

## SuperKEKB beam collimation

*On behalf of the Belle II beam background and MDI groups*

Dr. **Andrii Natochii**

Postdoctoral researcher

University of Hawaii

Email: [natochii@hawaii.edu](mailto:natochii@hawaii.edu)



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

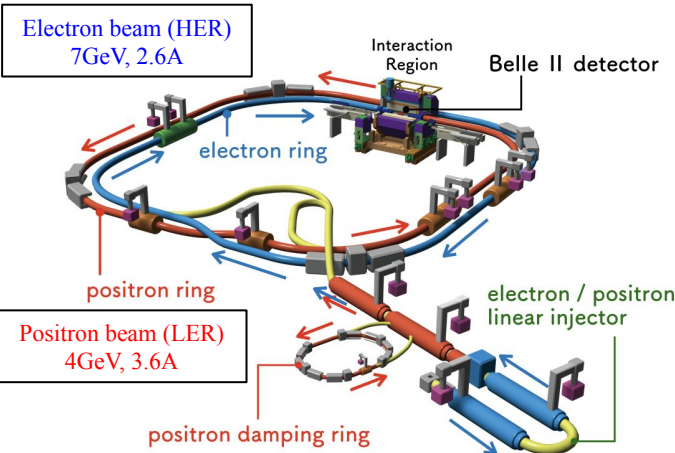
## SuperKEKB: design parameters of “Low Energy Ring” (LER) & “High Energy Ring” (HER)

	LER ( $e^+$ )	HER ( $e^-$ )	
Energy	4.000	7.007	GeV
Half crossing angle	41.5		mrاد
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*) $\times 10^{35}$		$\text{cm}^{-2}\text{s}^{-1}$

**Current luminosity**  $3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

**WORLD RECORD**

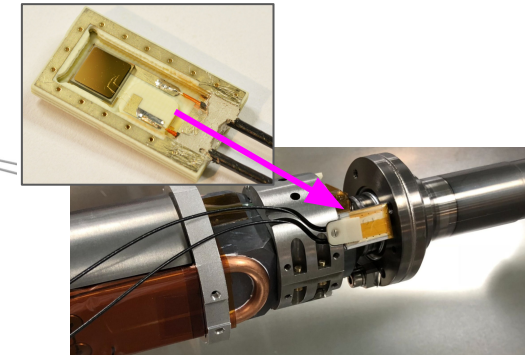
*\* new design conditions extrapolated from the current machine/detector performance.*



### Belle II detector at the interaction region

- Pixel Detector (PXD)
- Silicon Vertex Detector (SVD)
- Central Drift Chamber (CDC)
- TOP counter (TOP)
- Aerogel RICH counter (ARICH)
- Electromagnetic Calorimeter (ECL)
- $K_L^0$ /Muon Detector (KLM)

### 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** ( $\beta_Y^*$ ) 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)

**Touschek**  $\propto \sigma^{-1} E^{-3}$

**Coulomb**  $\propto I \cdot P$

**Bremsstrahlung**  $\propto I \cdot P$

### Colliding beams (Luminosity)

**Radiative Bhabha proc.**  $\propto L$

**Two-photon proc.**  $\propto I$

### Synchrotron radiation

$\propto I$

### Injection (top-up, continuous)

**Injected beam**

**Machine aperture**

### 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)

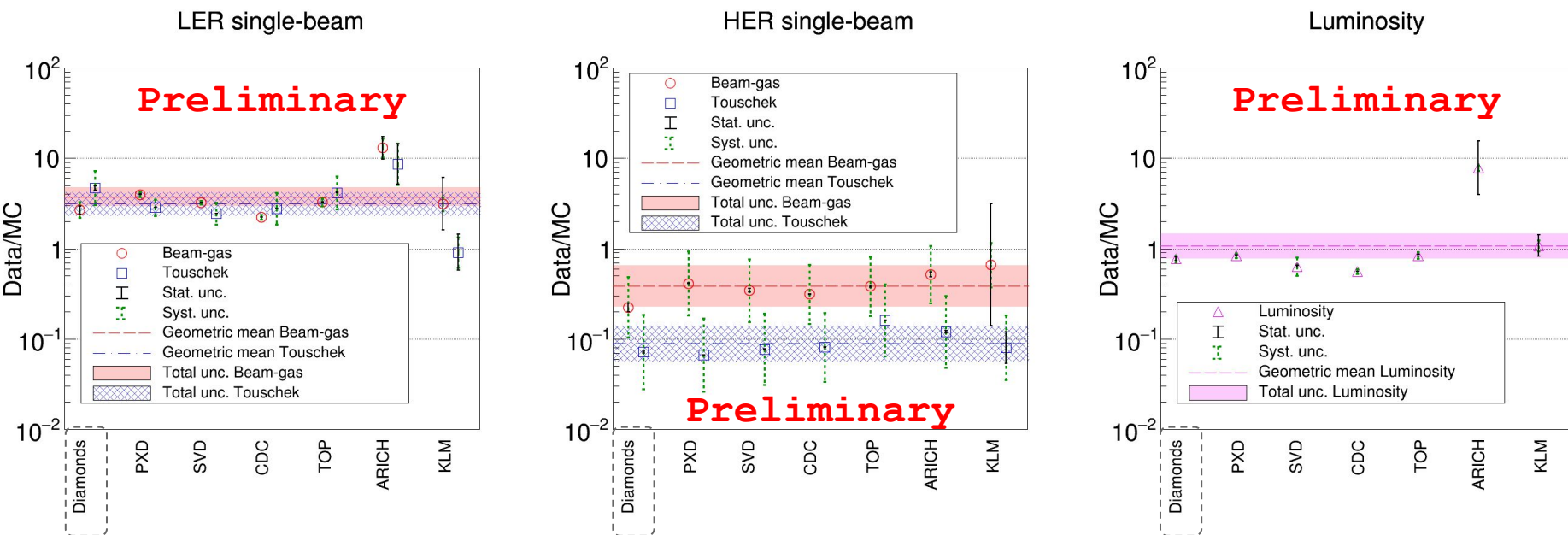
### Injection

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

$$\text{Data/MC} = 10^{-2}\text{-}10^3 \text{ [2016-2018]} \rightarrow 10^{-1}\text{-}10^1 \text{ [2020-2021]}$$

