LumiBelle2, a fast luminosity monitor for beam tuning and feedback at the interaction point of SuperKEKB

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The SuperKEKB/Belle II project

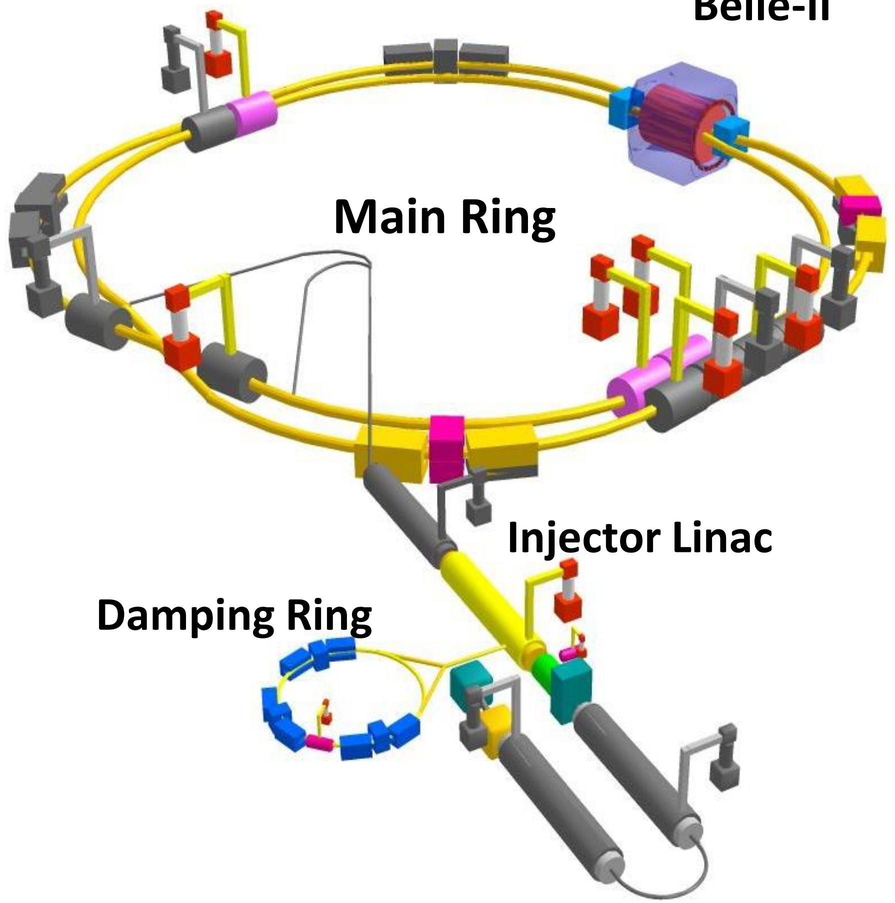
SuperKEKB (Electron-Positron Collider)

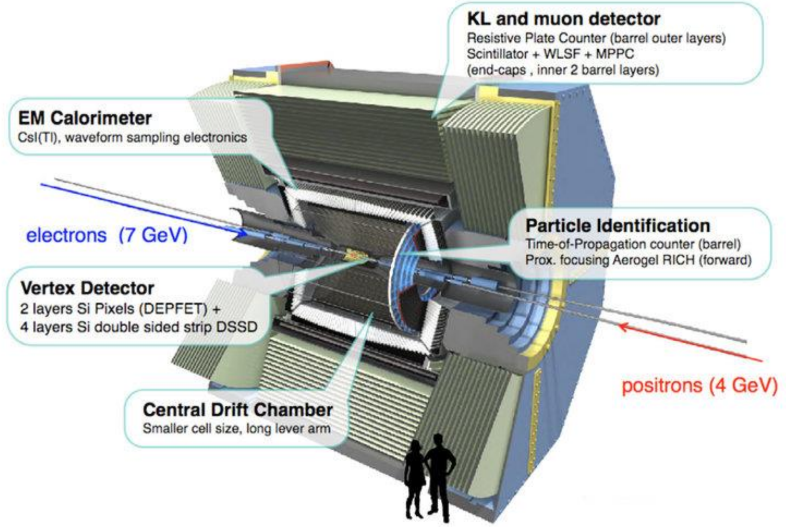
C.M.S. Energy: $\sqrt{s}$ = 10.58 GeV

Luminosity: **L = 8 x 10^{35} $cm^{-2}s^{-1}$**

(Luminosity Frontier Machine)

