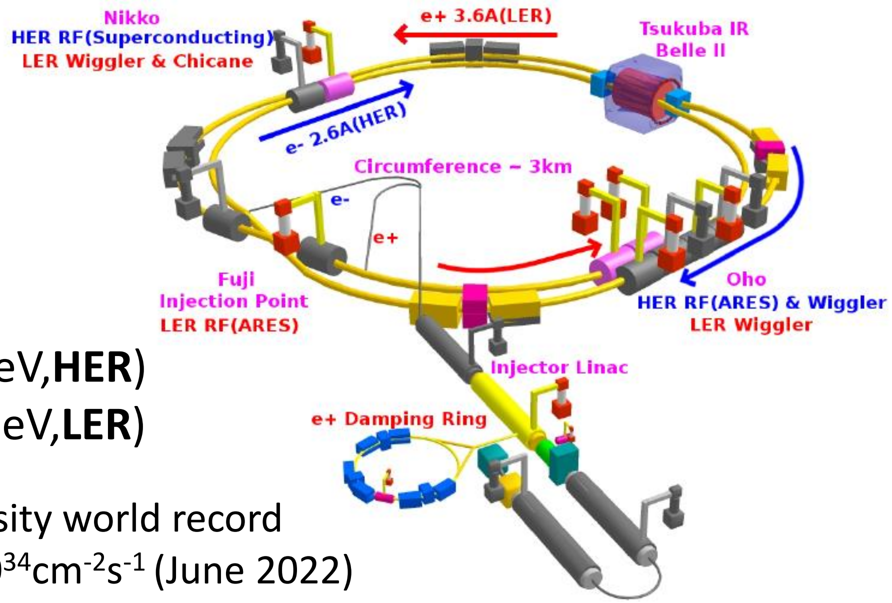
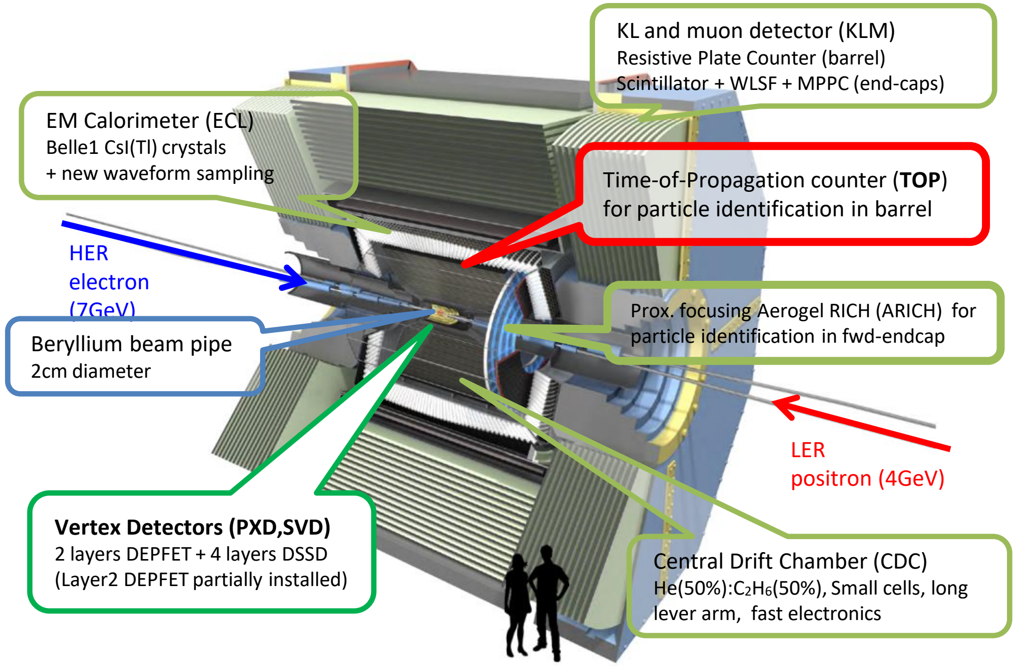
SuperKEKB



e- (7GeV,**HER**)
e+ (4GeV,**LER**)

Luminosity world record
$4.7 \times 10^{34} cm^{-2}s^{-1}$ (June 2022)

Belle II

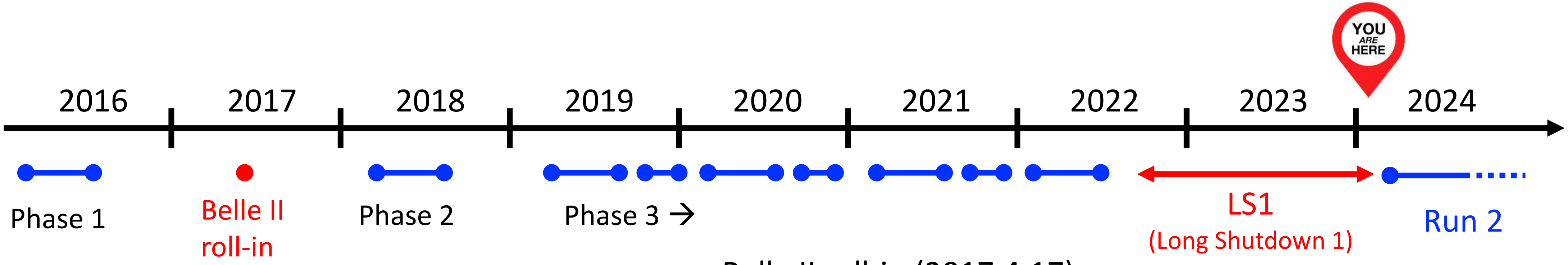


SuperKEKB beam background and countermeasures

Hiroyuki Nakayama (KEK), on behalf of
SuperKEKB/Belle II collaboration

hiroyuki.nakayama@kek.jp

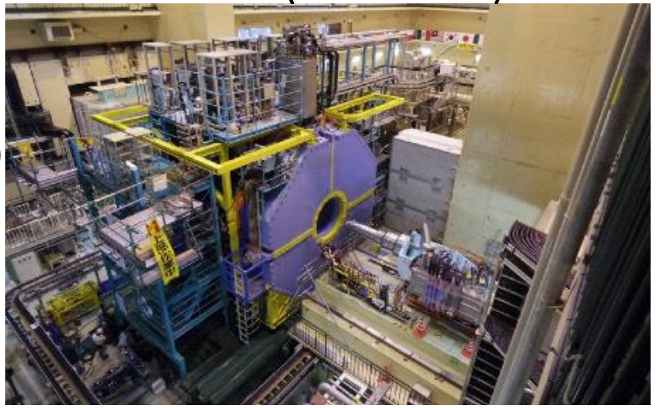
SuperKEKB/Belle II Operation History



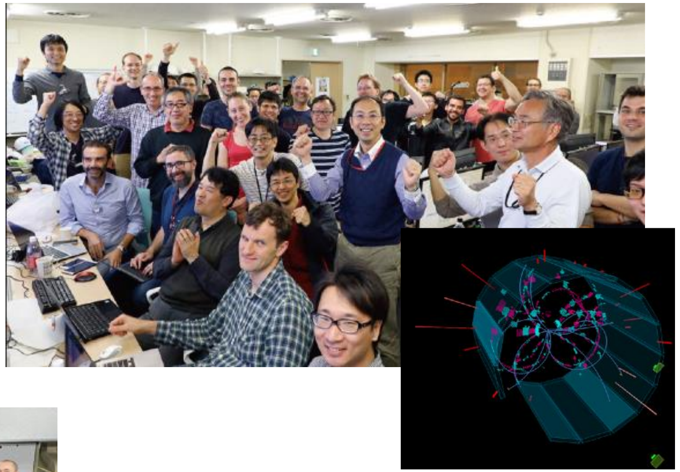
QCS: final focusing system

- Phase 1 (w/o QCS/Belle II)
  - Accelerator tuning w/ single beams
  - Background machine studies (BEAST II)
- Phase 2 (w/ QCS/Belle II, but w/o VXD)
  - Verification of nano-beam scheme
  - Understand beam background
  - Collision data w/o VXD
- Phase 3 (w/ all detectors, 2019 spring~)
  - Production of physics data
  - Investigation for higher luminosity
- The new run after LS1 will start in early 2024

Belle II roll-in (2017.4.17)

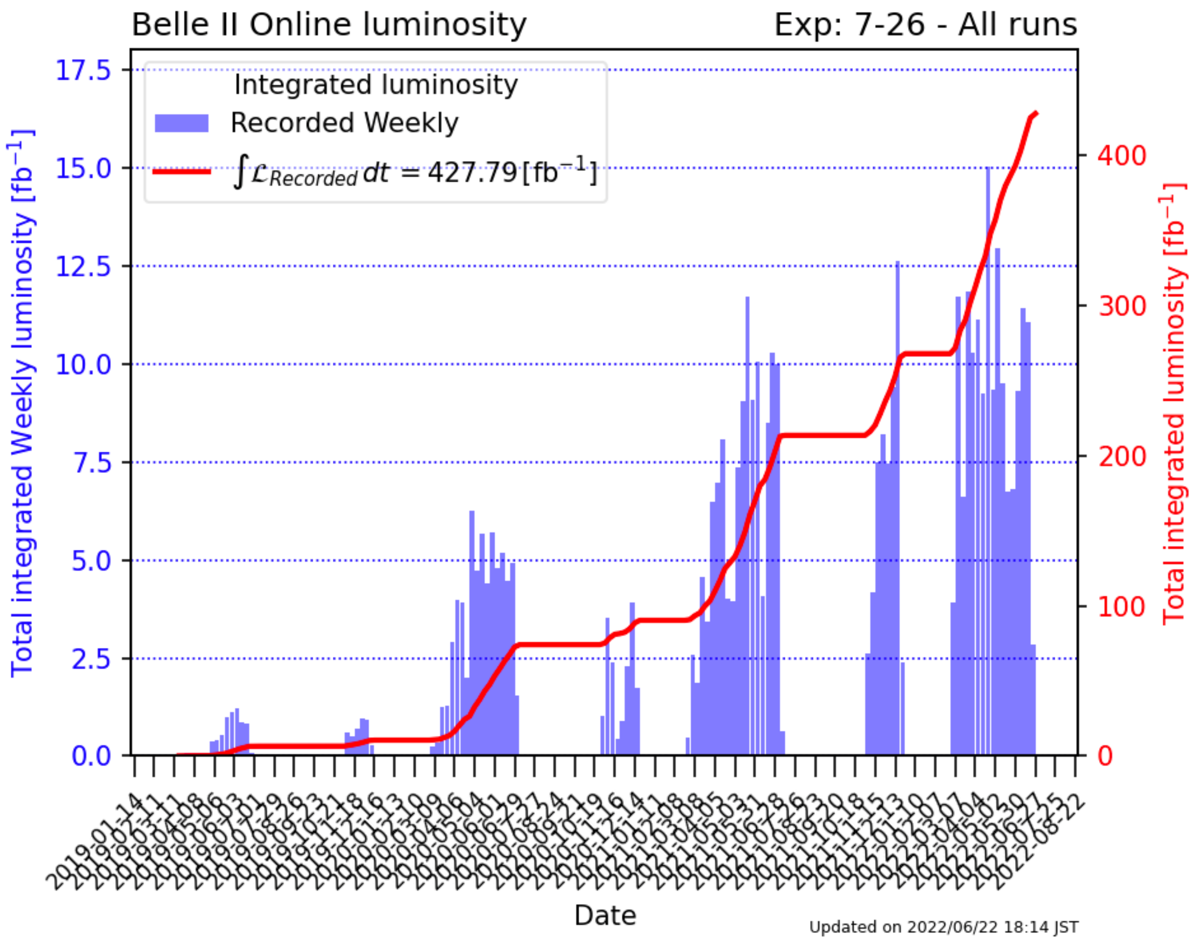


First collisions (2018.4.26)



Phase 3
Start of physics run
(2019.3.25)

Luminosity achievements before LS1



- During ~3 years of operation before the Long Shutdown 1 (LS1), Belle II collected the integrated luminosity of **424 fb^{-1}**, about a half of Belle-I dataset integrated over ~10 years of operation

- The maximum instantaneous luminosity reached **4.7 x 10^{34}/cm2/s**, a factor 2 larger than the KEKB record (2.1 x 10^{34}/cm2/s).

  ~x4 of the PEP-II record (1.2 x 10^{34} /cm2/s)

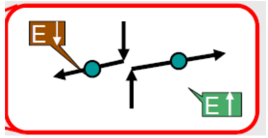
- The luminosity record is achieved at lower beam currents than KEKB, highlighting the effectiveness of the nano-beam collision scheme of SuperKEKB

Going back to 2010, when we started realistic design of SuperKEKB/Belle II …

Beam background at SuperKEKB

- Beam-induced background (beam BG) is dangerous for SuperKEKB/Belle II
- Beam BG determines **survival time** of Belle II sensor components and might lead to **severe instantaneous damage**
- It also increases **sensor occupancy** and irreducible analysis BG

Touschek



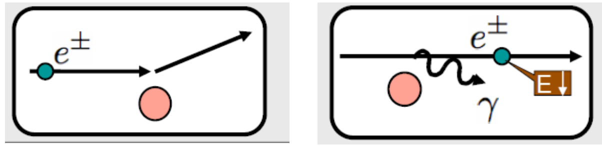
- SuperKEKB Beam BG sources

  - *Single-beam BG*: Touschek, Beam-gas Coulomb/Bremsstrahlung, Synchrotron radiation, injection BG

  - *Luminosity BG*: Radiative Bhabha, two-photon BG, etc..

Beam-gas

Coulomb Brems



Lumi-BG is now smaller than single-beam BGs, but will dominate at the full design current

Rad. Bhabha: $e^+e^- \rightarrow e^+e^-\gamma$
Two photon: $e^+e^- \rightarrow e^+e^-e^+e^-$

How to cope with beam BG?

