2022 Belle II Summer Workshop

Beam backgrounds in Belle II

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On behalf of the beam background and MDI groups

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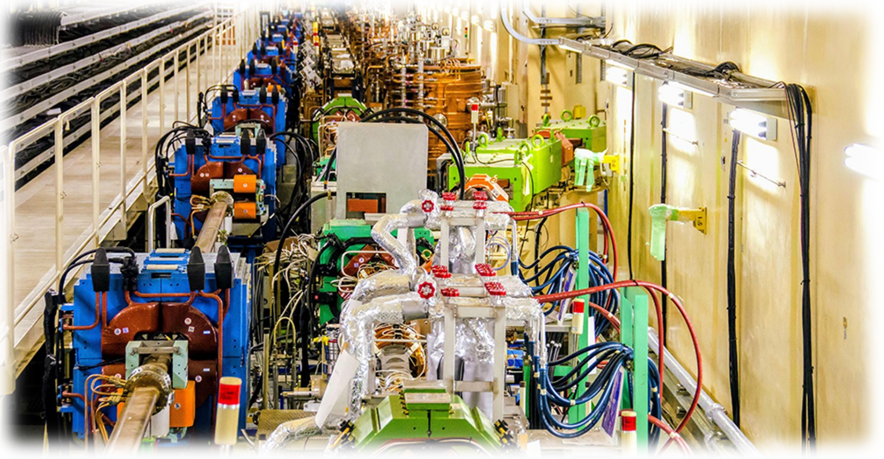
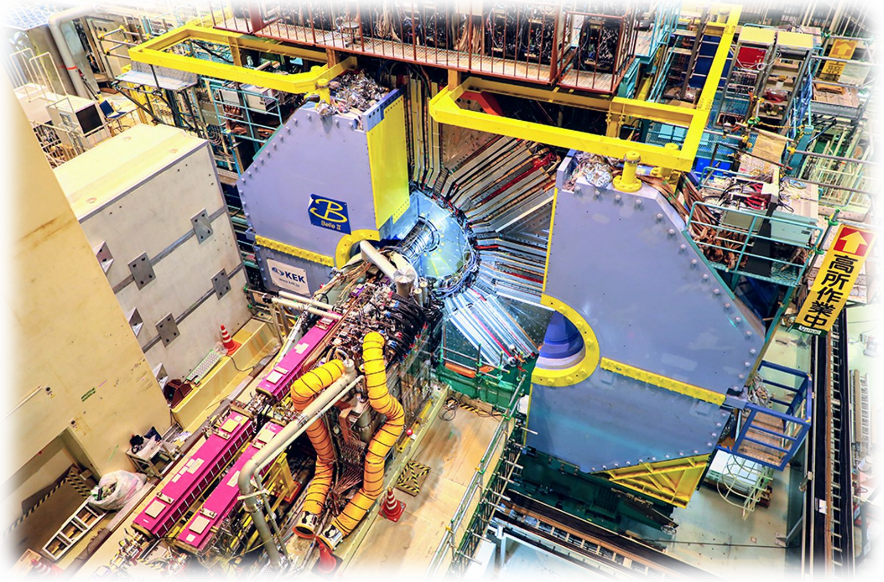
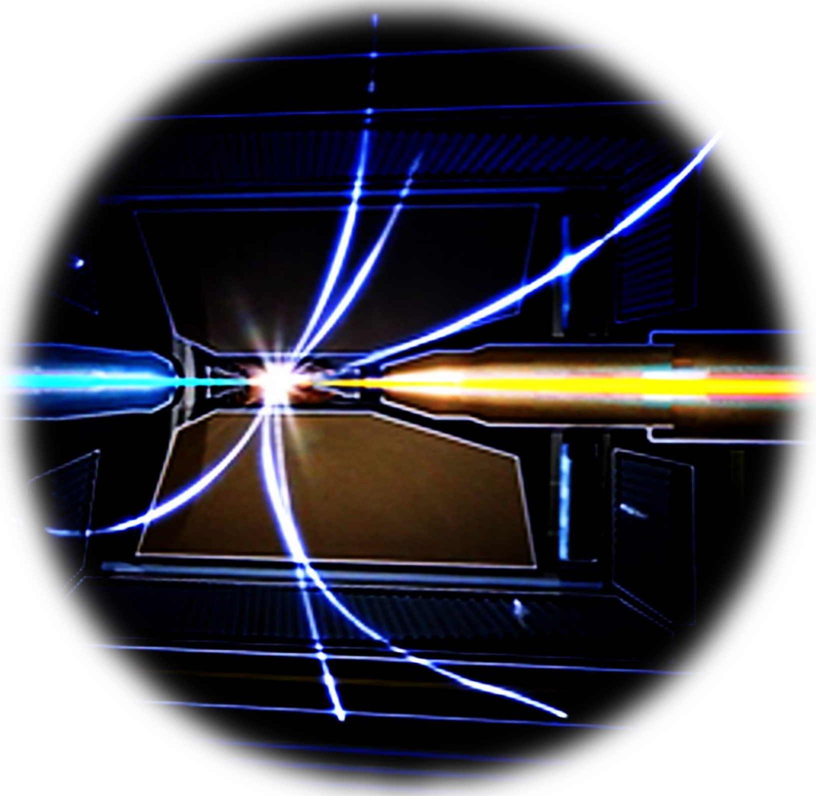
Iowa State 2022





Outline

- ❖ Introduction
- ❖ Belle II and SuperKEKB
- ❖ Luminosity gain and consequences
- ❖ Beam background overview
  - ➢ Sources and mitigation
  - ➢ Measurements
  - ➢ Current status
  - ➢ Simulation
- ❖ Future plans and prospects
- ❖ Summary



Introduction: *B*-factories

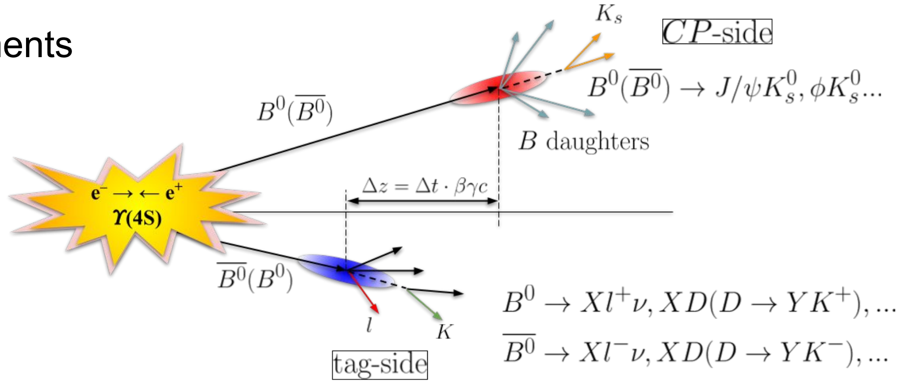
- Goals of **Belle** and **Belle II** experiments
  - Study the *CP*-symmetry violation in the *B*-meson system
  - Searching for New Physics beyond the Standard Model
- Requirements for **KEKB** and **SuperKEKB** colliders
  - Produce a large number of $B\overline{B}$-pairs
    - *High collision luminosity*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

