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on the High Energy
Circular Electron Positron Collider (CEPC)
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https://indico.ihep.ac.cn/event/11444/

Belle II beam background simulation

On behalf of the Belle II Beam Background Group

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KEK

Super KEKB

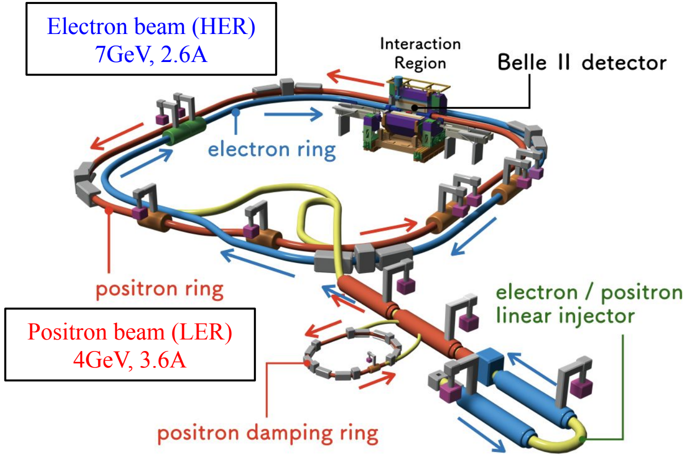
Belle II

- Recent achievements.
- Beam background sources & countermeasures.
- Collimation system description.
- Background simulation tools.
- Single-beam particle tracking.
- Improvements.
- Benchmark of the code.
- Collimator misalignment.
- Summary.

SuperKEKB: design parameters of the "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}		$cm^{-2}s^{-1}$

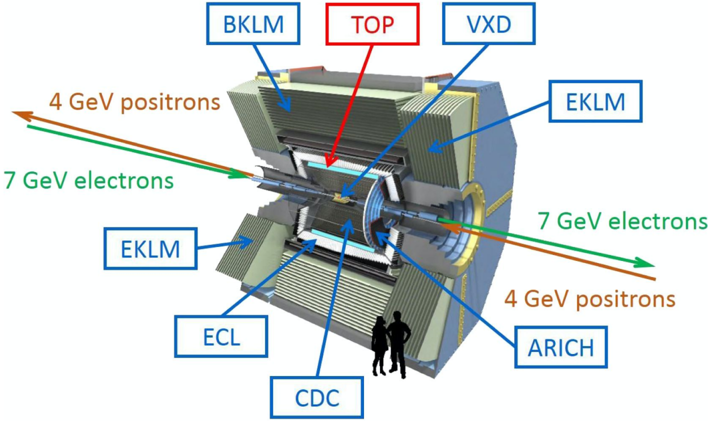
* *new design conditions extrapolated from the current machine/detector performance.*



- Over the last year, we have made many modifications to the background simulation.
- We have resolved the long-standing HER simulation problem (e.g., Touschek, see yellow fields).
- For the first time, data and MC agree within one order of magnitude: **data/MC ratio = 10^2-10^3 → 1-10**.
- This presentation is about how we achieved this significant improvement.

Sub-detector	BG type	Data/MC BEFORE LER / HER	Data/MC AFTER LER / HER
PXD	*Beam-gas*	1.4 / 6.5	2.6 / 4.8
	Touschek	1.7 / 251.7	2.5 / 0.6
SVD	*Beam-gas*	4.4 / 15.0	4.6 / 5.5
	Touschek	1.9 / 490.0	2.0 / 0.2
CDC	*Beam-gas*	5.5 / 50.0	5.5 / 12.0
	Touschek	4.5 / 80.0	4.0 / 1.2
TOP	*Beam-gas*	6.7 / 24.0	6.7 / 1.8
	Touschek	2.1 / 72.0	2.0 / 0.3

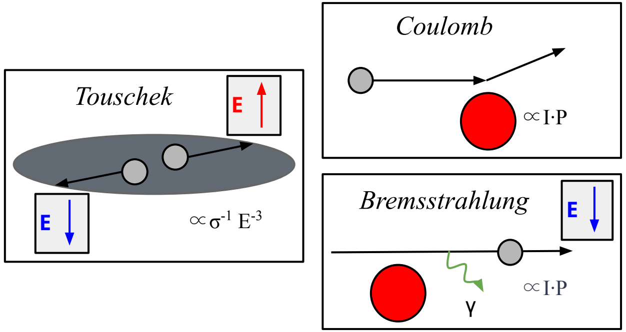
Belle II Detector



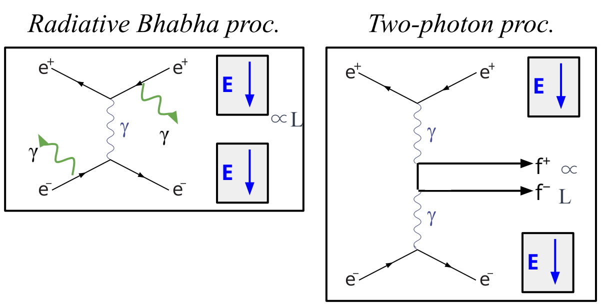
The SuperKEKB design has **x30-40 higher luminosity** than KEKB with **x1.5-2 higher beam currents** (*I*) and **x20 smaller vertical beta functions** (β^*) at the interaction point (IP). This implies higher beam-induced background in the Belle II detector.

