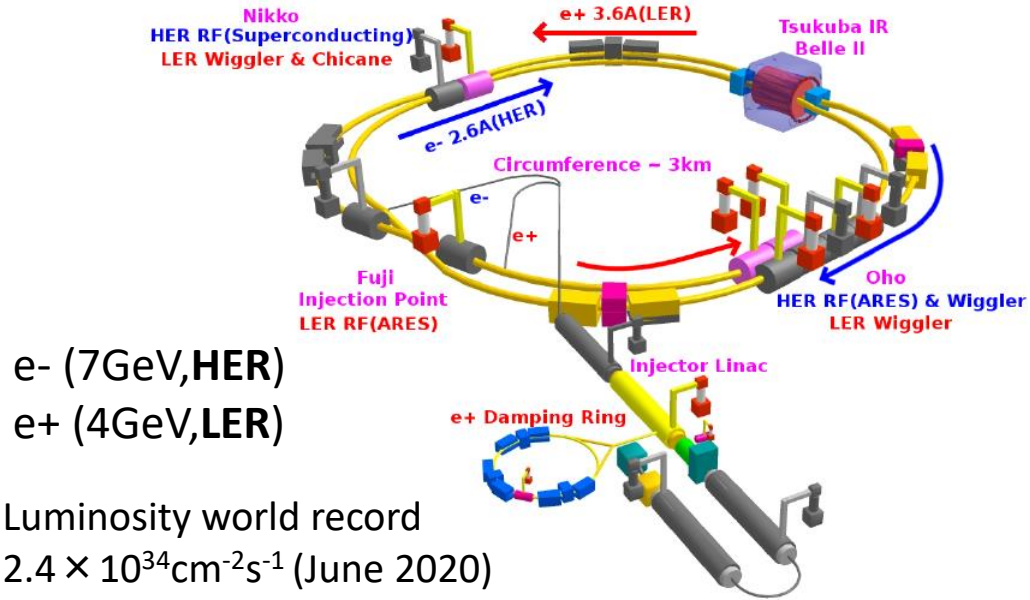
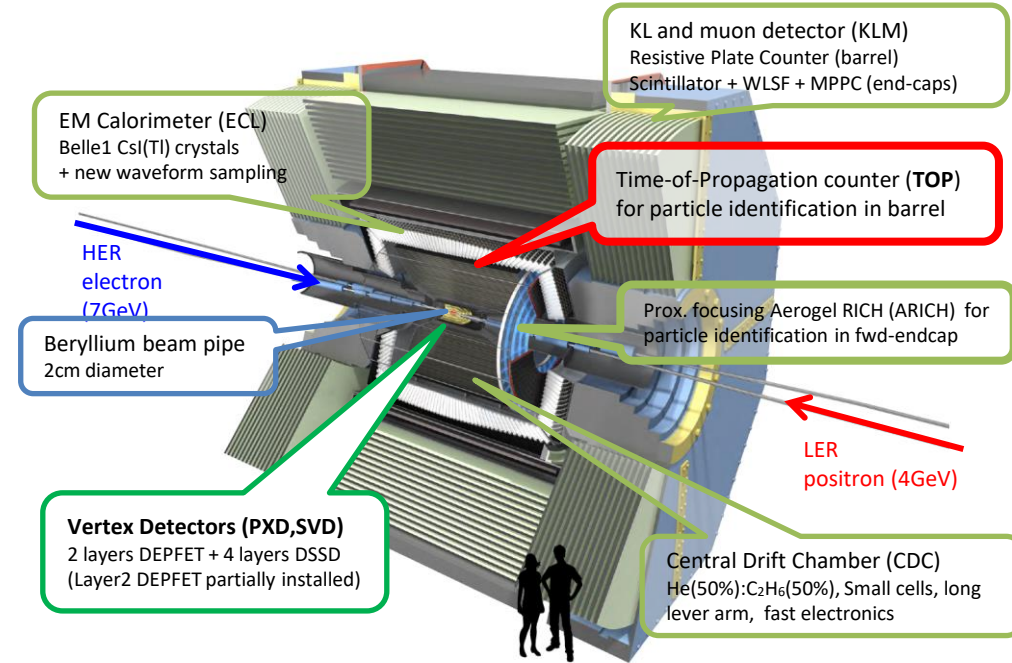


## SuperKEKB



## Belle II



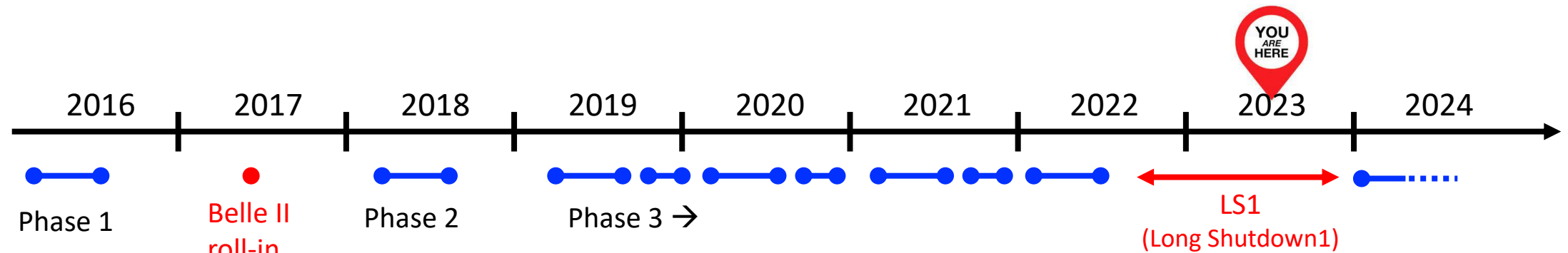
# Beam background and Machine-Detector Interface design at SuperKEKB/Belle-II



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

hiroyuki.nakayama@kek.jp

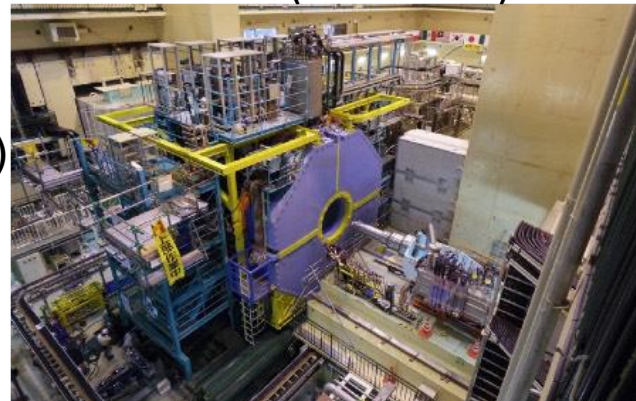
# SuperKEKB/Belle II Operation History



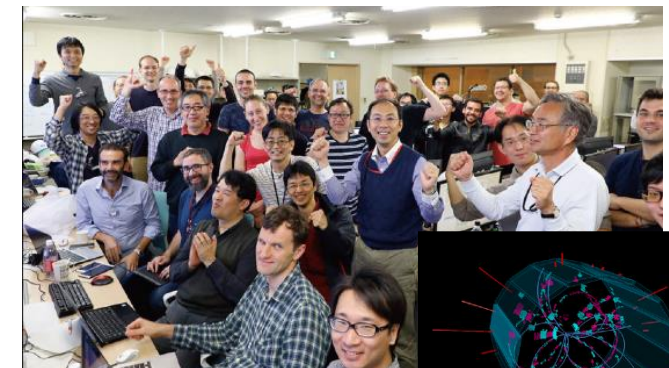
- **Phase 1 (w/o QCS/Belle II)**
  - Accelerator tuning w/ single beams
  - Background machine studies (BEAST II)
- **Phase 2 (w/ QCS/Belle II, but w/o VXD)**
  - Verification of nano-beam scheme
  - Understand beam background
  - Collision data w/o VXD
- **Phase 3 (w/ all detectors, 2019 spring~)**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

QCS: final focusing system

Belle II roll-in (2017.4.17)

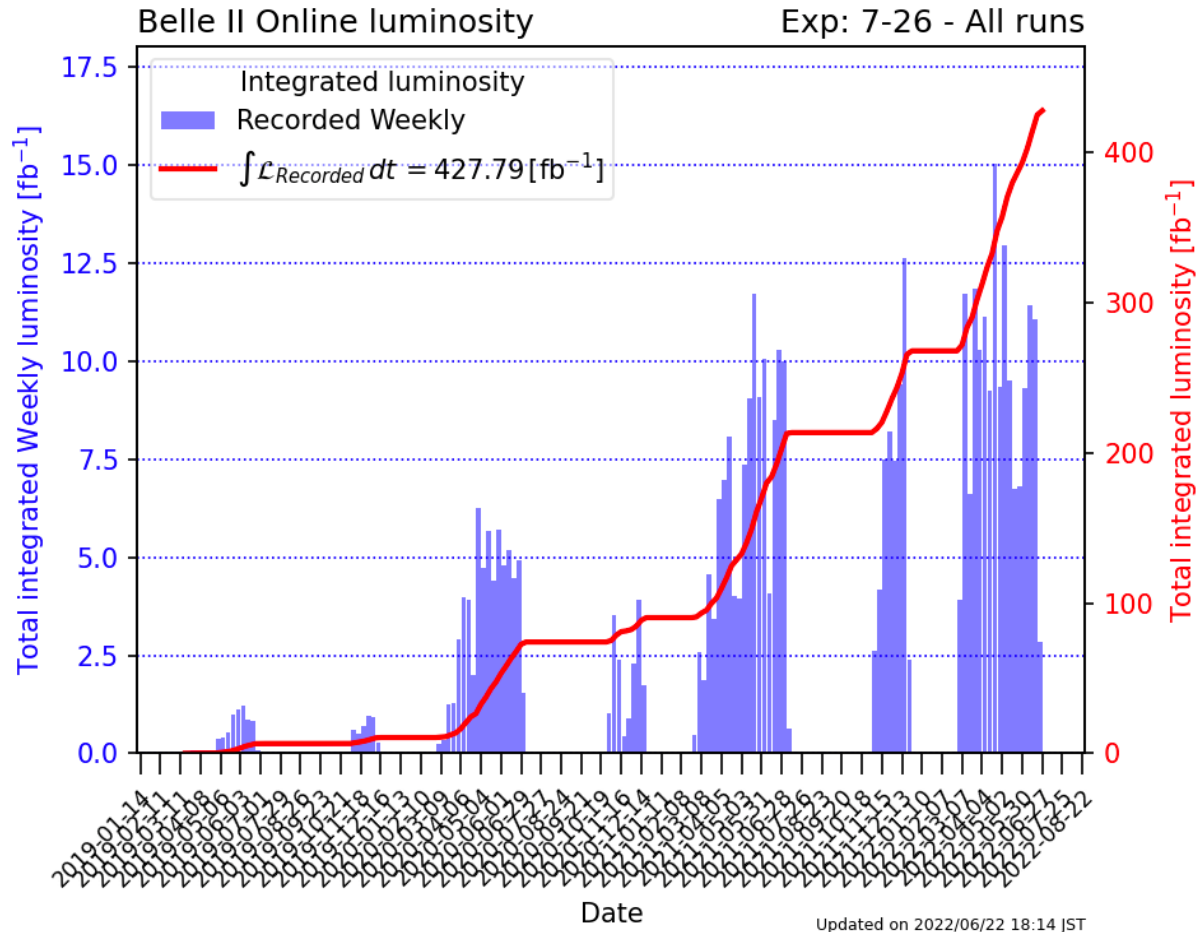


First collisions (2018.4.26)



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<sup>-1</sup>**, about a half of Belle-I dataset integrated over ~10 years of operation
- The maximum instantaneous luminosity reached **4.7 x 10<sup>34</sup>/cm<sup>2</sup>/s**, a factor 2 larger than the KEKB record (2.1 x 10<sup>34</sup>/cm<sup>2</sup>/s).  
~x4 of the PEP-II record (1.2 x 10<sup>34</sup>/cm<sup>2</sup>/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

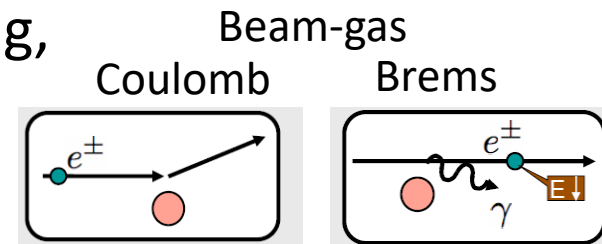
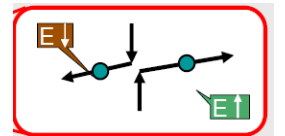
- SuperKEKB Beam BG sources

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

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

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

Touschek



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



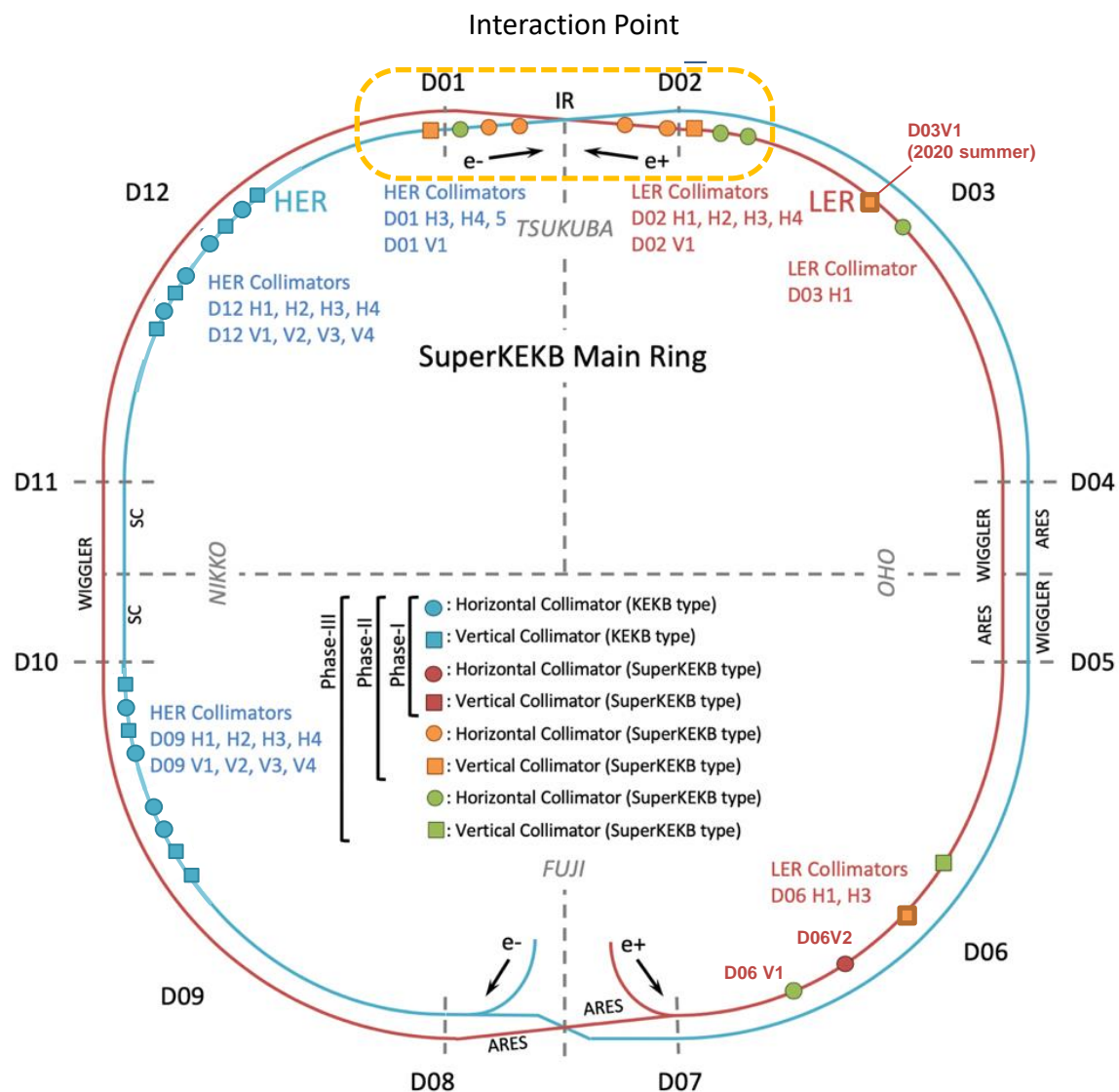
# SuperKEKB Collimators

e<sup>-</sup> (7GeV,HER)

e<sup>+</sup> (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



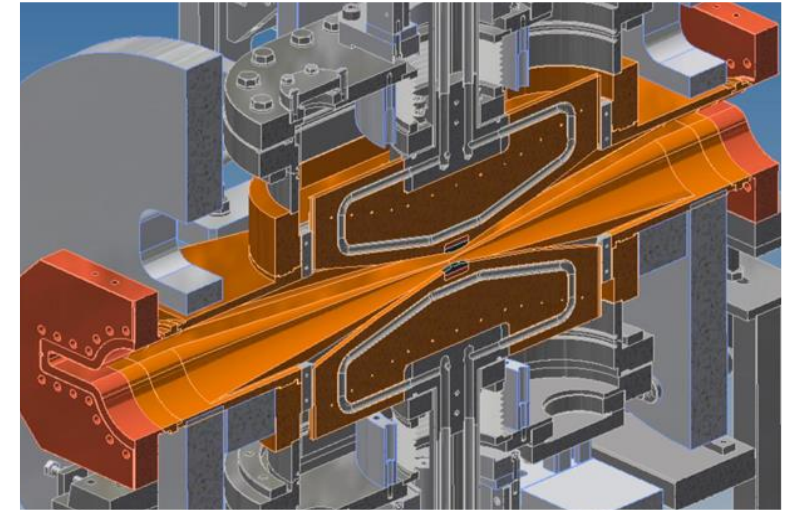
# Vertical Collimators: very narrow

- To reduce beam-gas Coulomb IR loss, we need very narrow (<~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<sub>y</sub> is rather small