1999-2010

BELLE — KEKB

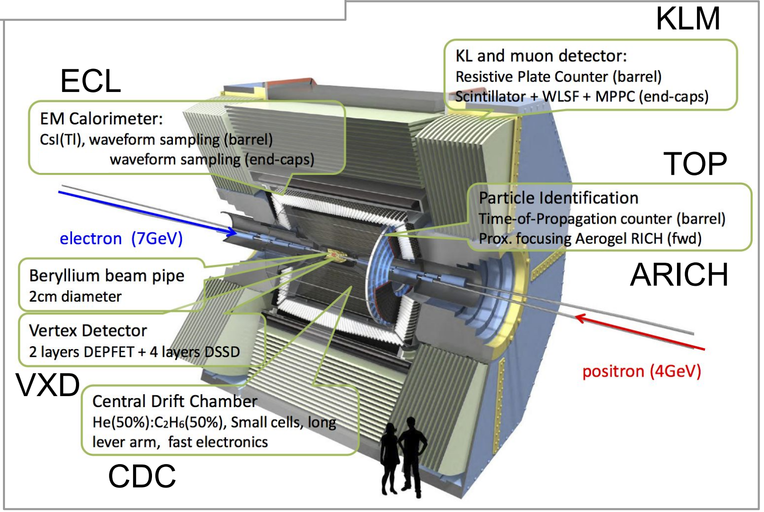
Since 2016

Belle II — SuperKEKB

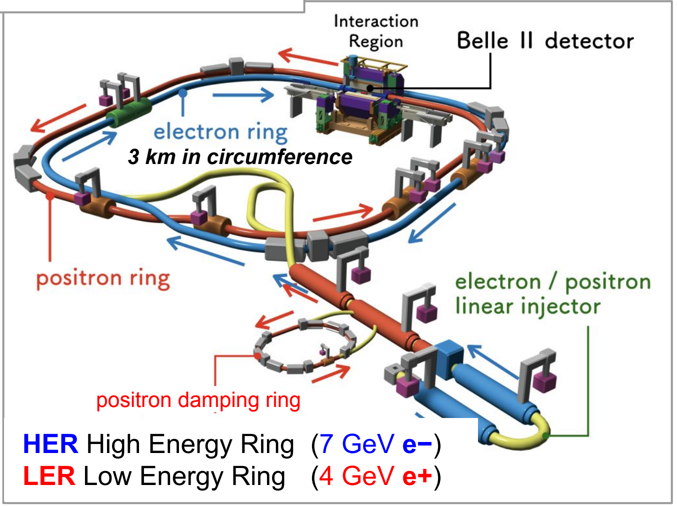


Belle II and SuperKEKB

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

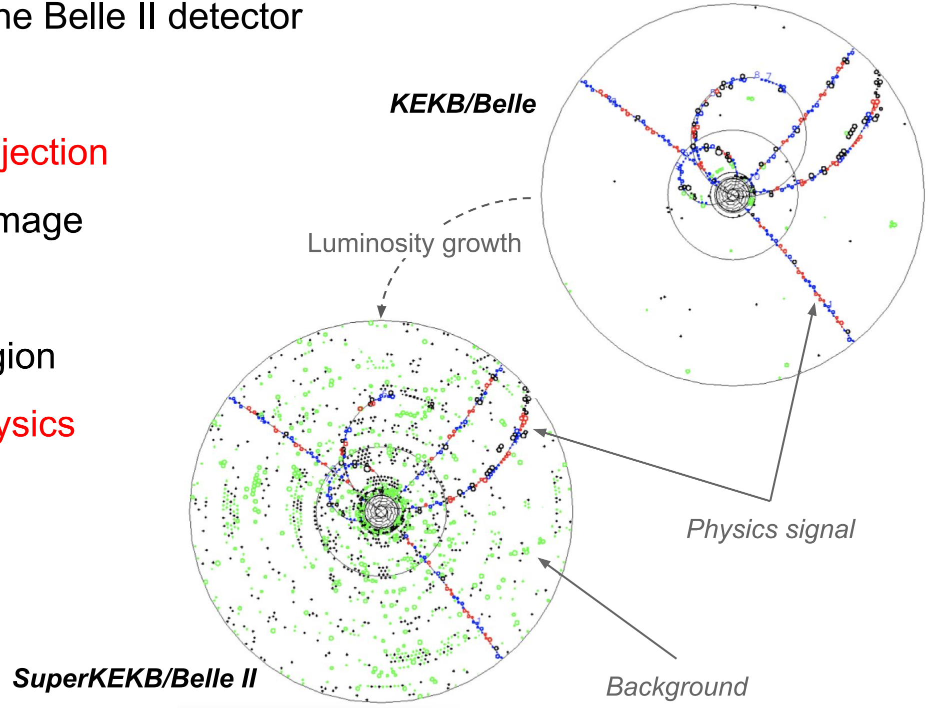
 Recognized by the 2008 Physics Nobel Prize

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 2030s

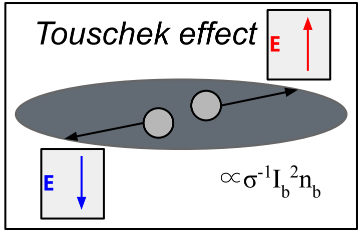
Luminosity gain and consequences

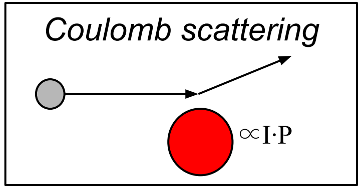
- The SuperKEKB **design** has x40 higher luminosity ($L \sim I_{\pm}/\beta^*_y$ [cm^{-2}s^{-1}]) than KEKB with x2 higher beam currents ($I_{\pm}$ [A]) and x20 smaller vertical beta functions (β^*_y [m]) at the interaction point (IP).
- This implies higher beam-induced backgrounds in the Belle II detector
  - High rate of particles leaving the beam
    - Requires a more frequent fresh beam injection
  - 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

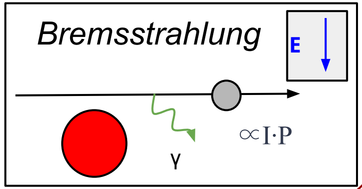


Background sources

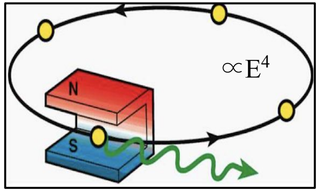
Particle scattering (Single-beam)



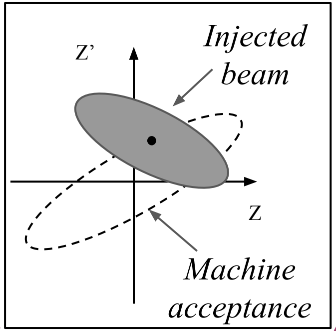




Synchrotron radiation

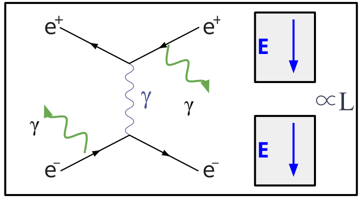


Injection (top-up, continuous)

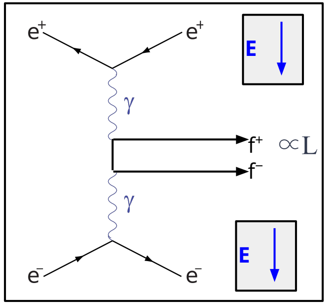


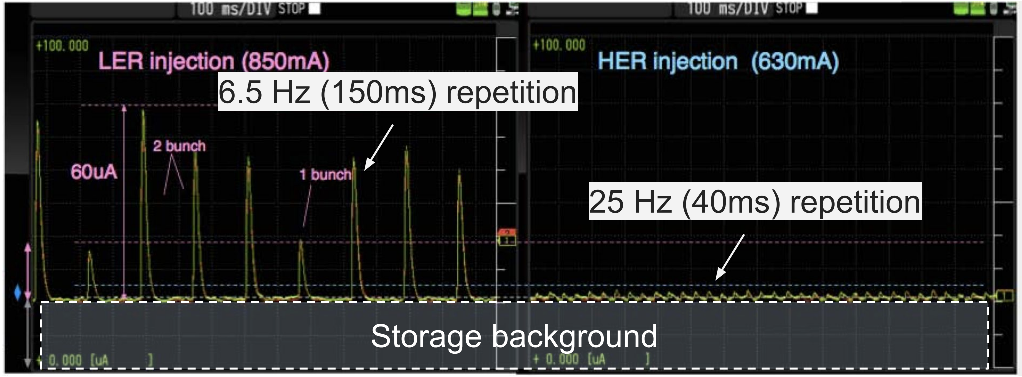
Colliding beams (Luminosity)

Radiative Bhabha proc.



Two-photon proc.



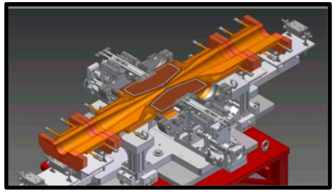


CDC background during injection (2021)

Background countermeasures

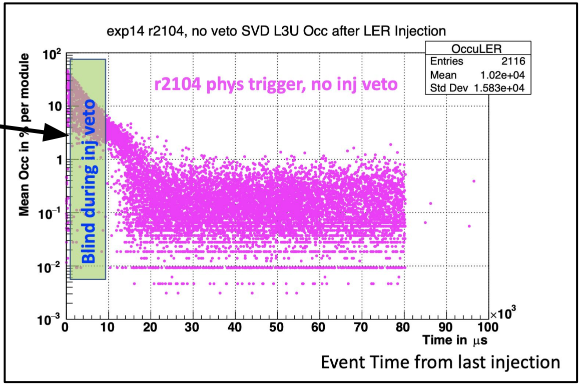
Particle scattering (Single-beam)

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



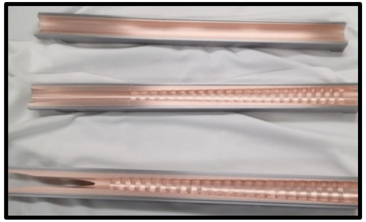
Injection

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



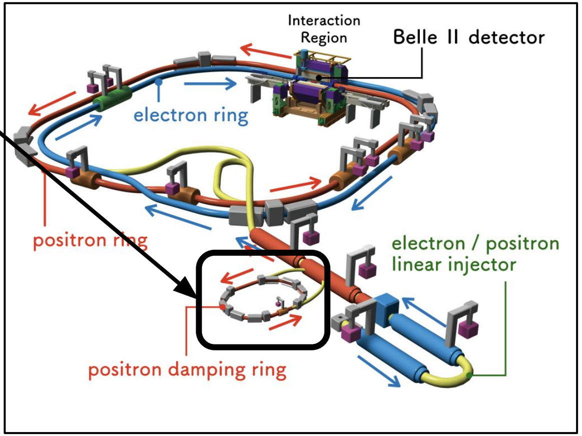
Synchrotron radiation

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



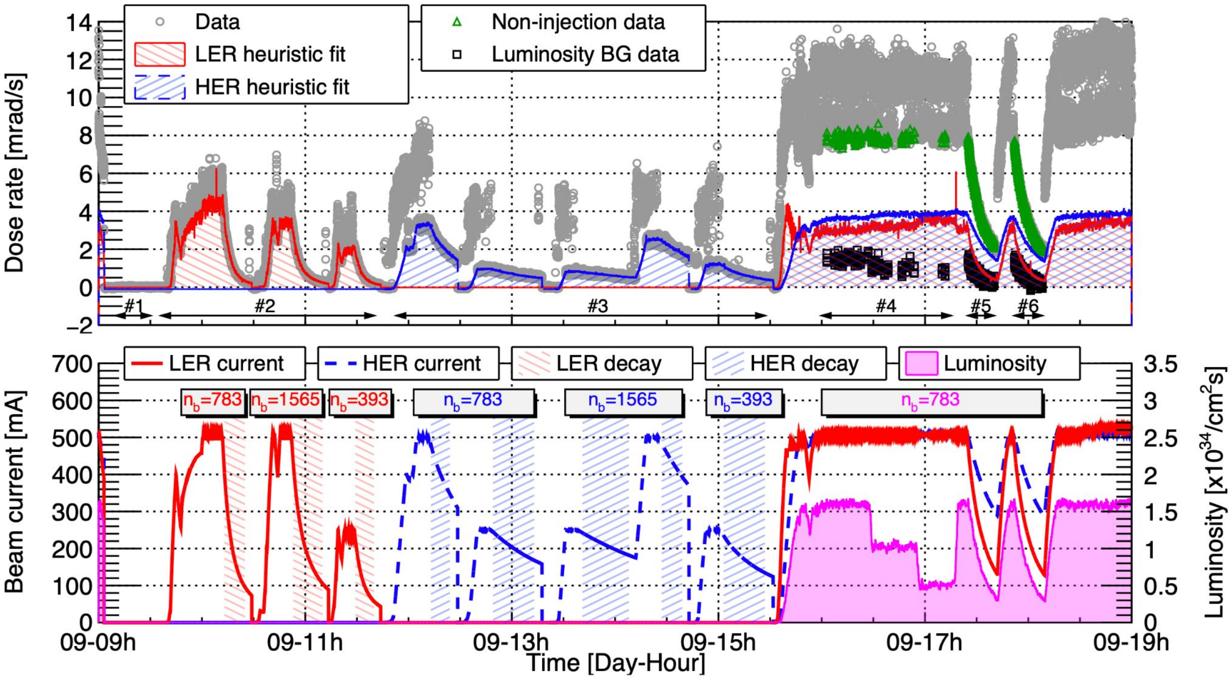
Colliding beams (Luminosity)

