The EIC Accelerator
Partnership Workshop 2021

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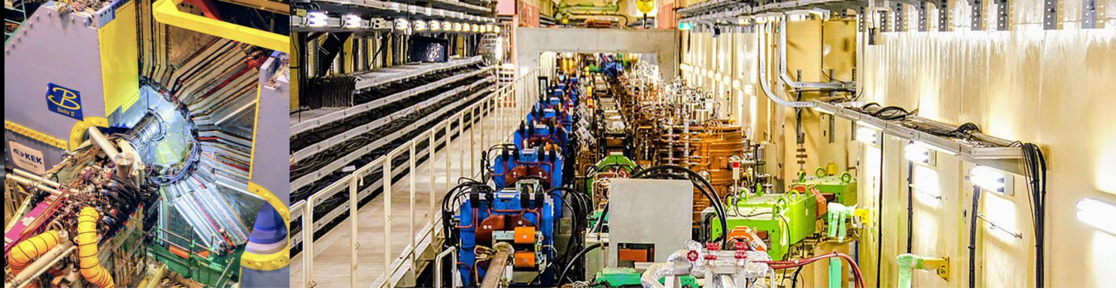

SuperKEKB beam collimation

On behalf of the Belle II beam background and MDI groups

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KEK

Super KEKB

Belle II

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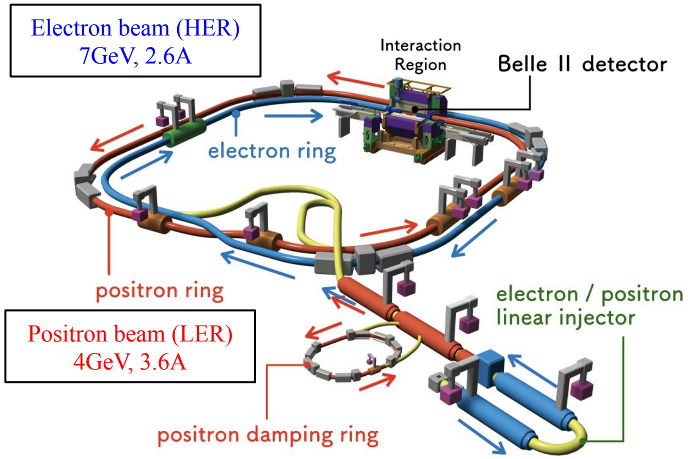
- ❖ Beam background sources & countermeasures
- ❖ Current understanding
- ❖ Collimation system description
- ❖ Background simulation tools
- ❖ Improvements & validation
- ❖ Collimation system alignment and optimization
- ❖ Summary

SuperKEKB: design parameters of
"Low Energy Ring" (**LER**) & "High Energy Ring" (**HER**)

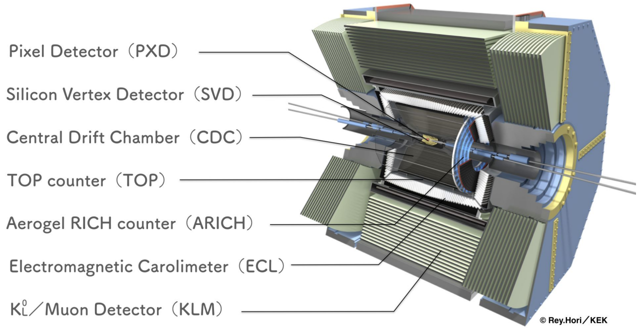
	LER (e^+)	HER (e^-)	
Energy	4.000	7.007	GeV
Half crossing angle	41.5		mrad
Horizontal emittance	3.2	4.6	nm
Emittance ratio	0.27	0.25	%
Beta functions at IP (x/y)	32 / 0.27	25 / 0.30	mm
Beam currents	3.6 (2.8*)	2.6 (2.0*)	A
Beam-beam parameter	0.0881	0.0807	
Luminosity	8 (6.5*) x 10^{35}		$cm^{-2}s^{-1}$

WORLD RECORD → **Current luminosity** **3 x 10^{34} $cm^{-2}s^{-1}$**

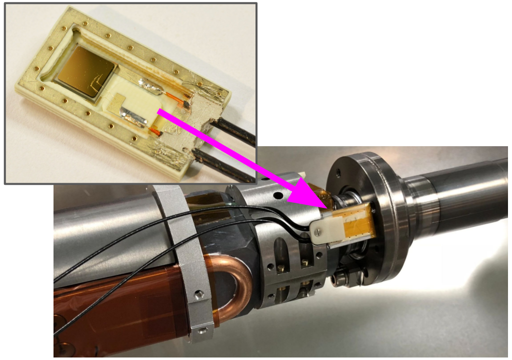
* *new design conditions extrapolated from the current machine/detector performance.*



Belle II detector at the interaction region



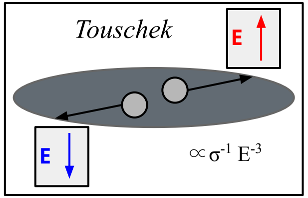
28 diamond detectors around the interaction region beam pipe

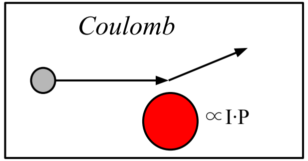


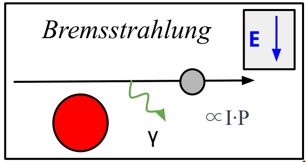
The SuperKEKB design has x30-40 higher luminosity (L) than KEKB with x1.5-2 higher beam currents ($I_{\pm}$) and x20 smaller vertical beta functions (β_Y^*) at the interaction point (IR). This implies higher beam-induced backgrounds in the Belle II detector.

$$L \sim \frac{I_{\pm}}{\beta_Y^*}$$

Particle scattering (Single-beam)

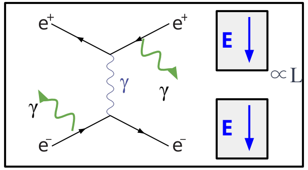




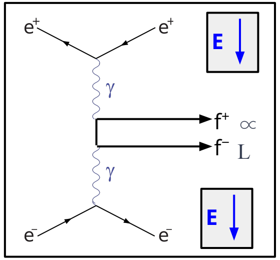


Colliding beams (Luminosity)

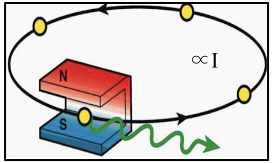
Radiative Bhabha proc.



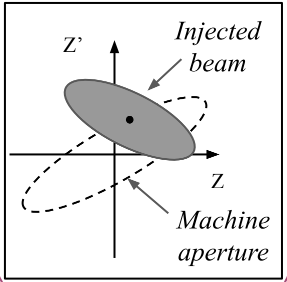
Two-photon proc.