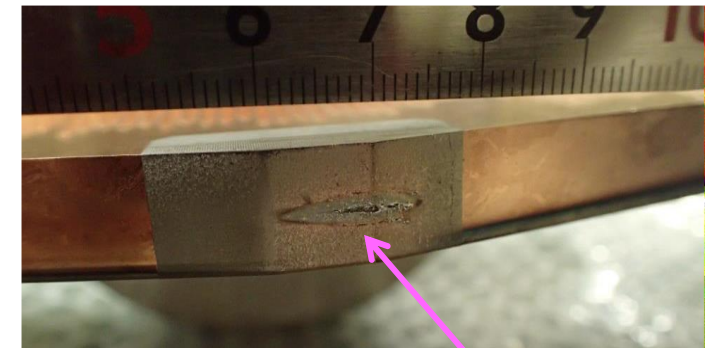
(\*) "Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability", H, Nakayama et al, *Conf.Proc.C 1205201* (2012) 1104-1106

- Precise head control ( $\Delta d \sim 50 \mu\text{m}$ ) 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.
  - 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

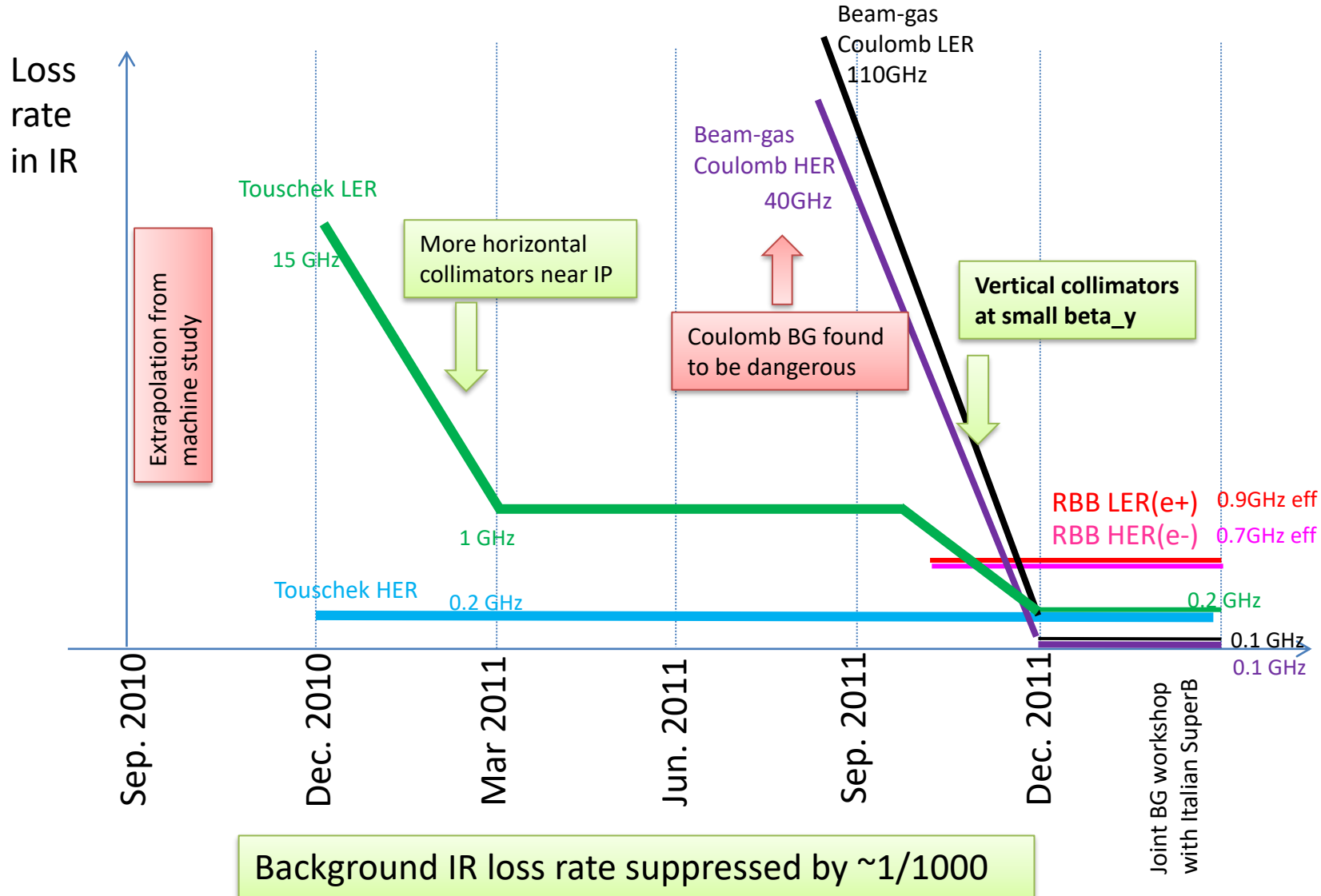


Collimator head damaged by severe beam loss



Scar along the beam line

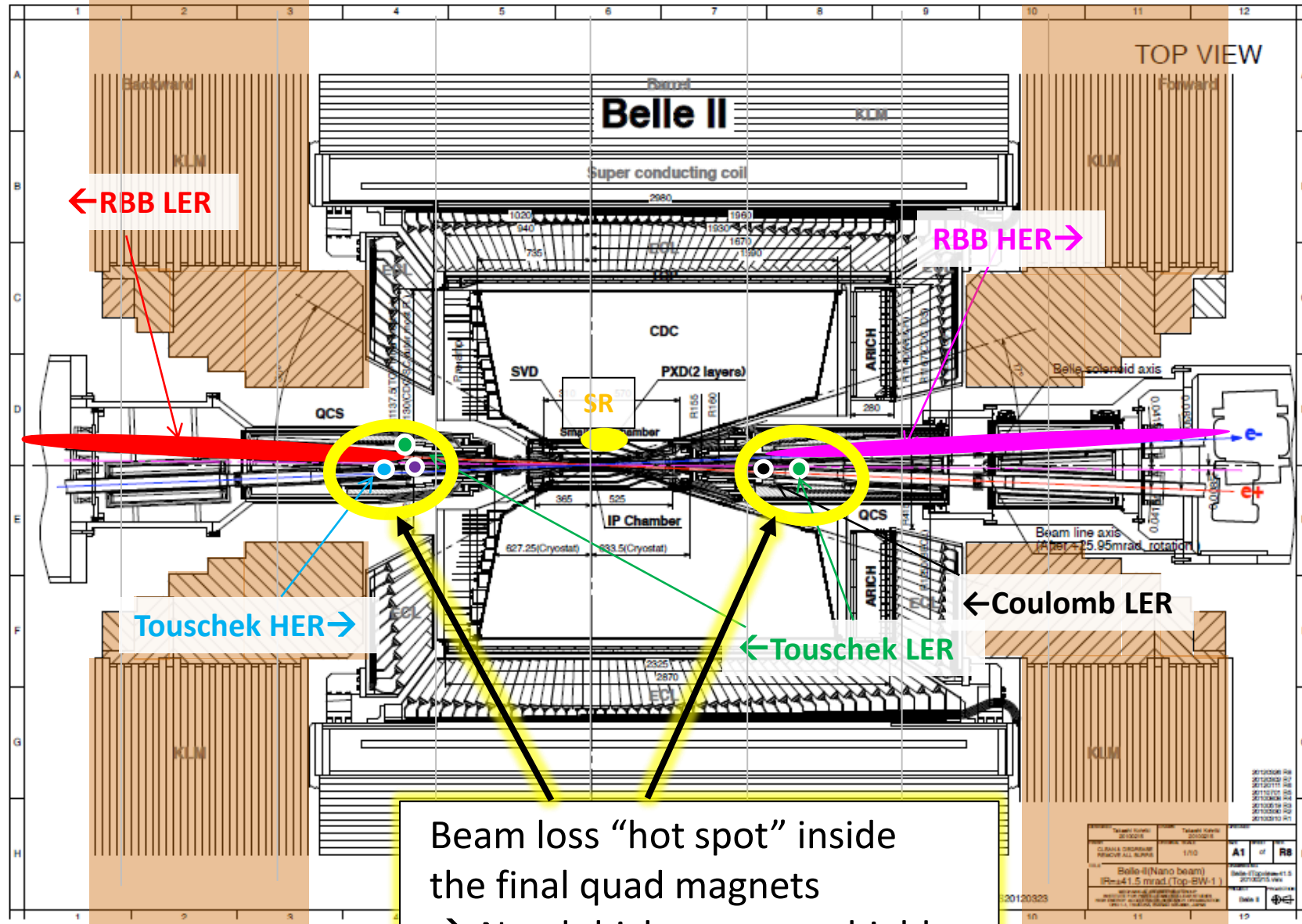
# Background reduction in simulation by adding more collimators



Beam background mitigation #2

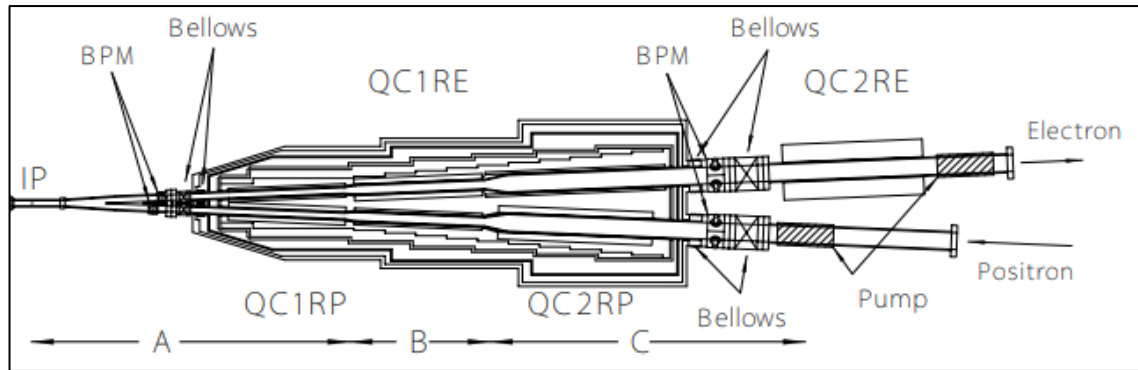
# Shielding

# Beam loss distribution inside Belle II detector



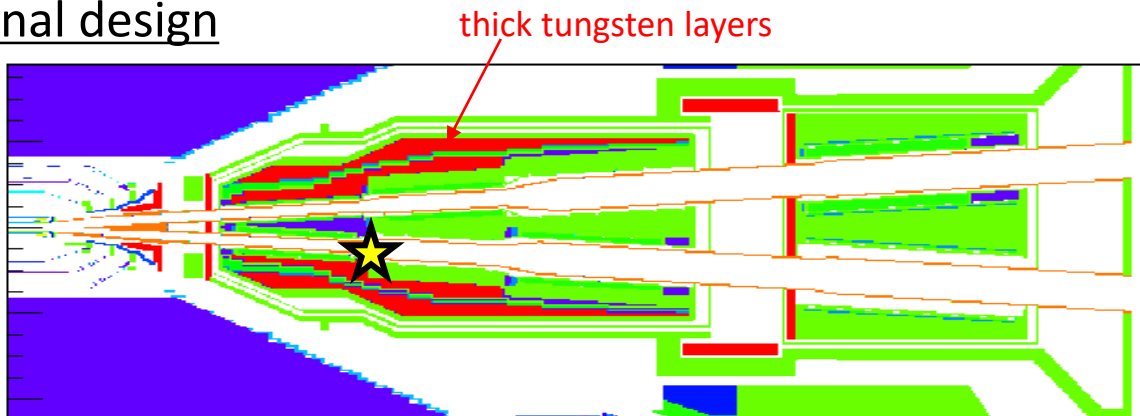
# Thick tungsten shield inside final-focus cryostat

TDR(2010)



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

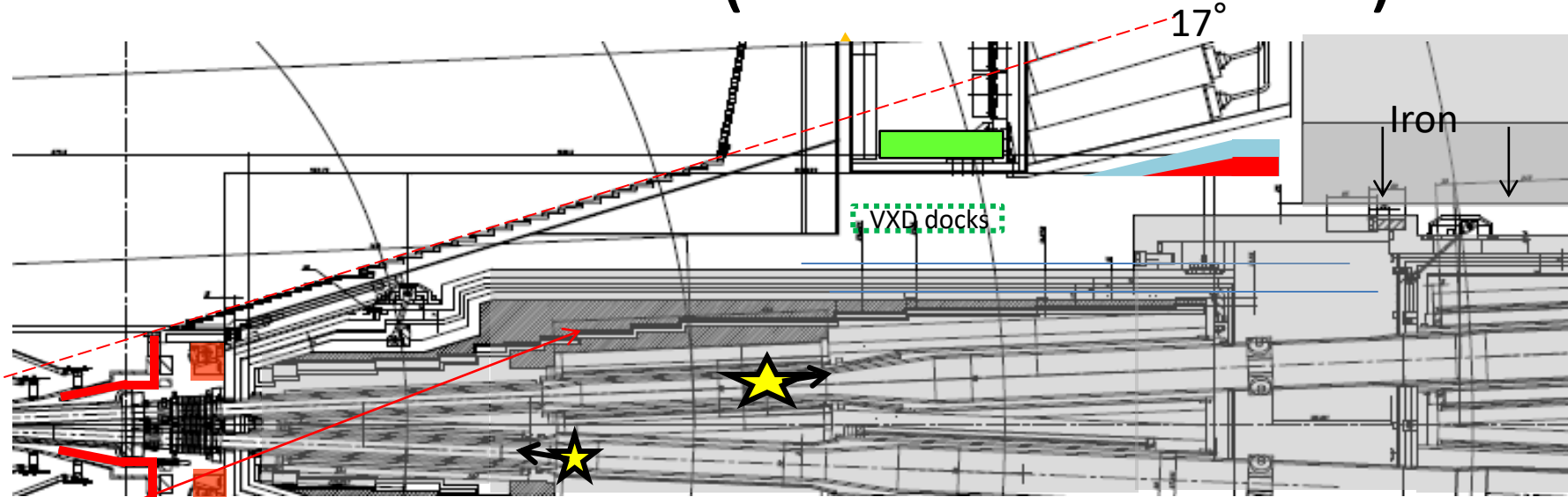
Final design



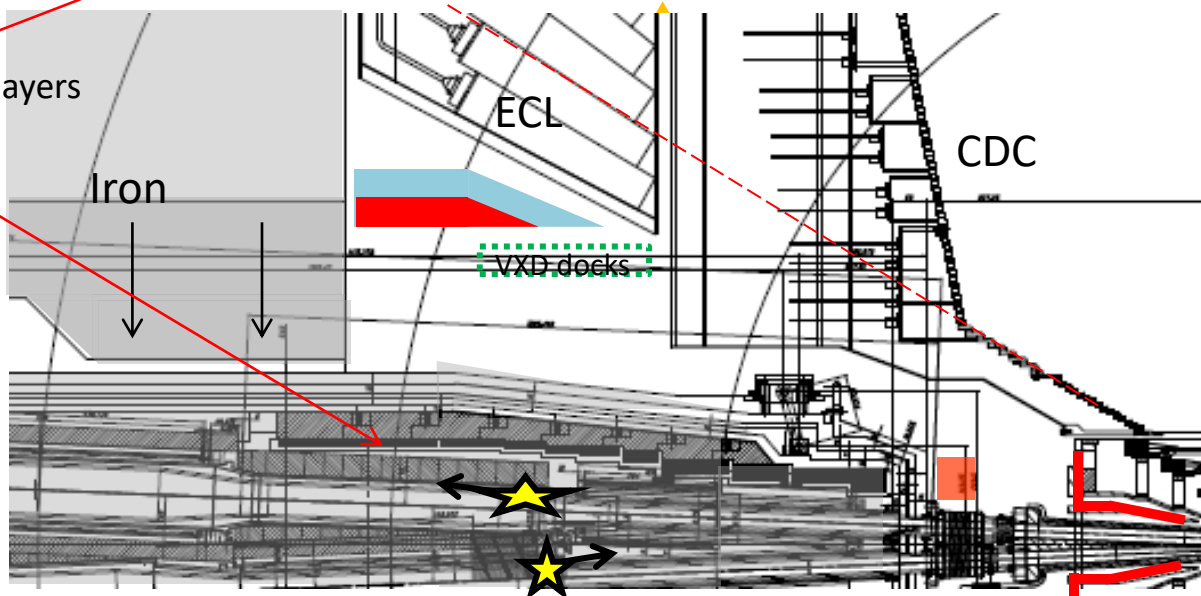
- As background simulation developed, we found a **significant beam loss inside the final focus magnet**
- I made a strong request to put as much heavy-metal shield as possible inside the cryostat
- It required major modification on the already-started cryostat fabrication process