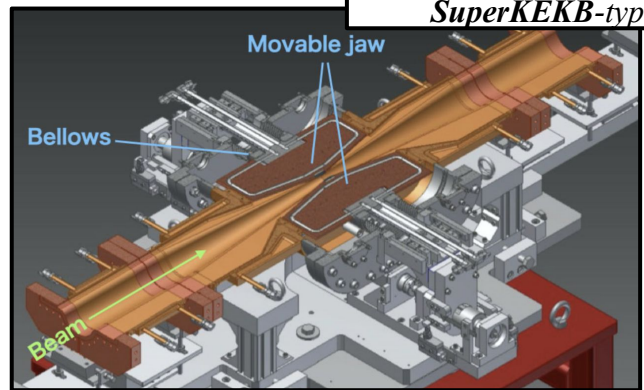
- Focusing mainly on Diamonds and SuperKEKB collimation system this presentation is about how we achieved this **significant improvement**



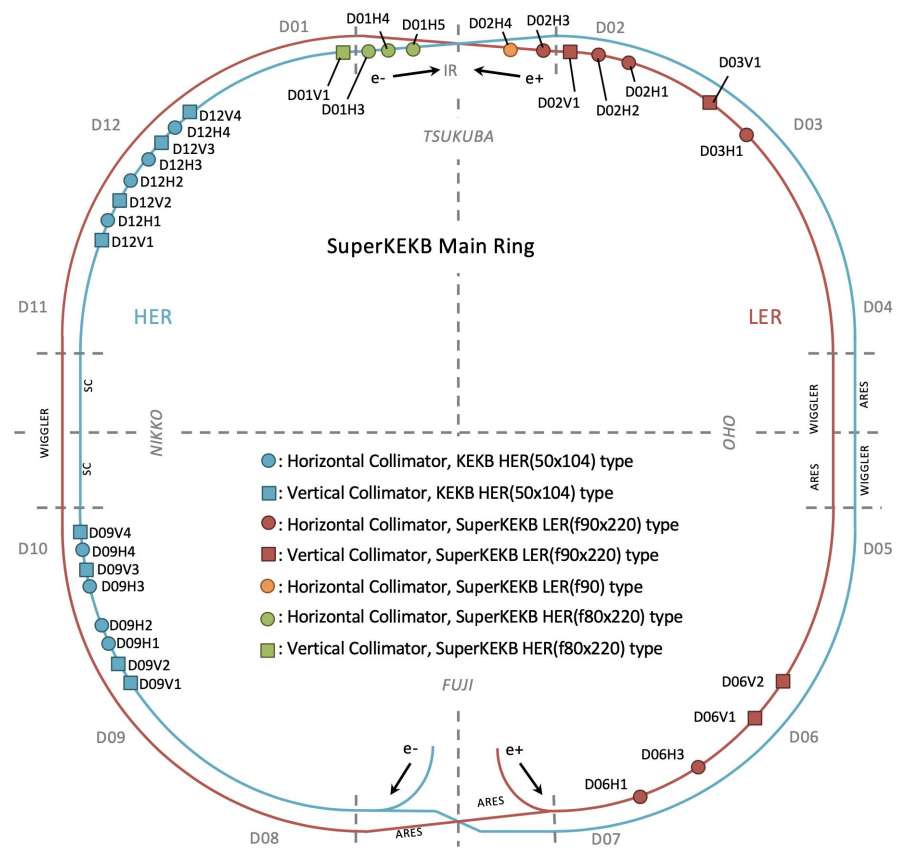
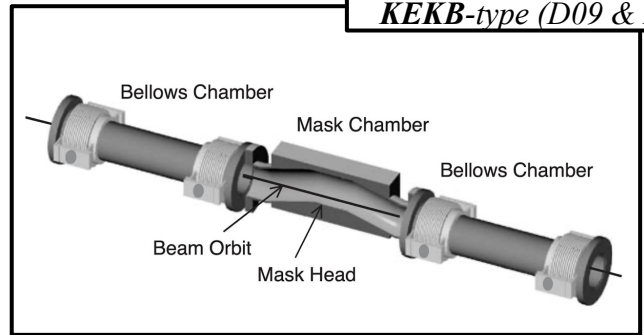
**Excellent data/MC agreement!**

- 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)

*Strategic Accelerator Design (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

