Belle II MDI and Beam Background

2024年超级陶粲装置研讨会

- Introduction
- Recent activities in Belle II MDI group
- Belle II beam background study and simulation
- Collimator optimization
- Summary

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Introduction

SuperKEKB and Belle II

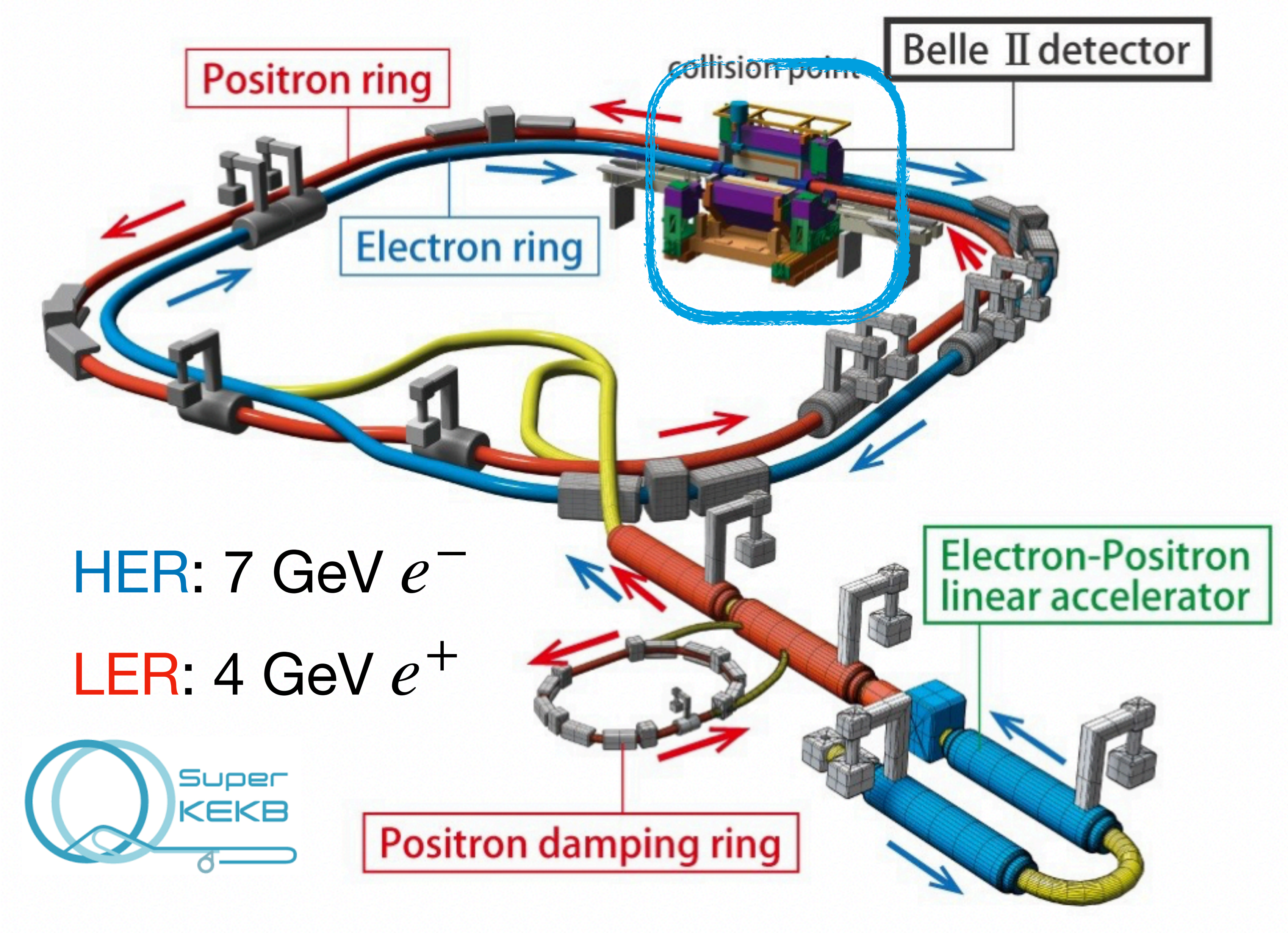
Super KEKB

- Asymmetric e^+e^- collider
- $E_{cm} = M_{\Upsilon(4S)} \approx 10.58$ GeV, B factory
- Goal: $L_{peak} = 6 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$
  - Nano-beam scheme and increased currents
  - $4.7 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ (**June 2022**, world record)

Belle II

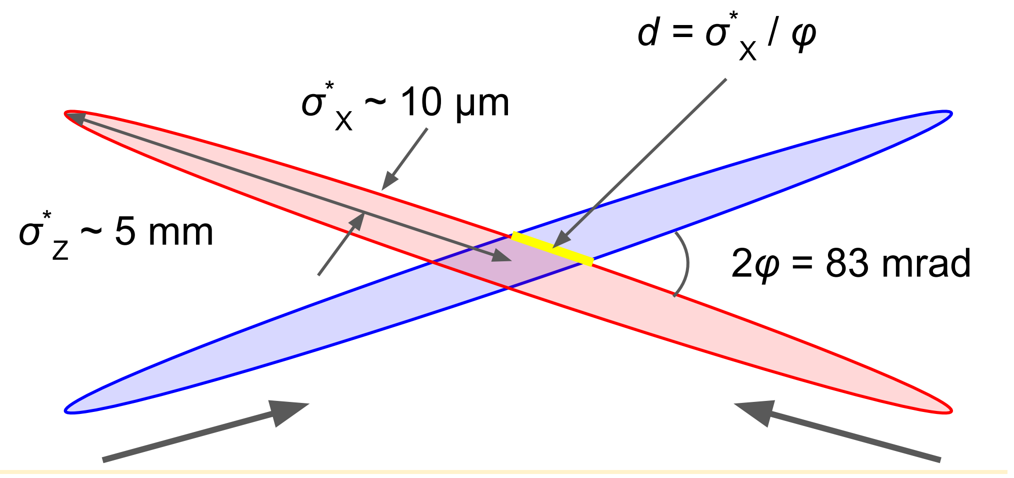
- Target L_{int}: $50\,\mathrm{ab^{-1}}$ by 2030/2031
  - Physics data taking with full setup in March 2019
  - $531.34\,\mathrm{fb^{-1}}$ has been recorded by July 2024
- Upgraded trigger rate
- Upgraded detectors

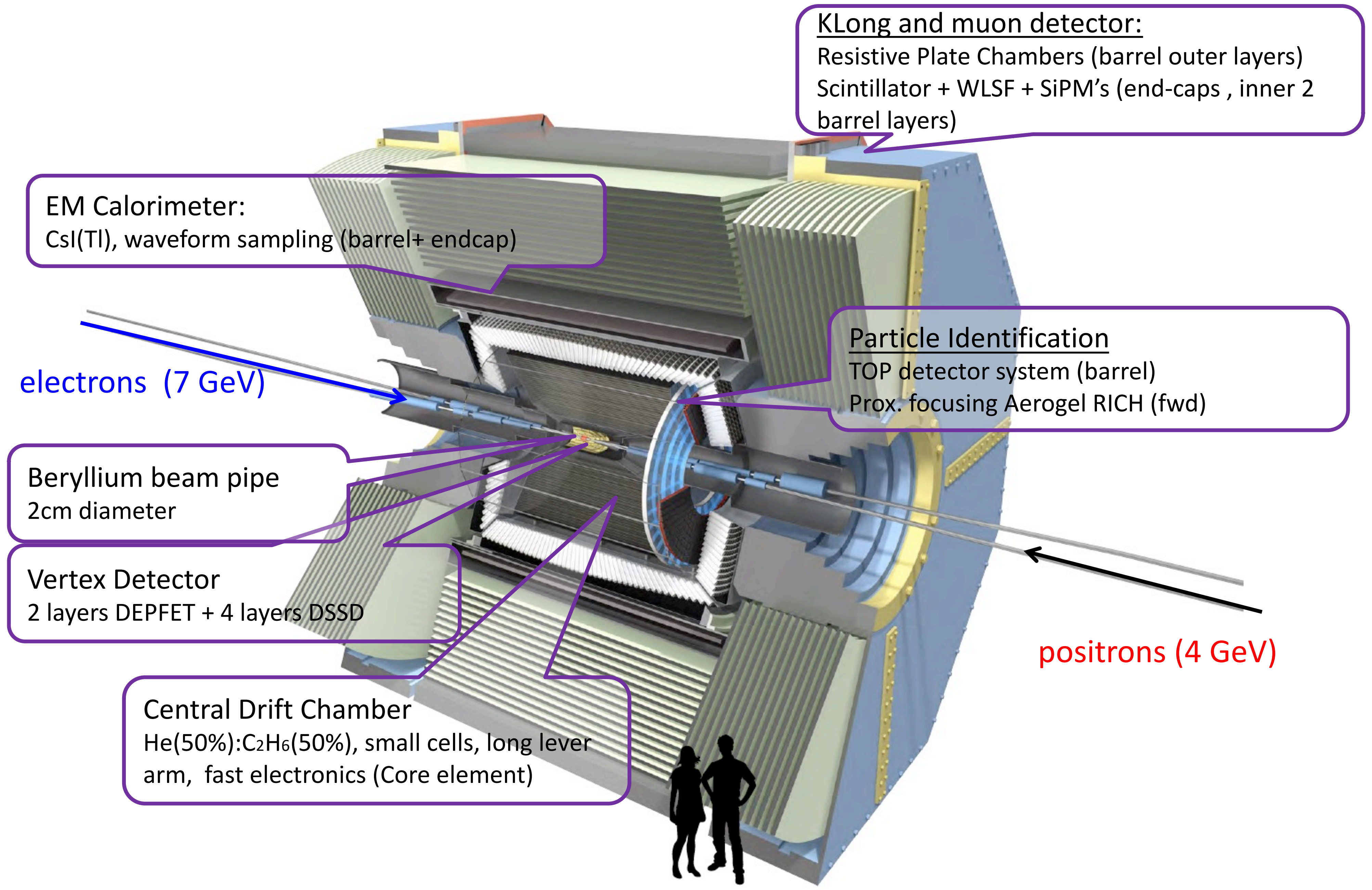
← High beam background!



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

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP





Machine detector interface group at SuperKEKB/Belle II

Including beam background group and beam loss monitor group

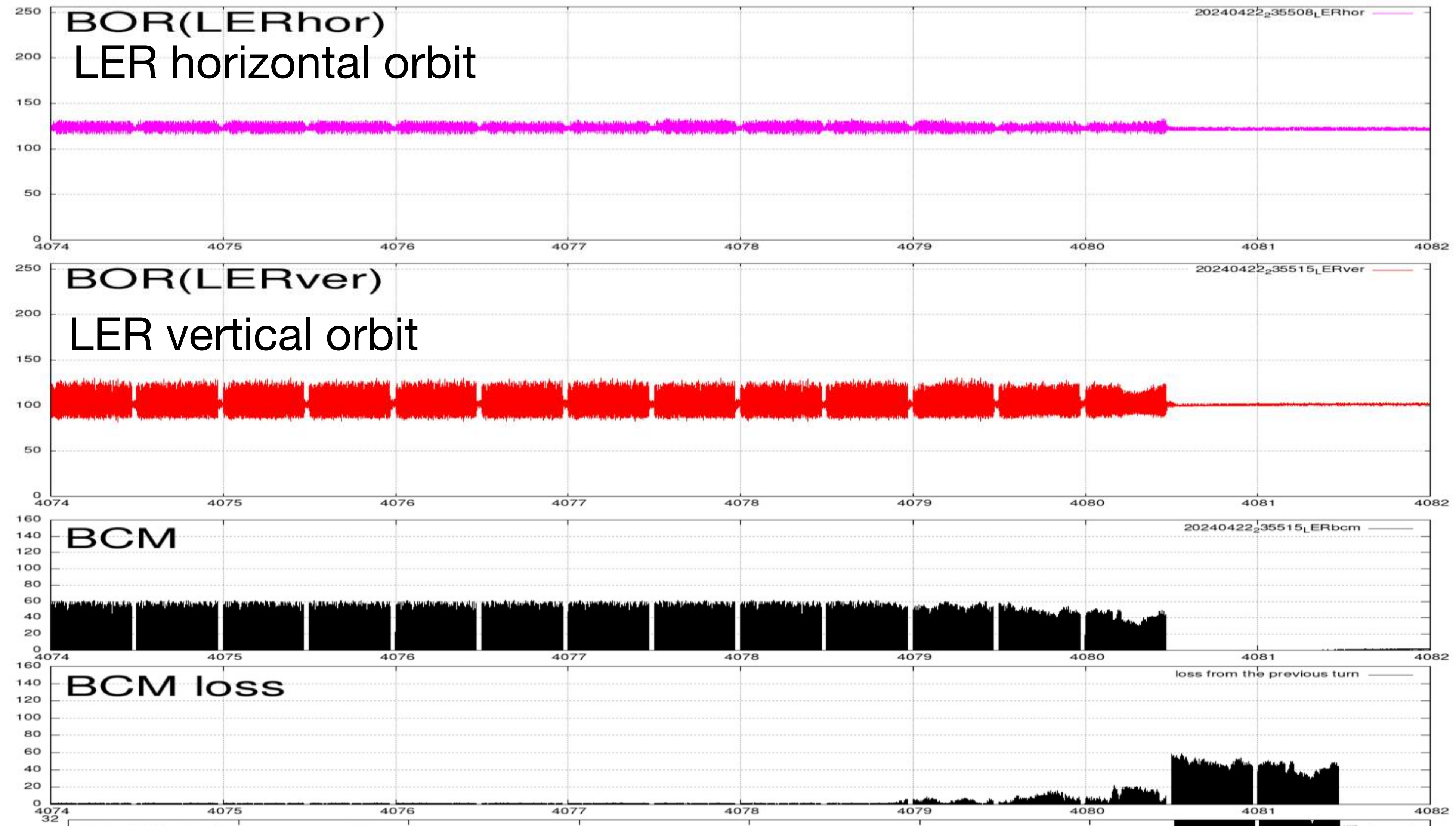
- Interface among SuperKEKB, Injector and Belle II
- Topics:
  - **Sudden beam loss**:
    - Added new loss monitors, beam orbit recorders (BORs) and acoustic sensors
  - Collimator&Injection
    - **Collimator optimization**, injection efficiency, long injection BG duration, …
    - Main upgrade: **Non-linear collimator (NLC)**, marked as D5V1 for the low energy ring (LER, e^+), to reduce impedance
  - **Beam background**
    - New shielding, reinforced neutron detectors around devices affected by single event upset (SEU), **real-time BG monitors**