	Electron	Positron
Energy (GeV)	7	4
Current (A)	3.6	2.6





Belle II (General purpose detector)

Vertex detectors: Pixel Vertex Detector (PXD),
Silicon strip Vertex Detector (SVD)

Tracking: Central Drift Chamber (CDC)

Calorimeter: Electromagnetic CaLorimeter (ECL)

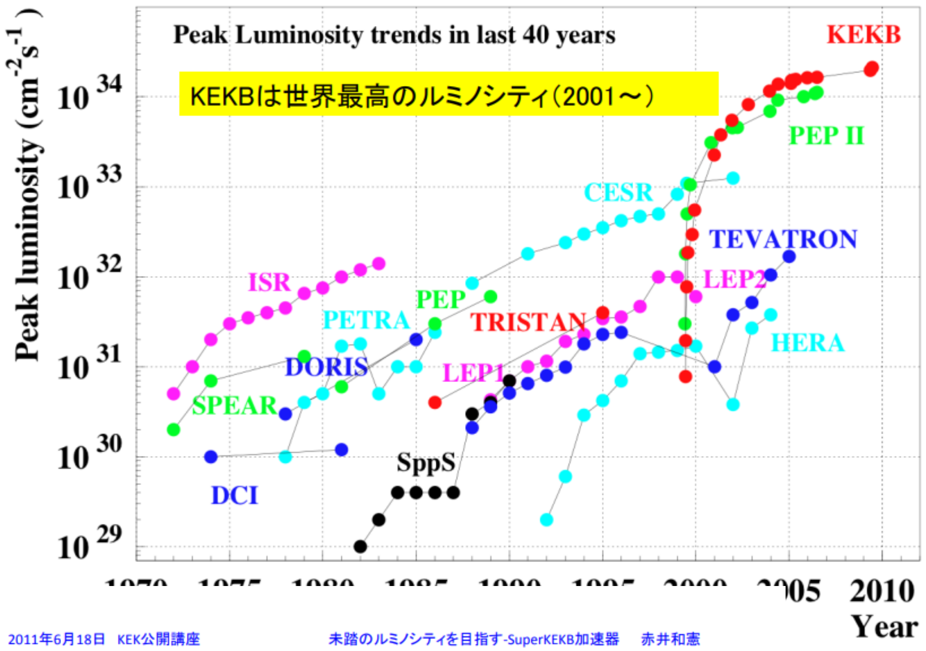
Particle ID: Aerogel Ring Image CHerenkov detector (ARICH)
K-Long and Muon detector (KLM)
Time-Of-Propagation counter (TOP)

Luminosity Frontier

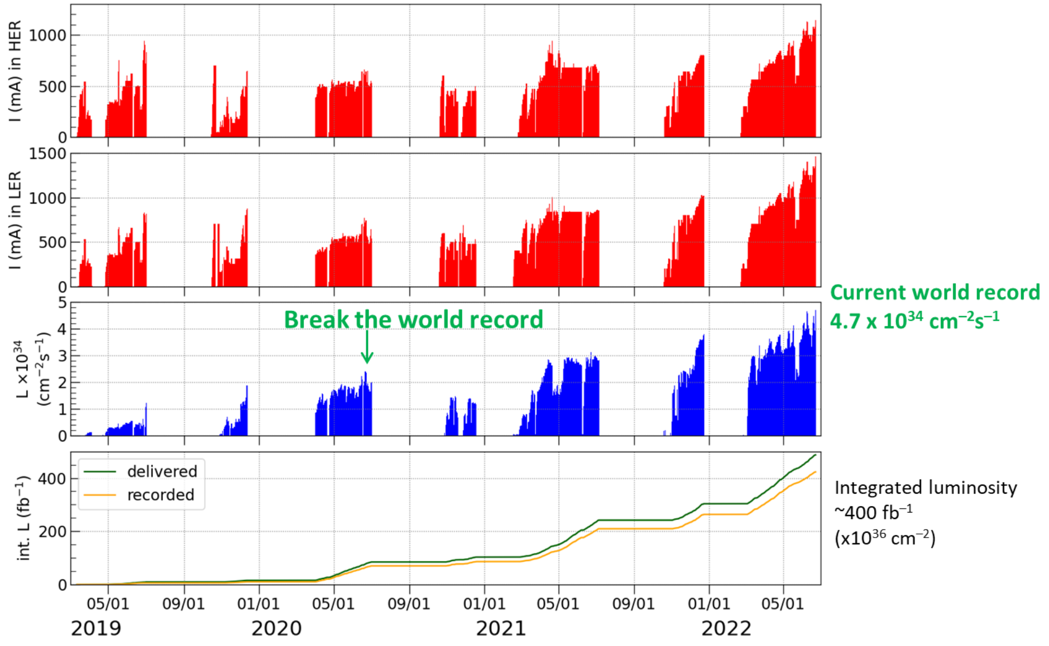
B-pair production rate (pair/sec) : $N = \sigma \times L$

