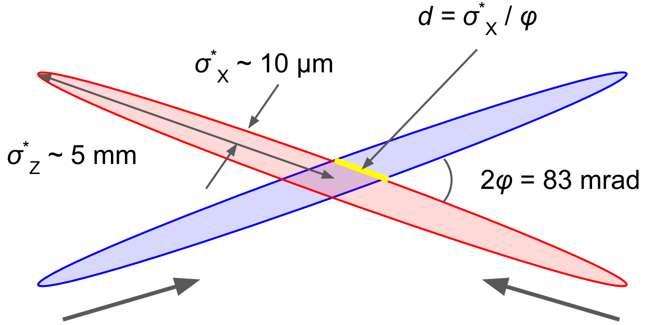
Factor of **30** increase in luminosity
based on the **nano-beam scheme**!

KEKB head-on
(crab crossing)



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

SuperKEKB
nano-beam + crab waist scheme

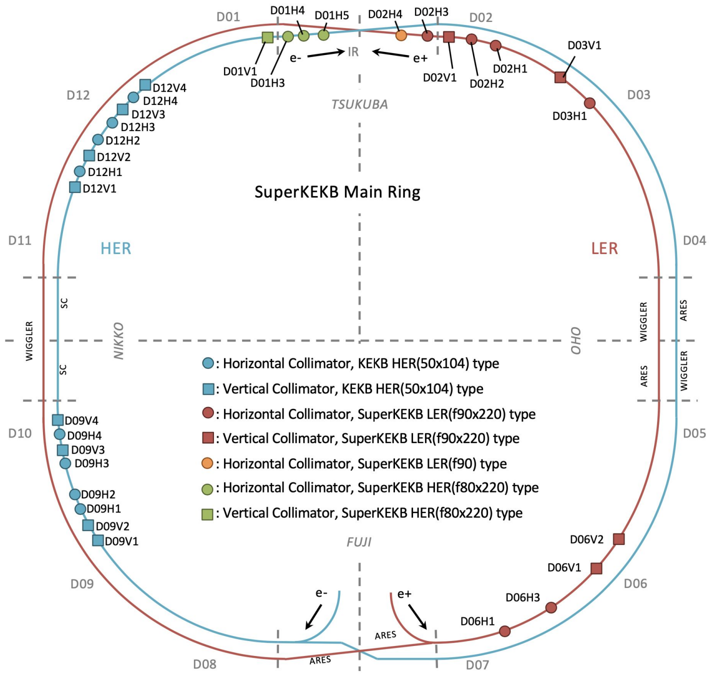


Overlap region << bunch length
Hourglass requirement:
$\beta^*_Y \geq \sigma^*_Z$ ~240 μm

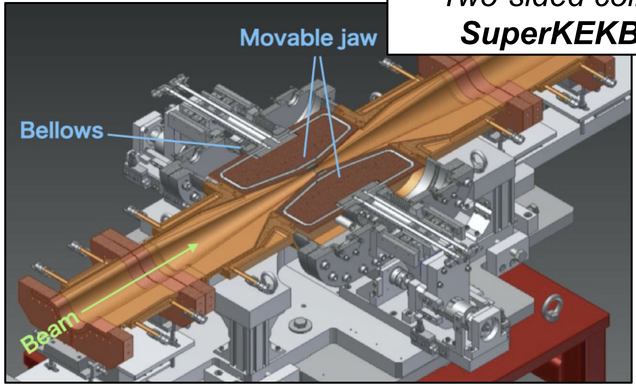
Beam halo cleaning

To avoid radiation damage to the Belle II detector and to avoid QCS quenches due to stray beam particles

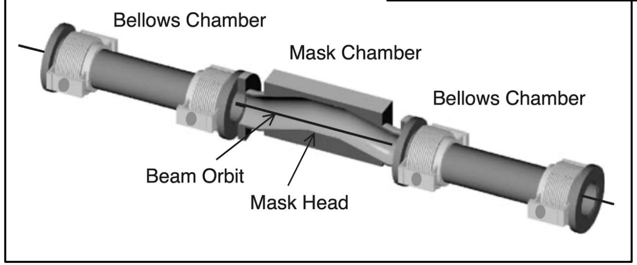
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)



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



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



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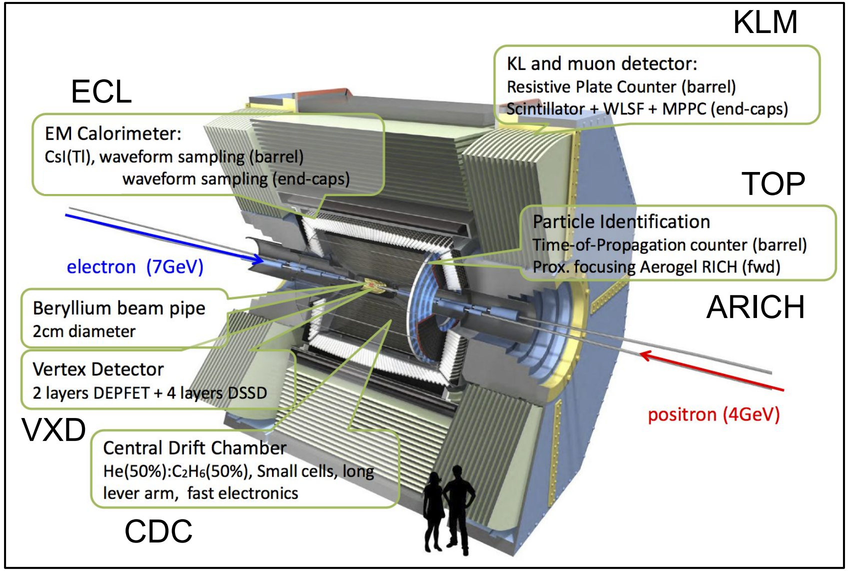
Belle → Belle II upgrades

Designed and optimized for the observation of

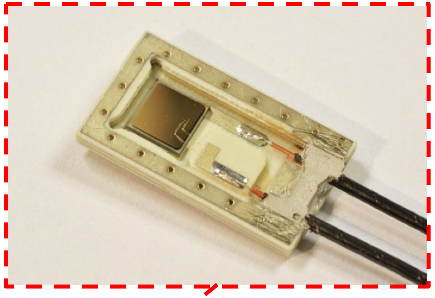
***CP*-violation in the *B*-meson system**