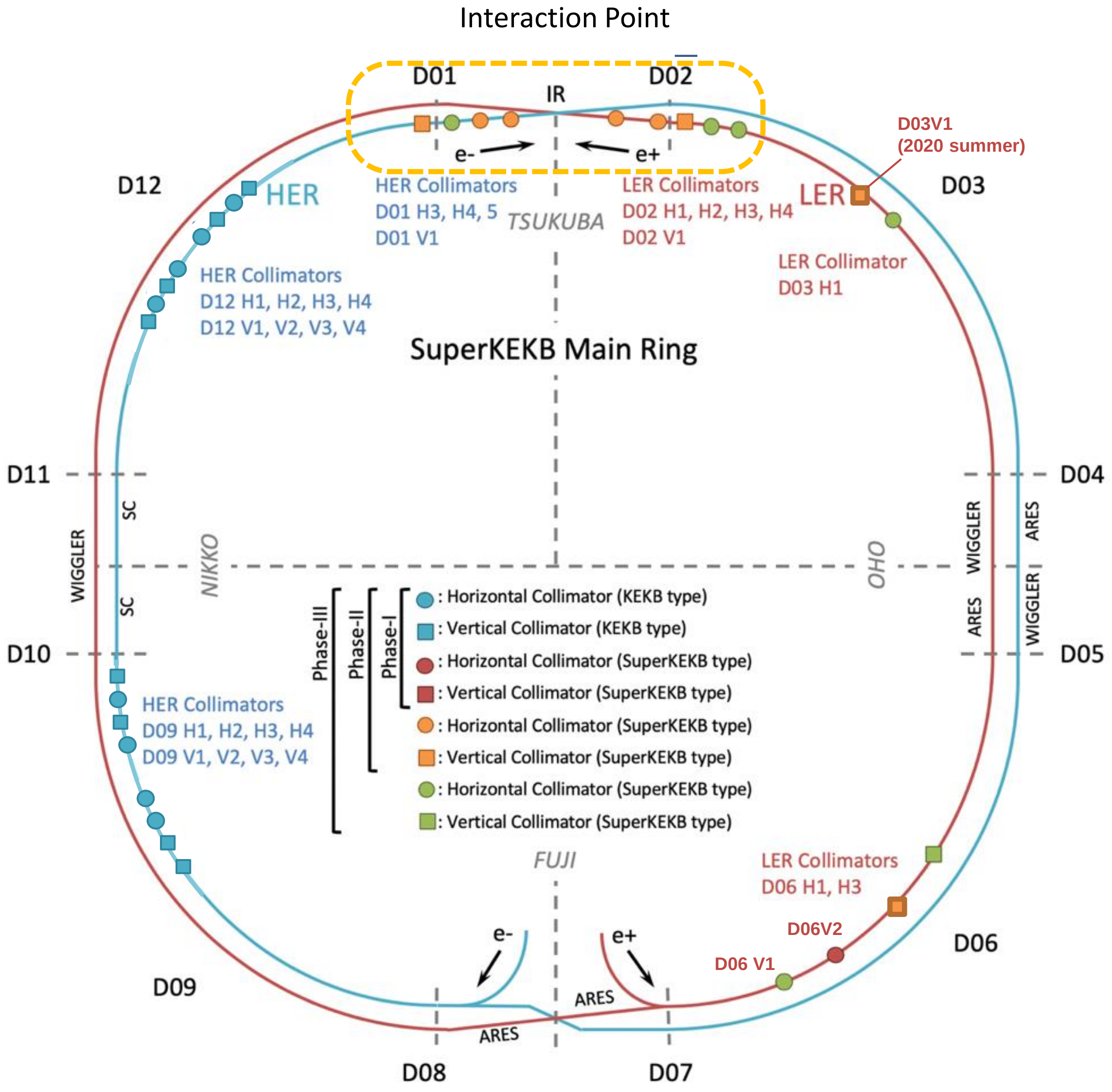
1. Movable collimators in the main ring
   – Cut beam tails/halos: stop stray particles before they reach the Belle II detector region

2. Thick tungsten shield around the major beam loss spots near the detector
   – Showers generated inside the final focus quads are stopped before entering Belle II physics acceptance
   – Careful design of Machine-Detector Interface(MDI) region is a key

Beam background mitigation #1

Movable collimator

SuperKEKB Collimators



e- (7GeV,**HER**)
e+ (4GeV,**LER**)

As of 2022,

31 movable collimators installed

LER(11):

- 7 horizontal, 4 vertical "SuperKEKB type" collimators
  - horizontal: D06H1, D06H3, D03H1
    D02H1, D02H2, D02H3, D02H4
  - vertical: **D06V1**, D06V2, D03V1, **D02V1**

HER(20):

- 3 horizontal, 1 vertical "SuperKEKB type" collimators
  - horizontal: D01H3, D01H4, D1H5
  - vertical: D01V1
- 8 horizontal, 8 vertical "KEKB type" collimators
  - horizontal: D12{H1,H2,H3,H4},D09{H1,H2,H3,H4}
  - vertical: D12{V1, V2, V3, V4},D09{V1,V2,V3,V4}

Horizontal collimators → Touschek BG
Vertical collimators → Beam-gas Coulomb BG

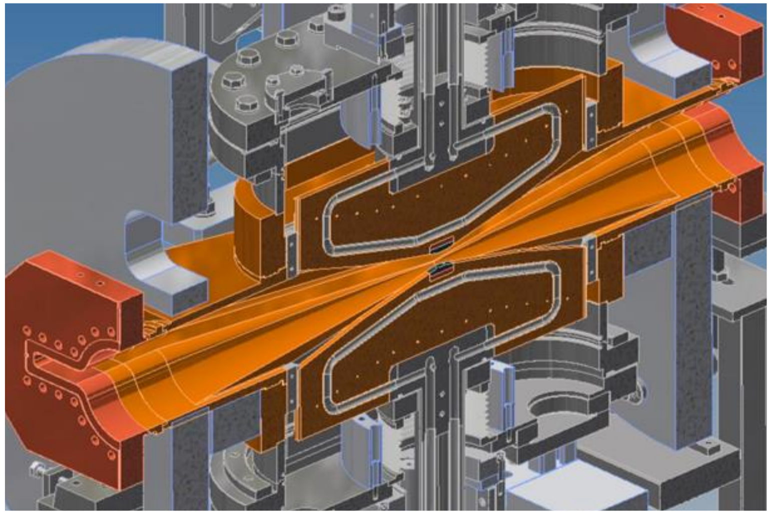
Vertical Collimators: very narrow

- To reduce beam-gas Coulomb IR loss, we need very narrow (1~2mm half width) vertical collimators
- TMC instability is an issue: low-impedance head design is important, and collimators should be installed at the position where beta_y is rather small

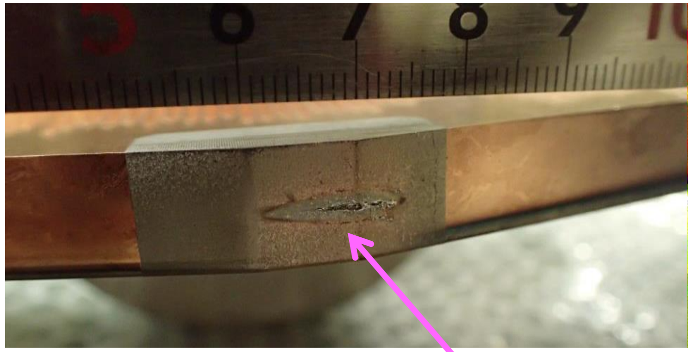
  (*) "Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability", H, Nakayama et al, *Conf.Proc.C* 1205201 (2012) 1104-1106

- Precise head control (Δd~50um) is required, (IR loss is quite sensitive to the collimator width)
- Collimator head should survive severe beam loss
  - Tungsten (or Tantalum) jaws were severely damaged and replaced several times due to large beam loss
  - Low-Z head tip (carbon) was installed in 2020 autumn run but its impedance was found out to be too large (Beam size blow up due to TMC instability was observed)
  - More robust head are considered (MoGr, Ti, Ta+Gr)

SuperKEKB-type vertical collimator



Collimator head damaged by severe beam loss

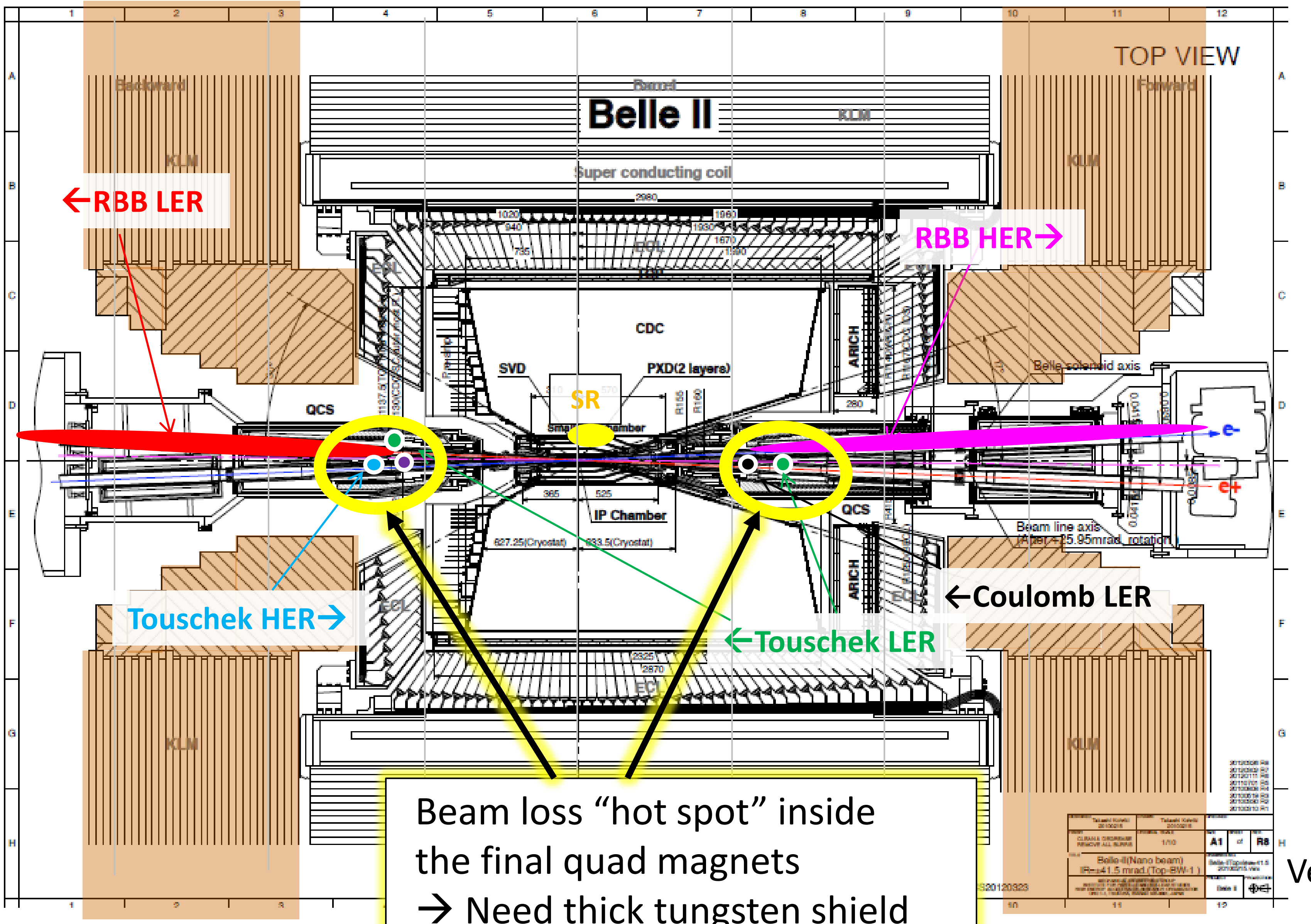


Scar along the beam line

Beam background mitigation #2

Shielding

Beam loss distribution inside Belle II detector

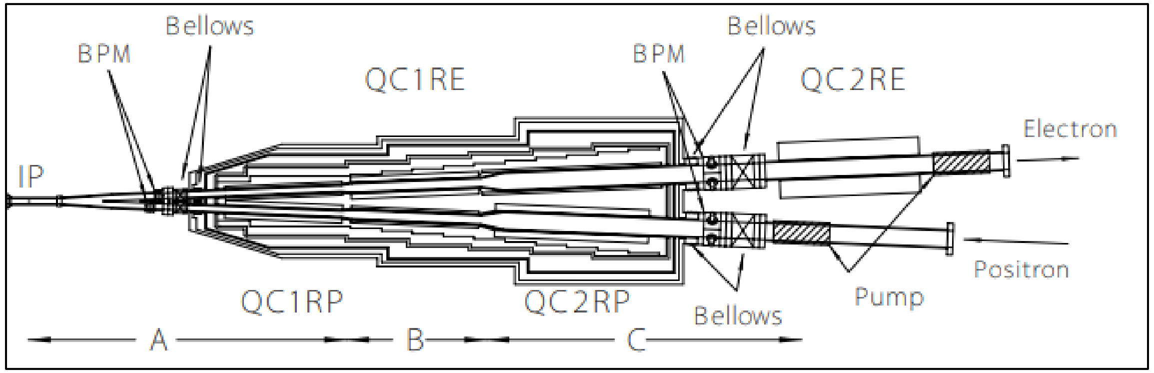


Beam loss "hot spot" inside the final quad magnets
→ Need thick tungsten shield

Ver. 2017.1.31

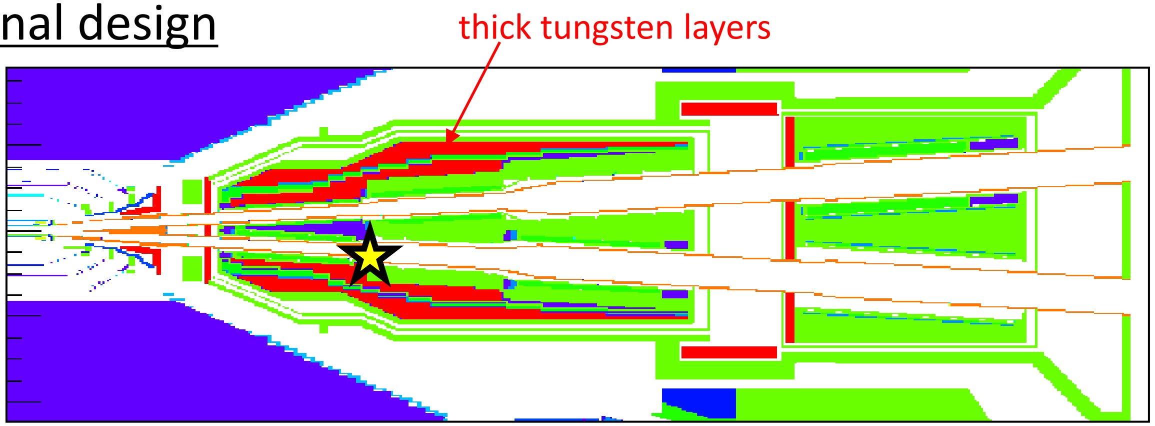
Thick tungsten shield inside final-focus cryostat

TDR(2010)



- TDR is prepared just after the change of SuperKEKB design concept (“High current ” → “Nano-beam”)
- Therefore, at that time, no beam background estimation was available for the “Nano-beam” optics
- No shield considered inside the cryostat

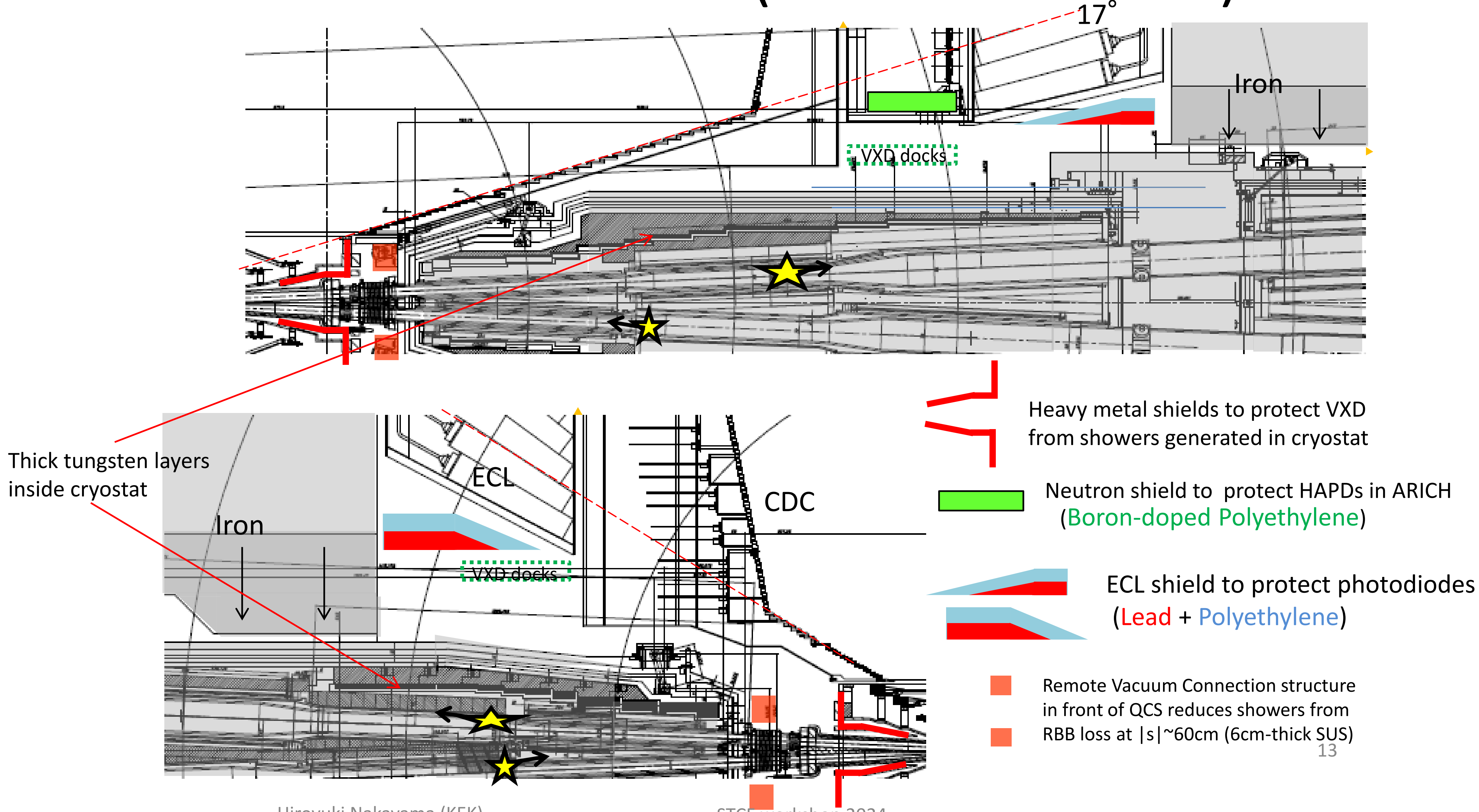
Final design



- As background simulation developed, we found a significant beam loss inside the final focus magnet
- I made a strong request to put as much heavy-metal shield as possible inside the cryostat
- It required major modification on the already-started cryostat fabrication process

Takeaway message: Reserve enough space for the BG shields between detectors and beam pipes!