Steel and polyethylene shields *(neutrons flux reduction)*



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

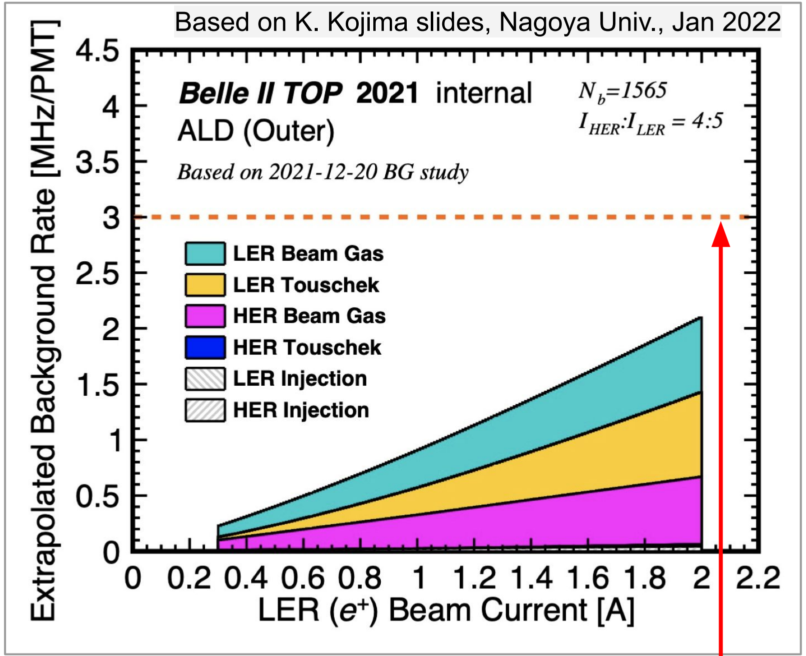
$$O_{\mathrm{Touschek}} = T \times \frac{I^2}{n_b \sigma_x \sigma_y \sigma_z}$$

Luminosity background
Radiative Bhabha and two-photon processes

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

Current background level in Belle II

One of the most vulnerable sub-detectors is
the Time of Propagation (TOP) particle ID system

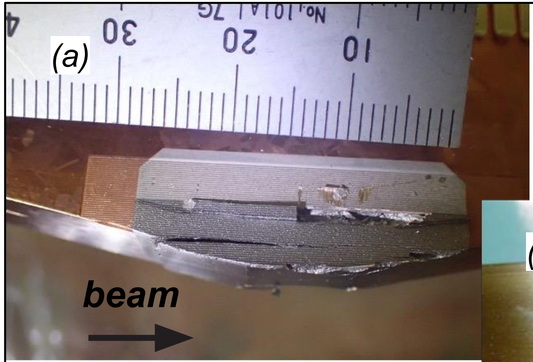


Background limit for the TOP PMT rate in 2021

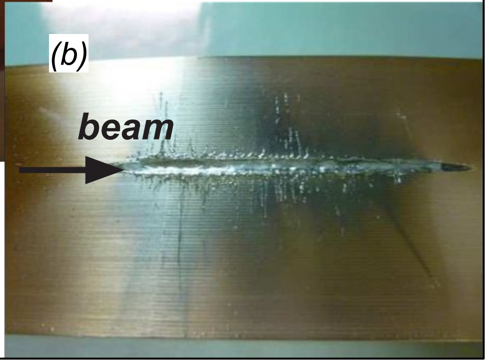
- Current background rates in Belle II are acceptable and below limits
- Belle II did not limit beam currents in 2021 and 2022
    - It will limit SuperKEKB eventually, without further background mitigation
- To reach the **target** luminosity (6.3x10^{35} cm^{-2}s^{-1}) an upgrade of crucial detector components is foreseen (e.g. TOP short lifetime conventional PMTs)

Uncontrolled beam losses

- During stable machine operation unexplained beam instabilities and beam losses may occasionally occur in one of the rings causing **fast beam losses** at a specific location around the ring due to
  - Injection kicker errors
  - Beam-dust interaction
  - Vacuum element defects
- **Consequences**
  - Detector and/or collimators damage
  - Superconducting magnet quenches
  - Belle II background increase
- Usually only a few such catastrophic beam loss events happen per year
  - In 2022, we had many of these events in the LER trying to go beyond 0.7 mA/bunch
- **Cures**
  - Upgraded abort system → fast abort signal
  - Low-Z materials for collimator heads (MoGr, Ta+Gr)
  - Understand the source of the unstable beam (vacuum system inspection, beam dynamics study)



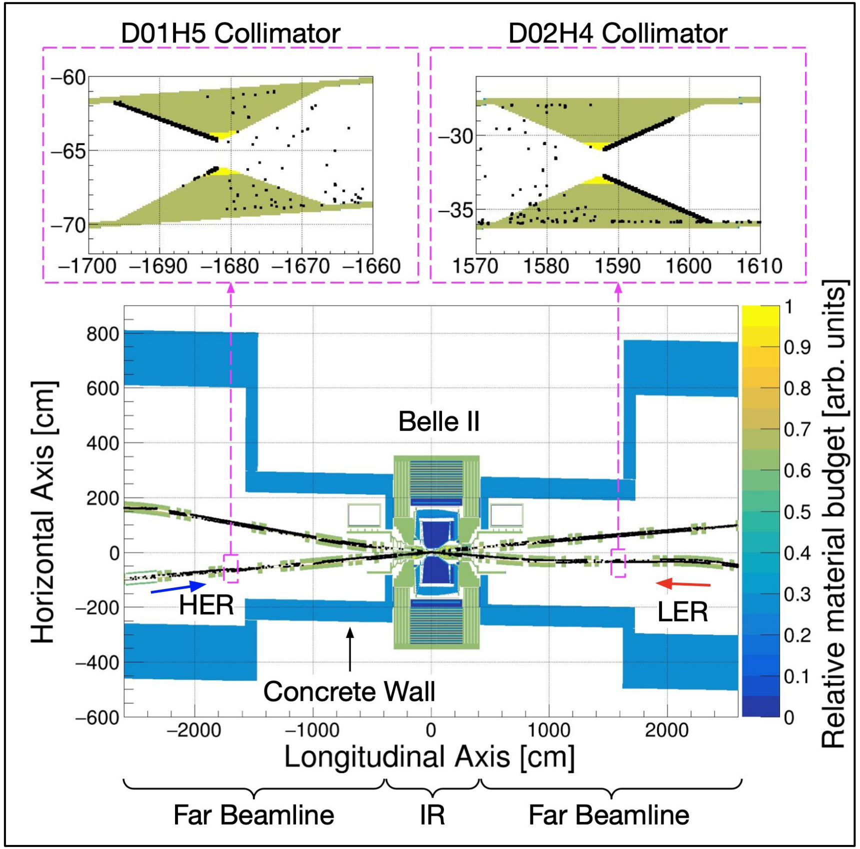
*(a) Severely damaged **tungsten** head ~720 μSv/h*



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

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)

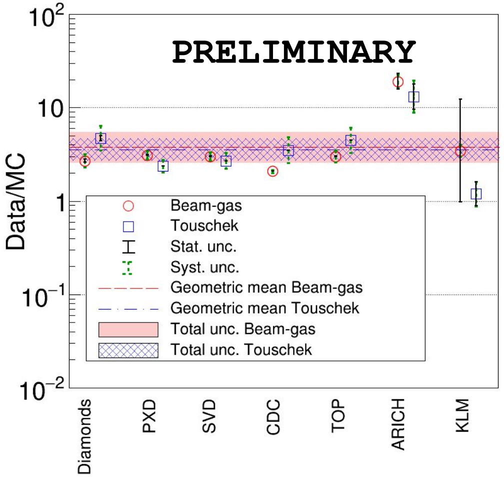


Recently improved `Geant4` model of Belle II and collider cavern. Black dots represent single-beam losses