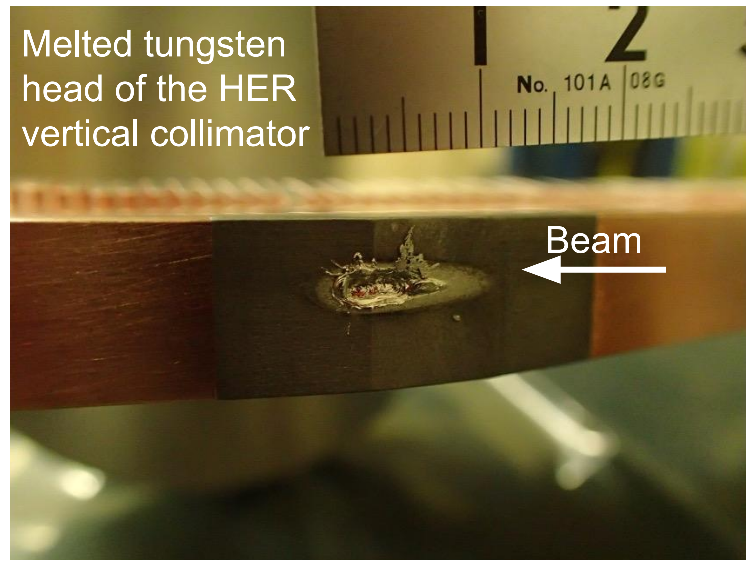
Sudden beam loss (SBL) at SuperKEKB

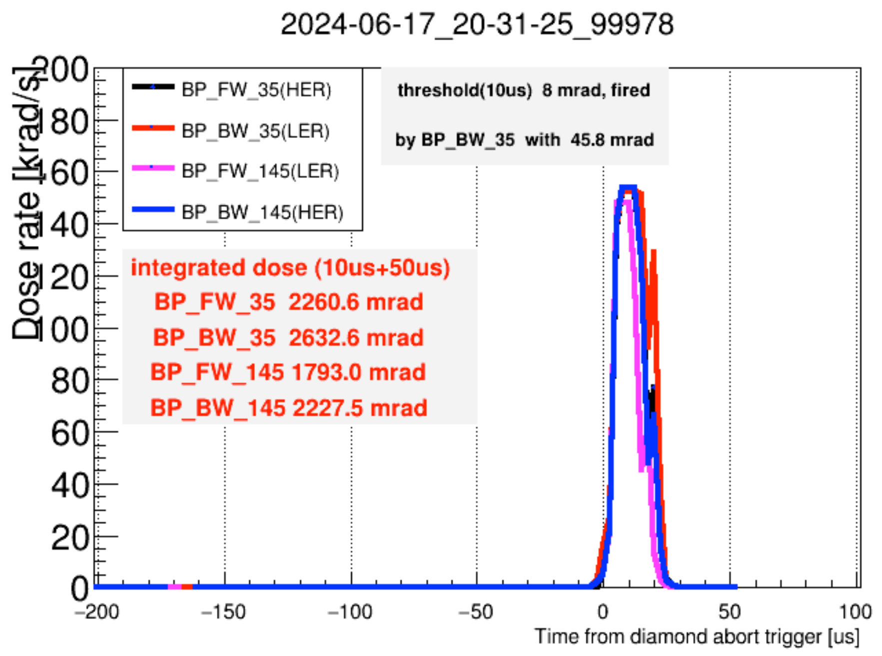
Highest priority

- Occurs **suddenly** within 1 turn (10 μs)
- **No precursory** phenomena
- Catastrophic damage: Belle II pixel detector (PXD) was off during physics run to protect its ASICs
  - Very high instantaneous radiation dose
    - Could be > 2000 mrad within 30 μs(diamond sensor saturation)
  - Damage collimators, other accelerator components, Belle II diamond amplifier, switcher ASICs of PXD, …
  - Quench the final focusing superconducting magnets (QCS)
- Cause is not clear
  - Appears to be associated with **dust in beam pipe**
    - Pressure burst in certain region (not always lead to SBL)
    - Could produce SBL manually by knocking the beam pipe

Bunch Oscillation Recorder(BOR) & Bunch Current Monitor(BCM)

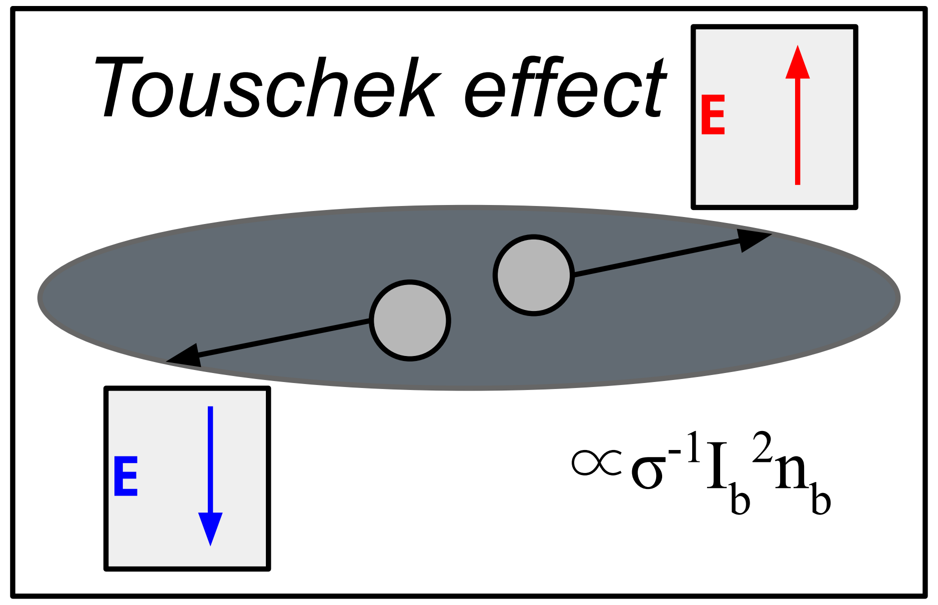


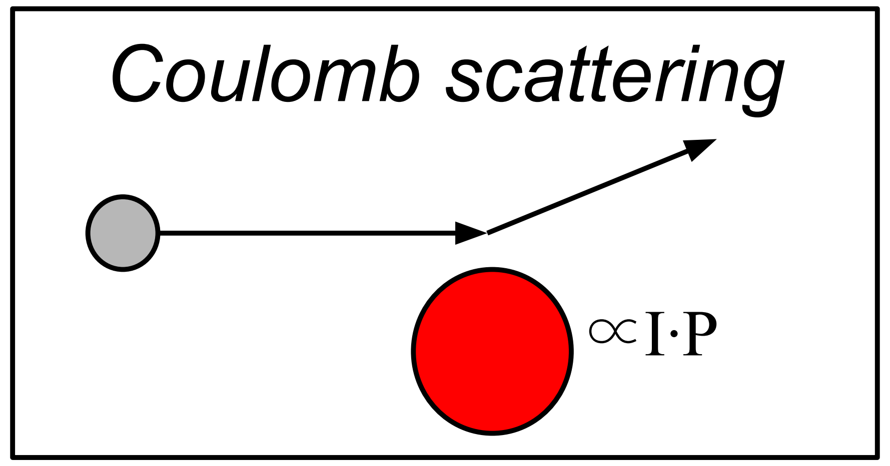


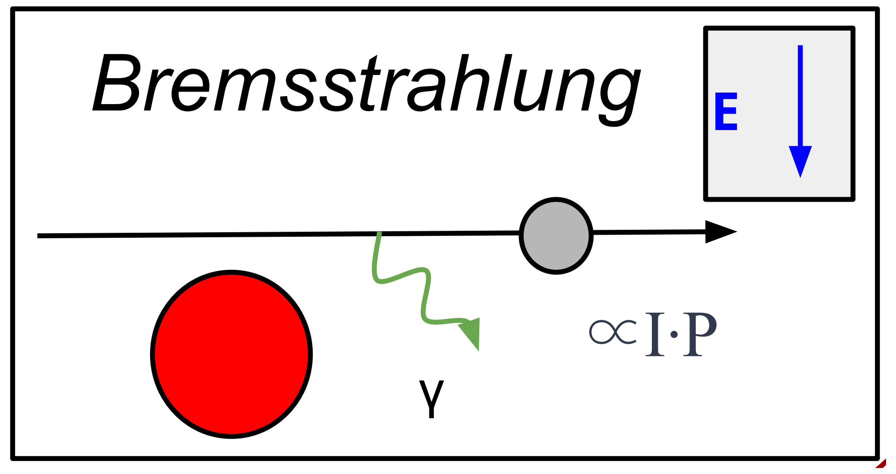


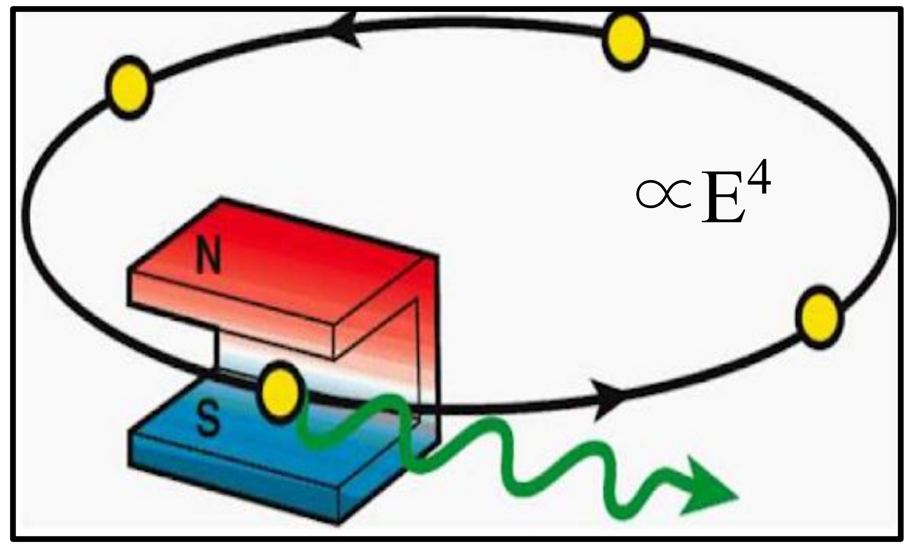
Backgrounds in Belle II

- **Single-beam** background
  - ***Touschek*** effect: $\propto \sigma^{-1} E_{beam}^{-3} I_{bunch}^{2} n_{bunch}$
    - Countermeasure: horizontal collimators at large β_x or ϵ_x
  - ***Beam-gas*** effect: $\propto I_{beam} P$
    - Coulomb scattering and Bremsstrahlung
    - Countermeasure: vacuum scrubbing, vertical collimators at small β_y
      - constraints from QCS aperture and Transverse Mode Coupling Instability (TMCI)
- **Luminosity background**: $\propto \mathscr{L}_{inst.}$
  - Radiative Bhabha, Two photon process
- Synchrotron radiation: $\propto E_{beam}^{4}$, *back scattered* photons are ***observed by the PXD***
- **Injection background**: ∝ injection repetition rate, could be at a similar level of storage BG
  - Newly injected beam is unstable -> high particle loss for ~ 10 ms
  - Countermeasure: injection trigger veto, injection chain tuning, damping ring for e^+

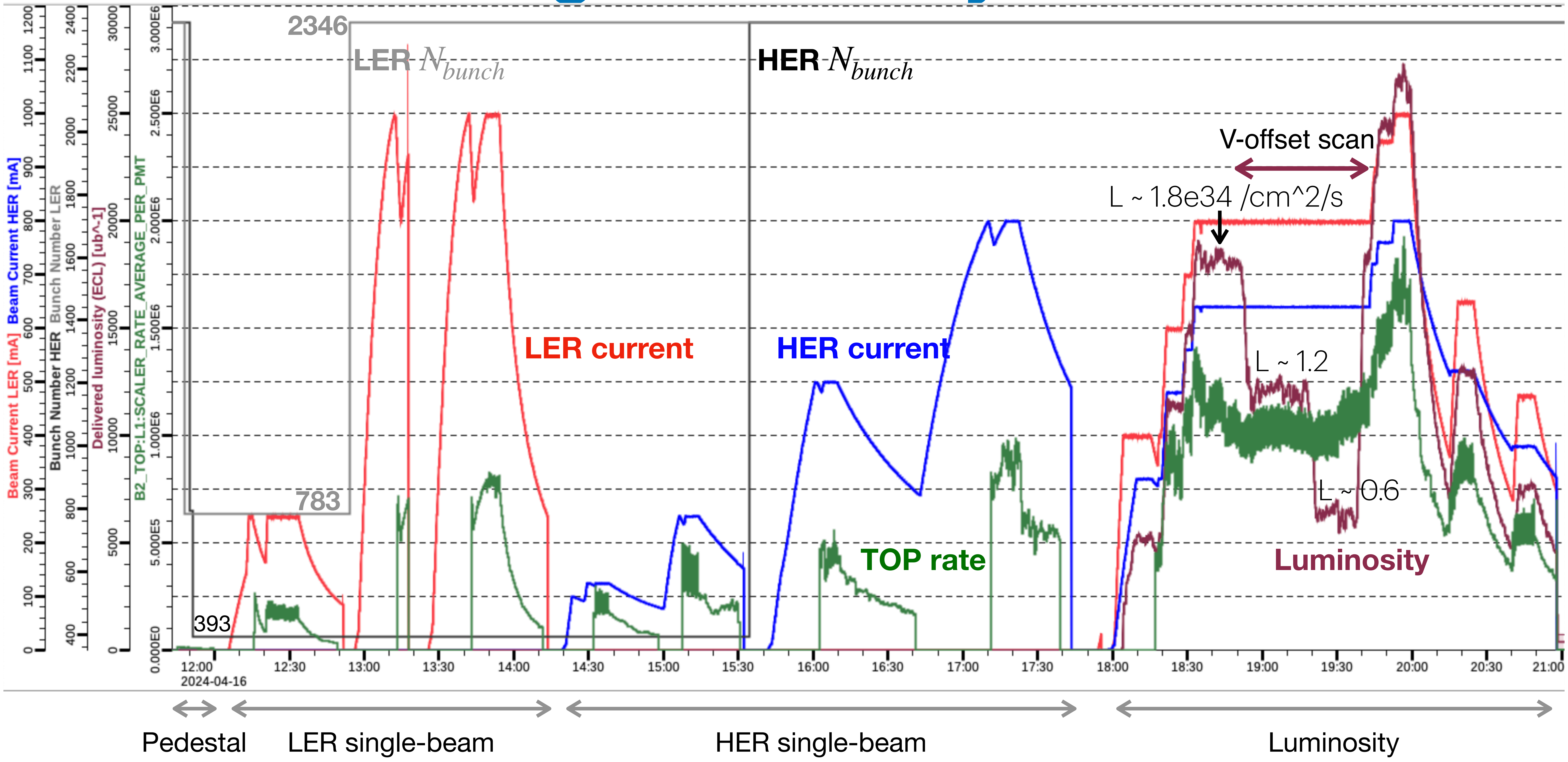








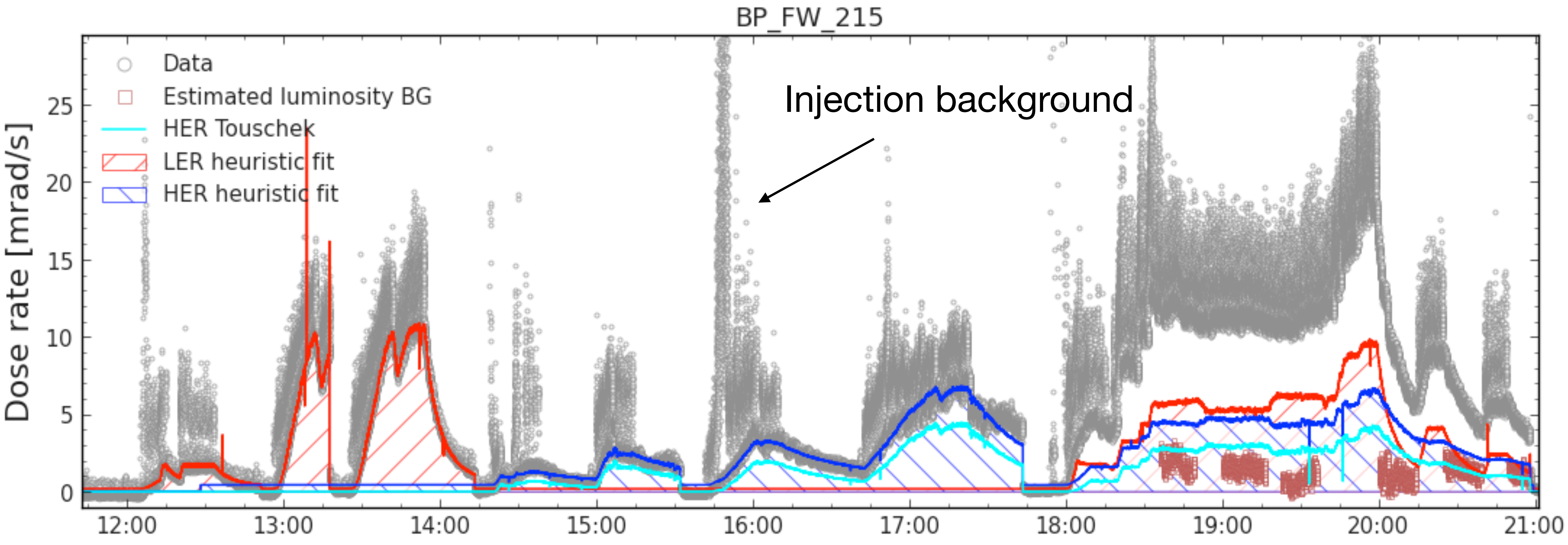
Dedicated background study and heuristic fit