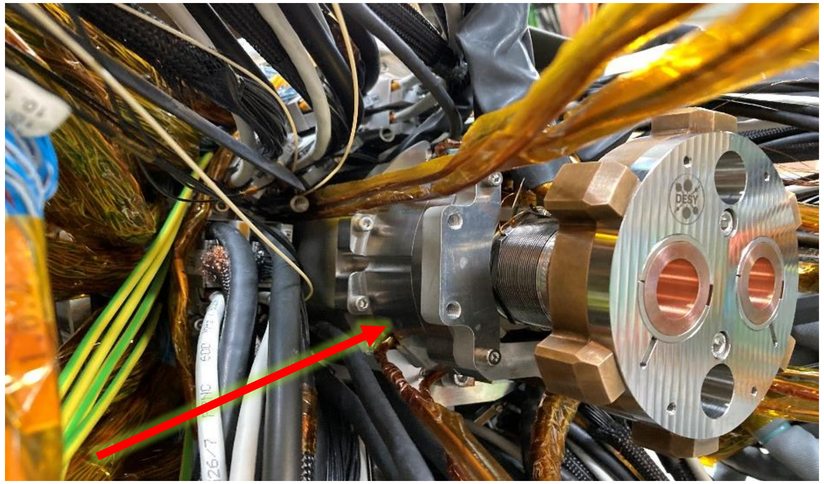
Other shields (for neutron etc..)

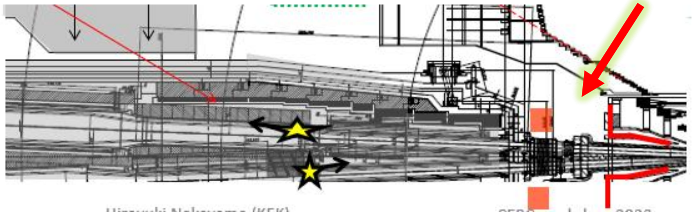


More shields installed during LS1

New !!

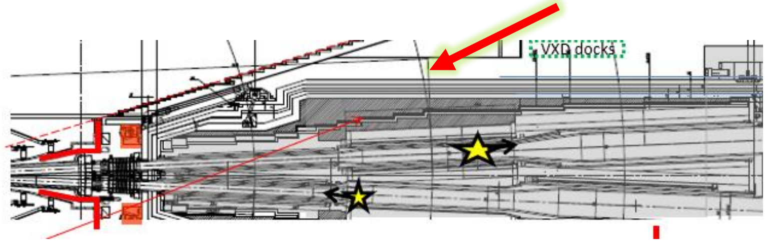
Bellows shield





New tungsten shield around the bellows pipes joining QCS cryostat and inner detector volumes. Careful 3D design was required for this, since remaining space was quite limited due many sensor cables occupying the area.

QCS neutron shield



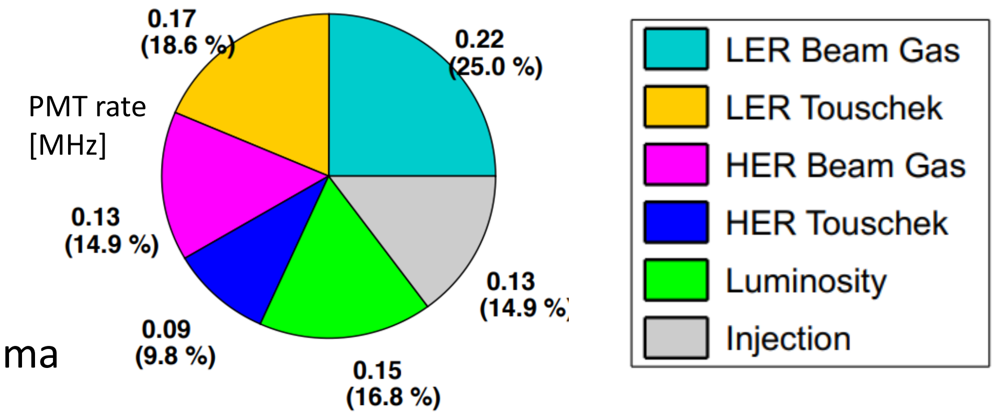
The shield made from HDPE plates covered by a boron sheet fills the small gap between QCS cryostat and detector volume outside.
The shield is expected to provide further mitigation of neutron flux entering Belle II detector.

Measurement of beam background
(2016 - now)

Belle II Beam Background in recent runs

- Belle II beam BG didn't limit beam currents in 2021 and 2022
  - Thanks to successful BG mitigation by collimators, vacuum scrubbing progress, etc..
  - However, it will be a problem at higher luminosity without further BG mitigation
- TOP counter is the most vulnerable sub-detector to beam backgrounds
  - Finite PMT photocathode lifetime, replacement work during long shutdown needed
  - Major contribution from LER beam-gas, LER Touschek, Luminosity BG, etc..

TOP background breakdown
during recent physics runs



K. Kojima

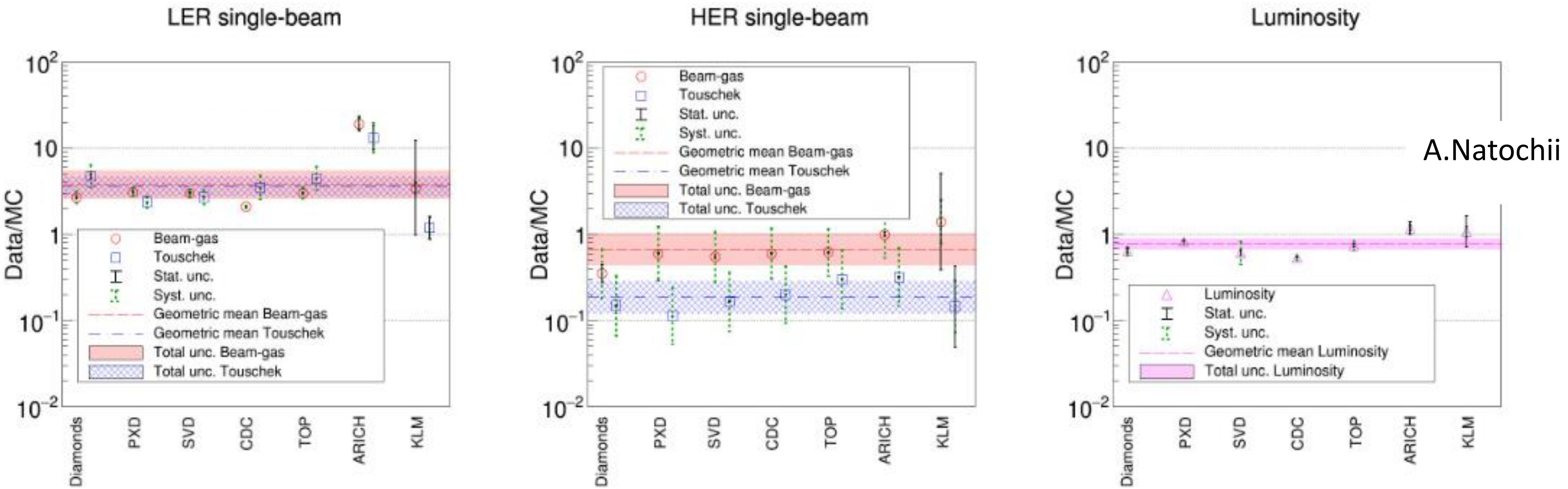
June 28, 2020
beta*y = 0.8mm

Input values
to calculate background rate.

$$I^{\rm HER} = 500~{\rm mA}$$
$$\sigma_y^{\rm HER} = 34~\mu{\rm m}$$
$$N_b^{\rm HER} = 978$$
$$I^{\rm LER} = 480~{\rm mA}$$
$$\sigma_y^{\rm LER} = 66~\mu{\rm m}$$
$$N_b^{\rm LER} = 978$$
$$\mathcal{L} = 1.5 \times 10^{34}~{\rm cm^{-2}s^{-1}}$$

e- (7GeV,**HER**)
e+ (4GeV,**LER**)

Data/MC ratio of each BG component

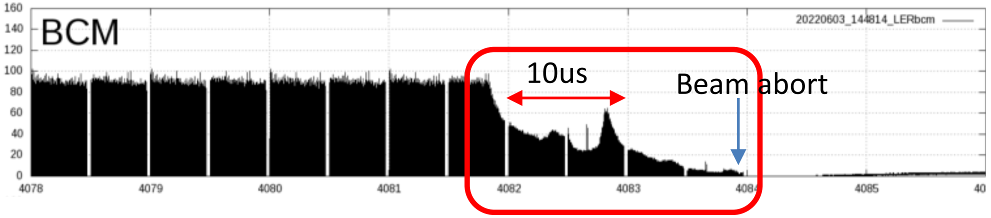


- Data/MC ratio is now within one order of magnitude from unity (with improved simulation)
- Measured lumi-BG stays consistent with prediction (will dominate at full luminosity)
- This confirms our good understandings on beam loss processes at SuperKEKB
- Those ratios are used to rescale simulated beam background rates toward higher luminosity

Issues: Sudden Beam Losses (SBL)

- Sudden beam loss (SBL) events
  - Very fast beam loss within few turns (= 20-30 us)
  - Lead to QCS quench, sensor/collimator damage
  - Seems to occur at higher (bunch) currents
  - Showstopper for high luminosity challenge
- The cause of SBL? -- still unknown
  - Beam-dust event? Beam instability? Arcing?
  - Find the initial beam loss location based on the precise beam loss timing recorded by various loss monitors along the ring.
  - Investigation ongoing in the framework of [international taskforce]
  - Our presentations at the [CERN Beam Dust Workshop] this summer
  - During LS1, we installed more sensors to better understand SBL events

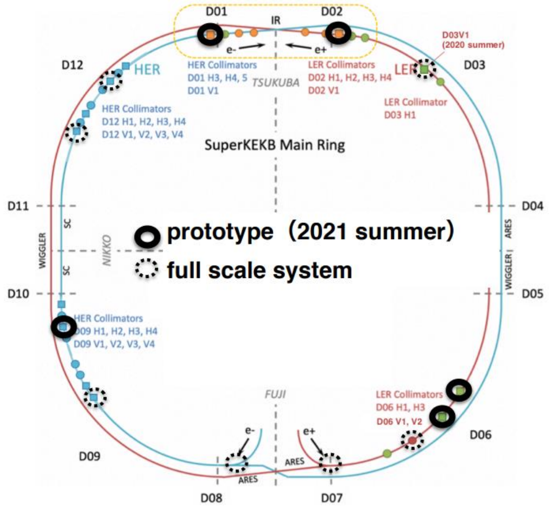
Bunch current monitor



>80% of stored beam lost within ~20us !!

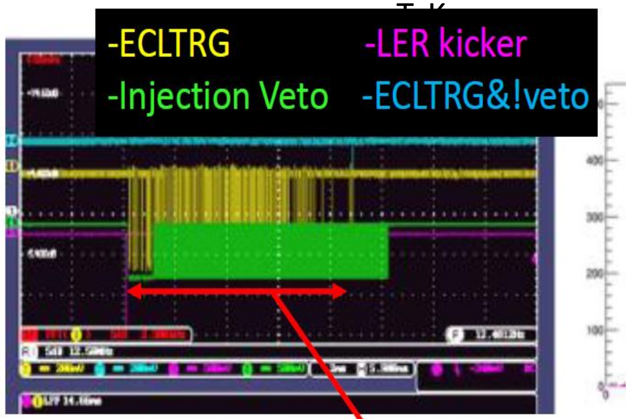

Collimator head damage due to SBLs

Beam loss monitors along the main ring



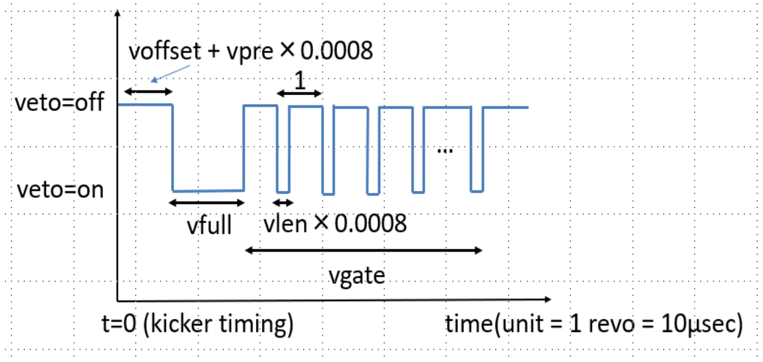
Issues: Injection BG duration

- Belle II DAQ applies trigger veto after each injections, since injected bunches become noisy for a while
- Typical duration of injection BG → LER: ~10ms, HER:~5ms
  - Corresponds to 5~10% (!) deadtime
- In 2022 runs, injection BG duration gets worse with squeezed beta*y (=0.8mm), higher beam currents, and after severe LER collimator damage, etc..
  - Larger BG observed even in recorded events (outside veto)
  - Impact on physics performance started to be seen
- To achieve more integrated luminosity, it is crucial to understand why the duration of injection BG is so long
- Several improvements in the injector chain (LINAC/BT) are implemented during LS1 and later



“Injection BG duration”

Injection veto window



Summary

- Beam background at SuperKEKB is dangerous and various countermeasures have been implemented
- Interaction region of SuperKEKB is carefully designed to mitigate beam background
- Machine studies carried out to measure beam background components have demonstrate the validity of our simulation
- To achieve the target luminosity, we need contribution from new people with novel idea/technology. Come and join us!

Job Opportunities

- We are looking for a term-limited assistant professor at KEK, working for the Belle II MDI group
  - https://www.kek.jp/en/jobs/ipns23-13e/ (deadline: Fed. 14th)
  - **Various research topics available**: conduct machine studies to mitigate beam background, estimate a physics performance degradation due to beam background, develop a ML-based optimization of beam injection tuning or collimator adjustment, etc..