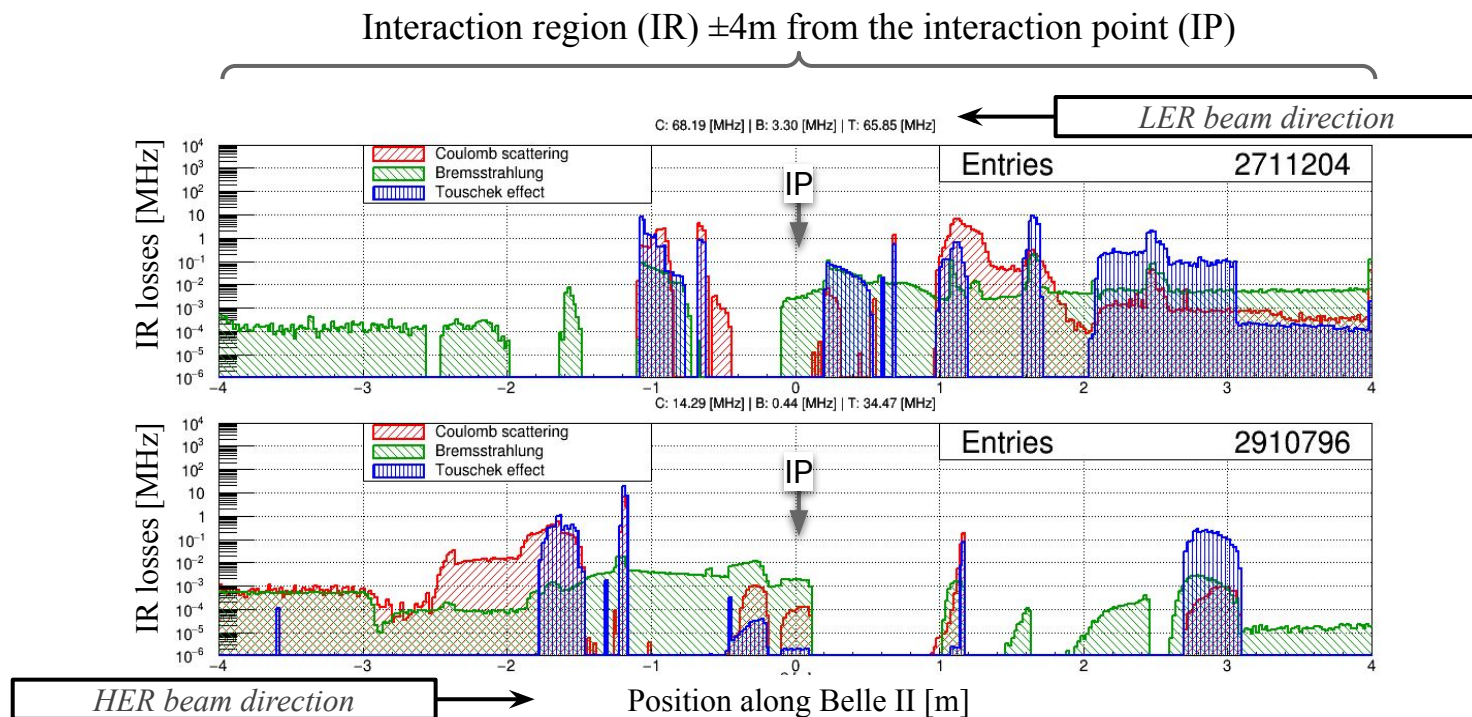
### New tracking scheme

- 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

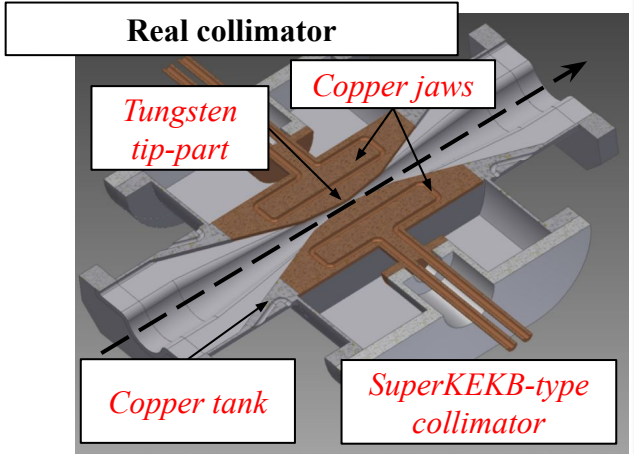
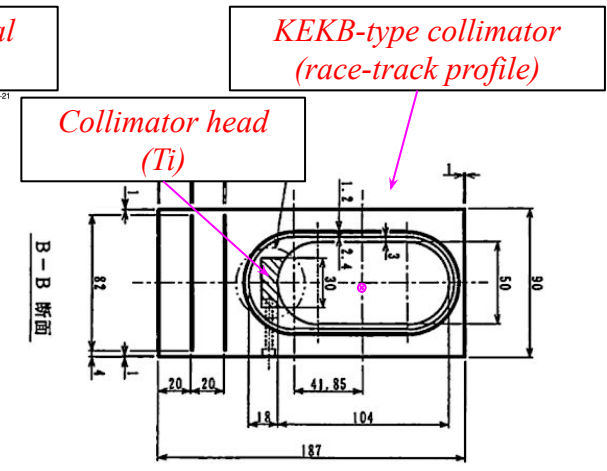
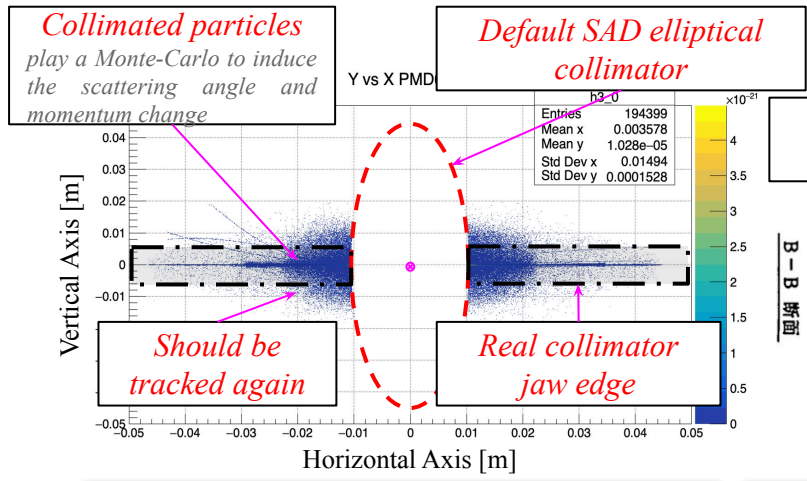
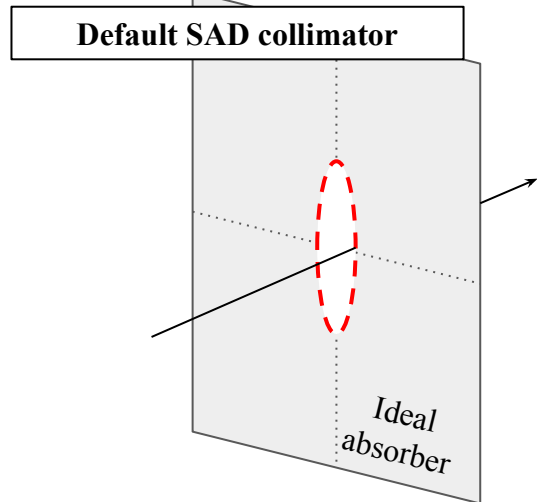
### Benefits