- 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



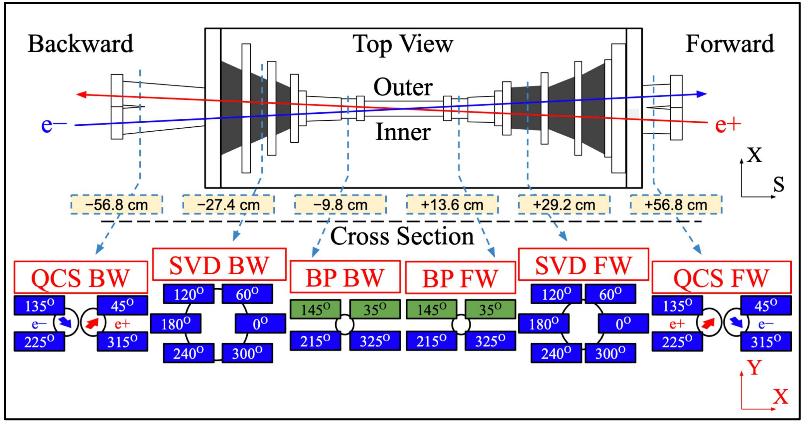
Belle II detector

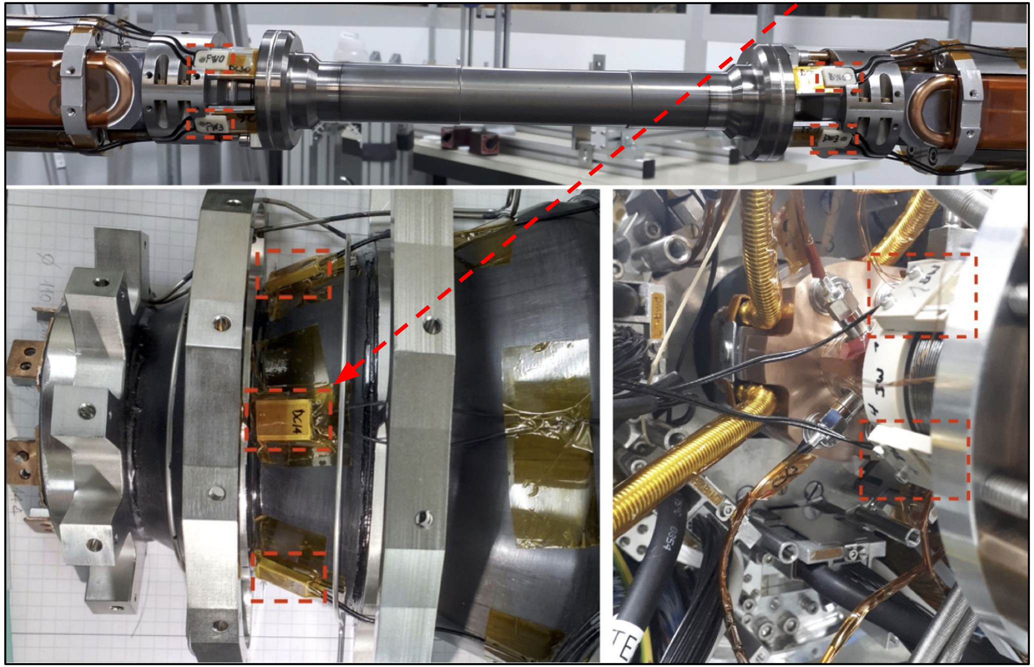
Beam background monitoring system: Diamonds



Diamond sensor-based detectors (Diamonds)

- Monitor the radiation dose rate around the IR beam pipe
- Four sensors (green) are a part of the fast beam abort system



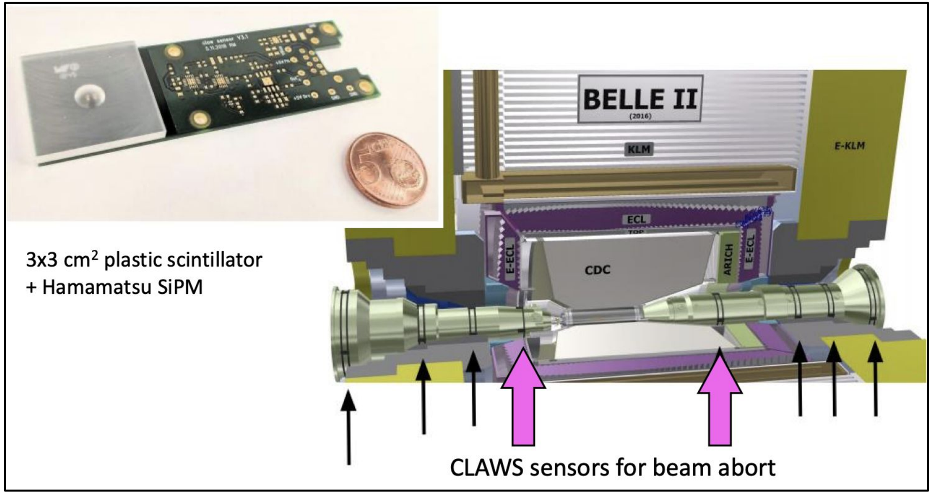


Beam background monitoring system: CLAWS

The sCintillation Light And Waveform Sensors (CLAWS) detector system, based on plastic scintillators and silicon photomultipliers, is primarily used for

- Monitoring Belle II backgrounds in time with beam injection into the main ring
- Included into the beam abort logic
- Excellent timing performance

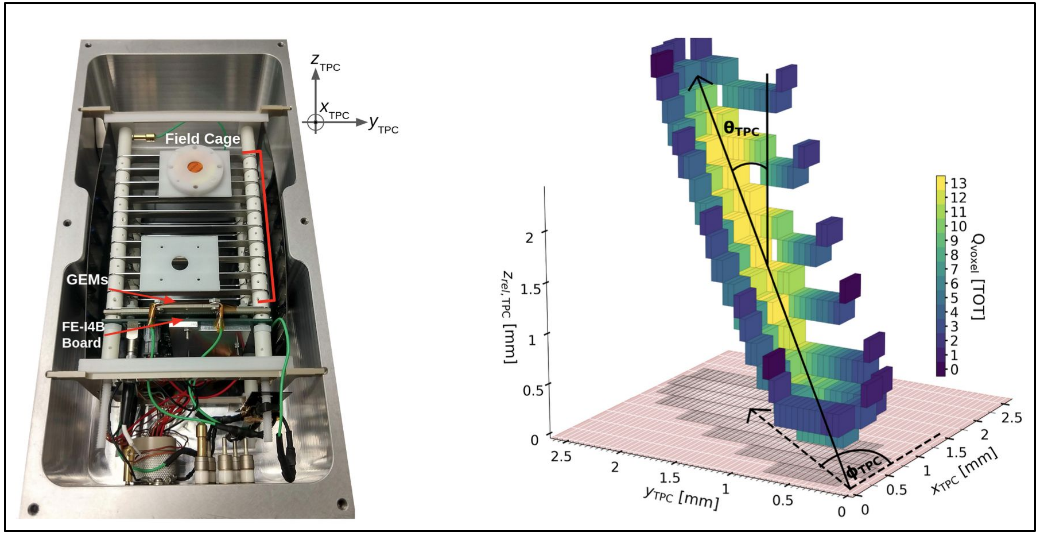
Can trigger a beam abort ~10μs earlier than Diamonds



Beam background monitoring system: TPC & He3-tubes

Time Projection Chambers (TPCs)

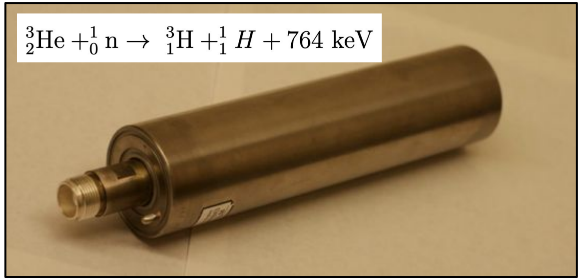
- Provide directional measurements of the fast neutron flux in the accelerator tunnel
- Three TPCs in FWD and BWD tunnels



***Left:** Internal structure of the TPC. **Right:** Visualization of a nuclear recoil track reconstructed into 3D voxels.*

He3-tubes

- Used for the thermal neutron counting around Belle II



Stainless steel tubes 24 cm long and 5 cm in diameter filled with ^{3}He at 4 atm of pressure.

Future machine and detector upgrades

There are two major upgrades of the machine planned in the next ten years

- **Long Shutdown 1 (LS1)** in 2022-2023
  - VXD detector upgrade
  - Installation of a new IP beam pipe with an additional gold layer and slightly modified geometry to reduce the amount of the backscattered SR
  - Replace the TOP short lifetime conventional MCP-PMTs due to their quantum efficiency degradation
  - Additional EM and neutrons shielding installation (under discussion)
  - Non-linear collimation (NLC) insertion (under discussion)
    - A pair of skew sextupole magnets and V-collimator in between
- **Long Shutdown 2 (LS2)** around 2027 (under discussions)
  - IR upgrade

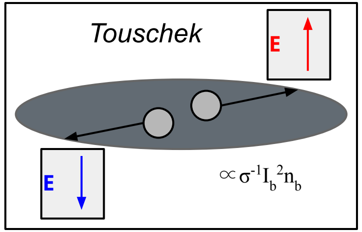
Our possible future upgrade of the detector is strongly linked to upgrades of the machine

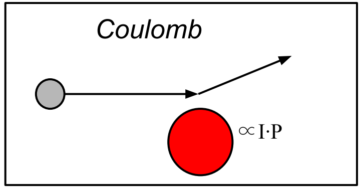
End of the machine and detector overview section

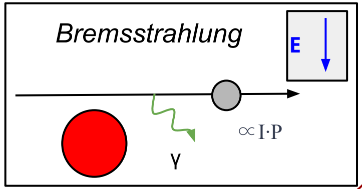
Questions?