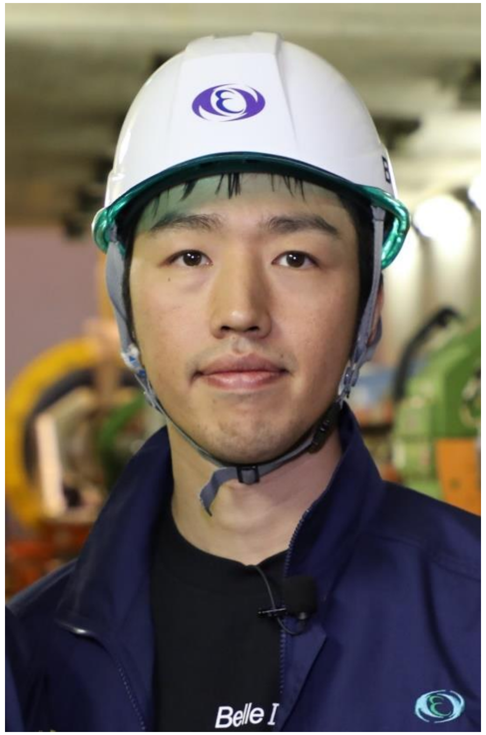
- SuperKEKB will resume beam operation soon. It’s a good opportunity for young generation to gain valuable experiences at the operating accelerator!

- If you’re interested (or if you know a good candidate), please contact me!
  - hiroyuki.nakayama@kek.jp

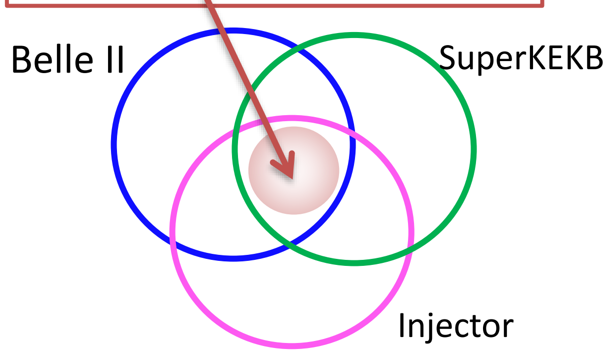
backup

Who is the speaker?

- Hiro Nakayama, associate professor at KEK, Japan
- Joined the Belle II collaboration in 2010
- Since then, I have been closely collaborating also with SuperKEKB colleagues
- Serve as a leader of “MDI (Machine-Detector Interface)” group in the collaboration
- The MDI group oversees not only the mechanical design of the interaction region, but also any challenges arising between Belle II detector, SuperKEKB main storage ring, and injector LINAC.



MDI group
(MDI= Machine-Detector Interface)



Ultimate goal:

More integrated luminosity

Key Objectives

- Higher instantaneous luminosity
- Increase effective beam time

Major strategies

- Squeeze beam size at IP
- Increase beam currents
- Reduce downtime due to troubles
- Minimize DAQ deadtime

Challenges

- Short beam life due to narrow dynamic/physical aperture at small beta*y optics
- Beam blowup at higher beam currents
- Poor **injection efficiency** due to instability of injection beam charge and quality (emittance blowup in BT)
- Non-optimal **collimator settings** due to poor injection quality, TMC instability, and head surface damage caused by severe beam loss
- **Beam background** impact on sensor lifetime and data quality for physics analysis
- Beam current limit due to RF power
- **Sudden Beam Loss** (SBL) events causing QCS quenches and severe collimator/sensor damage
- **Long injection BG duration** and large DAQ deadtime
- and so on…

topics covered by MDI activities

Major MDI-related improvements during LS1

- Installed **additional BG shields** (Bellows shield, QCS neutron shield)
- Reinforced neutron measurements on top of Belle II (to understand PXD PS trips)

- Installed a **Non-Linear Collimator** (NLC) to LER ring
- Modified injection chain (positron BT 1st arc) to **mitigate CSR effect** and suppress emittance

- Added more loss monitors and acoustic sensors to understand SBL events
- Added beam Orbit Recorders (BORs) to understand SBL events

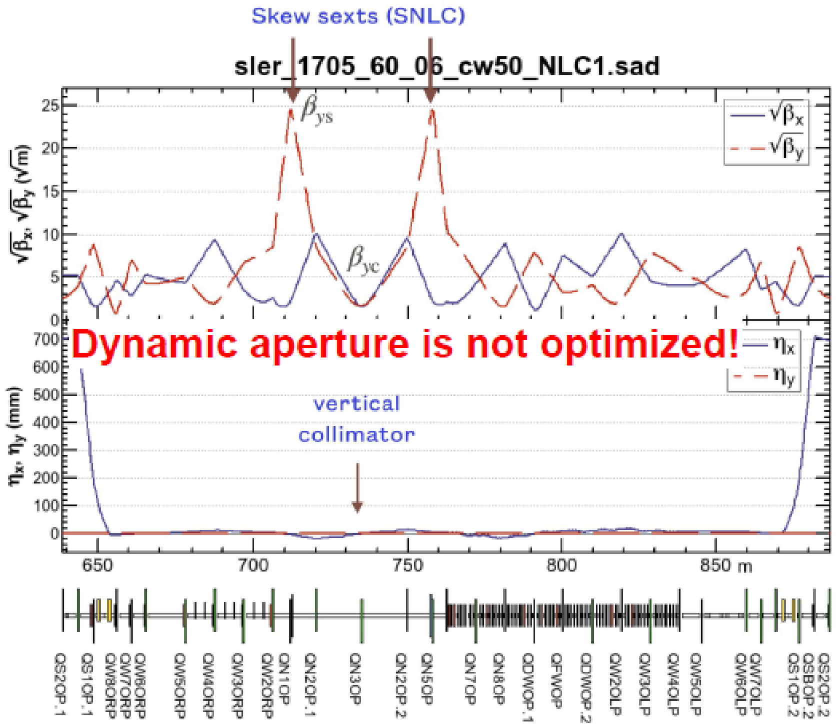
- Developed real-time BG monitor to support injection/collimator tuning
- Start investigation for using **Machine-learning technique** for machine tuning

Non-Linear Collimator(NLC)

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, $y_q = 10.0\,\mathrm{mm}$ at QC1 ($30\sigma_y$ with $\varepsilon_y/\varepsilon_x = 2\%$).
- It is equivalent to $y_s = y_q\sqrt{\beta_{ys}/\beta_{yq}} = 6.8\,\mathrm{mm}$ at the NLC skew sextupole SNLC.
- The sextupole kicks the beam vertically by

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

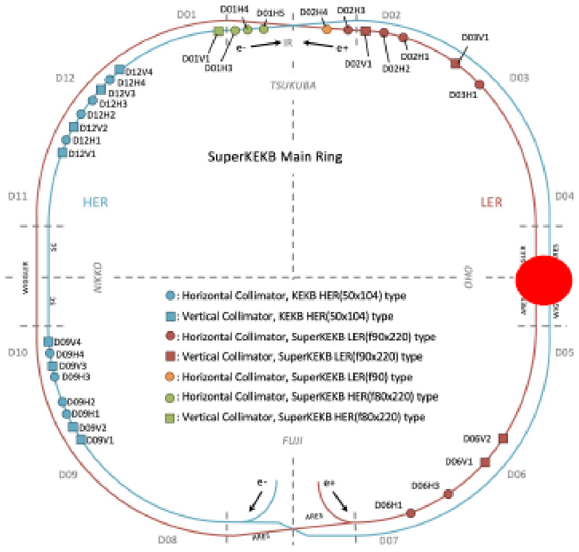
$$s' \equiv \frac{L_s}{B\rho}\frac{\partial^2 B_x}{\partial y^2}\,. \quad (2)$$

    - For instance, $s' = 6.0/\mathrm{m}^2$, $\Delta p_{ys} = 0.14\,\mathrm{mrad}$, 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: $\beta_{ys} = 570\,\mathrm{m}$, $\beta_{yc} = 2.9$ m.



NLC benefits

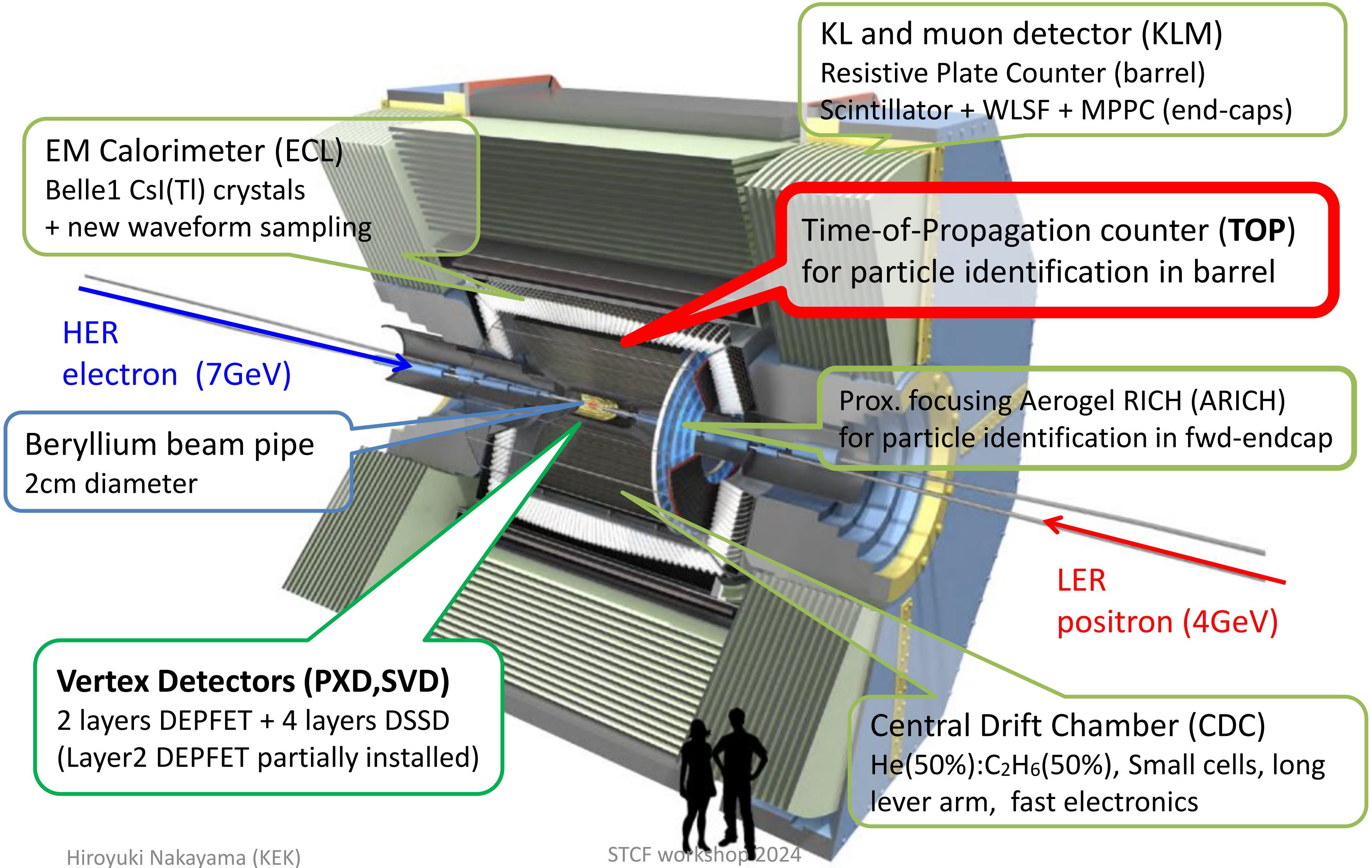
- Does not affect significantly the TMCI limit
  - May be tightly closed while other collimators may be opened
- Effectively suppresses Belle II backgrounds
  - Helps to control beam backgrounds leaving more margin for the injection background and other unexpected beam losses
- Collimates in both planes 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.*

BG measurements

Where's "TOP" in Belle II Detector



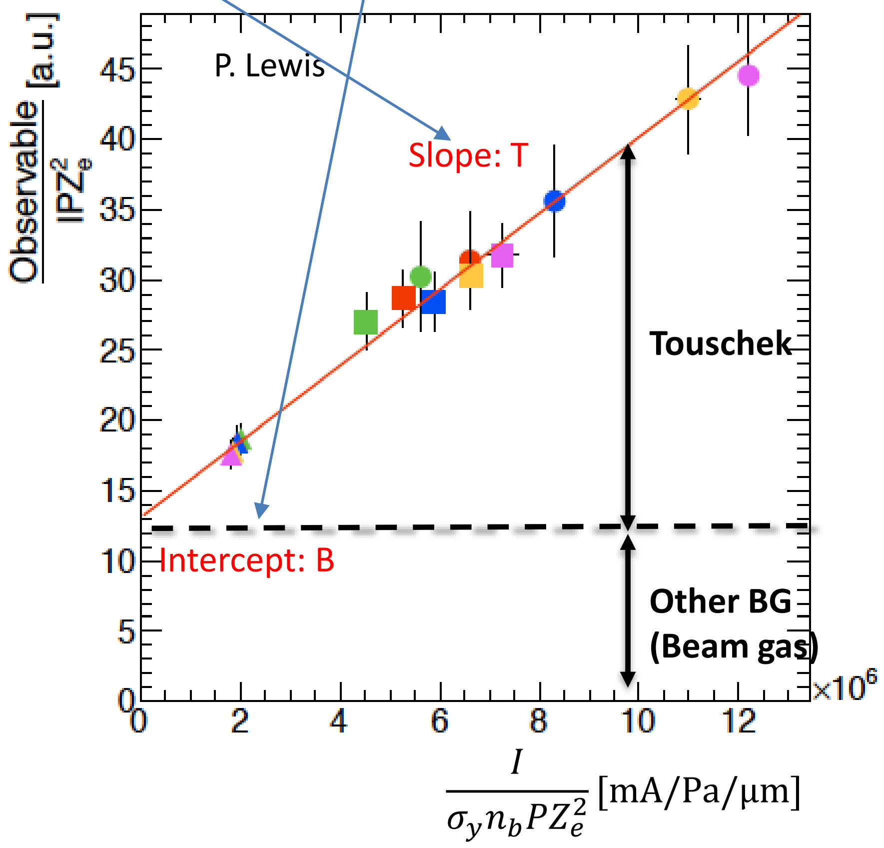
Separate measurement of each BG component

$P = P_0 + cI$

$$Rate = T\frac{I^2}{\sigma_y n_b} + BZ_e^2 IP \rightarrow Rate/Z_e^2 IP = T\frac{I}{\sigma_y n_b P Z_e^2} + B$$

T, B: Touschek/Beam-gas coefficient
σ_y: vertical beam size, n_b: number of bunches
P: pressure, I: beam current
Z_e: effective atomic number of residual gas

Touschek component also depends on bunch length σ_z

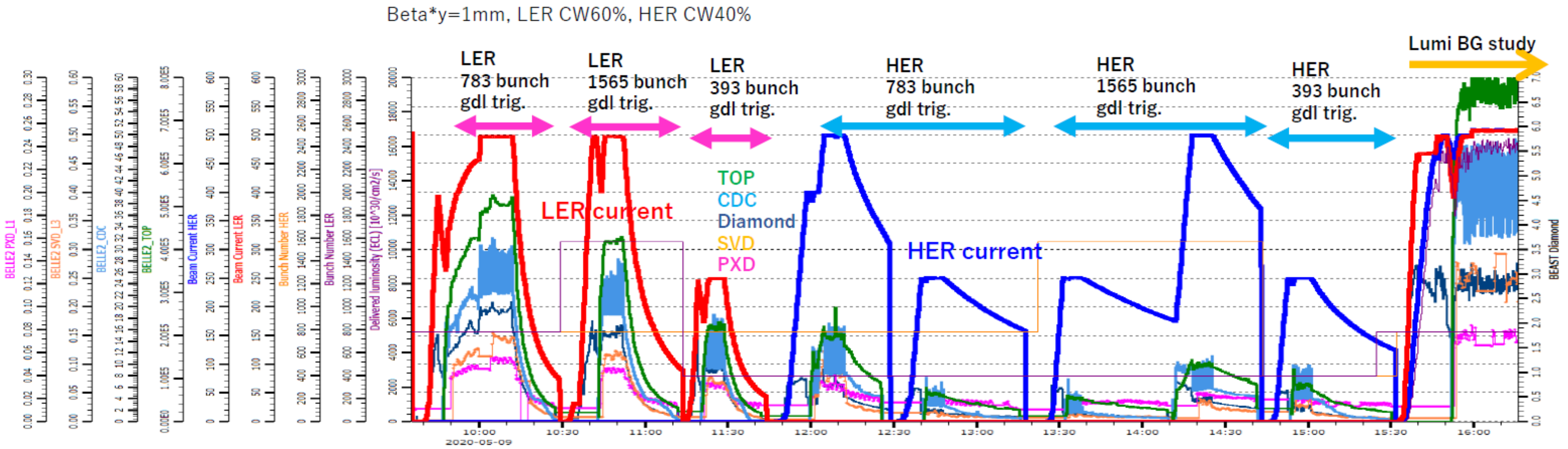


<u>Strategy:</u>

- Single-beam (no collision). Assume Touschek + Beam-gas and no other BG component
- Vary number of bunches (or beam size), which should affect Touschek component only
- Fit for T and B coefficients and compare them against estimation by MC
- Use measured data/MC ratio for correcting the simulated BG rates at future optics
- Lumi-BG can also be measured by varying lumi only