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

# Other shields (for neutron etc..)



Thick tungsten layers  
inside cryostat



Heavy metal shields to protect VXD  
from showers generated in cryostat

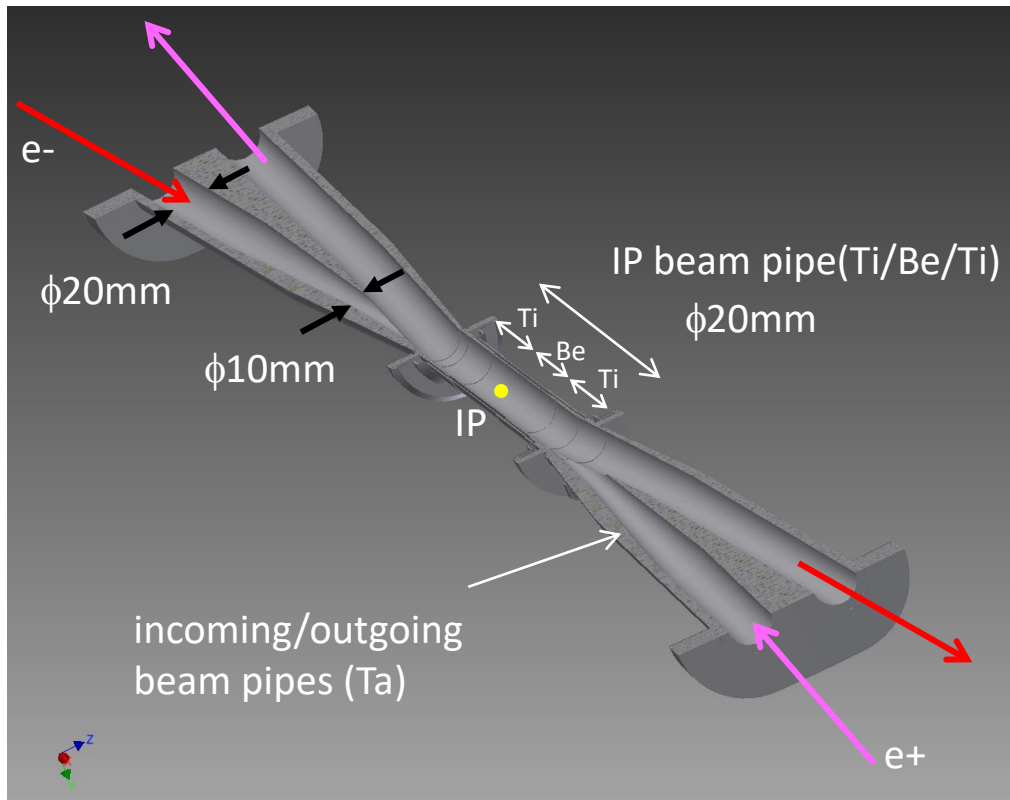
Neutron shield to protect HAPDs in ARICH  
(**Boron-doped Polyethylene**)

ECL shield to protect photodiodes  
(**Lead** + **Polyethylene**)

Remote Vacuum Connection structure  
in front of QCS reduces showers from  
RBB loss at  $|s| \sim 60\text{cm}$  (6cm-thick SUS)

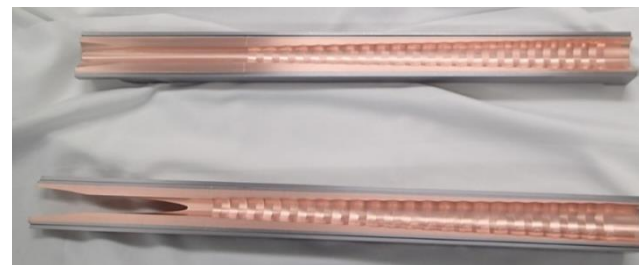


# Dedicated IP beam pipe design to mitigate synchrotron radiation BG



- Belle II IP beam pipes are specially designed to mitigate SR background
- **Collimation on incoming beam pipe** ( $\phi 20\text{mm} \rightarrow \phi 10\text{mm}$ ) 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 (10 $\mu\text{m}$ )



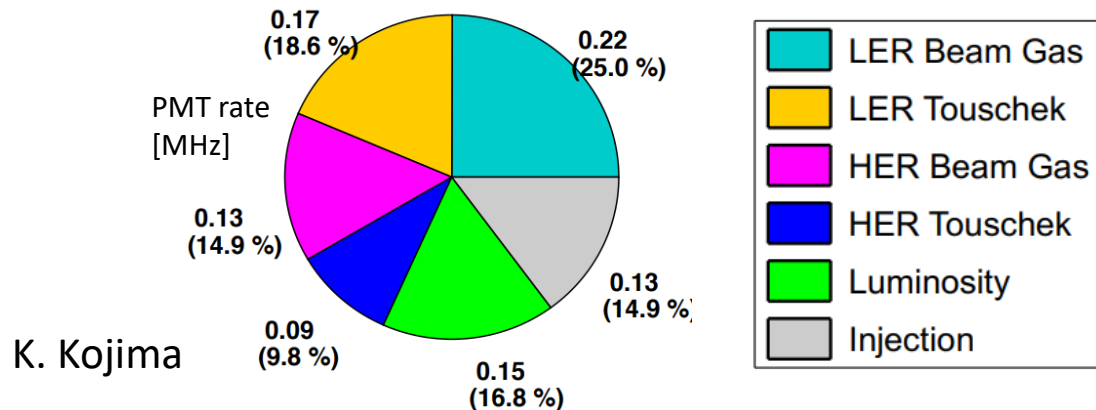
Ridge structure

# Background measurements (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



June 28, 2020  
 $\beta^* \gamma = 0.8 \text{ mm}$

Input values  
to calculate background rate.

$$\begin{aligned} I_{\text{HER}} &= 500 \text{ mA} \\ \sigma_y^{\text{HER}} &= 34 \text{ } \mu\text{m} \\ N_b^{\text{HER}} &= 978 \end{aligned}$$

$$\begin{aligned} I_{\text{LER}} &= 480 \text{ mA} \\ \sigma_y^{\text{LER}} &= 66 \text{ } \mu\text{m} \\ N_b^{\text{LER}} &= 978 \end{aligned}$$

$$\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

e<sup>-</sup> (7GeV,HER)  
e<sup>+</sup> (4GeV,LER)

# Separate measurement of each BG component

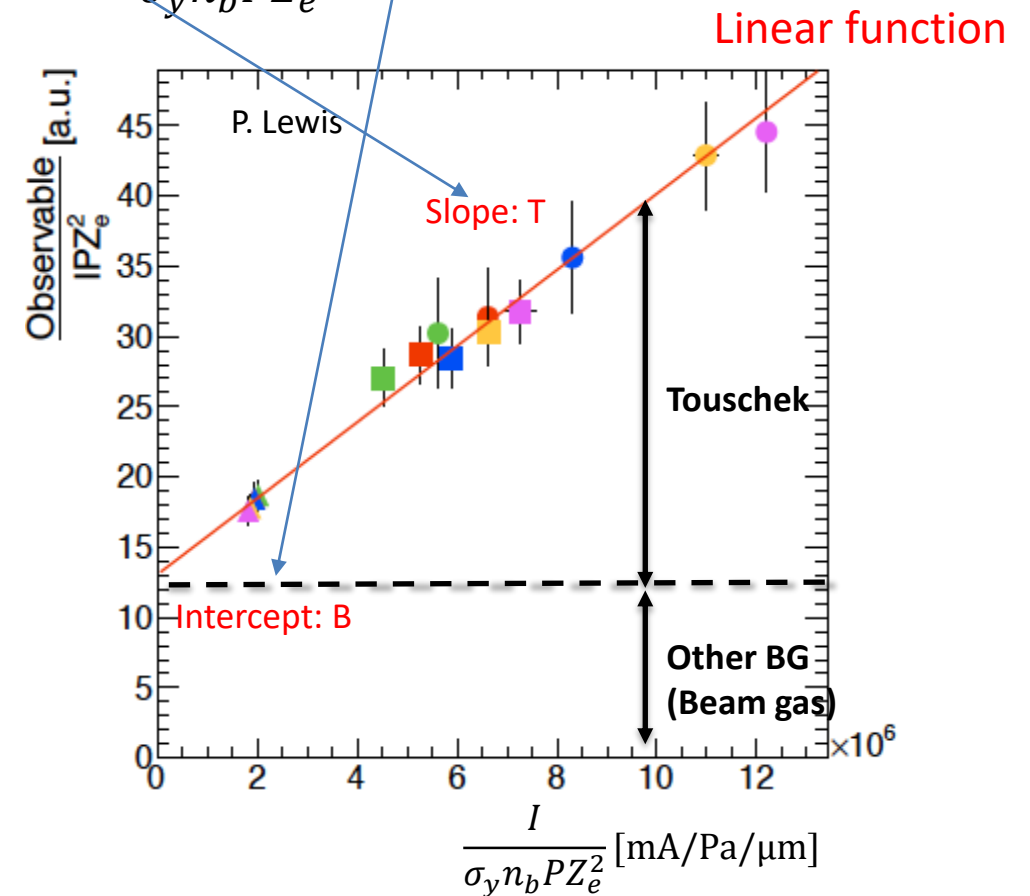
$$Rate = T \frac{I^2}{\sigma_y n_b} + B Z_e^2 IP \quad \xrightarrow{P = P_0 + cI} \quad Rate/Z_e^2 IP = T \frac{I}{\sigma_y n_b P Z_e^2} + B$$

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

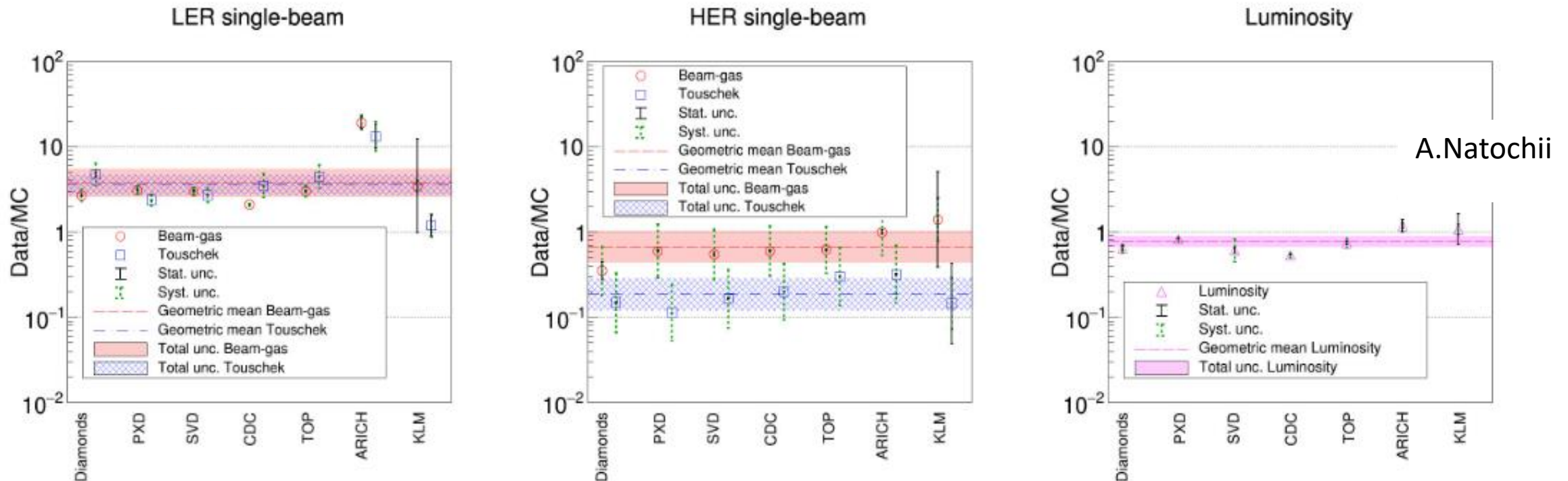
Touschek component also depends on bunch length  $\sigma_z$

## Strategy:

- 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



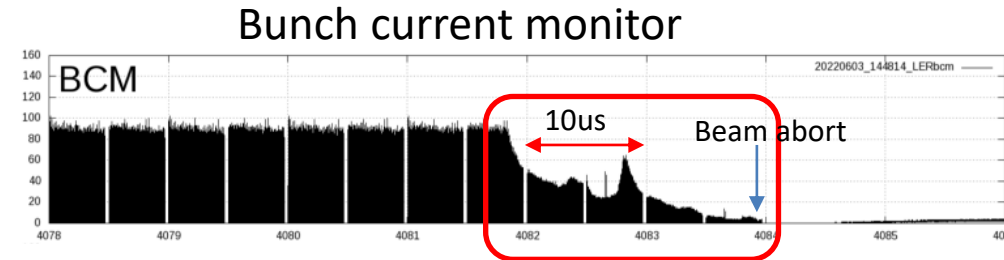
# Data/MC ratio of each BG component



- 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)

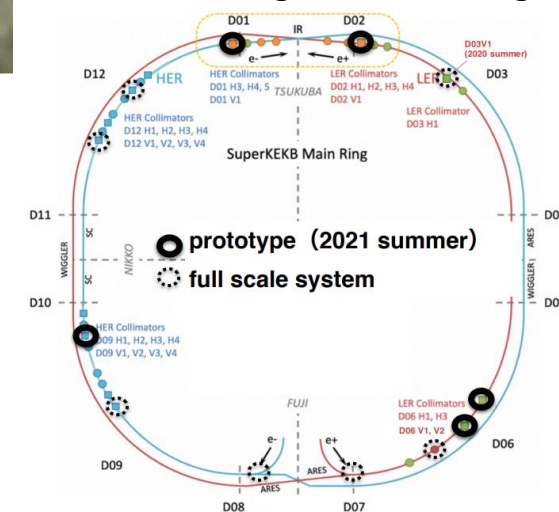
- Sudden beam loss (SBL) events
  - Very fast beam loss within few turns (= 20-30 us)
  - Lead to QCS quench, sensor/collimator damage
  - Seems to occur at higher (bunch) currents
  - Showstopper for high luminosity challenge
- The cause of SBL? -- still unknown
  - Beam-dust event? Beam instability? 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](#)
  - [Beam Dust Workshop at CERN](#) next week (presentations by H.Ikeda, T.Abe)



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



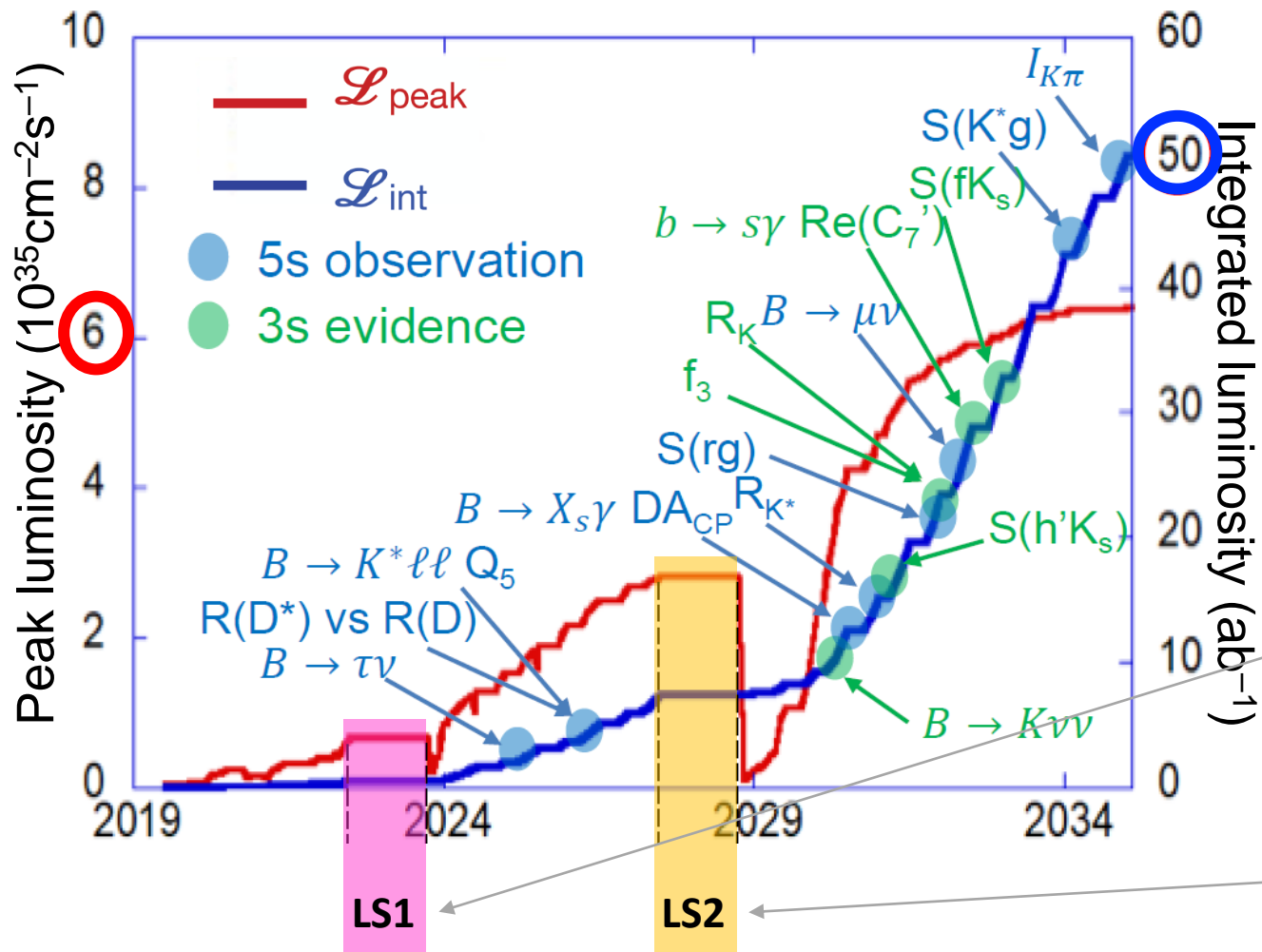
Beam loss monitors along the main ring





# The road towards 50 $\text{ab}^{-1}$

Anticipate a rich abundance of physics results



Need to increase beam currents ( $I=1 \rightarrow 3 \text{ A}$ ) and squeeze IP beam-size ( $\beta^* y = 1.0 \rightarrow 0.3 \text{ mm}$ )

## Key challenges:

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

my area of expertise !