KEKB ArchiverViewer

Dedicated background study and heuristic fit

Example: preliminary fit result for diamond BP_FW_215



$$\mathcal{O}_{\mathrm{Touschek}} = \mathrm{T} \times \frac{\mathrm{I}^2}{\mathrm{n_b}\sigma_x\sigma_y\sigma_z}$$

$$\mathcal{O}_{\mathrm{beam-gas}} = \mathrm{B} \times \mathrm{I}\bar{\mathrm{P}}_{\mathrm{eff}}$$

$$\mathcal{O}_{\mathrm{pedestal}} = \mathrm{D}$$

Estimation of BG components: →

Phase3 paper

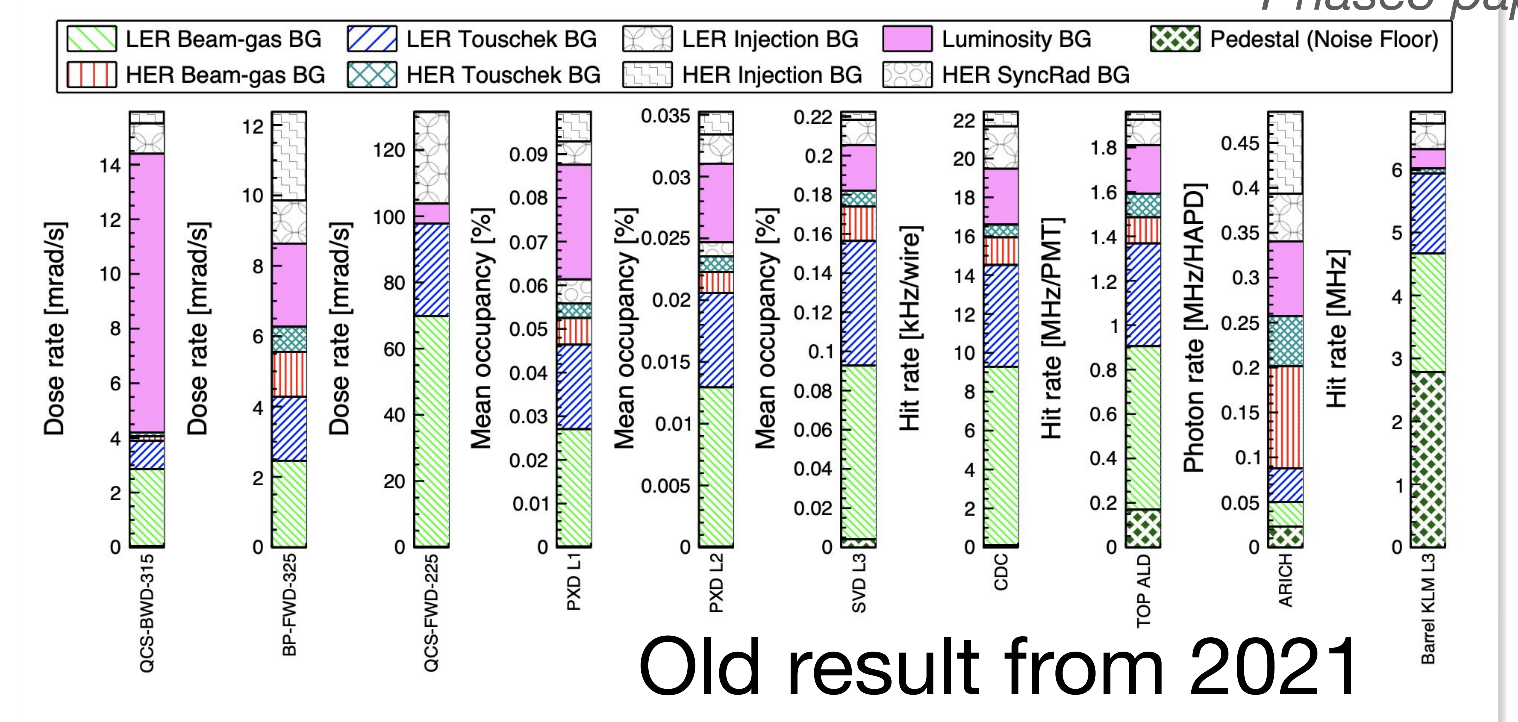


Figure 14: Measured Belle II background composition on June 16, 2021. Each column is a stacked histogram. QCS-BWD-315, BP-FWD-325 and QCS-FWD-225 indicate backward QCS, beam pipe and forward QCS Diamond detectors, respectively, with the higher dose rate. Barrel KLM L3 corresponds to the inner-most RPC layer in the barrel region of the KLM detector. TOP ALD shows the averaged background over ALD-type MCP-PMTs, slots from 3 to 9.

Background simulation in Belle II

Good understanding of background processes is the key to make reasonable prediction

- **Injection** background: still waiting for input from machine experts
- **Luminosity** background: using ***BBBREM/BHWIDE*** and ***AAFH*** in basf2
    - With more detailed magnetic field map -> slower than MC production for physics analyses
- **Single beam** background (only for storage background)
    - SAD: Strategic Accelerator Design
        - beam particle tracking and simulation of lost particles (e^+,e^-)
    - Basf2: full Geant4 simulation for far beam line, ± 29 m around the IP
        - Generator interface to create primary particles from SAD output

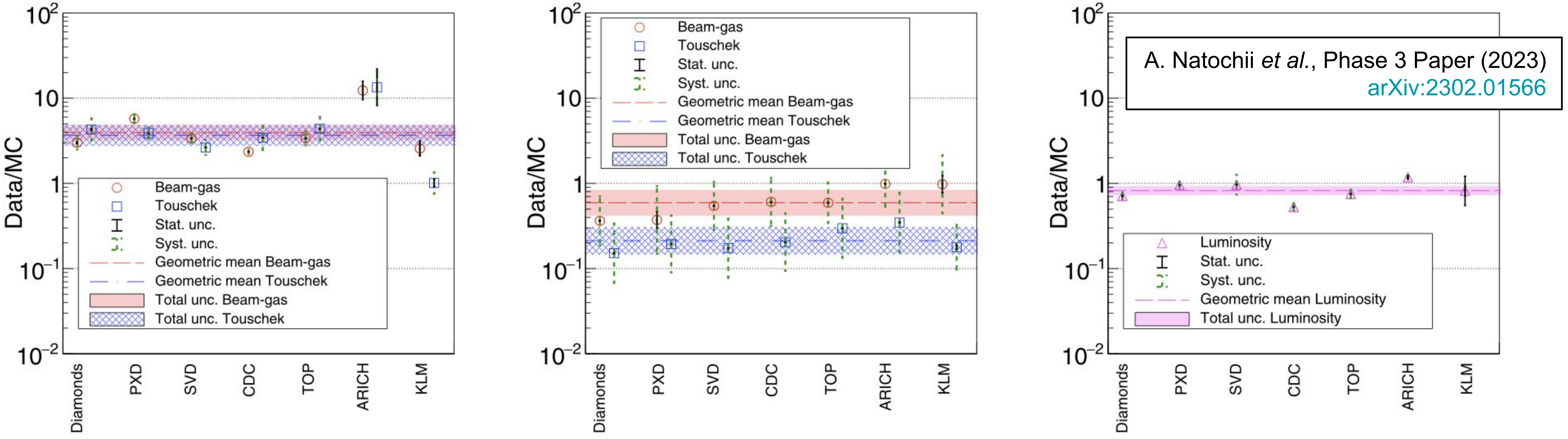
Using a reference beam condition, then extrapolate the result to any current, bunch number, beam size, …

LER: $\mathrm{I_{LER}} = 1.2$ A, $n_b = 1576$, $\beta^*_{\mathrm{y(x)}} = 1(80)$ mm, $\epsilon_\mathrm{x} = 4.3$ nm, $\epsilon_y/\epsilon_x = 0.01$, CW=80%

Background simulation with SAD and basf2

Data-MC ratios have been improved substantially during Run1

- Recap of the Data-MC comparison in Run1:



(a) LER single-beam background. (b) HER single-beam background. (c) Luminosity background.

  - Confirms our good understanding of beam loss processes in SuperKEKB -> ECL-based BG monitor to decompose background online using templates generated by the MC!