- 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:  $\sim 10$ min for LER &  $\sim 40$ min for HER



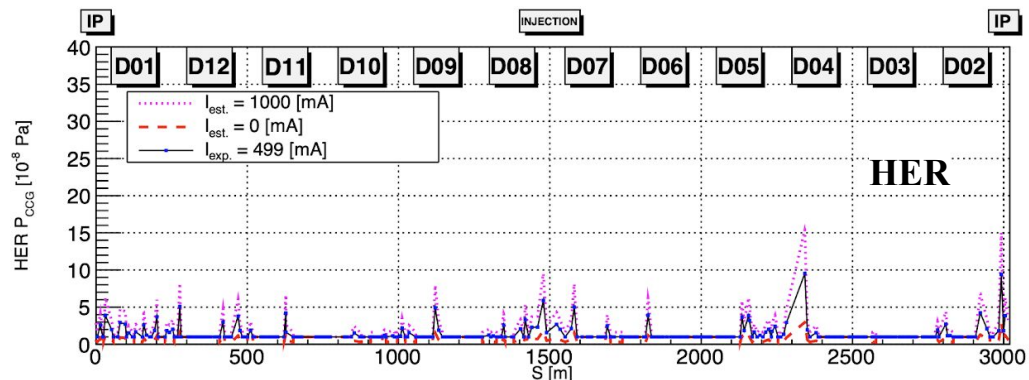
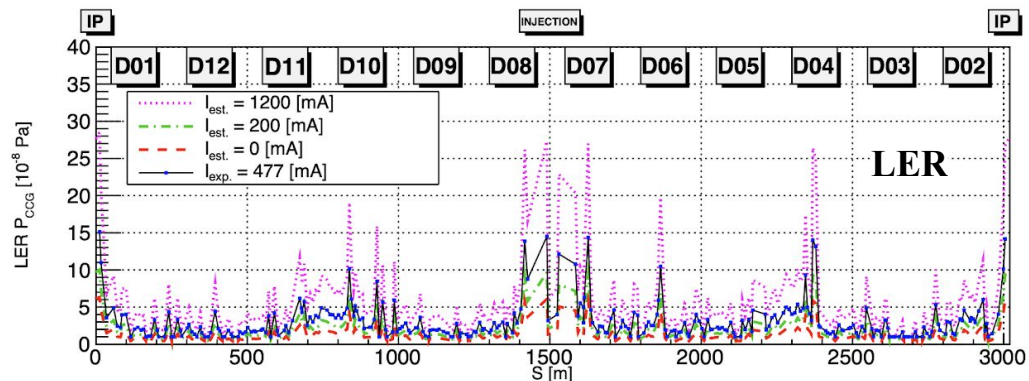




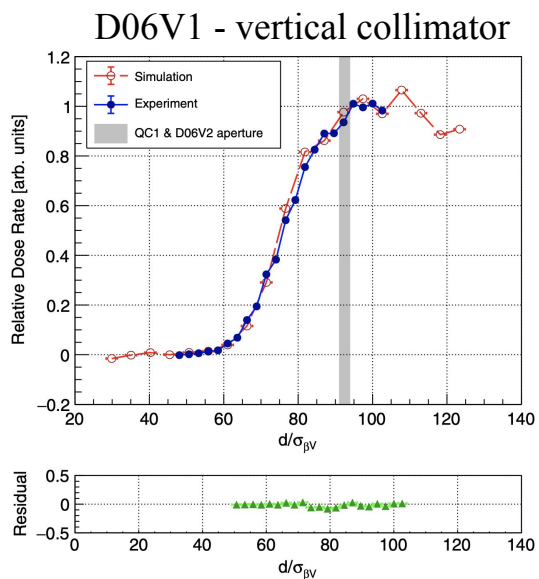
- **Default collimator**
  - does not reflect true geometry
  - particle losses outside the real collimator
- **Improved collimator**
  - realistic shape of jaws
  - particles outside the edge of the jaws are tracked again until they will be lost

- 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 9

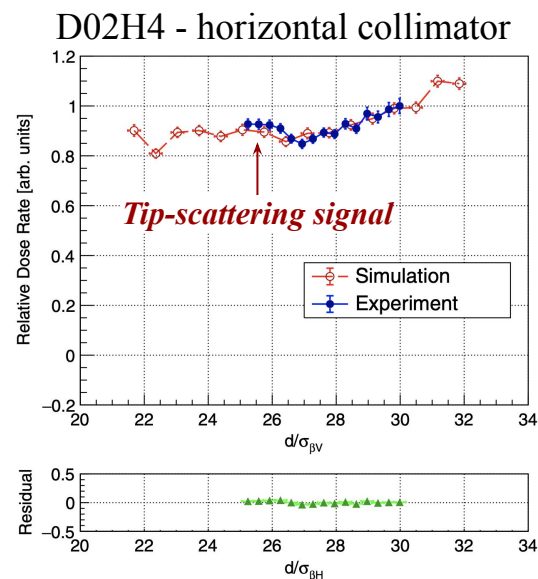
- The actual beam-pipe gas pressure distribution is not uniformly constant around the ring:  $P = f(\text{position}, \text{current})$ .
- The pressure measured by Cold Cathode Gauges (CCG) is now used for the beam-gas scattering simulation.
- The saturation of CCGs (10 nPa) affects  $\langle P \rangle$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