Synchrotron radiation

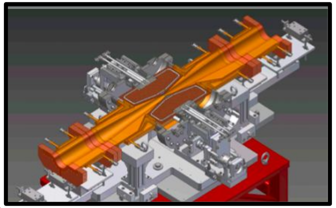


Injection (top-up, continuous)



Particle scattering (Single-beam)

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

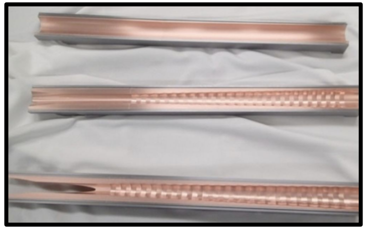


Colliding beams (Luminosity)

Steel and polyethylene shields *(neutrons flux reduction created from luminosity beam losses)*

Synchrotron radiation

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



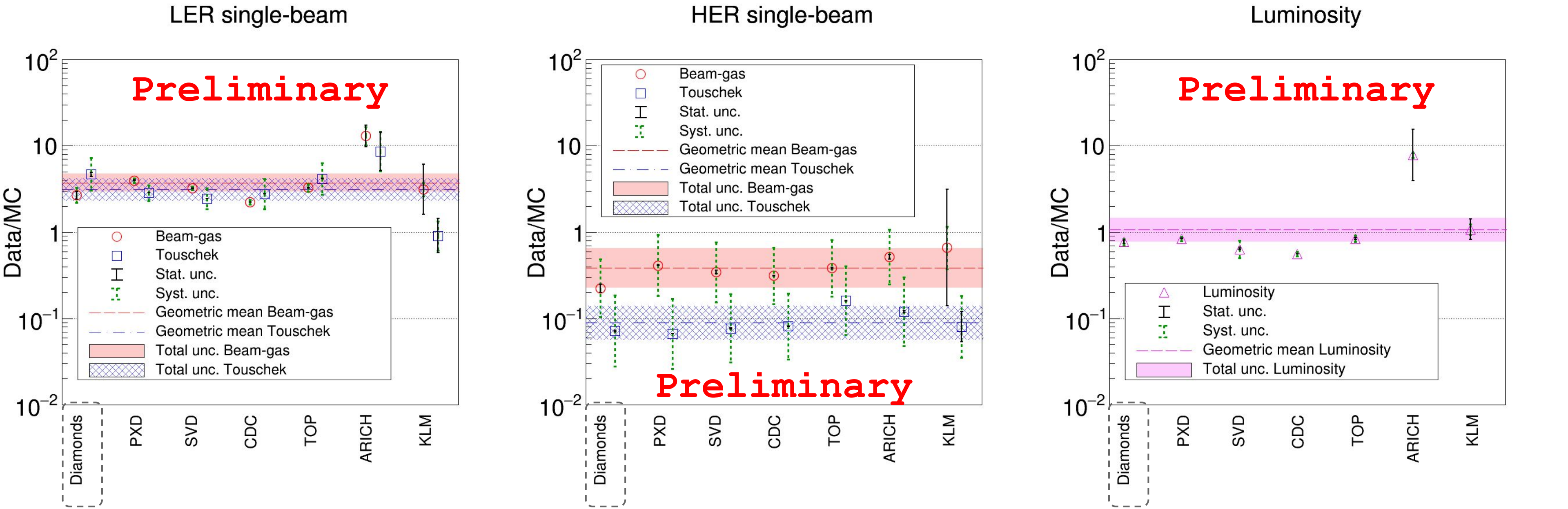
Injection

Damping ring for positrons *(to reduce the emittance)*, injection trigger veto since the SuperKEKB keeps beam currents constant by performing top-up (continuous) injection

- Over the last years, we have made many modifications to the background simulation
- For the first time, data and MC agree within two orders of magnitude

Data/MC = 10^{-2}-10^{3} [2016-2018] → **10^{-1}-10^{1}** [2020-2021]

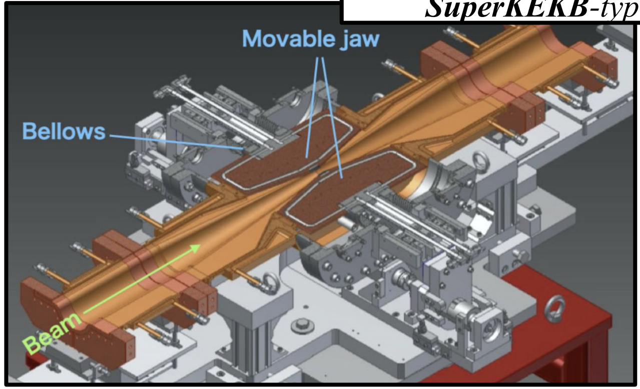
- Focusing mainly on Diamonds and SuperKEKB collimation system this presentation is about how we achieved this significant improvement



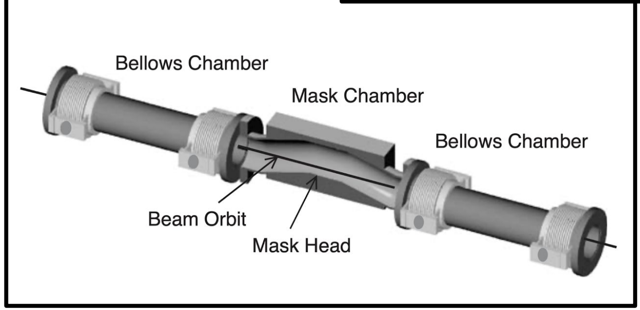
Excellent data/MC agreement!

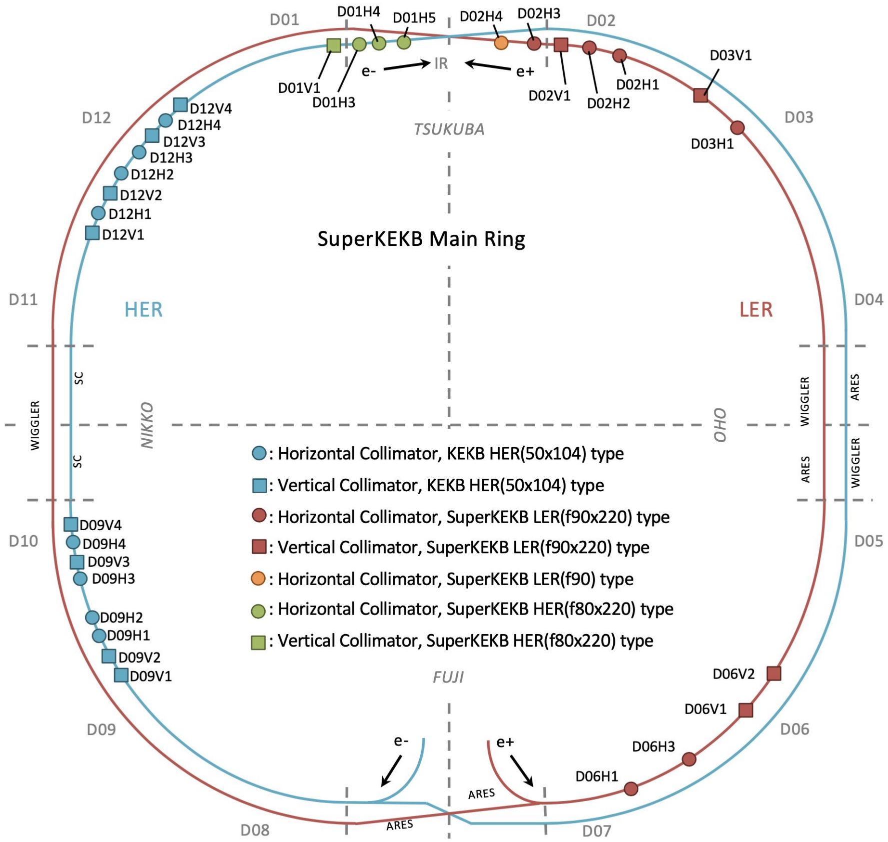
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)

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



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





The crucial & the most complicated part of the background simulation

- **Single-beam background:**
  - SAD (multi-turn particle tracking)
  - Geant4 (detector modeling)
- **Luminosity background:**
  - Geant4 (single-turn effect, colliding beams)
- **Synchrotron radiation background:**
  - Geant4 (close to the Belle II detector)

***S**trategic **A**ccelerator **D**esign (**SAD**) is a computer program complex for accelerator design. It has been developed at KEK since 1986.

https://acc-physics.kek.jp/SAD/

SAD simulation steps:

1. Each ring is split into 500 equidistant scattering points with randomly distributed bunches of scattered particles.
2. An intrinsic weight calculated using specific scattering theories is assigned to each particle.
3. Lost particle coordinates are collected after 1000 machine turns (synchrotron radiation & acceleration by radiofrequency cavities are ON).