σ = cross-section for B pair production = 1.1nb   L = luminosity.
→ 110 pairs of B mesons produced / second for L = 10^{35} $cm^{-2}s^{-1}$.

World's history before SuperKEKB



Our history, current record: 4.7x10^{34} cm^{-2}s^{-1}



SuperKEKB → unchartered luminosity territory → new techniques

KEKB ↔ SuperKEKB parameters

		KEKB		SuperKEKB		
		LER (e^+)	HER (e^-)	LER (e^+)	HER (e^-)	Units
Beam energy	E	3.5	8.0	4.0	7.007	GeV
Circumference	C	3016.262		3016.315		m
Half crossing angle	θ_x	$0(11^{(*)})$		41.5		mrad
Piwinski angle	ϕ_{piw}	0	0	24.6	19.3	rad
Horizontal emittance	ε_x	18	24	3.2(1.9)	4.6(4.4)	nm
Vertical emittance	ε_y	150	150	8.64	12.9	pm
Coupling		0.83	0.62	0.27	0.28	%
Beta function at IP	β_x^*/β_y^*	1200/5.9	1200/5.9	32/0.27	25/0.30	mm
Horizontal beam size	σ_x^*	147	170	10.1	10.7	μm
Vertical beam size	σ_y^*	940	940	48	62	nm
Horizontal betatron tune	ν_x	45.506	44.511	44.530	45.530	
Vertical betatron tune	ν_y	43.561	41.585	46.570	43.570	
Momentum compaction	α_p	3.3	3.4	3.20	4.55	10^{-4}
Energy spread	σ_ε	7.3	6.7	7.92(7.53)	6.37(6.30)	10^{-4}
Beam current	I	1.64	1.19	3.60	2.60	A
Number of bunches	n_b	1584		2500		
Particle/bunch	N	6.47	4.72	9.04	6.53	10^{10}
Energy loss	U_0	1.64	3.48	1.76	2.43	MeV
Long. damping time	τ_z	21.5	23.2	22.8	29.0	msec
RF frequency	f_{RF}	508.9		508.9		MHz
Total cavity voltage	V_c	8.0	13.0	9.4	15.0	MV
Total beam power	P_b	~ 3	~ 4	8.3	7.5	MW
Synchrotron tune	ν_s	-0.0246	-0.0209	-0.0245	-0.0280	
Bunch length	σ_z	~ 7	~ 7	6.0(4.7)	5.0(4.9)	mm
beam-beam parameters	ξ_x/ξ_y	0.127/0.129	0.102/0.090	0.0028/0.088	0.0012/0.081	
Luminosity	L	2.108×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$
Integrated luminosity	$\int L$	1.041		50		ab^{-1}

× 1/20 β_y

$\sigma_y \approx$ 50-60 nm

(similar as ILC/ATF2)

× 2-3 beam currents

similar beam-beam strength (tune-shift)