Beam background sources

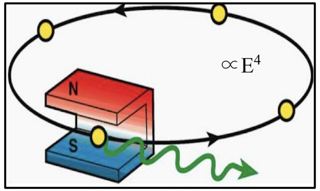
Particle scattering (Single-beam)



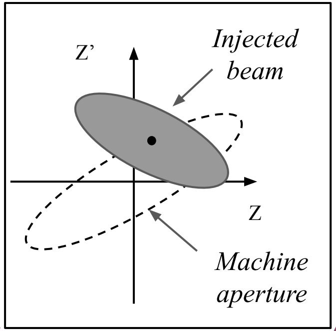




Synchrotron radiation

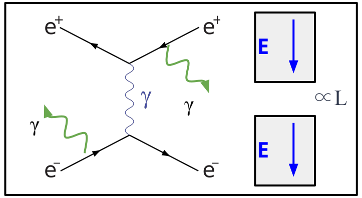


Injection (top-up, continuous)

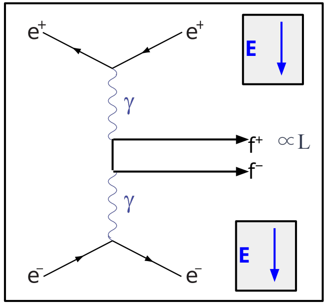


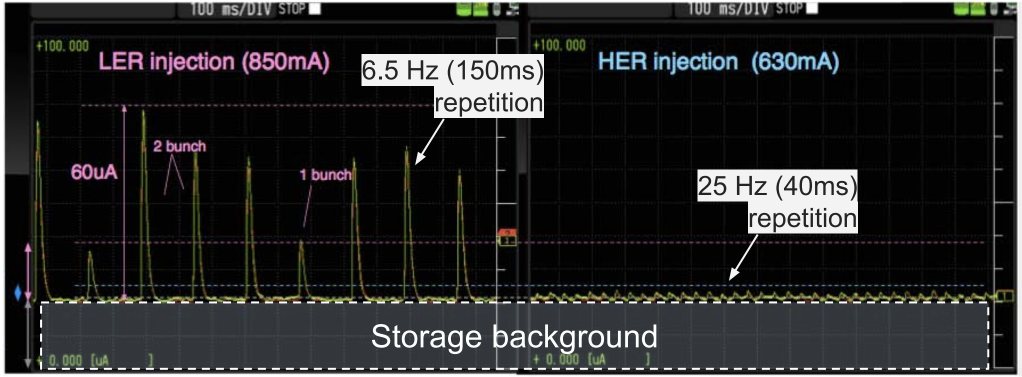
Colliding beams (Luminosity)

Radiative Bhabha proc.



Two-photon proc.



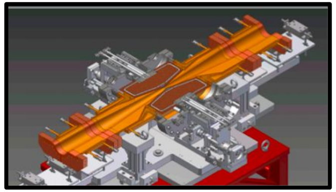


CDC leakage current during injection

Beam background countermeasures

Particle scattering (Single-beam)

Collimators *(off-momentum particles stop)*, Vacuum scrubbing *(residual gas pressure reduction)*, Heavy-metal shield outside the IR beam pipe *(detector protection against EM showers)*

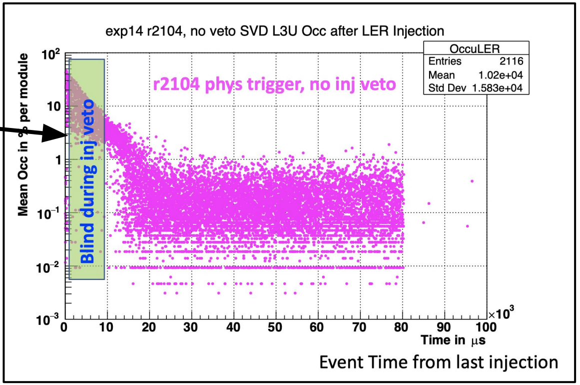


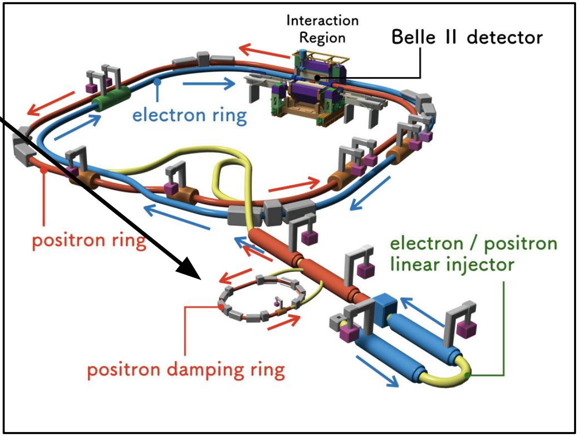

Injection

Injection trigger veto

Injection chain tuning

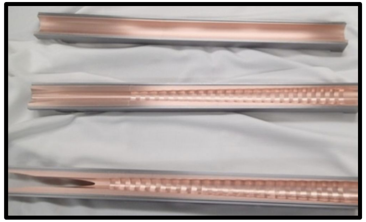
Damping ring for positrons *(to reduce the emittance)*





Synchrotron radiation

Beryllium beam pipe is coated with a gold layer + ridge surface of the beam-pipe *(to avoid direct SR hits at the detector)*

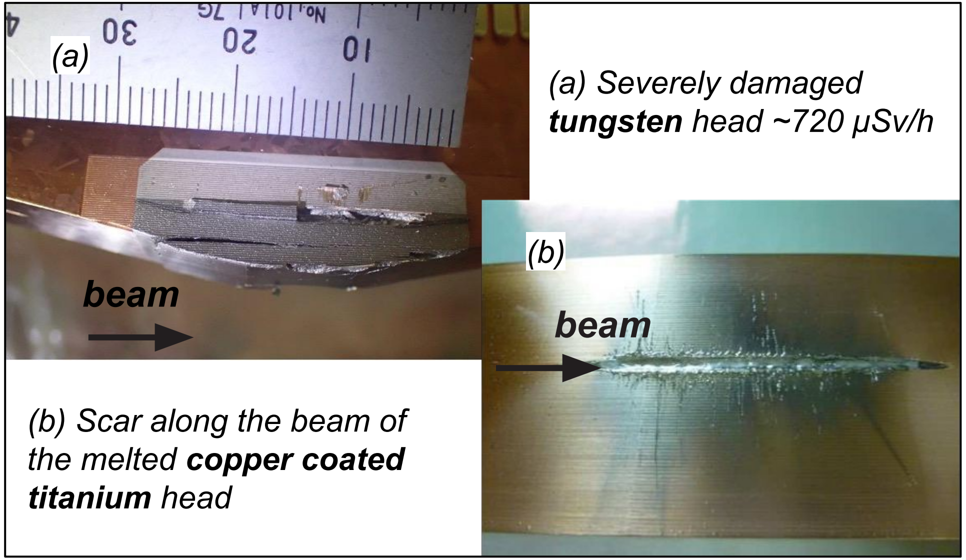


Colliding beams (Luminosity)

Steel and polyethylene shields *(neutrons flux reduction)*

Uncontrolled beam losses

- During stable machine operation unexplained beam instabilities and beam losses may occasionally occur in one of the rings
  - One shot at a specific location around the ring due to
    - Injection kicker errors
    - Beam-dust interacting
    - Unknown reasons (under discussion)
- Consequences
  - Detector or collimators damage
  - Superconducting magnet quenches
- Usually only a few such catastrophic beam loss events happen per year
- Cures
  - Upgraded abort system → fast abort signal
    - Diamonds
    - + CLAWS detectors near the IR
    - + CsI-crystals around each ring (pin down high beam losses)



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

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

Detector background limits

Table 1: Background rate limits for different Belle II detector sub-systems. The third column shows the total measured background rate in June 2021 excluding the pedestal rate. TOP limits before/after LS1 are related to the replacement of TOP conventional PMTs planned for the LS1. The upper background rate limit quoted for the Diamond read-out electronics can be increased by selecting a lower signal amplification. The KLM detector limit corresponds to the muon reconstruction efficiency drop of about 10 %.