Old tracking scheme

- track stray particles until they are lost from the beam
- or until stopped by collimators
- record loss position

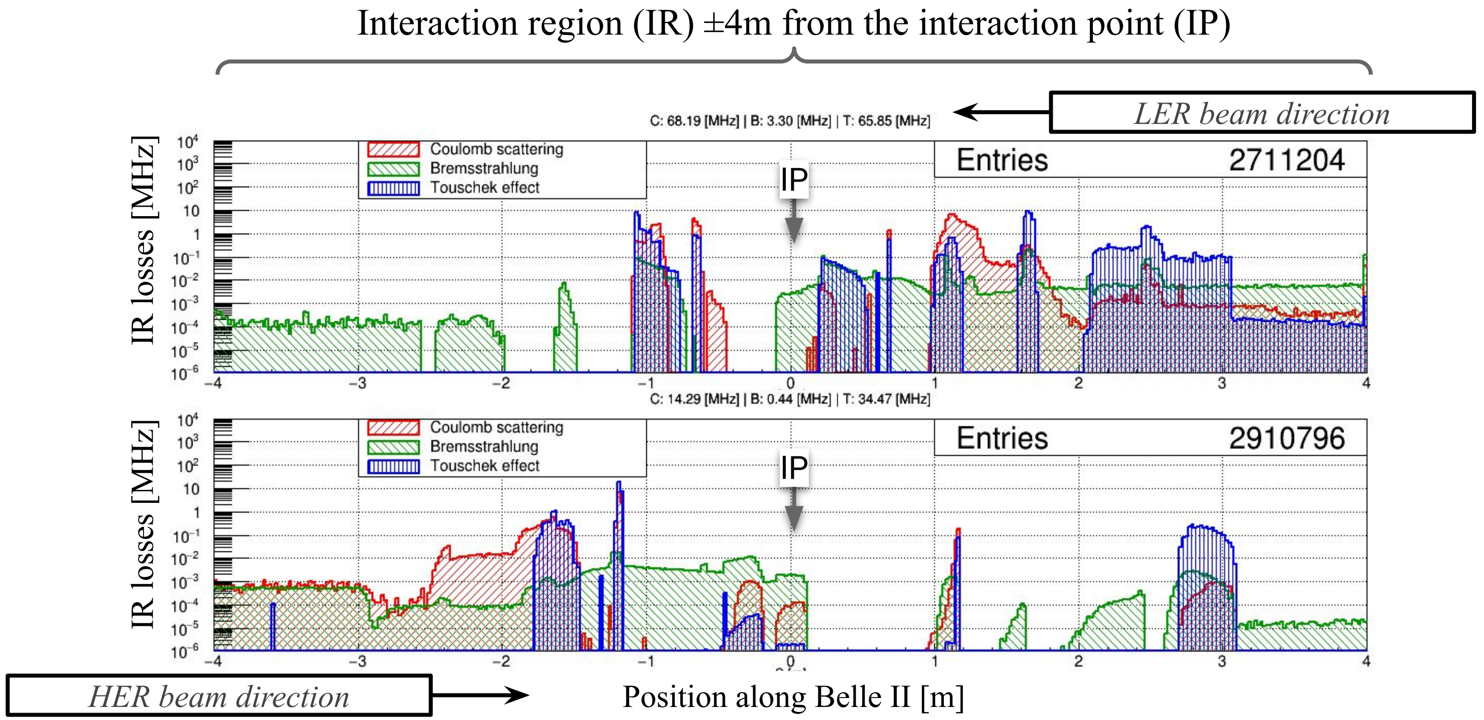
New tracking scheme

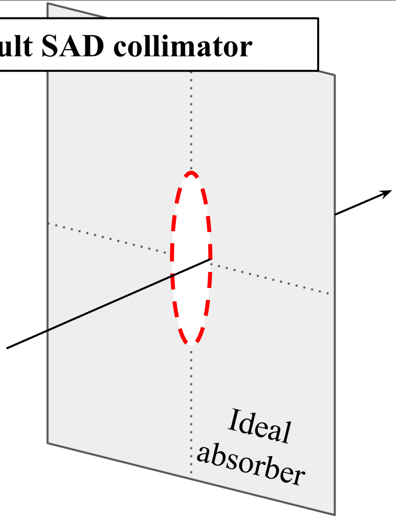
- track stray particles from collimator to collimator - *sequential tracking*
- apply collimator aperture and store 6D coordinates (x , p_x/p , y , p_y/p , z , $\Delta p/p$)
- continue to track survived particles
- record loss position

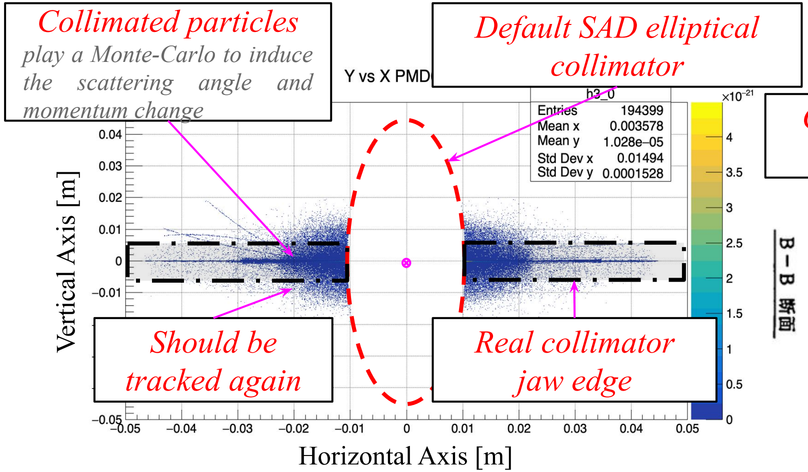
Benefits

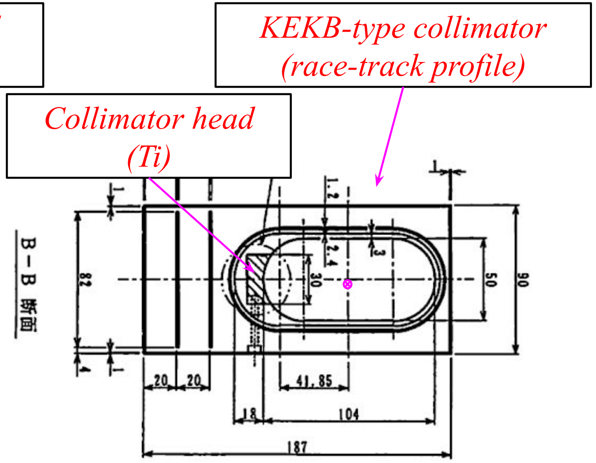
- enables study of the beam dynamics **turn by turn**
- greatly reduced CPU time for collimator optimisation (**days → hours**)

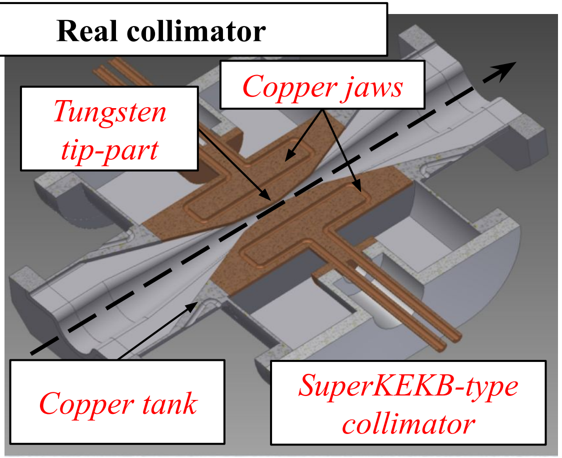
- Beam losses are not uniformly distributed
- For LER, the beam-gas background is at the same level as Touschek
- For HER, the Touschek background is dominant
- Beam lifetime is mainly defined by Touschek losses: ~10min for LER & ~40min for HER