A snapshot from a single-beam BG study

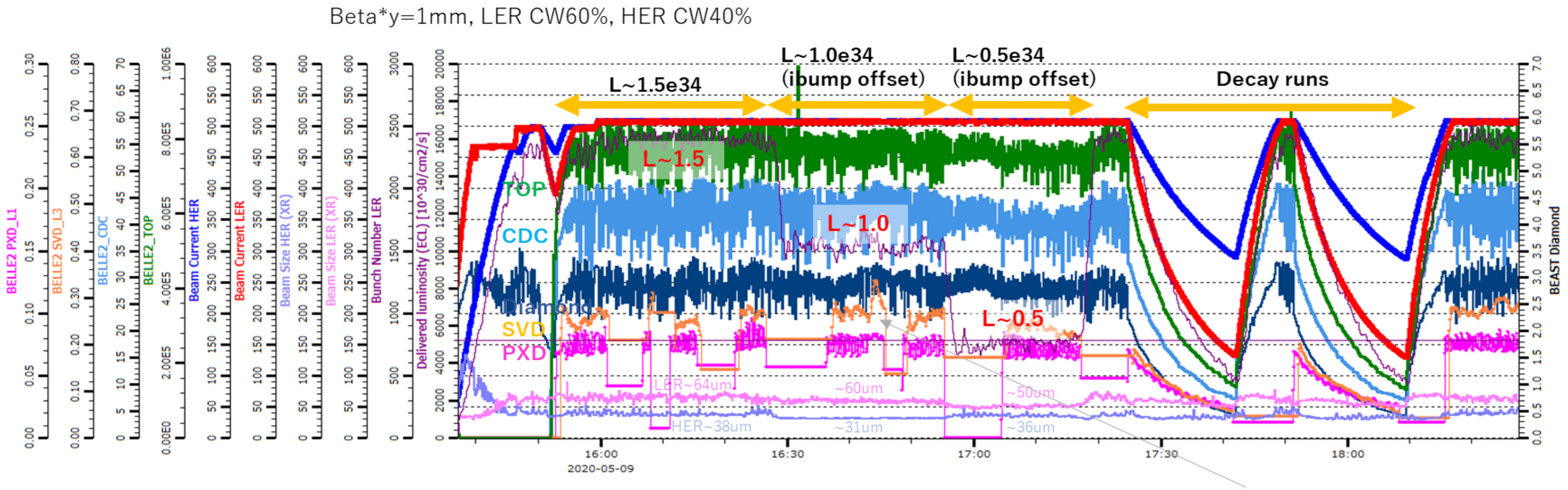
Example: LER/HER single-beam study on May 9th, 2020



- Number of bunches: Nb=783/1565/393.
- As we increase number of bunches, Belle II BG rates at the same beam current becomes smaller (due to decrease in Touschek BG)
- Beam size scan is not used recently, since unexpected BG increase was observed at larger beam size.

- <u>Observed dependency are consistent with the "Touschek+ Beam-gas" model (no significant indication of other BG sources)</u>

A snapshot from a Lumi-BG study



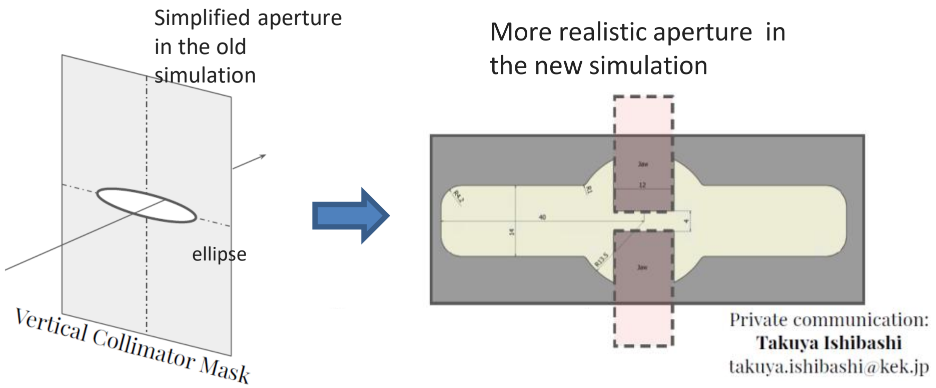
- "Continuous injection" runs
  - L=1.5→1.0→0.5e34, by vertically displacing two beams ("ibump V-offset")
  - Beam sizes slightly changes as luminosity changes
- "Beam decay" runs (no injections)
  - Measurement not affected by injection BG
- Measure lumi-BG component by subtracting single-beam BG components scaled with current, beam size, etc..

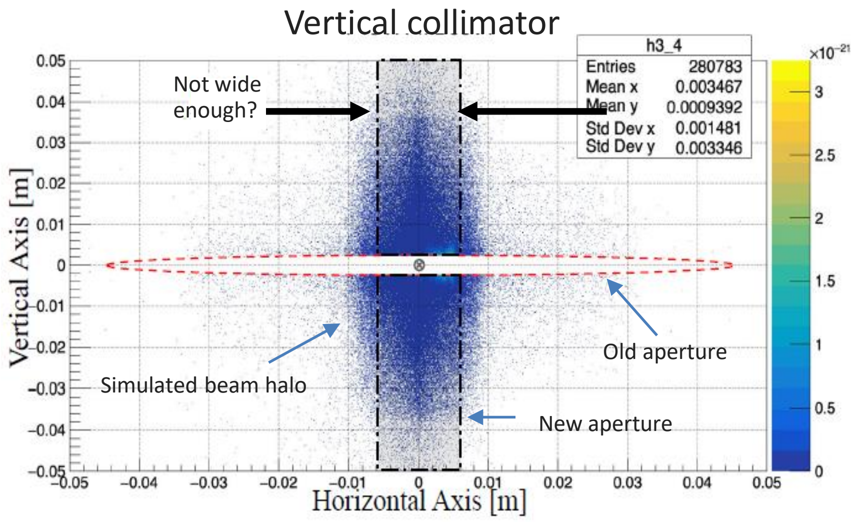
- Measured Lumi-BG agrees with simulation at the ~10% level in TOP, PXD !!
  - Also agrees between "continuous injection" and "beam decay" data

Recent improvements to simulation

- Andrii Natochii implemented an improved framework for beam-particle tracking in SuperKEKB
  - New features: apply collimation after particle tracking, pressure-weighted beam-gas simulation, custom beam pipe aperture shapes, etc..
- Largest impact: implementation of correct SuperKEKB collimator shape + tip scattering
  - Particles previously stopped by the collimators can now reach the IP
- Up to factor 1000(!) increase in simulated Belle II detector rates, resolving a longstanding HER data/MC discrepancy
- Surprisingly, largest effect from collimator shape change transverse to beam axis
  - This may imply we could benefit from wider collimator heads for HER D1V1, in plane transverse to beam → should be studied (kick factor, etc.)

A. Natochii





Background simulation tools

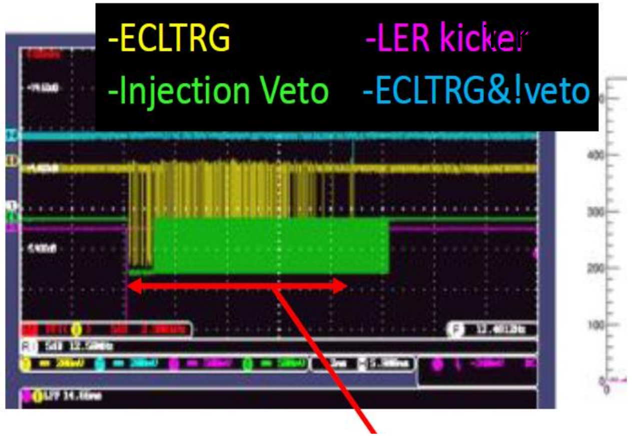
- Use SAD for multi-turn tracking in the entire rings
  - collimator tip-scattering: recently implemented by Andrii Natochii
- Use GEANT4 for single-turn tracking within detector and full simulation

BG type	BG generator	Tracking	Detector full simulation
Touschek/Beam-gas	Theoretical formulae [1]	SAD [2] (up to ~1000 turns)	GEANT4
Radiative Bhabha	BBBREM/BHWIDE	GEANT4 (multi-turn loss is small)	GEANT4
2-photon	AAFH	GEANT4 (multi-turn loss is small)	GEANT4
Synchrotron radiation	Physics model in GEANT4 (SynRad)	GEANT4	GEANT4

[1] Y. Ohnishi et al., PTEP **2013**, 03A011 (2013).
[2] SAD is a “Home-brew” tracking code by KEKB group, http://acc-physics.kek.jp/SAD/

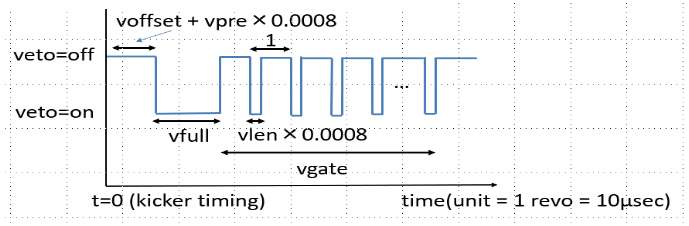
Issues: Injection BG duration

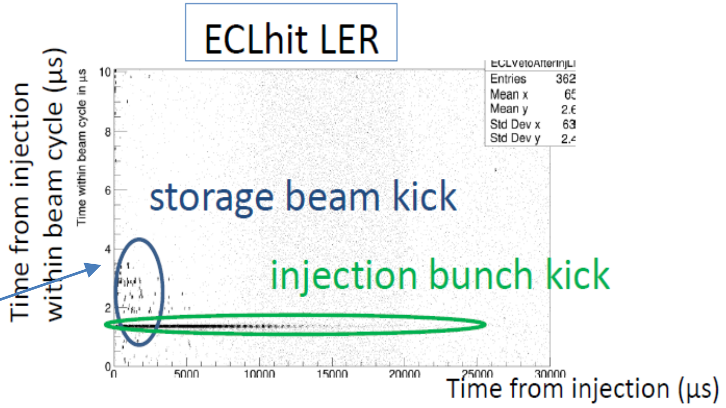
- Belle II DAQ apply trigger veto after each injection, since the injected bunch gets noisy for a while
- Typical duration of injection BG → LER: <u>~10ms</u>, HER:<u>~5ms</u>
  - Corresponds to 5~10% deadtime
  - longer veto window → lose integrated luminosity
  - In 2022 run, duration gets longer after the severe collimator damage
- Dedicated machine studies are conducted in 2020
  - Single beam: BG duration ∝ bunch current
  - Colliding beams: BG duration longer than single-beam
    → *beam-beam effect?*
  - Not only the injected bunch, but also later bunches are lost. However, "blank-shot" injections don't give any BG duration
    → *Coupling btw. injected bunch and later bunches?*
    Delayed arrival of neutrons generated at upstream collimators?
  - Simulation effort to reproduce these behaviors is ongoing



"Injection BG duration"