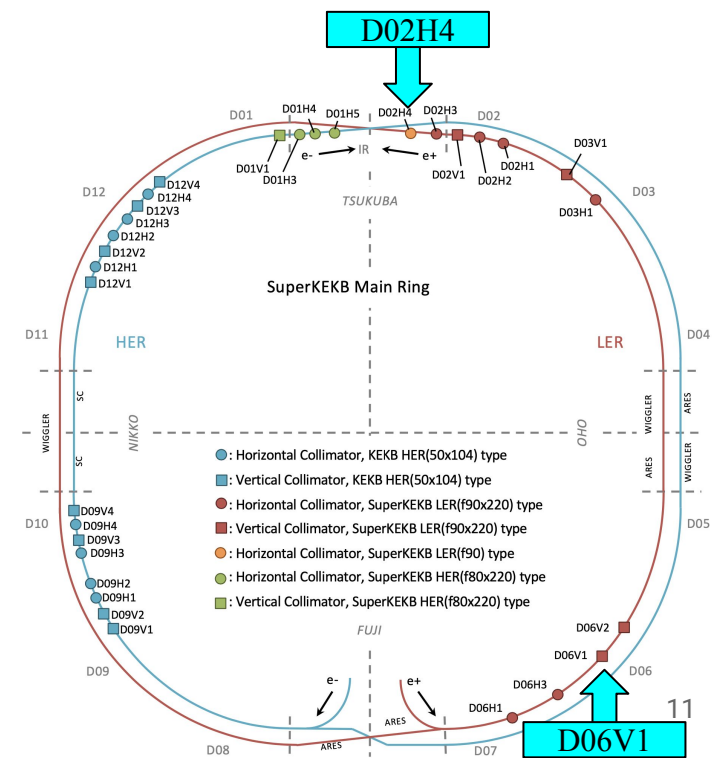
- Goal:** validate the beam-induced background simulation and collimators model
- Method:** measure dose rate in the interaction region versus collimator aperture
- Setup:** Belle II HV - OFF, use only Diamond sensors;  $I_{LER} = 200\text{mA}$  in continuous injection
- Result:** good agreement between experiment and simulation, thanks to all implemented features discussed before



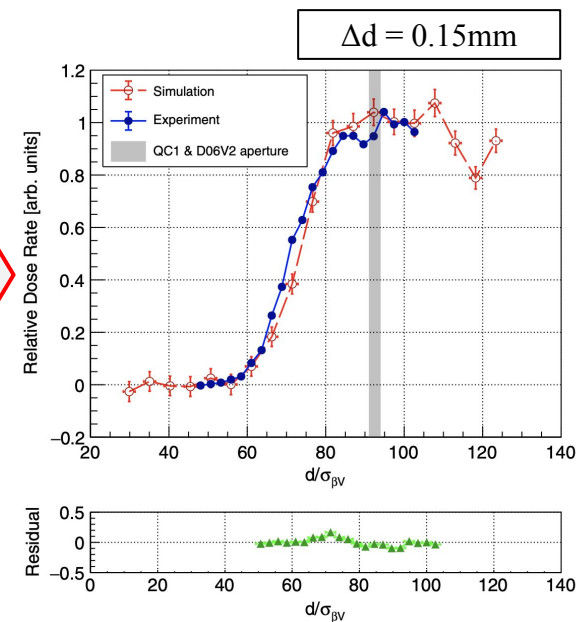
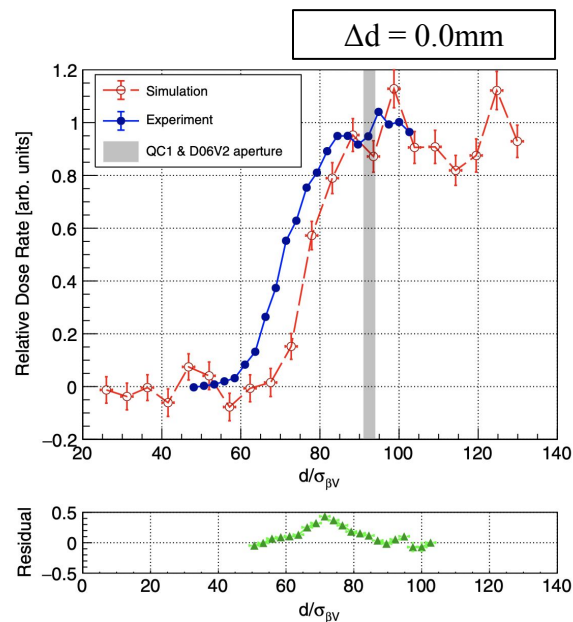
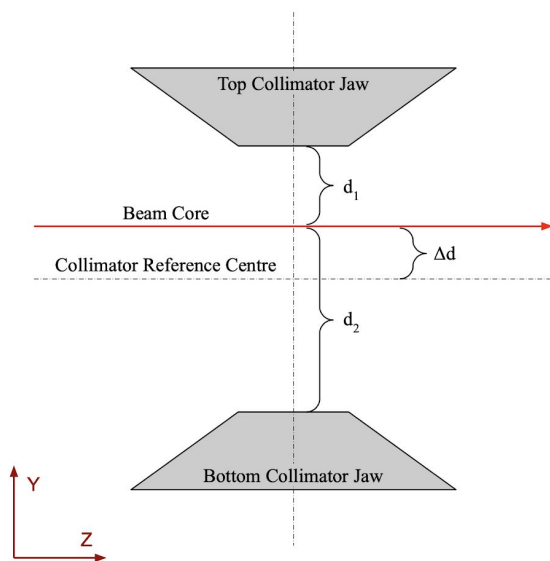
*Diamond detector  
~60cm upstream IP, FWD*



*Diamond detectors  
±10cm from IP*



- 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



Beam-pipe Diamonds ( $\pm 10\text{cm}$  from IP)

Schematic drawing of the vertical offset ( $\Delta d$ ) between the position reference of the D06V1 collimator and the beam core induced by the alignment uncertainty ( $\sim 0.2\text{mm}$ ).