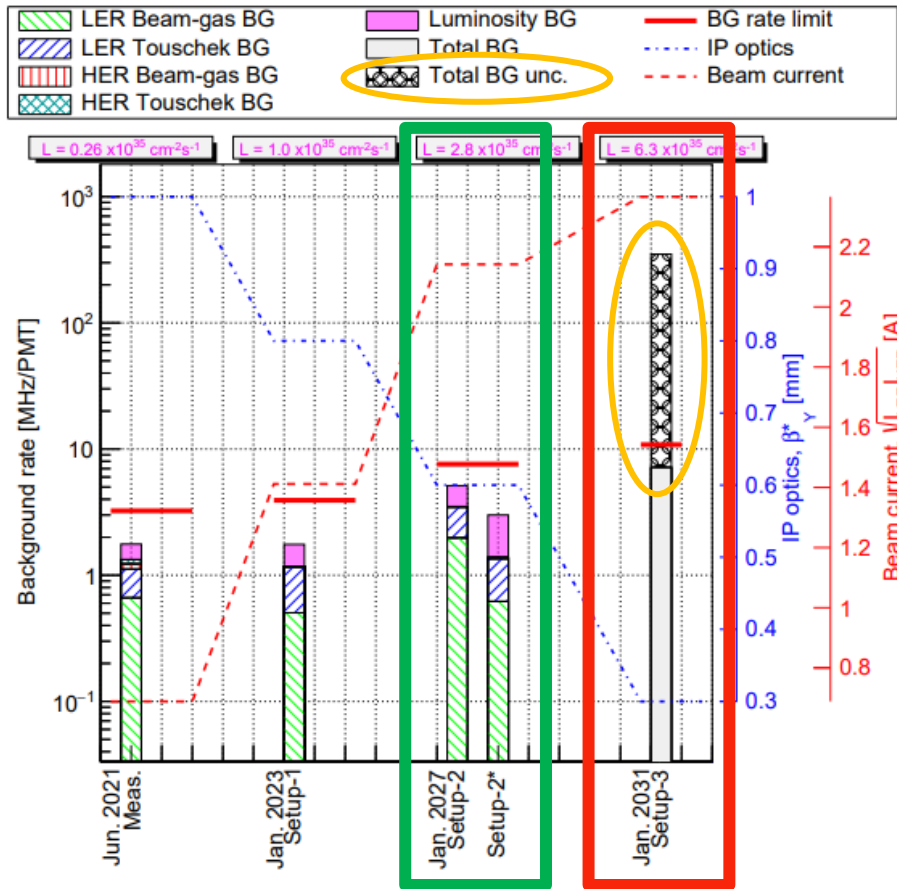
## Long Shutdown 1 (LS1)

- 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  $\text{L}_{\text{peak}} = 6 \times 10^{34} / \text{cm}^2 / \text{s}$

# Future extrapolation of beam background



Snowmass paper (arxiv:2203.05731)

- Beam background has been acceptable so far, up to  $L = 4.7 \times 10^{34} / \text{cm}^2/\text{s}$  for  $\beta^* y = 1.0 \text{ mm}$
- According to the latest studies, beam background will remain high but acceptable up to:  
 $L = 2.8 \times 10^{35} / \text{cm}^2/\text{s}$  for  $\beta^* y = 0.6 \text{ mm}$
- Toward the target luminosity of the SuperKEKB:  
 $(L = 6 \times 10^{35} / \text{cm}^2/\text{s} \text{ for } \beta^* y = 0.3 \text{ mm})$   
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**

# Summary

- Beam background at SuperKEKB is very dangerous and various countermeasures have been implemented
- Interaction region of SuperKEKB is carefully designed to mitigate beam background
- Machine studies are carried out to measure beam background components and demonstrate the validity of our simulation
- To achieve the target luminosity, we need a novel idea/technology

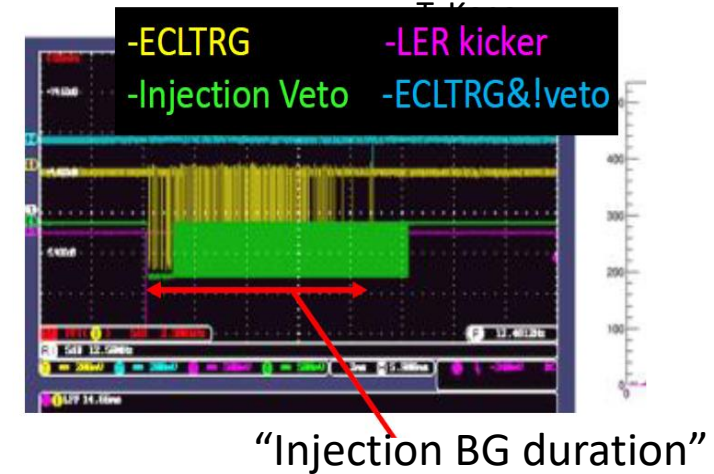
# Job Opportunities

- We are looking for a new KEK postdoc(s) working for the Belle II MDI group
  - 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 operation in ~6 month. Good opportunity to gain valuable experiences in the operating machine!
- If you're interested (or you know a good candidate), please contact me!
  - [hiroyuki.nakayama@kek.jp](mailto:hiroyuki.nakayama@kek.jp)

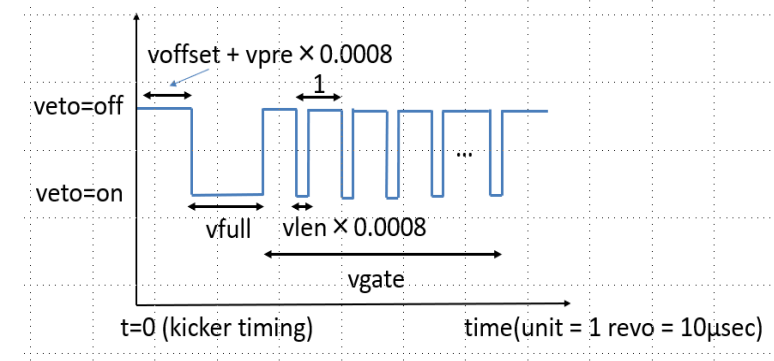
backup

# 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  $\rightarrow$  LER:  $\sim 10\text{ms}$ , HER:  $\sim 5\text{ms}$ 
  - Corresponds to 5~10% deadtime
  - longer veto window  $\rightarrow$  lose integrated luminosity
- In 2022 runs, injection BG duration gets worse with squeezed beta\*y ( $=0.8\text{mm}$ ), higher beam currents, and after severe LER collimator damage
  - Larger BG observed even in recorded events (outside veto)
  - Impact on physics performance started to be seen
- Many improvements in LINAC/BT are planned during LS1 and later



Injection veto window

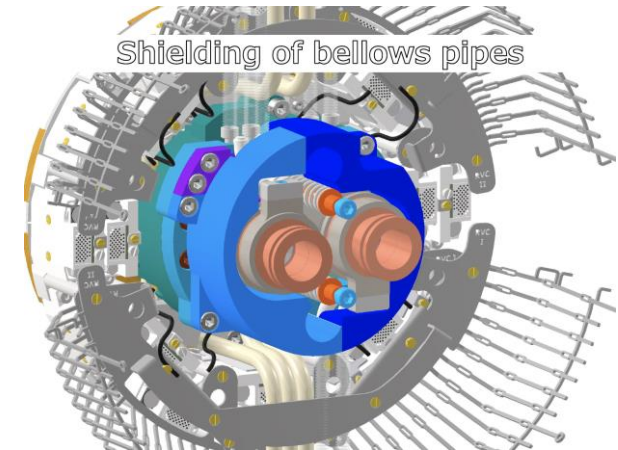




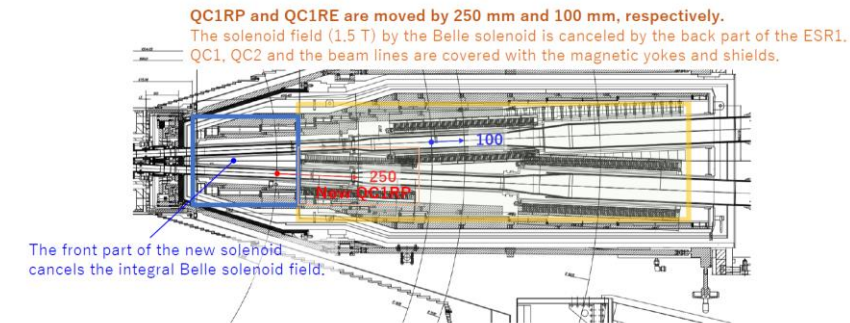
# Further BG mitigation possibilities

- Vacuum scrubbing
  - beam-gas background will be gradually improved as baking proceeds
- Collimators
  - “Non-linear collimator” with low impedance budget (2023)
  - Achieve better BG mitigation while avoiding TMC instability
- Additional shield around QCS bellows (2023)
  - Cover the bellows pipe area where BG showers leak out
  - Only small space left for the shield (mostly occupied by sensor cables)
  - Further BG reduction for TOP/CDC
- Final focus magnet modification (2026 or later?)
  - Less overlap of solenoid and quads → suppress beam-beam blowup
  - Wider beam pipe aperture → less beam loss, wider collimator and relax collimator impedance
  - Design not finalized yet

Additional shield around QCS bellows



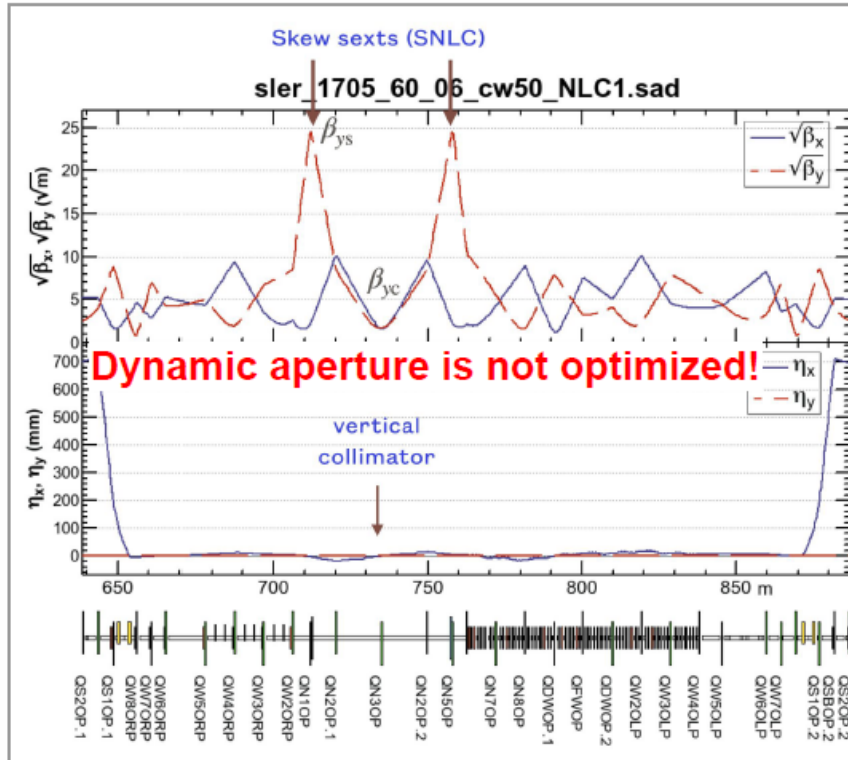
Final focus magnet modification



# 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  $\beta_{x/y} \sim 3\text{m}$
- **Vertical angular kick** for distant halo particles in both planes  $\Delta p_y \sim (y^2 - x^2)$
- A big aperture step  $\sim 1\text{mm}$  affects  $< 4\sigma$  at the QC1  $\rightarrow$  fine tuning with the NLC
  - For other V-collimators:  $\sim 1\text{mm}$  step  $\Rightarrow 20\text{-}40\sigma$  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,  $y_q = 10.0\text{ mm}$  at QC1 ( $30\sigma_y$  with  $\varepsilon_y/\varepsilon_x = 2\%$ ).
- It is equivalent to  $y_s = y_q \sqrt{\beta_{ys}/\beta_{yq}} = 6.8\text{ mm}$  at the NLC skew sextupole SNLC.
- The sextupole kicks the beam vertically by

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

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

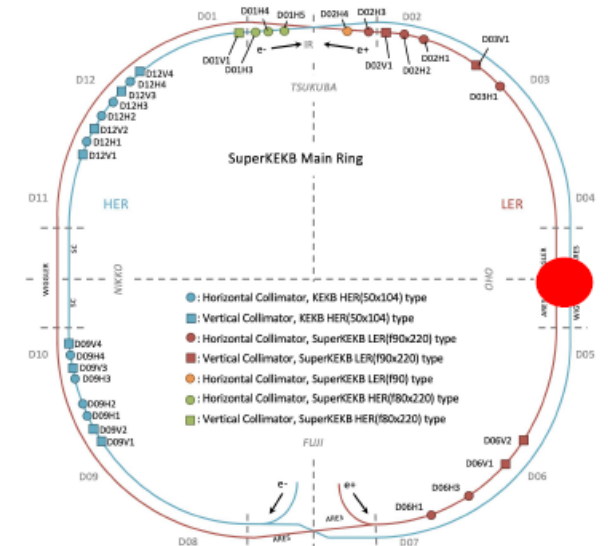
- For instance,  $s' = 6.0/\text{m}^2$ ,  $\Delta p_{ys} = 0.14\text{ mrad}$ , with  $|y_s| \gg |x_s|$ .

- Then the kick makes a vertical displacement at the collimator:

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

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

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



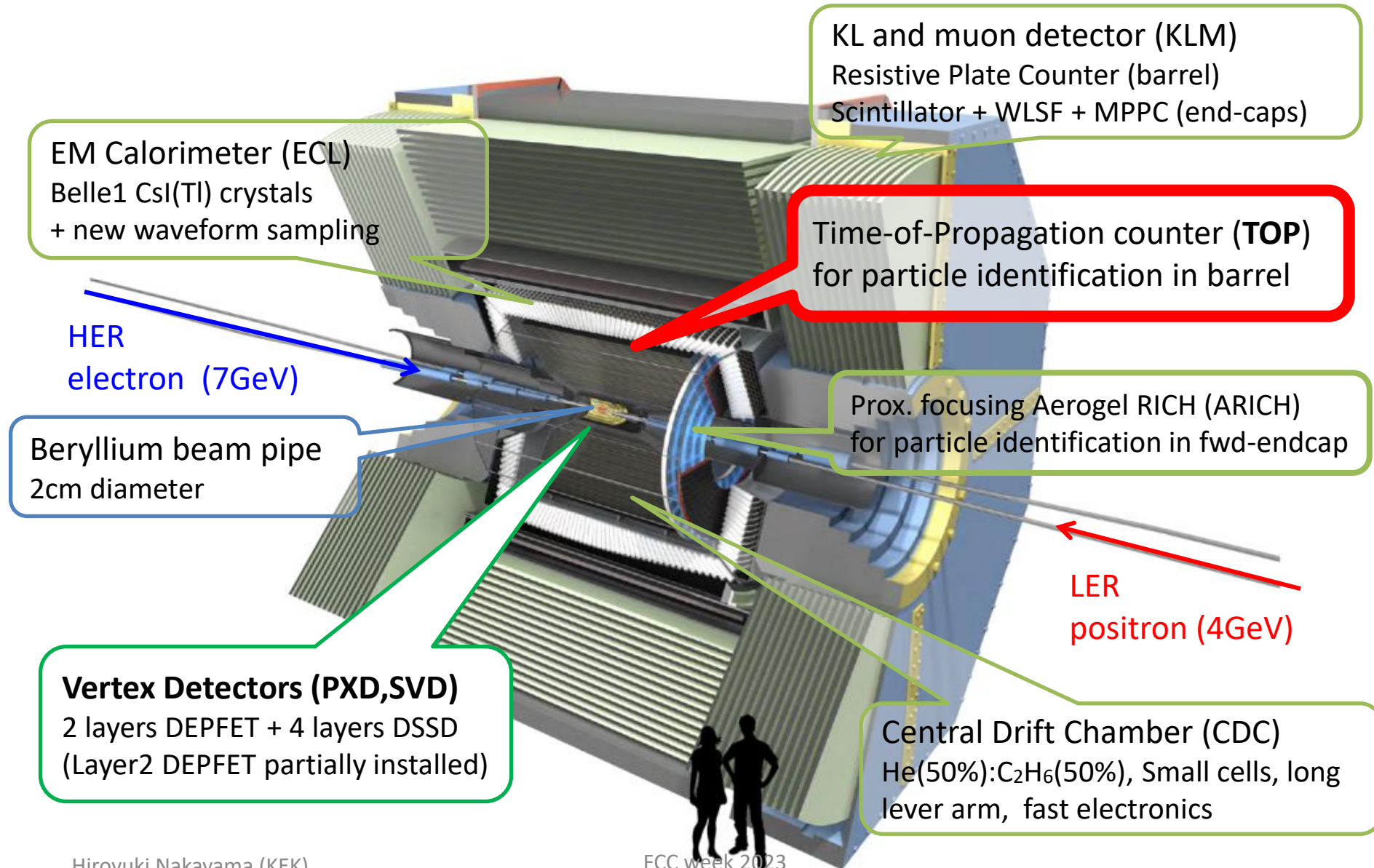
# NLC benefits

- 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  $\beta_y^* = 0.6$  mm,  $\sim 1\sigma$  of the aperture change at QC1
    - D06V1:** 55  $\mu\text{m}$  step
    - D02V1:** 25  $\mu\text{m}$  step
    - NLC:** 250  $\mu\text{m}$  step

- 1) Although the Belle II background is below the detector limit at  $\beta_y^* = 0.6$  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  $\beta_y^* = 0.3$  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  $\rightarrow$  **need more studies,  $\beta_y^* = 0.3$  mm optics with NLC is not available for now**.