→ up to × 40 peak luminosity

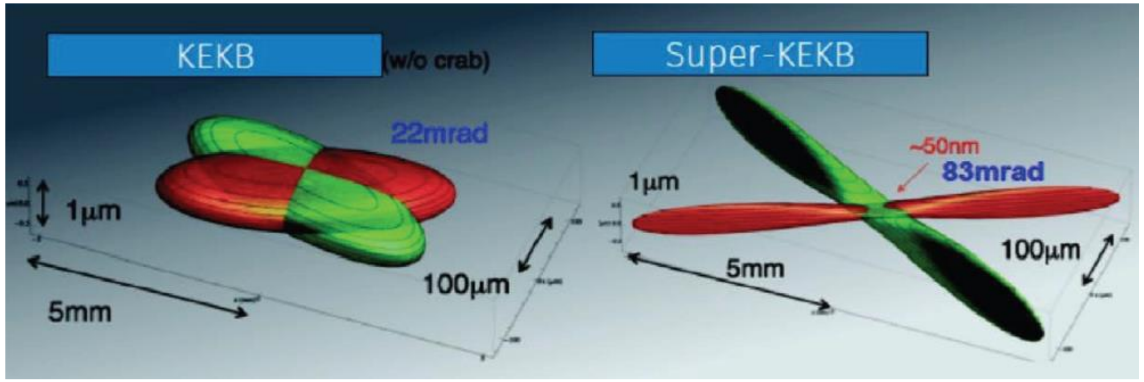
Nanobeam collision scheme

Opportunities

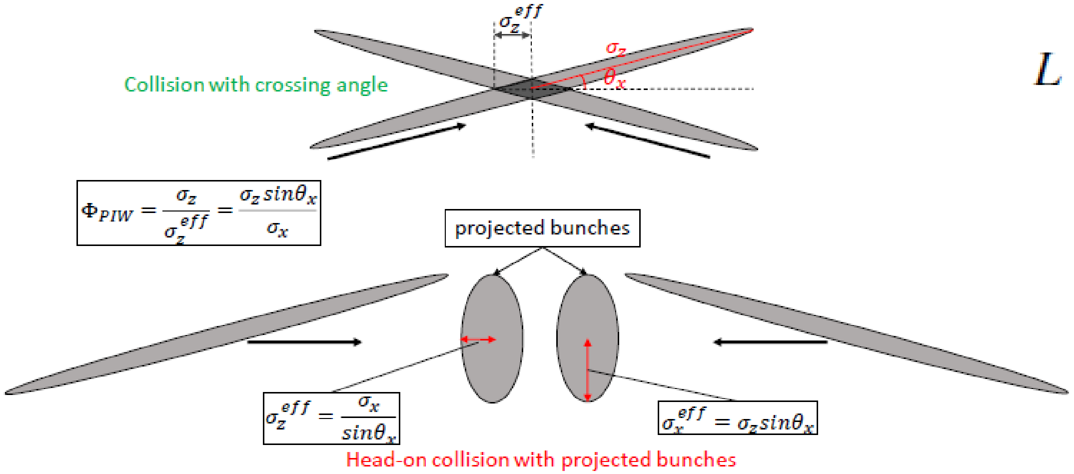
- ✓ Very small β_y avoids "hour-glass" limitation (effective bunch length ≈ depth of field of the optics)
- ✓ Collide more charge @ tiny vertical beam size with similar beam-beam tune-shift strength parameter

Challenges

1. Optical aberrations near IP must be cancelled to achieve / maintain tiny beam spots
2. Control beam-beam tune-shift with more complex IP beam-beam dynamics + optical aberrations
3. Continuously inject intense beams in strongly demagnified IP optics → injection backgrounds… beam tails…



$$\xi_{xy\pm} = \frac{r_e}{2\pi\gamma_\pm} \frac{N_\mp \beta^*_{xy}}{\sigma^*_{xy}(\sigma^*_x + \sigma^*_y)} R_{\xi_{xy}}$$



$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma^*_y}{\sigma^*_x}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