## 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

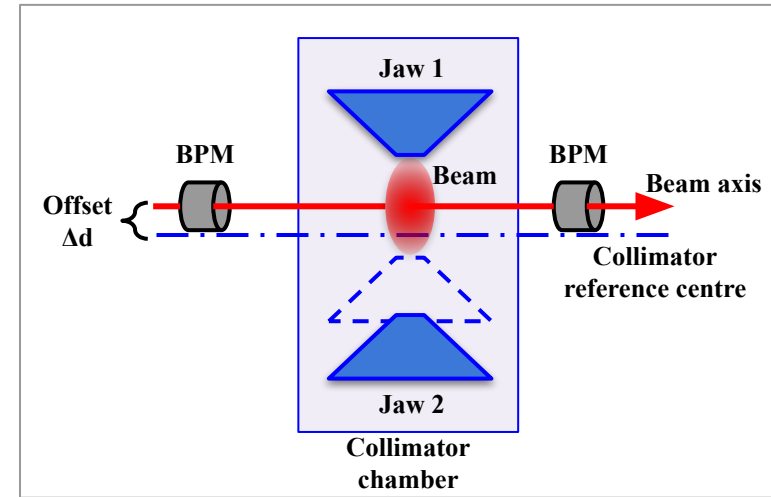
- Narrow aperture is needed to see the reasonable signal of beam losses
- Very short beam lifetimes
- Risk to damage collimators at high beam currents due to unstable injection
- Dedicated/sensitive instrumentation is not installed

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

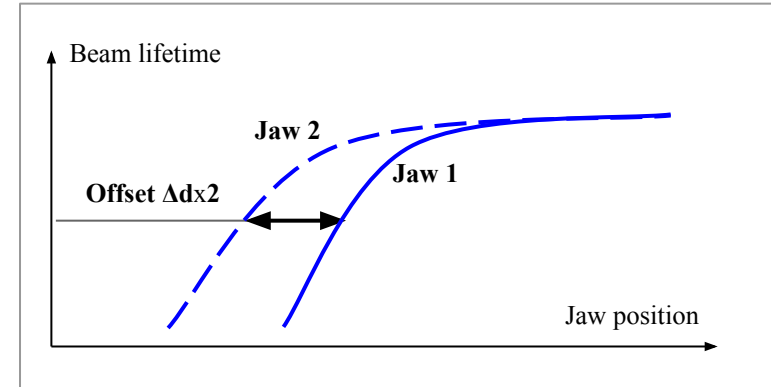
- Perform an aperture scan for each jaw till beam lifetime drops
- Compare jaws position at the same lifetime, see Figures

## 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*

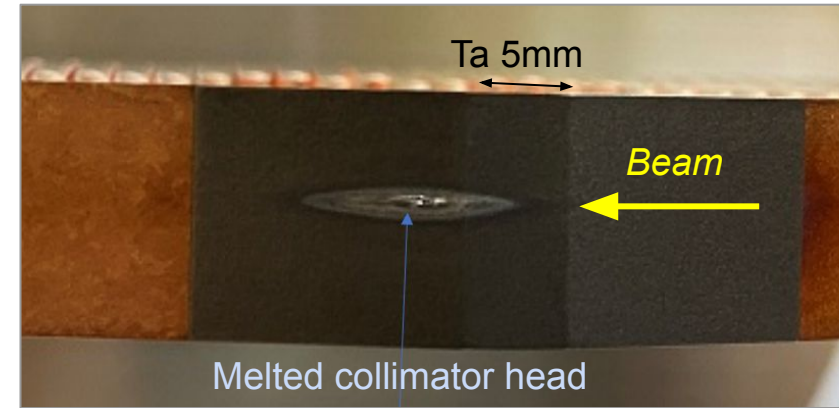
## Goals

- 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:**

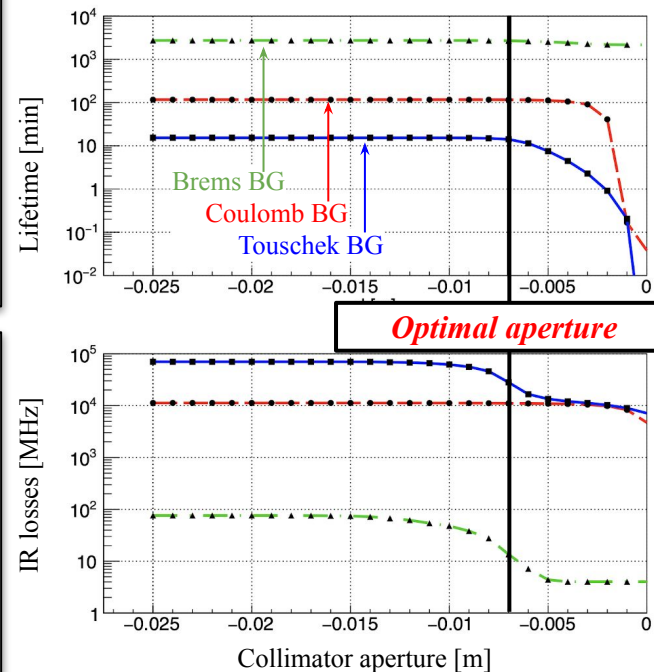
- (+) real machine and detector response
- (-) time-consuming and does not provide the best settings due to many degrees of freedom (11 + 20 collimators)