- We are working on the new BG study of the last run period

  - Unexpected BG development

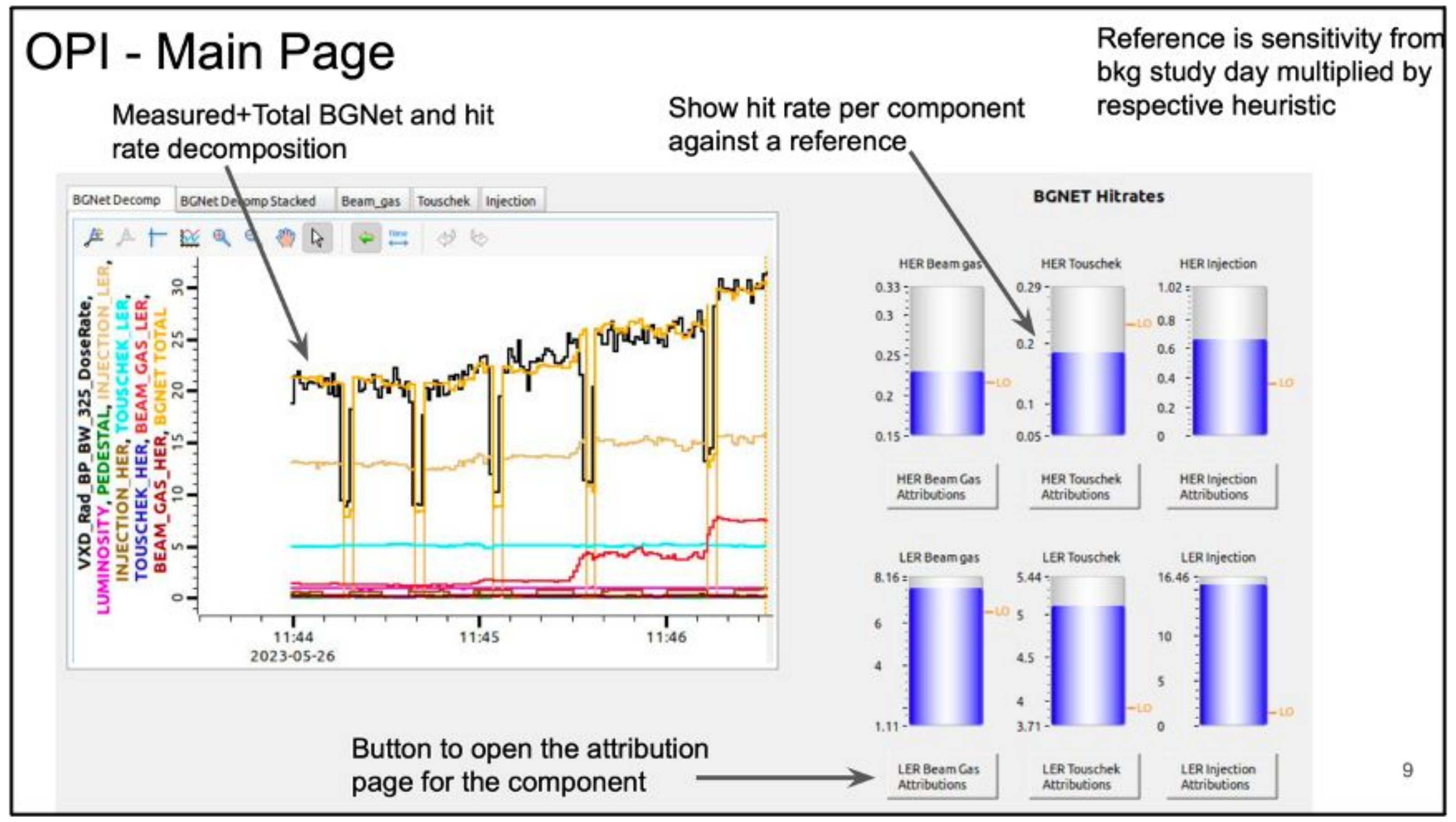
  - Inefficient MC production

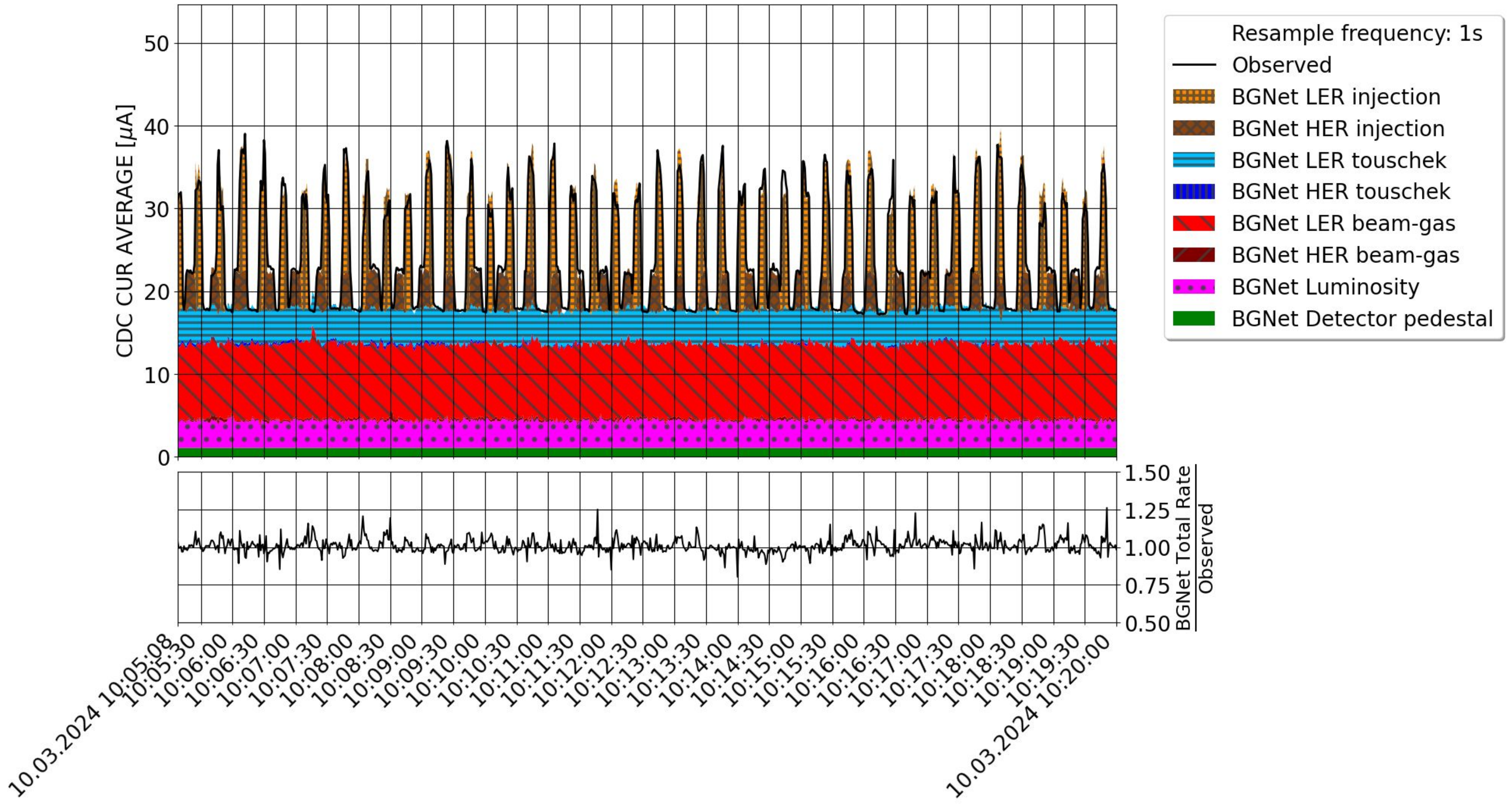
Real-time BG monitors

BGNET

- BGNET (neural network + heuristic sensitivities) uses EPICS PVs to train a neural network:
    - Decompose backgrounds online -> not ready for now
    - Provide which beam parameter contributes most to background change via feature attribution

Y. Buch (Göttingen Univ.)



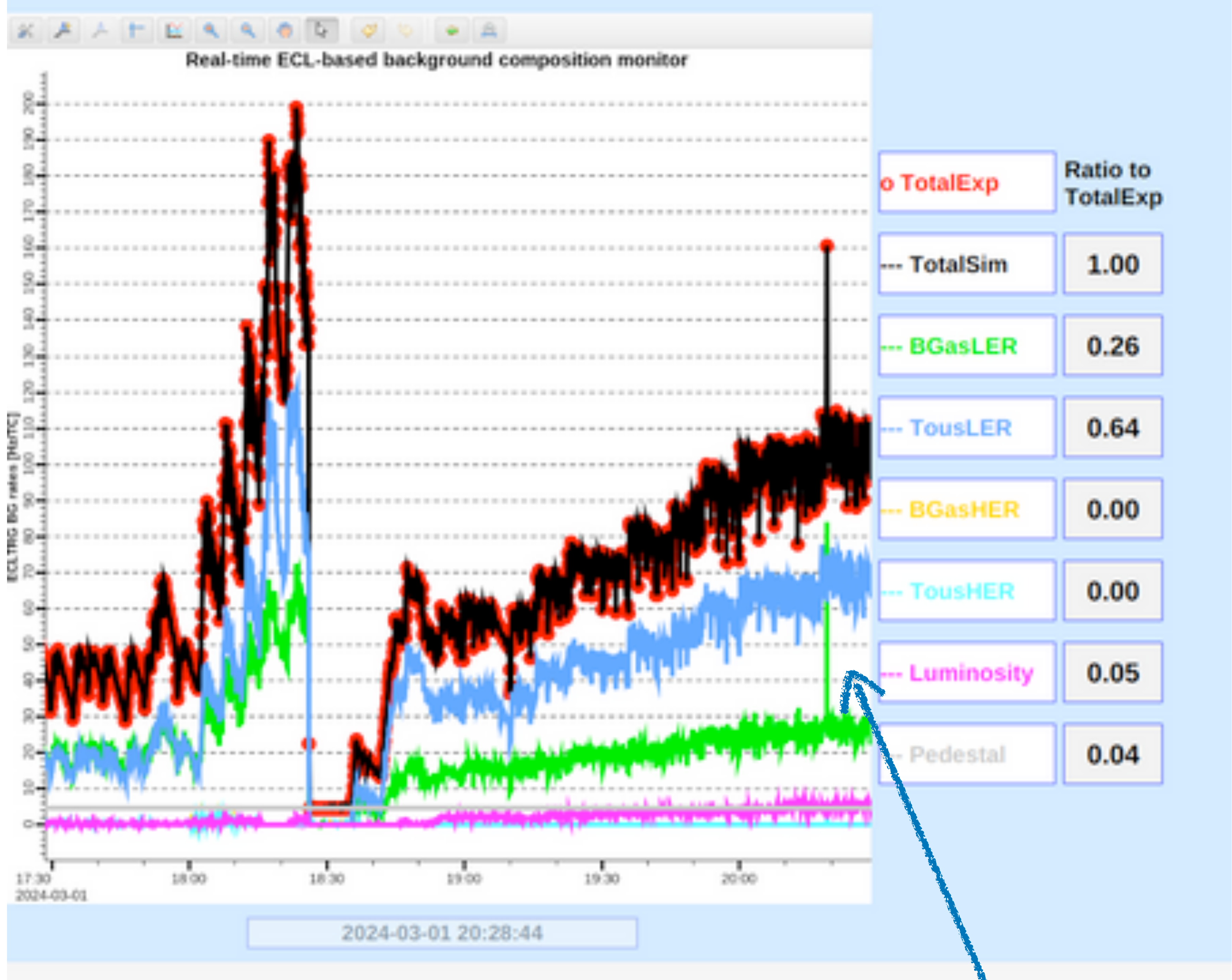


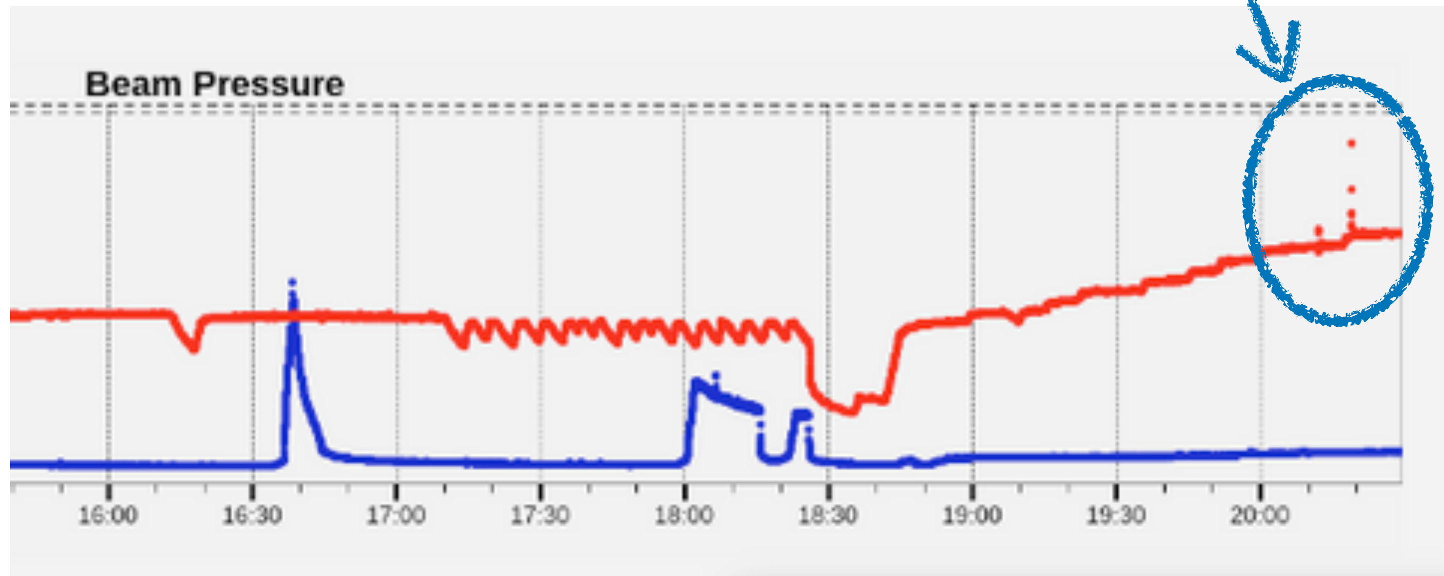
Real-time BG monitors

ECL-based BG monitor

- ECL-based BG monitor uses MC templates to fit ECL trigger rates with injection veto:
  - Running since beginning of Run2, using templates from Dec. 2021
  - Already helped collimator experts to tune apertures
  - Know issues:
    - Fluctuation due to low stat.
    - HER BG is not decomposed correctly, probably due to the low rate of this component

Screenshots of the monitor panel





Detected some pressure spikes with beam-gas sensitivity

Collimator optimization

In practice

- Collimators are optimized regularly
  - better injection efficiency
  - lower beam background in Belle II
  - Used as spoiler and absorber (D06H3/H4)
    - to protect machine components like inj. kicker

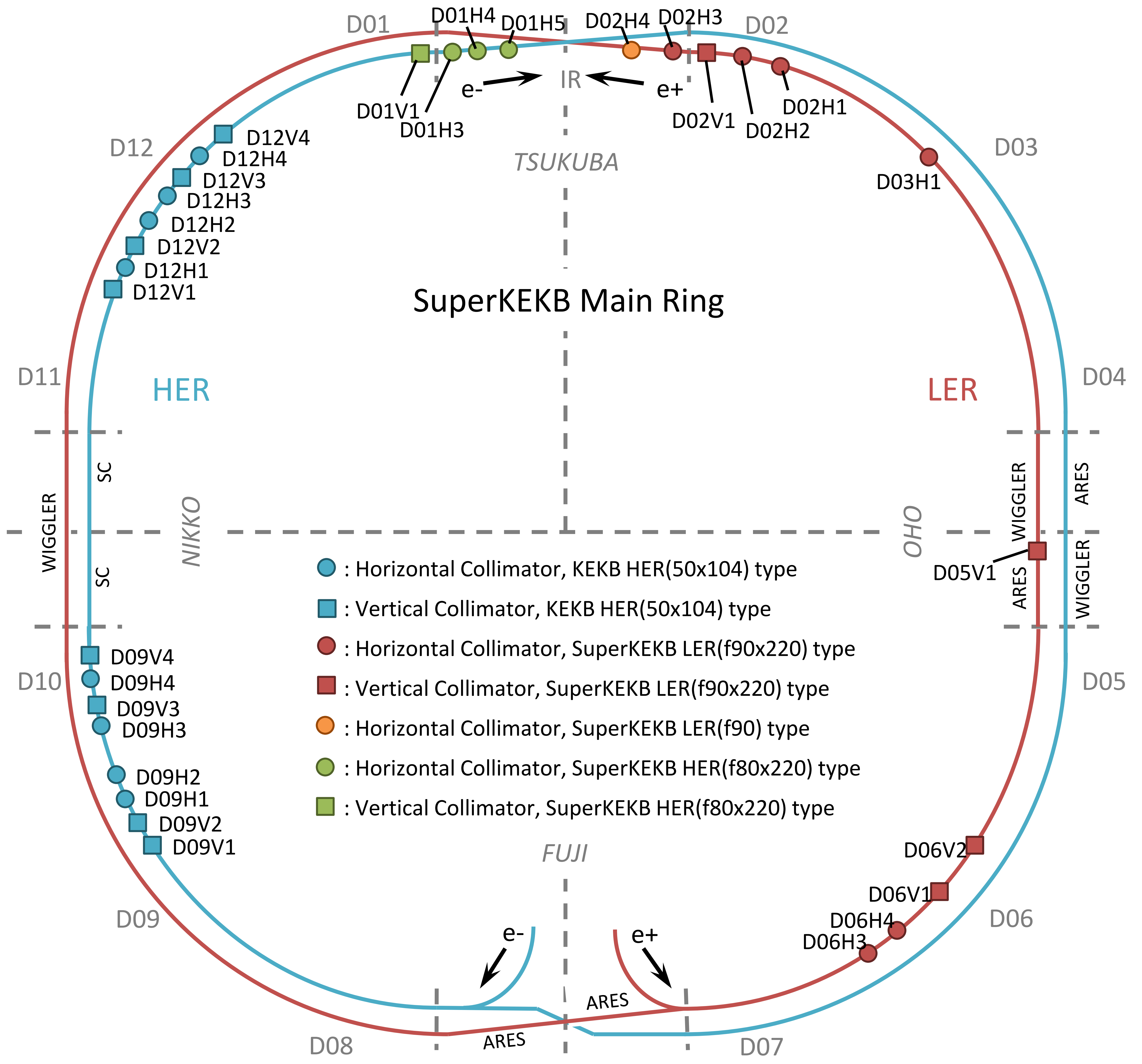
LER: 11 collimators

- Vertical collimator

Name	Type	Tip Material	Cu coating	Tip condition
D02V1	SuperKEKB	Ta (160 mm)	○	○
D05V1	SuperKEKB	Ta (4 mm)	○	○
D06V1	SuperKEKB	Ti (10 mm)	○	○
D06V2	SuperKEKB	Hybrid (3 mm)	○	○

- Horizontal collimator

Name	Type	Tip Material	Cu coating	Tip condition
D02H1-H4	SuperKEKB	W (10 mm)	×	○
D03H1	SuperKEKB	W (10 mm)	×	○
D06H3	SuperKEKB	C (160 mm)	○	○
D06H4	SuperKEKB	Ta (10 mm)	×	○



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    - to protect machine components like inj. kicker