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

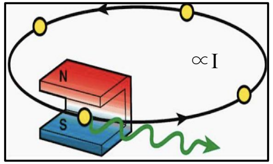
Particle scattering (Single-beam)



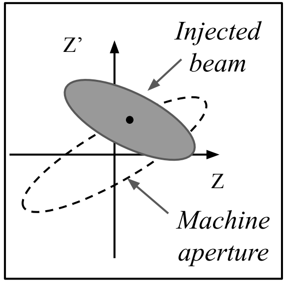
Colliding beams (Luminosity)



Synchrotron radiation



Injection



Off-axis injection mismatch
Optical parameters mismatch

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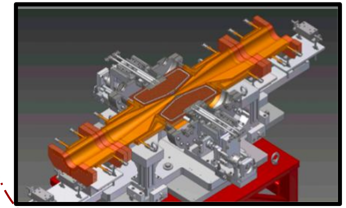
Particle scattering (Single-beam)

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

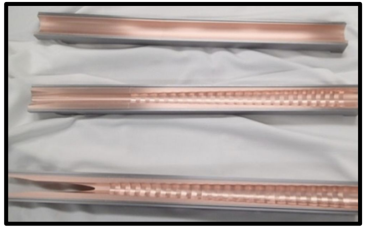


Colliding beams (Luminosity)

Steel and polyethylene shields *(neutrons flux reduction)*

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)*



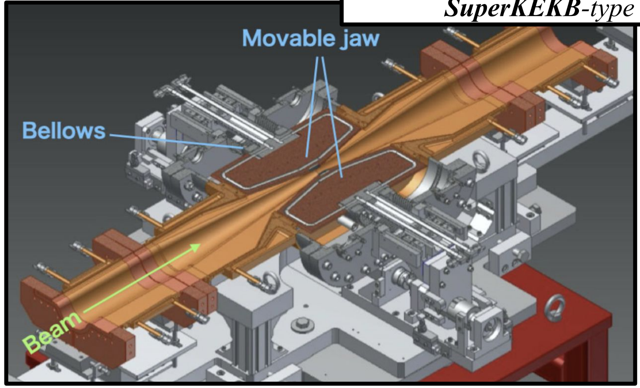
Injection

Damping ring for positrons *(to reduce the emittance)*, injection trigger veto

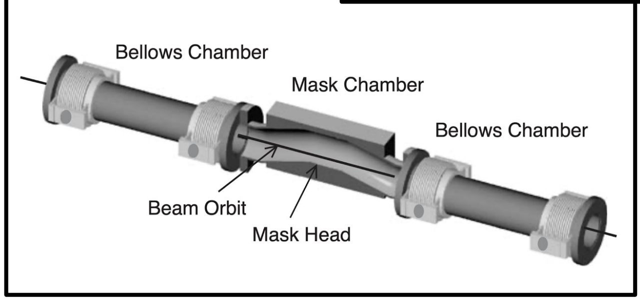
Collimation system

- **LER → 11 collimators (** 7 horizontal & 4 vertical**)** & **HER → 20 collimators (**11 horizontal & 9 vertical)
- SuperKEKB keeps beam currents constant by performing top-up (**continuous**) **injection**.

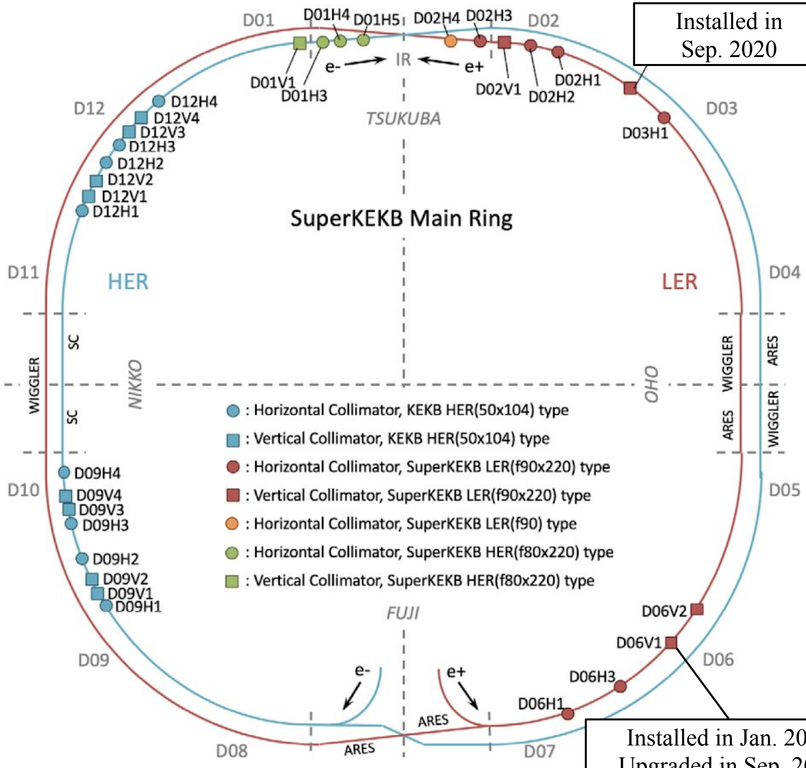
Two-sides collimator
***SuperKEKB**-type*