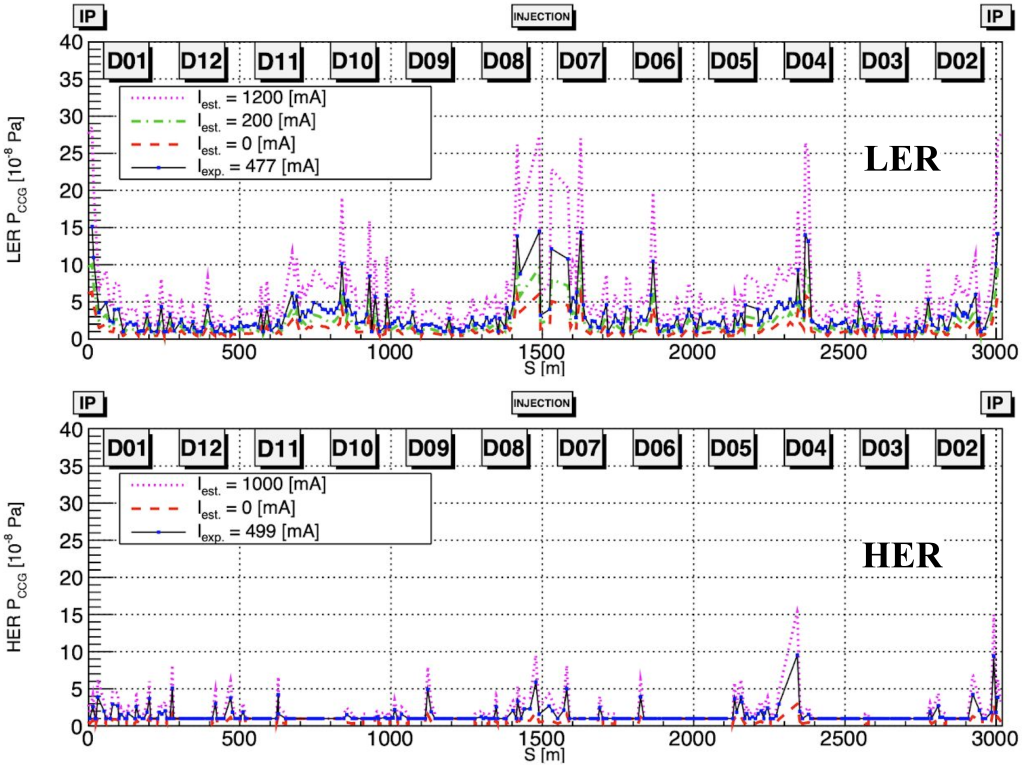


- **Default collimator**
  - does not reflect true geometry
  - particle losses outside the real collimator
- **Improved collimator**
  - realistic shape of jaws
  - particles outside the edge of the jaws are tracked again until they will be lost

An ellipse is a good approximation for the KEKB-type collimators

- 80 mm titanium (X_0 = 35.6 mm) head
- induces large momentum changes and scattered angles
- covering stray particle transverse distribution
- tip-scattering can be neglected
  - collimators are far enough from the interaction region

- The actual beam-pipe gas pressure distribution is not uniformly constant around the ring: P = *f*(position , current).
- The pressure measured by Cold Cathode Gauges (CCG) is now used for the beam-gas scattering simulation.
- The saturation of CCGs (10 nPa) affects <P> calculation (mainly for HER).



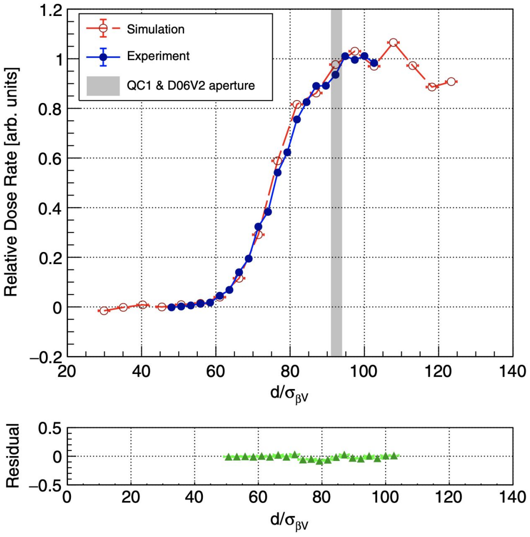
Goal: validate the beam-induced background simulation and collimators model

Method: measure dose rate in the interaction region versus collimator aperture

Setup: Belle II HV - OFF, use only Diamond sensors; I_{LER} = 200mA in continuous injection

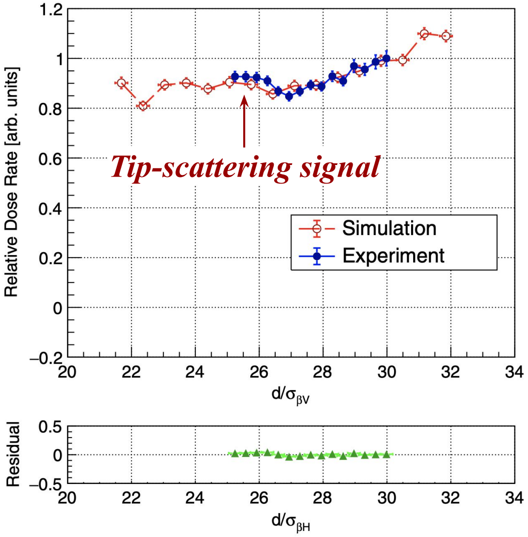
Result: good agreement between experiment and simulation, thanks to all implemented features discussed before