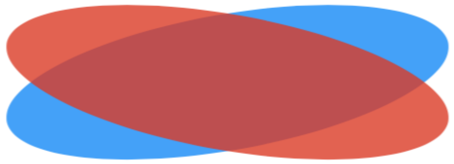
× 1/20 β_y × 2-3 beam currents

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} R_L$$

× 1/20 σ_y

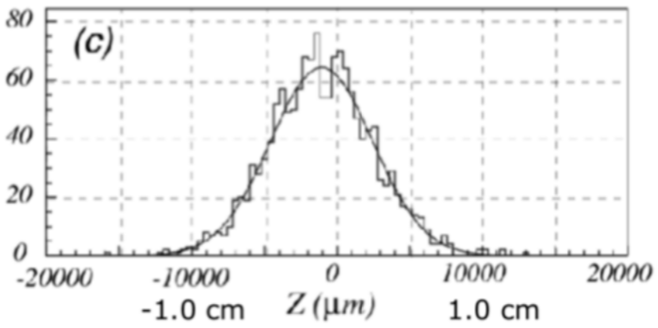
Nanobeam scheme reduced bunch overlap visible on reconstructed track vertex Z distribution

Ordinary collision KEKB



Z vertex distribution

Belle case 1999 data

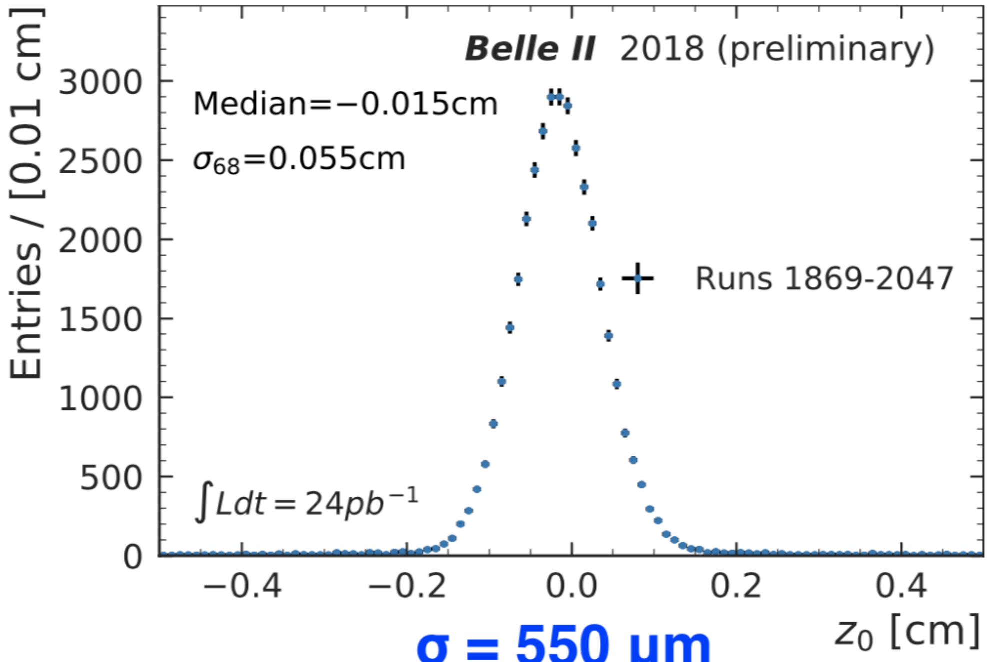


σ = 4.5 mm

Nano-Beam (SuperKEKB)

Z vertex distribution

Belle II case 2018 data



σ = 550 μm

IP optical aberrations blowing up the beam size are unavoidable

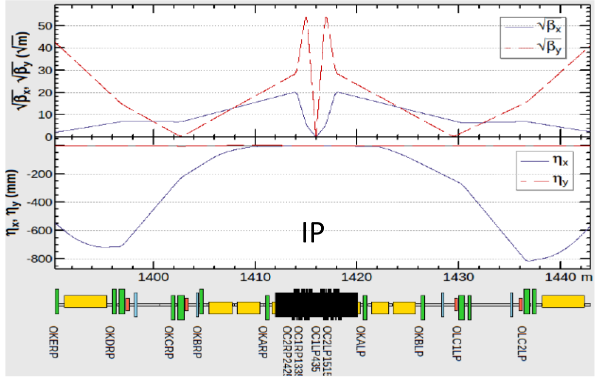
→ reliable measurement for correction only possible at the IP…

$$\sigma_y^2 = \mu^2 \varepsilon_y \left(\beta_y + \frac{\Delta s^2}{\beta_y}\right) + \left\{ \frac{(R_2 + R_4 \Delta s)^2}{\beta_x} + \beta_x (R_1 + R_3 \Delta s)^2 \right\} + (\eta_y \sigma_\delta)^2$$