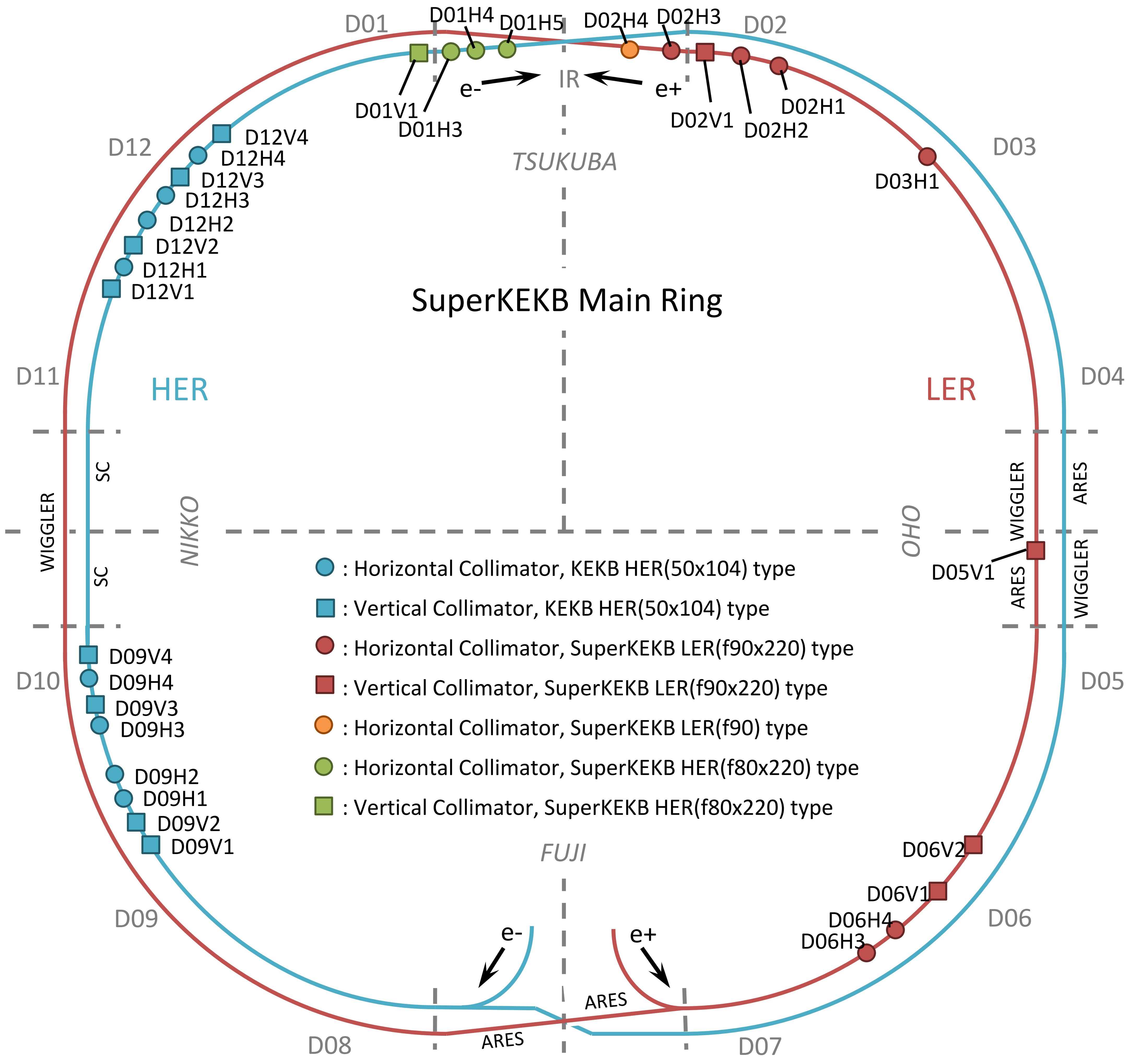
HER: 20 collimators

- Vertical collimator

Name	Type	Tip Material	Cu coating	Tip condition
D01V1	SuperKEKB	Ta (10 mm)	◯	◯
D12V1, V2	KEKB	Ti (40 mm)	◯	×
D12V3, V4	KEKB	Ti (40 mm)	◯	◯
D09V1-V4	KEKB	Ti (40 mm)	◯	◯

- Horizontal collimator

Name	Type	Tip Material	Cu coating	Tip condition
D01H3-H5	SuperKEKB	W (10 mm)	×	◯
D12H1, H3	KEKB	Ti (40 mm)	×	◯
D12H2	KEKB	Ti (40 mm)	◯	×
D12H4	KEKB	Ti (40 mm)	◯	◯
D09H1-H4	KEKB	Ti (40 mm)	◯	×

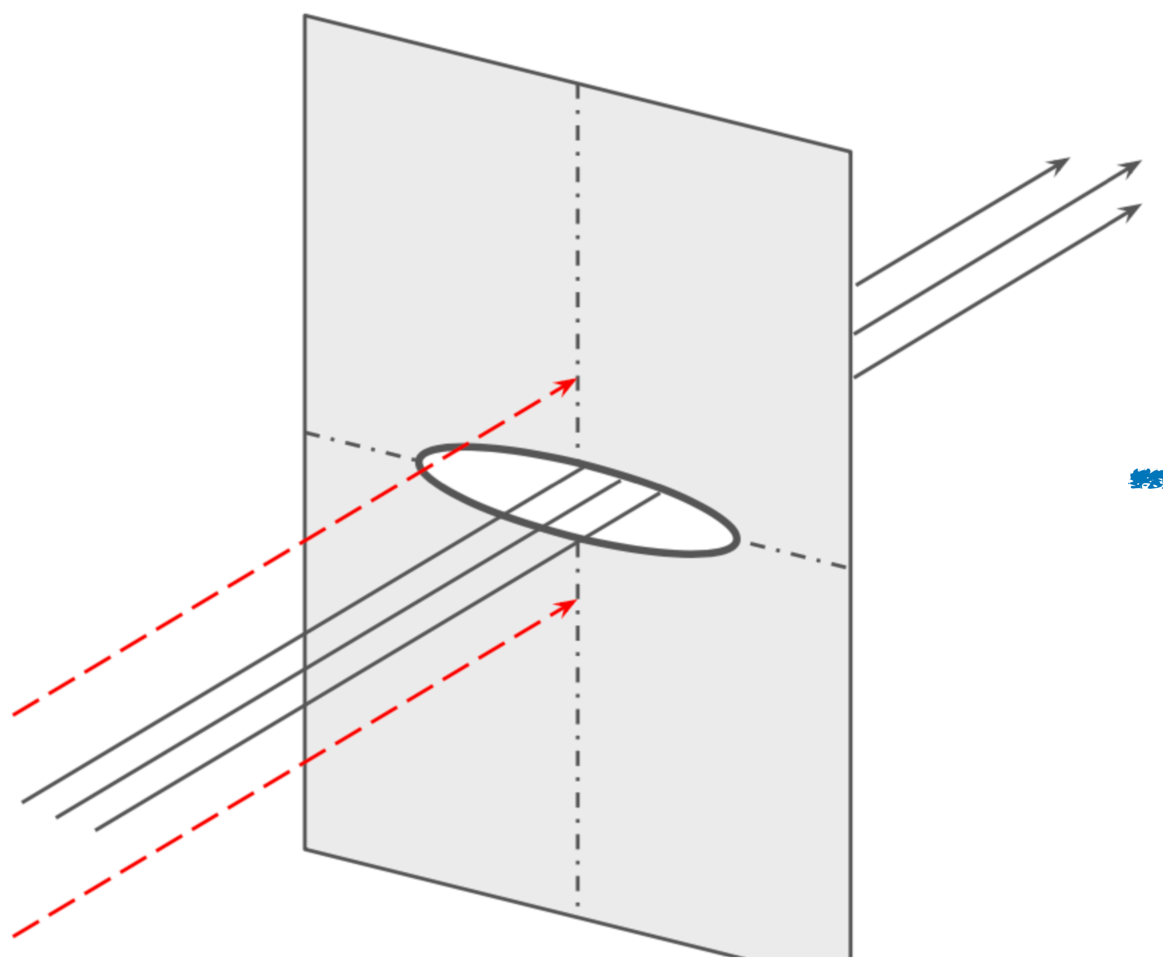


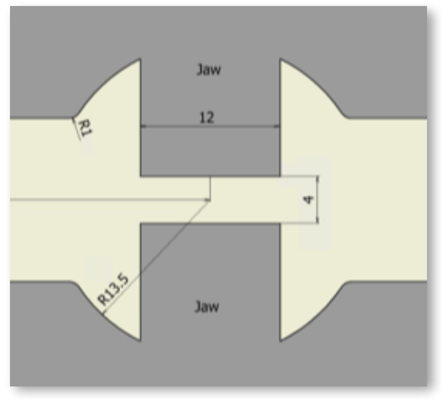
KEKB type: only one jaw

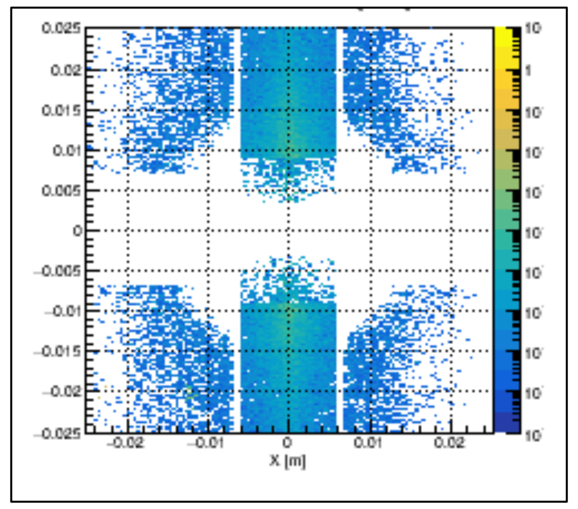
Collimator optimization

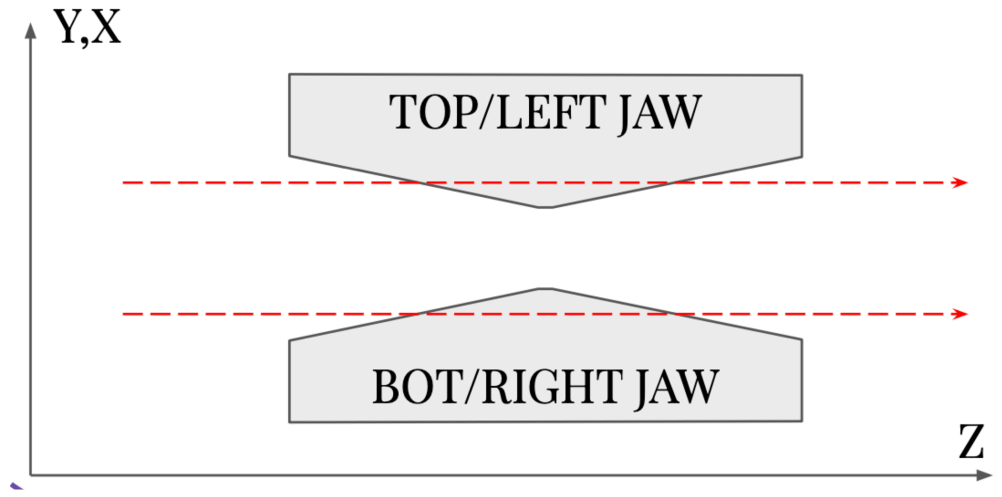
Simulation based on SAD

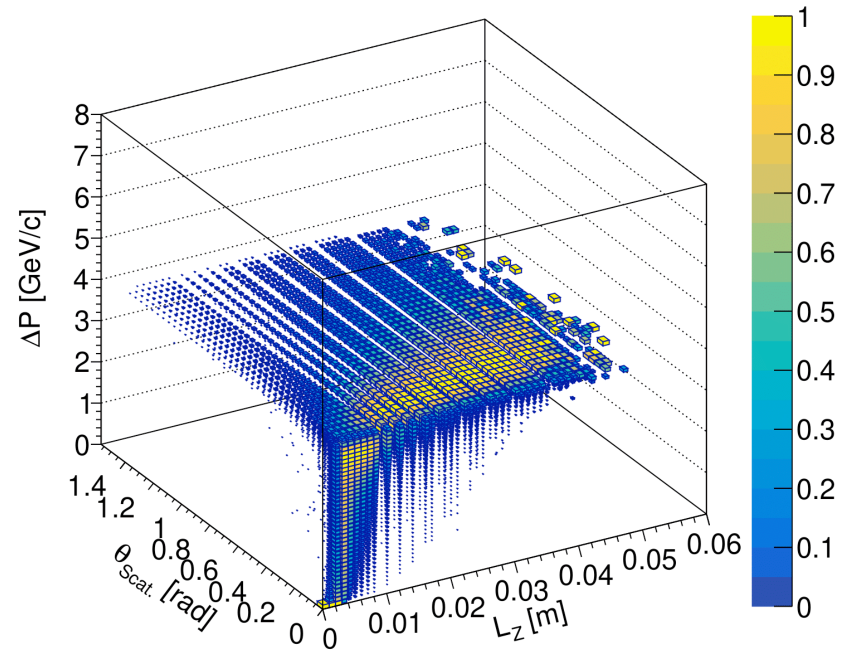
- Optimization in SAD doesn't consider injection efficiency or injection BG
- Procedure:
    - Open all collimators and record tracks for 1000 turns in SAD
    - Scan collimator settings and calculate particle loss rates at IR and at each collimator
    - The optimal setting is determined by requiring the minimum Touschek/Coulomb lifetime
    - Estimate final loss rates and lifetime with tip scattering

