2023 Belle II Summer Workshop

Beam backgrounds in Belle II at SuperKEKB

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On behalf of the Beam Background group

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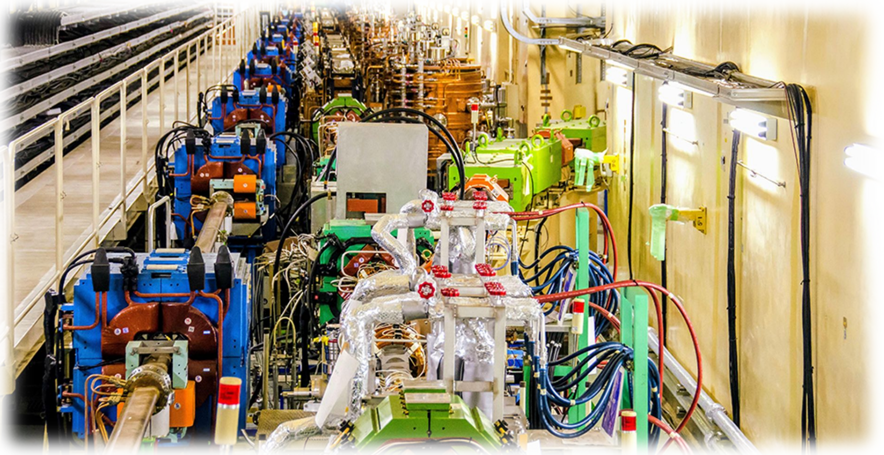
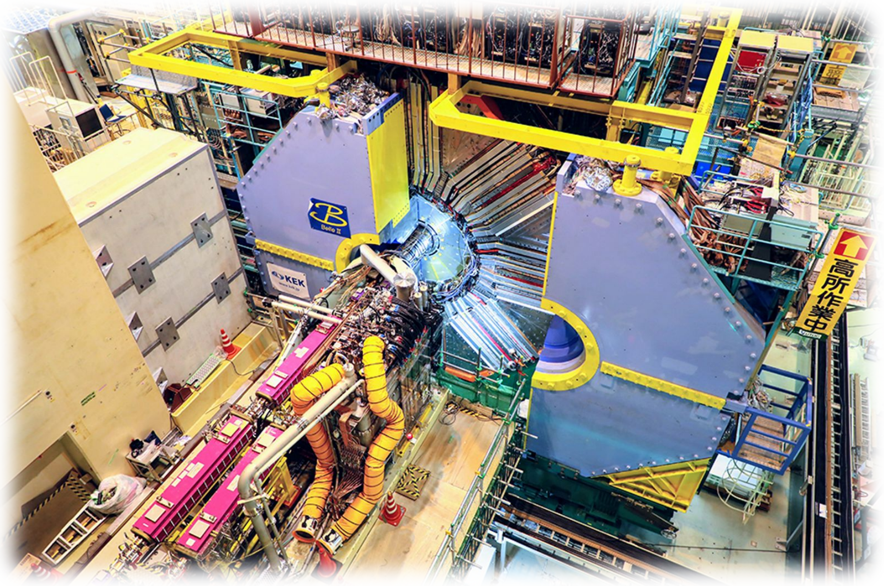
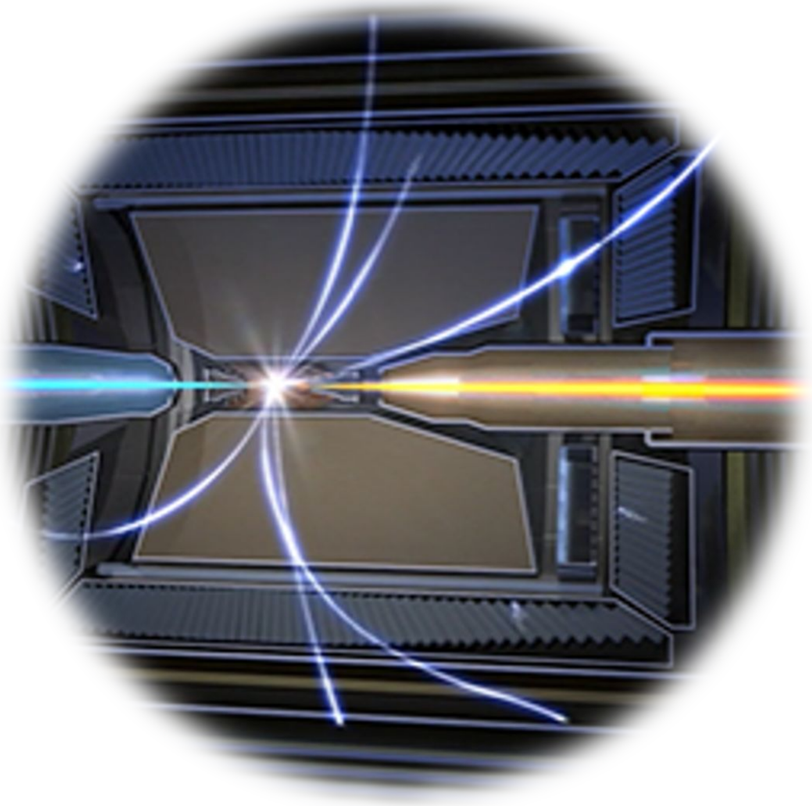




Outline

- Introduction
- Beam-induced backgrounds
  - Overview
  - Measurements
  - Simulation
- Future plans and prospects
- Summary



Introduction: *B*-factories

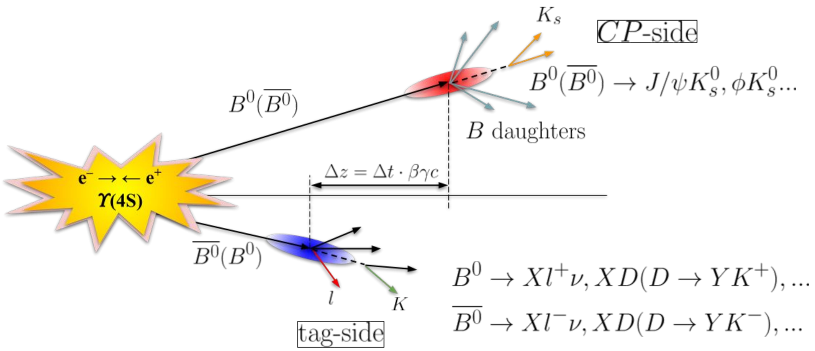
- Goals of **Belle** and **Belle II** experiments
  - Study the *CP*-symmetry violation in the *B*-meson system
  - Searching for New Physics beyond the Standard Model
- Requirements for **KEKB** and **SuperKEKB** colliders
  - Produce a large number of $B\overline{B}$-*pairs*
    - *High collision luminosity*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

1999-2010

BELLE KEKB

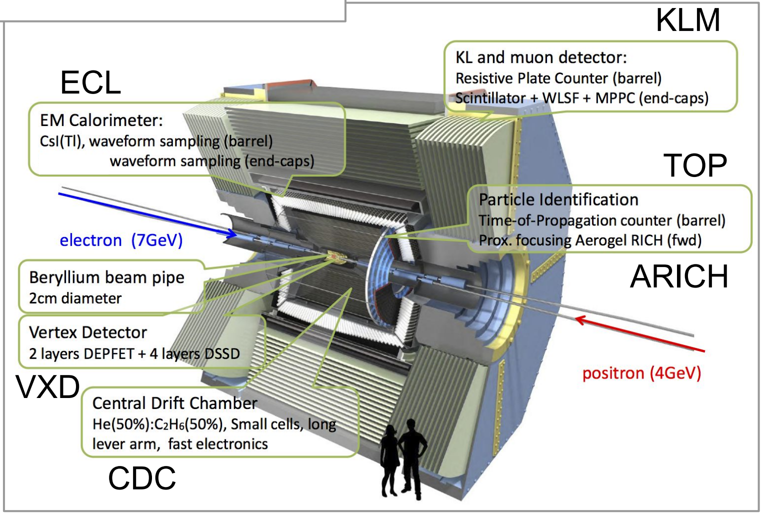
Since 2016

Belle II SuperKEKB

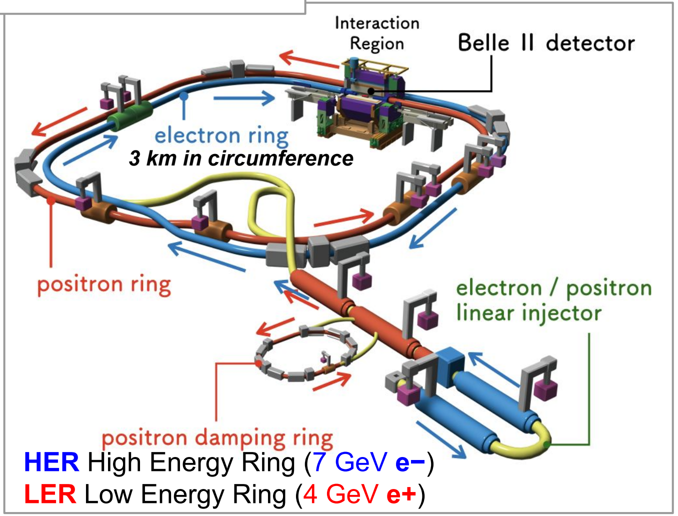


Belle II and SuperKEKB

Belle II detector



SuperKEKB collider



ab ≡ attobarn = 10^{-42} cm^2

KEKB/Belle

- Collected **~1 ab^{-1}** of data ~10^9 of *$B\bar{B}$-pairs*
- Along with PEP-II/BaBar, observed large time-dependent *CP*-asymmetries

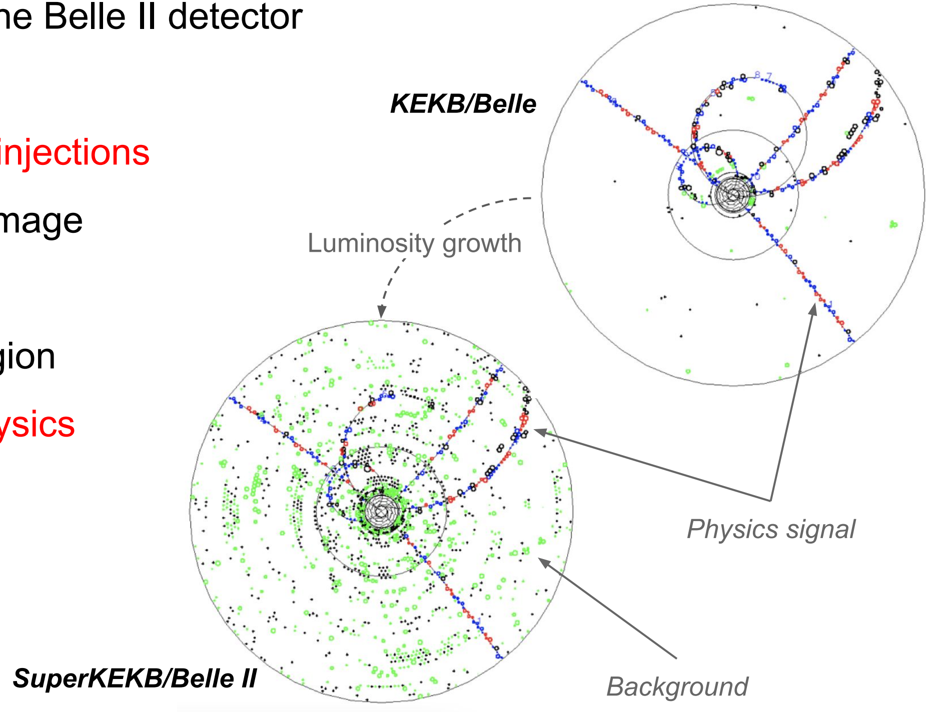
 Contributed to the 2008 Physics Nobel Prize

SuperKEKB/Belle II

- Almost all subsystems are upgraded for better performances
- Nano-beam and Crab Waist collision scheme
- Aims to collect **50 ab^{-1}** of data by the 2030s

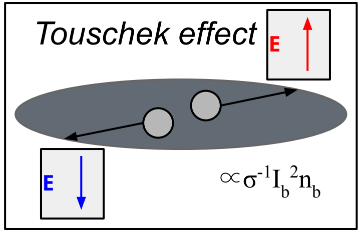
Luminosity gain and consequences

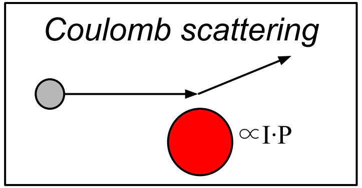
- The SuperKEKB **goal** is to reach x30 higher luminosity ($L \sim I_{\pm}/\beta^{*}_{y}$ [cm^{-2}s^{-1}]) than KEKB with x2 higher beam currents ($I_{\pm}$ [A]) and x20 smaller vertical beta functions (β^{*}_{y} [m]) at the interaction point (IP).
- This implies higher beam-induced backgrounds in the Belle II detector
  - High rate of particles leaving the beam
    - Requires a more frequent top-up beam injections
  - Sensitive detector and collider component damage
    - Reduces components longevity
  - High rate of beam losses in the interaction region
    - Increased Belle II hit occupancy and physics analysis backgrounds

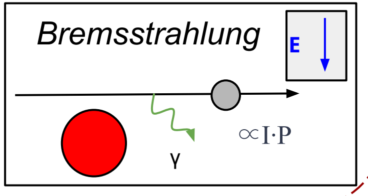


Background sources

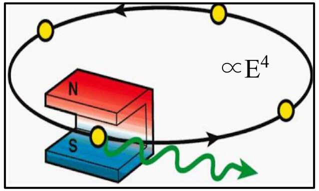
Particle scattering





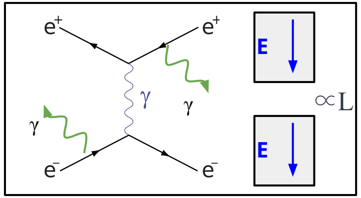


Synchrotron radiation

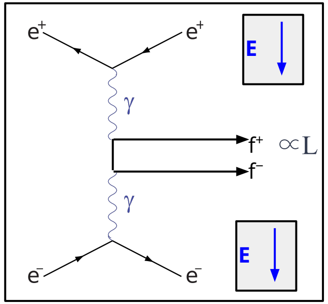


Colliding beams (Luminosity)

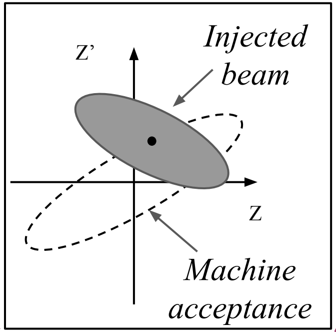
Radiative Bhabha proc.



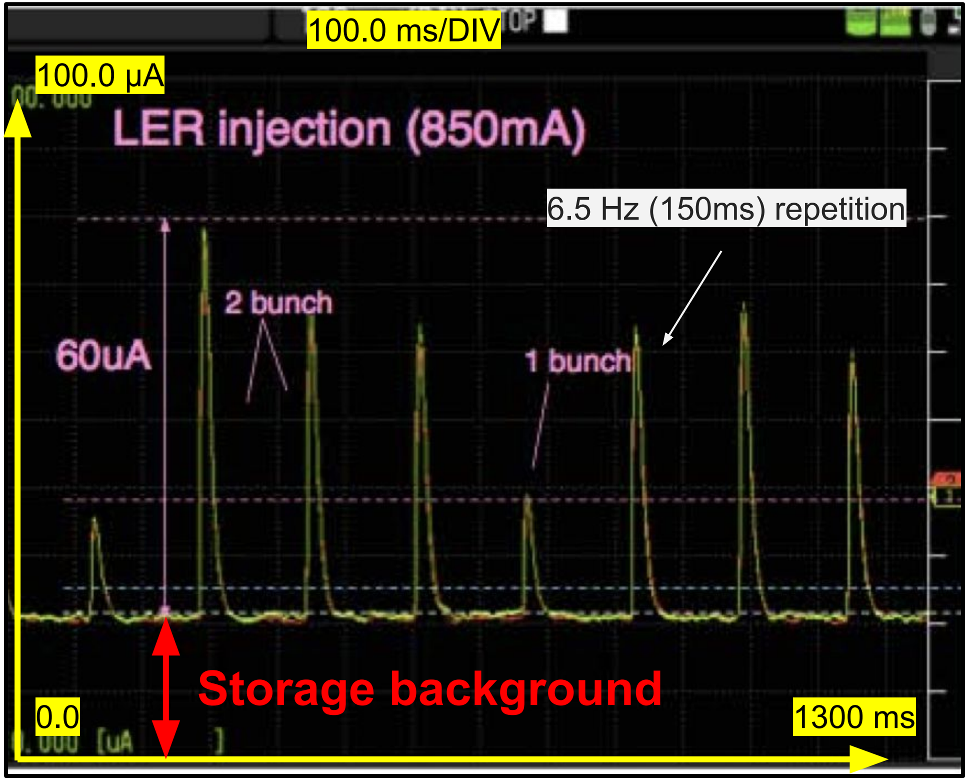
Two-photon proc.



Injection (top-up, continuous)



Injection background



CDC background (leakage current) during injection (2021)

- Injection beam loss spikes are seen on top of the storage background for a short period of time (~10 ms) after each injection
- The injection background in Belle II is much higher than the storage background
  - Degrades detector performances
  - Affects components longevity

What do we need?