**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)

**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**

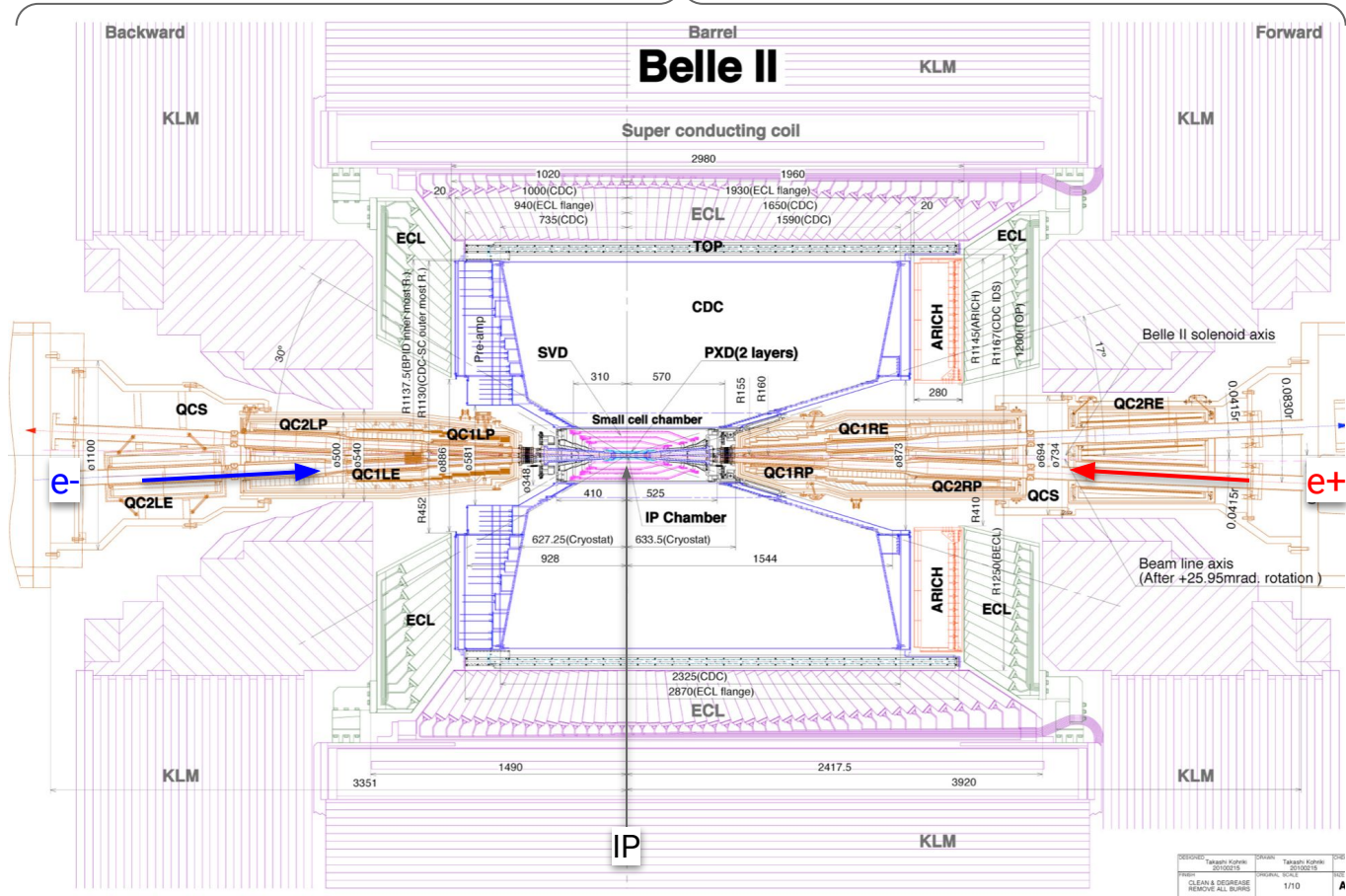
- A **new multi-turn particle tracking** software framework based on SAD was developed including
  - realistic gas pressure distribution
  - a true collimator profile
  - tip-scattering
  - Reached a **good agreement** between measured and simulated beam backgrounds
  - **Better** collimation system **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. Natchii, 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
  - Installation of additional beam loss monitors near collimators

**Thanks for your attention!**

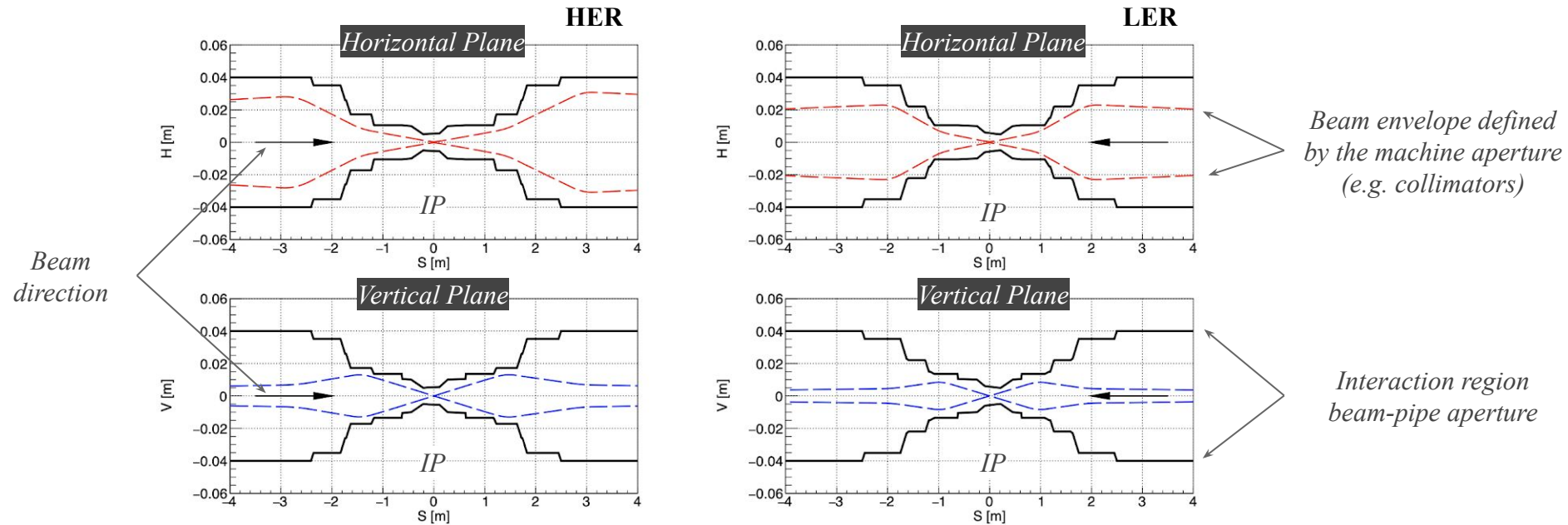




Interaction region (IR)  
 $\pm 4\text{m}$  from the interaction point (IP)