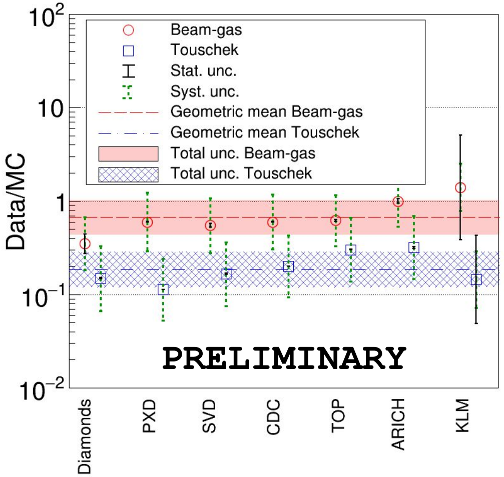
Background simulation: Accuracy

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

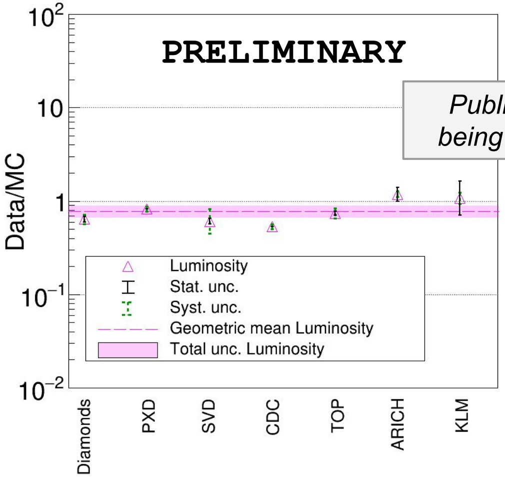
LER single-beam



HER single-beam



Luminosity



Publication is being prepared

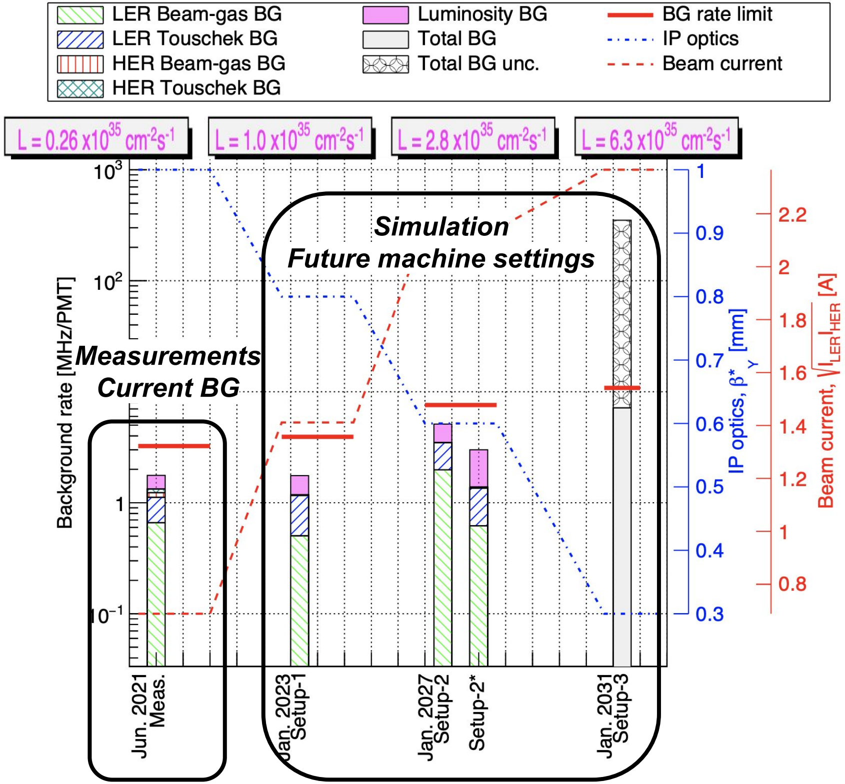
- Current data/MC ratios are within one order of magnitude from the unity
  - Improved compared to measurements in 2016 and 2018
  - Confirms our good understanding of beam loss processes in SuperKEKB
- These ratios are used to extrapolate detector backgrounds towards higher luminosities

Background simulation: Benefits

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 6.3x10^{35} $cm^{-2}s^{-1}$ machine condition is very uncertain to make an accurate background prediction

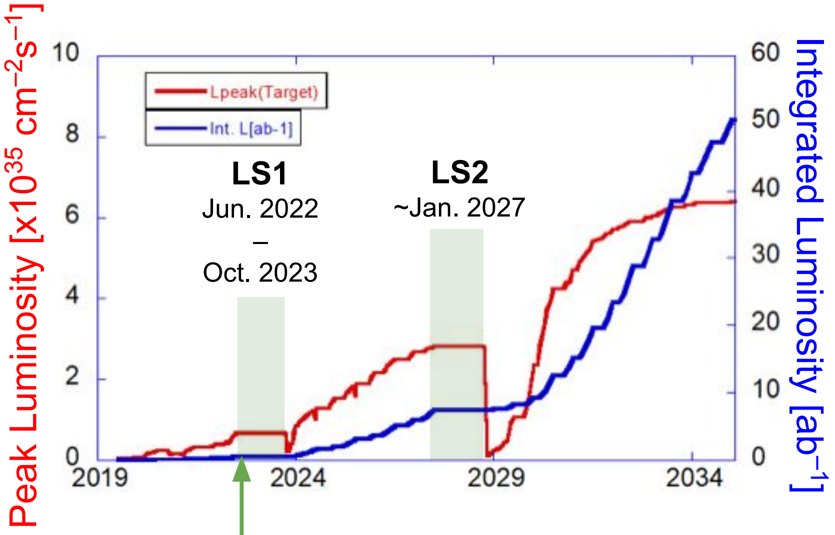


Measured and predicted Belle II backgrounds

Future plans and prospects

To reach the **target** luminosity of ~6 x10^{35} $cm^{-2}s^{-1}$ by 2030s we plan

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



We are currently here

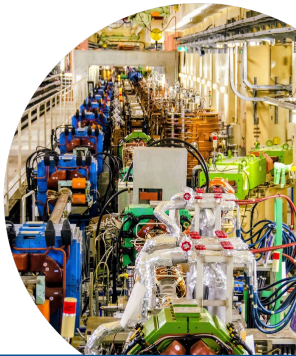
- L_{peak} ~0.5 x10^{35} $cm^{-2}s^{-1}$ ← *World's record*
- L_{int} ~0.4 ab^{-1} ← *BaBar's dataset size*

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

Summary

- In 2022, SuperKEKB and Belle II reached the world record luminosity of ~4.7 x10^{34} $cm^{-2}s^{-1}$
  - This 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 and machine damages**
- We have successfully reached a good agreement between measured and simulated beam-induced backgrounds which helps us to study future background evolutions [*link*]
- In the next decade, at stable machine operation, backgrounds in Belle II are expected to remain acceptable until at least 2.8x10^{35} $cm^{-2}s^{-1}$ [*link*]
- 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 6.3 x10^{34} $cm^{-2}s^{-1}$

The Belle II beam background and MDI groups are 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

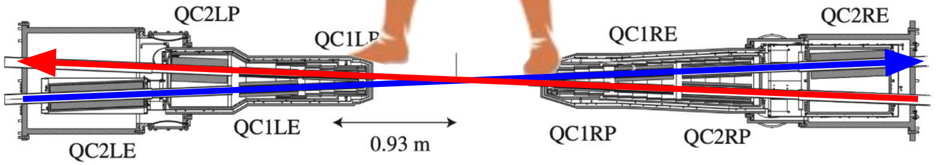
Belle II Detector
Physics data collection
New physics study

Machine Detector Interface (MDI)
Detector radiation safety

Thank you for attention!

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

SuperKEKB Collider
High rate of particles collisions
Factory of new particles

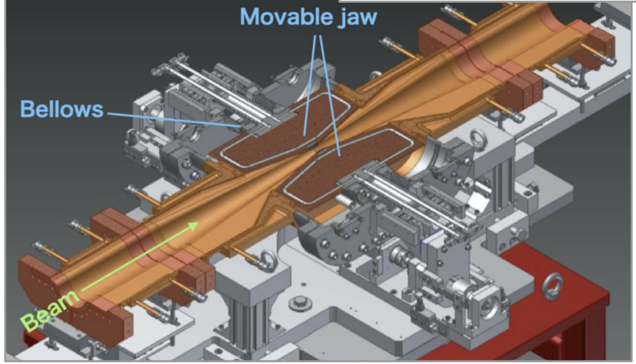


Backup slides

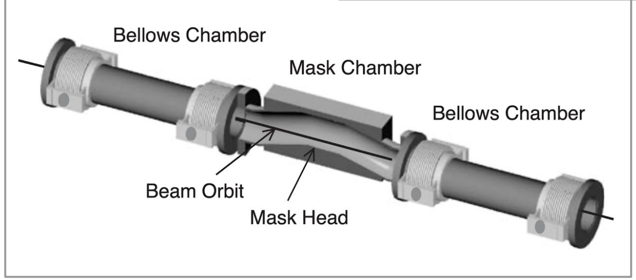
Collimation system

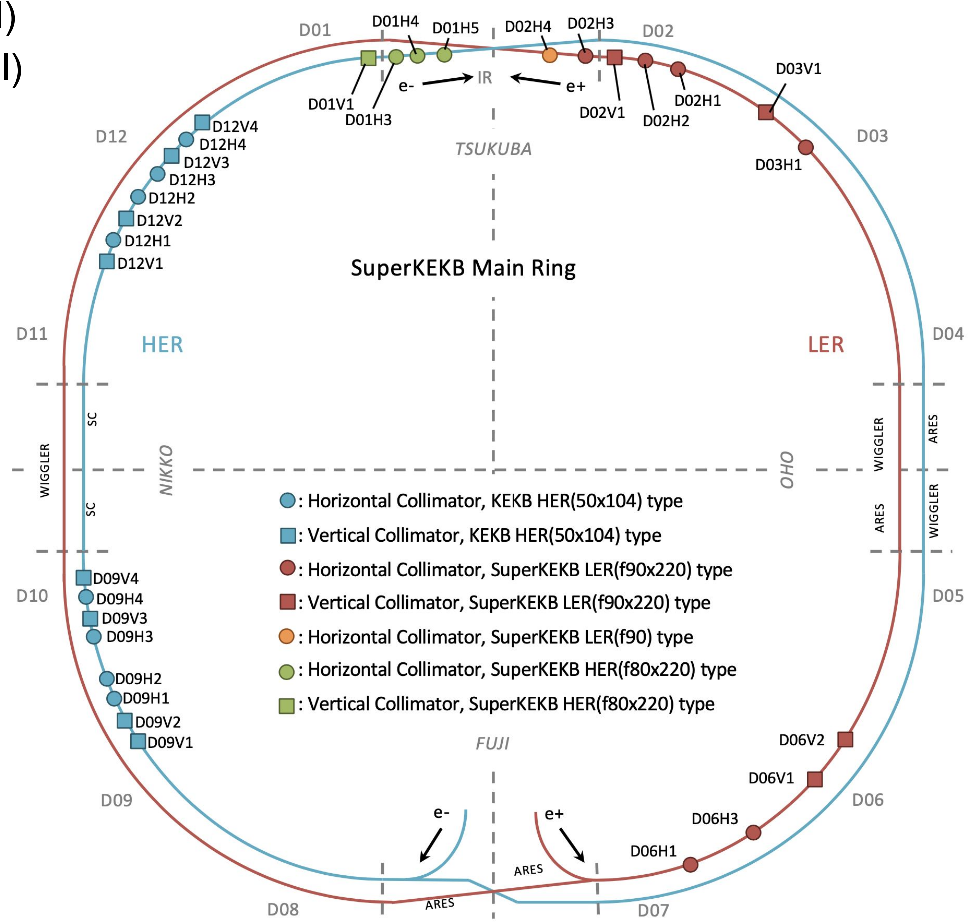
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)