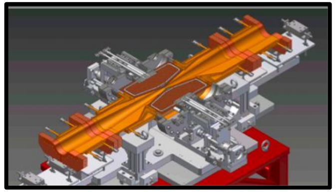
For stable and safe detector operation at target beam parameters, the injection should be clean

- High injection efficiency (> 40%)
- Low injection BG (< storage BG)

Background countermeasures

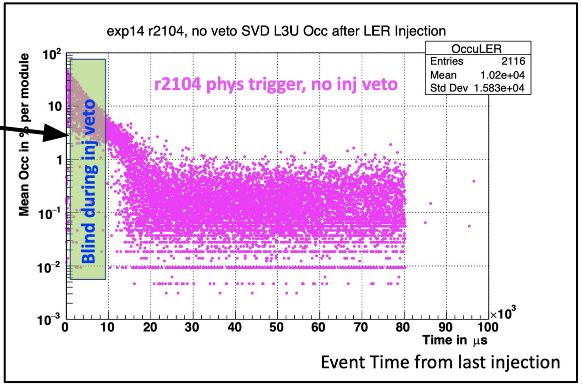
Particle scattering

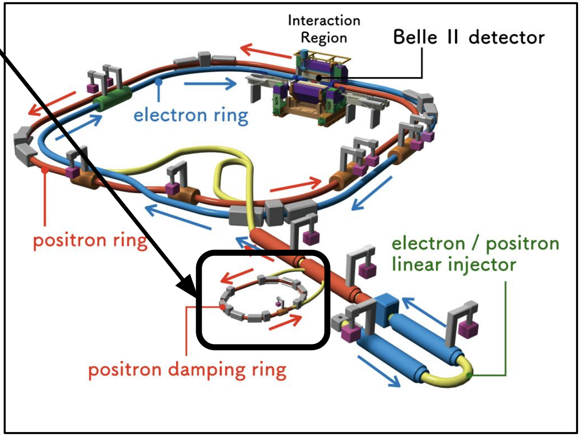
Collimators *(off-trajectory particles stop)*, Vacuum scrubbing *(residual gas pressure reduction)*, Heavy-metal shield outside the IR beam pipe *(detector protection against EM showers)*



Injection

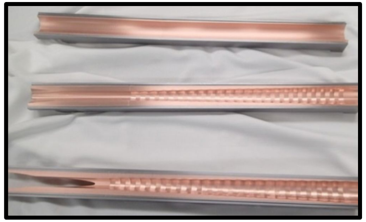
- Injection trigger veto
- Injection chain tuning
- Damping ring for positrons *(to reduce the emittance)*





Synchrotron radiation

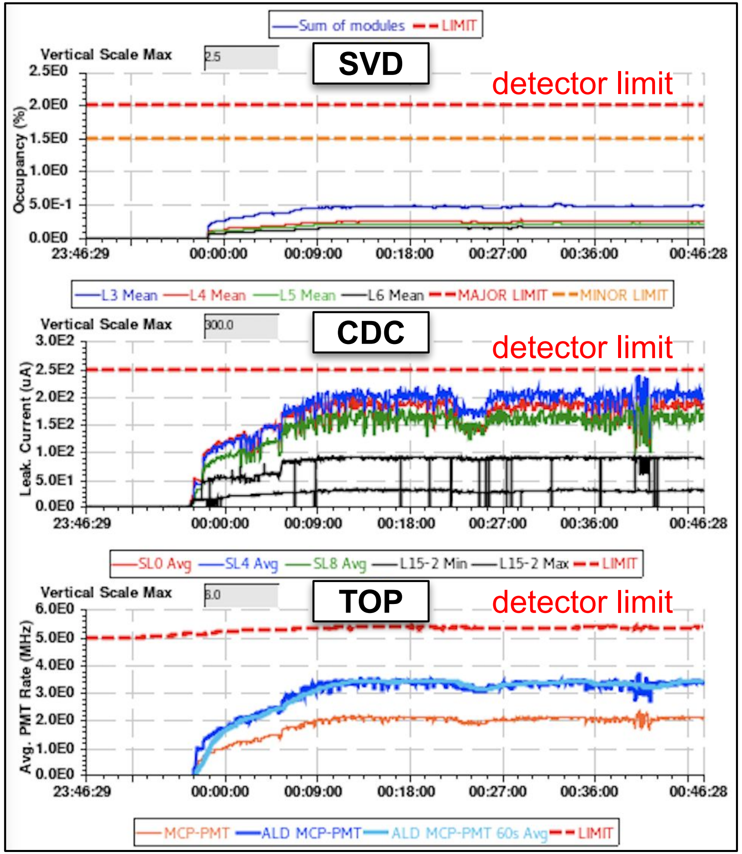
Beryllium beam pipe is coated with a gold layer + ridge surface of the beam-pipe + variable incoming beam pipe radius
(to avoid direct SR hits at the detector)



Colliding beams (Luminosity)

Lead and polyethylene shields
(neutron flux reduction)

Current background level in Belle II



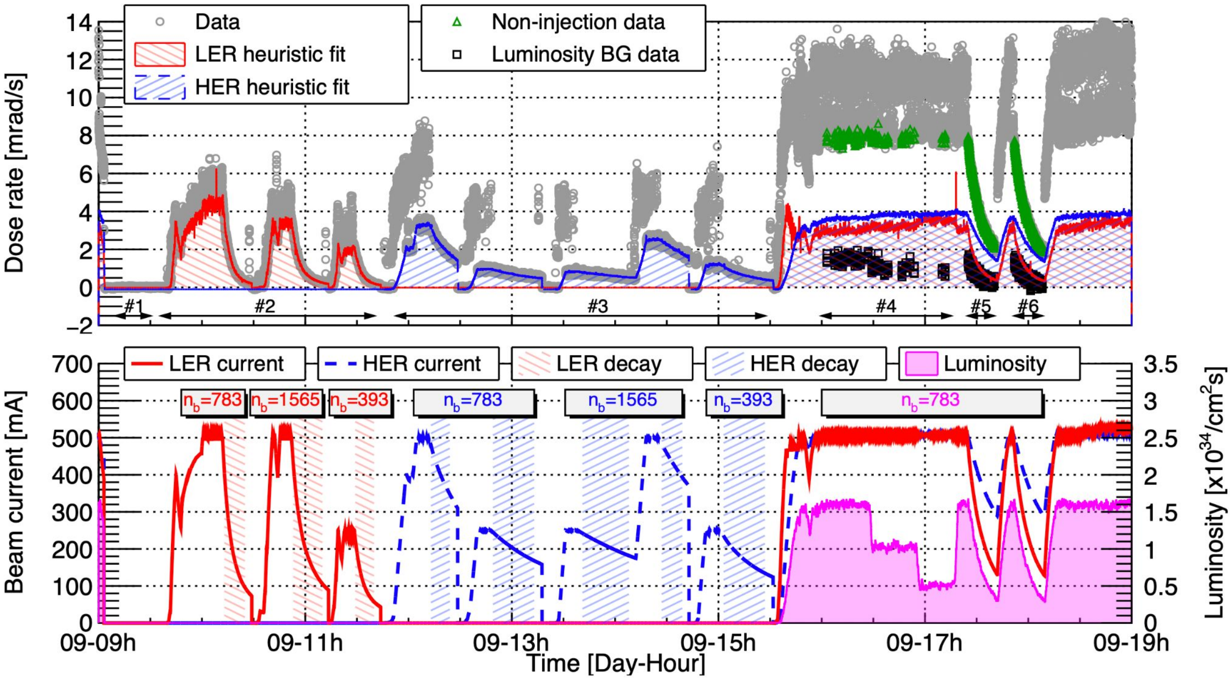
A snapshot of the operational Belle II background online monitor. June 20, 2022

- Current (2022) background rates in Belle II are acceptable and below limits
- Belle II did not limit beam currents in 2021 and 2022
  - It will limit SuperKEKB eventually, without further background mitigation
- To reach the **target** luminosity of $6x10^{35}$ $cm^{-2}s^{-1}$ an upgrade of crucial detector components is foreseen (e.g. TOP short lifetime conventional MCP-PMTs during LS1)

F. Forti, Snowmass Whitepaper (2022) arXiv:2203.11349

Background measurements

A dedicated beam-induced background measurement is performed to measure each background component separately, usually twice a year



An example of dedicated beam background measurements in SuperKEKB.
Top: typical measured detector background; bottom: measured machine parameters.

Beam-gas background

Elastic and inelastic particle scattering off of residual gas molecules

$$O_{\mathrm{beam-gas}} = B \times IP_{\mathrm{eff}}$$

Touschek background

Inelastic scattering of two particles in the same beam bunch

$$O_{\mathrm{Touschek}} = T \times \frac{I^2}{n_{\mathrm{b}}\sigma_{\mathrm{x}}\sigma_{\mathrm{y}}\sigma_{\mathrm{z}}}$$

Luminosity background

Radiative Bhabha and two-photon processes

$$O_{\mathrm{lumi}} = L \times \mathcal{L}$$

Background decomposition

- Dominant backgrounds
  - LER single-beam
  - Luminosity
- PXD SR & HER single-beam backgrounds are ~10%
- We start to see single-event upsets (SEUs) due to EM showers & neutrons
- In 2022, due to beam current increase and high beam background after injection (< 10 ms) we start seeing detector performance degradation (e.g. CDC dE/dx resolution drop)

A. Natochii *et al.*, Phase 3 paper (2023) arXiv:2302.01566

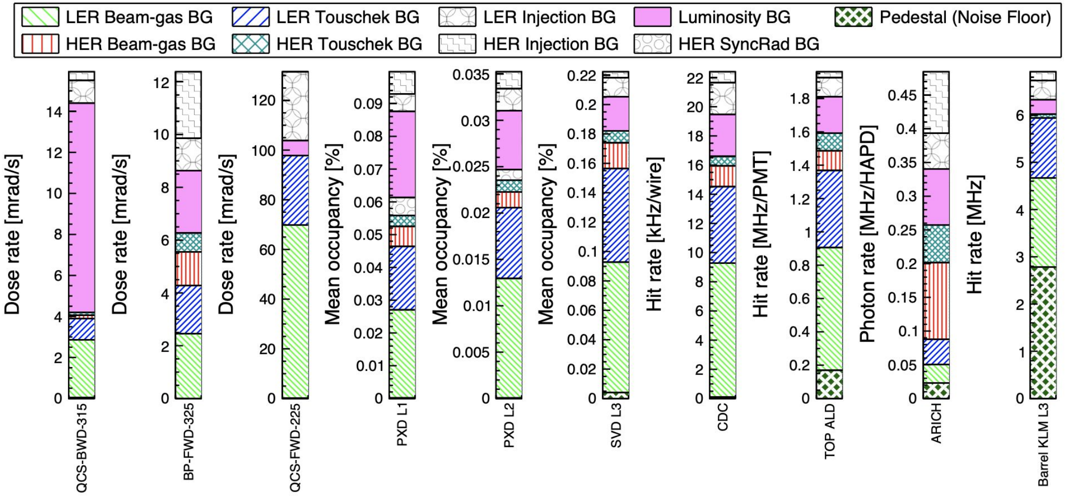
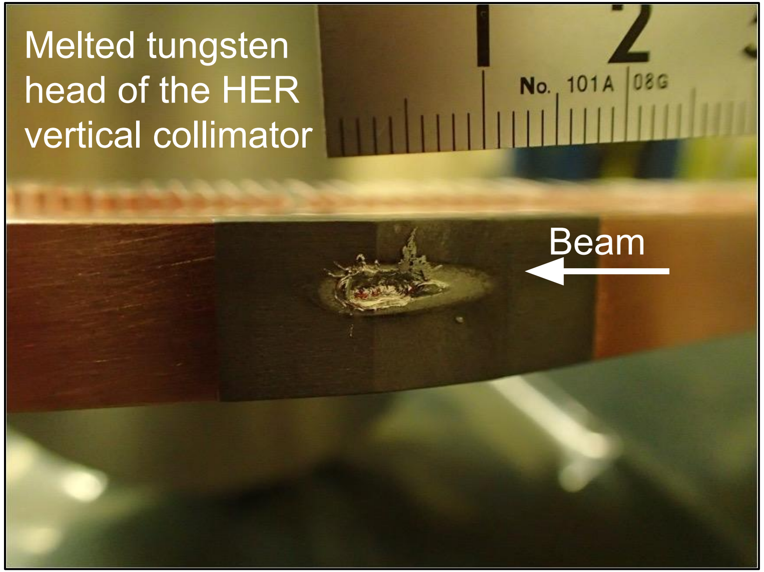


Figure 14: Measured Belle II background composition on June 16, 2021. Each column is a stacked histogram. QCS-BWD-315, BP-FWD-325 and QCS-FWD-225 indicate backward QCS, beam pipe and forward QCS Diamond detectors, respectively, with the higher dose rate. Barrel KLM L3 corresponds to the inner-most RPC layer in the barrel region of the KLM detector. TOP ALD shows the averaged background over ALD-type MCP-PMTs, slots from 3 to 9.

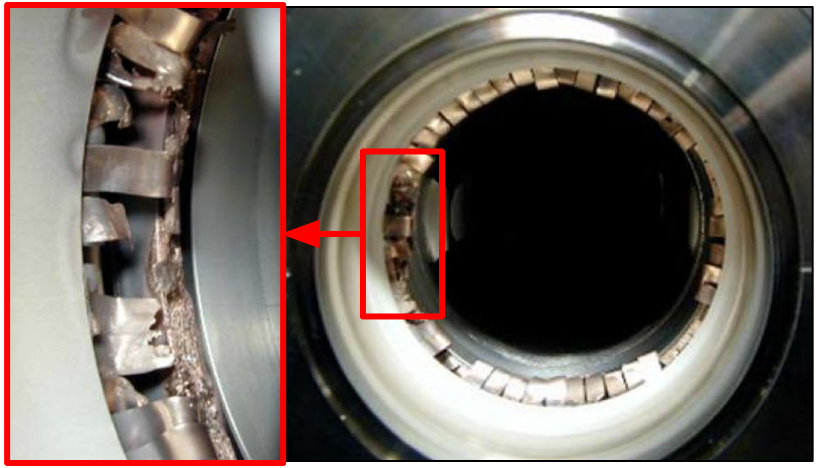
Uncontrolled beam losses (1)

- During stable machine operation unexplained beam instabilities and beam losses may occasionally occur in one of the rings causing **sudden beam losses (SBLs)** at a specific location around the ring due to
    - Machine element failure
    - Beam-dust interaction
    - Vacuum element defects
- **Consequences**
    - Detector and/or collimators damage, see Figure
        - Operation with damaged collimators results in increased Belle II backgrounds
        - Time consuming collimator replacement
    - Superconducting magnet quenches



Uncontrolled beam losses (2)

- Usually only a few such catastrophic beam loss events happen per year in each ring
  - In 2022, we had many (>50) SBLs in the LER when trying to increase the current above 0.7 mA/bunch
- **Cures**
  - Upgraded abort system → fast abort signal
  - Low-Z materials for collimator heads (MoGr, Ta+Gr) → robust collimators [1]
  - Understand the source of the unstable beam
    - *Vacuum system inspection (damaged RF fingers)*
    - *Beam dynamics study*
    - *Additional beam loss monitors*

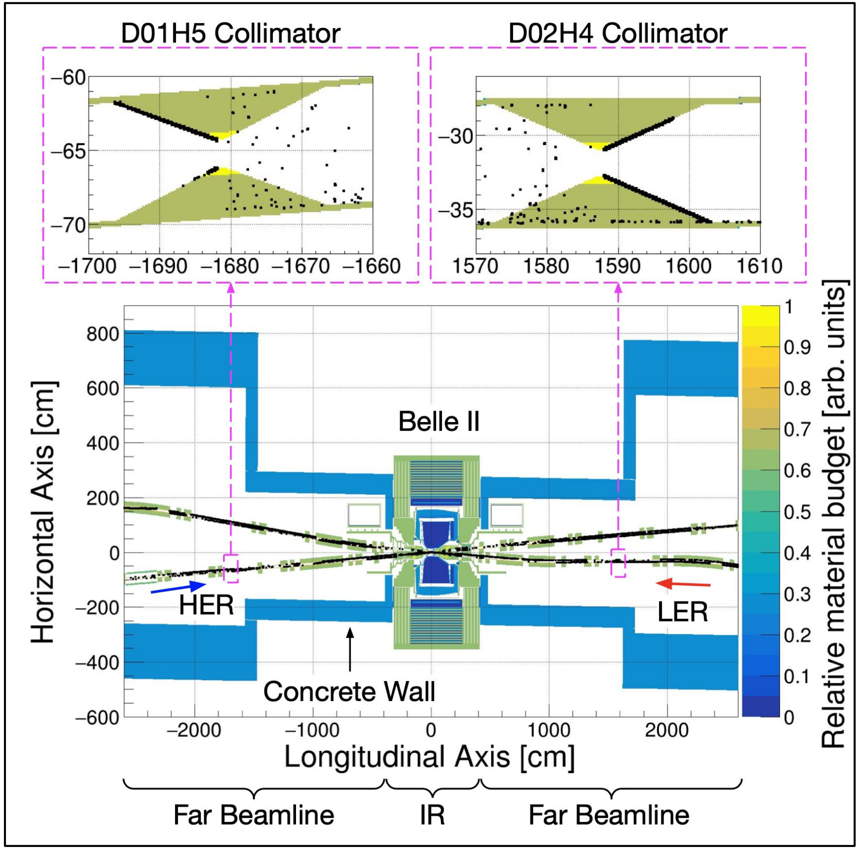


Damaged RF-shield in KEKB
PEP-II had similar issues

[1] S. Terui, A. Natochii et al., *JACoW* IPAC2021 (2021) 3537-3540 [link]

Background simulation: Tools

- **Single-beam background** (Beam-gas & Touschek)
  - Strategic Accelerator Design (SAD@KEK) (multi-turn particle tracking)
    - *Realistic collimator profile and chamber*
    - *Particle interaction with collimator materials*
    - *Measured residual gas pressure distribution around each ring*
  - `Geant4` (detector modelling)
- **Luminosity background:**
  - `Geant4` (single-turn effect, colliding beams)
- **Synchrotron radiation background:**
  - `Geant4` (close to the Belle II detector)

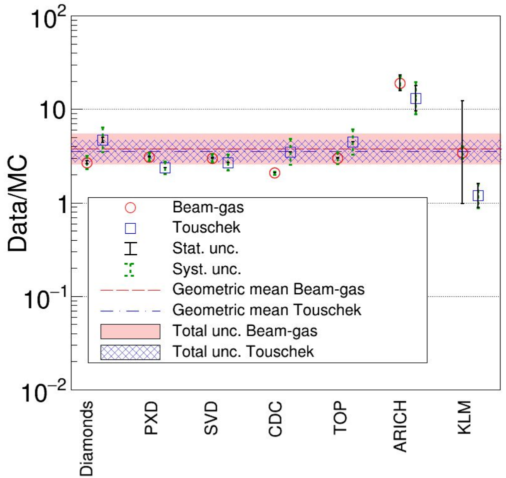


`Geant4` model of Belle II and collider cavern. Black dots represent single-beam losses