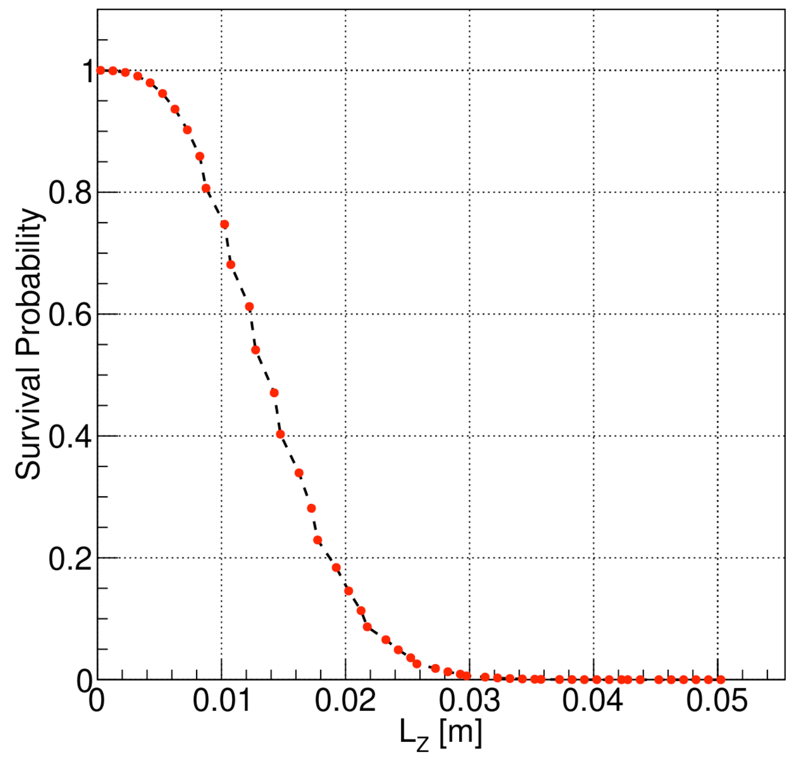


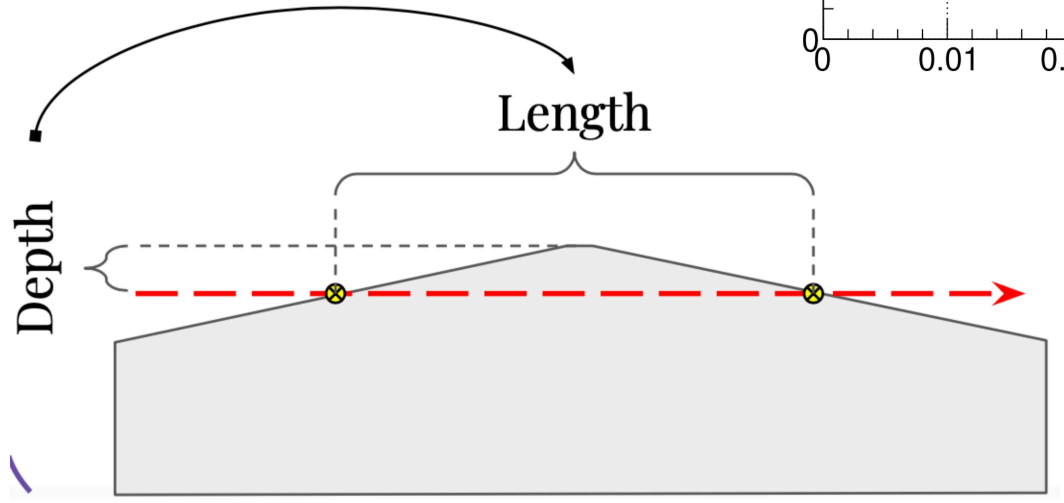












Collimator optimization

Simulation based on SAD

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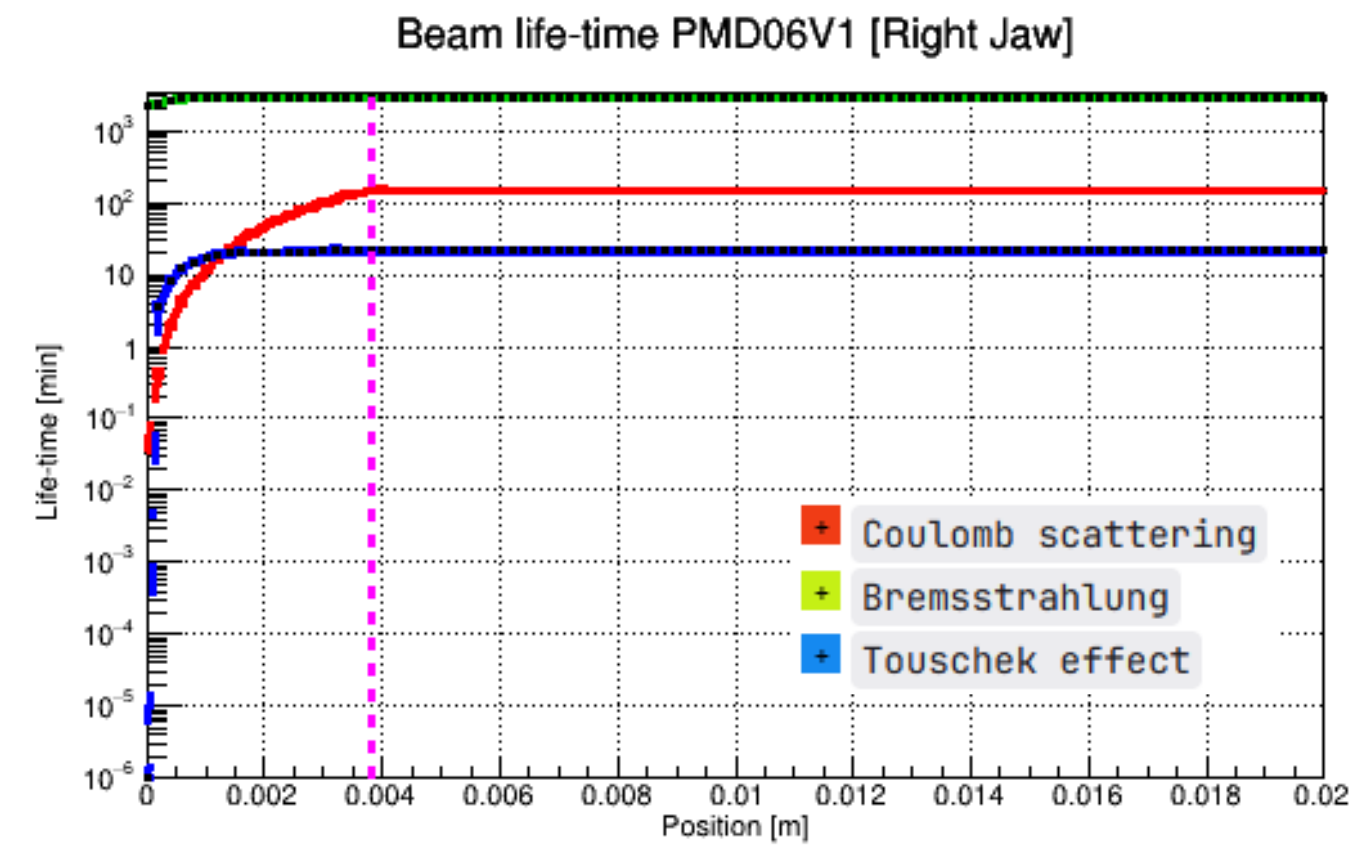
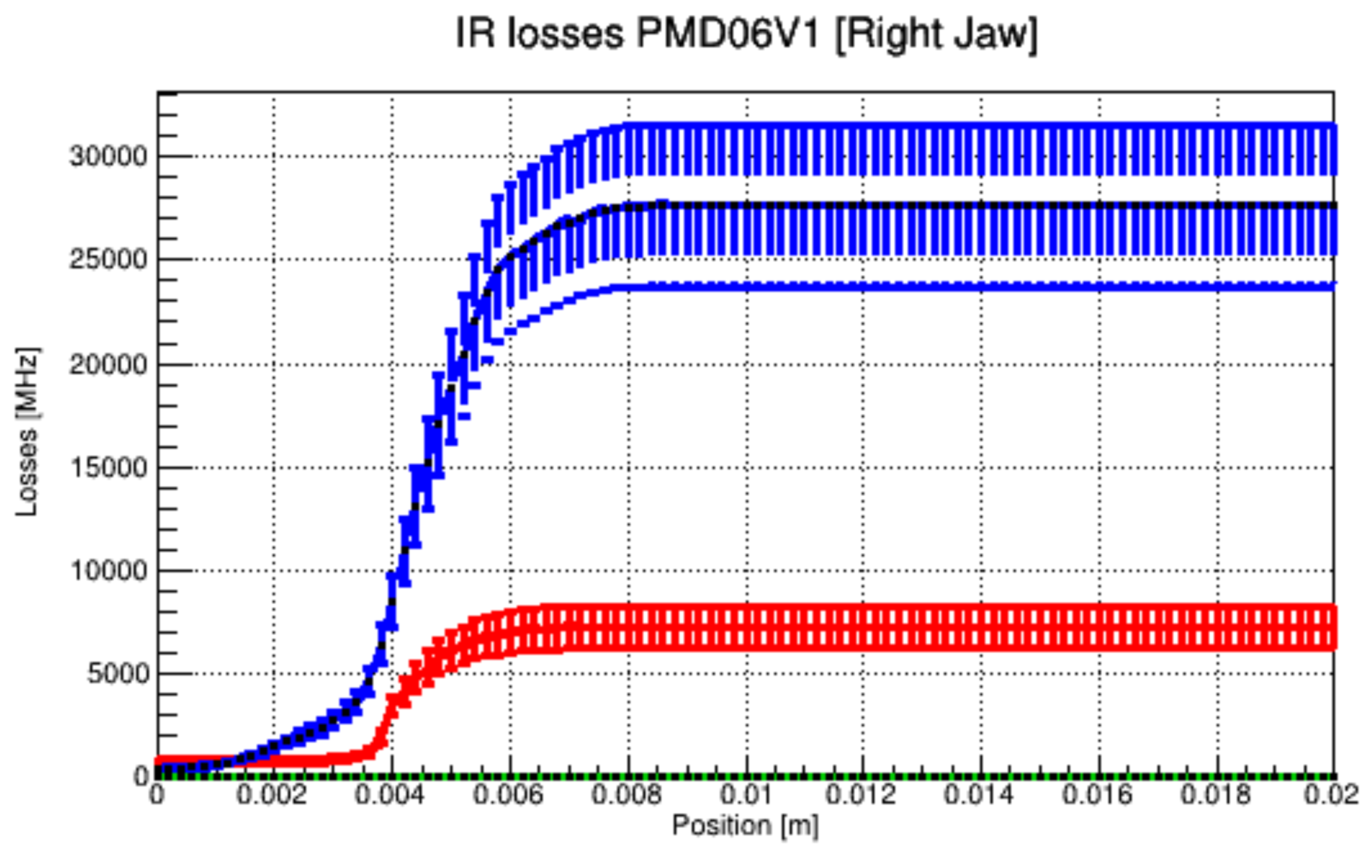
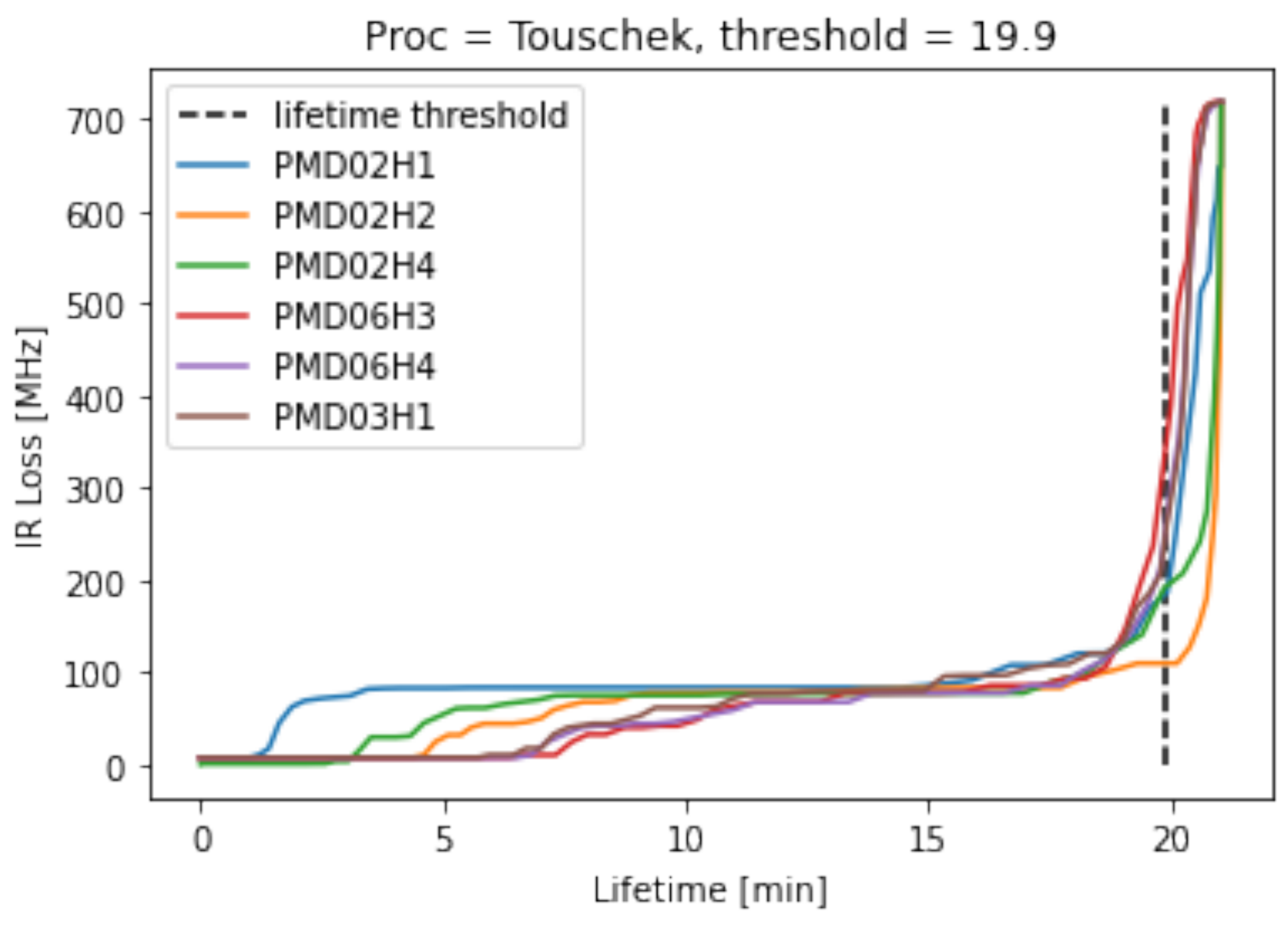
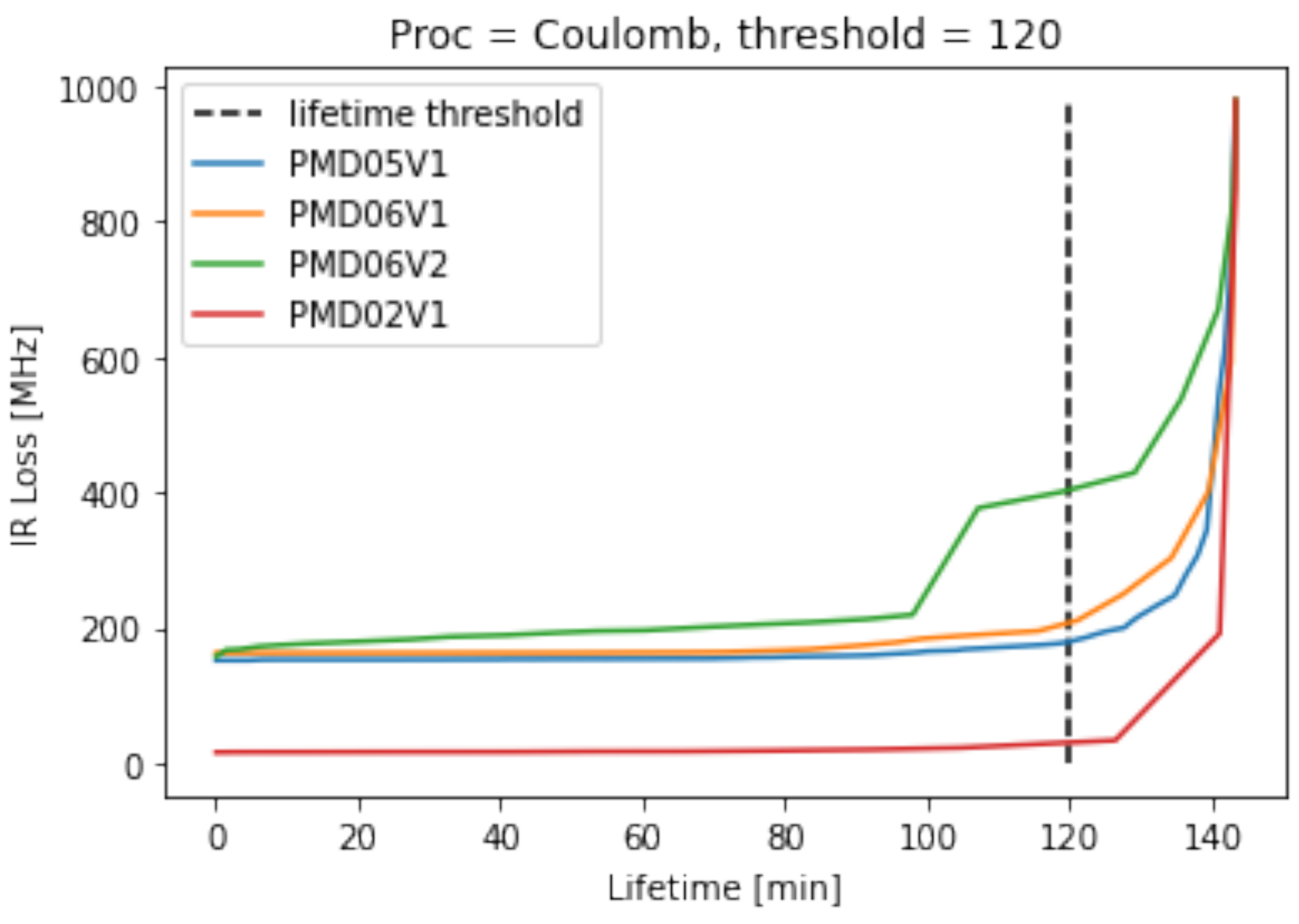