Injection veto window

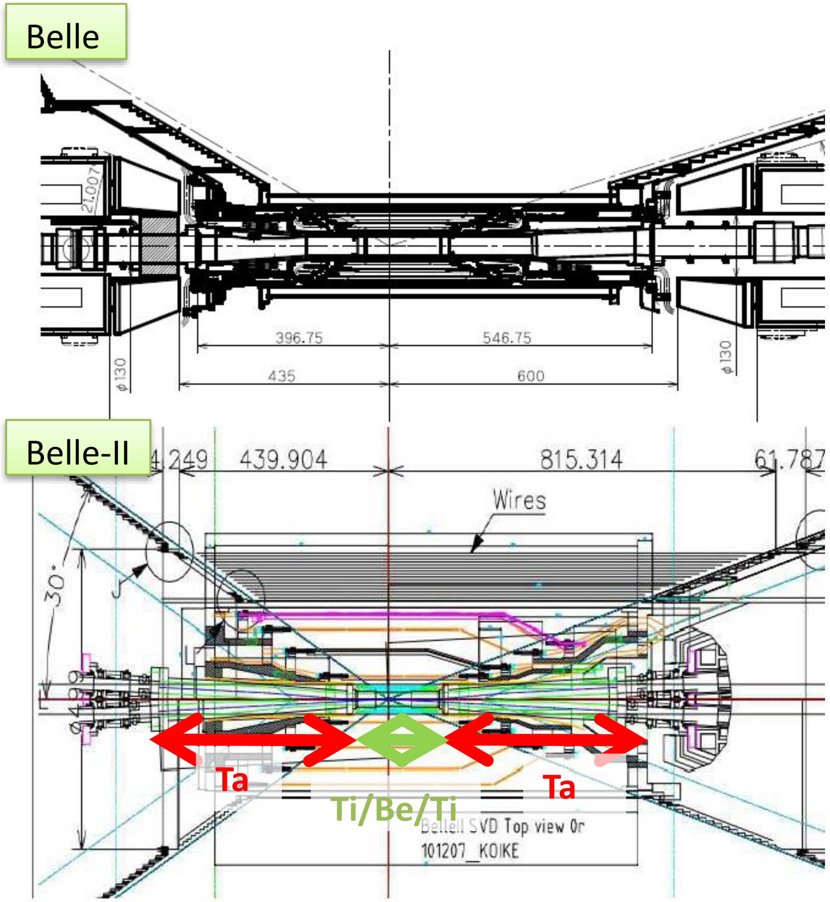


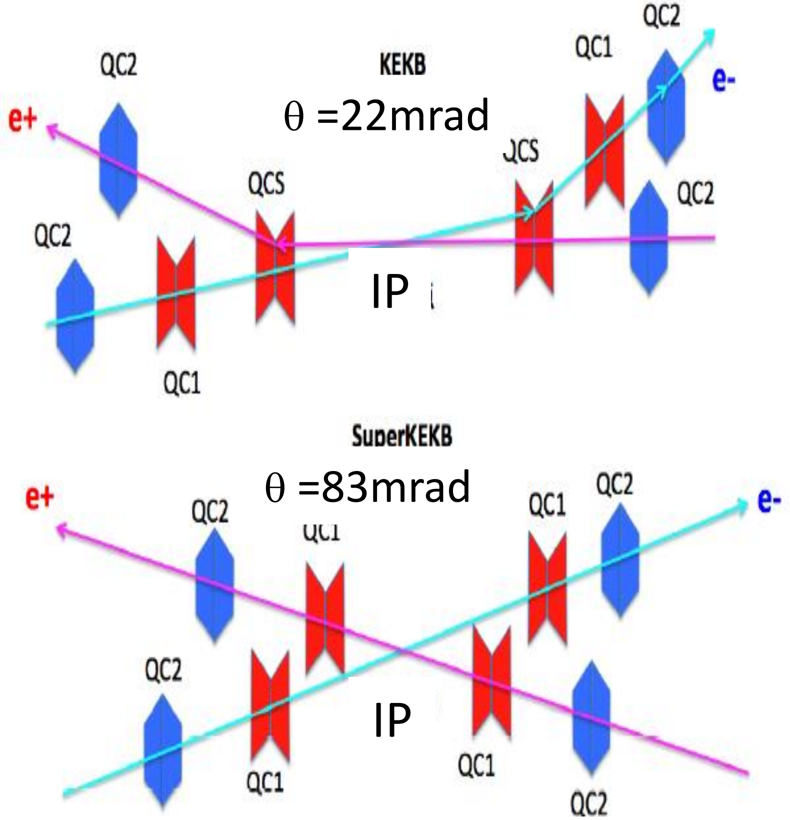


"blank-shot" injection: kickers are fired but no charge is injected

IP beam pipes

Interaction region design of Belle and Belle II



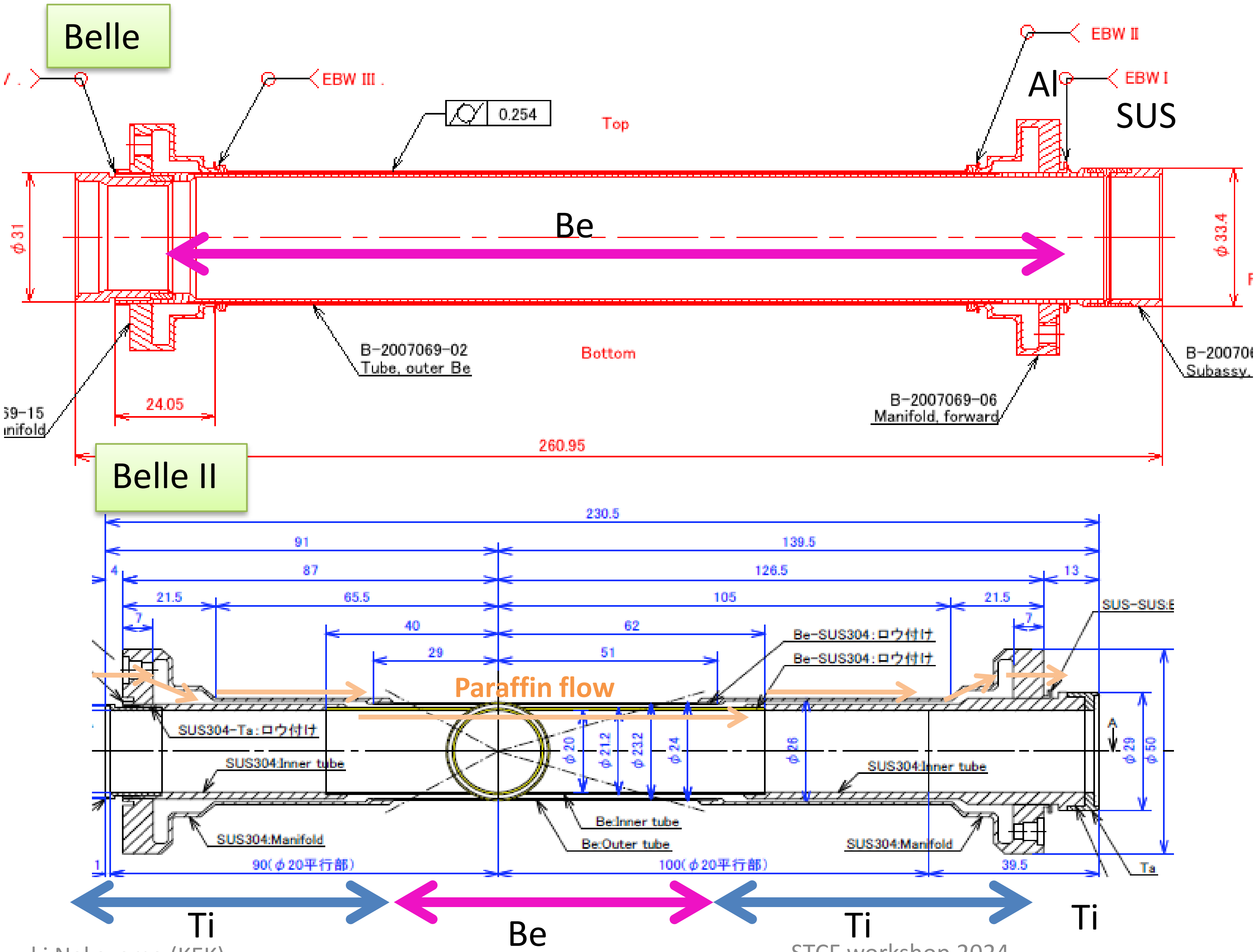


<u>Belle-II Interaction region</u>

- Smaller IP beam pipe radius （r=15mm⇒10mm） and wider beam crossing angle （22mrad⇒83mrad）
- Pipe crotch starts from closer to IP: pipe structure gets much complicated
- Innermost sensor (PXD) added: more cables to go out through limited space

- Final Q for each ring: more flexible optics design
- No orbit bend near IP: less emittance, less background from spent particles

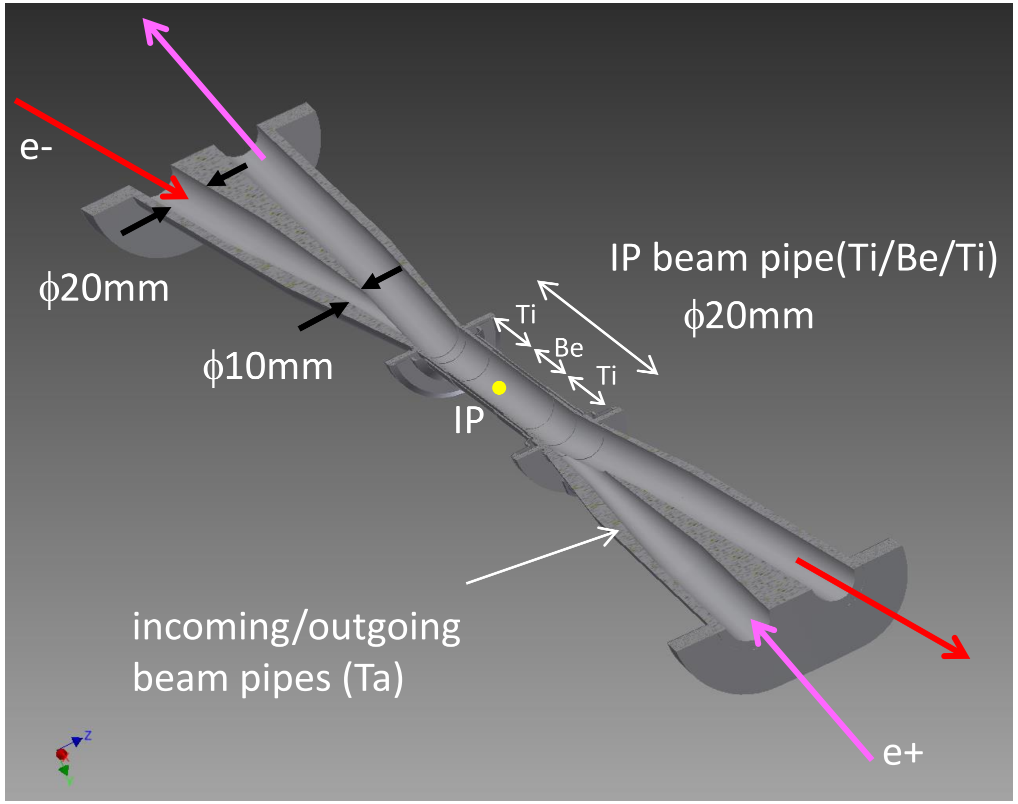
IP beam pipe (central straight section)



Belle II IP beam pipe

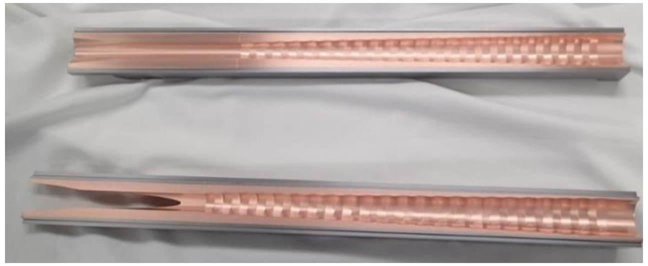
- Double-cylinder structure
- Smaller inner radius (15mm→10mm)
- Flow paraffin ($C_{10}H_{22}$) to remove heat deposit due to mirror current (~80W)
- Light material (Be) inside detector acceptance
- Gold plating (~10um) on inner wall to stop SR
- Much simpler Be shape (also much cheaper) since we allow paraffin and vacuum to attach both side of welding

Dedicated IP beam pipe design to mitigate synchrotron radiation BG



- Belle II IP beam pipes are specially designed to mitigate SR background
- Collimation on incoming beam pipe (ϕ20mm→ϕ10mm) stops most of SR photons in parallel with the beam
  - Direct SR hit on Be part of IP beam pipe is negligible
  - No collimation on outgoing pipes so that HOM can escape (no cavity structure)
- "Ridge" structures on inner surface of the collimation pipe can prevent forward-scattering of SR photons
  - One-bounce SR hit on Be part can also be negligible

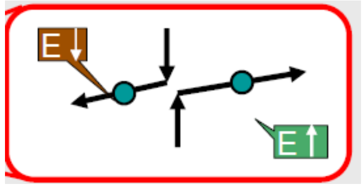
Inner surface of Be pipe are coated with Au layer (10um)



Ridge structure

SuperKEKB beam backgrounds

1.Touschek scattering



- Intra-bunch scattering : Rate∝(beam size)$^{-1}$,(E_{beam})$^{-3}$
- Touschek lifetime: should be >600sec (required by injector ability)

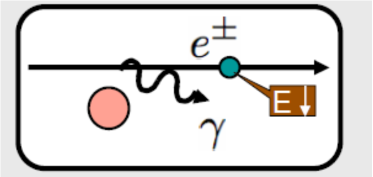
  → ring total beam loss: ~375GHz (LER), ~270GHz(HER)
- **<u>Countermeasure: horizontal collimators in the ring</u>**
  - collimators added at 0~200m upstream IP are very effective
  - only O(100MHz) loss inside Belle II detector

- Horizontal collimators are installed where beta_x or eta_x is large

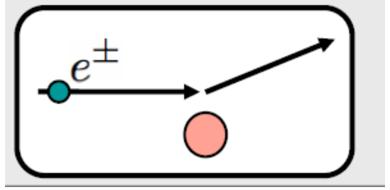
$$d_x = Max[d_{x\beta}, d_{x\eta}], \quad d_{x\beta} = n_x\sqrt{\varepsilon_x \beta_x}, \; d_{x\eta} = \eta_x (n_z \sigma_\delta)$$

2.Beam-gas scattering

Brems



Coulomb



- Scattering by remaining gas, Rate ∝ IxP
- Due to smaller beam pipe aperture and larger maximum βy at SuperKEKB, beam-gas Coulomb scattering could be more dangerous than in KEKB

$$\frac{1}{\tau_R} = c n_G \langle \sigma_R \rangle = c n_G \frac{4\pi \sum Z^2 {r_e}^2}{\gamma^2} \left\langle \frac{1}{{\theta_c}^2} \right\rangle$$

σ_R: cross section of the scattering
Z: atomic number of gas nucleus, n_G: $=2P/k_B/T$

	KEKB LER	SuperKEKB LER
QC1 beam pipe radius: $\mathbf{r_{QC1}}$	35mm	***13.5mm***
Max. vertical beta (in QC1): $\beta_{y,QC1}$	600m	2900m
Averaged vertical beta: $\langle\beta_y\rangle$	23m	50m
Min. scattering angle: θ_c	0.3 mrad	0.036 mrad
Beam-gas Coulomb lifetime: τ_R	>10 hours	35 min

- Countermeasures: Vertical collimators in the ring
  - very narrow (<~2mm) collimators
  - **TMC instability issue** at high current
  - Need to install where beta_y is rather small

Where should we put the vertical collimators?

Collimator aperture should be narrower than QC1 aperture.

$$d/\sqrt{\varepsilon\beta} < r_{QC1}/\sqrt{\varepsilon\beta_{QC1}} \Rightarrow d_{max} \propto \beta^{1/2}$$

TMC instability should be avoided.

Transverse Mode Coupling instability

Assuming following two formulae:

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)}$$

> 1.44 mA/bunch (LER)

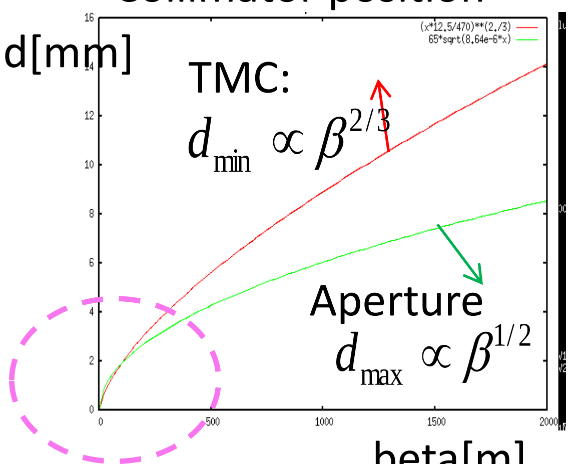
taken from "Handbook of accelerator physics and engineering, p.121"

Kick factor $k_\perp = 0.215 A Z_0 c \sqrt{\frac{\theta}{\sigma_z d^3}}$

(in case of rectangular collimator window)

$$\Rightarrow d_{min} \propto \beta^{2/3}$$

Collimator position

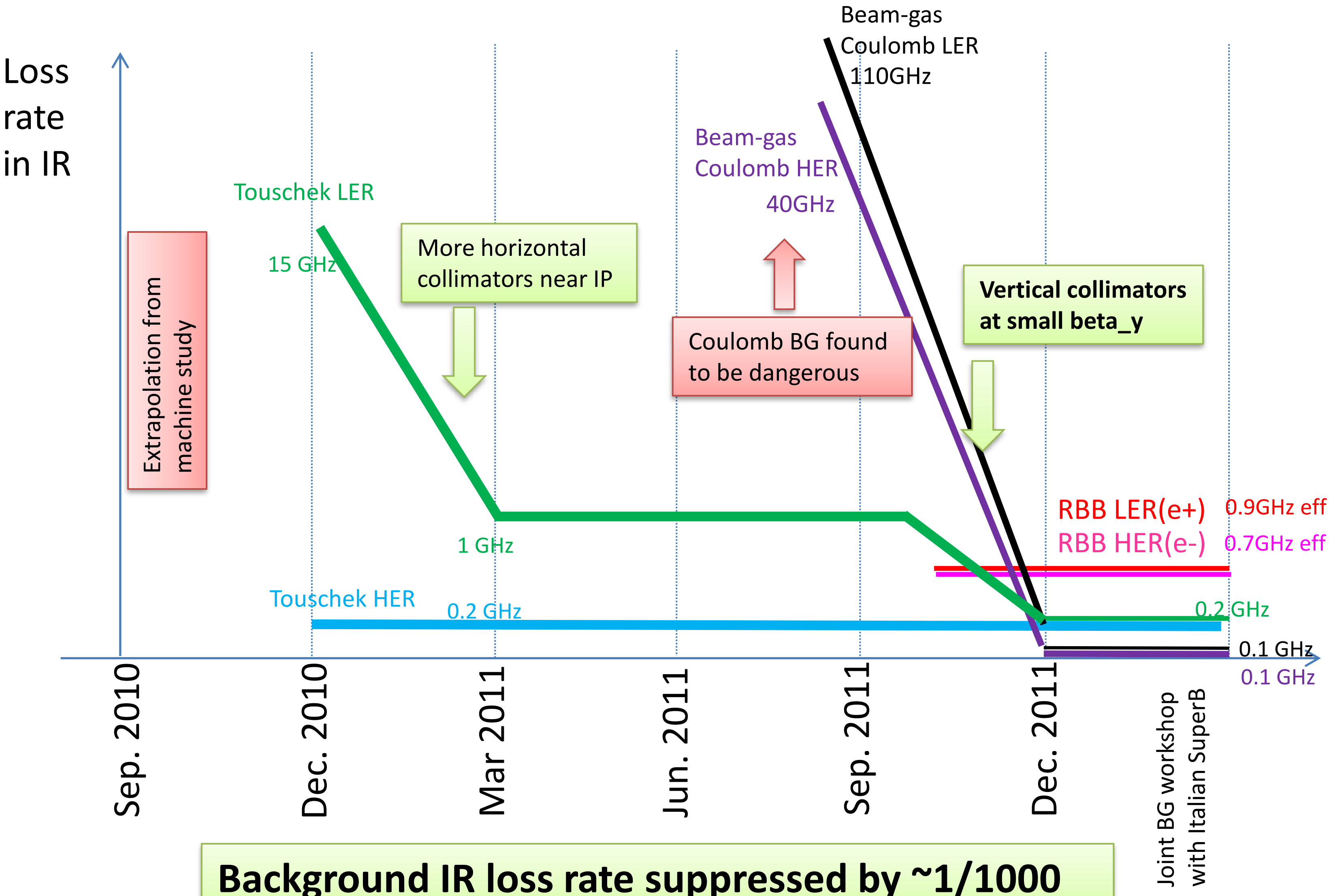


We should put collimator where beta_y is rather SMALL!