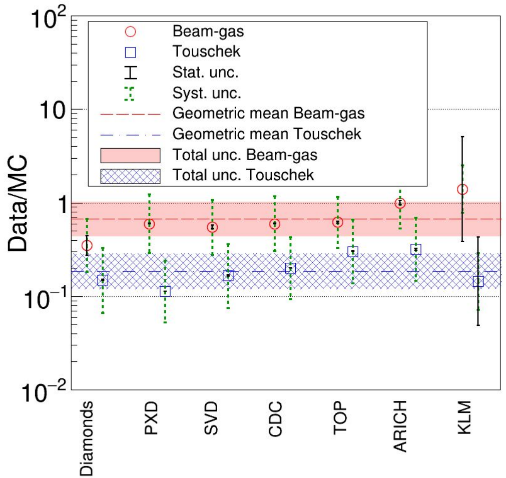
Background simulation: Accuracy

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

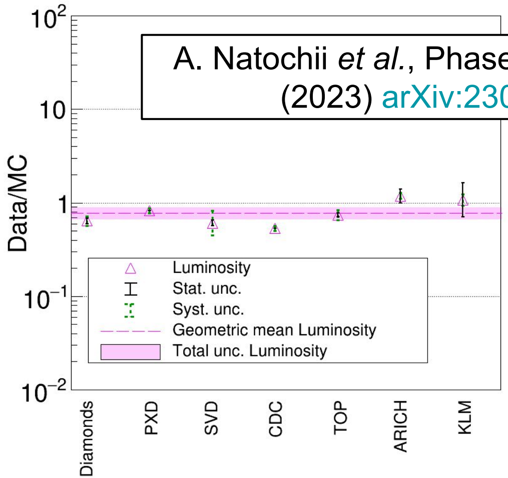
LER single-beam



HER single-beam



Luminosity



A. Natochii *et al.*, Phase 3 paper (2023) arXiv:2302.01566

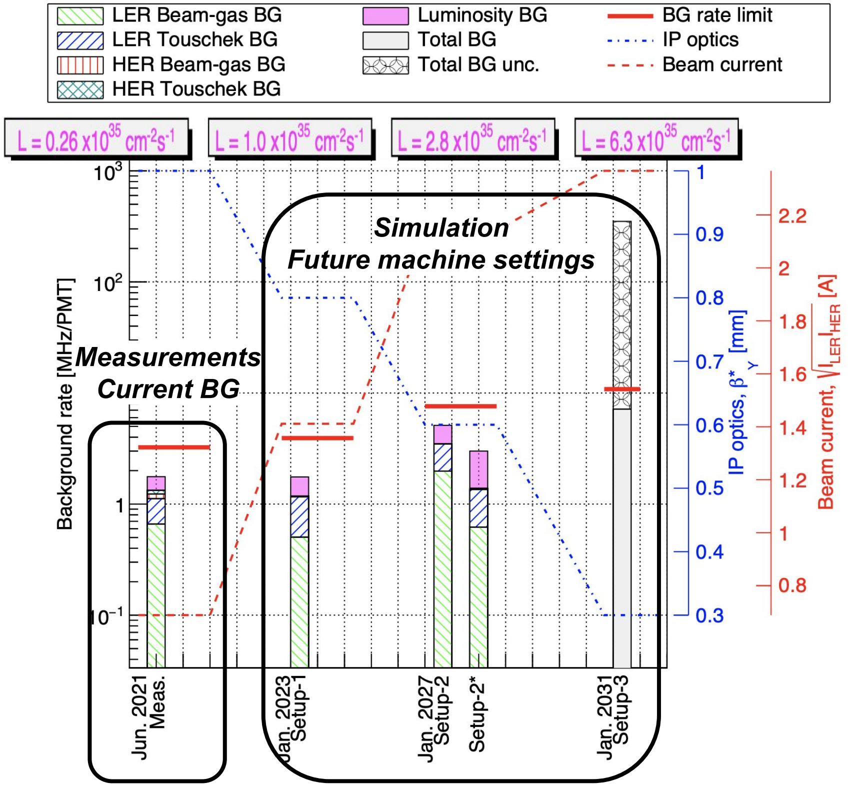
- Current data/MC ratios are within one order of magnitude from unity
  - **Substantial improvement** compared to measurements in 2016 [*link*] and 2018 [*link*]
  - This confirms our good understanding of beam loss processes in SuperKEKB
- These ratios are used to rescale simulated backgrounds toward higher luminosities

Background simulation: Benefits

Snowmass White Paper arXiv:2203.05731

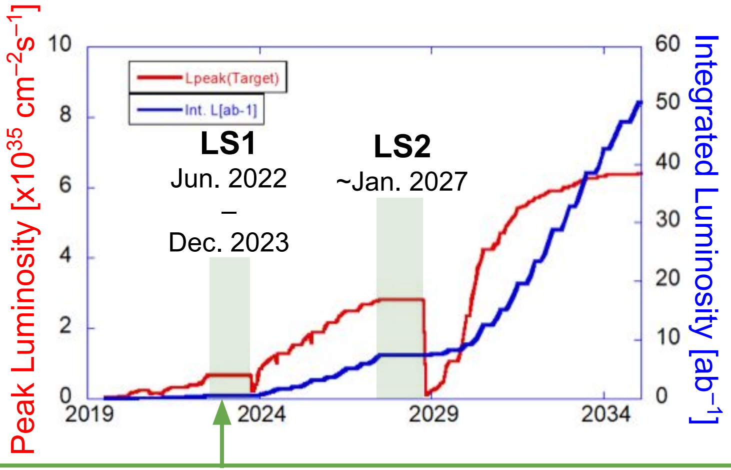
Our simulation with a good data/MC agreement helps us to

- Study an impact of beam optics parameters on Belle II backgrounds
- Develop new collimators
- Better mitigate backgrounds through machine or detector adjustments and upgrades
- Predict background evolution at future machine settings
  - Backgrounds will remain high but acceptable until a luminosity of about 2.8x10^{35} $cm^{-2}s^{-1}$ is reached
  - For the **target** luminosity of about 6x10^{35} $cm^{-2}s^{-1}$ machine conditions are very uncertain to make an accurate background prediction



Measured and predicted Belle II backgrounds.
Setup-2 = Setup-2 + NLC (see next slides)*

Future plans and prospects to reach the target luminosity by the 2030s



We are currently here

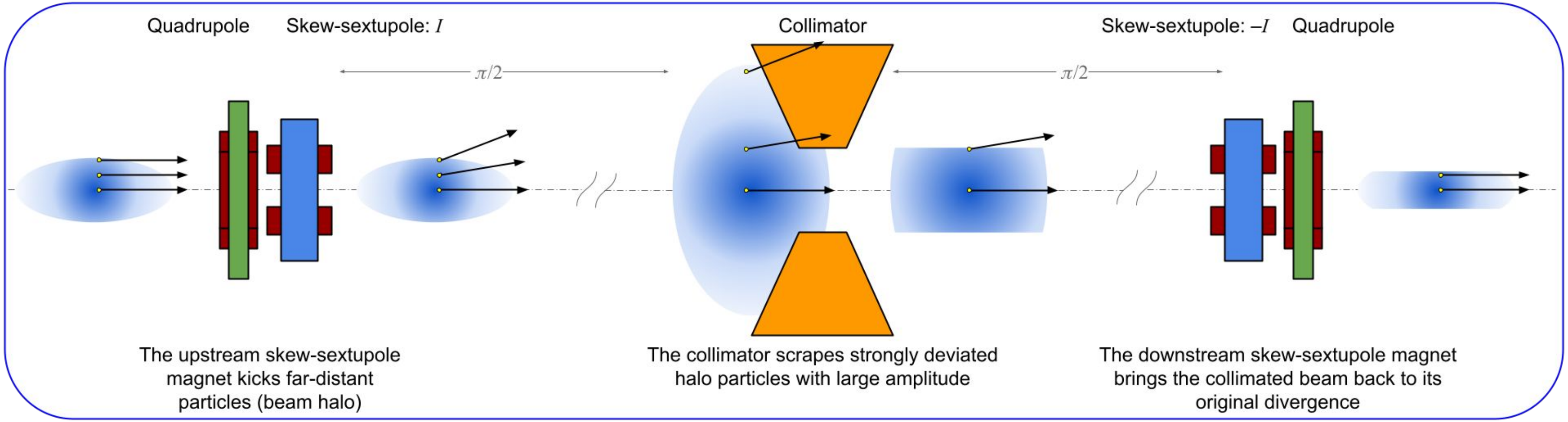
- L_{peak} ~0.5 x10^{35} cm^{-2}s^{-1} ← *World record*
- L_{int} ~0.4 ab^{-1} ← *BaBar's dataset size*

- Neutron background detectors [LS1]
  - ***He-3 tubes & novel BEAST TPC directional neutron detector system***
    - *To fully understand neutron backgrounds around Belle II*
- Development of real-time BG composition monitors [LS1]
  - ***Neural Network- & ECL-based BG composition monitors***
    - *To estimate each BG component online during SuperKEKB operation*

- Detector upgrades (e.g., PXD, TOP PMTs) [LS1]
  - *Damage sensors replacement*
  - *Fully assembled PXD with two layers*
  - *Replace short-lifetime conventional MCP-PMTs in the TOP*
- Additional shielding in/outside Belle II against SR, EM-showers and neutrons [LS1]
  - *More **polyethylene and concrete shieldings** on end-caps and around the final focusing magnets (QCS)*
  - *New IP beam pipe with an additional Au layer*
  - *High-Z bellow shielding*
- Collimation system upgrade [LS1]
  - ***Nonlinear collimation (NLC) insertion in the LER** (see the next slide)*
    - *Low impedance budget*
    - *Better background control*
  - *More robust collimator heads installation (MoGr, Ti, Ta+Gr)*
- Injection chain and feedback system upgrade [LS1]
  - *For stable machine operation and low injection backgrounds*
- IR redesign [LS2]
  - *To use the Crab Waist scheme at β^*_y = 0.3 mm (design)*
  - *Reduce the IR impedance budget*

***LS** = **L**ong **S**hutdown, which is the period of no beam used for machine and detector upgrades*

Nonlinear collimation (NLC)



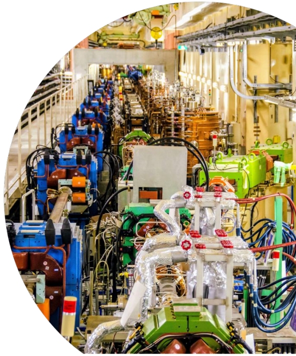
Nonlinear optics region in the LER with a pair of skew-sextupoles (~800 m upstream the IP) + V-collimator

- Low-betatron function in between (at the collimator) $\beta_{x/y}$ ~3 m → low impedance at narrow aperture
- Vertical angular kick for distant halo particles in both planes $\Delta p_y \sim (y^2 - x^2)$ → effective halo cleaning
- A big aperture step of ~1 mm corresponds to only 4σ at the QCS → fine aperture tuning
  - Other V-collimators: ~1 mm step ⇒ 20-40σ

NLC can work as a primary collimator with effective background suppression and low impedance

Summary

- In 2022, SuperKEKB and Belle II reached the world record luminosity of ~4.7×10^{34} cm^{-2}s^{-1}
  - **This achievement required a close collaboration between machine and detector experts** to keep the balance between high collision rate and acceptable background level in Belle II avoiding unwanted detector or machine damage
- We have achieved a good agreement between measured and simulated beam-induced backgrounds, which helps us predict and plan for future background levels [10.1103/PhysRevAccelBeams.24.081001]
- In the next decade, at stable machine operation, storage beam backgrounds (beam-gas, Touschek, luminosity) in Belle II are expected to remain acceptable until at least L = 2.8×10^{35} cm^{-2}s^{-1} [arXiv:2203.05731, arXiv:2302.01566]
- Further machine and detector improvements are foreseen
- We are closely collaborating with other accelerator laboratories around the globe on optimizing upgrades of SuperKEKB and reaching the **target** luminosity of about 6×10^{35} cm^{-2}s^{-1}



The Beam Background group is open to new people motivated and willing to bring their fresh ideas and unique expertise in beam background mitigation for safe and productive machine and detector operation

Acknowledgements

KEK is hiring a postdoc for MDI-related activities

The possible tasks would include beam background simulation and machine studies, study of beam background impact on physics analysis, and machine-learning application for accelerator tuning.

Contact person: Hiroyuki Nakayama
hiroyuki.nakayama@kek.jp

WE ARE HIRING

The University of Hawaii is hiring a postdoc for beam background activities [details]

The successful candidate will be my successor working on the discussed topics and play a leading role in understanding and controlling beam backgrounds in Belle II at SuperKEKB.

Contact person: Sven Vahsen
sevahsen@hawaii.edu

WE ARE HIRING

Thank you for attention!

And thanks a lot to all SuperKEKB and Belle II colleagues for their contribution and hard work!

Backup slides

Belle II vulnerability to beam backgrounds

- The Belle II/SuperKEKB project in 2019: The machine was at the early commissioning stage and the detector just started first physics data collection
- Belle II safety factors based on optimistic background simulations were already too low (< 1), indicating that the experiment might require parts replacement or further upgrades due to extremely high beam backgrounds
- Also, the agreement between first measurements and simulation at that time was poor

P.M. Lewis et al. *Nuclear Inst. and Methods in Physics Research, A 914 (2019) 69–144*

Table 43
Belle II detectors most vulnerable to beam backgrounds in SuperKEKB Phase 3. Upper limits and safety factors assume ten years of SuperKEKB operation at full luminosity. Only detectors with safety factors less than five are included. Although all limits have been converted into rates, in several cases the detector degradation is a cumulative, rather than rate-dependent effect. Neutron flux numbers are in units of 10^{11} /cm^2 /yr and NIEL-damage weighted. See text for further explanation and discussion.

Belle II detector	Quantity	Expected value	Upper limit value	Safety factor	Dominant process(es)
PXD	occupancy	1.1%	3%	3	two-photon, synchrotron radiation
CDC	wire hit rate	400 kHz	200 Hz	0.5	radiative Bhabha, two-photon
CDC	electr. neutron flux	2.5	1	0.3	radiative Bhabha, Touschek
CDC	electr. dose rate	250 Gy/yr	100	0.3	radiative Bhabha, two-photon
TOP	PMT hit rate	5–8 MHz	1 MHz	0.2	radiative Bhabha, two-photon
TOP	PCB neutron flux	0.35	0.5	3	radiative Bhabha, Touschek
ARICH	HAPD neutron flux	0.3	1.0	3	radiative Bhabha
ECL	crystal dose rate	6 Gy/yr in BWD	10 Gy/yr	2	radiative Bhabha, two-photon

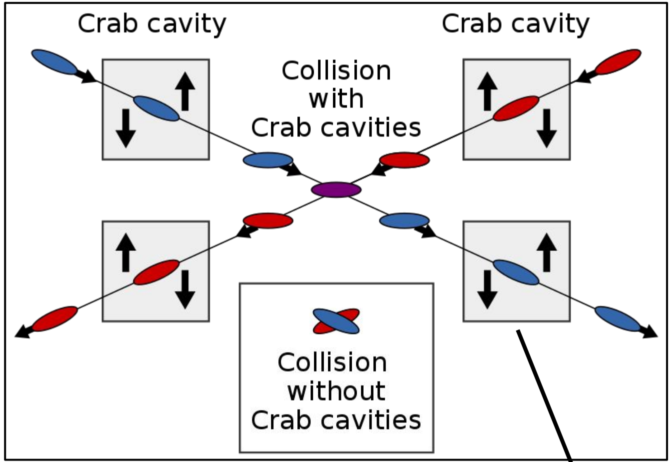
Working area

- **Improve the beam-induced background simulation**
  - For better understanding of beam loss mechanisms in the machine
- **Perform background measurements and data analysis**
  - For background decomposition
- **Compare experimental data and Monte-Carlo simulation results**
  - For accurate background evolution prediction and further machine-detector upgrade

Beam background	P. M. Lewis *et al.* **2016** data/MC ratios [link]	Z. J. Liptak *et al.* **2018** data/MC ratios [link]
	W/o final focusing system	*W/ final focusing system*
LER Beam-gas	0.5 – 6.2	2.8 – 29.4
LER Touschek	0.3 – 3.2	0.6 – 1.6
HER Beam-gas	44.0 – 288.0	32.3 – 483.5
HER Touschek	2.0 – 13.0	113.9 – 127.8

Confusion elimination

Crab cavities at KEKB



- Crab cavities are not compatible with nano-beam scheme
- Uninstalled and moved to the Ueno Science Museum in Tokyo

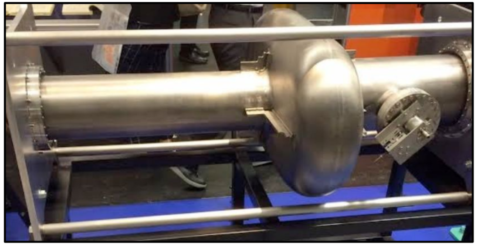
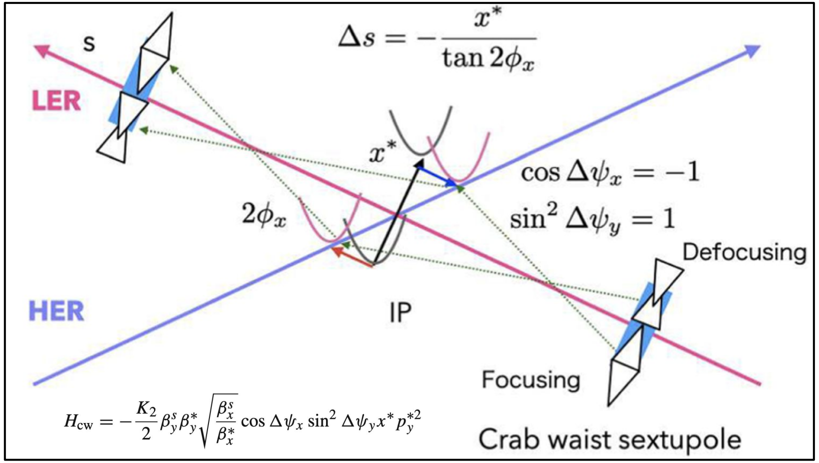


Photo of the KEKB crab cavity from the Tokyo Museum

Crab waist at SuperKEKB



- Suppress the strength of betatron and synchro-beta resonances induced by beam–beam interactions
- Reduce geometric luminosity loss due to deviated waist of particles with horizontal offset