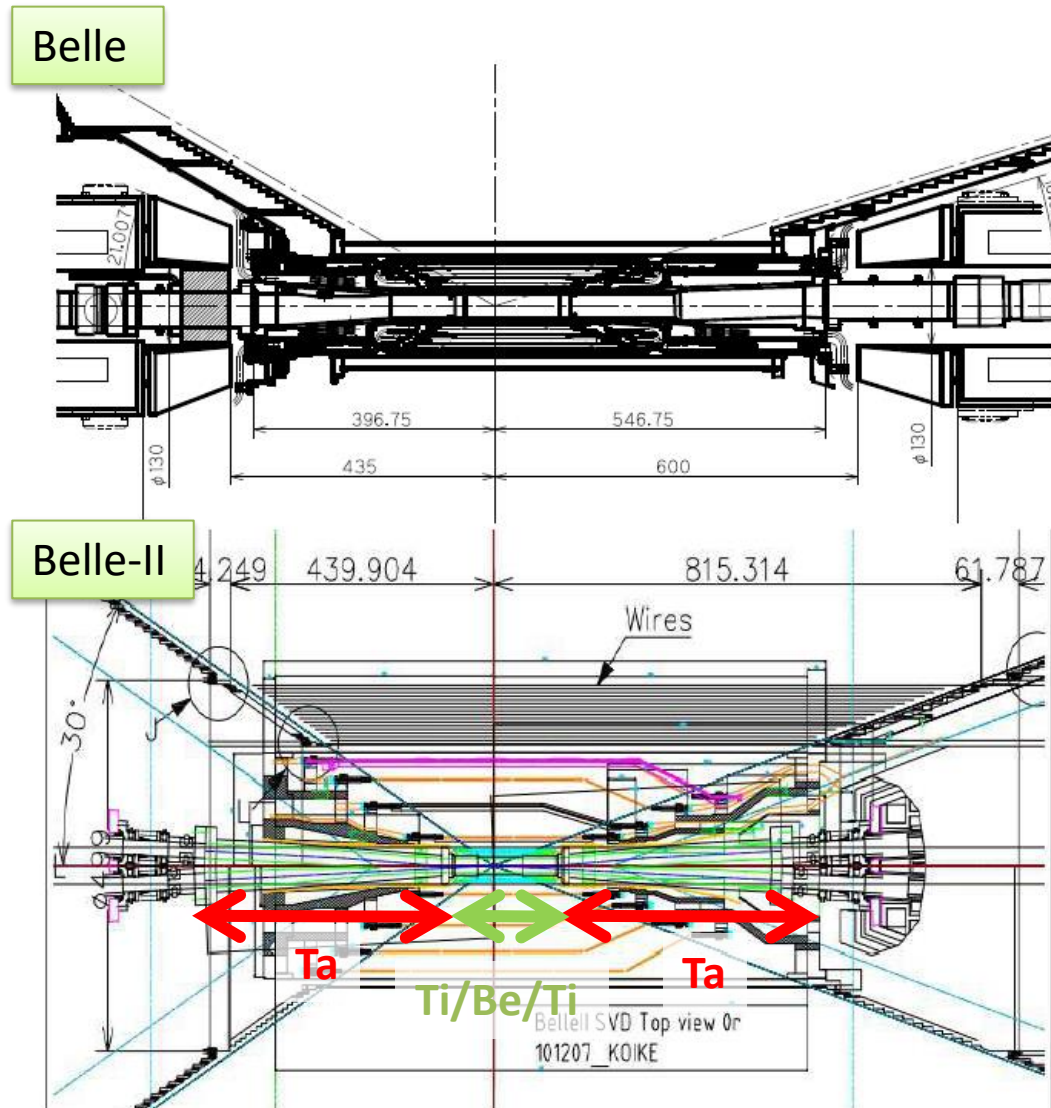


# Where's "TOP" in Belle II Detector



# MDI design

# Interaction region

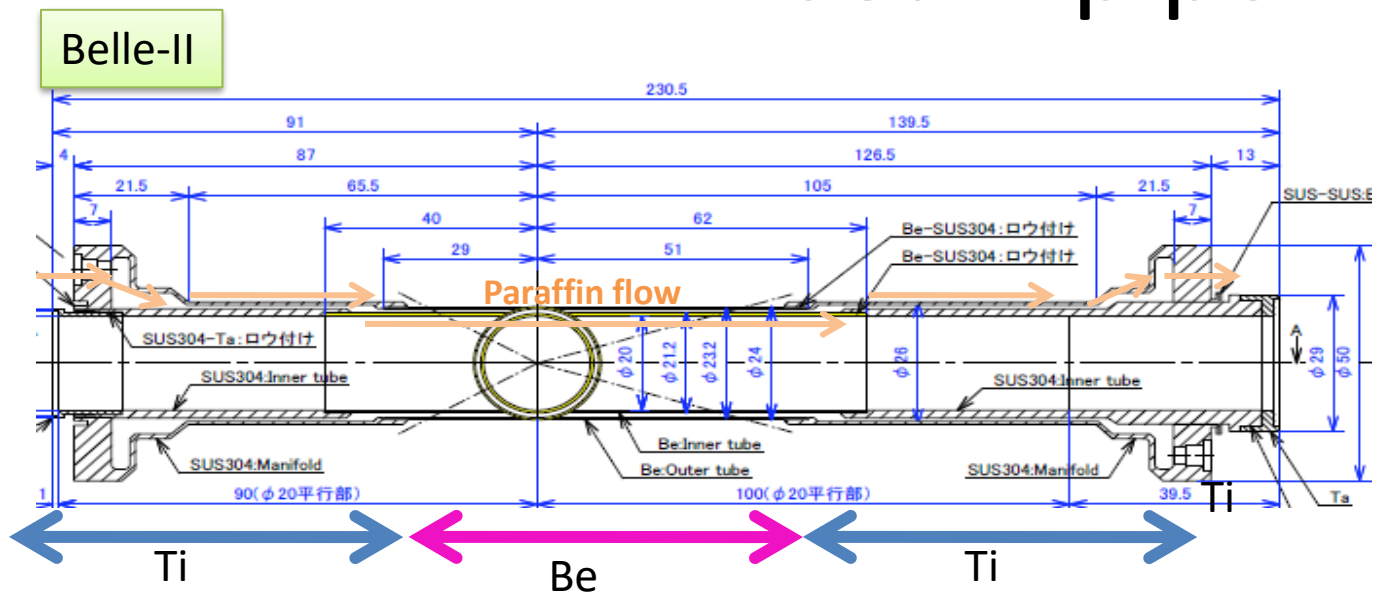


## <Belle-II>

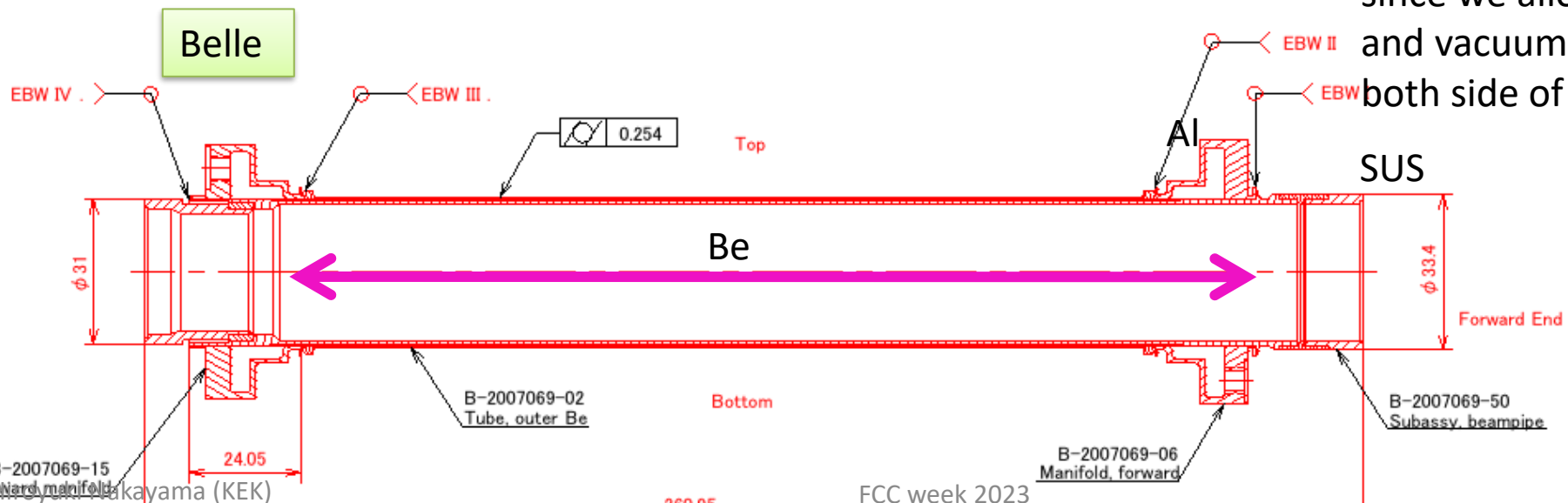
- Smaller IP beam pipe radius ( $r=15\text{mm} \Rightarrow 10\text{mm}$ )
- Wider beam crossing angle ( $22\text{mrad} \Rightarrow 83\text{mrad}$ )
- Crotch part: Ta pipe
- Pipe crotch starts from closer to IP, complicated structure
- New detector: PXD (more cables should go out)



# IP beam pipe



- Light material (Be) inside detector acceptance
- Paraffin ( $C_{10}H_{22}$ ) flow to remove heat from mirror current ( $\sim 80W$ )
- Gold plating ( $\sim 10\mu m$ ) 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



# 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

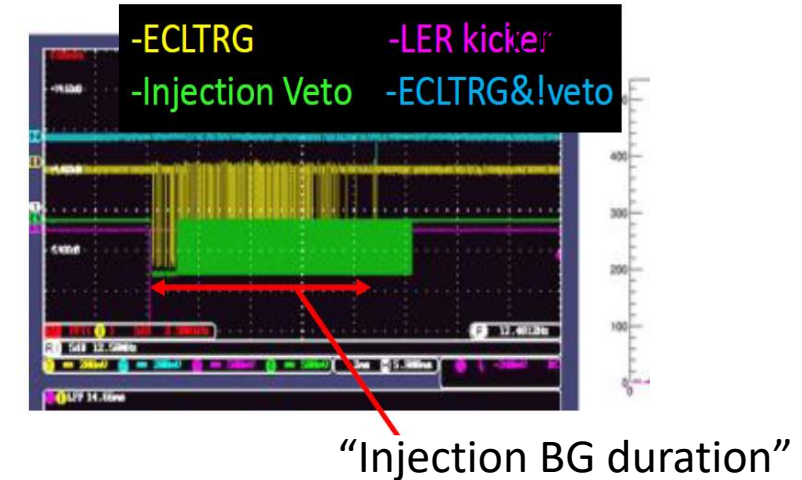
[1] Y. Ohnishi et al., PTEP **2013**, 03A011 (2013).

[2] SAD is a “Home-brew” tracking code by KEKB group, <http://acc-physics.kek.jp/SAD/>

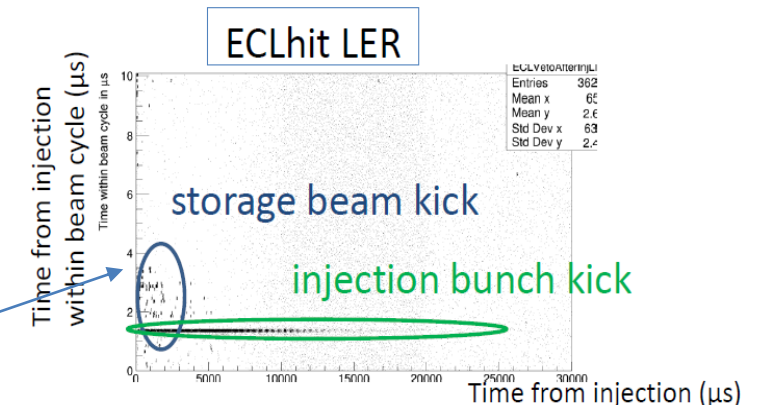
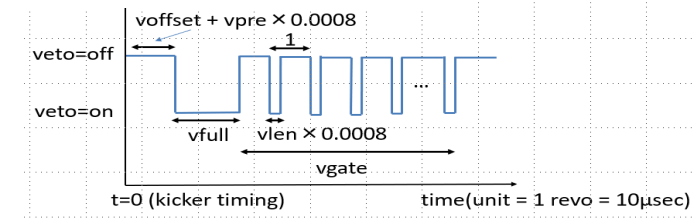
# BG measurements

# 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  $\rightarrow$  LER:  $\sim 10\text{ms}$ , HER:  $\sim 5\text{ms}$ 
  - Corresponds to 5~10% deadtime
  - longer veto window  $\rightarrow$  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  $\propto$  bunch current
  - Colliding beams: BG duration longer than single-beam
    - $\rightarrow$  *beam-beam effect?*
  - Not only the injected bunch, but also later bunches are lost. However, “blank-shot” injections don’t give any BG duration
    - $\rightarrow$  *Coupling btw. injected bunch and later bunches?*
    - Delayed arrival of neutrons generated at upstream collimators?*
  - Simulation effort to reproduce these behaviors is ongoing



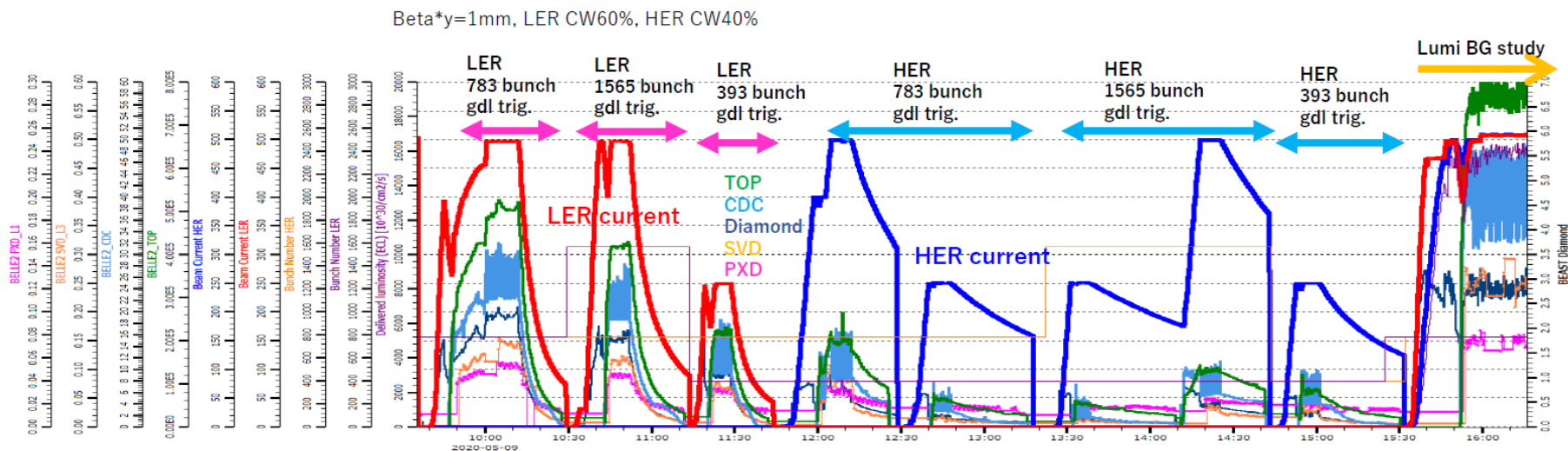
Injection veto window



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

# A snapshot from a single-beam BG study

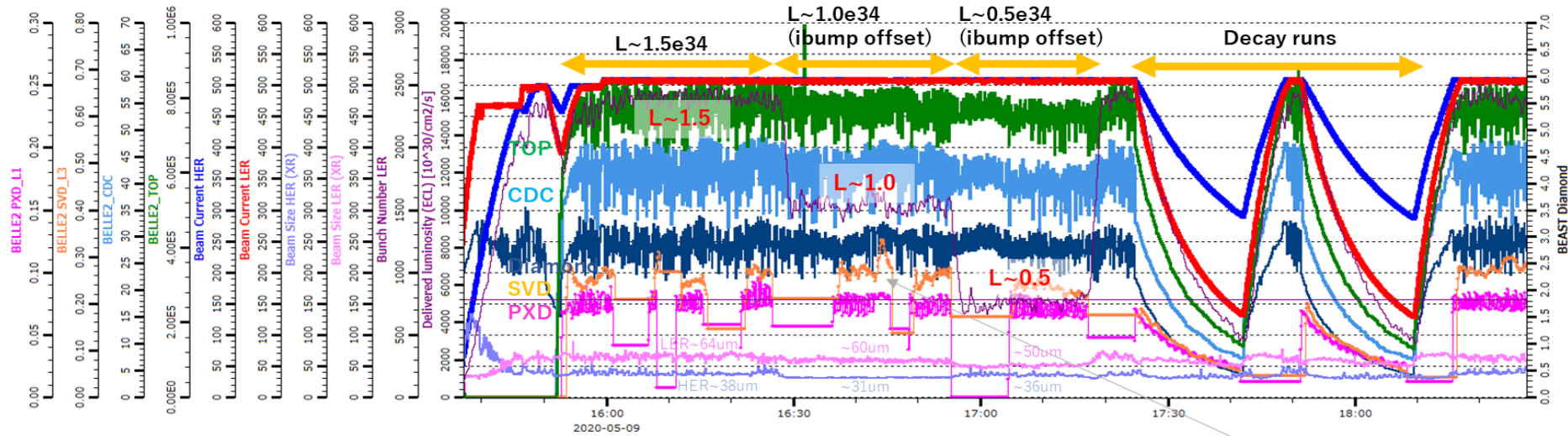
Example: LER/HER single-beam study on May 9<sup>th</sup>, 2020