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



Installed in Sep. 2020



Installed in Jan. 2020
Upgraded in Sep. 2020

The crucial & the most complicated part of the background simulation

- **Single-beam background:**
  - SAD (multi-turn particle tracking)
  - basf2/Geant4 (detector modeling)
- **Luminosity background:**
  - basf2/Geant4 (single-turn effect, colliding beams)
- **Synchrotron radiation background:**
  - basf2/Geant4 (close to the Belle II detector)

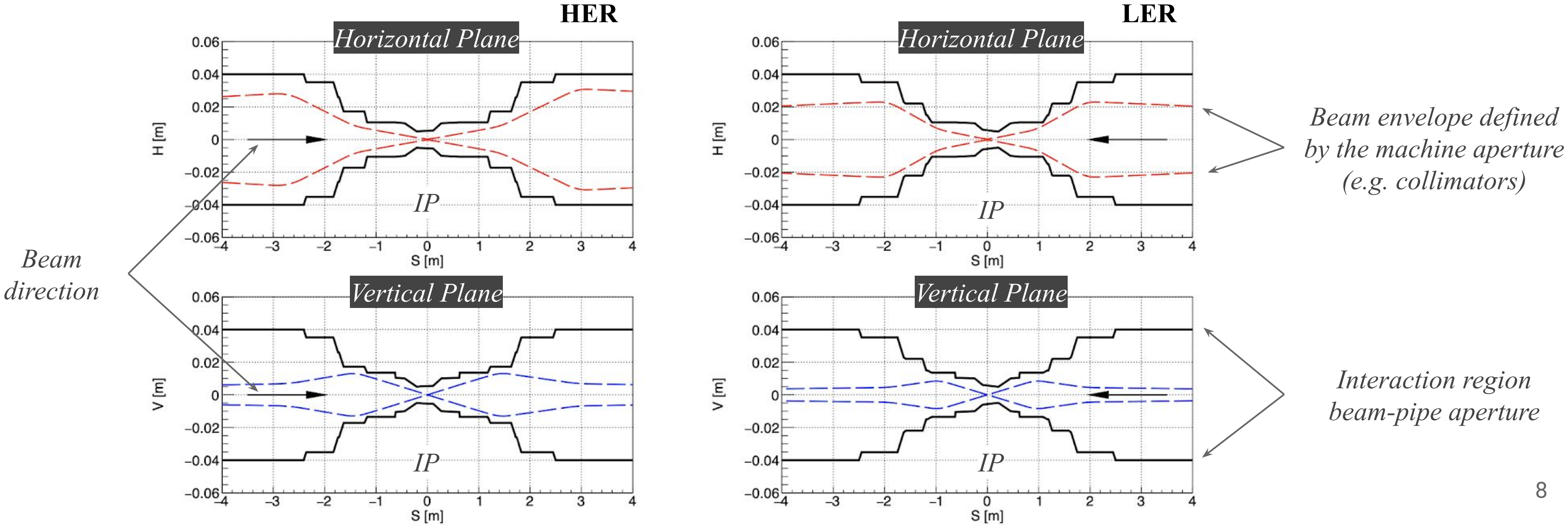
Strategic ***A***ccelerator ***D***esign (***SAD***) is a computer program complex for accelerator design. It has been developed at KEK since 1986.

Functionality:

- Design of accelerator beams.
- Optics calculation & matching.
- Emittance calculation.
- 6D full symplectic tracking of macroparticles.
- Mathematica-like scripting language.

The main SAD simulation settings:

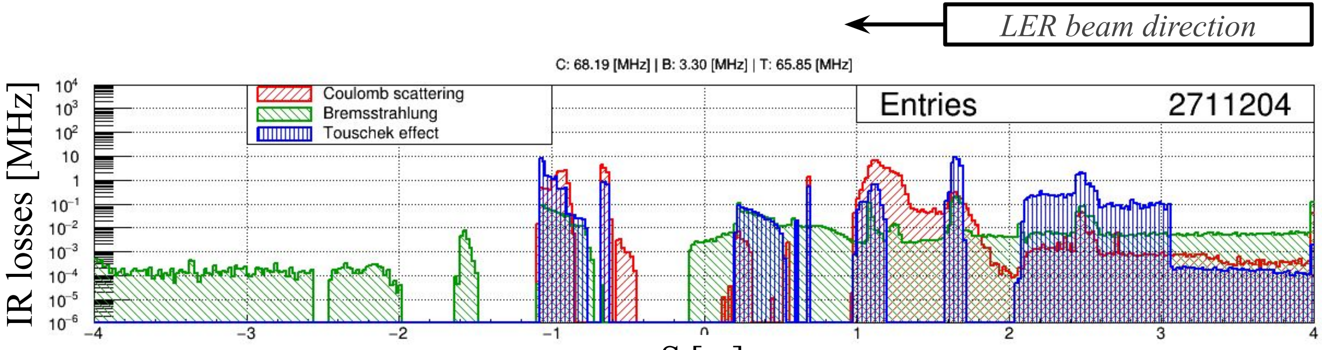
1. Start by splitting each ring into a set of 500 equidistant scattering points per each ring with randomly distributed bunches of scattered particles.
2. An intrinsic weight calculated using specific scattering theories is assigned to each particle.
3. The vacuum level is uniform around the machine at 1 nTorr (≈133 nPa).
4. Lost particle coordinates are collected after 1000 machine turns (synchrotron radiation & acceleration by radiofrequency cavities are ON).



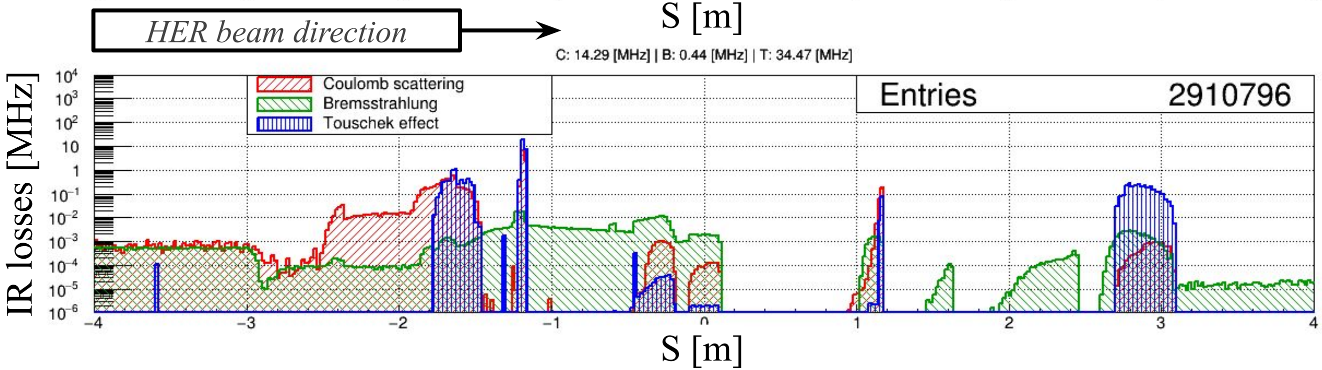
	LER	HER
$\beta^*_{X/Y}$ [mm]	**60.0/0.8**	**60.0/0.8**
CrabWaist strength [%]	**80**	**40**
Beam current [A]	**1.2**	**1.0**
No of bunches [bunches]	**1576**	**1576**

An example of the particle loss rate (in MHz) distribution at IR simulated in SAD:

- Beam losses are not uniformly distributed.
- For LER, Beam-gas BG is at the same level as Touschek, while for HER, it is twice lower.
- Beam lifetime is mainly defined by the Touschek losses.



Coulomb IR losses:	68.19 ± 0.89	[MHz]
Brems IR losses:	3.30 ± 0.03	[MHz]
Touschek IR losses:	65.85 ± 1.43	[MHz]
Coulomb lifetime:	32.55 ± 1.25	[min]
Brems lifetime:	2325.0 ± 8.0	[min]
Touschek lifetime:	13.93 ± 0.04	[min]



Coulomb IR losses:	14.29 ± 0.26	[MHz]
Brems IR losses:	0.44 ± 0.01	[MHz]
Touschek IR losses:	34.47 ± 3.21	[MHz]
Coulomb lifetime:	242.58 ± 12.45	[min]
Brems lifetime:	7872.0 ± 50.0	[min]
Touschek lifetime:	44.28 ± 0.55	[min]

Old tracking scheme:

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

New tracking scheme:

- track stray particles from collimator to collimator - *tracking by segments*;
- apply collimator mask and store 6D coordinates;
- continue to track survived particles;
- record loss position.

Benefits:

- allows to study the beam dynamics turn by turn;
- greatly reduced CPU time for the collimator optimisation (days → hours).

Goals:

- reduction of the BG level at the interaction region (IR);
- ensure beam losses occur mainly at collimators.

Bottlenecks:

- aggressive closing of the mask:
  - degradation of the injection efficiency (IE);
  - very short beam lifetime;
  - increase of local losses at collimators (activation).
- wide open collimators:
  - the Belle II BG level increase.