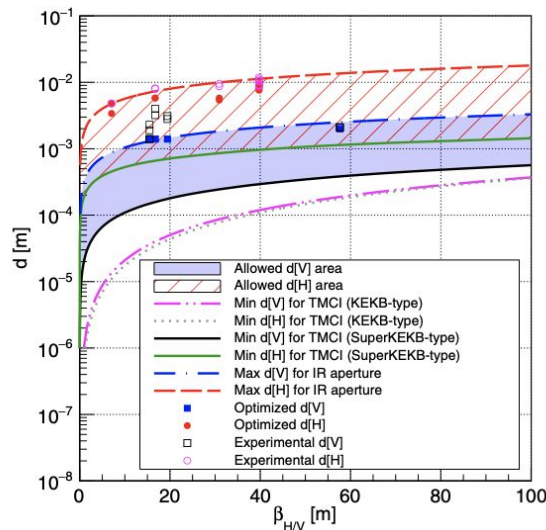
00000000	Takahashi Kohichi	00000000	Takahashi Kohichi	00000000
1/1	1/1	1/1	1/1	1/1



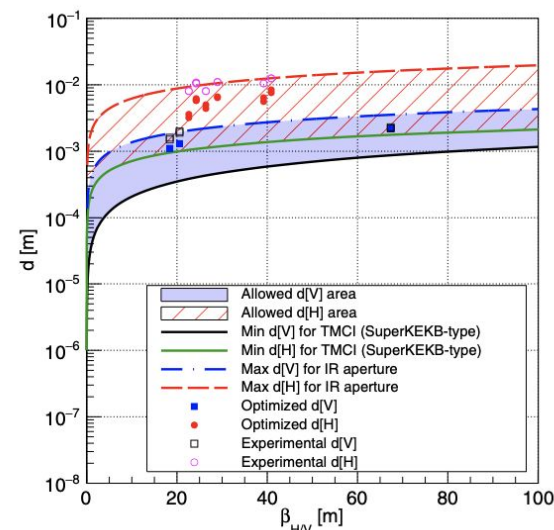
Although minimum IR losses and acceptable lifetime can be achieved in simulation by the collimation system optimization, the collimators also have to satisfy specific requirements to avoid what is known as transverse mode coupling instability (TMCI).

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

where  $I_{\text{thresh}}$  is the upper limit on the bunch current,  $f_s = 2.13$  kHz or  $f_s = 2.80$  kHz is the synchrotron frequency for LER or HER, respectively,  $E$  is the beam energy,  $e$  is the unit charge,  $\beta_j$  and  $k_j$  are the beta function and kick factor of the  $j$ th collimator, respectively.

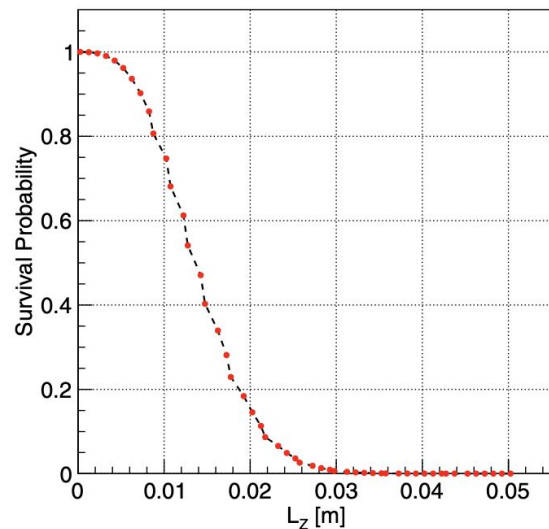


(a) HER

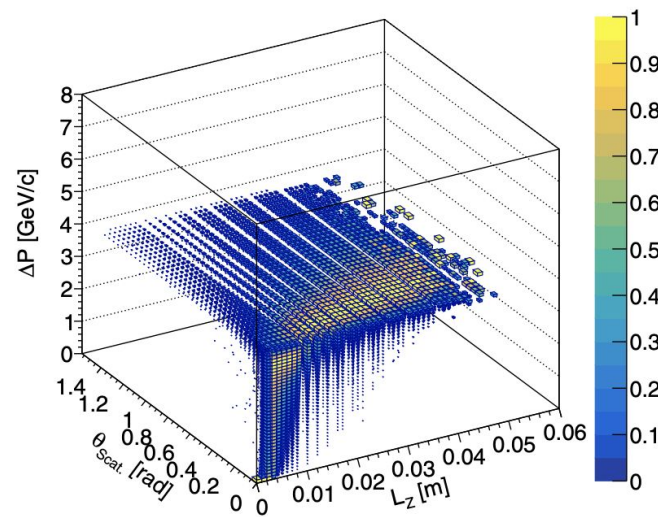


(b) LER

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 KEBB-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,  $\Delta P$ , versus scattering angle,  $\theta_{\text{Scat.}}$ , and path length inside the jaw. Each slice of  $L_z$  is normalized so that its maximum value in the  $\Delta P$ - $\theta_{\text{Scat.}}$  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  $\Delta P$  and  $\theta_{\text{Scat.}}$ . Bin size is  $1\text{mm} \times 40\text{mrad} \times 100\text{ MeV/c}$ .