- 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.
- Observed dependency are consistent with the “Touschek+ Beam-gas” model (no significant indication of other BG sources)

# A snapshot from a Lumi-BG study

Beta\* $\gamma$ =1mm, LER CW60%, HER CW40%

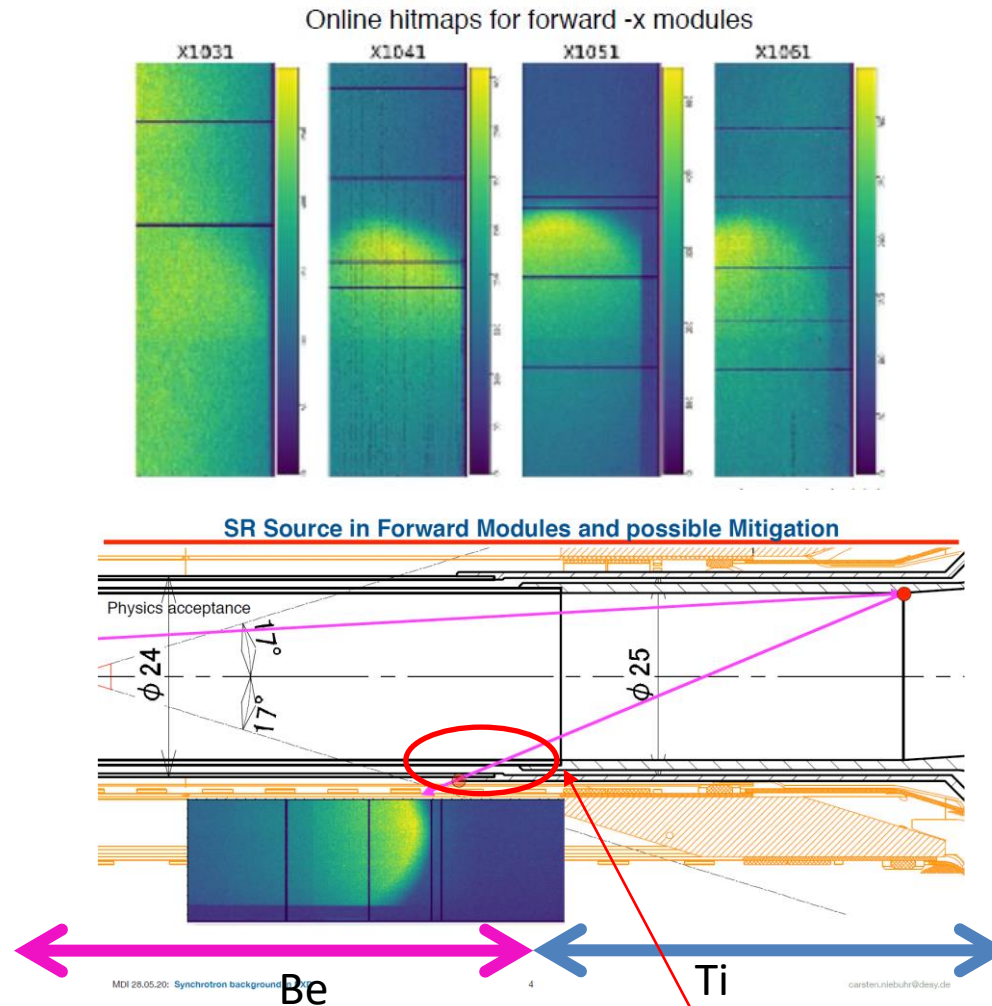


- “Continuous injection” runs
  - $L=1.5 \rightarrow 1.0 \rightarrow 0.5e34$ , by vertically displacing two beams (“ibump V-offset”)
  - Beam sizes slightly changes as luminosity changes
- “Beam decay” runs (no injections)
  - Measurement not affected by injection BG
- Measure lumi-BG component by subtracting single-beam BG components scaled with current, beam size, etc..
- Measured Lumi-BG agrees with simulation at the  $\sim 10\%$  level in TOP, PXD !!
  - Also agrees between “continuous injection” and “beam decay” data



# Issues: PXD SR during HER injection

Carsten



- SR hit pattern on PXD forward -X modules
- Became stronger when HER beta\*\_x was squeezed
- **Only visible during HER injection**
  - not observed with “blank-shot” HER injections
- HER horizontal tune adjustment shows no significant improvement within acceptable tune range
- HER D01H collimator adjustment didn't improve SR

PXD SR is not critical right now, but we need to keep our eyes on it.

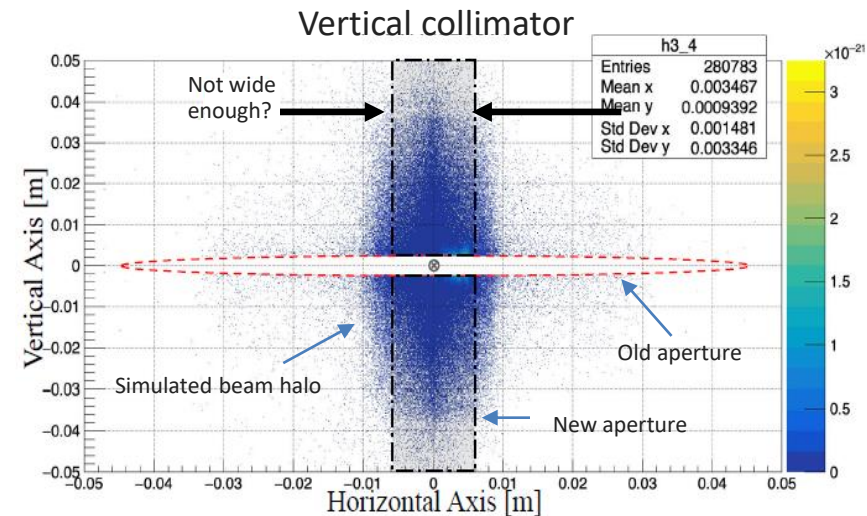
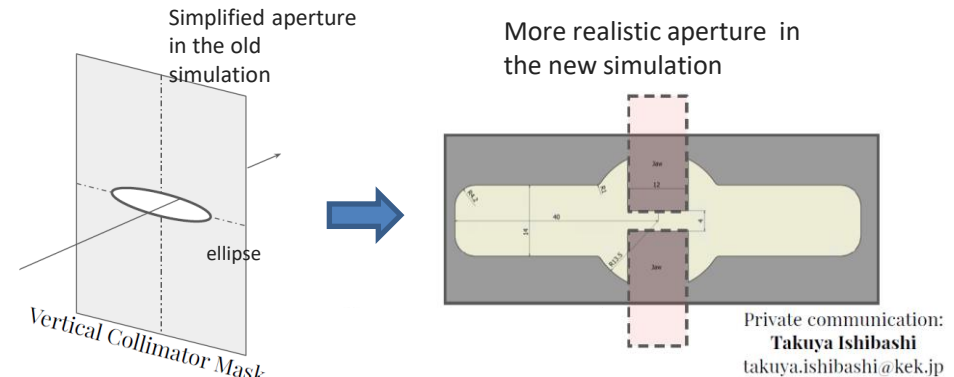
We plan to add gold layer here for the new beam pipe (2022)



# Recent improvements to simulation

A. Natochii

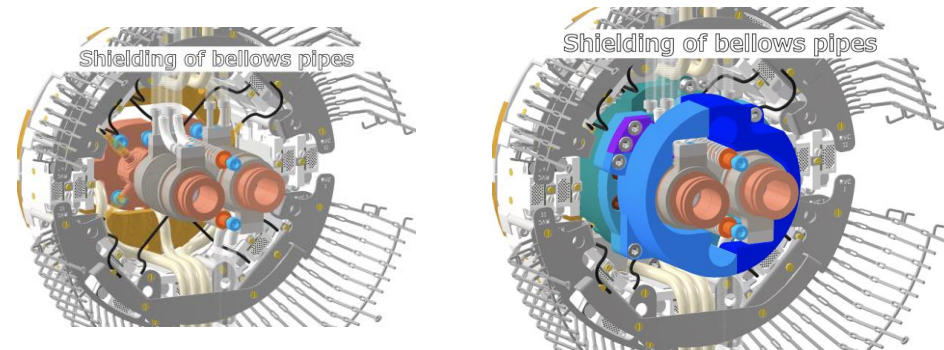
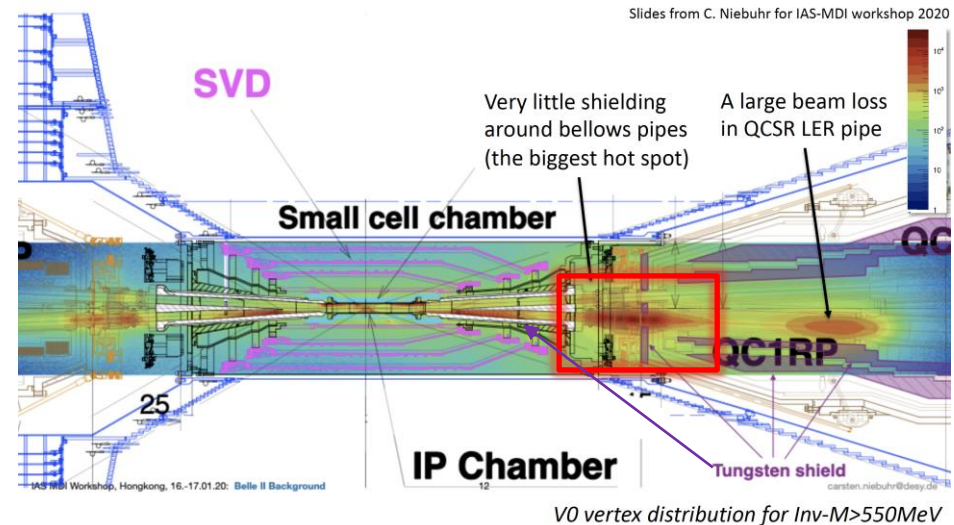
- **Andrii Natochii** implemented an improved framework for beam-particle tracking in SuperKEKB
  - New features: apply collimation after particle tracking, pressure-weighted beam-gas simulation, custom beam pipe aperture shapes, etc..
- Largest impact: implementation of **correct SuperKEKB collimator 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.)



# Mitigation ideas: Bellows shielding

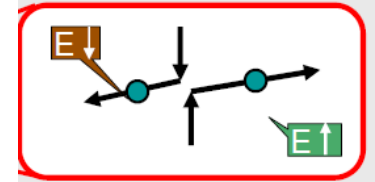
- To reach design luminosity, we need further background mitigation.
- One of ongoing project is an additional shield around bellows pipe where we see “hot spot” in data (also seen in simulation).
- Showers generated at  $z=1\text{m}$  leak out to the detector from the bellows part, where we cannot put enough shielding due to inner detector cables
- Shield design is ongoing. The beam loss simulation predicts LER coulomb bkg can be reduced by 53% (CDC), 28% (TOP) with this shield. Also effective to suppress Lumi-BG.

## Hot Spots around IR from V0 analysis



# SuperKEKB beam backgrounds

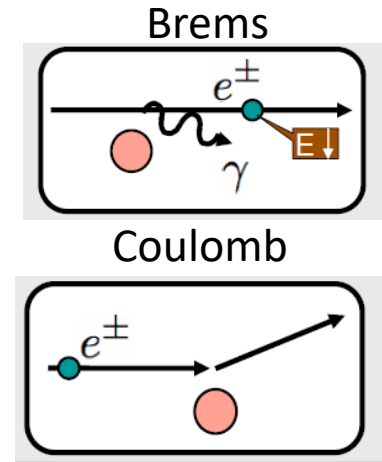
# 1. Touschek scattering



- Intra-bunch scattering :  $\text{Rate} \propto (\text{beam size})^{-1}, (E_{\text{beam}})^{-3}$
- Touschek lifetime: should be >600sec (required by injector ability)
  - ring total beam loss: ~375GHz (LER), ~270GHz(HER)
- **Countermeasure: horizontal collimators in the ring**
  - 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

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

## 2. Beam-gas scattering



- Scattering by remaining gas, Rate  $\propto I \times P$
- Due to smaller beam pipe aperture and larger maximum  $\beta_y$  at SuperKEKB, beam-gas Coulomb scattering could be more dangerous than in KEKB

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

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

- Countermeasures: Vertical collimators in the ring
  - very narrow ( $< \sim 2\text{mm}$ ) collimators
  - **TMC instability issue** at high current
  - Need to install where  $\beta_{y\_}$  is rather small

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

# Where should we put the vertical collimators?

Collimator aperture should be narrower than QC1 aperture.

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

TMC instability should be avoided.

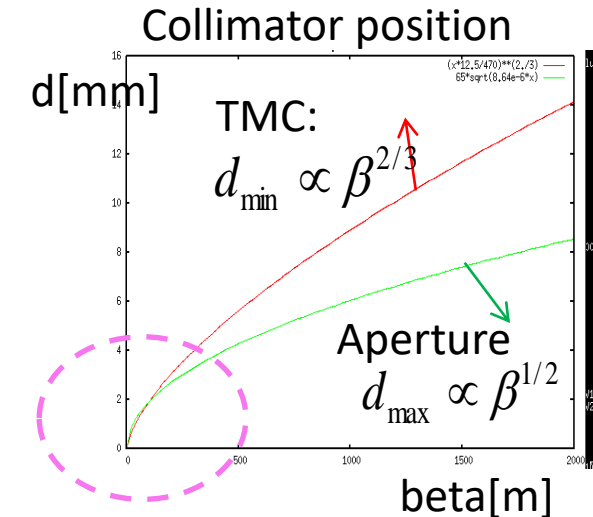
Transverse Mode Coupling  
instability

Assuming following two formulae:

$$I_{\text{thresh}} = \frac{C_1 f_s E / e}{\sum_i \beta_i k_{\perp i}(\sigma_z)} > 1.44 \text{ mA/bunch (LER)}$$

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)



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

**We should put collimator where beta\_y is rather SMALL!**

For more details, please check out following paper:

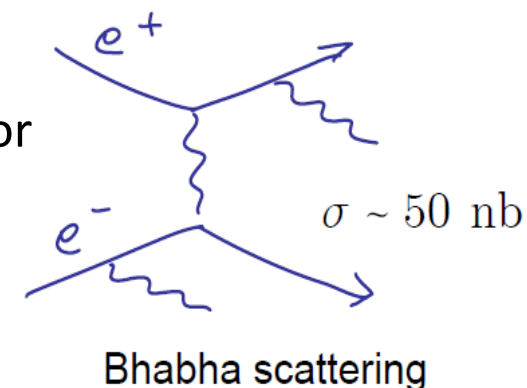
H. Nakayama et al, "Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability", Conf. Proc. C **1205201**, 1104 (2012)