Detector	BG rate limit			Measured BG
Diamonds	1–2 rad/s			< 125 mrad/s
PXD	3 %			0.11 %
SVD L3, L4, L5, L6	4.7 %, 2.4 %, 1.8 %, 1.2 %			< 0.22 %
CDC	200 kHz/wire			27 kHz/wire
ARICH	10 MHz/HAPD			0.5 MHz/HAPD
Barrel KLM L3	50 MHz			3.8 MHz
	non-luminosity BG		luminosity BG	
	before LS1	after LS1	per 10^{35} $cm^{-2}s^{-1}$	
TOP ALD	3 MHz/PMT	5 MHz/PMT	0.9 MHz/PMT	2 MHz/PMT

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Measured Belle II background level

- Dominant backgrounds
  - LER single-beam
  - Luminosity
- HER single-beam background ~10%
- SR is of no concern for the PXD
- We start to see single-event upsets (SEUs) due to EM shows and neutrons

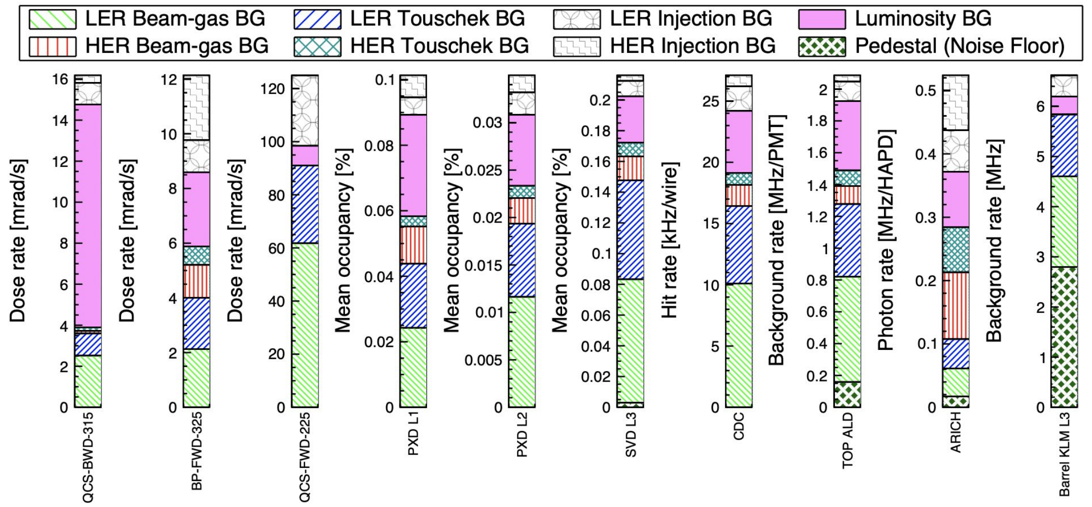


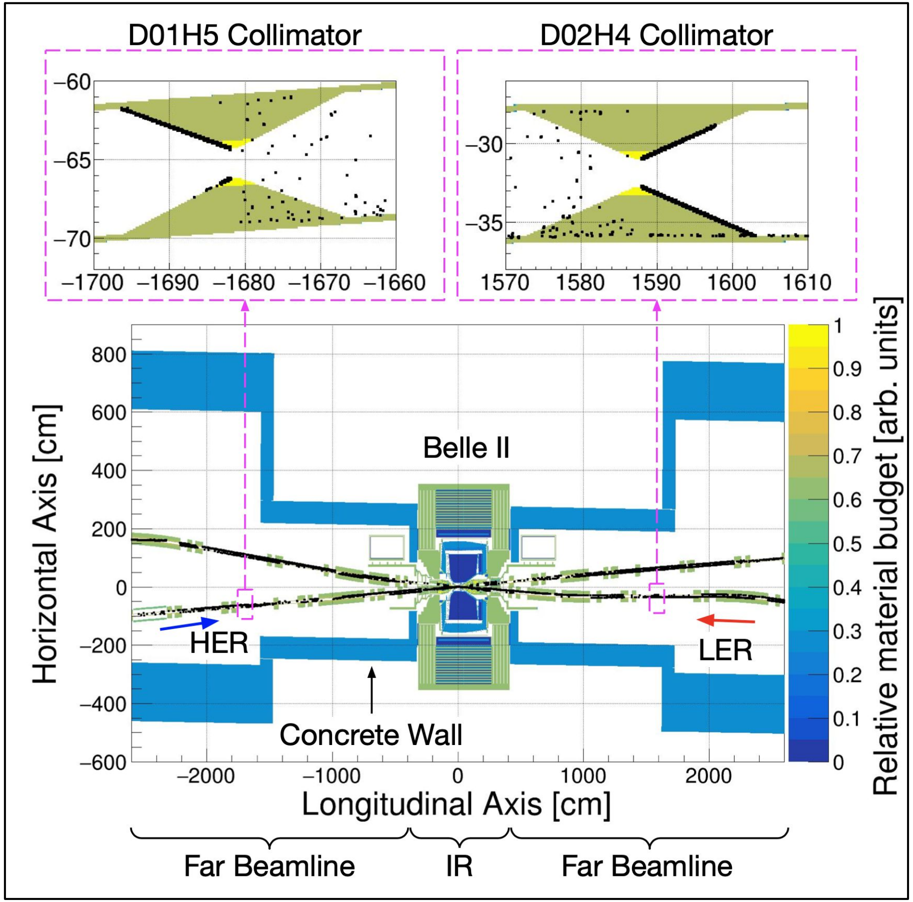
Figure 4: Measured Belle II background in June 2021. Each column is a stacked histogram. The PXD SR background is too low ($< 1 \times 10^{-3}$ %) to be displayed. QCS-BWD-315, BP-FWD-325 and QCS-FWD-225 indicates backward QCS, beam pipe and forward QCS Diamond detectors, respectively, with the higher dose rate. Barrel KLM L3 corresponds to the innermost RPC layer in the barrel region of the KLM detector. TOP ALD shows the averaged background over ALD-type MCP-PMTs, slots from 3 to 8.

End of the background overview section

Questions?