Luminosity gain

Beam current — Beam-beam parameter

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

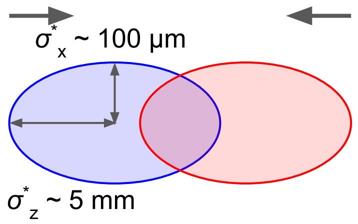
Vertical beta-function at IP

	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}**	**→ 6.0×10^{35} $cm^{-2}s^{-1}$**

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

KEKB head-on

crab crossing using crab cavities



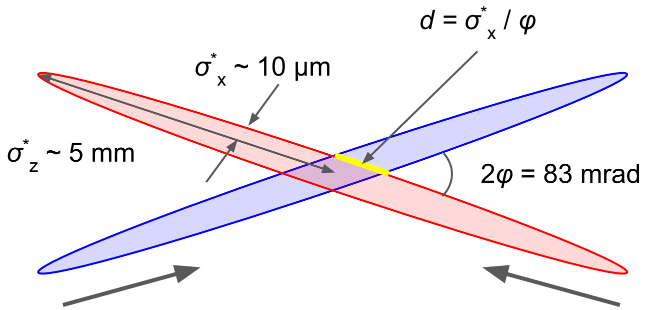
Overlap region = bunch length

Hourglass requirement:

$\beta^*_y \geq \sigma^*_z$ ~5 mm

SuperKEKB

nano-beam + crab waist scheme



Overlap region << bunch length

Hourglass requirement:

$\beta^*_y \geq d$ ~240 µm

Beam parameter extrapolation

A. Natochii *et al.*, Snowmass Whitepaper (2022) arXiv:2203.05731

Table 2: Predicted SuperKEKB parameters, expected to be achieved by the specified date. β^*, $\mathcal{L}$, I, BD_{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_{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
$\varepsilon_{\mathrm{y}}/\varepsilon_{\mathrm{x}}$(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

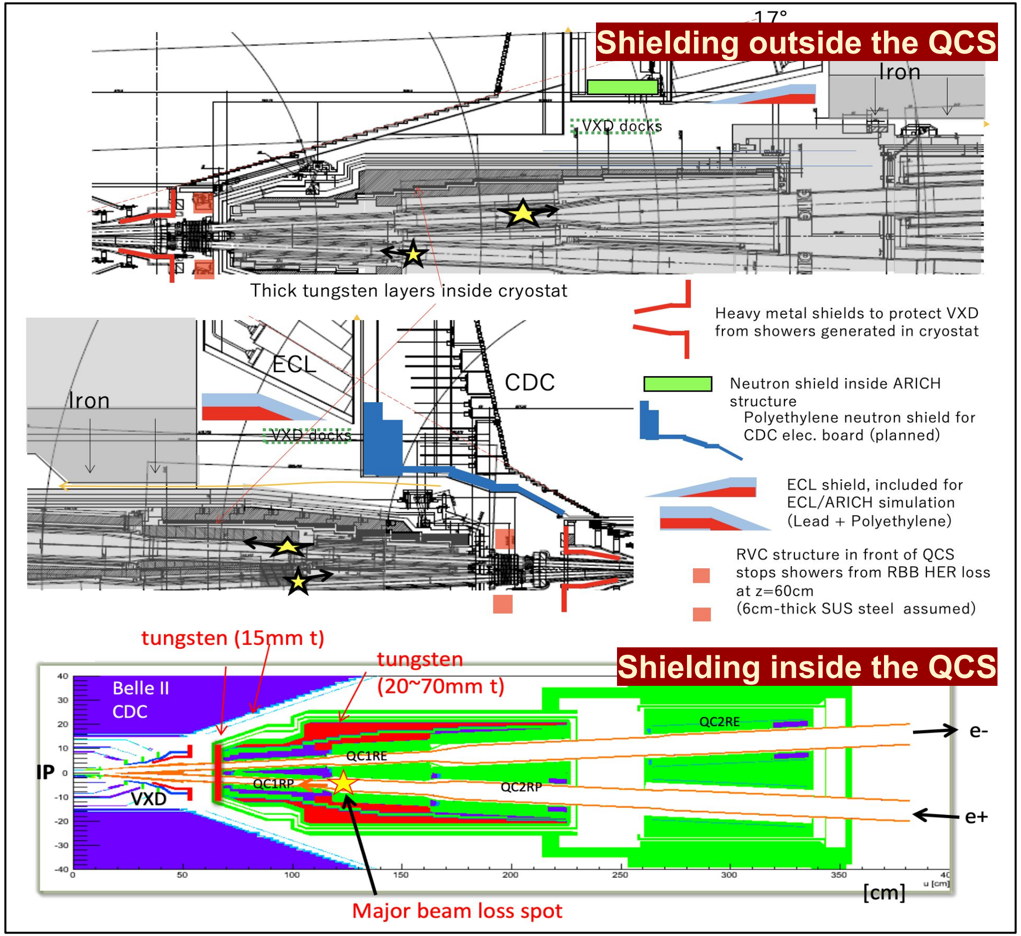
Target beam parameters at design optics

We do not have a working lattice for design optics

- No solution for the Crab Waist scheme
  - *Narrow dynamic aperture (DA)*
  - *Too short beam lifetime* τ *< 10 min*
- Final IR geometry is not defined

Belle II shielding

- Most of IR beam losses occur inside the QCS
  - Partially considered in the TDR 2010 [1]
- Installed additional detector protection
  - Heavy metal shield inside VXD
  - Polyethylene+lead shield inside ECL, ARICH & CDC
- In 2021-2022, detector saw single-event upsets (SEU) on FPGAs electronics boards
  - SEUs are presumably from neutrons created in EM showers
  - Still acceptable level
- Planned detector protection for the LS1 (2022-2023)
  - Additional EM and neutron shielding around QCS and Belle II to suppress SEUs

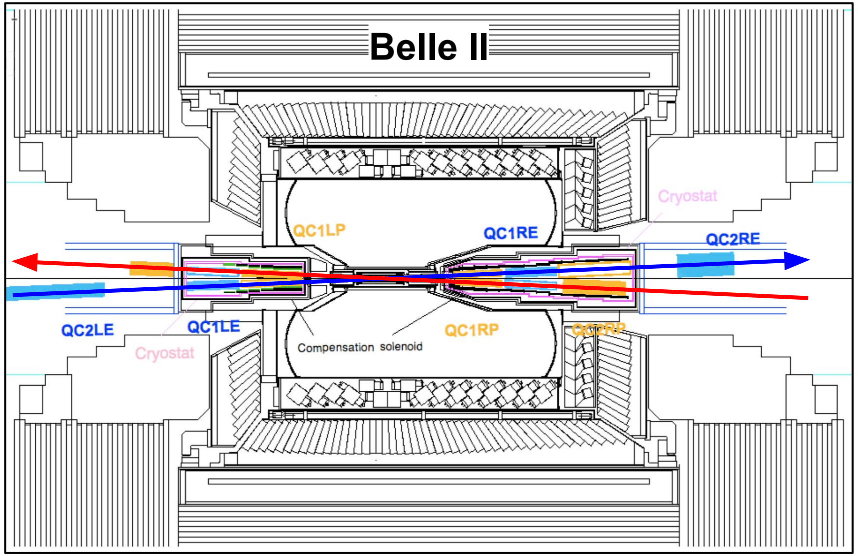


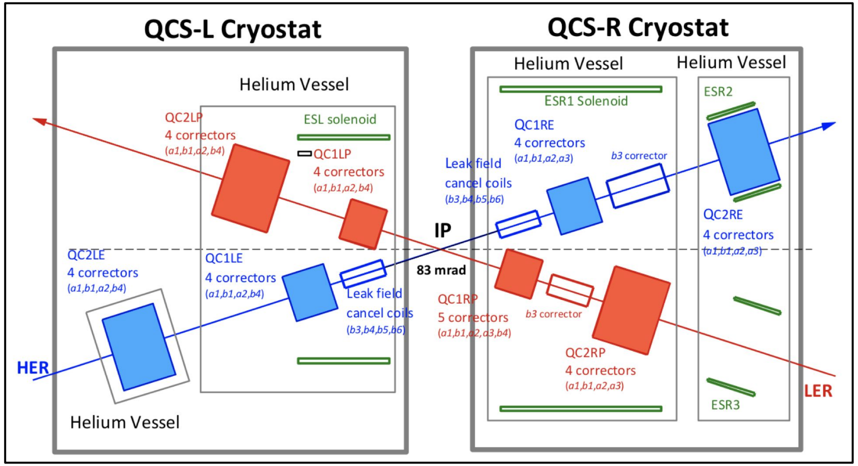
[1] T. Abe, et al., "Belle II Technical Design Report", KEK-REPORT-2010-1, 2010, https://doi.org/10.48550/arXiv.1011.0352

Final focusing system

To squeeze the beams at the IP and for fine beam tuning, the beam final focus system is installed in the Interaction Region (IR) [1]

- 8 superconducting (SC) main quadrupole magnets (QCS) (to focus and defocus the beams)
- 4 SC compensation solenoid magnets (to fully compensate the detector solenoid field of 1.5 T)
- 35 SC corrector coils (to tune the beams), constructed at BNL
- 8 magnets (to cancel the leakage field from the QCS)



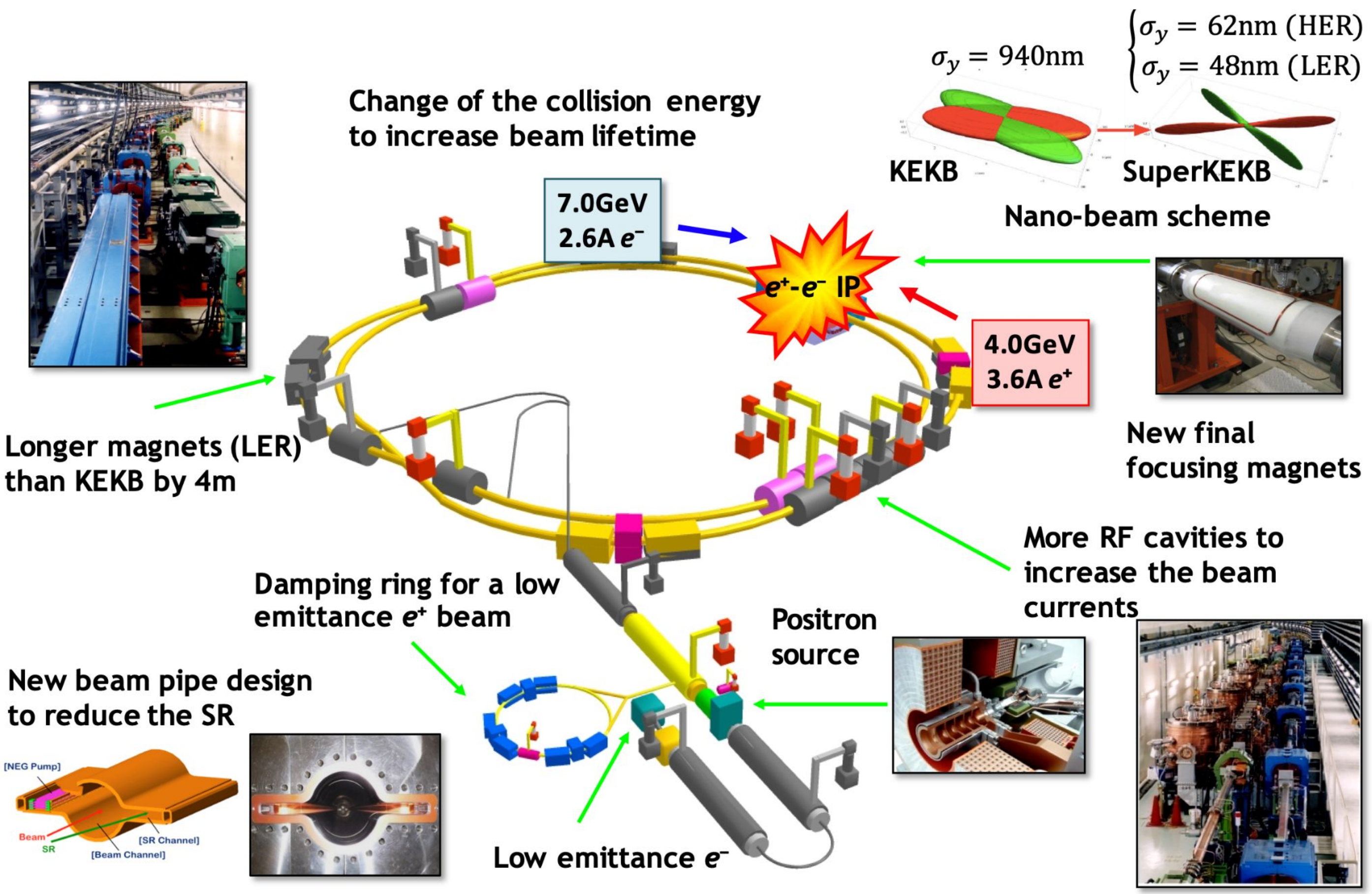


[1] N. Ohuchi, et al., "SuperKEKB beam final focus superconducting magnet system", Nuclear Inst. and Methods in Physics Research, A 1021 (2022) 165930

KEKB to SuperKEKB

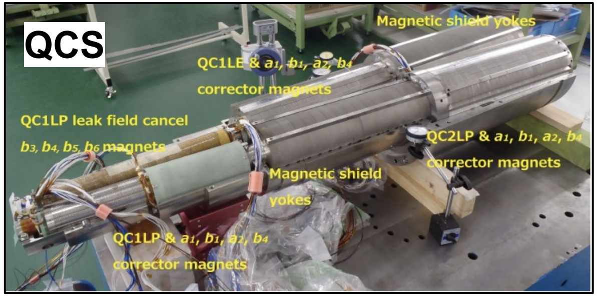
Machine modifications

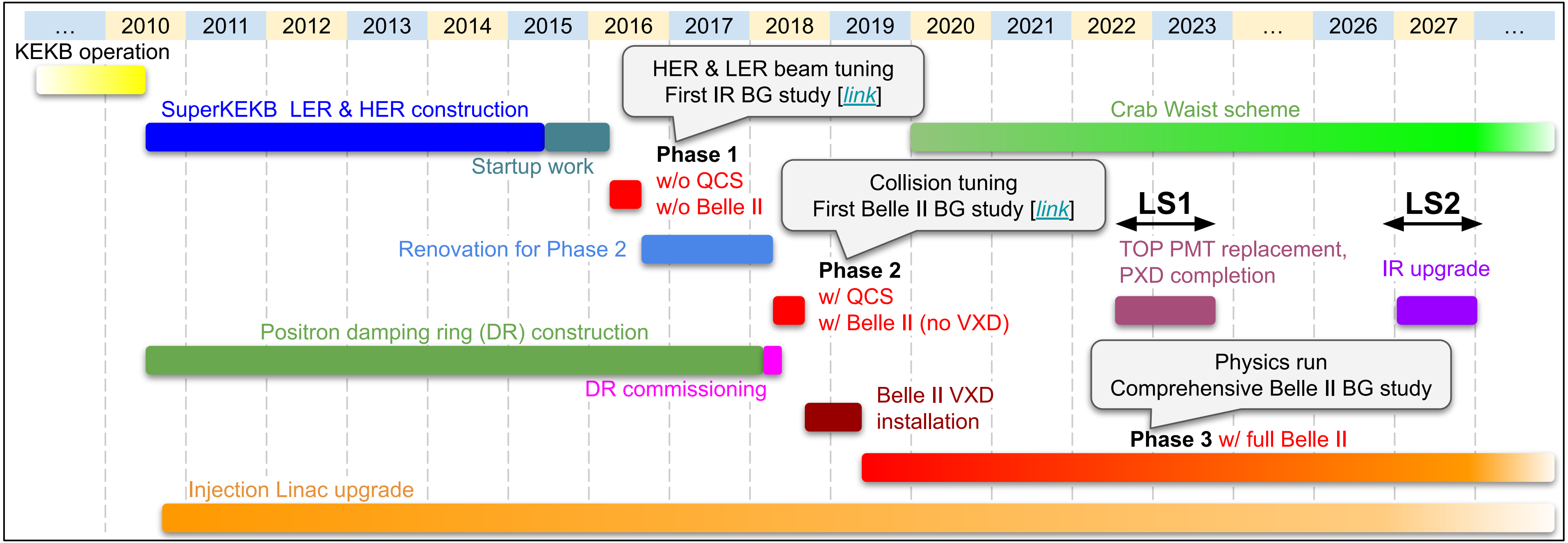
- Replaced short dipoles with longer ones (LER)
- Redesigned the lattices and IR (LER & HER)
- Installed antechambers (LER)
- Damping ring to reduce the emittance (LER)
- New superconducting final focusing quads (QCS) near the IP (LER and HER)
- Modified RF systems



Timeline of the machine upgrade

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



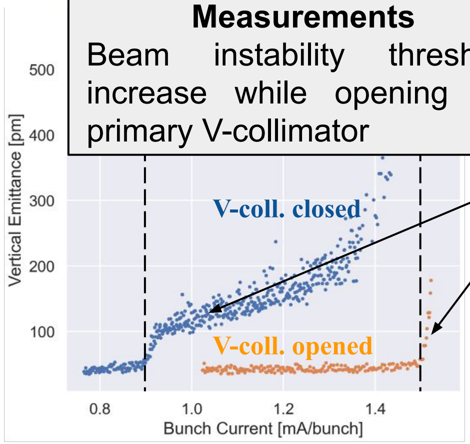


Single-beam instabilities

Expected beam losses due to the **T**ransverse **M**ode **C**oupling **I**nstability (**TMCI**)

- A result of the wake-field effect from bunches traveling through the ring aperture
- Leads to the onset of the bunch current head-tail instability
- Depends on the most narrow and steep aperture in the ring (collimators, IR beam pipe)
    - Beam size blow-up and betatron tune shift
- Currently, the TMCI threshold (~2 mA/bunch) is much higher than our operation bunch current (~1 mA/bunch)

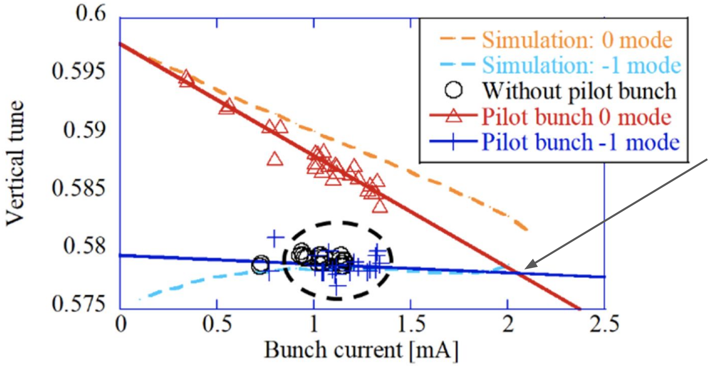
Measurements
Beam instability threshold increase while opening the primary V-collimator



Beam size blow-up at higher bunch currents

T.Ishibashi @KEK, 2022

S. Terui et al., *JACoW* IPAC2022 (2022) WEPOTK050 [link]



Estimated from measurements TMCI bunch current threshold ~2 mA/bunch

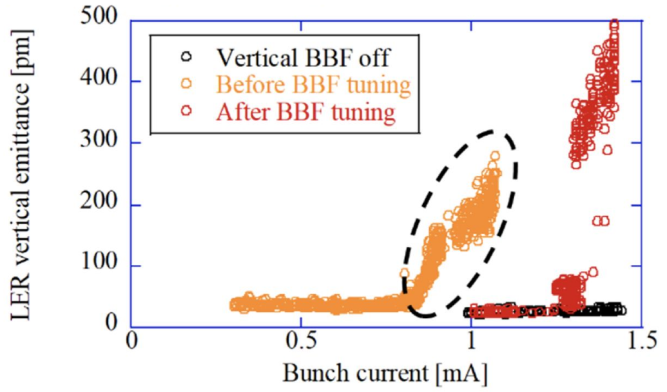
FFT peaks of the LER vertical oscillation versus the bunch current.