Optimized setting vs the tuned during operation

Guideline to KEK collimator group for the lattice during dedicated BG study

- Our optimization shows the potential of a given lattice
- It might be impossible to apply the setting due to constraints of injection efficiency, too high injection background, limit of loss rate at a specific collimator, …

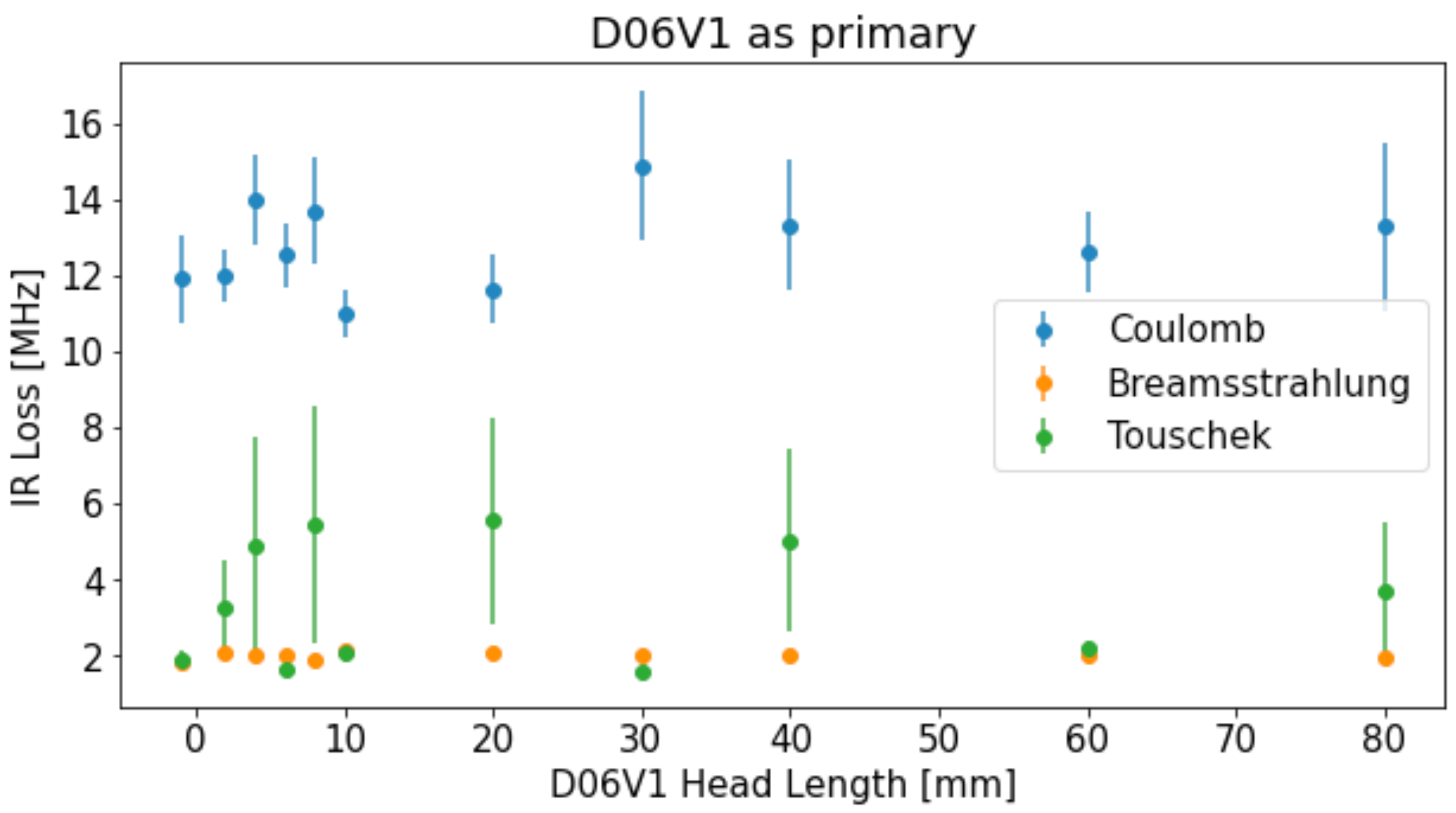
Ring	Process	IR loss		Lifetime	
		value [MHz]	stat. unc. [MHz]	Value [min]	stat. unc. [min]
Exp.	Coulomb	**12.923**	0.043	**27.795**	0.403
	Brems	6.009	0.020	2112.41	2.31
	Touschek	**16.419**	0.433	**17.154**	0.034
Opt.	Coulomb	**12.25**	0.385	**50.998**	1.785
	Brems	5.800	0.060	2107.20	7.94
	Touschek	**5.393**	0.843	**17.908**	0.066

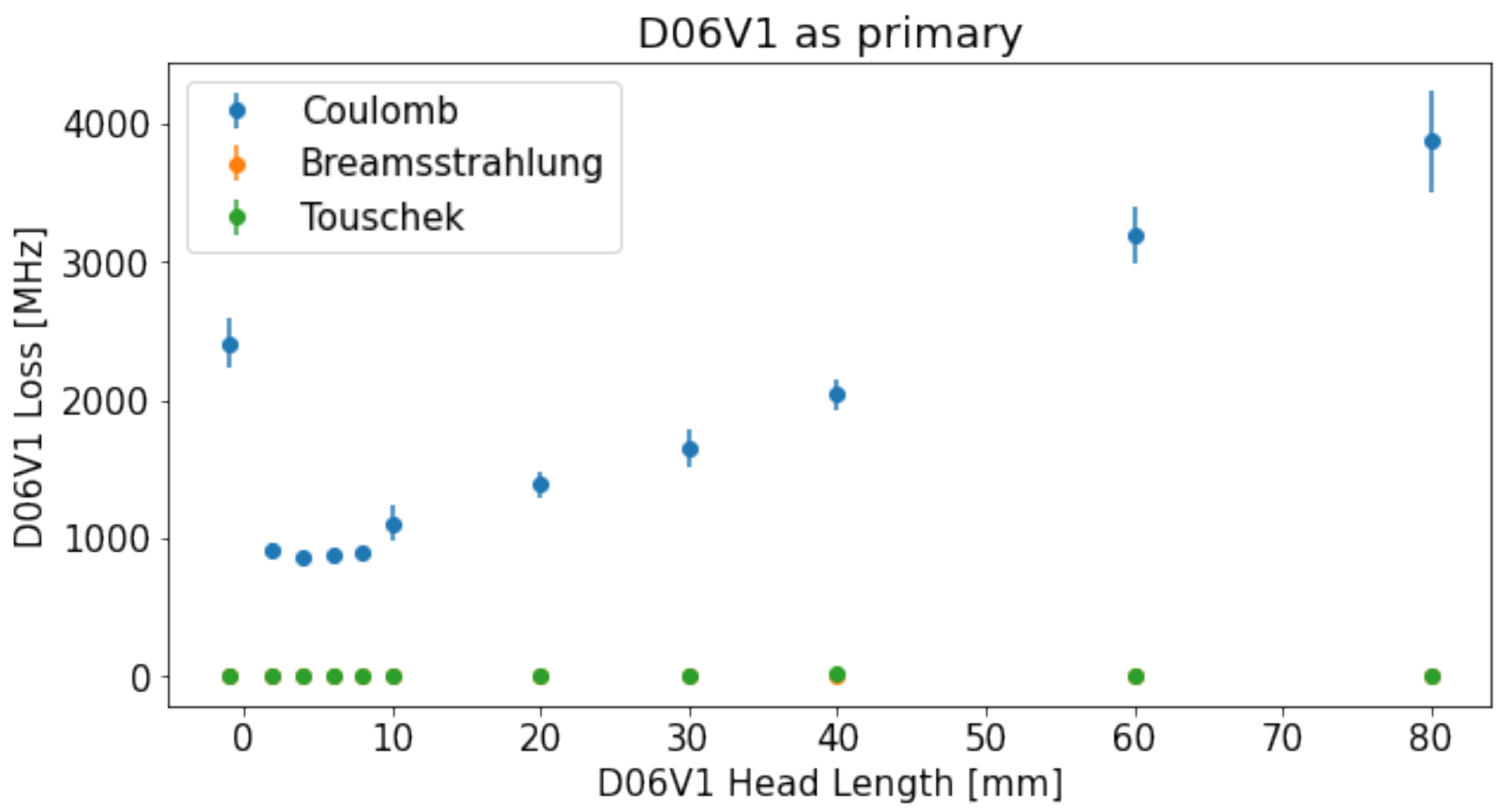
Higher lifetime and lower IR loss with the optimal setting

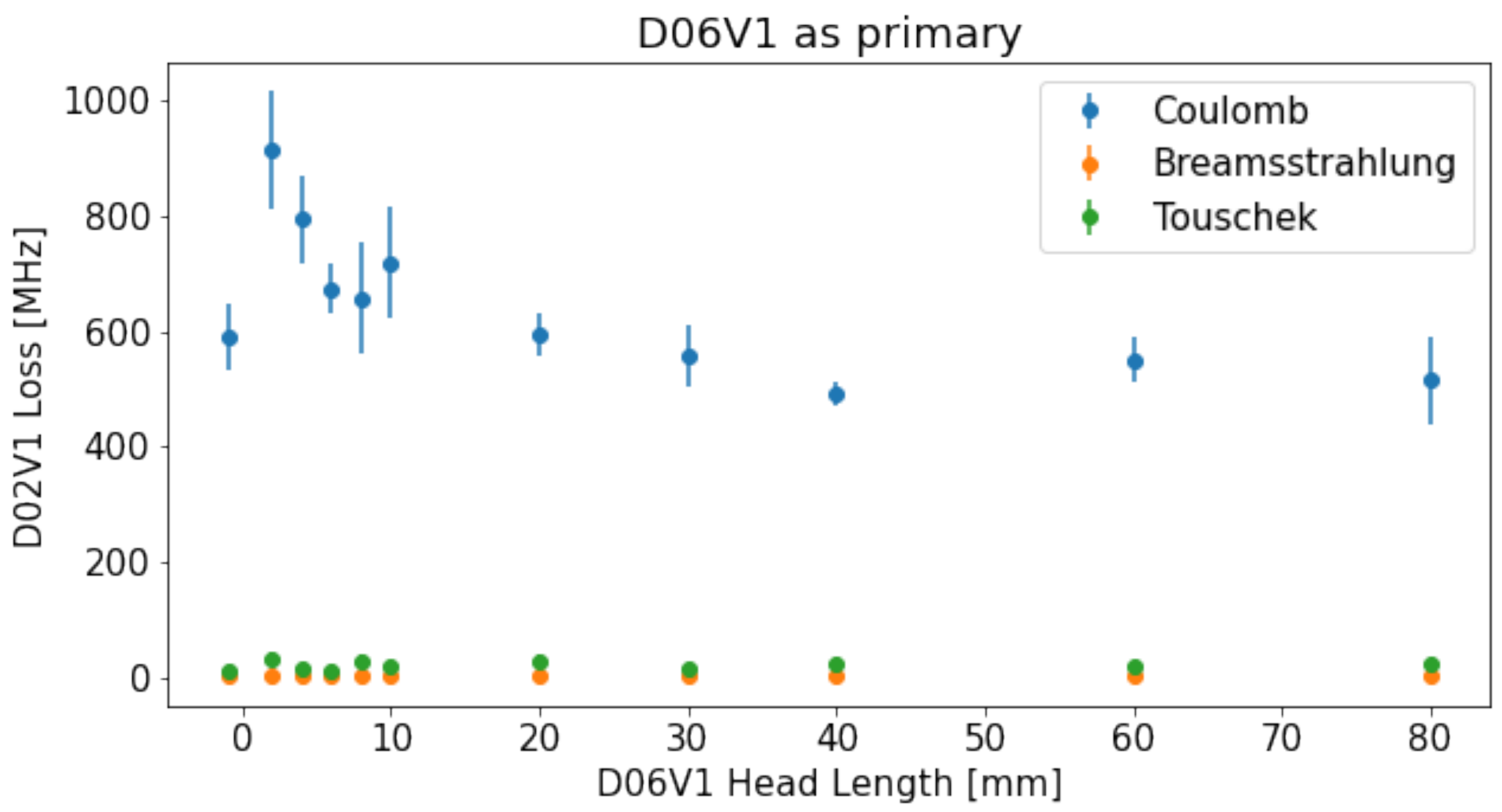
Collimator study

Close collaboration with KEK vacuum group

- Example: Study copper impregnated graphite (CuGr) as head material for D06V1
  - 2.75 g/cm^3, can withstand higher current
  - Head length scan with an optimized collimator setting (-> backup slides)







-1 mm used for the default head: 10-mm Titanium

Summary

- Main Belle II MDI activities are introduced
- Achievements and procedure of Belle II background (BG) study
  - Effective BG monitors to decompose different components online
- Collimator optimization and studies with SAD offer guidelines to KEK collimator group and vacuum group.

Thanks!