Beam background simulation

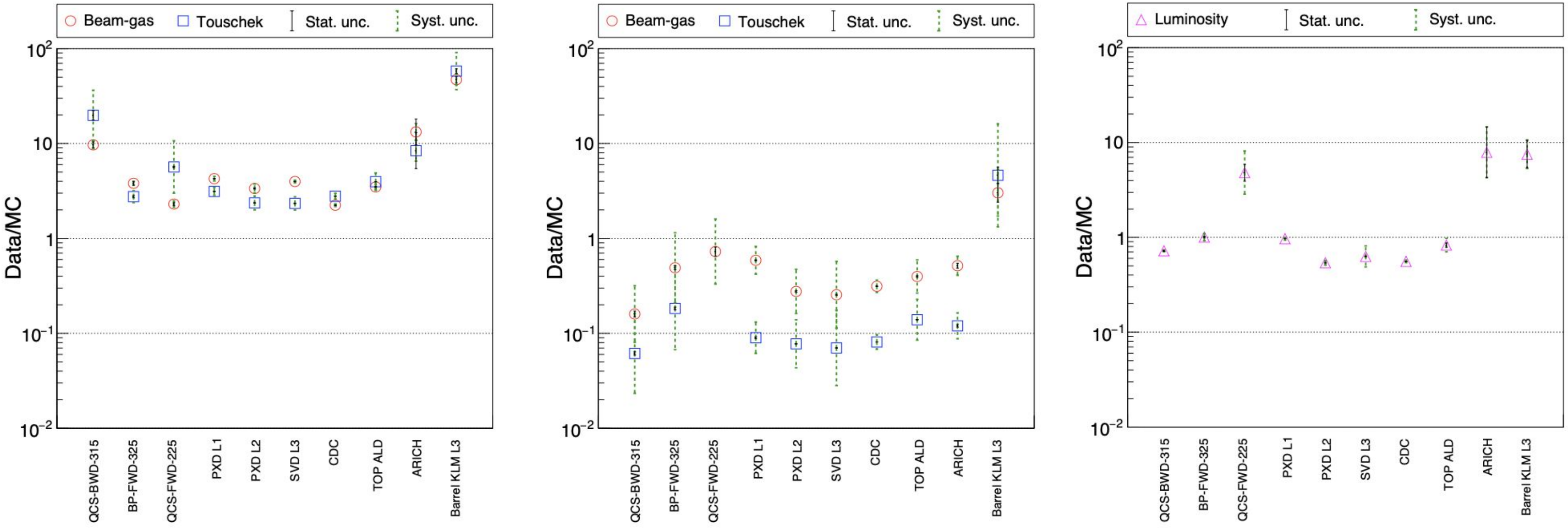
- **Single-beam background:**
  - Strategic Accelerator Design (SAD @KEK, multi-turn particle tracking)
    - Realistic collimator shape
    - Particle interaction with collimator materials
    - Measured residual gas pressure distribution around each ring
  - Geant4 (detector modeling)
    - Realistic 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)



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

Background prediction accuracy

- Ratios of measured to simulated background rates, a.k.a. data/MC ratios
    - Illustrate accuracy of our beam background prediction
- They are now within one order of magnitude of unity
    - Based on May & June 2020 and June 2021 dedicated background studies
    - Substantial improvement compared to the early SuperKEKB commissioning phases in 2016 and 2018



(a) LER single-beam background. (b) HER single-beam background. (c) Luminosity background.

Background prediction for higher luminosities

Table 2: Predicted SuperKEKB parameters, expected to be achieved by the specified date. β^*, $\mathcal{L}$, I, $BD_{\rm int}$, $\overline{P}$, n_b, ε, σ_z and CW stand for the betatron function at the interaction point, luminosity, beam current, integrated beam dose, average beam pipe gas pressure, number of bunches, equilibrium beam emittance, bunch length and Crab-Waist sextupoles, respectively.

Parameter	Setup-1	Setup-2	Setup-3
Date	Jan 2023	Jan 2027	Jan 2031
β_y^*(LER/HER) [mm]	0.8/0.8	0.6/0.6	0.27/0.3
β_x^*(LER/HER) [mm]	60/60	60/60	32/25
$\mathcal{L}$ [$\times 10^{35}$ cm^{-2}s^{-1}]	1.0	2.8	6.3
I(LER/HER) [A]	1.66/1.20	2.52/1.82	2.80/2.00
$BD_{\rm int}$ [kAh]	10	45	93
$\overline{P}$(LER/HER) [nPa]	93/23	48/17	33/15
n_b [bunches]	1370	1576	1761
ε_x(LER/HER) [nm]	4.5/4.5	4.6/4.5	3.3/4.6
$\varepsilon_y/\varepsilon_x$(LER/HER) [%]	1/1	1/1	0.27/0.28
σ_z(LER/HER) [mm]	7.58/7.22	8.27/7.60	8.25/7.58
CW	ON	ON	OFF

Based on the SuperKEKB Roadmap-2020

We have only old optics files for the design lattice

- No solution for the Crab-Waist scheme
  - *Narrow dynamic aperture (DA)*
  - *Too short beam lifetime*
- Final IR geometry is not defined

Setup-2*: Non-linear collimation
LER insersion with two skew sextupoles +
V-collimator → beam halo cleaning in both planes