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

Method I:

(i) The optics phase-advance analysis (so-called *betatron collimation*) - a half-integer phase-advance between IR and a given mask is the most effective.
(ii) At a low beam current an accurate **manual tuning of each mask** one by one. Monitoring IE and IR background.

Pros & Cons:

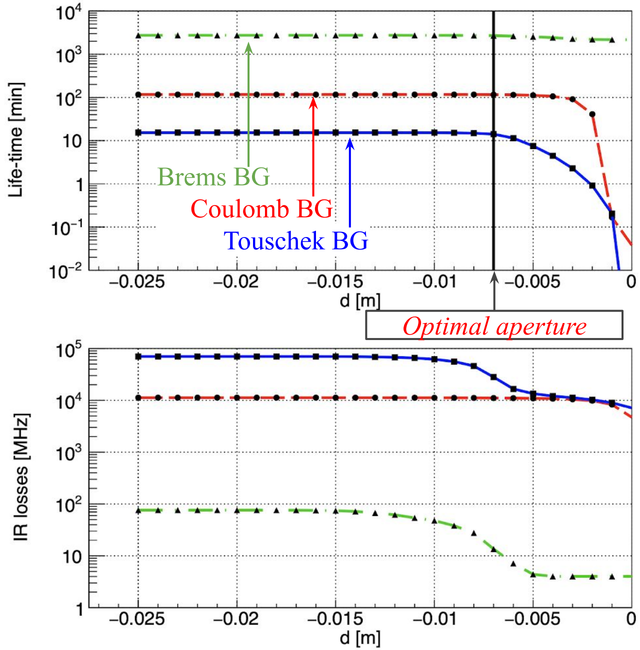
(+) a real machine & detector response;
(−) time-consuming & does not provide the most advantageous settings → many degrees of freedom (11 + 20 collimators).

Method II:

(i) A Monte-Carlo simulation of the single-beam background at a wide-open collimator aperture, collecting beam history (*online* simulation) using SAD tracking segmentation approach.
(ii) A **linear scan for each mask**, keeping a constant beam lifetime and lowest IR losses (*offline* simulation) using ROOT/C++-based scripts.
(iii) Bunch current limitation check due to the Transverse Mode Coupling Instabilities (TMCI, head-tail, wake-field effects [https://accelconf.web.cern.ch/e00/PAPERS/TUP4A12.pdf]).

Pros & Cons:

(+) the optimal settings in a few hours for a single-beam BG suppression → a guideline for the machine operator;
(−) does not take into account injection steering errors which limits the aperture of the mask due to the beam-lifetime.

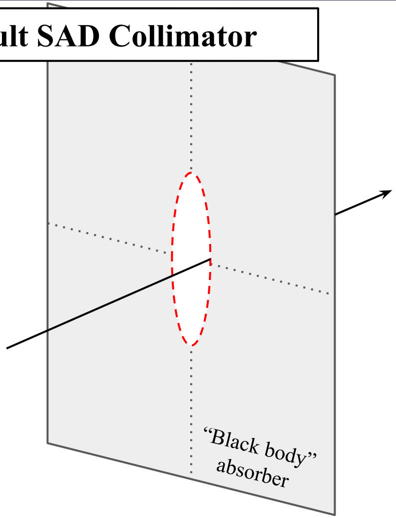


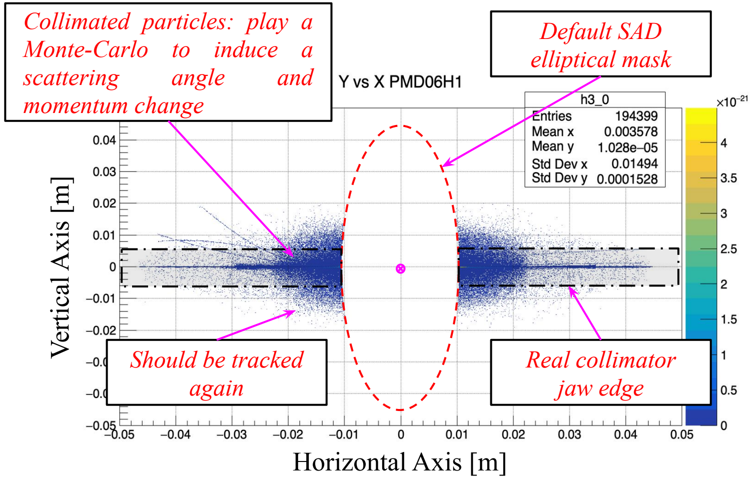
Offline aperture scan. **Top**: beam lifetime as a function of the collimator aperture. **Bottom**: IR BG as a function of the collimator aperture.