For more details, please check out following paper:

H. Nakayama et al, "Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability", Conf. Proc. C **1205201**, 1104 (2012)

Background reduction (in our simulation) by adding more collimators

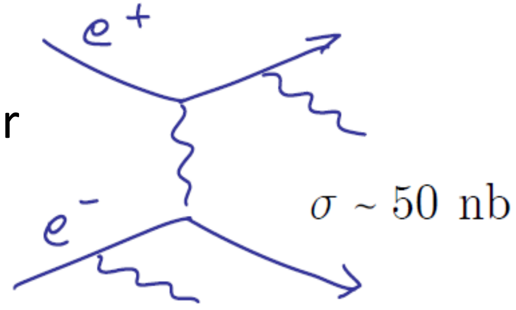


Background IR loss rate suppressed by ~1/1000

4. Luminosity-dependent background

Radiative Bhabha scattering

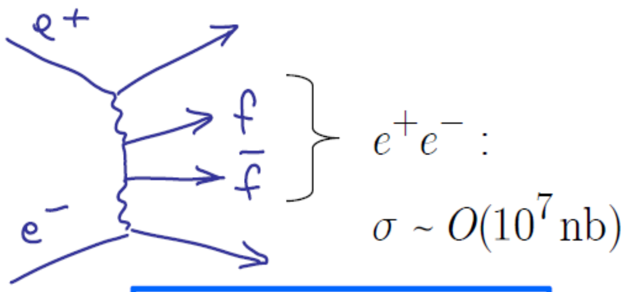
- Rate ∝ Luminosity (KEKBx40)
- Spent e+/e- with large ΔE could be lost inside detector due to due to kick from detector solenoid kick (even with separate final focus magnets for each ring)
- Emitted γ hit downstream magnet outside detector and generate neutrons via giant-dipole resonance



Bhabha scattering

2-photon process

- Rate ∝ Luminosity (KEKBx40)
- e+ e- → e+ e- e+ e-
- Emitted e+e- pair curls by solenoid and might hit inner detectors multiple times

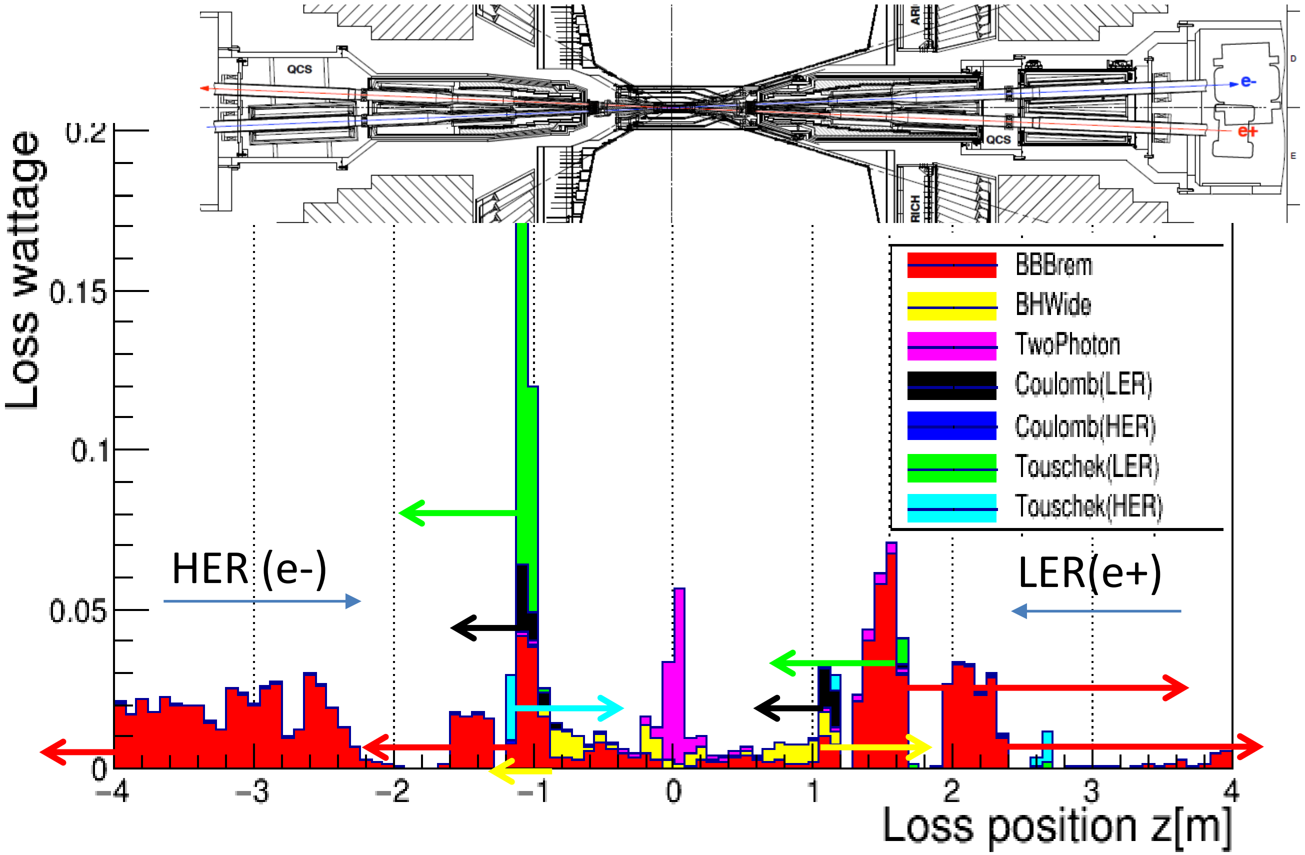


2-photon-processes

Simulated IR beam loss distribution (design luminosity)

15th campaign
(2017)

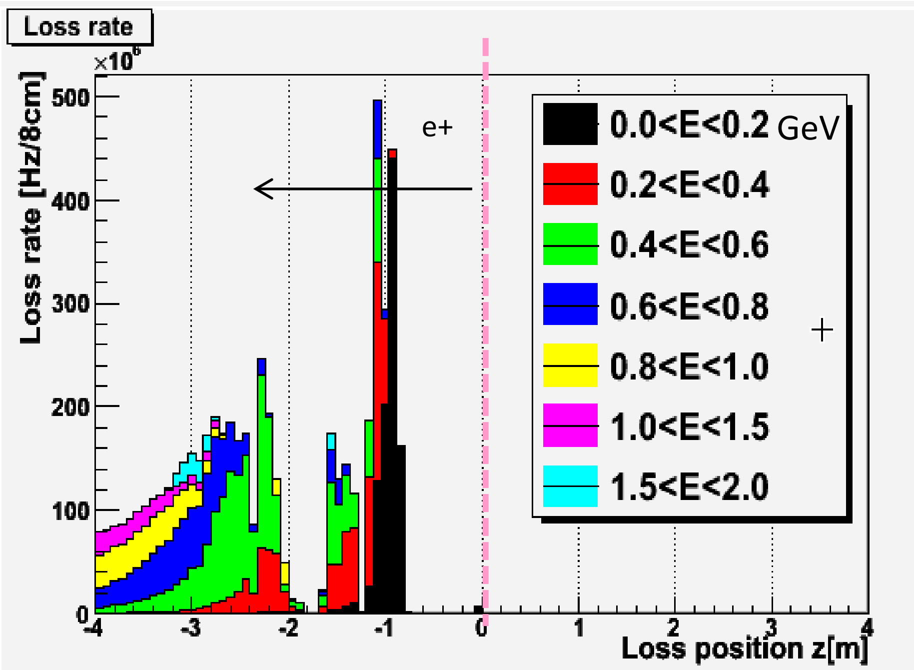
"Loss wattage [W/8cm]"
= loss rate
* energy of loss particle



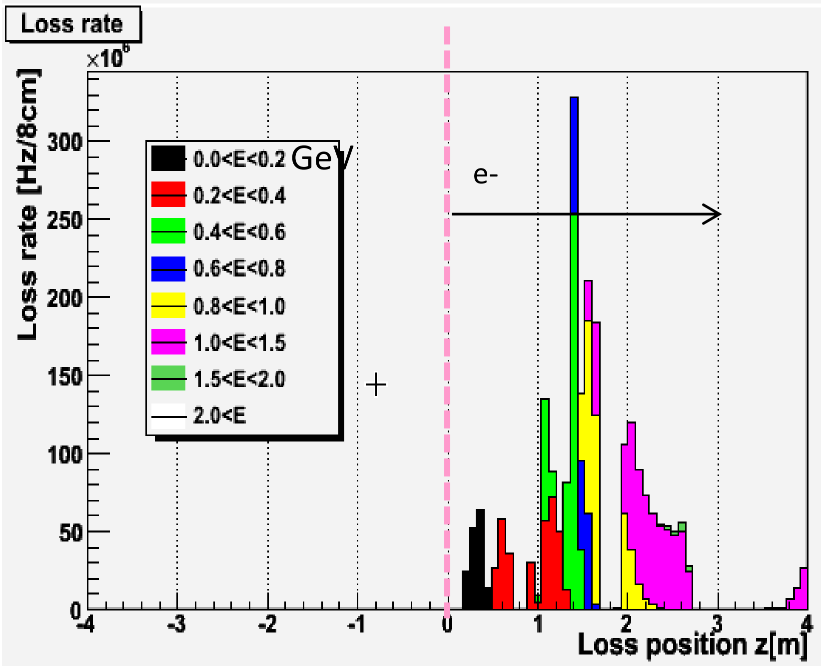
	LER (4GeV e+)	HER (7GeV e-)
Lumi-dependent BG	BBBrem: **1.08 W** (0.06 W in |z|<65cm) BHWide: 0.11 W (0.04 W), 2photon: 0.14 W(0.11W)	
Touschek	0.27 W (0.42GHz)	0.04 W (0.03GHz)
Coulomb	0.06 W (0. 10Hz)	0.00 W (0.002GHz)

Spent e+/e- loss position after RBB scattering

LER(orig. 4GeV)

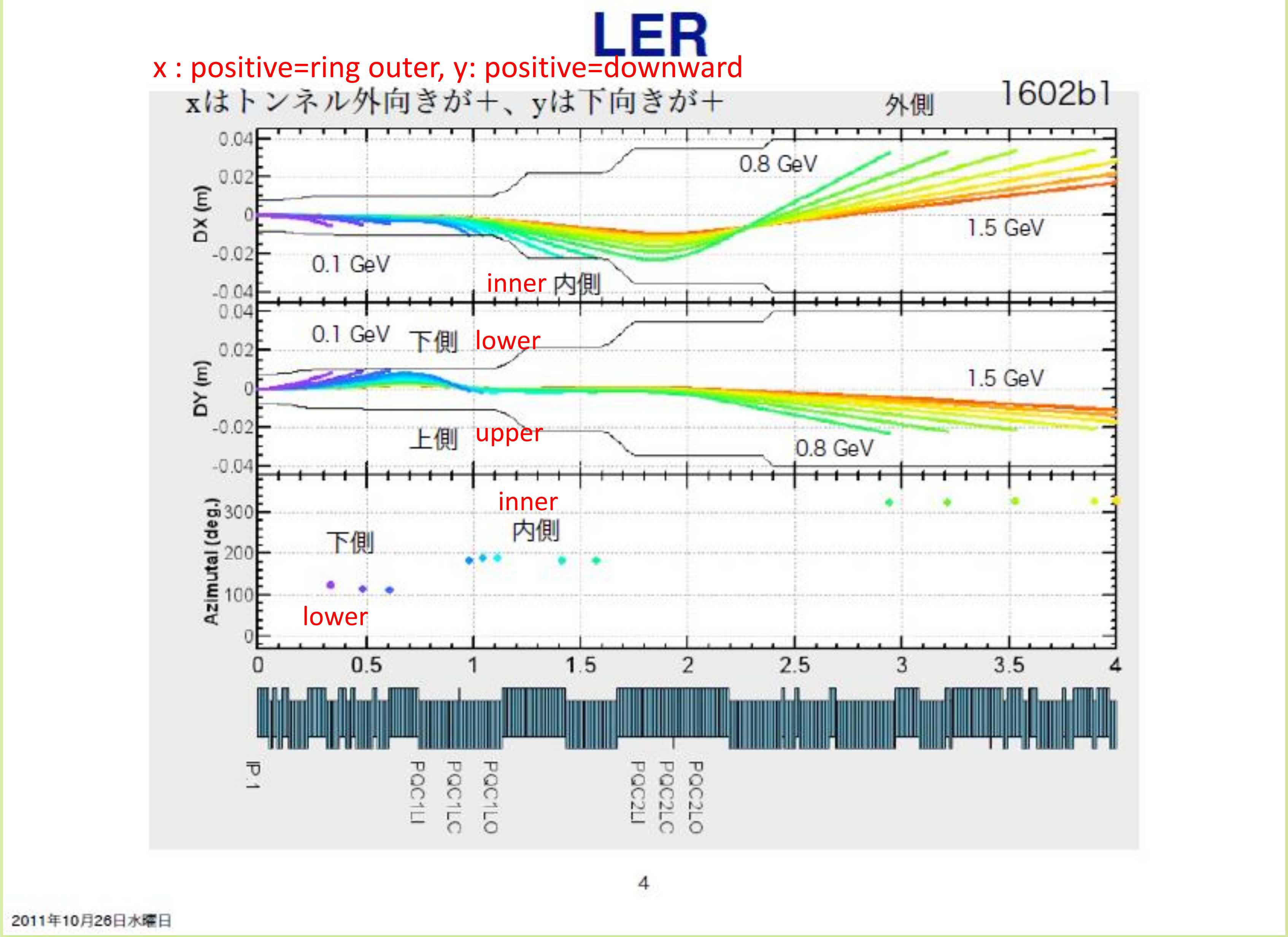


HER(orig. 7GeV)