“–1 mode” instability

- We observed a vertical beam size blow-up around 0.8-1.0 mA/bunch in the LER
  - Much lower than the expected TMCI threshold ~2 mA/bunch
  - The blow-up is attributed to coherent oscillations at the frequency corresponding to **–1 mode** ($\nu_y - \nu_s$)

- During the nominal Belle II physics run, the Bunch-by-Bunch Feedback system (BBF) is intended to damp the frequency of the **0 mode**
  - The bunch current threshold of the vertical beam size blow-up is found to be higher with **BBF off** or **after BBF tuning** than **before BBF tuning**, see Figure
    - *Moreover, the number of bunches cannot be increased due to multi-bunch instability with BBF off*

https://inspirehep.net/literature/2137784



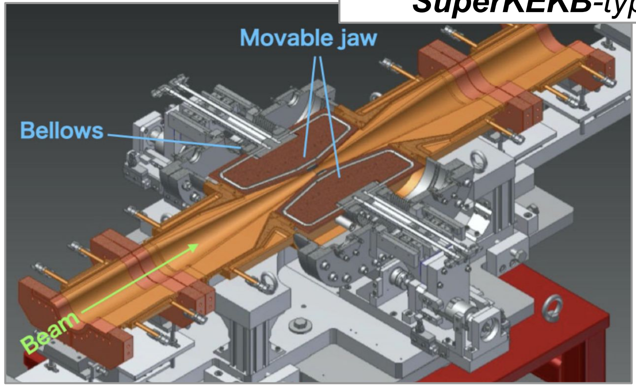
The LER vertical emittance before and after BBF tuning and BBF off versus bunch current

- From collision and single-beam measurements, we conclude that the beam-beam effect partially mitigates the vertical oscillation in the LER caused by the –1 mode
- We are currently working on i) adjusting the BBF and ii) reducing the machine impedance budget to mitigate beam instabilities at high bunch currents (> 1 mA/bunch)

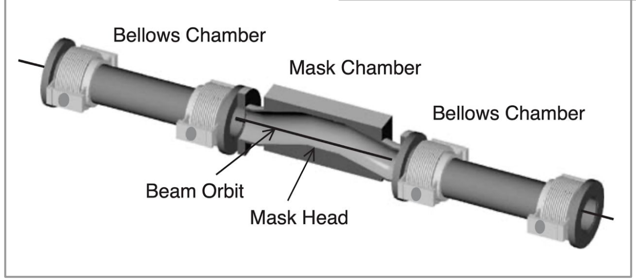
Collimation system

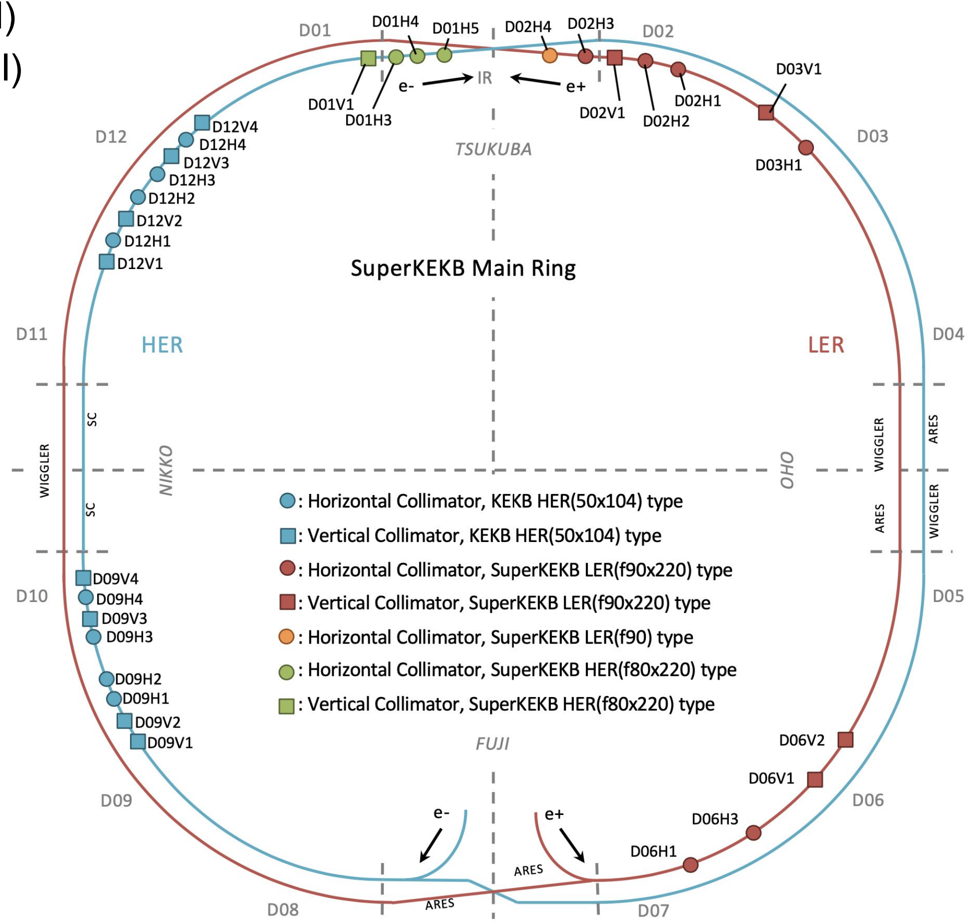
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)

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



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





Luminosity degradation & crab waist scheme

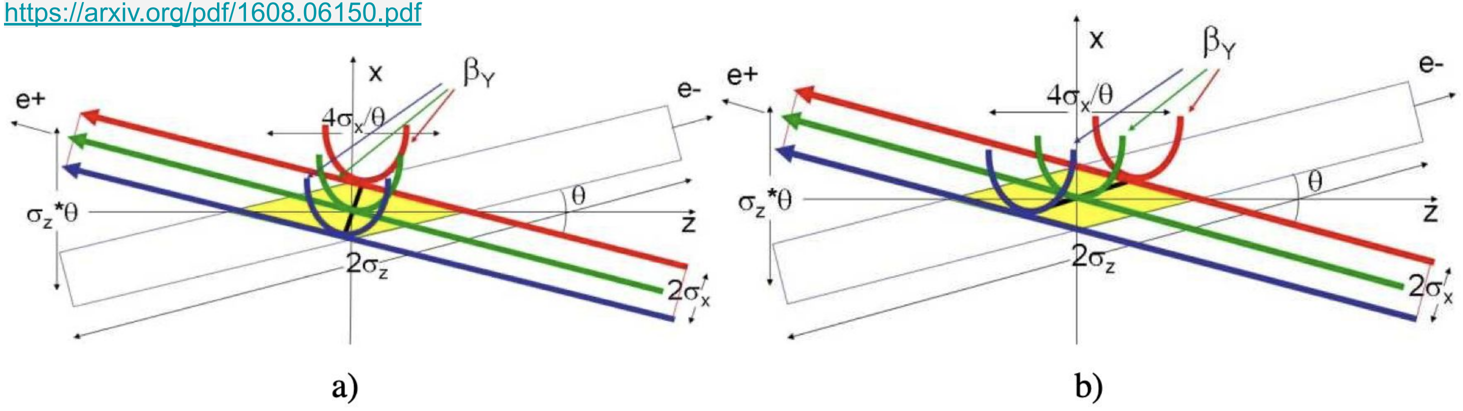
- **Initially**
  - Was hard to operate the SuperKEKB near the working point of the betatron tune (.57,.61)

    ← 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

Software for beam background simulation

Multi-turn particle tracking in `SAD` [1]
Beam-gas & Touschek [2]

- realistic collimator description
  jaw profile, chamber
- particle interaction with collimators
  a.k.a. tip-scattering
- measured vacuum pressure distribution
- random machine errors
  sextupole magnet offset

`Geant4` [3] + Belle II Analysis Software Framework (`basf2`) [4]

Single-beam background

Luminosity background
Two-photon [5] and Radiative Bhabha [6,7]

Synchrotron radiation

- realistic IR modelling (±30m from the IP)
  Belle II and SuperKEKB
- generating simulated data
- unpacking of real raw data
- reconstruction
  tracking, clustering, …
- high-level “analysis” reconstruction
  applying cuts, vertex-fitting, …

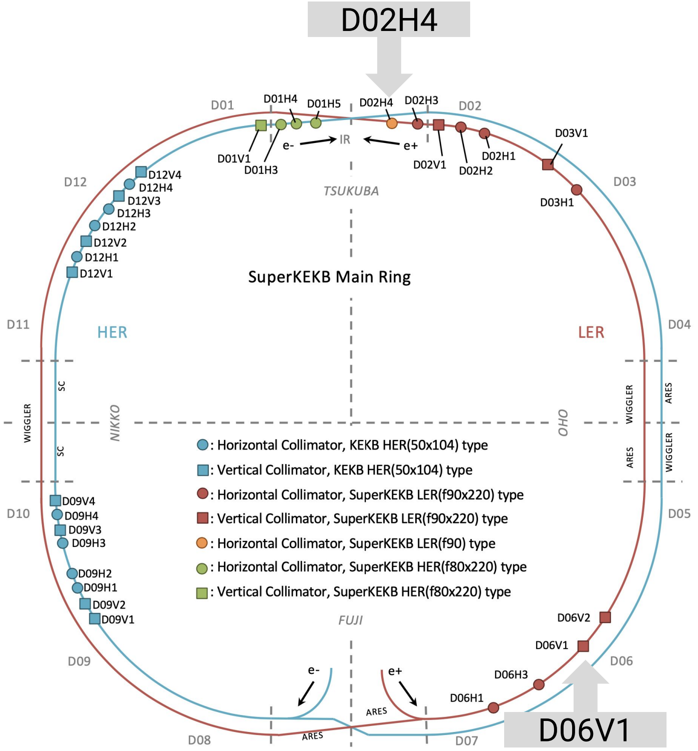
[1] Y. Ohnishi, et al., “Computer program complex sad for accelerator design, simulation and commissioning”, Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan (PASJ2019), WEOHP04, 2019
[2] Y. Ohnishi, et al., “Accelerator design at SuperKEKB”, Progress of Theoretical and Experimental Physics, Volume 2013, 2013, Pages 03A011
[3] Geant4 https://geant4.web.cern.ch
[4] A. Moll. The software framework of the belle II experiment. J. Phys. Conf. Ser., 331 (3):032024, 2011
[5] F.A. Berends, et al., “Complete lowest-order calculations for four-lepton final states in electron-positron collisions”, Nuclear Physics B, Volume 253, 1985, Pages 441-463
[6] R. Kleiss, et al, “BBBREM — Monte Carlo simulation of radiative Bhabha scattering in the very forward direction”, Computer Physics Communications, Volume 81, Issue 3, 1994, Pages 372-380
[7] S. Jadach, et al., “BHWIDE 1.00: O(α) YFS exponentiated Monte Carlo for Bhabha scattering at wide angles for LEP1/SLC and LEP2”, Physics Letters B,Volume 390, Issues 1–4, 1997,Pages 298-308

Background simulation: Validation

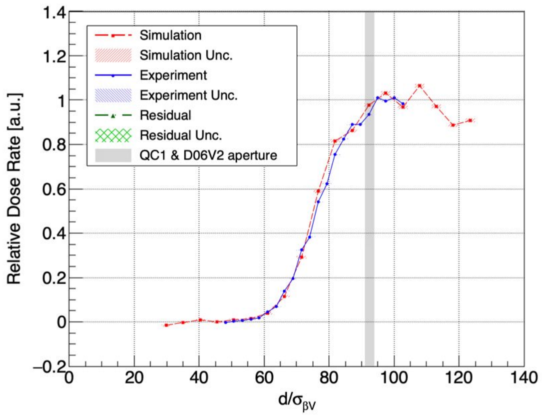
Our simulation reproduces the measured background in the IR at different collimator apertures

- D06V1 is the narrowest vertical collimator in the LER
- D02H4 is the closest to the IP horizontal collimator
- Tip-scattered particles contribute to the IR background

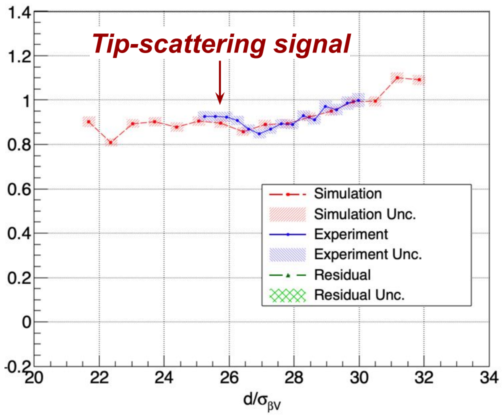
There is a good agreement between measurements and simulation



A. Natochii et al., PRAB (2021) 10.1103/PhysRevAccelBeams.24.081001



IR background vs D06V1 aperture



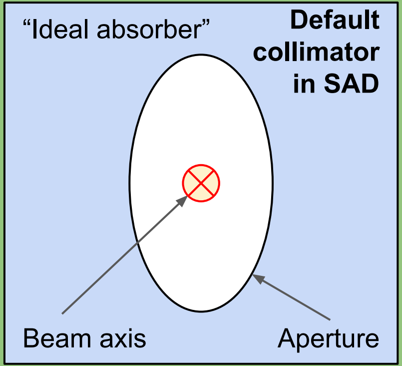
IR background vs D02H4 aperture

Evolution of the simulation accuracy in SAD

Data/MC ~ 10^{-3}–10^{3} → **Data/MC ~ 10^{-1}–10^{1}** → **Data/MC ~ 1**

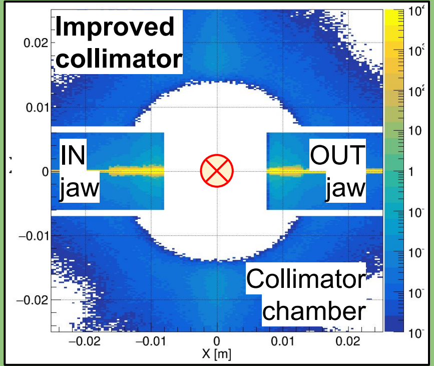
Phase 1 and Phase 2 experiences 2016–2018

IR beam pipe geometry improvement
+
Measured background decomposition methodology



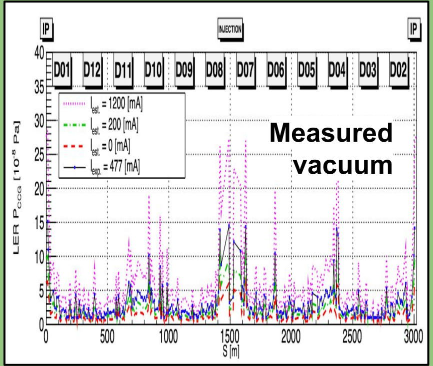
Early Phase 3 experiences 2019–2022

IR beam pipe geometry improvement
+
Realistic collimator profile
+
Particle interaction with collimator materials



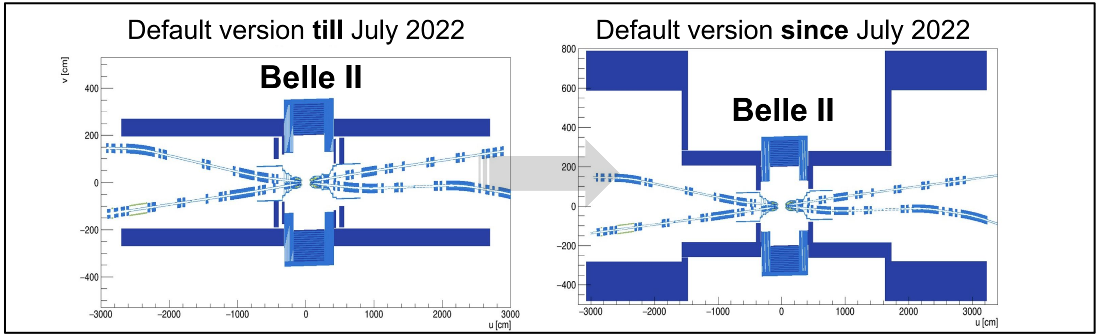
Early Phase 3 experiences 2019–2022

Measured beam pipe gas pressure
+
Accurate translation of beam losses from SAD to Geant4
+
Improved Geant4 model