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



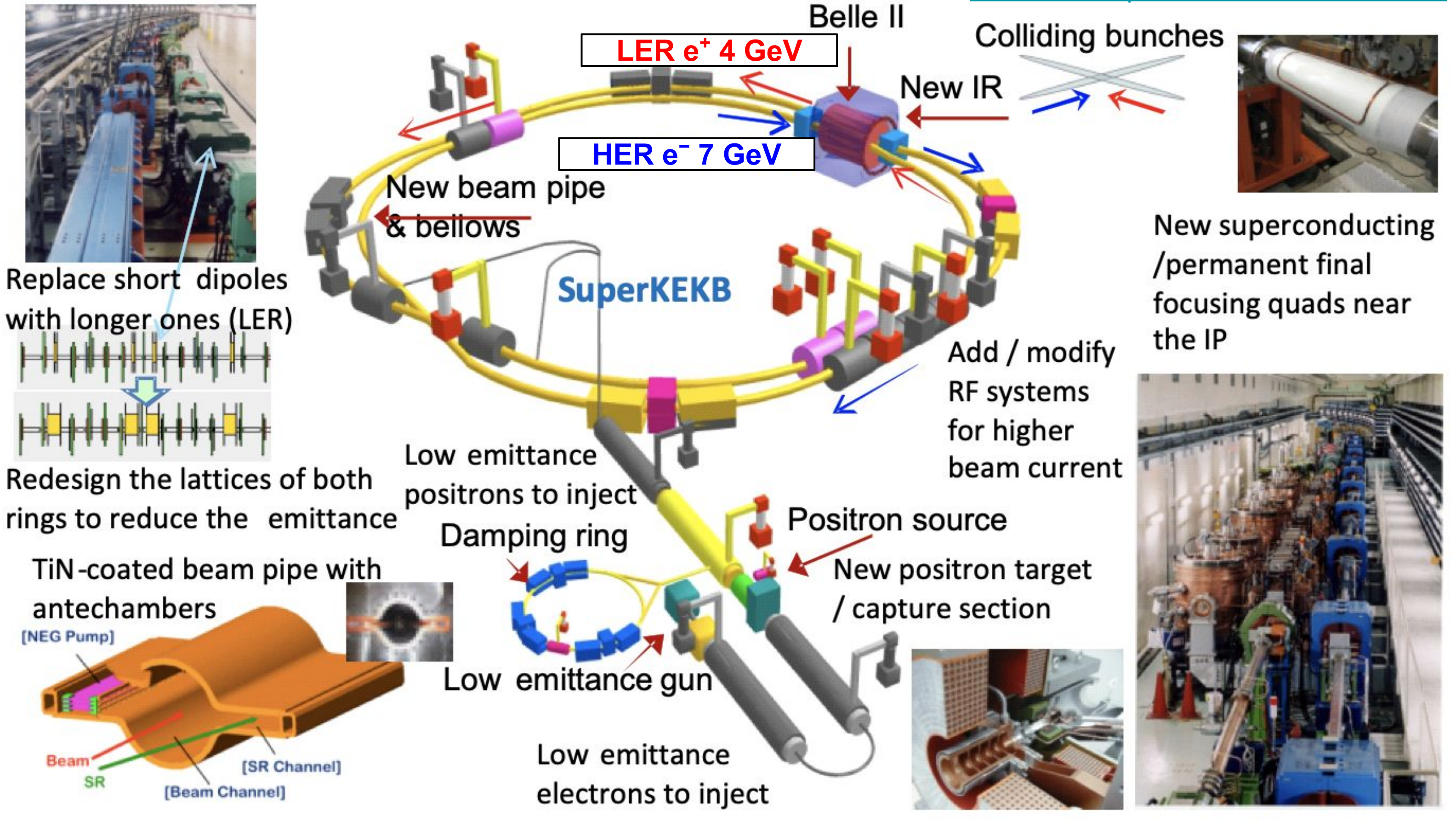
One-sided collimator
***KEKB**-type (D09 & D12)*





KEKB to SuperKEKB: Machine modification

K. Shibata, SuperKEKB VACUUM SYSTEM



Luminosity degradation & crab waist scheme

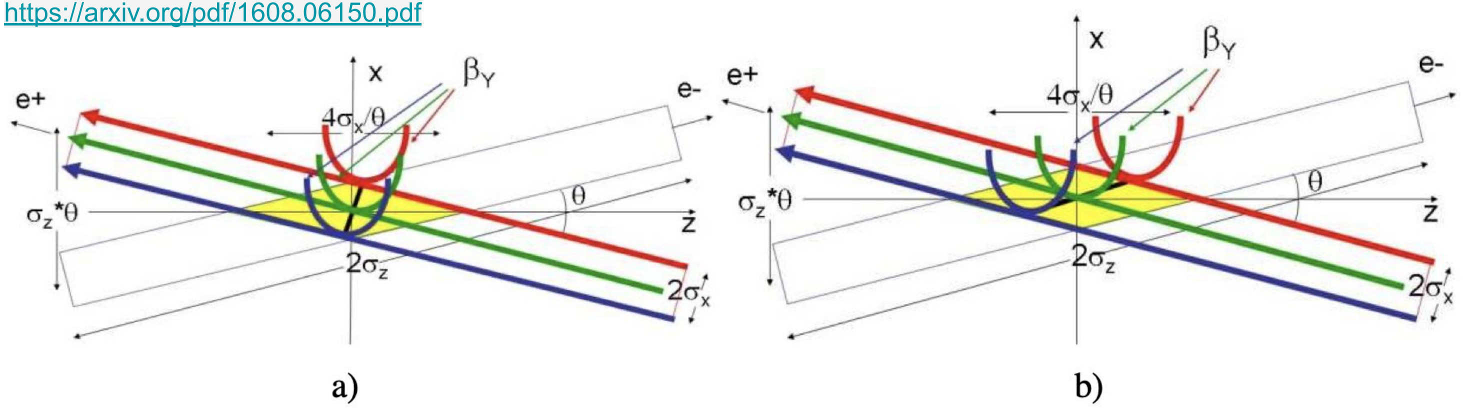
- **Initially**
  - Was hard to operate the SuperKEKB near the working point of the betatron tune (.57,.61)

    ← 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

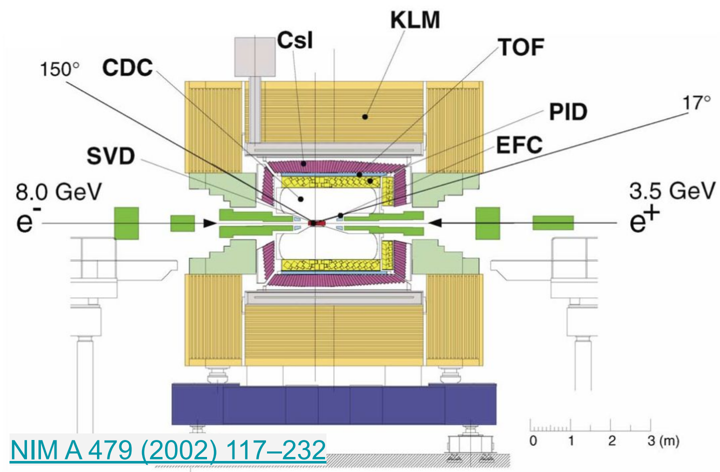


*Differently from the crab crossing scheme (**KEKB**) where bunches are tilted by the crab cavities with respect to the beam longitudinal axis, CW (**SuperKEKB**) rotates the optics function β_Y.*

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

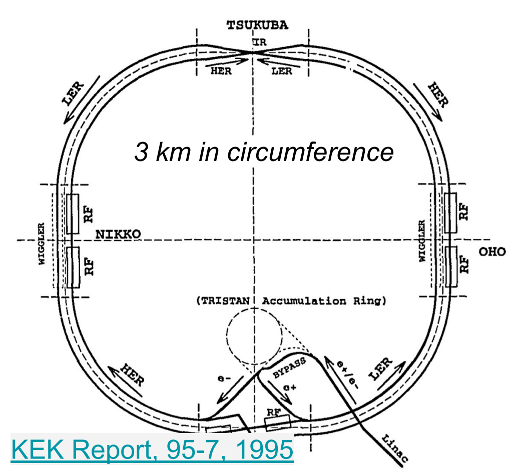
Belle and KEKB (1999-2010)

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

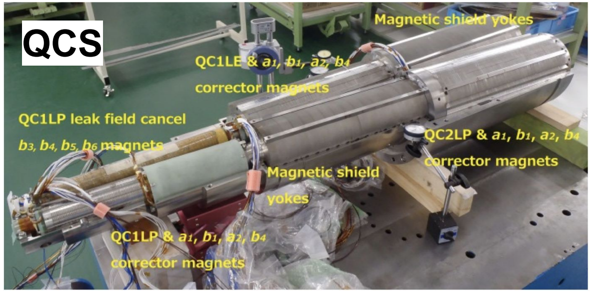
Beam energy		(GeV)	8.0 (e^-), 3.5 (e^+)
Beam current		(A)	1.2 (e^-), 1.6 (e^+)
Beam size at IP	x	(μm)	80
	y	(μm)	1
	z	(mm)	5
Luminosity		(cm^{-2} s^{-1})	2.1×10^{34}
Number of beam bunches			1584
Bunch spacing		(m)	1.84
Beam crossing angle		(mrad)	± 11 (crab-crossing)