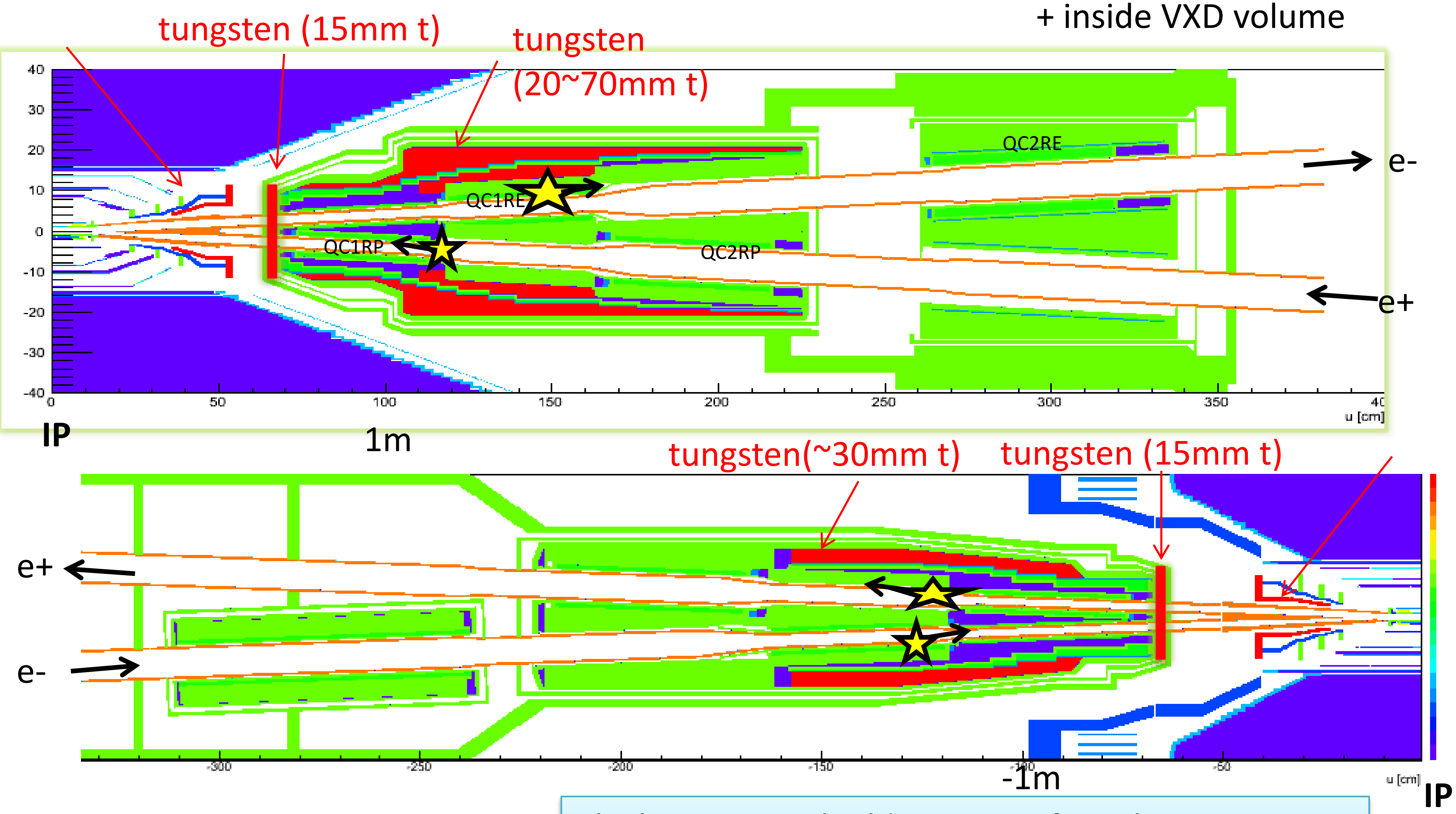
If ΔE is large and e+/e- energy becomes less than 2GeV, they can be lost inside the detector (<4m from IP), due to kick by the 1.5T detector solenoid with large crossing angle(41.5mrad)

Beam orbit after RBB scattering



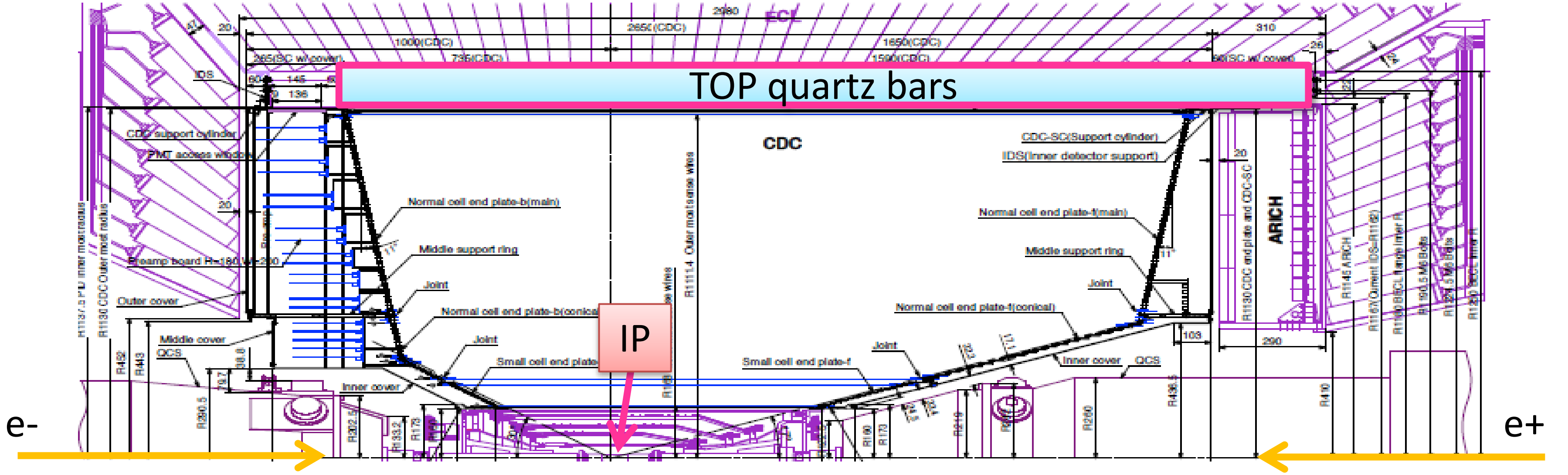
Tungsten shields inside final focus cryostat

+ inside VXD volume

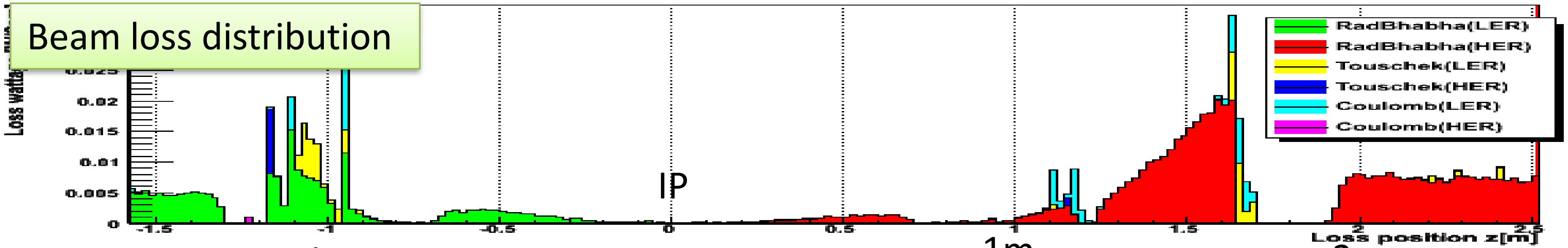


Major beam loss position by Touschek or Beam-gas

Thick tungsten shields can significantly stop background showers originated from |s|>65cm.



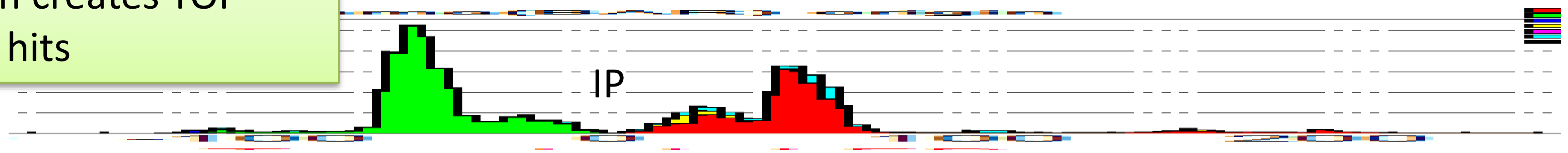
Beam loss distribution



-1m 1m 2m

Thick tungsten shield | Limited shield | Thick tungsten shield

Beam loss distribution which creates TOP PMT hits

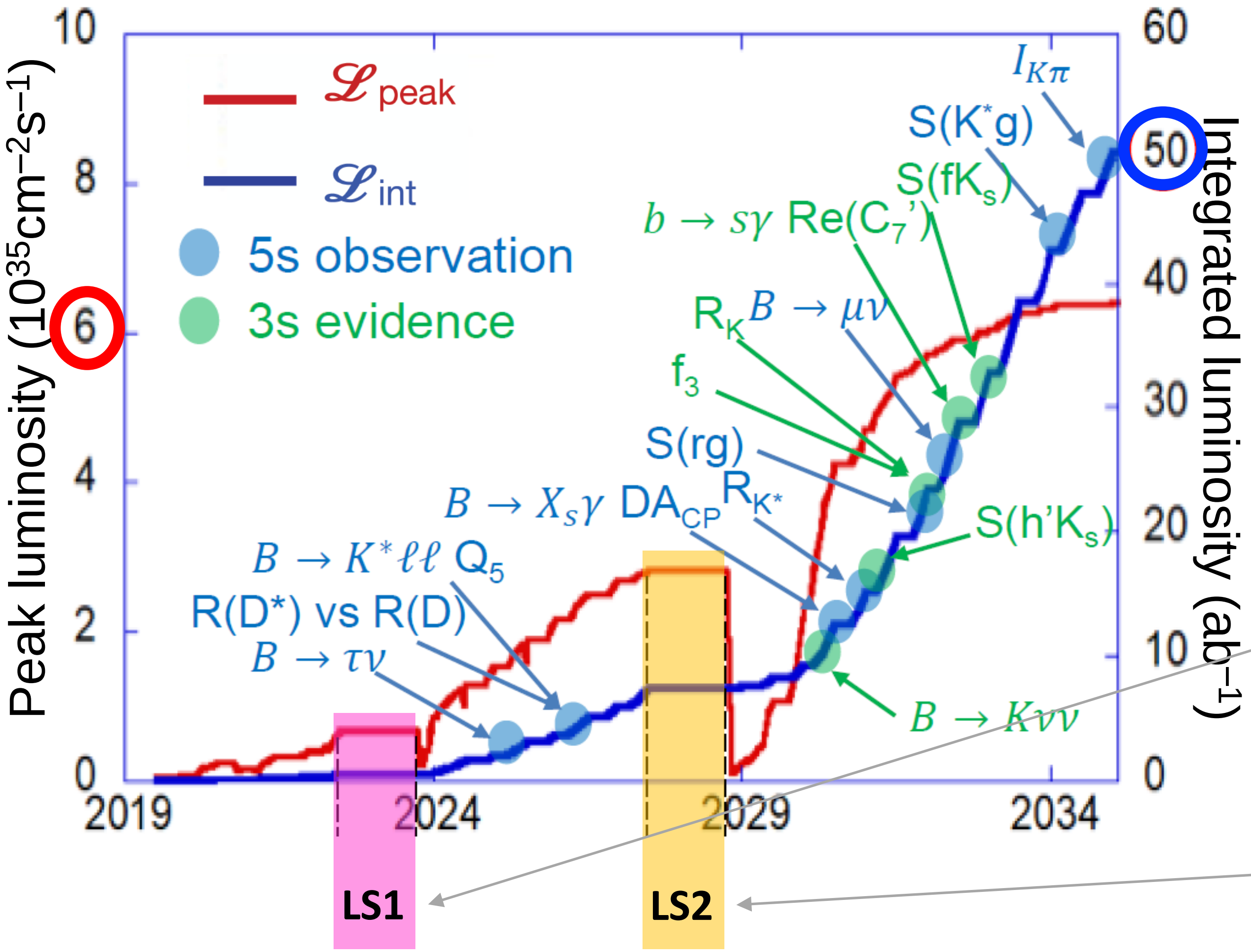


-1m 1m 2m

Future Beam BG extrapolation

The road towards 50 ab^{-1}

Anticipate a rich abundance of physics results



Need to increase beam currents (I=1→3 A) and squeeze IP beam-size (β*y = 1.0→0.3 mm)

Key challenges:

beam-beam blowup, stable injection performance, narrow dynamic aperture and short lifetime, sudden beam loss, beam background, etc..

my area of expertise !

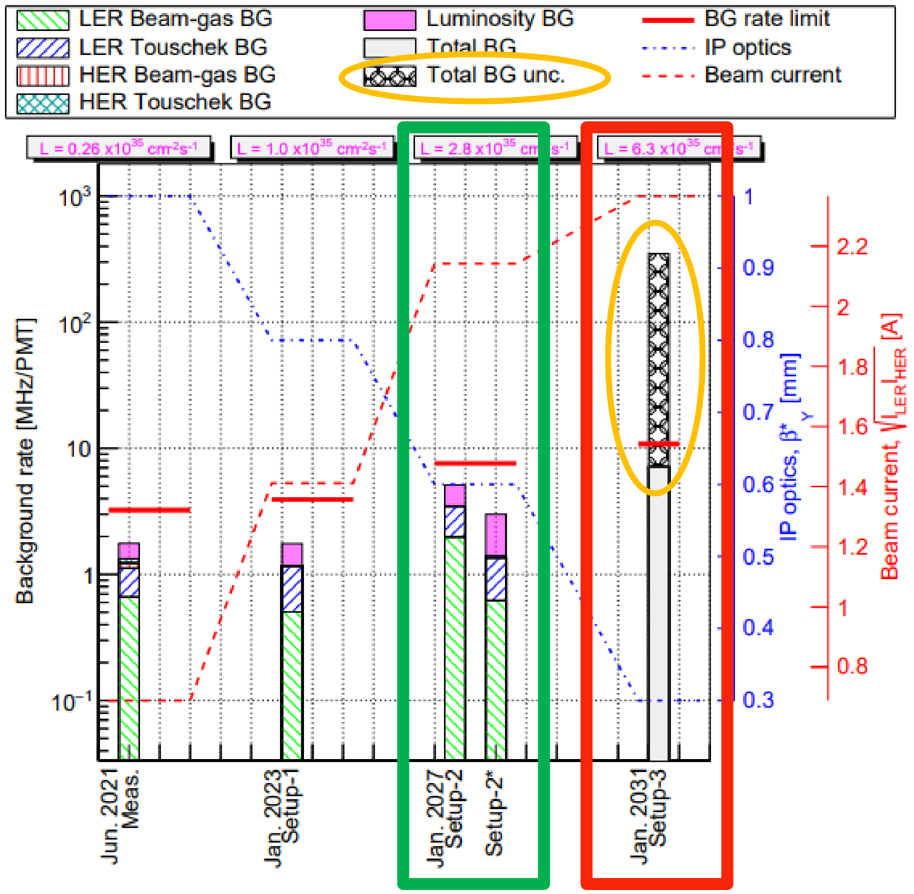
Long Shutdown 1 (LS1)

- Ongoing since summer 2022
- For maintenance and upgrade of the machine and detector
- Data taking will resume in early 2024

Long Shutdown 2 (LS2)

- To be confirmed
- Need new ideas and/or technology for SuperKEKB upgrade to enable L_{peak} = 6 x 10^{34} /cm2/s

Future extrapolation of beam background



Snowmass paper (arxiv:2203.05731)

- Beam background has been acceptable so far, up to L = 4.7 x 10^{34} /cm2/s for β*y = 1.0 mm
- According to the latest studies, beam background will remain high but acceptable up to:
  L = 2.8 x 10^{35} /cm2/s for β*y = 0.6 mm
- Toward the target luminosity of the SuperKEKB:
  (L = 6 x 10^{35} /cm2/s for β*y = 0.3 mm)
  background prediction is highly uncertain due to possible redesign of the Interaction Region during Long Shutdown 2

Machine-Detector Interface (MDI) is crucial to cope with the increased background and other issues, for which close collaboration of detector and accelerator colleagues is required