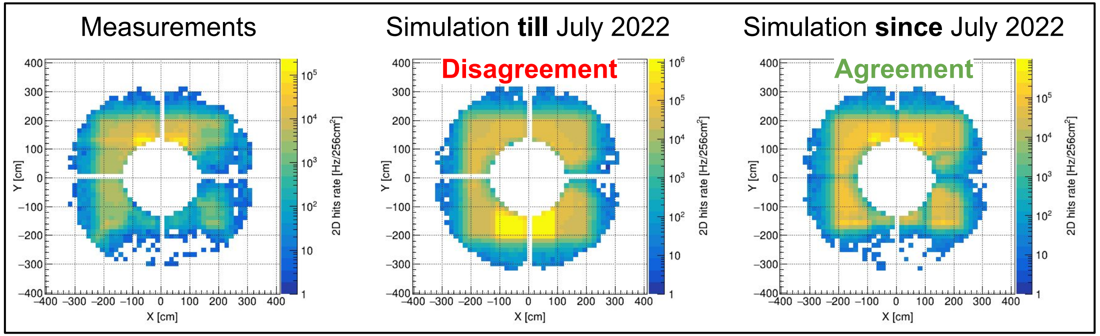


Geant4 model evolution and impact on backgrounds

- In the past two years we invested a lot of effort in improving the Geant4 modelling of the Belle II and SuperKEKB interaction region
- The latest version realistically describes detector materials and accelerator tunnel
  - Accurate IP beam pipe
  - Belle II shielding
  - Tunnel wall
  - Machine equipment (e.g. collimators)
- **Improved** the data/MC agreement
  - ARICH Lumi BG data/MC 10 → 1
  - Better endcap KLM hits 2D distribution
- Allows us to study the impact of the additional shielding planned for the LS1

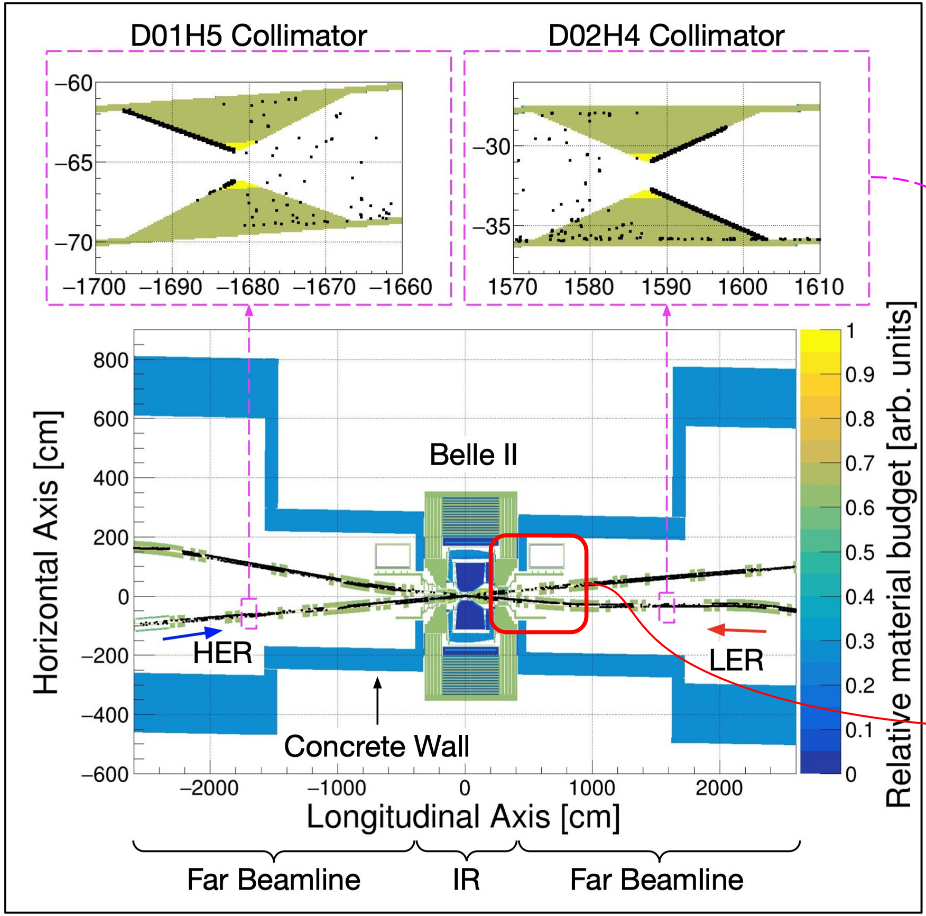


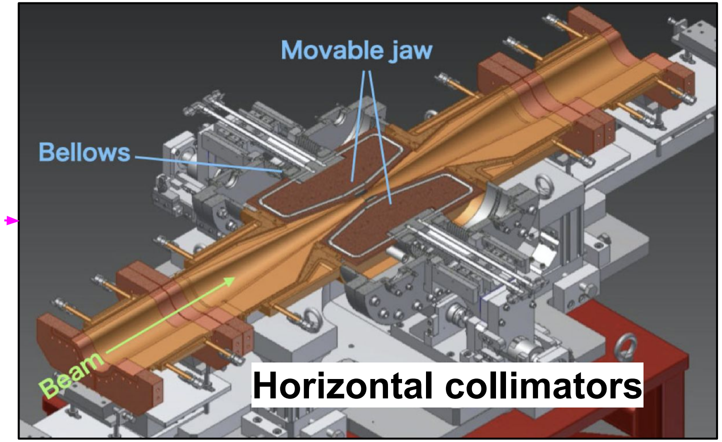
IR Geant4 model improvement. Skipping intermediate steps

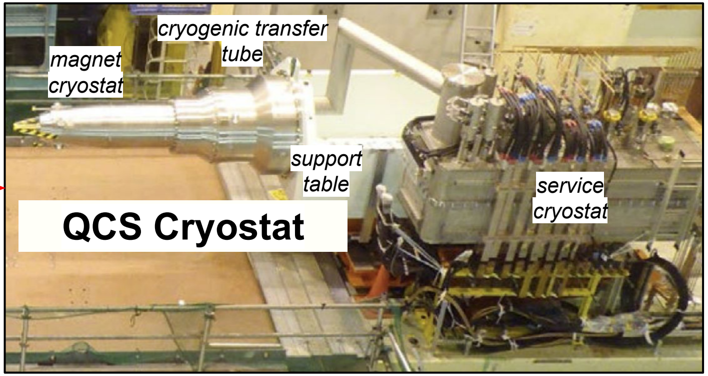


2D background hits on the outermost layer of the FWD KLM endcap

Current Geant4 model of the IR







SuperKEKB operation status

Courtesy of Y.Ohnishi, eeFACT2022 [link]
(Head of SuperKEKB commissioning)

Achievements until 2022 (1)

- Peak luminosity : 4.65 x 10^{34} $cm^{-2}s^{-1}$ (4.71 x 10^{34} $cm^{-2}s^{-1}$ w/o Belle II data taking)
- Integrated luminosity : 424 fb^{-1} (491 fb^{-1})
- Peak currents : 1.46 A (LER) / 1.14 A (HER), 2346 bunches (2-bucket spacing)
- β_y^* : 1 mm (0.8 mm) << bunch length ~6 mm → proof of the nano-beam scheme
- Crab waist scheme has been applied (80 % in the LER, 40 % in the HER). → luminosity improvement
- Beam-Beam parameter : 0.035 at 0.7 mA (0.045 at 1.1 mA for small number of bunches)
- Bunch-by-bunch FB tuning (gain, noise reduction) in the HER → luminosity improvements
- Bunch-by-bunch FB tuning (number of taps) in the LER → suppress single bunch blowup, luminosity improvements
- Chromatic X-Y coupling correction with rotatable sextupoles in the LER → luminosity improvements
- Long-term drift of QCS magnetic field (beta-beat) ← reduced by new QCS initialization procedure
- Orbit deviation due to IP knob tuning (beta-beat) ← suppressed with QCS corrector (ZHQC2RP)
- Increase of positron charge for the LER injection : 3 nC at the end of e^+ beam transport line
- 2-bunch injection for the LER and HER → improve injection efficiency
- Adjustment of injection orbit in the HER (septum, kicker) → improve injection efficiency (not enough)
- Reduce leakage orbit from injection kickers ← reduced by additional inductance for the coils

Only a factor of ~13 from the target luminosity

Big surprises and challenges

- Sudden beam losses *(see next slides)*
- Beam size blow-up in the LER
  - Beam instability *(see next slides)*
- Low beam-beam parameter
  - Design ξ_y = 0.08-0.09 → Achieved ξ_y = 0.02-0.04 (2021-2022)
  - Even when all single-beam instabilities are mitigated, the **beam-beam effect** remains a limiting factor for the further luminosity increase toward the target of 6.3×10^{35} $cm^{-2}s^{-1}$
- Beam current dependence of beam orbit at crab sexupoles
  - Beam line deformation due to intense SR heating
- Short beam lifetime in the LER
  - $\tau < 10$ min at $I > 1$ A
- Low injection efficiency
  - Less than 40% at $\beta^*_y < 1$ mm
- Earthquakes
  - Frequent orbit corrections

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

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp\beta_y^*}{\sigma_y^*(\sigma_x^*+\sigma_y^*)}R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

SuperKEKB is a novel machine with ambitious goals, so it is not shocking that we have so many unexpected difficulties and problems to solve

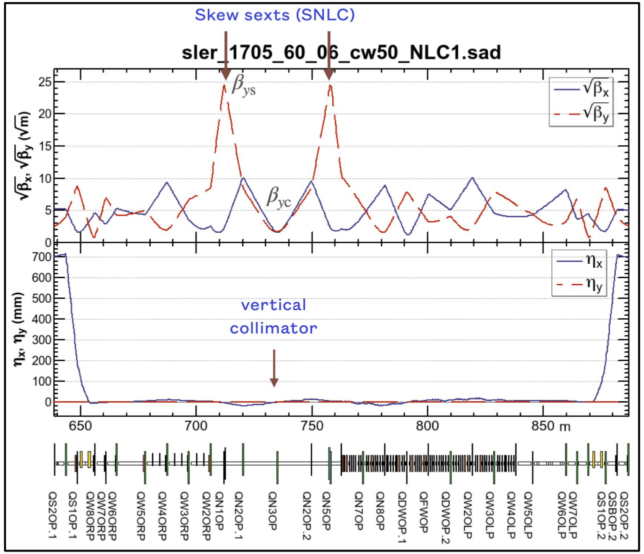
Nonlinear collimation (NLC)

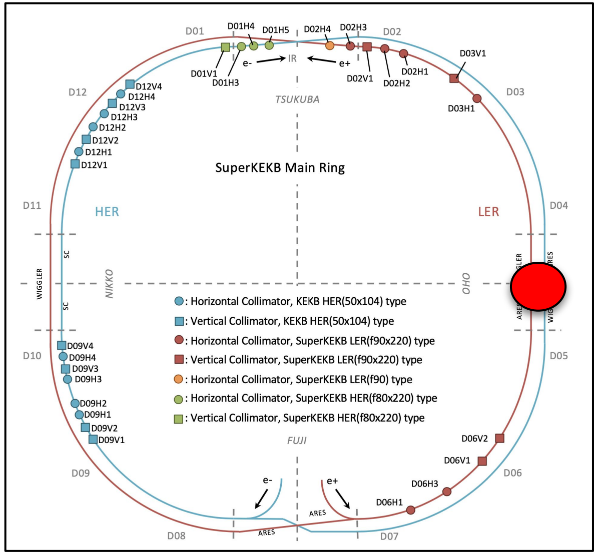
Create a nonlinear optics region by using a pair of skew-sextupoles in the Oho-section with a V-collimator

- Low betatron function in between (at the collimator) $\beta_{x/y}$ ~3 m → low impedance at narrow aperture
- Vertical angular kick for distant halo particles in both planes $\Delta p_y \sim (y^2 - x^2)$ → effective halo cleaning
- A big aperture step ~1 mm corresponds to 4σ at the QCS → fine aperture tuning
  - Other V-collimators: ~1 mm step ⇒ 20-40σ at the QCS

NLC can work as a primary collimator with effective background suppression and low impedance

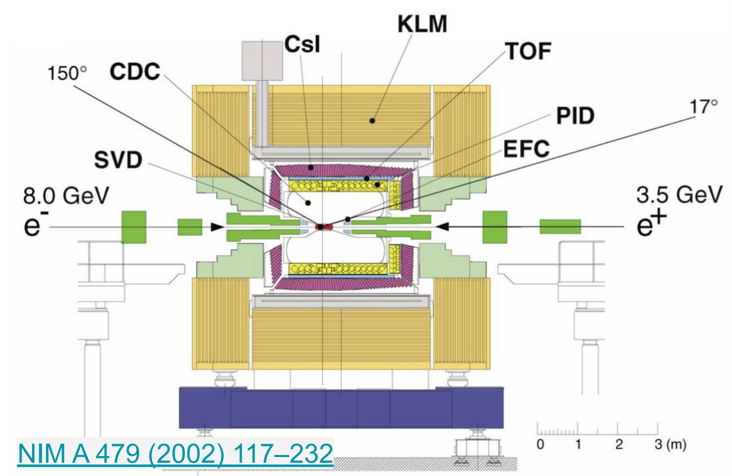
Introduced by K.Oide, CERN/KEK, 2021





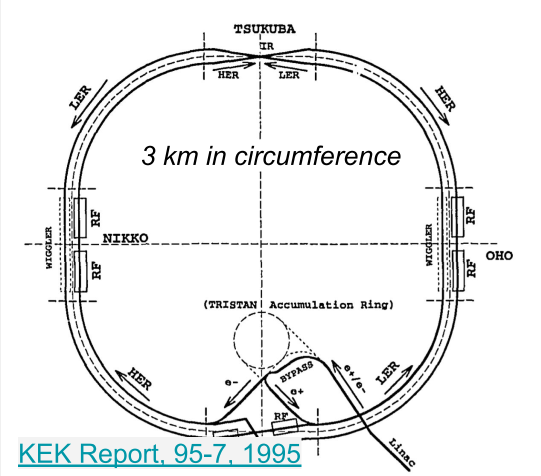
Belle and KEKB (1999-2010)

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		($cm^{-2}\,s^{-1}$)	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

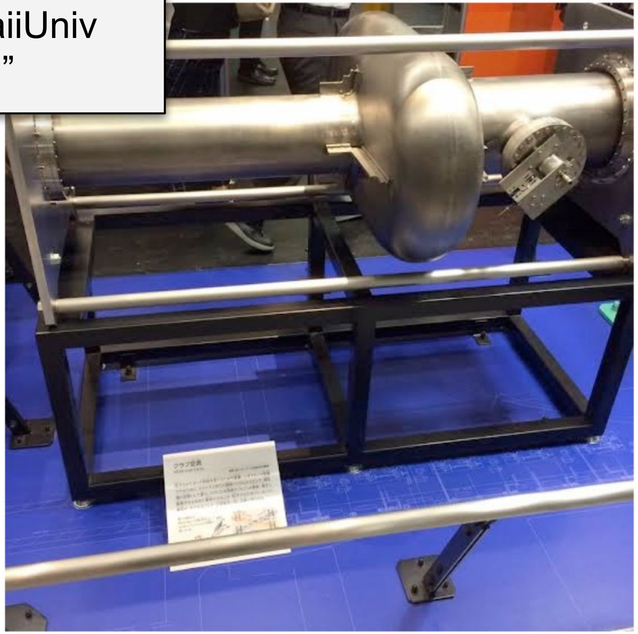
World's first operational set of superconducting crab cavities

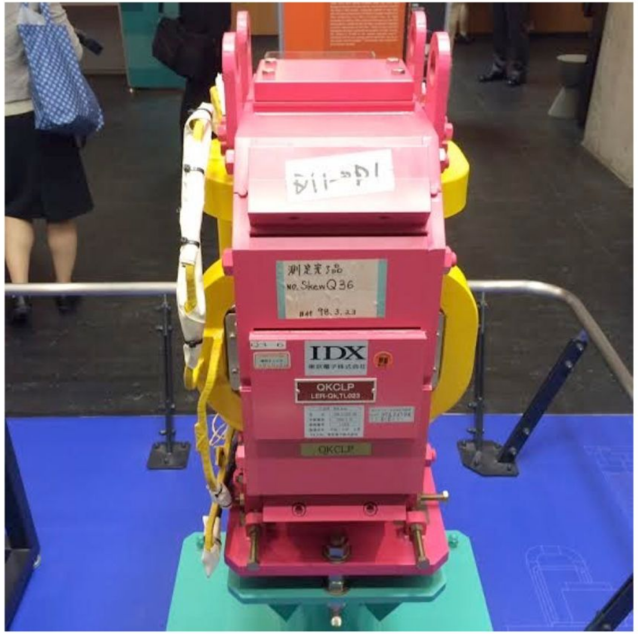
KEKB crab cavities moved from KEK to the Tokyo Museum

Crab cavity (superconducting) and a skew sextupole from KEKB in the Ueno Science Museum in Tokyo

Prof. Thomas E. Browder @ HawaiiUniv
"From Belle to Belle II and Beyond"

Not to be confused with the "crab waist"





On the left is a superconducting crab cavity used to rotate the beams in the crossing-angle scheme so that they achieve head-on collisions. The crab cavities were not effective until skew sextupoles were added to correct optical defects. Combining these two elements, a peak of luminosity of 2.1 x 10^{34} /cm^2/sec was achieved.

SuperKEKB design

PTEP **2013**, 03A011 Y. Ohnishi et al.

Table 1. Machine parameters. * indicates values at the IP.

	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
N_b	2500		
C	3016.315		m
ε_x	3.2	4.6	nm
ε_y	8.64	11.5	pm
β_x^*	32	25	mm
β_y^*	270	300	µm
$2\phi_x$	83		mrad
α_p	3.25×10^{-4}	4.55×10^{-4}	
σ_δ	8.08×10^{-4}	6.37×10^{-4}	
V_c	9.4	15.0	MV
σ_z	6	5	mm
ν_s	−0.0247	−0.0280	
ν_x	44.53	45.53	
ν_y	44.57	43.57	
U_0	1.87	2.43	MeV
τ_x/τ_s	43.1/21.6	58.0/29.0	msec
ξ_x	0.0028	0.0012	
ξ_y	0.0881	0.0807	
L	8×10^{35}		$cm^{-2}\ s^{-1}$

IR magnet system

- Since SuperKEKB has a big crossing angle (83 mrad) between two beamlines, the axis of the Belle II solenoid (1.5 T) is placed on the bisection line of the two beamlines.
- This configuration was chosen as optimal since we know that the tilt (θ_{tilt}) between the solenoid axis and a beamline generates a vertical emittance growth which depends on the tilt angle ($\varepsilon_y \sim\theta_{tilt}^4$).
- Therefore, we use skew dipole correctors to compensate for the emittance growth down to ~2 pm. X-Y coupling and vertical dispersion are corrected by skew quadrupoles and dipoles, respectively.