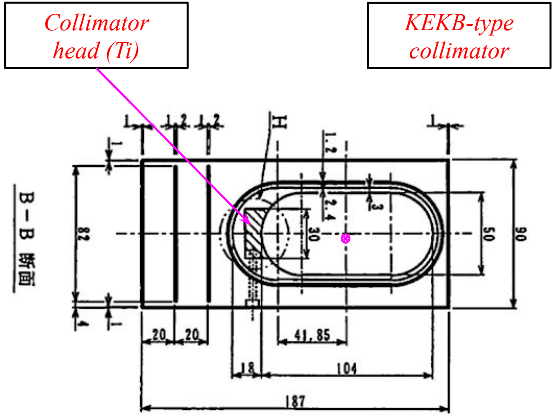
$$I_{\text{thresh.}} = \frac{C_1 f_s E/e}{\sum_j \beta_j k_j(\sigma_z, d)}$$

Limitation of a single-bunch current by a half-width of the mask (d) to avoid TMCI.

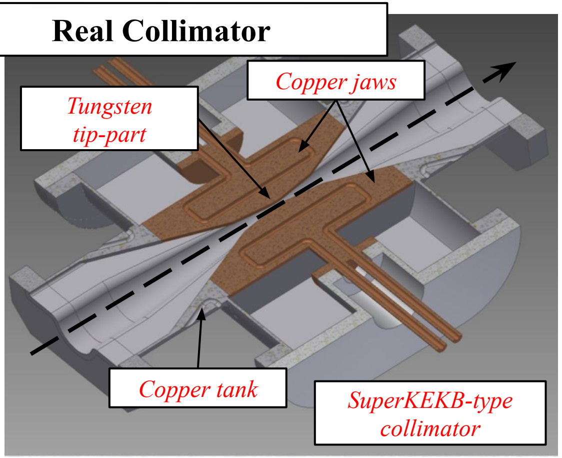
Default SAD Collimator







Real Collimator



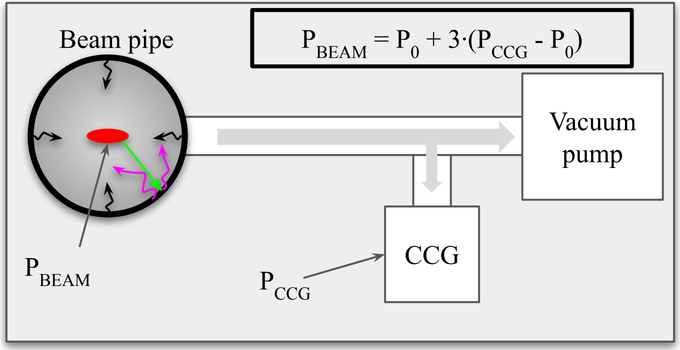
- **Default:** the collimator mask does not reproduce a realistic collimator structure. It causes stray particle losses in the transverse plane in the region **outside the real collimator**.

- **Improved:** a realistic shape of the collimator jaws is implemented. Particles outside the edge of the jaws are **tracked again** until they will be lost somewhere in the ring.

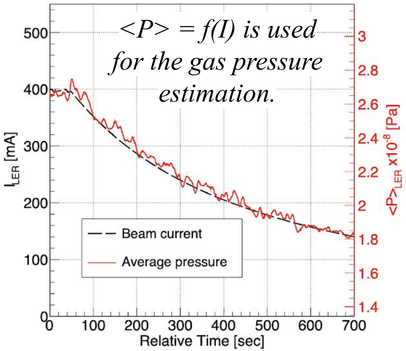
An initial elliptical mask is a good approximation for the race-track shape of the KEKB (D09, D12) collimator jaw.

An 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 since the collimators are far enough from the interaction region.

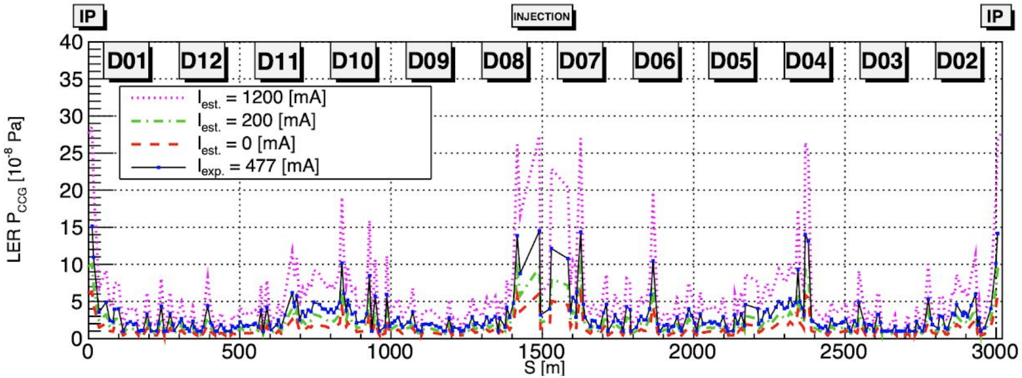
- There are ~300 Cold Cathode Gauges (CCG) around each ring.
- The actual beam-pipe gas pressure distribution is not uniformly constant around the ring P = *f*(position , current).
- CCG value saturation (10^{-8} Pa) affects <P> calculation (mainly for HER).
- To calculate gas pressure at the center of the beam-pipe (P_{BEAM}), P_{CCG} has to be scaled (see left plot, where P_0 − base pressure).