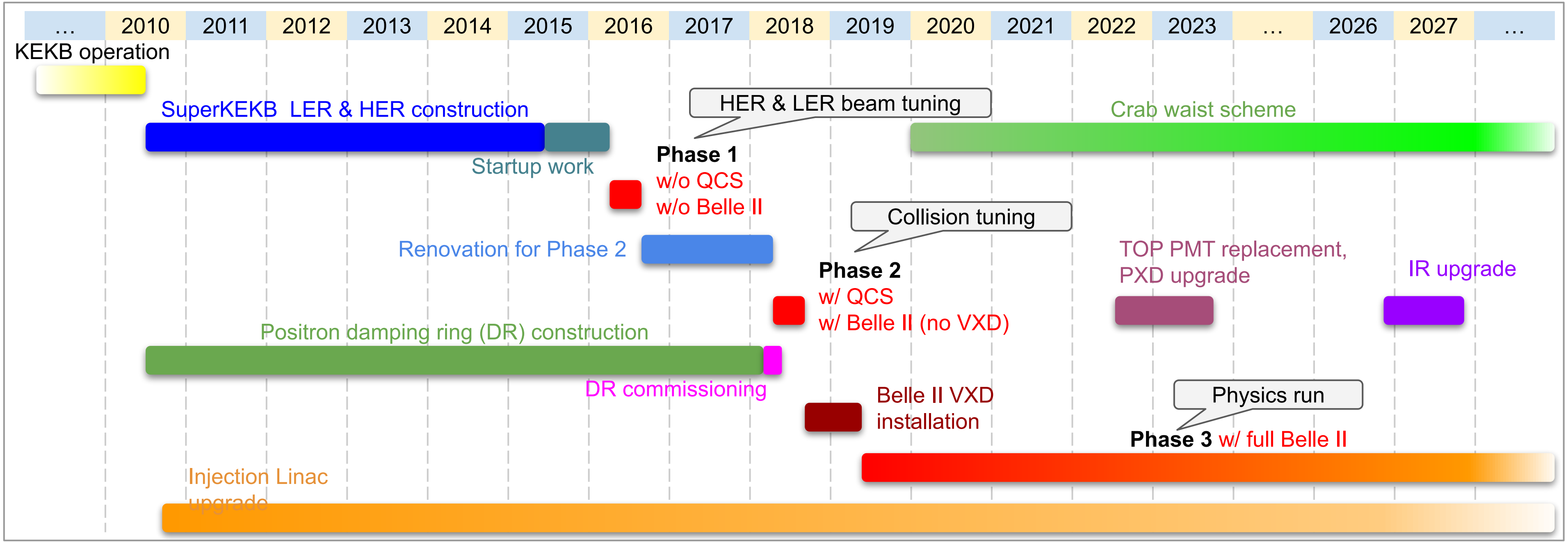
More than twice the original design goal

World's first operational set of superconducting crab cavities

Timeline for 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





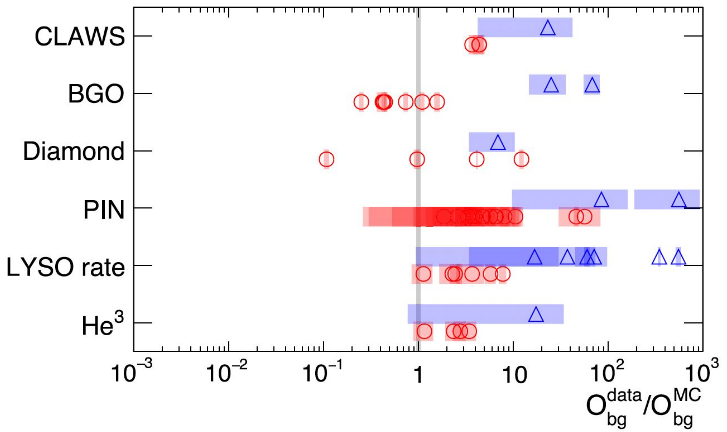
Phase 1 data/MC ratios

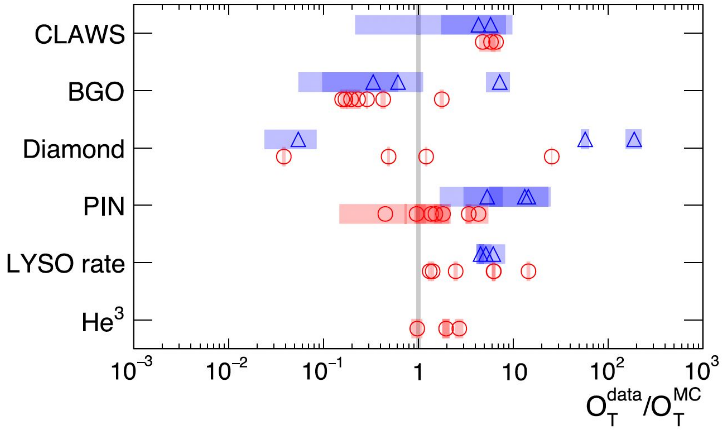
[P.M.Lewis *et al.*, "First measurements of beam backgrounds at SuperKEKB", NIMA 2019]

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]

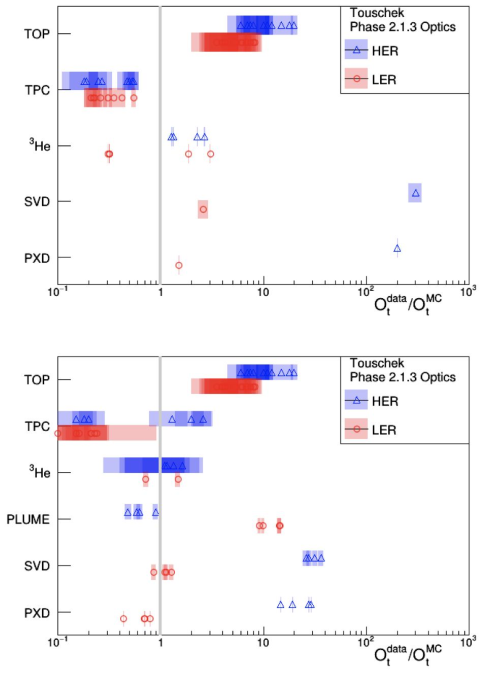


Figure 19: (color online) Ratio of observed to predicted Touschek background rates in all detectors studied with old (top) and new (bottom) simulation. Blue (Red) points represent HER (LER) results. From top to bottom, the detectors are ordered from radially outermost (TOP) to inermost (PXD).

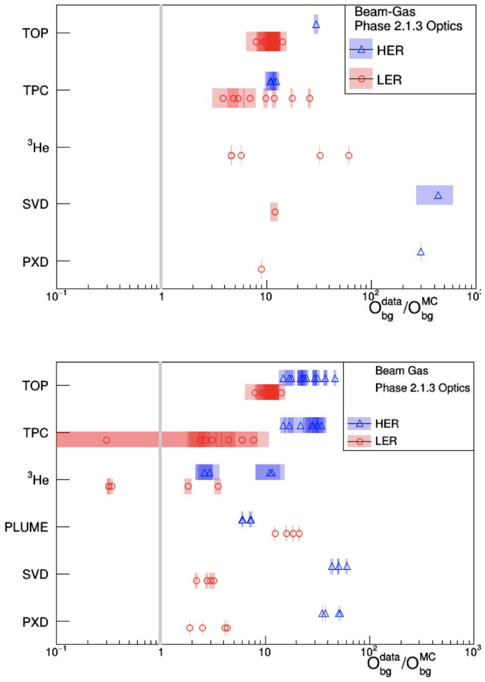


Figure 20: (color online) Ratio of observed to predicted Touschek background rates in all detectors studied with old (top) and new (bottom) simulation. Blue (Red) points represent HER (LER) results. From top to bottom, the detectors are ordered from radially outermost (TOP) to inermost (PXD).

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.

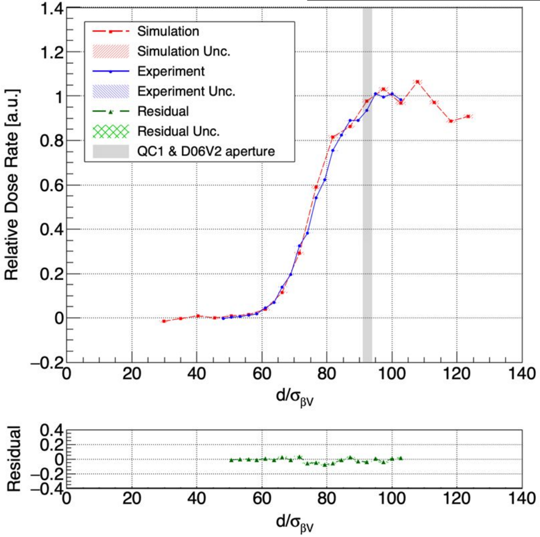
Background simulation: Validation

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

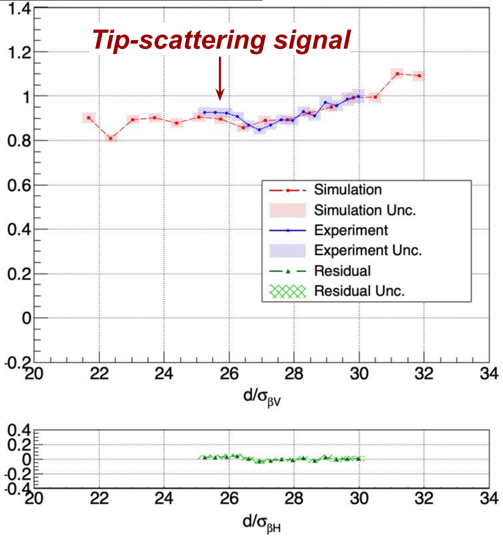
- D06V1 is the narrowest vertical collimator in the LER
- D02H4 is the closest to the IP horizontal collimator
- Tip-scattered particles contribute to the IR background

There is a good agreement between measurements and simulation

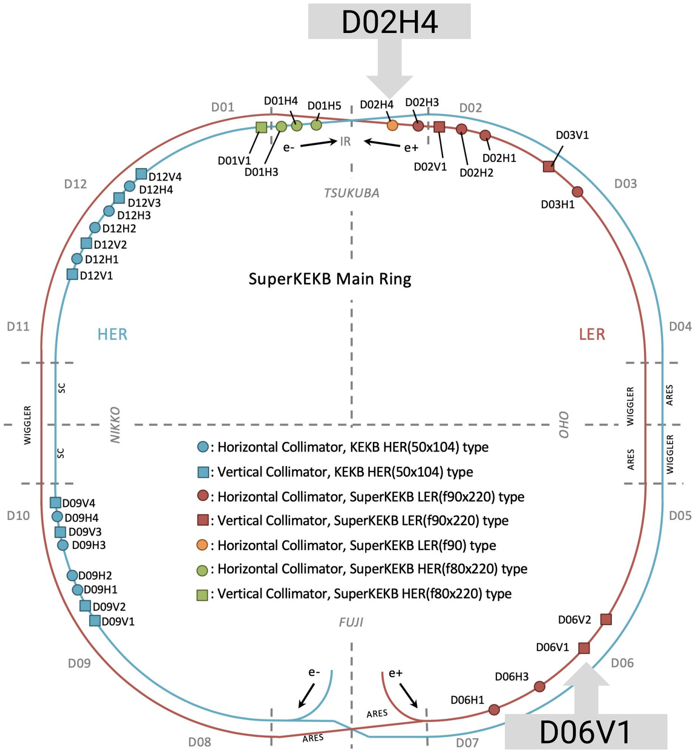
10.1103/PhysRevAccelBeams.24.081001



Interaction region background vs D06V1 aperture



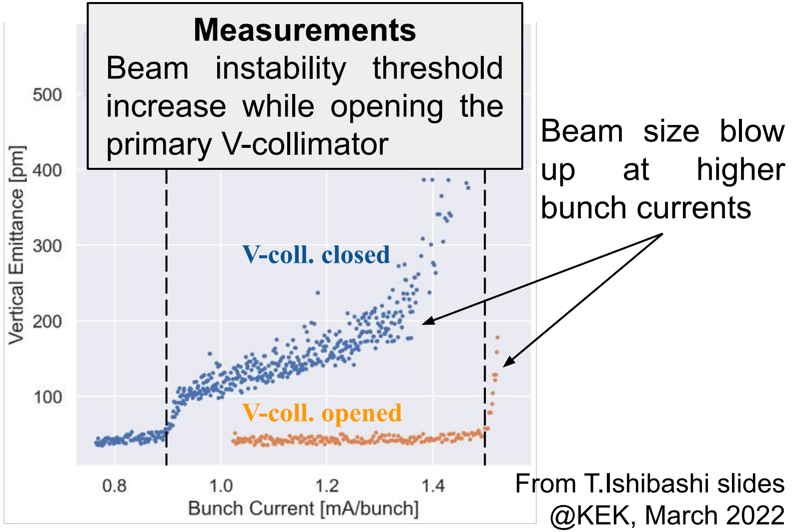
Interaction region background vs D02H4 aperture