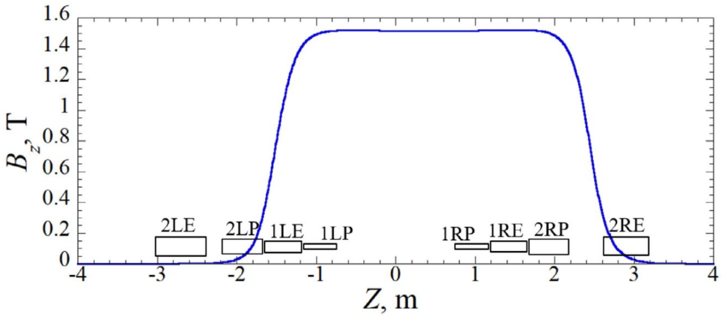


Fig. 4. Calculated magnetic field profile along the Belle II SC solenoid magnet. Z=0 corresponds to the IP position. The axial center of the solenoid magnet is located at Z=0.47 m. The quadrupole magnets with the distance from the IP are shown by the rectangle boxes.

Table 2
Main parameters of the final focus system.

Number of SC magnets	55
Main quadrupole	Integral field
QC1RP, QC1LP	22.96 T, 22.96 T
QC2RP, QC2LP	11.54 T, 11.48 T
QC1RE, QC1LE	25.39 T, 26.94 T
QC2RE, QC2LE	13.04 T, 15.27 T
Compensation solenoid	Integral field
ESR1 + ESR2 or ESR3	3.86 T•m
ESL	2.31 T•m
Magnet-cryostat	2 units
	Cold mass @ 4 K
QCS-R, QCS-L	3,139 kg, 1,522 kg
He refrigerator cryogenic system	2 units
Cooling power of one unit	250 W @ 4.5 K

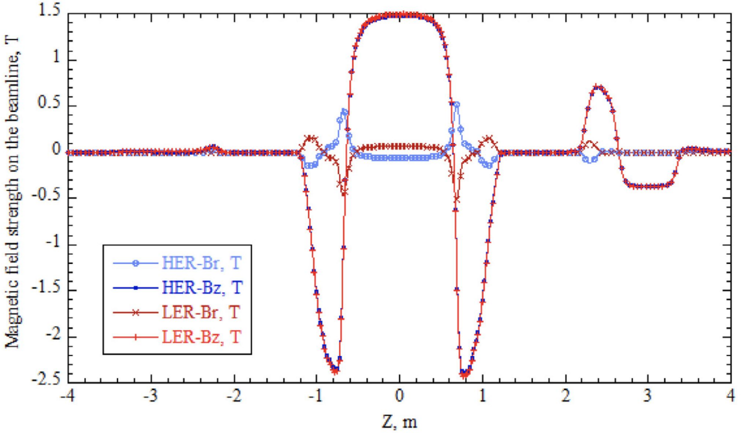


Fig. 16. Magnetic field profiles along the beam lines.

[1] N. Ohuchi, et al., "SuperKEKB beam final focus superconducting magnet system", Nuclear Inst. and Methods in Physics Research, A 1021 (2022) 165930

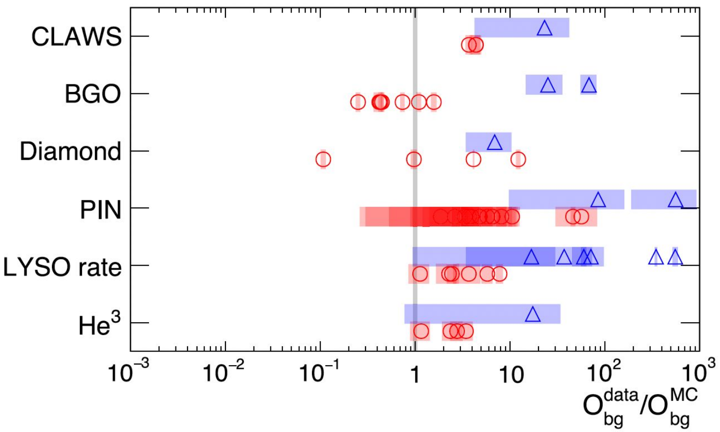
Phase 1 data/MC ratios

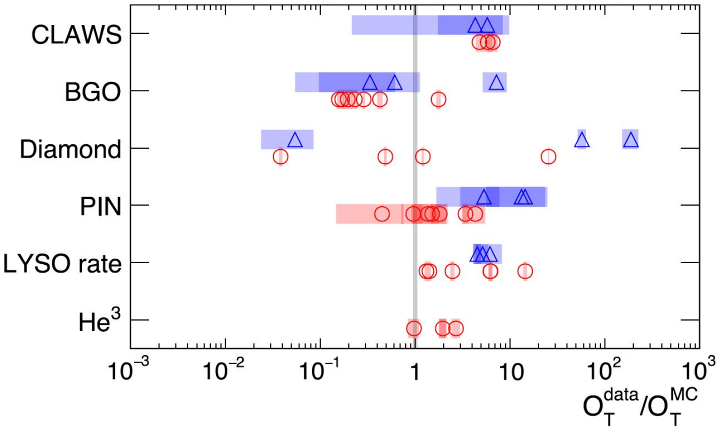
[P.M.Lewis *et al.*, "First measurements of beam backgrounds at SuperKEKB", NIMA 2019]

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: $4.8^{+8.2}_{-2.8}$.





Phase 2 data/MC ratios

[Z.J.Liptak *et al.*, "Measurements of Beam Backgrounds in SuperKEKB Phase 2", arXiv:2112.14537]

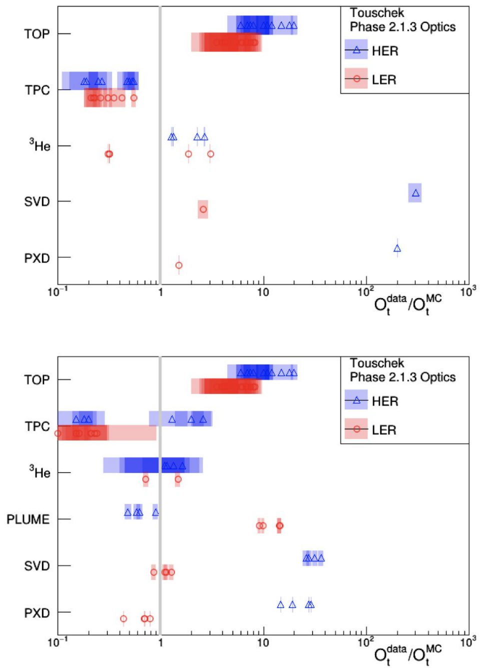


Figure 19: (color online) Ratio of observed to predicted Touschek background rates in all detectors studied with old (top) and new (bottom) simulation. Blue (Red) points represent HER (LER) results. From top to bottom, the detectors are ordered from radially outermost (TOP) to inermost (PXD).

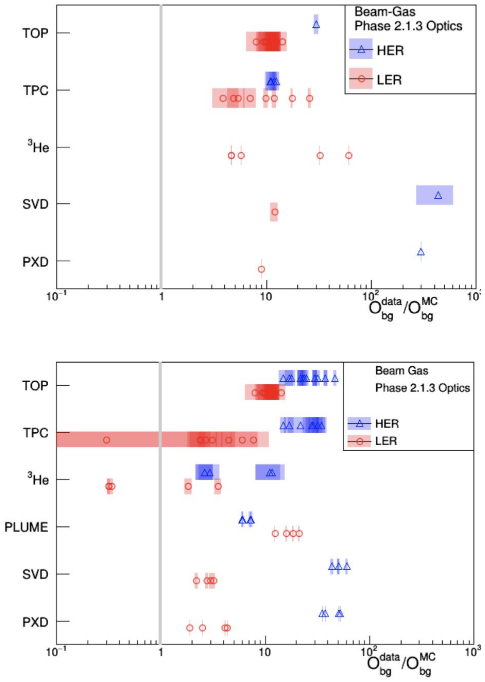


Figure 20: (color online) Ratio of observed to predicted Touschek background rates in all detectors studied with old (top) and new (bottom) simulation. Blue (Red) points represent HER (LER) results. From top to bottom, the detectors are ordered from radially outermost (TOP) to inermost (PXD).

Data-to-simulation Monte Carlo (Data/MC) fit results for all BEAST II and Belle II detectors are summarized in Figure 19 for Touschek backgrounds and Figure 20 for beam-gas results. Values for individual detector channels or physical locations, where applicable, are shown as separate points. The top plot in each figure represents the results of the Data/MC fits using the "old" simulation, while bottom plots show the same results using MC updated to better model the detector. Data/MC fit results are improved markedly with the new simulation, usually by orders of magnitude. Table 2 combines the individual detector results into a single overall ratio for Touschek and beam-gas backgrounds in the LER and HER. In Section 7 we use these

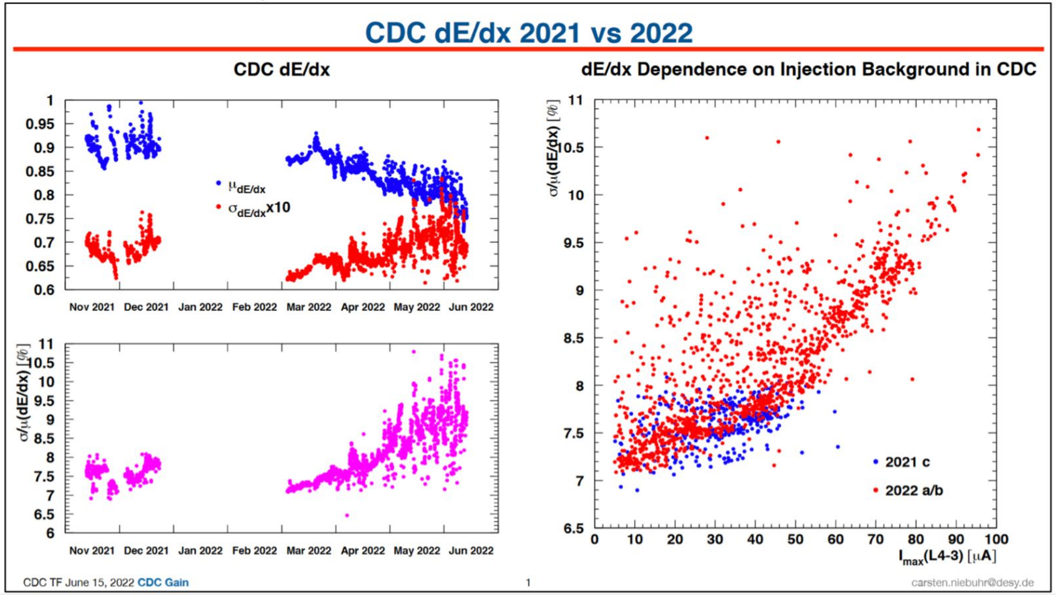
Ring	Background Source	October 2018 Simulation	February 2019 Simulation	October 2018/February 2019 Ratio
HER	Touschek	127.82	113.91	1.12
	Beam-gas	483.50	32.28	14.98
LER	Touschek	1.62	0.63	2.57
	Beam-gas	29.39	2.79	10.53

Table 2: Comparison of combined detector data/MC ratios, excluding PLUME. Averages are calculated first by taking the mean of all channels in each BEAST or Belle II detector, and then combining them into an average of averages.

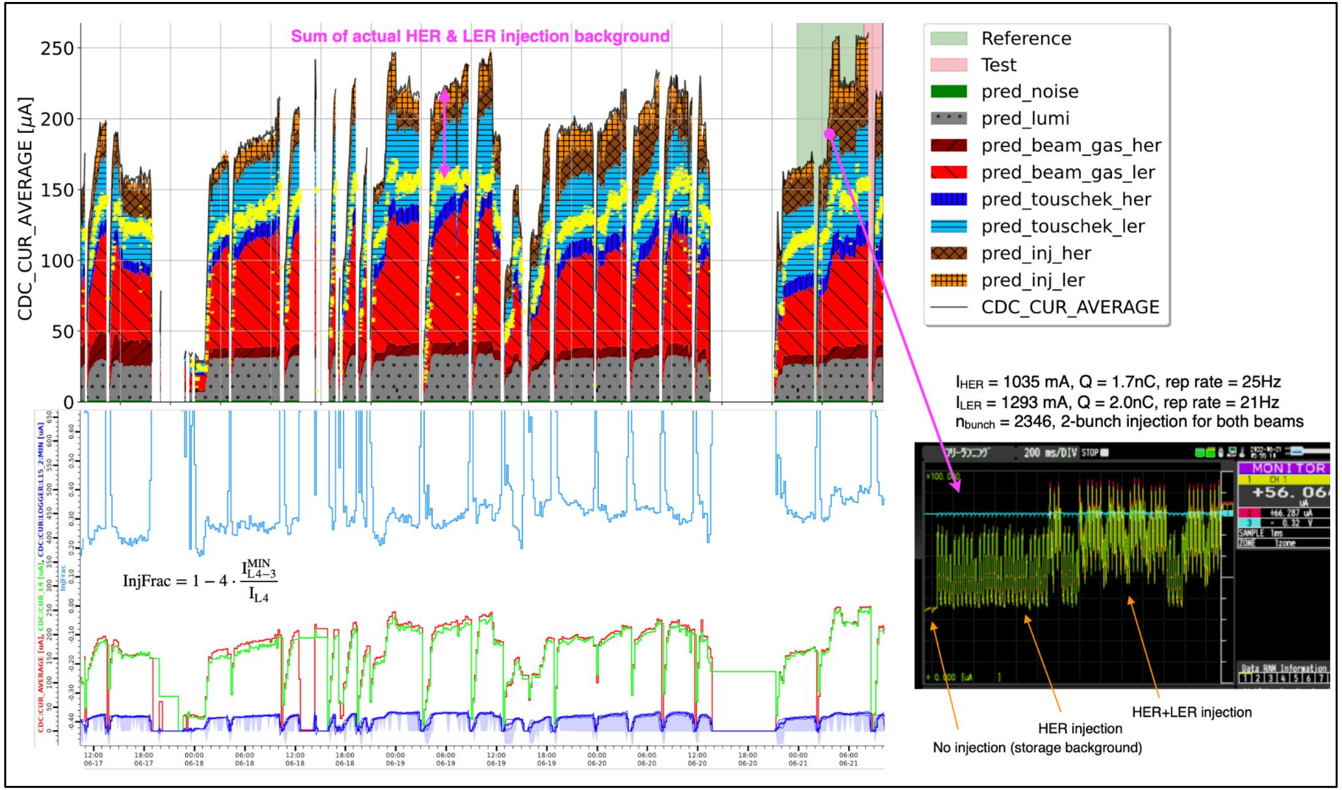
Injection background: CDC performance degradation

K. Matsuoka (KEK)
C. Niebuhr (DESY)

- Reduction of the injection veto dead time
  - Fixed veto pattern → Will study variable pattern (veto only when TRG hits exceed some limit)
- Reduction of the injection background and duration
  - Need more investigation and simulation to understand the injection background.
  - Will consider how to prevent the collimator head being damaged.
    - Need to pin down the cause of the fast beam loss.



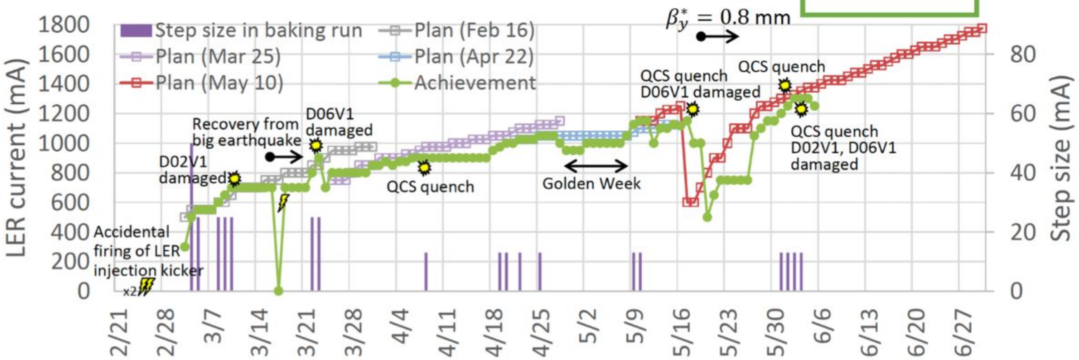
Injection background: CDC observable



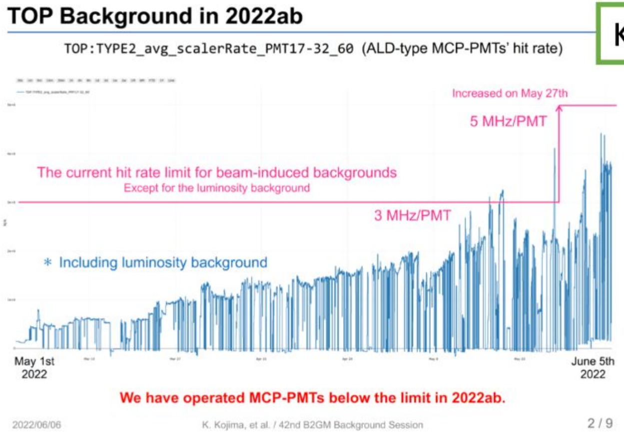
B. Schwenker
(Univ. of Göttingen)
C. Niebuhr (DESY)

Collimator damage and background history for 2022

Matsuoka



Kojima



Vahsen

Hypothesis for elevated backounds

- Throughout the run, backgrounds increase with beam currents (expected and unavoidable).
- As we increase beam-currents, the rates of catastrophic beam-loss events increase.
- This damages collimator jaws. Collimator team is then forced to re-adjust and typically open the collimators further.
- Both collimator jaw damage and opening collimators lead to an *additional* background increase as the run progresses.
- Collimator damage accumulates. Background situation gets progressively worse throughout the run.
- This also puts a lot of stress on the collimator group.