D06V1 - vertical collimator

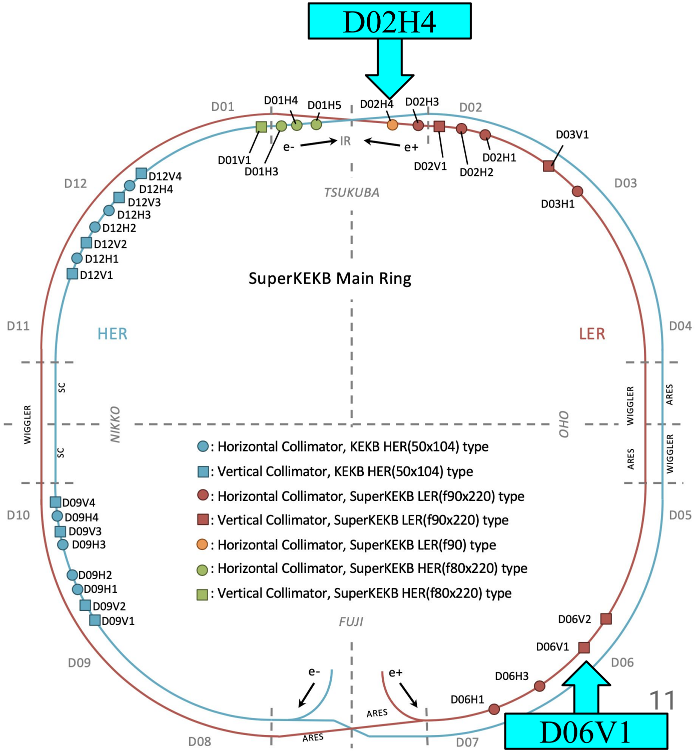


Diamond detector
~60cm upstream IP, FWD

D02H4 - horizontal collimator

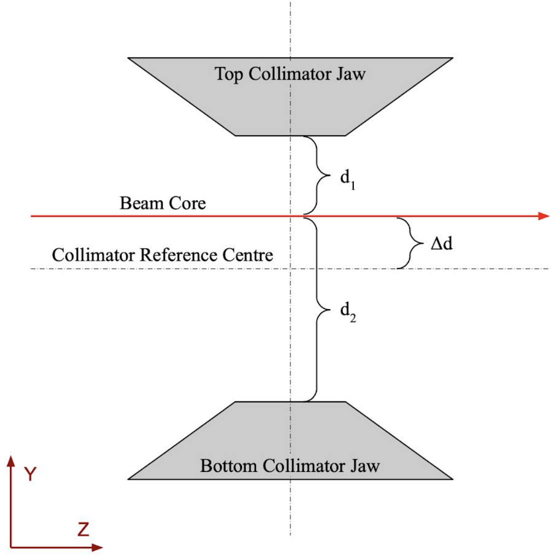


Diamond detectors
±10cm from IP

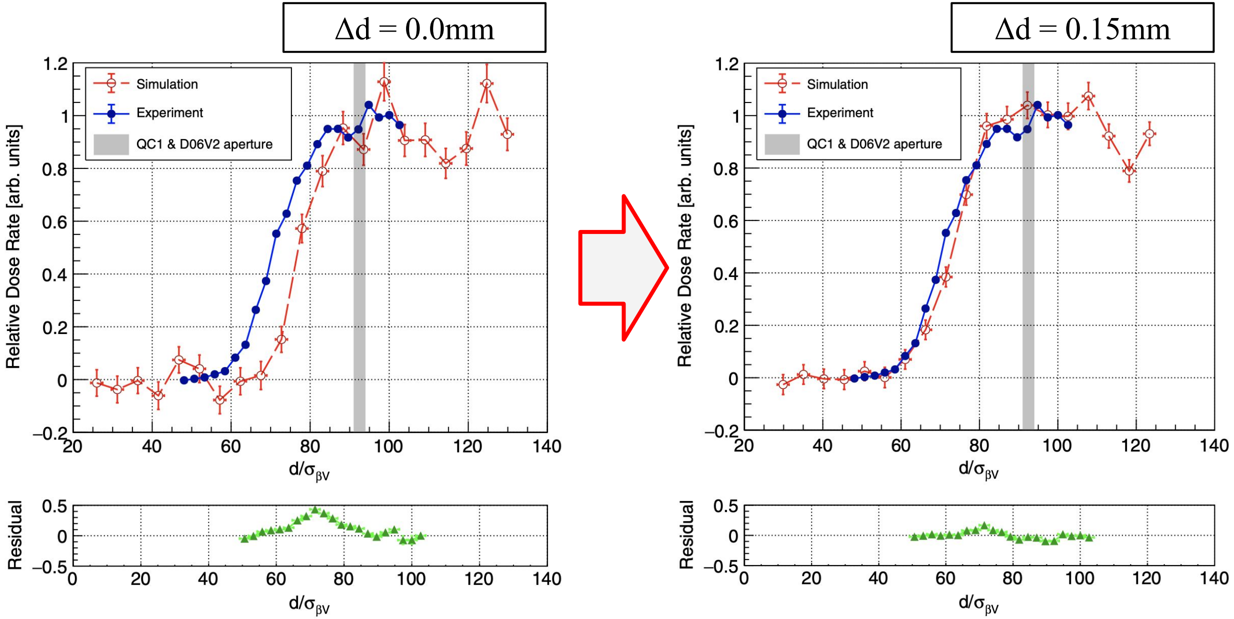


Collimator misalignment

- Simulation suggests a possible misalignment of the collimator with respect to the beam centre
- Precise alignment of collimators is crucial for
  - Better beam halo cleaning and background control
  - Suppressing collimator dipole kicks due to wake-field effects from asymmetric aperture



Schematic drawing of the vertical offset (Δd) between the position reference of the D06V1 collimator and the beam core induced by the alignment uncertainty (~0.2mm).



Beam-pipe Diamonds (±10cm from IP)

The standard procedure for hadron machines

- Close the primary collimator monitoring local beam losses
- At the same level of beam losses for two jaws define the aperture of the beam
- Align other collimators at the same aperture monitoring local beam losses

It is not applicable for the SuperKEKB lepton collider

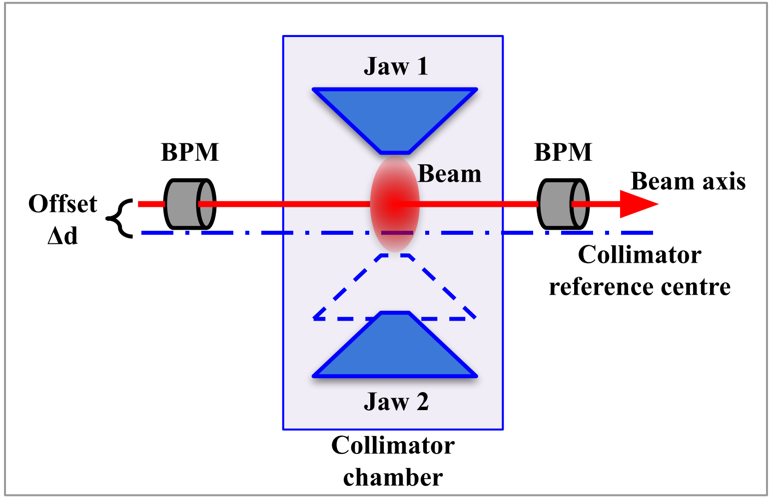
- Narrow aperture is needed to see the reasonable signal of beam losses
- Very short beam lifetimes
- Risk to damage collimators at high beam currents due to unstable injection
- Dedicated/sensitive instrumentation is not installed

Procedure (proposed by H.Nakayama-san, KEK)

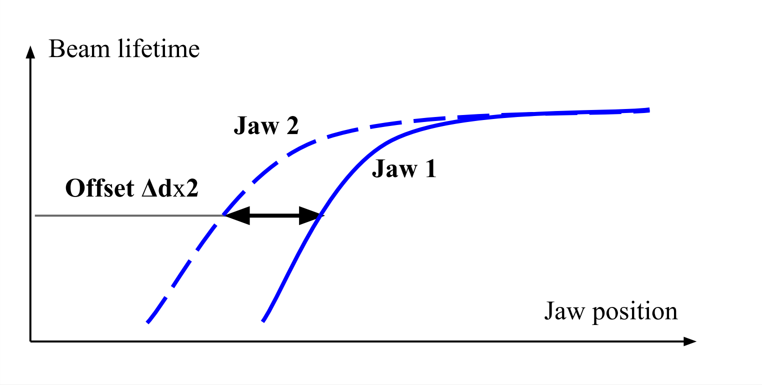
- Perform an aperture scan for each jaw till beam lifetime drops
- Compare jaws position at the same lifetime, see Figures

Settings

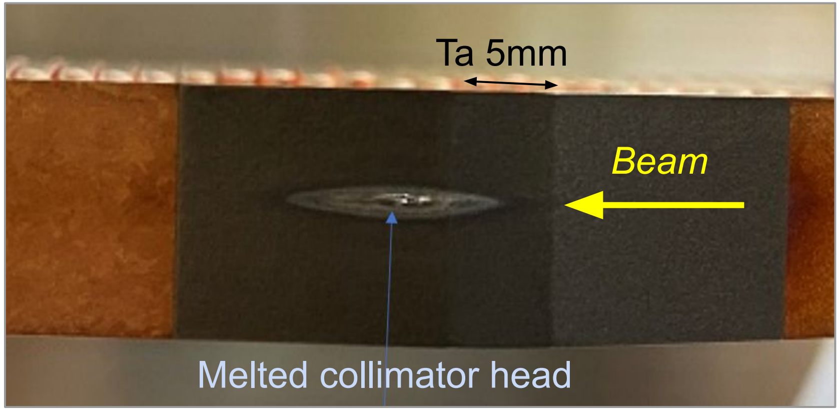
- Low beam currents 10-100mA , continuous and stable injection
- The collimator should be the narrowest one in the ring
- Assume symmetric beam tails



Schematic drawing of the collimator misalignment



Misalignment measurements scheme



Goals

- reduction of the background level in the IR
- ensure beam losses occur mainly at collimators

Bottlenecks

- aggressive closing of the collimator
  - degradation of the injection efficiency
  - very short beam lifetime
  - increase of local losses at collimators, activation
  - unstable injection may cause collimator damage, see Figure
- wide open collimators
  - the Belle II background level increase

Optimal collimation is a compromise between injection performance and particle losses in the machine.