Unexpected machine impedance

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)
  - Beam size blow up, see Figure
  - Betatron tune shift

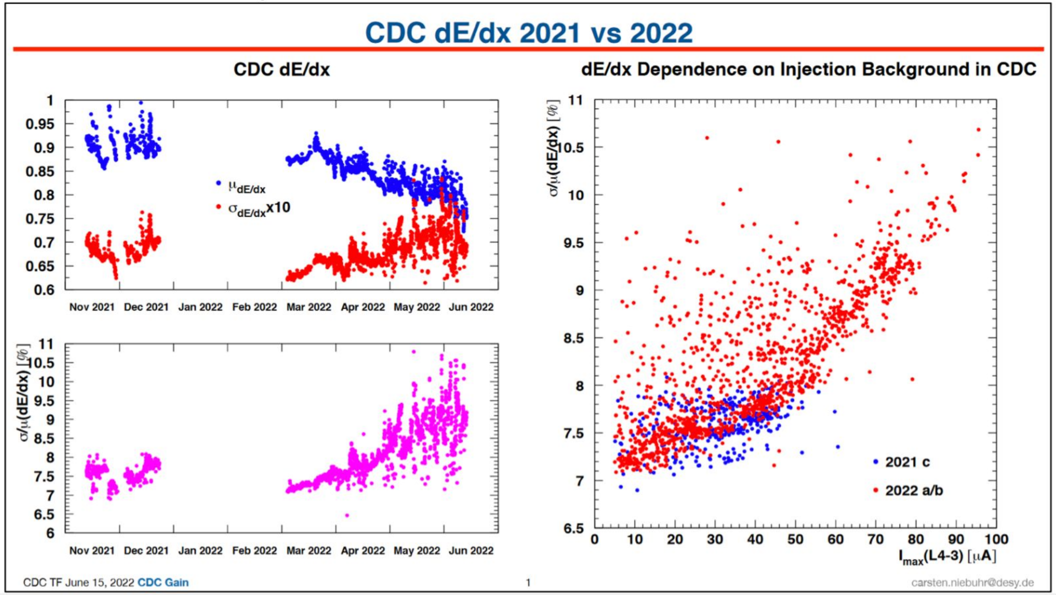


From T.Ishibashi slides @KEK, March 2022

- ❖ In 2020-2021, beam instabilities were one of the sources limiting bunch current increase
  - ➢ At higher bunch currents, may need to open collimators further and accept higher backgrounds
- ❖ When predicting future background levels, we take this expected effect of TMCI on collimator settings into account, but not all contributions are fully understood such as **unexpected tapered IR beam pipes wake-fields**
- ❖ Therefore, dedicated measurements of beam instabilities and studies of their mitigation are ongoing.

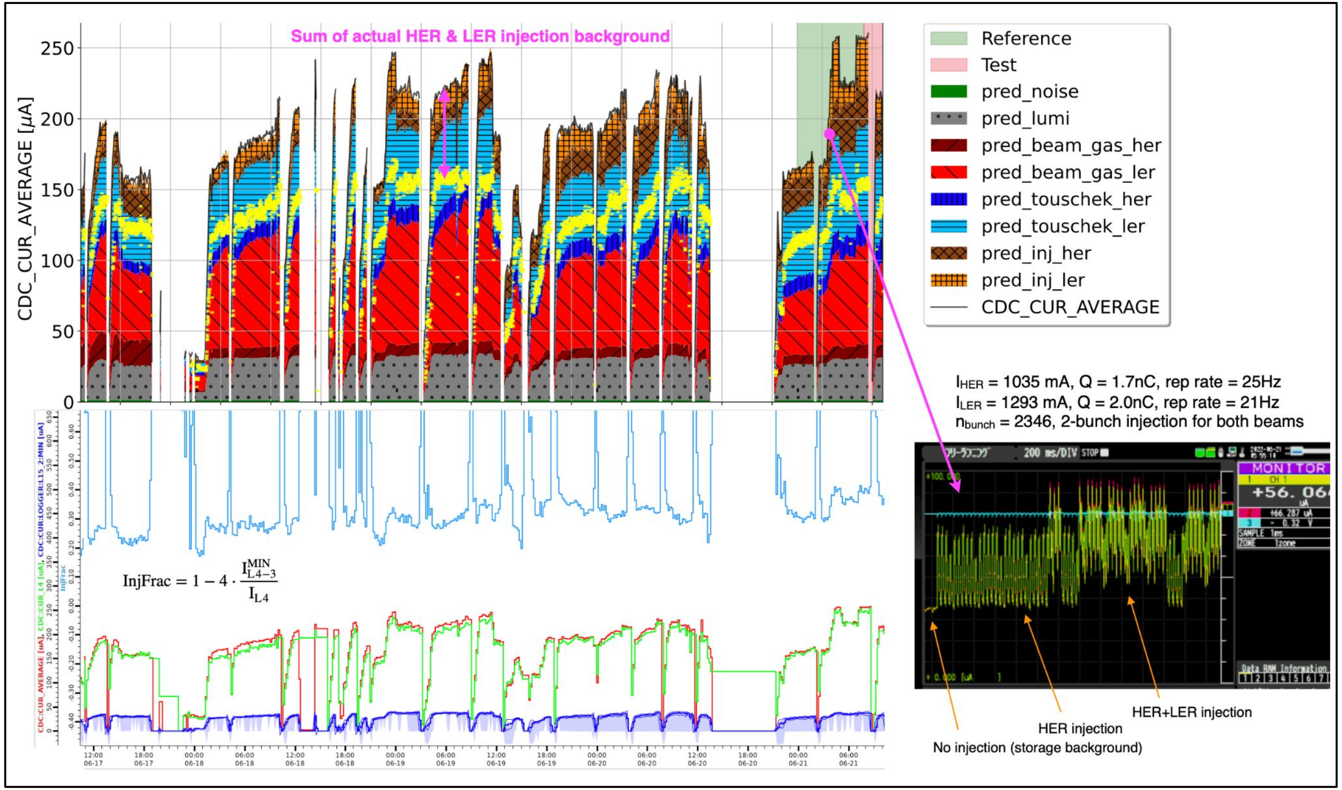
Injection background: CDC performance degradation

- 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.



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

Injection background: CDC observable

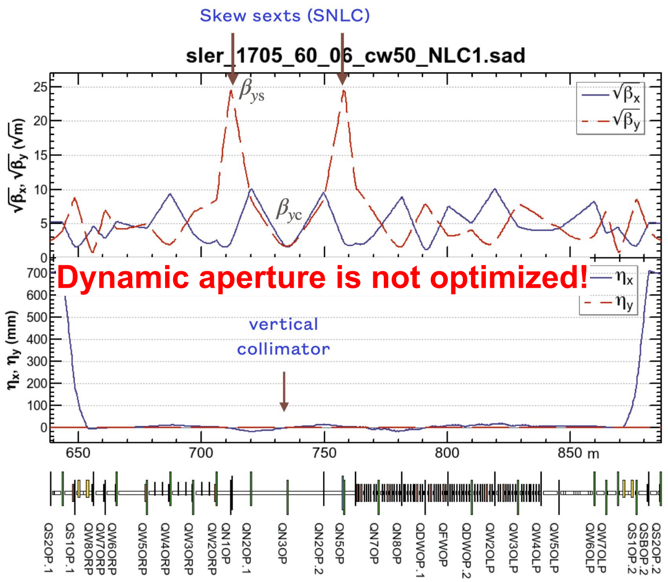


B. Schwenker
(Univ. of Göttingen)
C. Niebuhr (DESY)

Nonlinear collimation (NLC)

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

- Low betatron function in between $\beta_{x/y}$ ~3m
- Vertical angular kick for distant halo particles in both planes $\Delta p_y \sim (y^2 - x^2)$
- A big aperture step ~1mm affects < 4σ at the QC1 → fine tuning with the NLC
  - For other V-collimators: ~1mm step ⇒ 20-40σ at the QC1



Introduced by K.Oide, KEK, 2021

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

$$\Delta p_{ys} = \frac{s'}{2}(y_s^2 - x_s^2)\,, \quad (1)$$

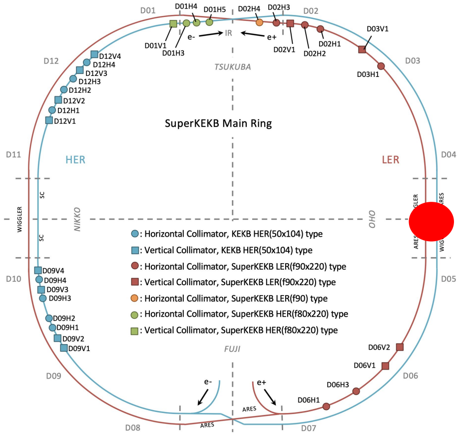
$$s' \equiv \frac{L_s}{B\rho}\frac{\partial^2 B_x}{\partial y^2}\,. \quad (2)$$