Expected backgrounds

$\beta^*_Y = 0.8$ mm

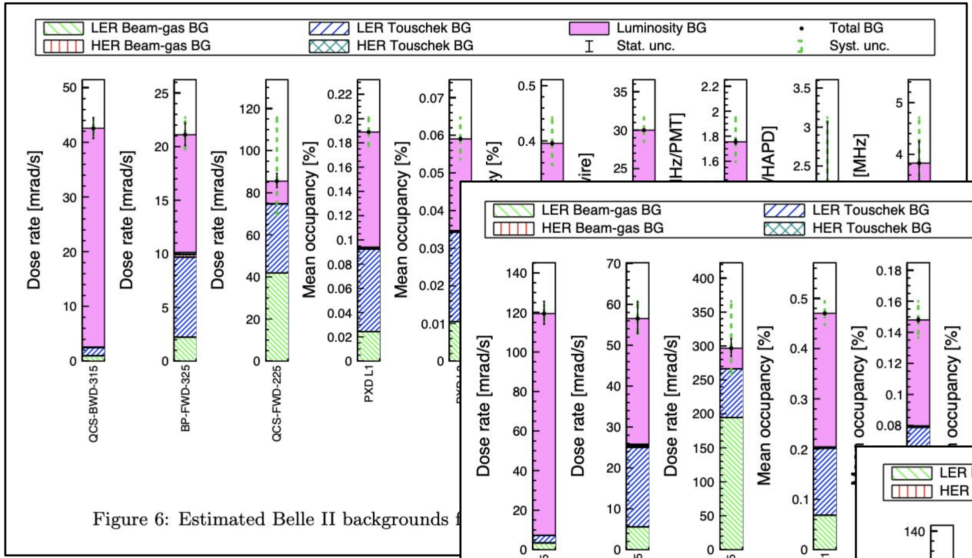


Figure 6: Estimated Belle II backgrounds f

$\beta^*_Y = 0.6$ mm

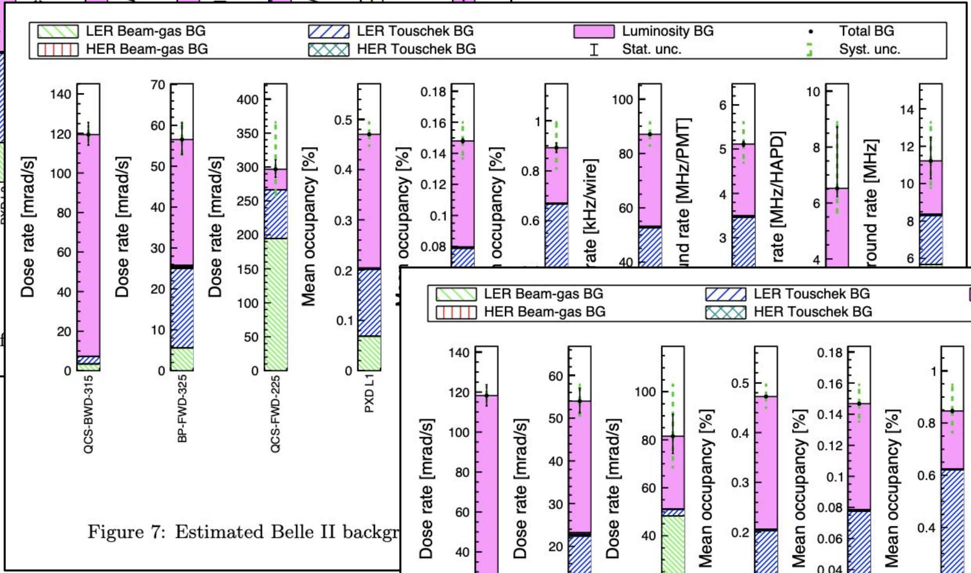


Figure 7: Estimated Belle II backgr

$\beta^*_Y = 0.6$ mm + NLC

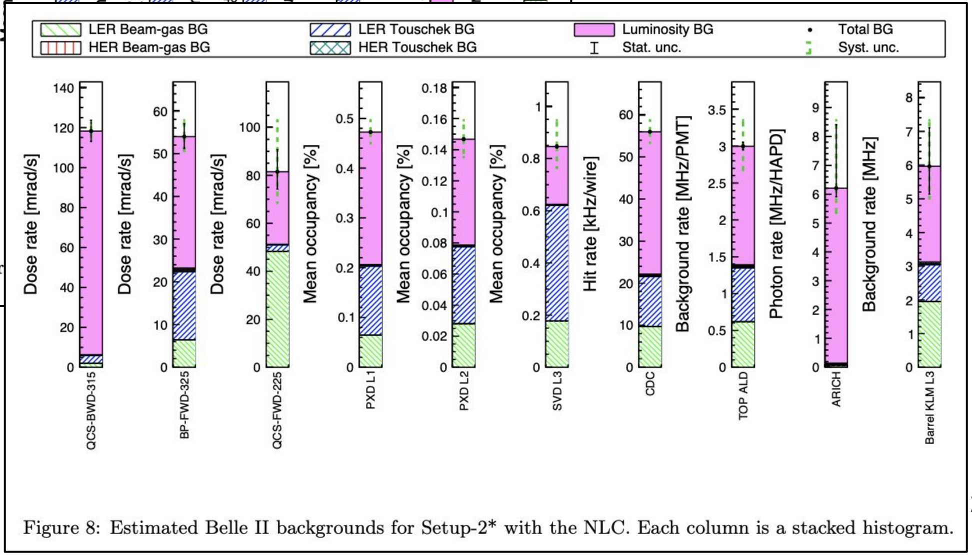


Figure 8: Estimated Belle II backgrounds for Setup-2* with the NLC. Each column is a stacked histogram.

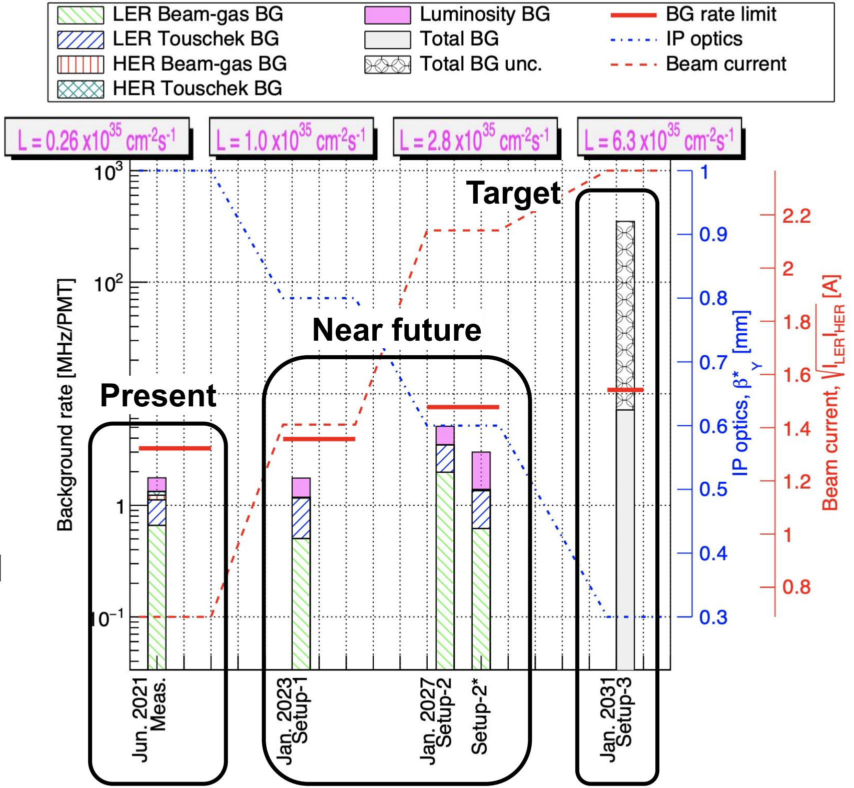
The predicted background levels for all setups are below the detector limits

Background status and evolution

- Current background rates in Belle II are well below limits, see Figure
  - There is margin for injection backgrounds and unexpected problems
- Backgrounds will remain high but acceptable until a luminosity of at least 2.8 $\times 10^{35}$ $cm^{-2}s^{-1}$ is reached

Predicted background levels are obtained as follows

1. Measure current levels of each background component
2. Simulate beam-induced backgrounds
3. Calculate Data/MC ratios
4. For future optics, adjust collimators in simulation
5. Simulate future background rates
6. Correct those by Data/MC



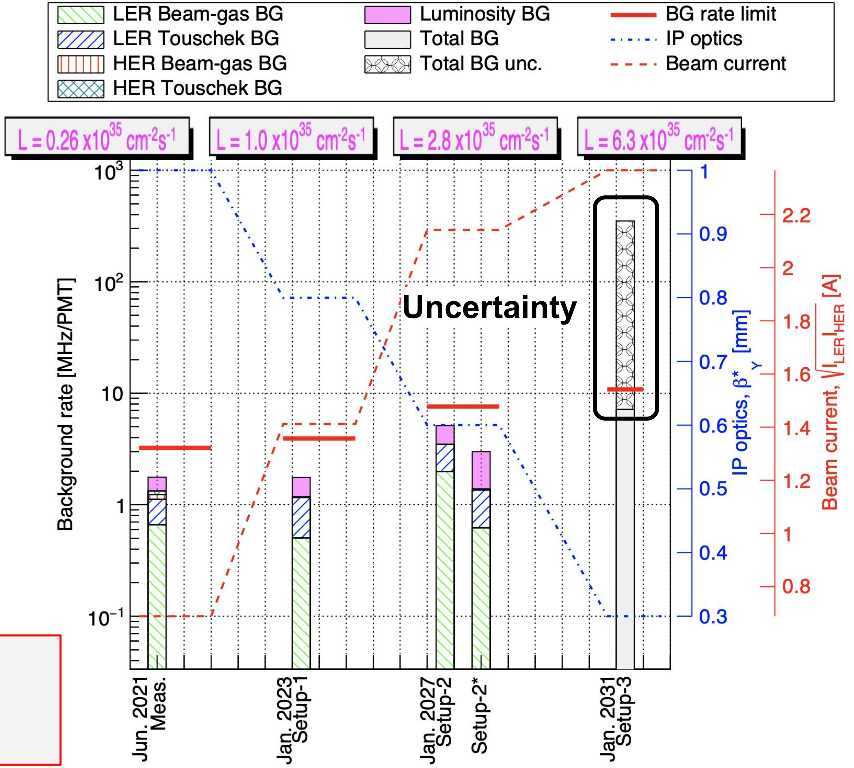
Measured and predicted beam background hit rates in the Belle II TOP detector, for various machine configurations. These PMTs are expected to be the detector components most vulnerable to beam backgrounds.

Background status and evolution

- The total background at target luminosity is very uncertain due to
  - Future IR redesign *(under discussion)*
  - Unexpected IR beam pipe contribution to beam instabilities *(under investigation)*

End of the background prediction section

Questions?



Measured and predicted beam background hit rates in the Belle II TOP detector, for various machine configurations. These PMTs are expected to be the detector components most vulnerable to beam backgrounds.