Method I:

(i) Phase-advance analysis (so-called *betatron collimation*), the most effective collimator has a half-integer phase-advance w.r.t. the interaction region

(ii) Manual tuning of each collimator one by one at low beam currents, monitoring injection efficiency and IR backgrounds

Pros & Cons:

(+) real machine and detector response

(−) time-consuming and does not provide the best settings due to many degrees of freedom (11 + 20 collimators)

Method II:

(i) Single-beam background simulation (SAD), collecting beam history at wide-open collimators apertures

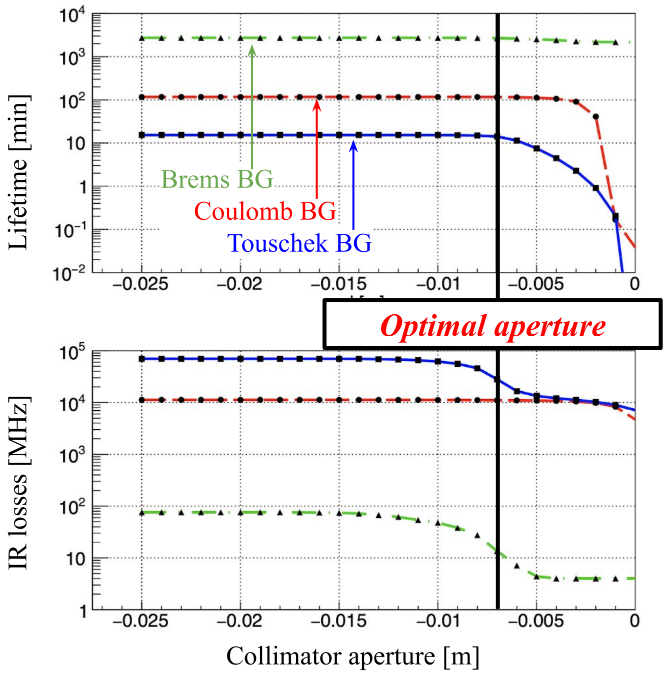
(ii) A linear scan for each collimator (C/C++) keeping a constant beam lifetime and lowest IR losses, see Figure

(iii) Bunch current limitation check due to Transverse Mode Coupling Instabilities (TMCI) ← **one of the limiting source to increase bunch current**

Pros & Cons:

(+) receive optimal settings in a few hours, serves a guideline for the machine operator

(−) it does not take into account the injection quality



A linear scan of the collimator aperture

SuperKEKB uses both methods

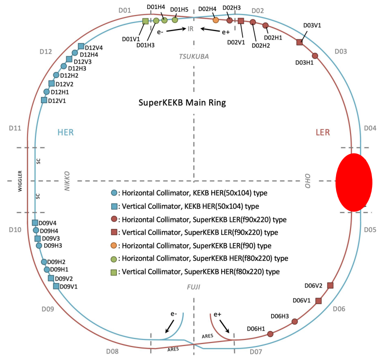
Proposal:

Using a pair of skew-sextupoles in the OHO section, create a nonlinear optics region

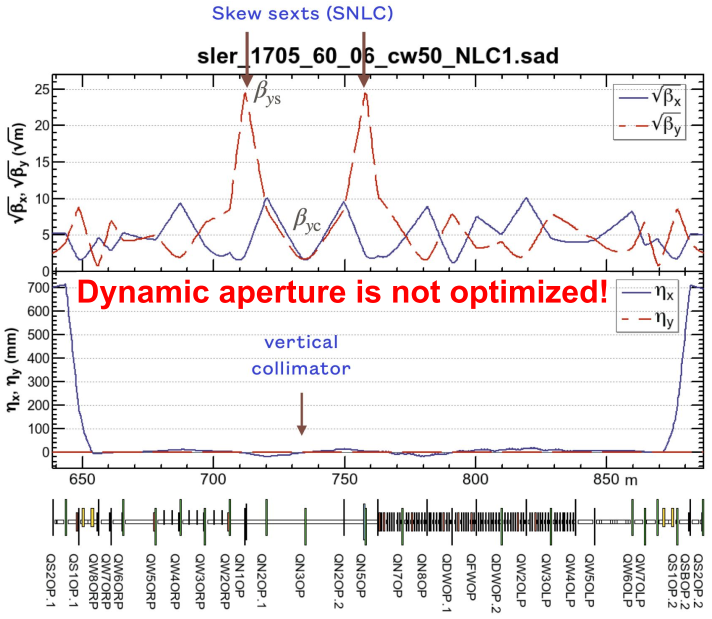
- Low betatron function in between $\beta_{X/Y}$ ~3m
- Vertical angular kick for distant halo particles in both planes $\Delta p_Y \sim (y^2 - x^2)$

Question:

How the non-linear collimator (NLC) installed at this location can affect backgrounds and TMCI threshold ?



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

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

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

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

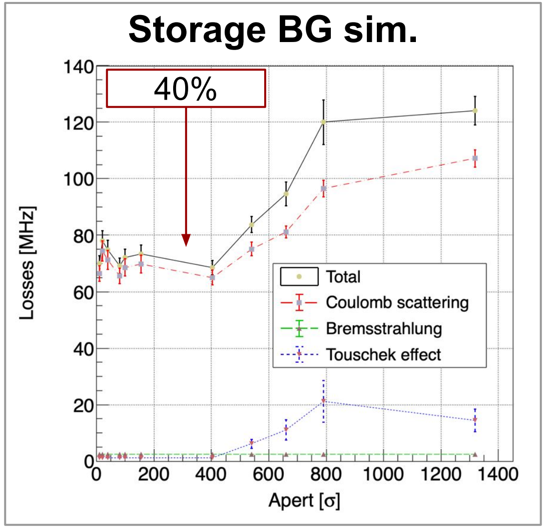
$$\Delta y_c = R_{34}\Delta p_{ys} = 5.7\,\mathrm{mm} \tag{3}$$

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

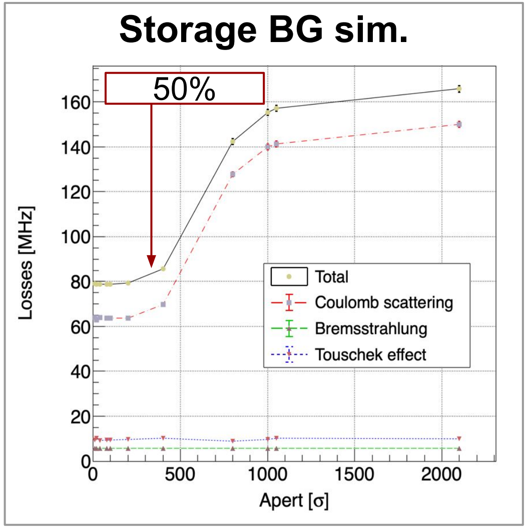
- This example optics: $\beta_{ys} = 570$ m, $\beta_{yc} = 2.9$ m.