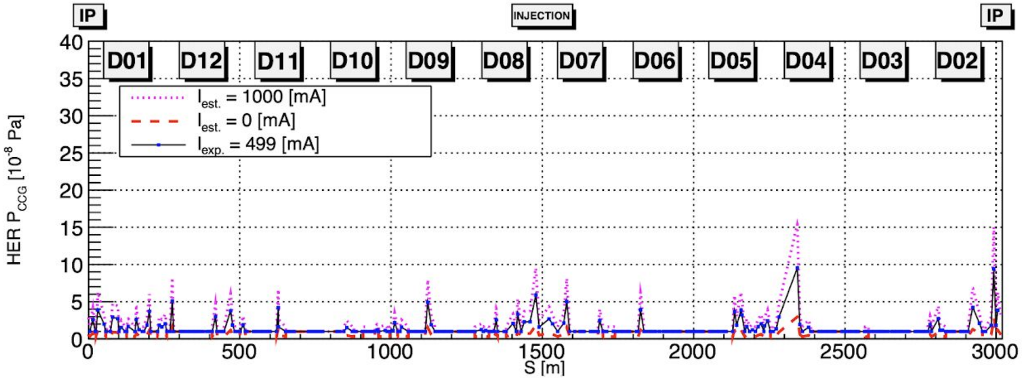
Schematic drawing of the vacuum system for the gas pressure measurements at SuperKEKB.



Behaviour of the beam current and average gas pressure during the beam pressure decay w/o injection.



LER



HER

Goal: to validate the collimator simulation in detail.

Method: measure dose rate at interaction region versus collimator aperture.

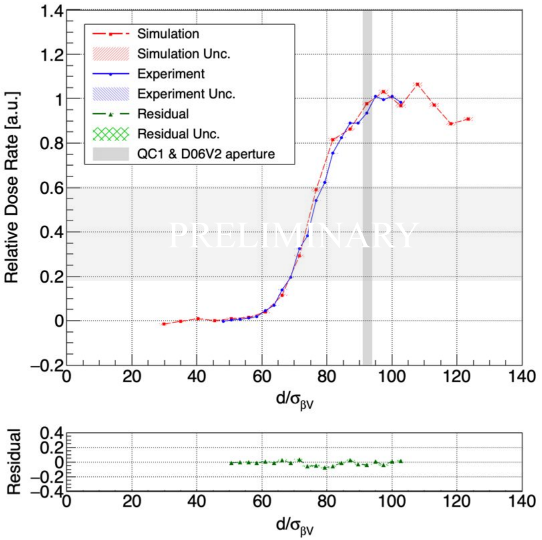
D06V1 − most recently installed collimator, Tantalum head was recently upgraded with a Low-Z material (Graphite).

D02H4 − collimator closest to IR, tip-scattering can reach Belle II.

Setup: Belle II HV - OFF; I_{LER} = 200mA; Continuous injection; 978 bunches; a step of the aperture scan = 0.2 mm ($5\sigma_\beta \rightarrow$ D06V1 & $1\sigma_\beta \rightarrow$ D02H4); Physics Run collimation system settings.

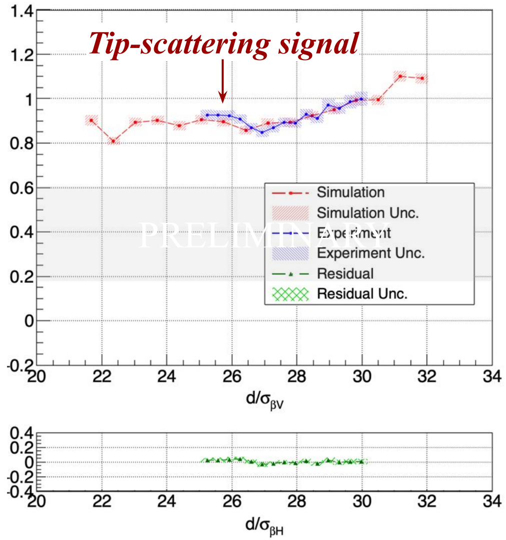
Result: good agreement between experiment and simulation, thanks to all implemented features discussed above.