Summary

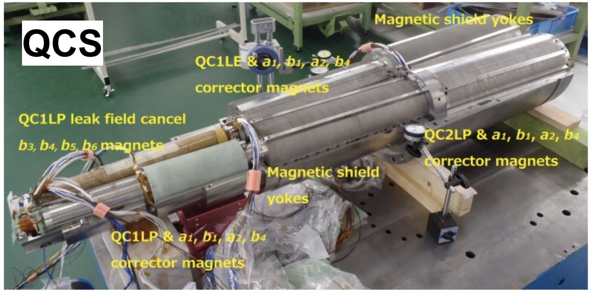
- Review SuperKEKB and Belle II upgrades
  - Stable operation at a world record luminosity ~4 x10^{34} $cm^{-2}s^{-1}$
  - Further machine and detector improvements are foreseen
    - Collimation system upgrade
    - Additional EM and neutrons shielding installation
    - IR geometry and machine lattice upgrade
- Beam-induced backgrounds are expected to remain acceptable
  - Until at least β^*_y = 0.6 mm (2027) before the LS2
    - Assuming TOP short-lifetime PMT replacement
  - There are several uncertainties that could affect our forecast in weather direction
    - Additional shielding installation
    - Require further studies and refinement
- It is too early to make accurate predictions for the design machine lattice
  - Too tight dynamic aperture
    - Short beam lifetime
    - Specific luminosity degradation
  - Background could exceed the detector's limit at β^*_y = 0.3 mm (2031)
  - Several machine operation schemes, instability and background countermeasures, and upgrades of the experiment are under consideration
- We are closely collaborating with EU, US and Asian accelerator laboratories on optimizing upgrades of SuperKEKB and reaching the target luminosity ~6 x10^{35} $cm^{-2}s^{-1}$

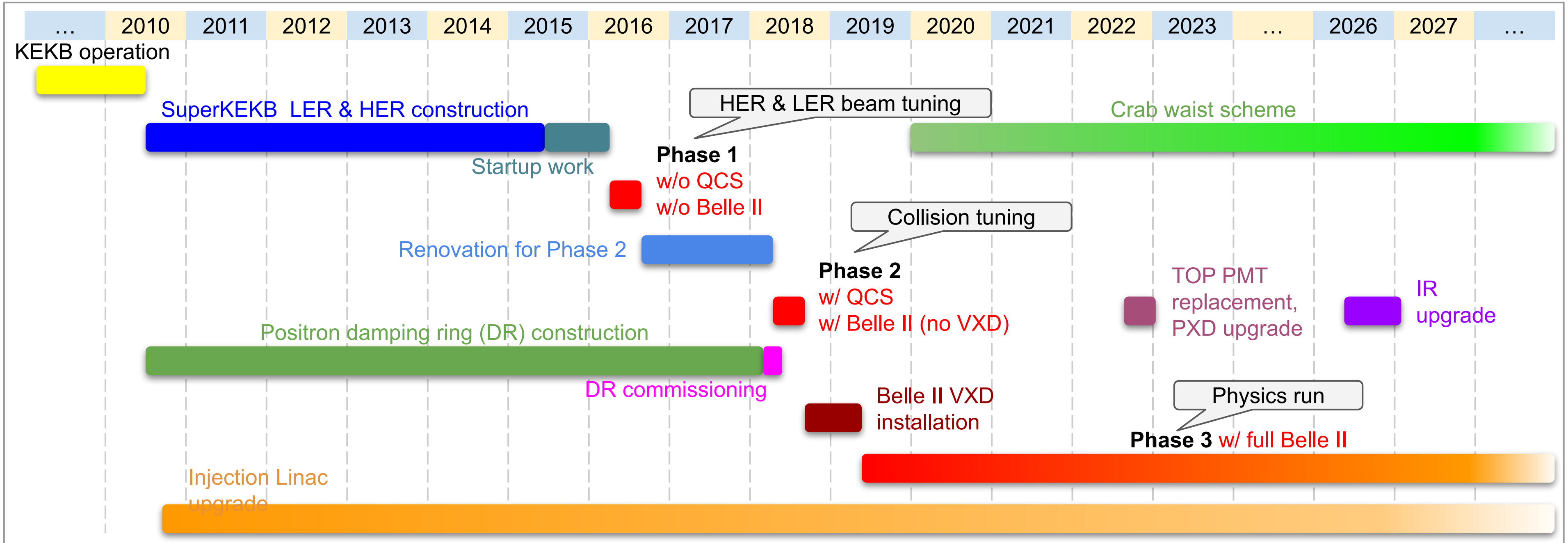
Thank you for attention!

BACKUPS

Timeline for machine upgrades

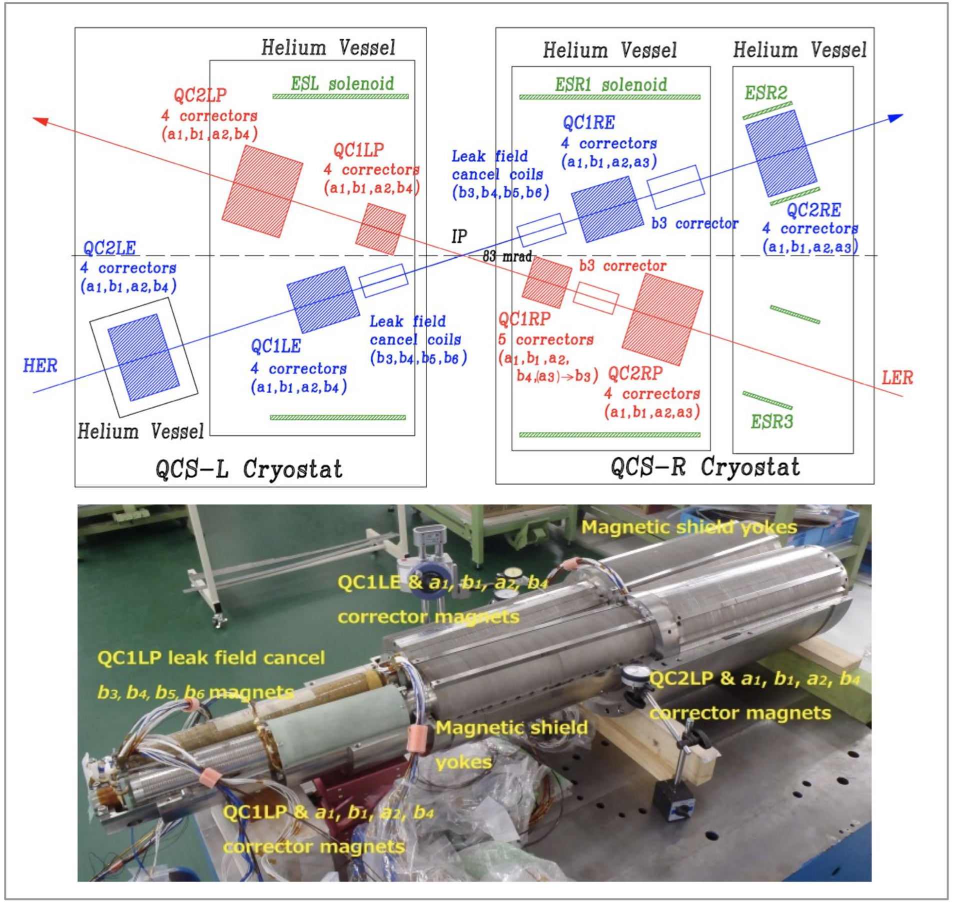
- **Phase 1** (2016) → Accelerator commissioning
- **Phase 2** (2018) → First collisions; partial detector; background study; physics possible
- **Phase 3** (2019) → Nominal Belle II start