- The optimal NLC aperture for storage and injection backgrounds mitigation is ±5.7mm which is about 300σ at the NLC → 40σ at skew sextupoles, while the IR is at 50σ
  - IR background reduction with no harm to the TMCI threshold I_{th} ~1.6mA/bunch
- Can fully replace the primary vertical collimator in LER (D06V1, β_Y ~70m)
- Can significantly relax the bunch current threshold due to TMCI ($I_{th}^{TMCI} \sim 1/\Sigma\beta_i k_i$) by allowing a much wider aperture for other vertical collimators

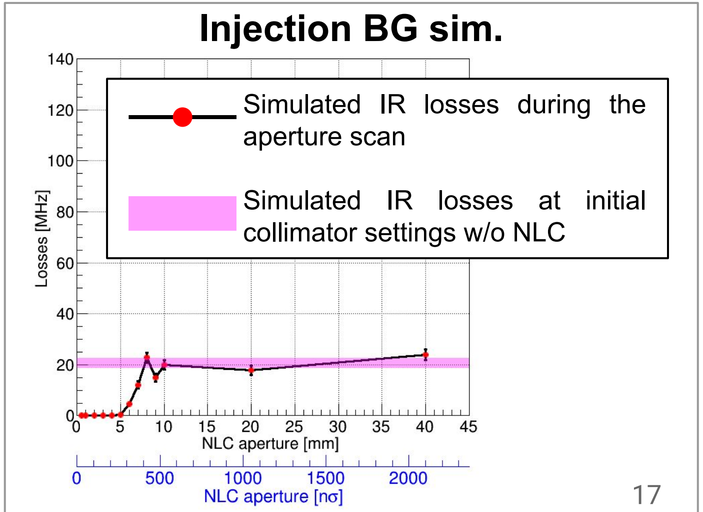
β^*_Y = 0.6mm, optimized collimator settings, beam lifetime ~8min



β^*_Y = 1.0mm, exp. collimator settings, beam lifetime ~10min



β^*_Y = 1.0mm, exp. collimator settings, injection efficiency ~30% (not optimized settings)



Summary

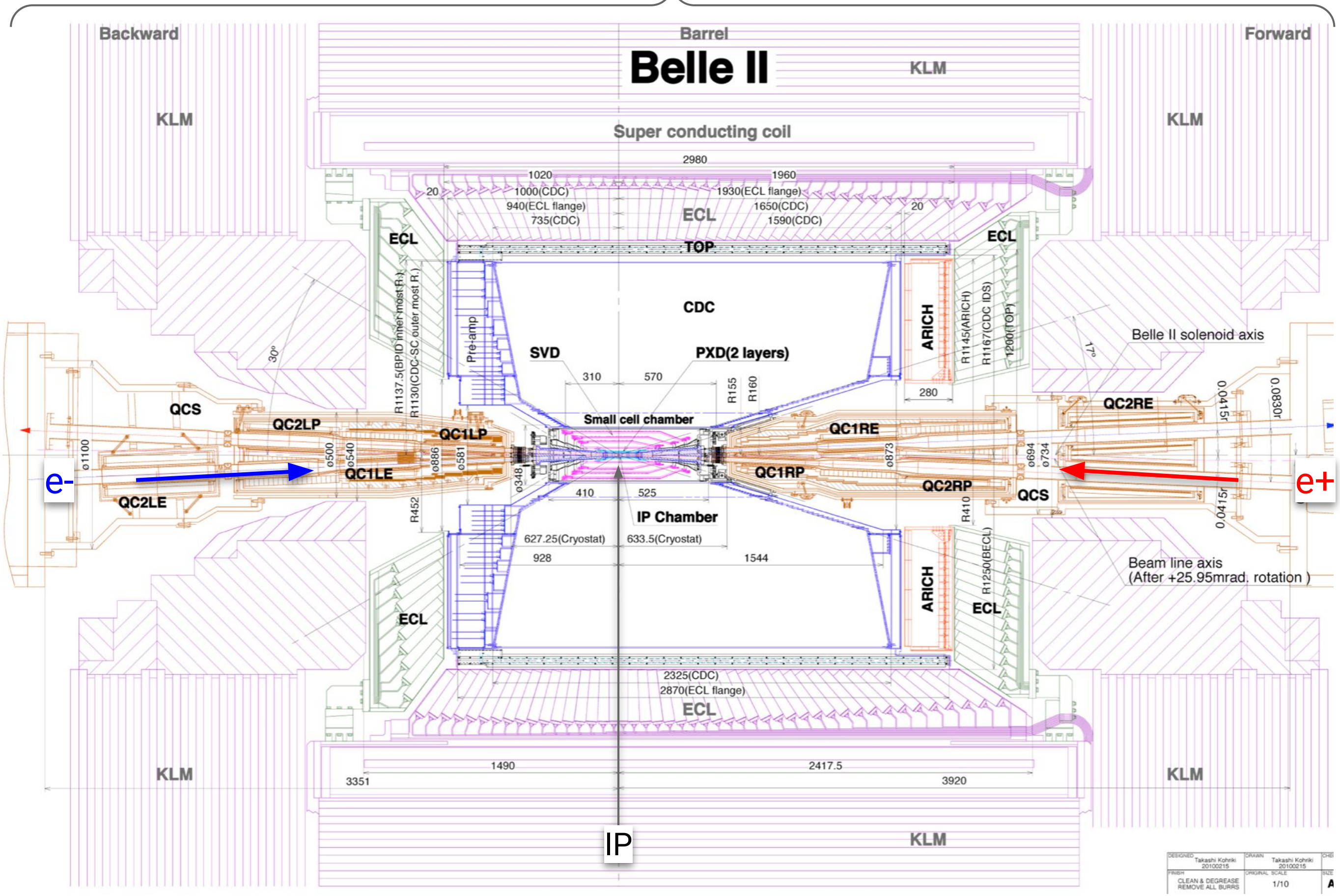
- A new multi-turn particle tracking software framework based on SAD was developed including
    - realistic gas pressure distribution
    - a true collimator profile
    - tip-scattering
  - Reached a good agreement between measured and simulated beam backgrounds
  - Better collimation system optimisation and background prediction
- Comparing simulated and experimental collimator scans appears sensitive to collimator misalignments
  - A new procedure for the collimator misalignment measurement is extensively used at SuperKEKB
- For more details regarding the beam-induced background simulation and collimation at SuperKEKB look at

  A. Natochii, S. E. Vahsen, H. Nakayama, T. Ishibashi, and S. Terui, "Improved simulation of beam backgrounds and collimation at SuperKEKB", Phys. Rev. Accel. Beams 24, 081001 (2021), https://link.aps.org/doi/10.1103/PhysRevAccelBeams.24.081001
- Further improvements and Belle II detector-specific background results will be published separately, stay tuned!
- Current collimation system status [see other talks during the KEKB: Lessons from SuperKEKB session]
  - Replaced damaged collimators
  - Developing new type of collimators, e.g. NLC
  - Installation of additional beam loss monitors near collimators

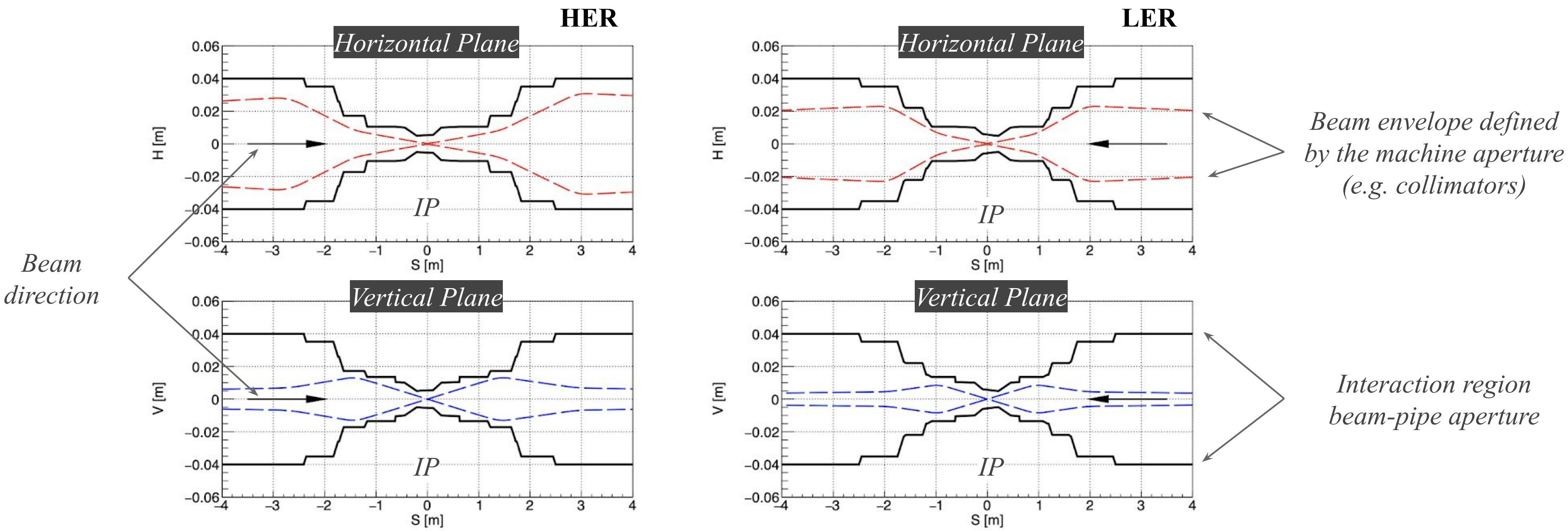
Thanks for your attention!