D06V1 - vertical collimator

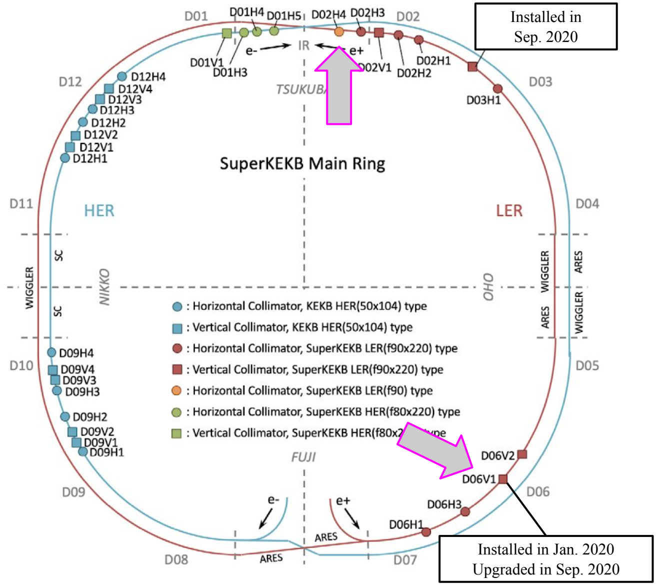


QCS Forward Diamonds (~60cm upstream IP)

D02H4 - horizontal collimator

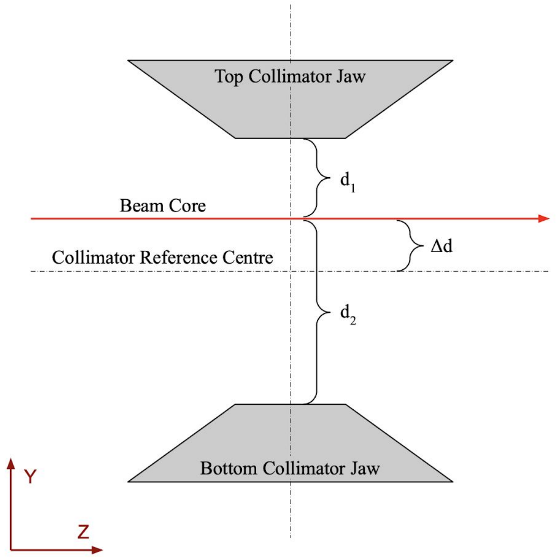


Beam-pipe Diamonds (±10cm from IP)

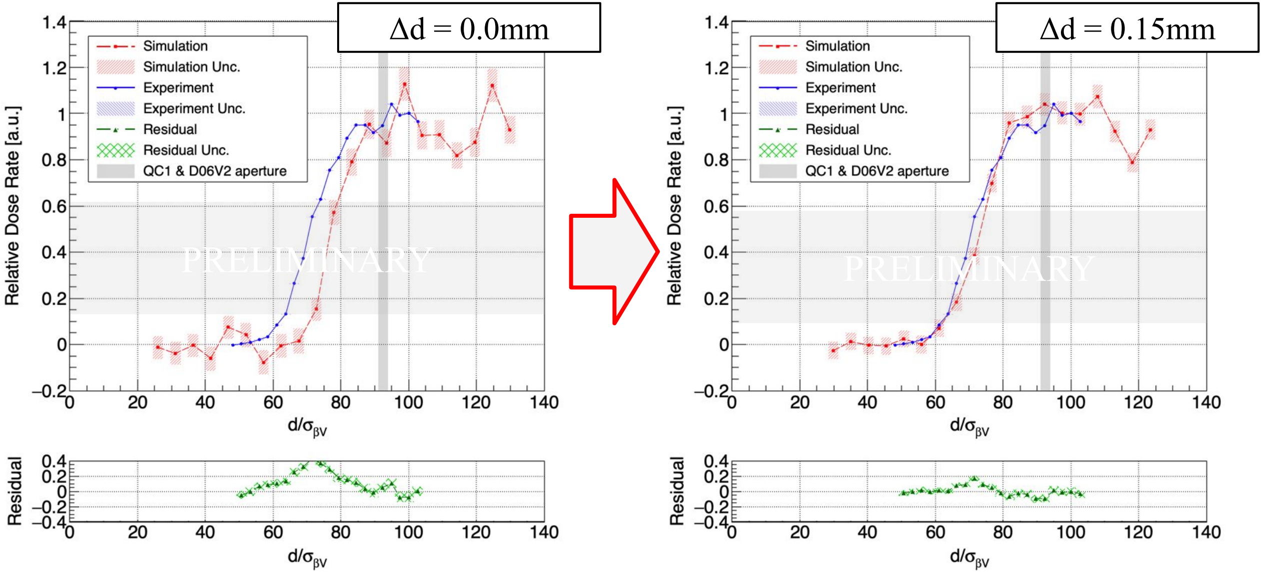


Collimator misalignment

- Simulation suggests **a possible misalignment of the collimator** with respect to the beam centre.
- Performing a set of simulations with different offsets, one can find the **physical shift** of the collimator chamber.



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)

- A new multi-turn particle tracking software framework based on SAD was developed.
- Several additional refinements (realistic gas pressure distribution, collimator profile, tip-scattering, and updated IR geometry) were also implemented.
- This led to significantly (up to factor 100-1000) improved agreement between measured and simulated beam backgrounds.
- Comparing simulated and experimental collimator scans appears sensitive to collimator misalignments.
- The new framework is used extensively at KEK for further collider optimisation and background mitigation towards design luminosity.

Thanks for your attention!