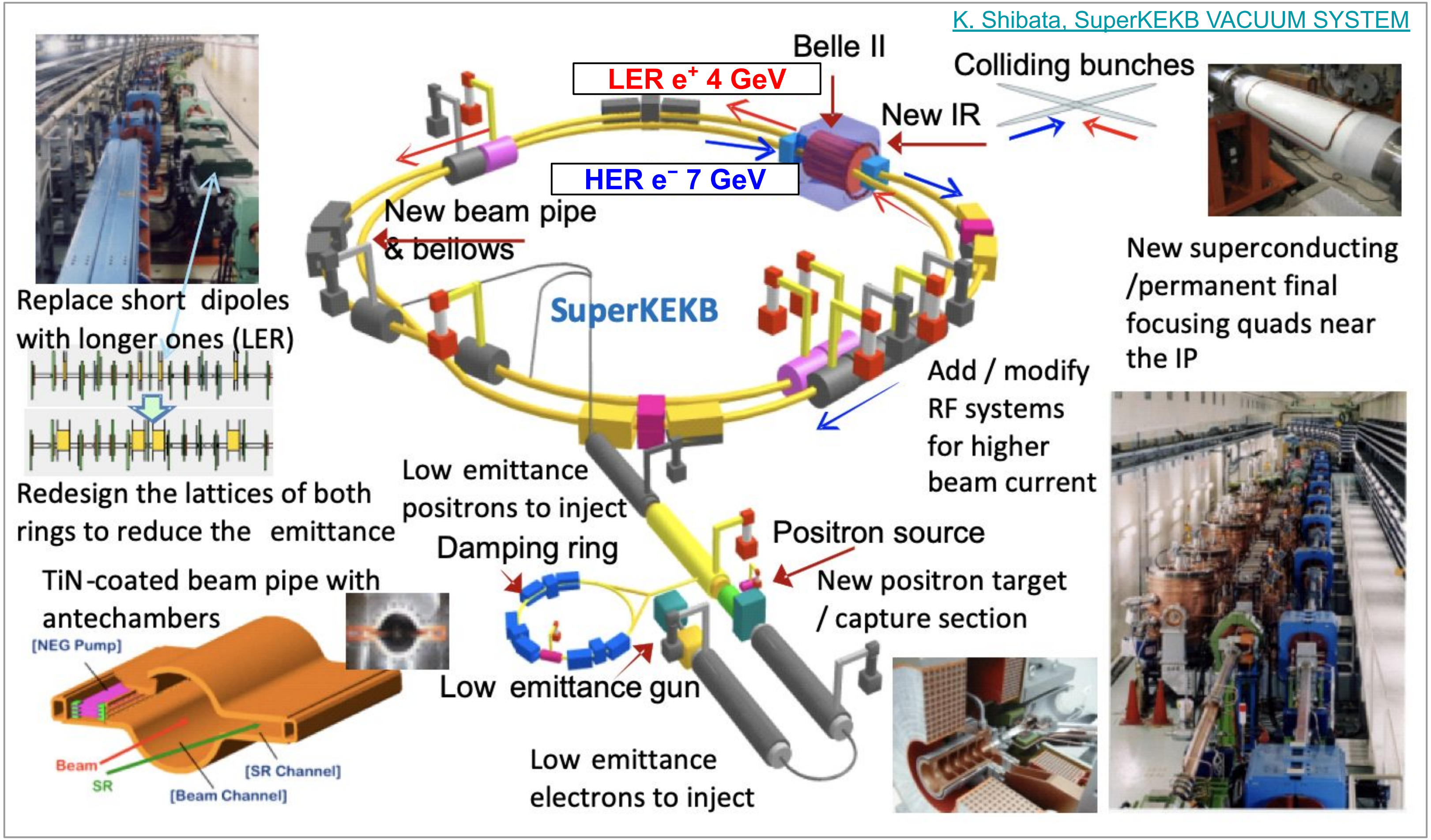


Based on M. Tobiyama slides, KEK, EIC workshop 2020

SuperKEKB final focusing system (QCS)



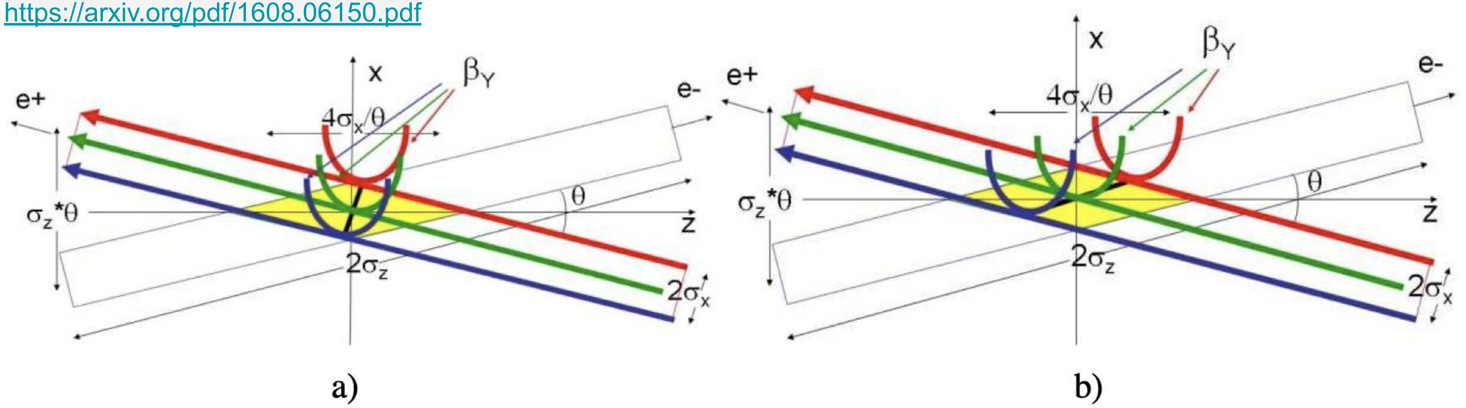
KEKB → SuperKEKB: machine modifications



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



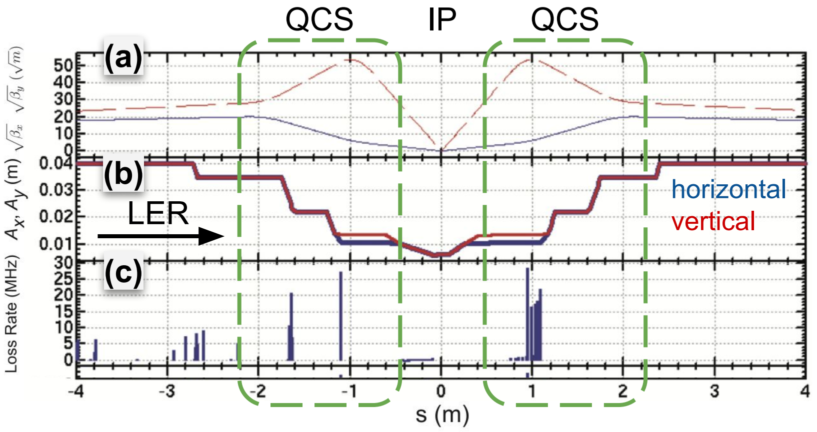
*Differently from the crab crossing scheme (**KEKB**) where bunches are tilted by the crab cavities with respect to the beam longitudinal axis, CW (**SuperKEKB**) rotates the optics function β_Y.*

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

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

- 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

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

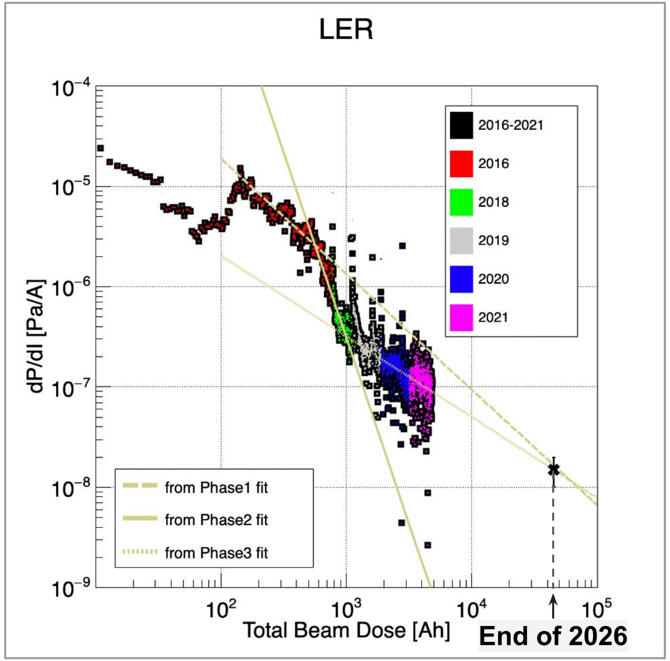


SuperKEKB interaction region (a) beta-function, (b) aperture, and (c) beam losses

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 ≲1 hour, while in KEKB >10 hours

$$P = P_{dynamic} + P_{base}$$
$$P_{dynamic} = I \times dP/dI$$
$$P_{base} = P(0\ \mathrm{A}) \approx 10\ \mathrm{nPa}$$



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 $\sim(\sigma_X\sigma_Y\sigma_Z)^{-1}$
  - 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)