BACKUP SLIDES

Interaction region (IR)
±4m from the interaction point (IP)



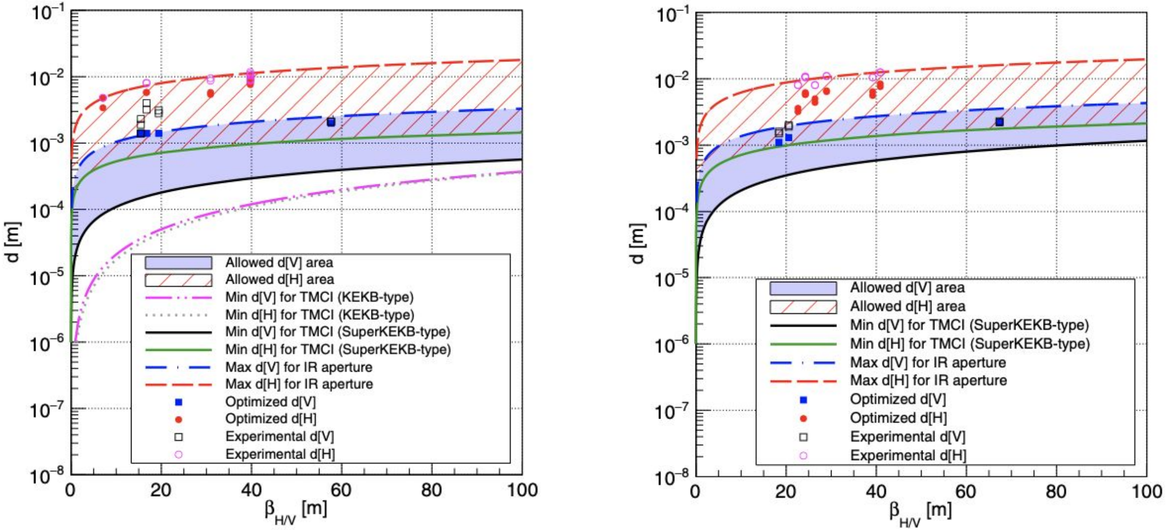
Interaction region aperture and beam envelope



Although minimum IR losses and acceptable lifetime can be achieved in simulation by the collimation system optimization, the collimators also have to satisfy specific requirements to avoid what is known as transverse mode coupling instability (TMCI).

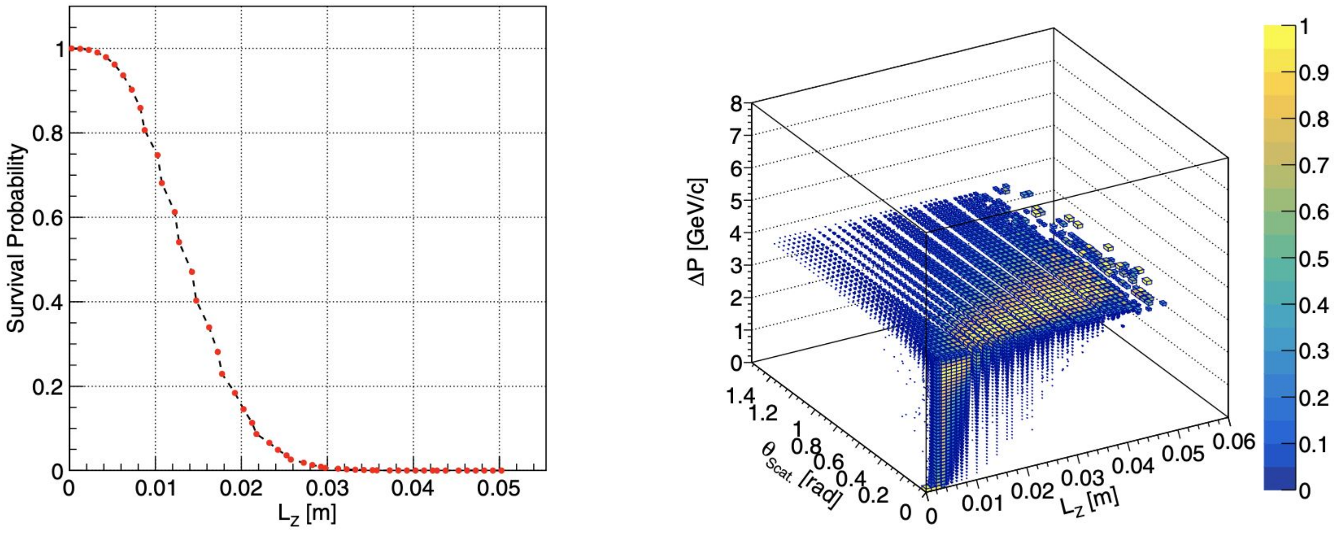
$$I_{\text{thresh}} = \frac{8 f_s E/e}{\sum_j \beta_j k_j(\sigma_S, d)}$$

where I_{thresh} is the upper limit on the bunch current, fs = 2.13 kHz or fs = 2.80 kHz is the synchrotron frequency for LER or HER, respectively, E is the beam energy, e is the unit charge, βj and kj are the beta function and kick factor of the jth collimator, respectively.



(a) HER (b) LER

SuperKEKB HER (a) and LER (b) collimator apertures and their constraints. Black, solid (green, triple-dot-dashed) and magenta, double-dot-dashed (gray, dotted) lines show the minimum allowed SuperKEKB-type and KEKB-type vertical (horizontal) collimator apertures at different beta function values, respectively, to avoid TMCI from a single collimator. The red, dashed and blue, dot-dashed lines show the maximum collimator aperture for horizontal and vertical collimators, respectively, beyond which we expect increased losses due to the IR aperture. Filled, red circles and filled, blue squares are optimized apertures of the horizontal and vertical collimators, respectively, based on simulation only; magenta, open circles and black, open squares are the experimental settings of the horizontal and vertical collimators used in June 2020.



(a) Survival probability

(b) Momentum change

Geant4 simulation results for 4 GeV/c positrons interacting with tungsten. (a) Particle survival probability versus path length inside the jaw, L_Z. Statistical error < 1%. (b) Momentum change, ΔP, versus scattering angle, $\theta_{Scat.}$, and path length inside the jaw. Each slice of L_Z is normalized so that its maximum value in the $\Delta P-\theta_{Scat.}$ plane is unity. Therefore, the color and the size of each box (bin) represent the relative probability for a scattered particle with a given L_Z to obtain a particular ΔP and $\theta_{Scat.}$. Bin size is 1mm×40mrad×100 MeV/c.