Time to consider collimator system upgrade?

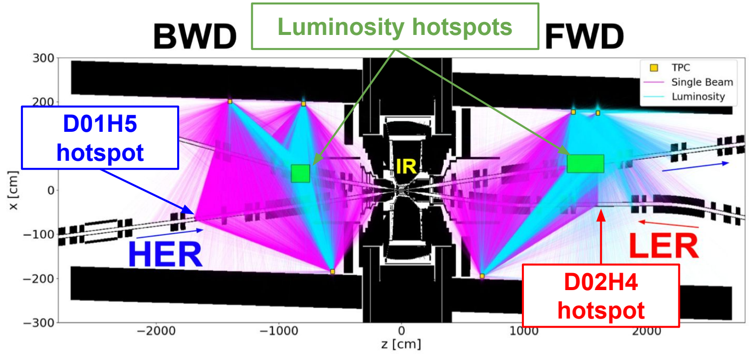
- More robust collimator heads
- Faster + cheaper to replace
- More granular and stable jaw positioning
- Automatic / improved absolute alignment

Neutrons from the accelerator tunnel

- 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

arXiv:2111.03841



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

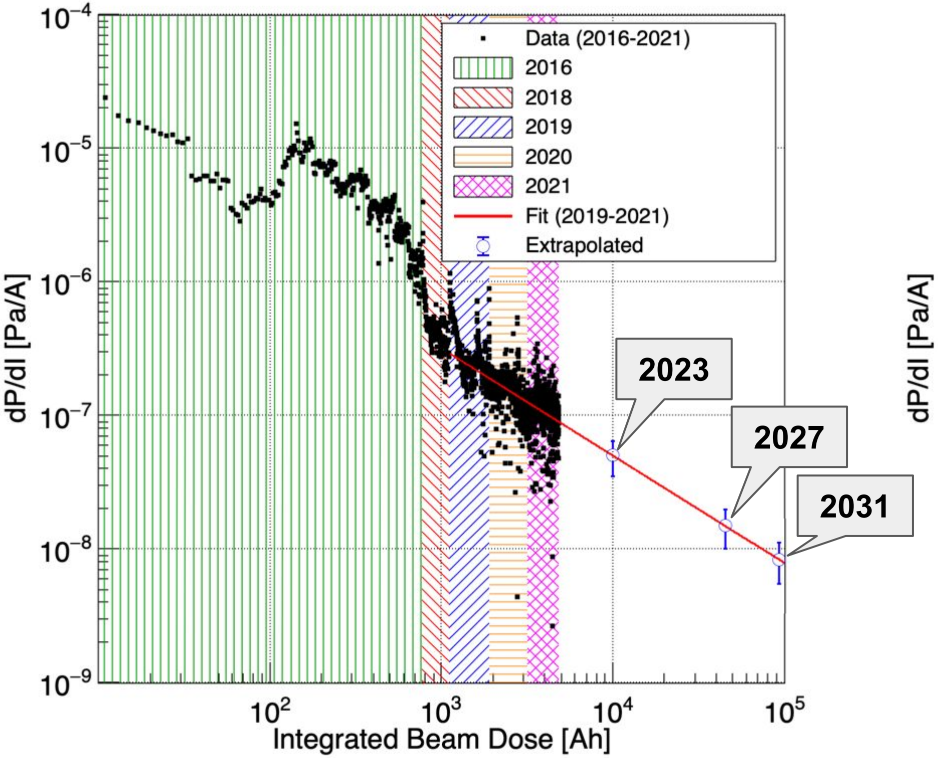
- Time Projection Chamber (TPC) measurements suggest localized regions along the beamline where neutrons originating from
  - Leading background in the forward cavern
  - Can be mitigated only via shielding, design is ongoing

Dynamic vacuum pressure estimation

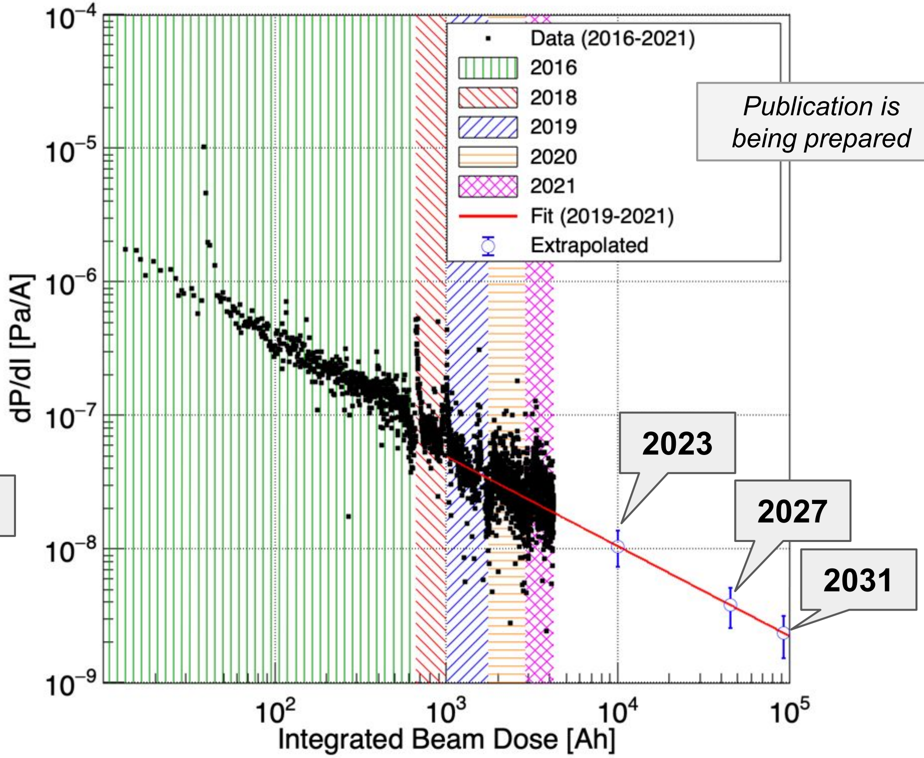
Extrapolation is based on Phase 3 data only: January 1, 2019 – July 5, 2021

Dynamic pressure

LER

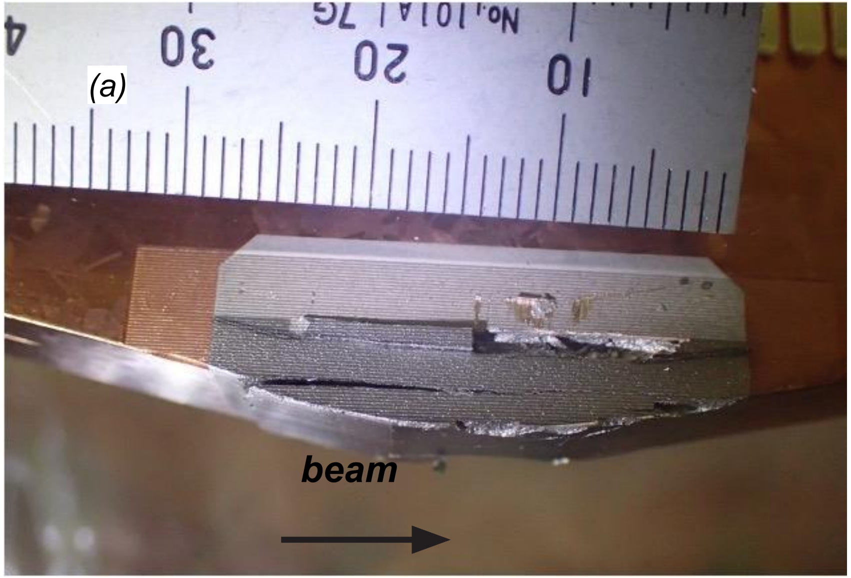


HER

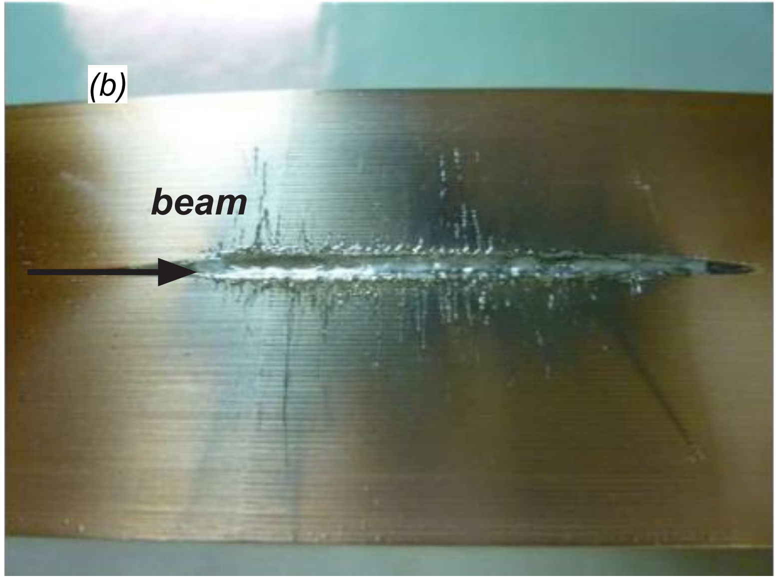


Publication is being prepared

Damaged collimators

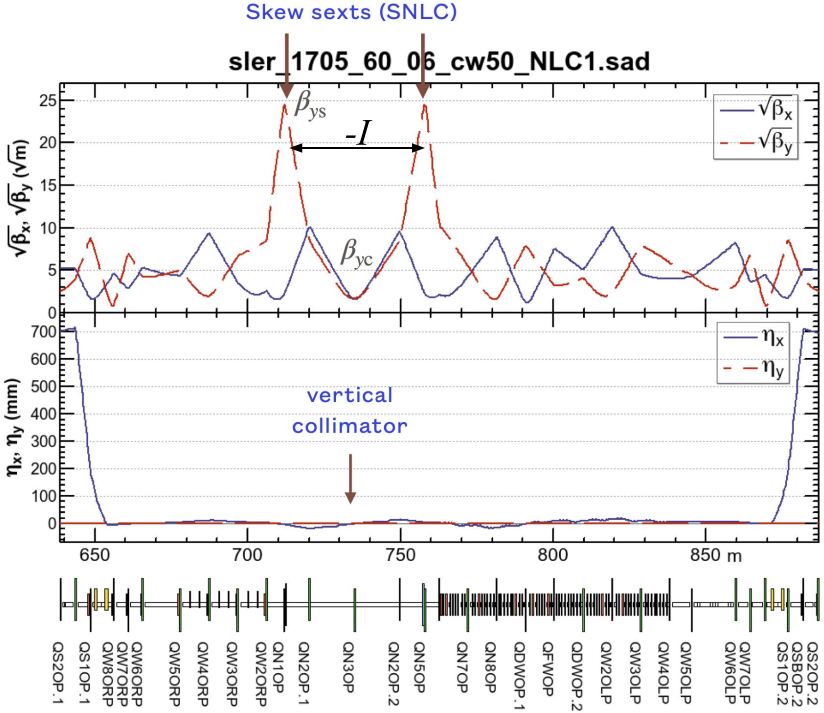


*(a) Severely damaged **tungsten** head*
Measured dose rate ~720 μSv/h



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

K. Oide



- Consider a collimation at a vertical amplitude y_q, which is equal to the *dynamic aperture.*
  - For the (60,0.6) mm optics, $y_\mathrm{q} = 10.0\,\mathrm{mm}$ at QC1 ($30\sigma_y$ with $\varepsilon_y/\varepsilon_x = 2\%$).
- It is equivalent to $y_\mathrm{s} = y_\mathrm{q}\sqrt{\beta_{ys}/\beta_{yq}} = 6.8\,\mathrm{mm}$ at the NLC skew sextupole `SNLC`.
- The sextupole kicks the beam vertically by

$$\Delta p_{ys} = \frac{s'}{2}(y_\mathrm{s}^2 - x_\mathrm{s}^2)\,, \tag{1}$$

$$s' \equiv \frac{L_\mathrm{s}}{B\rho}\frac{\partial^2 B_x}{\partial y^2}\,. \tag{2}$$

  - For instance, $s' = 6.0/\mathrm{m}^2$, $\Delta p_{ys} = 0.14\,\mathrm{mrad}$, with $|y_\mathrm{s}| \gg |x_\mathrm{s}|$.
- Then the kick makes a vertical displacement at the collimator:

$$\Delta y_\mathrm{c} = R_{34}\Delta p_{ys} = 5.7\,\mathrm{mm} \tag{3}$$

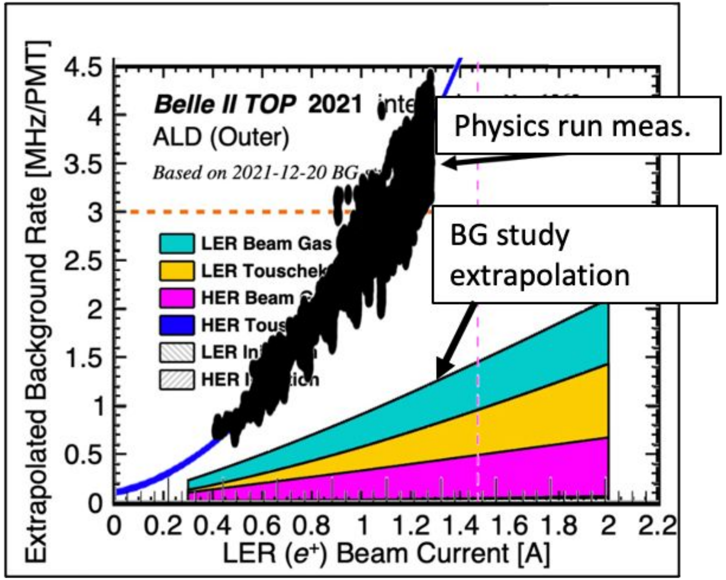
$$R_{34} \approx \sqrt{\beta_{yc}\beta_{ys}} = 40.8\,\mathrm{m} \tag{4}$$

- This example optics: $\beta_{ys} = 570\,\mathrm{m}$, $\beta_{yc} = 2.9\,$ m.

Real-time BG decomposition

- To achieve higher collision luminosities, we should be able to **control beam losses in the machine in real-time**
  - Currently, we only obtain reliable updates of single-beam and luminosity background fractions during dedicated background studies (usually twice a year)
- This results in **large discrepancy with Physics Run** measurements; see Figure
- **Two real-time background composition monitors** based on a neural network (NN) and ECL detector were developed to
  - React fast to BG changes
  - Accurately suppress BGs through machine tuning
  - Develop strategies for further luminosity increase

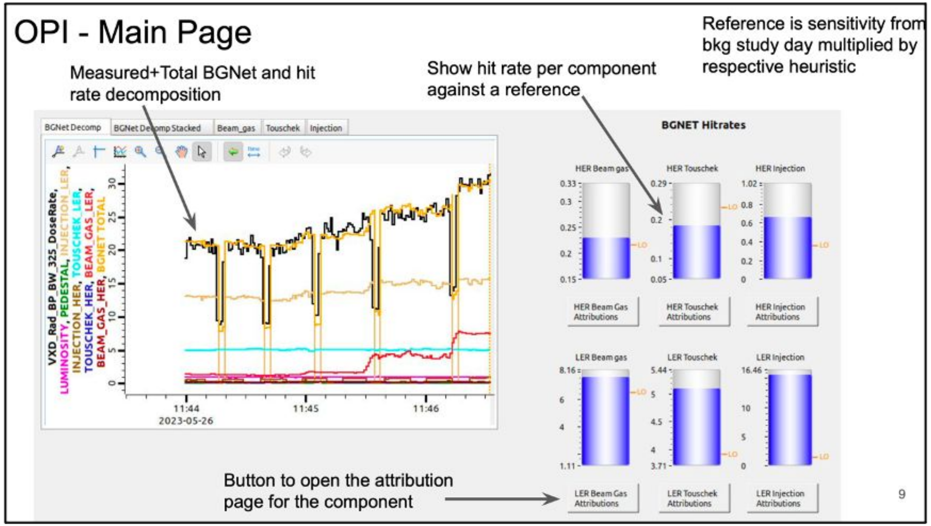
K. Kojima (Nagoya Univ.)



Neural Network (BGNet)

- Supports multi-sensor training and training is pipelined
  - It can be run on different systems
- Demonstrated that EPICS+BGNet could be used for the real-time decomposition of beam backgrounds using a set of machine parameters
- Through a feature attribution BGNet can provide feedback to the machine operators regarding which beam parameters contribute the most to a background change
- The Göttingen team is currently working on the required hardware and network setup for the system installation at KEK during LS1

Y. Buch (Göttingen Univ.)

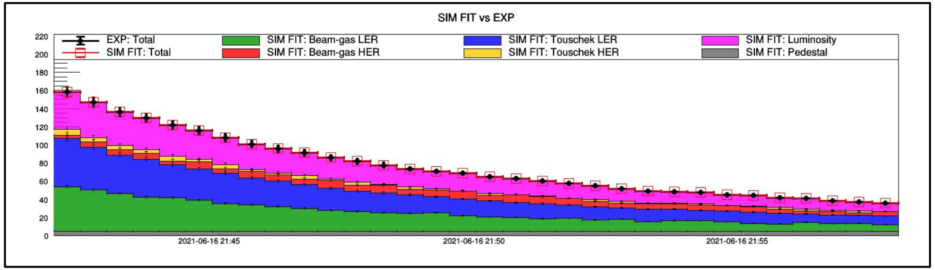


ECL-based BG composition monitor

- To provide an online background decomposition to the BCG shifter
- Uses high statistics Monte-Carlo templates to fit measured hit distribution in ECL trigger cells
- Benefits
  - Accurate decomposition of the measured background using only 10-sec-long integrated data
    - *The standard heuristic fit requires dedicated one-day-long BG measurements*
  - Follows BG changes during collimator aperture scans
    - *The heuristic fit fails*
- The prototype of the system was successfully tested at KEK
  - A rack-mount computer server was installed in June

A. Natochii (Univ. of Hawaii)

- To finalize the system
  - The ECL group (Y. Unno-san) is working on developing ECL EPICS PVs with injection veto since the monitor works only with non-injection data



Decomposed ECL background during LER and HER beam decay