Optimized setting for the dedicated BG study in April

Beam condition, optics and collimators apertures

- Beam condition: $I_{LER} = 1.2$ A, $n_b = 1576$, $\beta^*_{y(x)} = 1(80)$ mm, $\epsilon_x = 4.3$ nm, $\epsilon_y/\epsilon_x = 0.01$, CW=80%
- Optics: sler_2024-04-16
- Collimator settings:

Vacuum group:

D6H3 should be fixed at 10.5

NAME	D1[mm]	D2[mm]	D1[nSigma]	D2[nSigma]	dNu[1/2pi]
IR	-10.5	10.5	-34.54	34.54	0.8791
PMD06H3	-10.50	10.50	-32.50	32.50	0.8165
PMD06H4	-9.20	9.20	-28.48	28.48	0.2983
PMD03H1	-9.80	9.80	-27.75	27.75	0.0293
PMD02H1	-6.00	6.00	-20.03	20.03	0.8521
PMD02H2	-8.90	8.90	-22.46	22.46	0.3332
PMD02H3	-11.80	11.80	-25.25	25.25	0.0668
PMD02H4	-7.10	7.10	-23.94	23.94	0.8237
IR	-13.5	13.5	-73.56	73.56	0.2522
PMD06V1	-3.30	3.30	-61.29	61.29	0.2775
PMD06V2	-2.40	2.40	-80.66	80.66	0.9178
PMD05V1	-6.80	6.80	-514.82	514.82	0.5536
PMD02V1	-1.40	1.40	-61.88	61.88	0.2487

Simulation setup for D06V1 study

Beam condition, optics and collimators apertures

- Beam condition: $\mathrm{I_{LER}} = 1.2\ \mathrm{A}$, $n_b = 1576$, $\beta^*_{\mathrm{y(x)}} = 1(80)\ \mathrm{mm}$, $\epsilon_{\mathrm{x}} = 4.3\ \mathrm{nm}$, $\epsilon_y/\epsilon_x = 0.01$, CW=80%
- Optics: sler_1801_sx1
- Collimator settings:

```
(* SuperLER movable masks *)
maskSet={
   "PMD06H3"->{xy->"X",d1->-0.01350,d2->0.01350},
   "PMD06H4"->{xy->"X",d1->-0.00800,d2->0.00800},
   "PMD03H1"->{xy->"X",d1->-0.00940,d2->0.00940},
   "PMD02H1"->{xy->"X",d1->-0.00600,d2->0.00600},
   "PMD02H2"->{xy->"X",d1->-0.00850,d2->0.00850},
   "PMD02H3"->{xy->"X",d1->-0.01220,d2->0.01220},
   "PMD02H4"->{xy->"X",d1->-0.00670,d2->0.00670},
   "PMD06V1"->{xy->"Y",d1->-0.00330,d2->0.00330},
   "PMD06V2"->{xy->"Y",d1->-0.00220,d2->0.00220},
   "PMD05V1"->{xy->"Y",d1->-0.00760,d2->0.00760},
   "PMD02V1"->{xy->"Y",d1->-0.00142,d2->0.00142},

  Null[]
  };
```

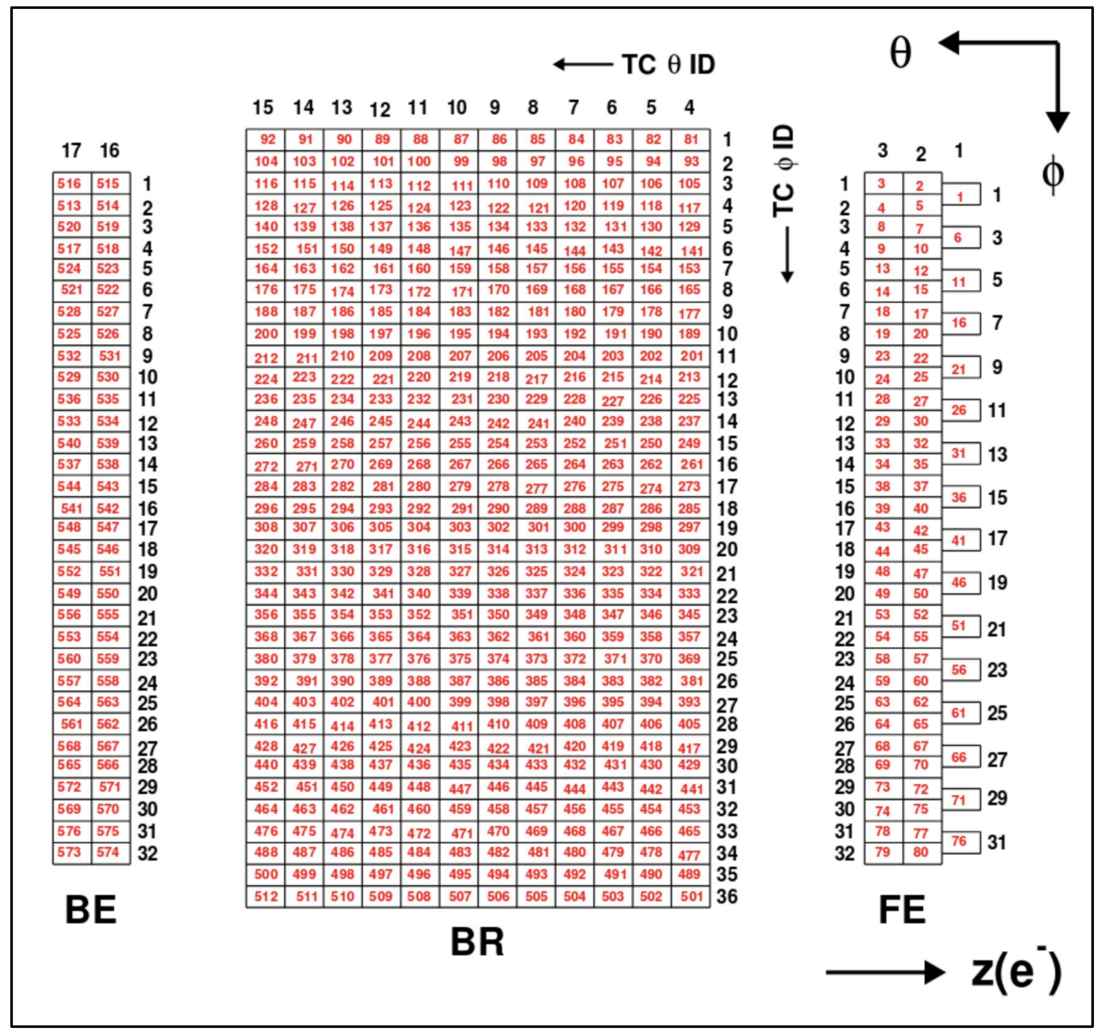
NAME	D1[mm]	D2[mm]	D1[nSigma]	D2[nSigma]	dNu[1/2pi]
IR	-10.5	10.5	-34.53	34.53	0.8791
PMD06H3	-13.50	13.50	-41.78	41.78	0.8165
PMD06H4	-8.00	8.00	-24.76	24.76	0.2983
PMD03H1	-9.40	9.40	-26.62	26.62	0.0293
PMD02H1	-6.00	6.00	-20.03	20.03	0.8521
PMD02H2	-8.50	8.50	-21.44	21.44	0.3332
PMD02H3	-12.20	12.20	-26.10	26.10	0.0668
PMD02H4	-6.70	6.70	-22.58	22.58	0.8237
IR	-13.5	13.5	-73.55	73.55	0.2522
PMD06V1	-3.30	3.30	-61.28	61.28	0.2775
PMD06V2	-2.20	2.20	-73.92	73.92	0.9178
PMD05V1	-7.60	7.60	-575.29	575.29	0.5536
PMD02V1	-1.42	1.42	-62.76	62.76	0.2488

61.66 at SNAP.1

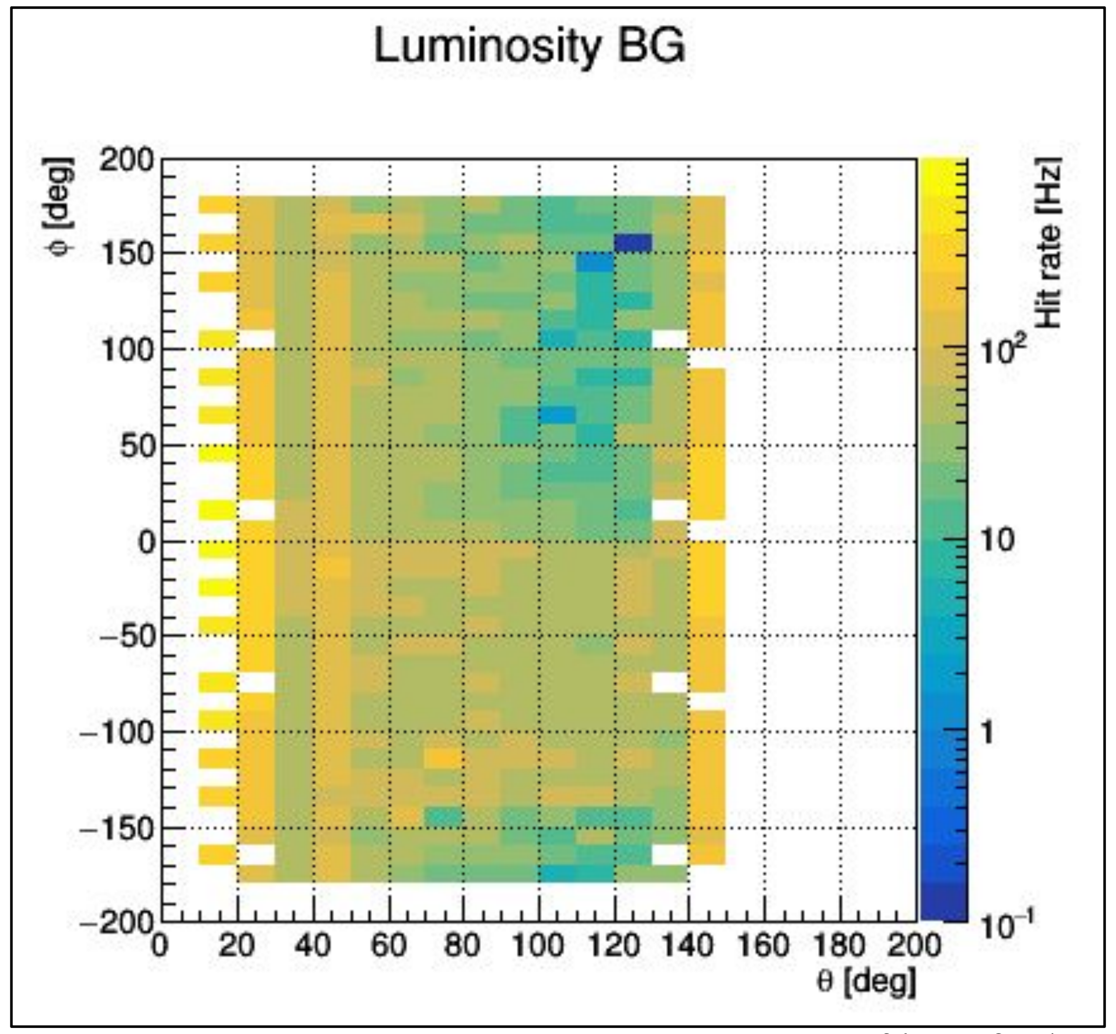
ECL-based BG monitor

Online background decomposition

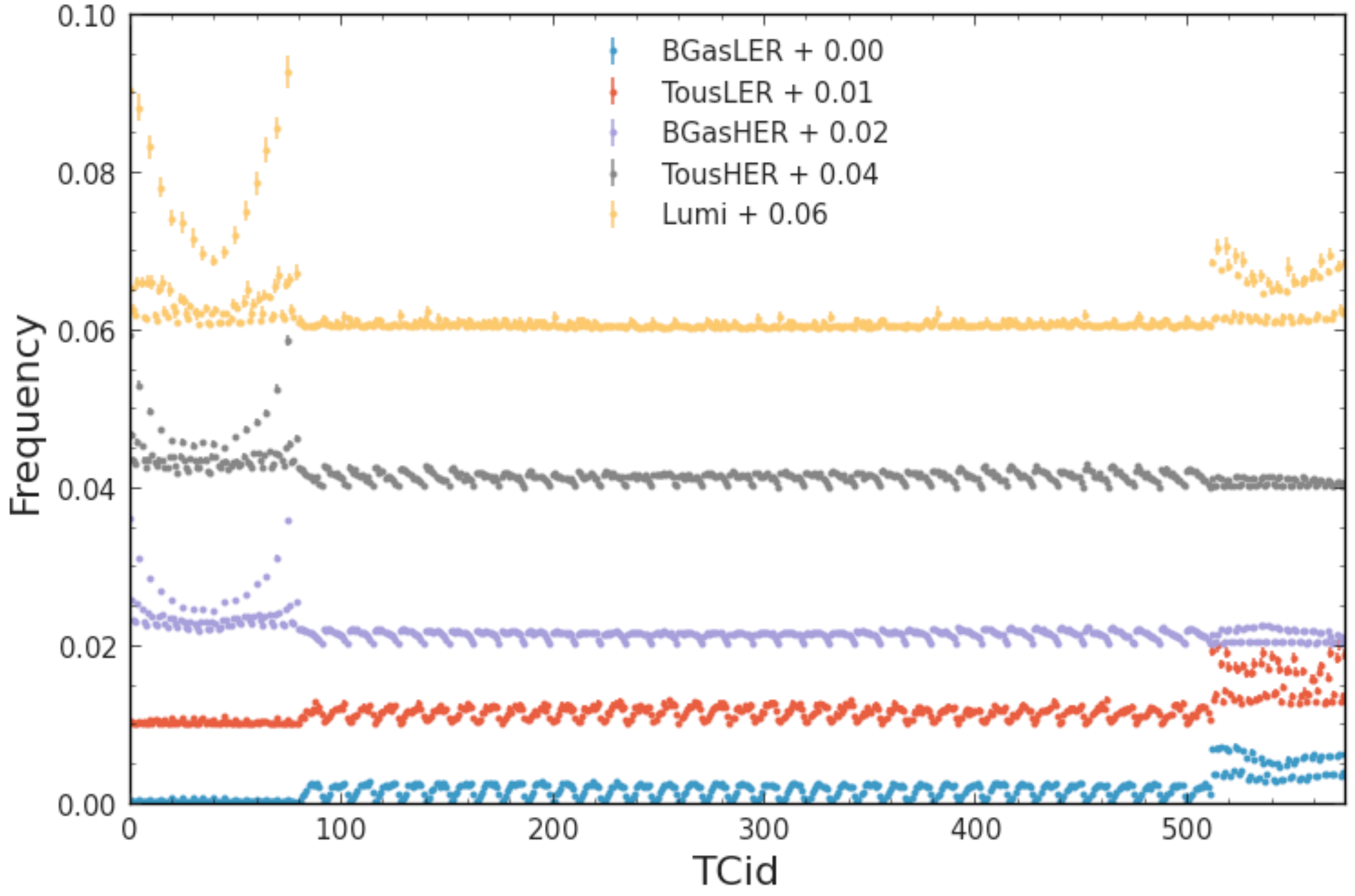
- Extract BG components online
  - Fit ECL hit rate PVs of **576** trigger cells (TC)
    - More details in *Andrii's slides*
    - Using local injection veto → **storage** BG
      - PV for each TC: B2_nsm:get:ECLTRG_ETM_BKGMON:TCRateInjV_TCIdXXX
  - MC templates from **May 9th, 2020**
  - Adjustable parameters:
    - Template files
    - PV integration/update time: 10 s
    - Local veto parameters (only for this monitor)



TC mapping. Red numbers indicate the TC ID.



ECL estimated Luminosity BG at $\mathcal{L}$ = 2.6 x10^{34} cm^{-2}s^{-1} (June 2021).



PV: EPICS process variable

Effective pressure

- Cold Cathode Gauge (CCG) for pressure measurement
  - ~300 for each ring with sensitivity $> 1 \times 10^{-8}$ Pa

$$\mathcal{O}_{\mathrm{beam-gas}} = \mathrm{B} \times \mathrm{I}\bar{\mathrm{P}}_{\mathrm{eff}}$$

$$\downarrow$$

$$\bar{\mathrm{P}}_{\mathrm{eff}} = 3\mathrm{I}(\mathrm{d}\bar{\mathrm{P}}/\mathrm{dI})_{\mathrm{CCG}} + \bar{\mathrm{P}}_{0,\mathrm{CCG}} = 3\bar{\mathrm{P}}_{\mathrm{CCG}} - 2\bar{\mathrm{P}}_{0,\mathrm{CCG}}$$

$$\downarrow$$

$$3(\bar{\mathrm{P}}_{\mathrm{CCG}} - \bar{\mathrm{P}}_{0,\mathrm{CCG}})$$