# 4. Luminosity-dependent background

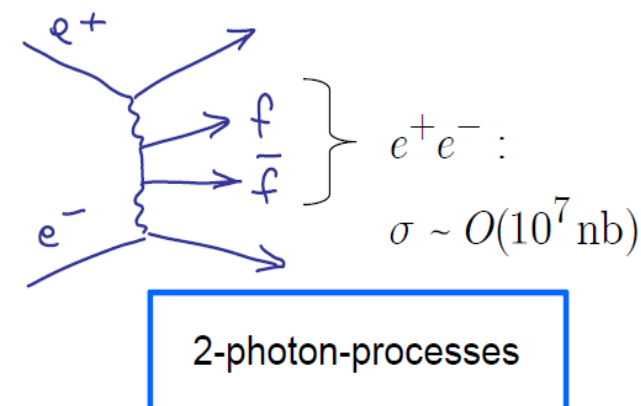
## Radiative Bhabha scattering

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

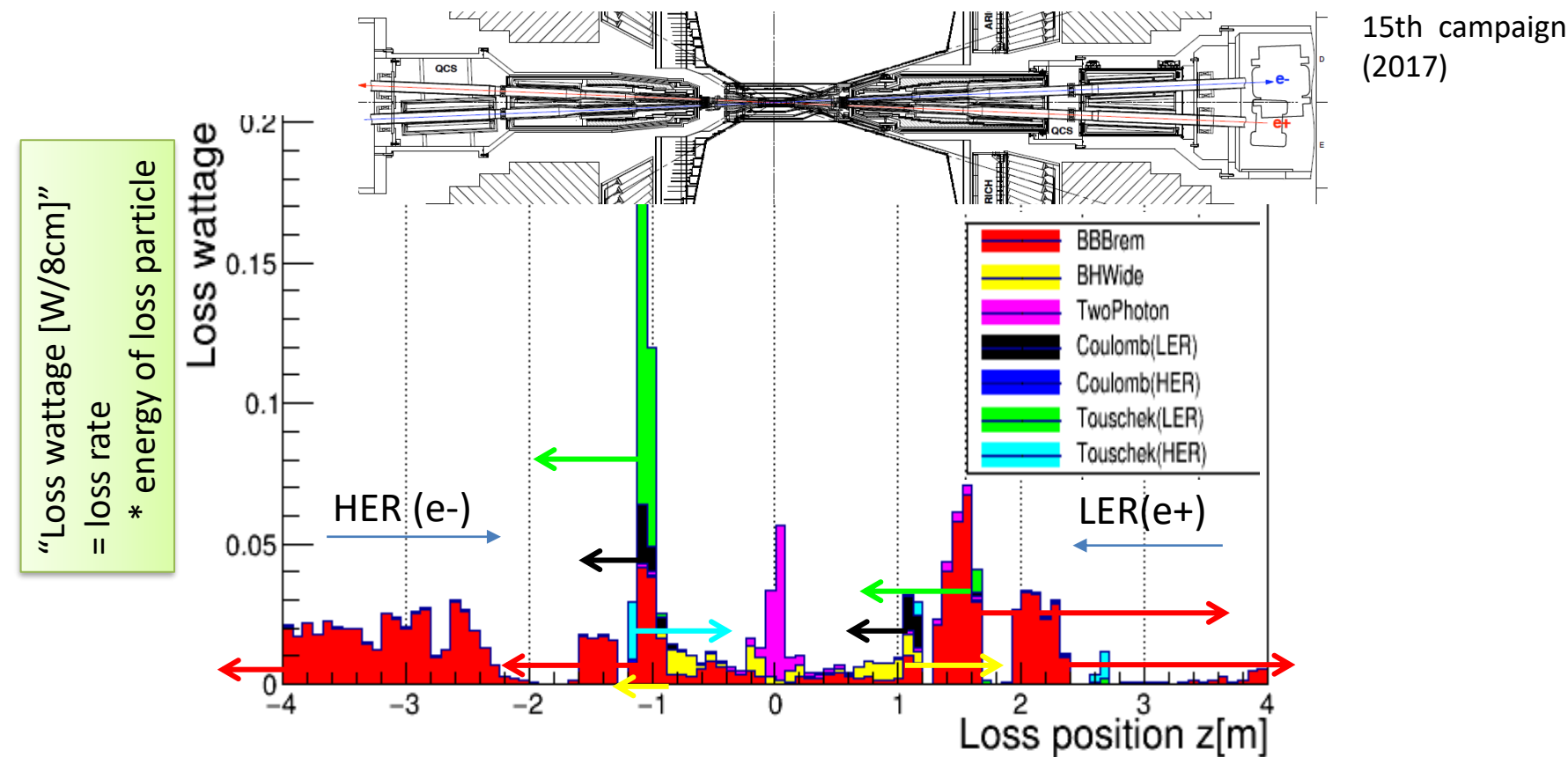


## 2-photon process

- Rate  $\propto$  Luminosity (KEKBx40)
- $e^+ e^- \rightarrow e^+ e^- e^+ e^-$
- Emitted  $e^+e^-$  pair curls by solenoid and might hit inner detectors multiple times

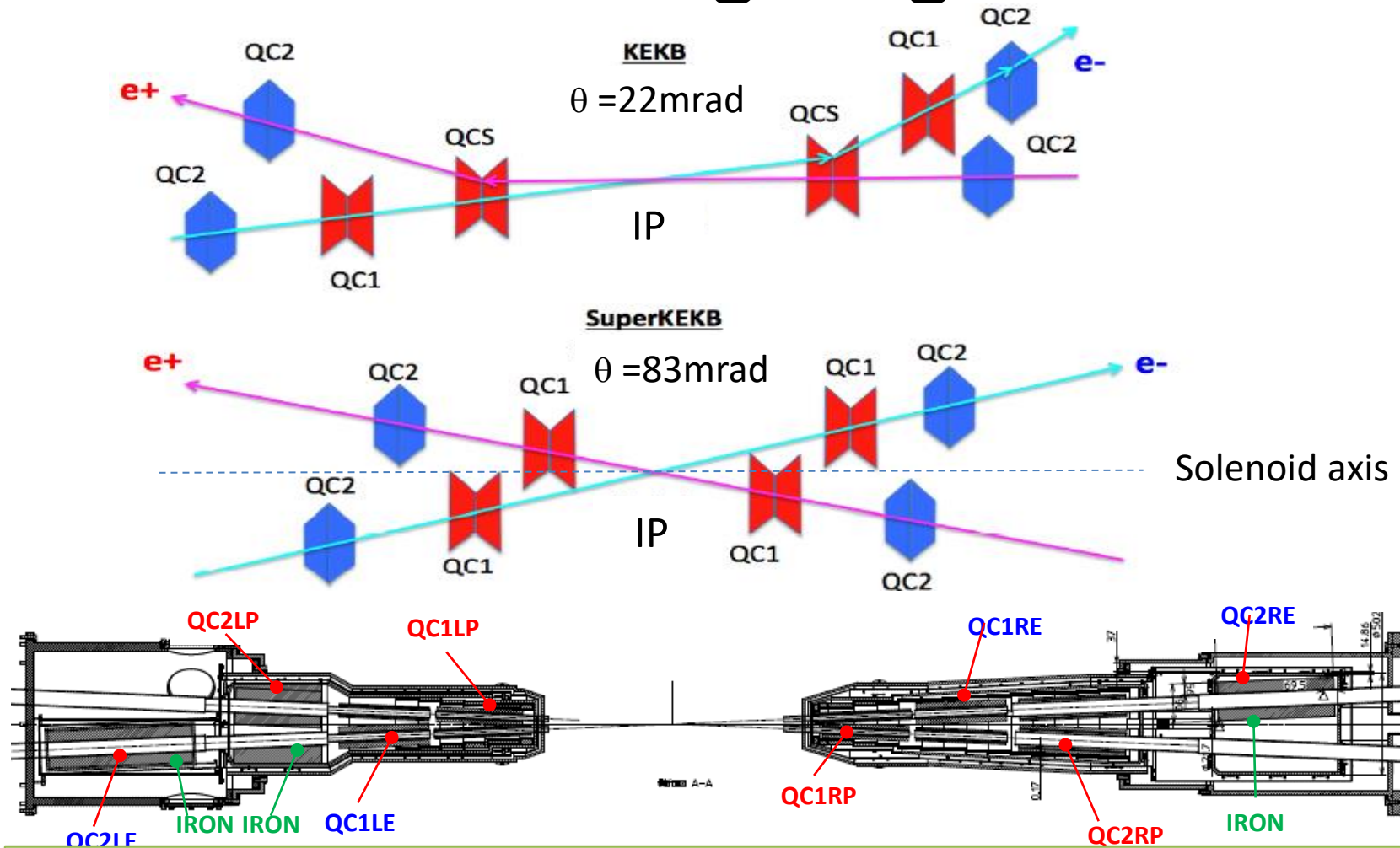


# Simulated IR beam loss distribution (design luminosity)



	LER (4GeV e+)	HER (7GeV e-)
Lumi-dependent BG	BBBrem: <b>1.08 W</b> (0.06 W in $ z  < 65\text{cm}$ ) 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)

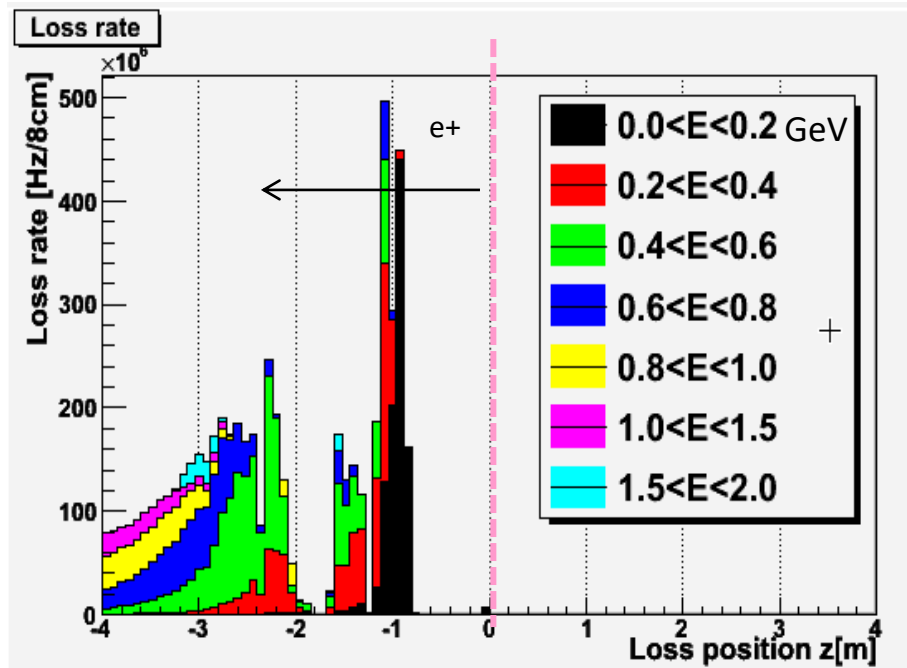
# Final focusing magnets



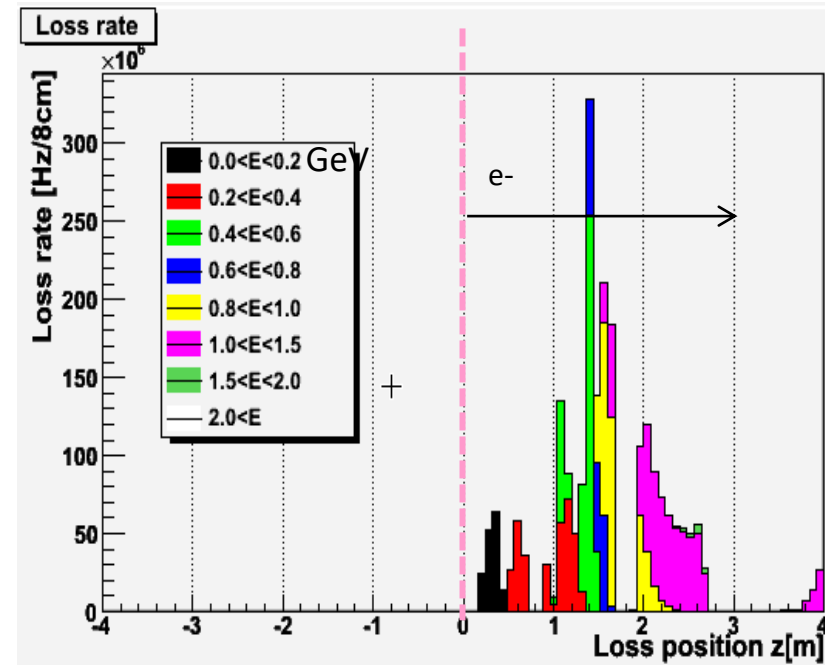
- Larger crossing angle  $\theta$  than KEKB
- Final Q for each ring  $\rightarrow$  more flexible optics design
- No bend near IP  $\rightarrow$  less emittance, less background from spent particles

# Spent e<sup>+</sup>/e<sup>-</sup> loss position after RBB scattering

LER(orig. 4GeV)



HER(orig. 7GeV)



If  $\Delta E$  is large and e<sup>+</sup>/e<sup>-</sup> 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)

LER

xはトンネル外向きが+、yは下向きが+



Hiroyuki Nakayama (KEK)

# MDI design



# How to cope with those beam BG?

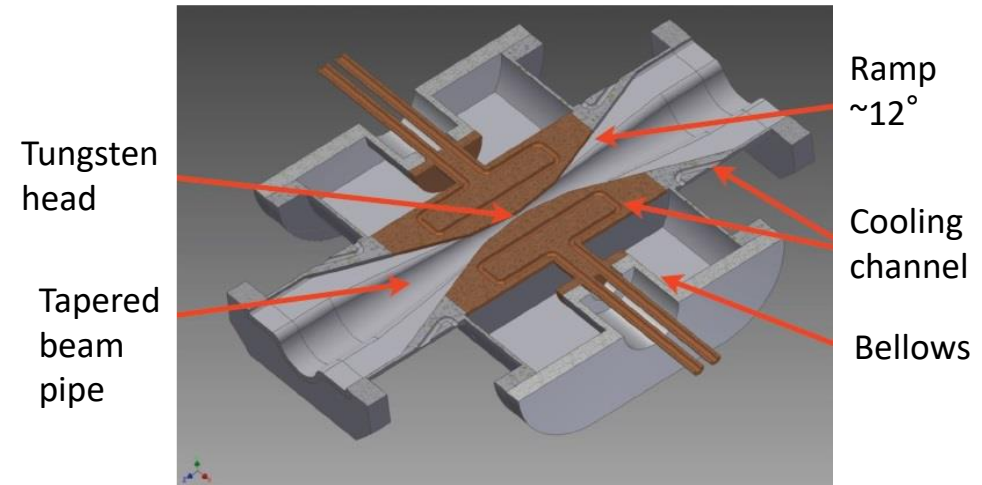
- Movable collimators

- Horizontal collimators at arc sections and the straight section near IP for Touschek BG
- Very narrow ( $\sim < 2\text{mm}$  half width) vertical collimators for Beam-gas BG

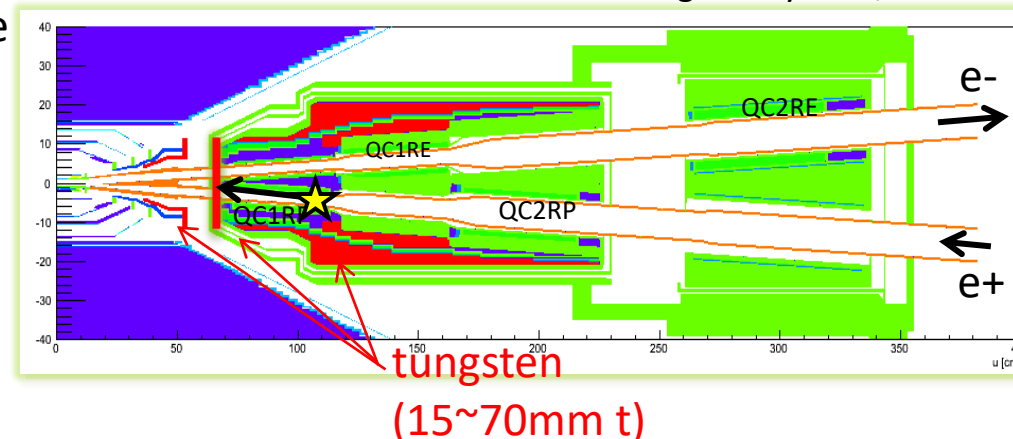
- Shielding structures

- Thick tungsten structures inside final focus cryostat and vertex detector volume
- Stops showers from beam loss “hot spot” ★ at  $\sim 1\text{m}$  upstream from IP (maximum  $\beta_y$ )
- Polyethylene shields for neutrons