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

$$\Delta y_c = R_{34}\Delta p_{ys} = 5.7\,\mathrm{mm} \quad (3)$$

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

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



NLC benefits

- Does not affect significantly the TMCI limit
  - May be tightly closed while other collimators may be opened
- Effectively suppresses Belle II backgrounds
  - Helps to control beam backgrounds leaving more margin for the injection background and other unexpected beam losses
- Collimates in both planes stopping stray particles due to beam-gas and Touschek scatterings
- Does not require high positioning accuracy
  - For β^*_y = 0.6 mm, ~1σ of the aperture change at QC1

    D06V1: 55 μm step

    D02V1: 25 μm step

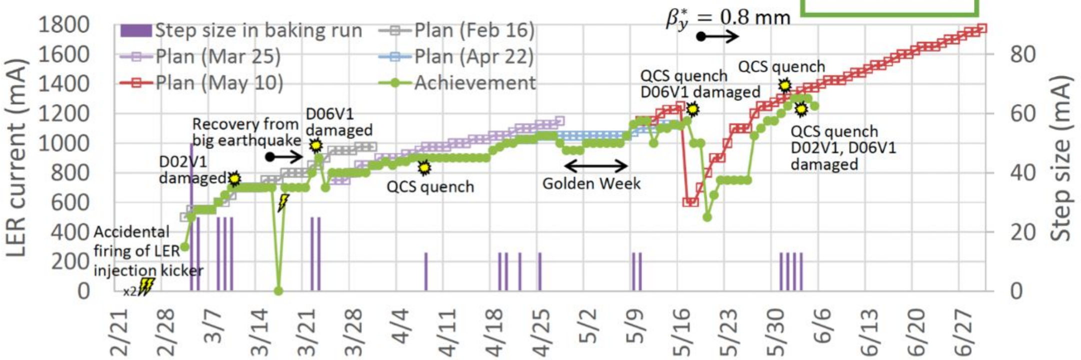
    NLC: 250 μm step

1) Although the Belle II background is below the detector limit at β^*_y = 0.6 mm optics without NLC, there could be some unexpected beam losses and injection performance degradation leading to the background increase exceeding the detector limit. Since tightening of the key collimators reduces TMCI limit, NLC may help to suppress Belle II backgrounds keeping the bunch current limit unchanged.

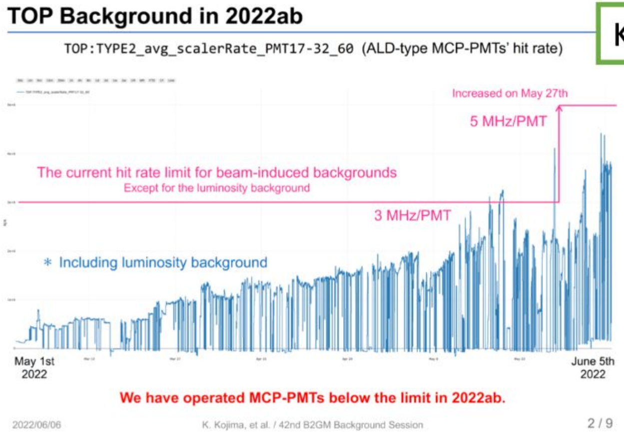
2) NLC looks promising for a better beam background control at design optics of β^*_y = 0.3 mm. Even if we are limited to use only one V-collimator, NLC may be used in addition without affecting the TMCI limit and effectively suppressing backgrounds → *need more studies, β^*_y = 0.3 mm optics with NLC is not available for now.*

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?

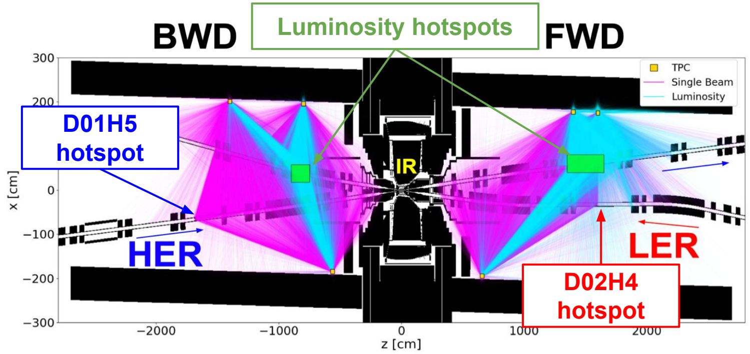
- More robust collimator heads
- Faster + cheaper to replace
- More granular and stable jaw positioning
- Automatic / improved absolute alignment

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

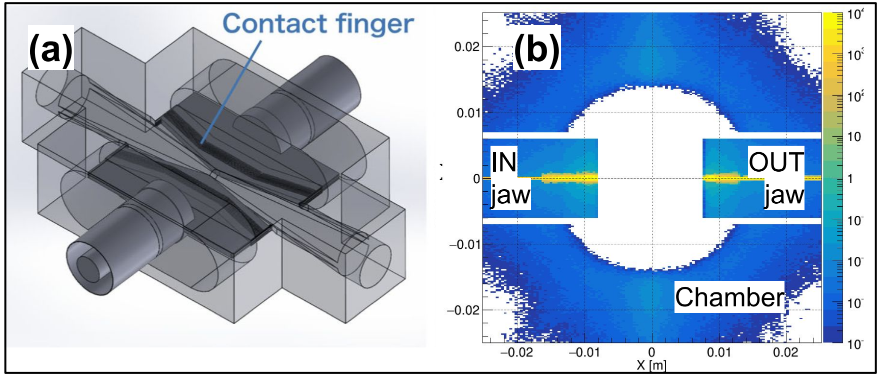
Neutrons from collimator hotspots

- 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

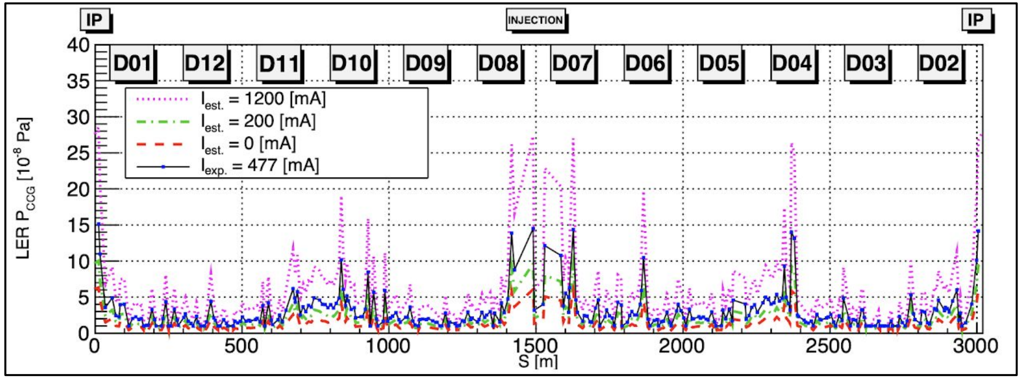
Neutrons from luminosity hotspots

- 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

- **Single-beam background** (Beam-gas & Touschek)
  - Strategic Accelerator Design (SAD@KEK) (multi-turn particle tracking)
    - *Realistic collimator shape 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)



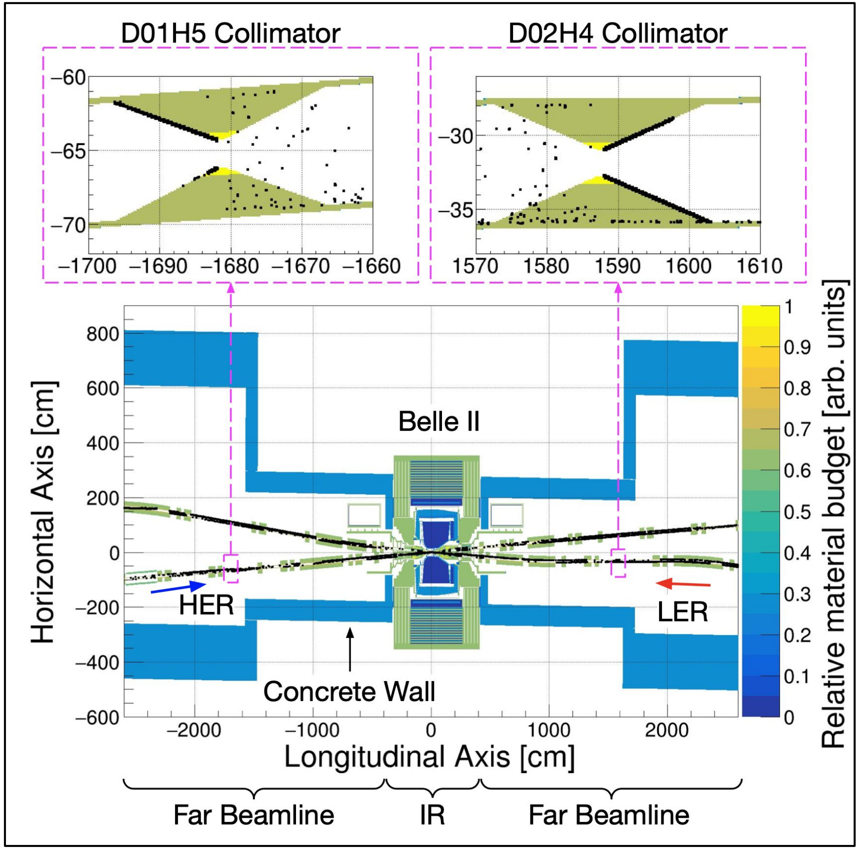
Collimator chamber 3D model (a) and simulated absorbed particles at a collimator (b)



Measured and estimated vacuum pressure distribution around the LER

Background simulation: Detector response

- **After particle tracking in `SAD`**
  - Lost particles within the extended interaction region (±30m from the IP) are **transferred** to `Geant4`
- **`Geant4` simulation**
  - **Includes** a realistic model of the detector and its surroundings (e.g. collider cavern)
  - **Generates** lost particles onto the inner surface of the beam pipe
  - **Propagates** primary and secondary (e.g. EM showers) particles through the detector
  - **Produces** output files with collected particle hit information mimicking detector response



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

Dynamic vacuum pressure estimation

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

Dynamic pressure