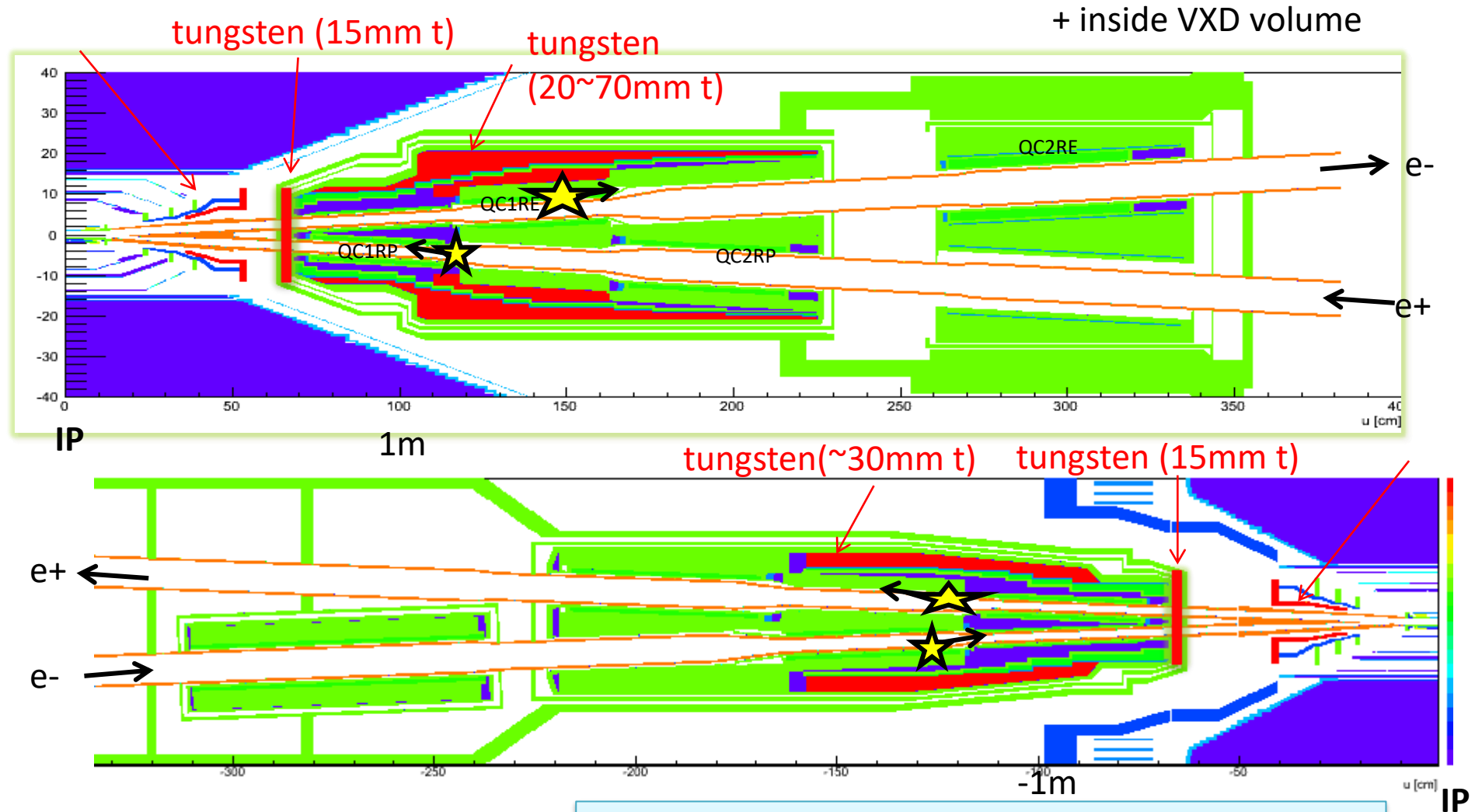
SuperKEKB horizontal collimator



Final focus magnet cryostat, R-side



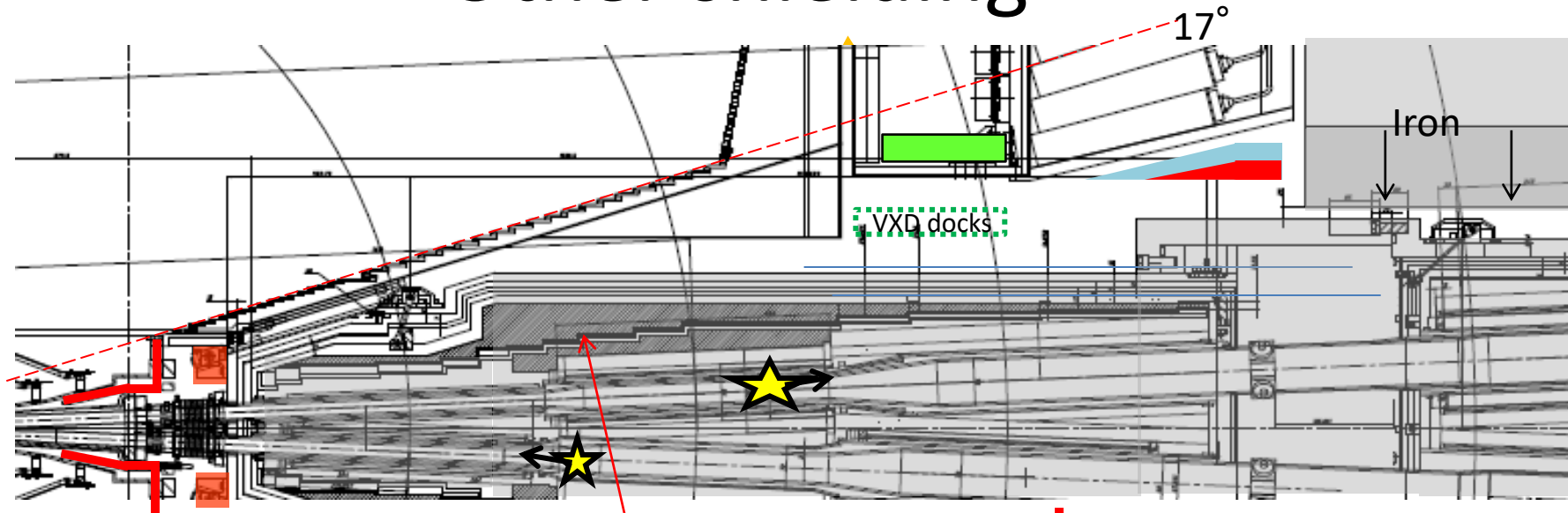
# Tungsten shields inside final focus cryostat



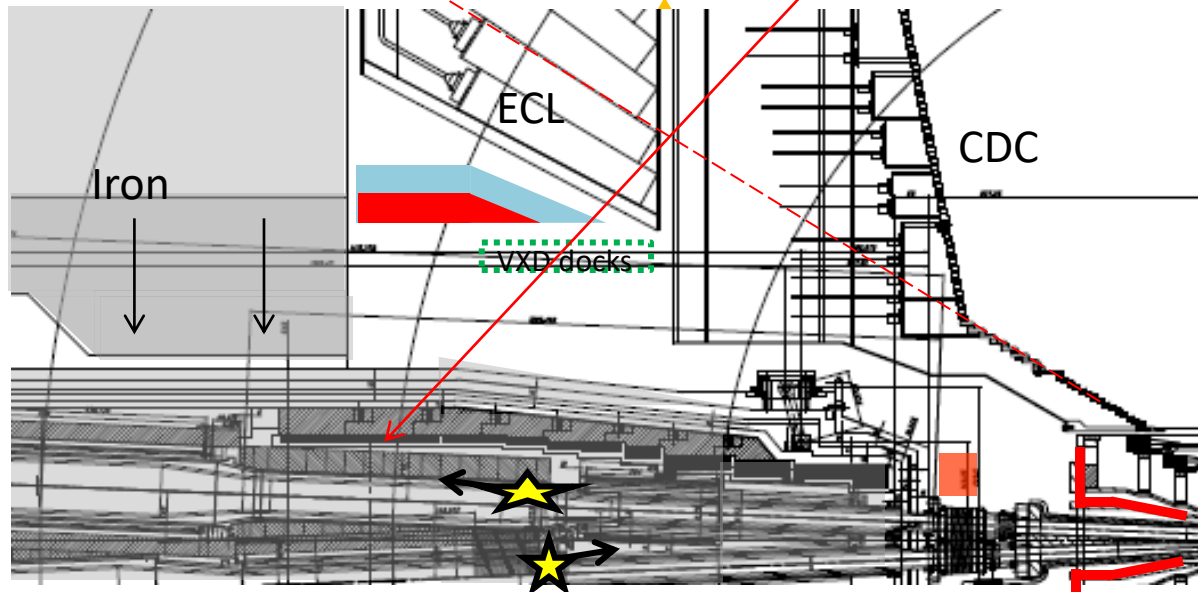
★ Major beam loss position by Touschek or Beam-gas


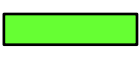


Thick tungsten shields can significantly stop background showers originated from  $|s| > 65\text{cm}$ .

# Other shielding

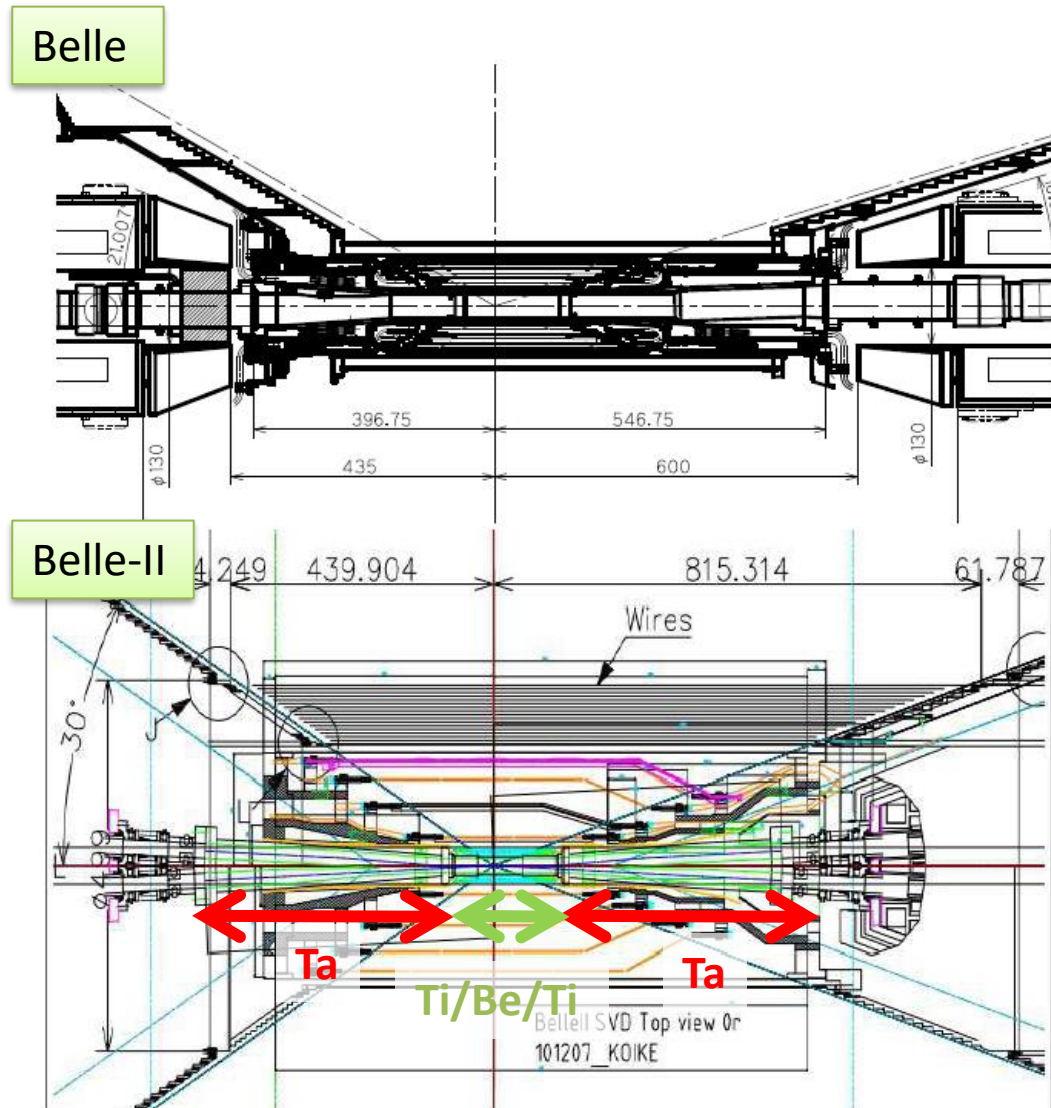


Thick tungsten layers inside cryostat



-  Heavy metal shields to protect VXD from showers generated in cryostat
-  Neutron shield to protect HAPDs in ARICH (Boron-doped Polyethylene)
-  ECL shield, for included for (Lead + Polyethylene)
-  Remote Vacuum Connection structure in front of QCS reduces showers from RBB loss at  $|s| \sim 60\text{cm}$  (6cm-thick SUS)

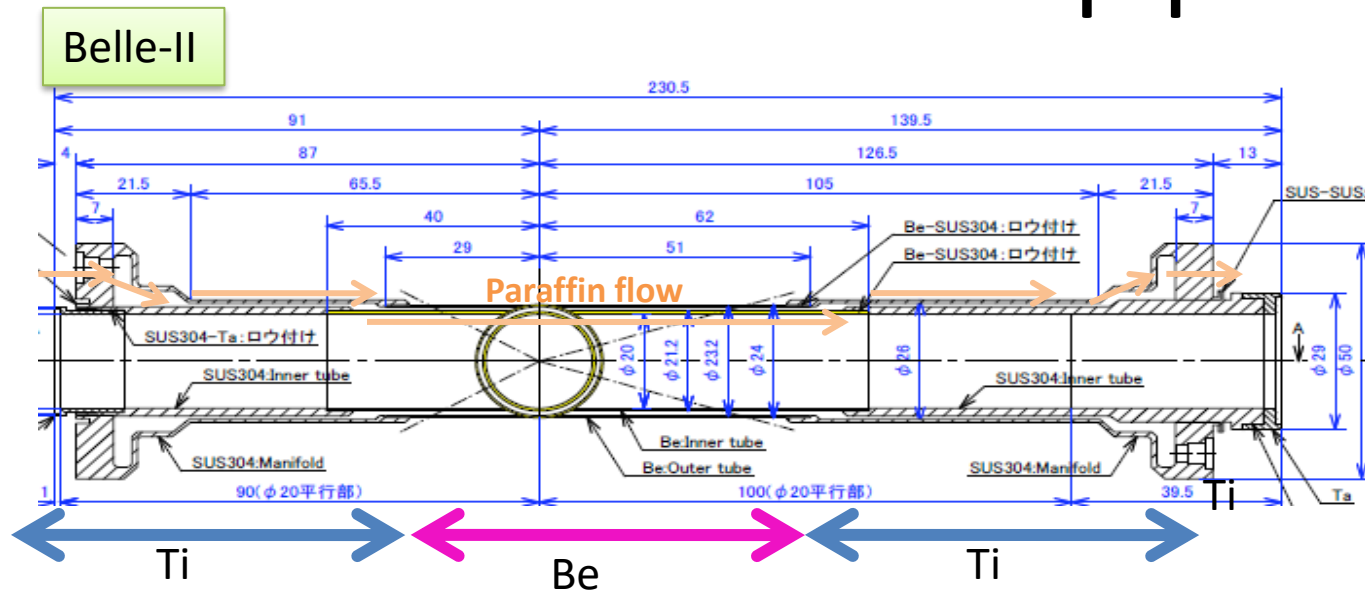
# Interaction region



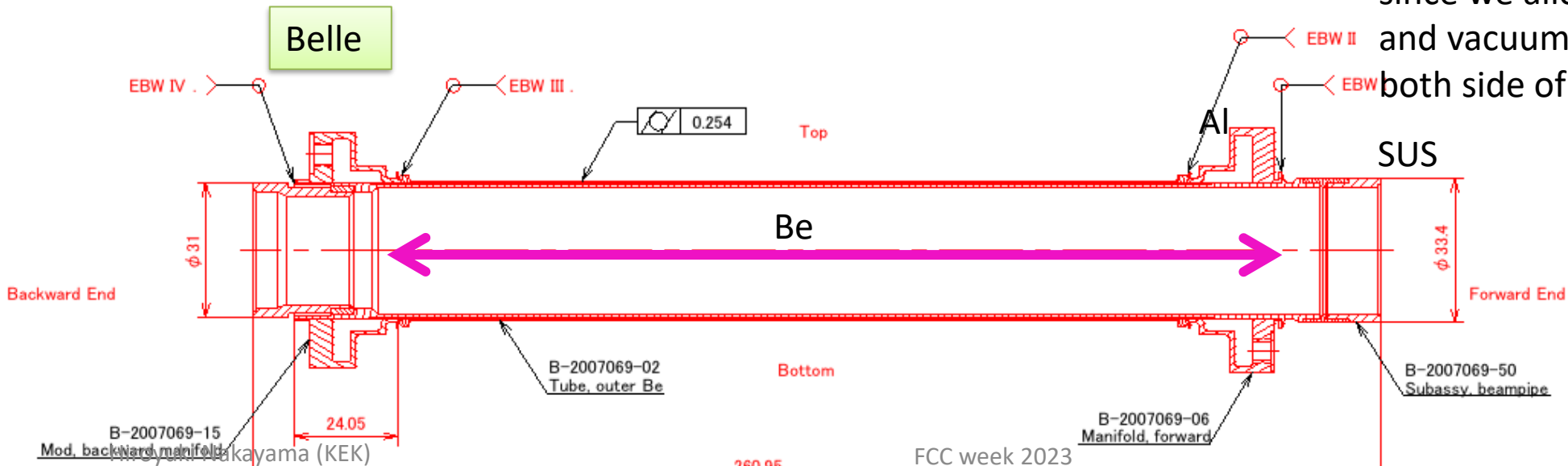
## <Belle-II>

- Smaller IP beam pipe radius ( $r=15\text{mm} \Rightarrow 10\text{mm}$ )
- Wider beam crossing angle ( $22\text{mrad} \Rightarrow 83\text{mrad}$ )
- Crotch part: Ta pipe
- Pipe crotch starts from closer to IP, complicated structure
- New detector: PXD (more cables should go out)

# IP beam pipe



- Light material (Be) inside detector acceptance
- Paraffin ( $C_{10}H_{22}$ ) flow to remove heat from mirror current ( $\sim 80W$ )
- Gold plating ( $\sim 10\mu m$ ) 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





# Background Global picture

Ver. 2017.1.31