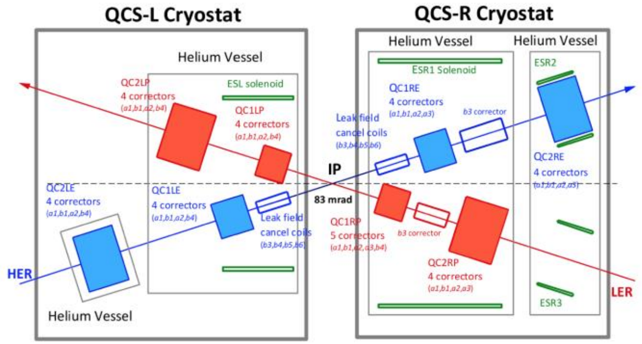
+ higher order terms
(geometric & chromo-geometric)

ideal spot waist shift — linear x-y coupling — linear dispersion

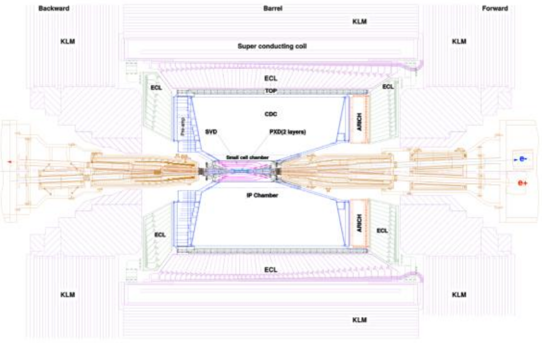
Optical functions in LER ±27 m around IP



SC final focus system



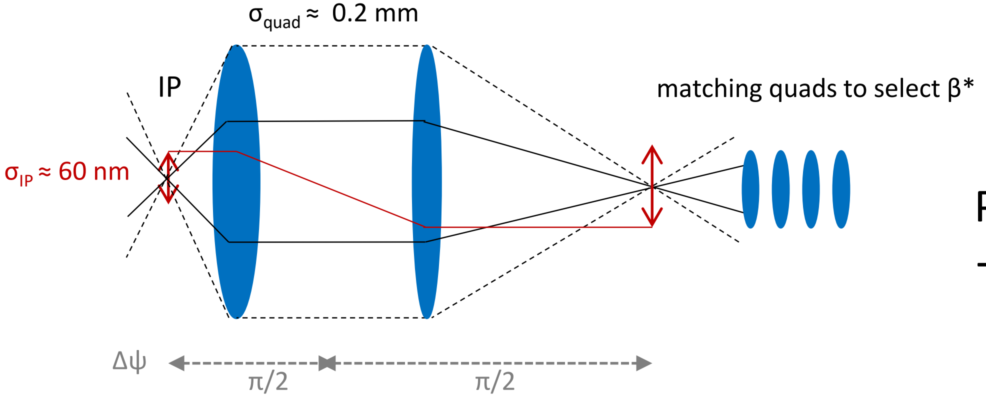
integration with Belle II



quad strength tolerance for waist shift < β* / L* ≈ 3 10^{-4}

$$M(s_2|s_1) = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\psi + \alpha_1 \sin\psi) & \sqrt{\beta_1\beta_2}\sin\psi \\ -\frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\psi + \frac{\alpha_1-\alpha_2}{\sqrt{\beta_1\beta_2}}\cos\psi & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\psi - \alpha_2\sin\psi) \end{pmatrix}$$

$\Delta\psi = \int \frac{ds}{\beta(s)} \approx \pi/2$ except near a waist



Propagate IP aberration in low-β insertion
→ no visibility (except, possibly, at a secondary waist)

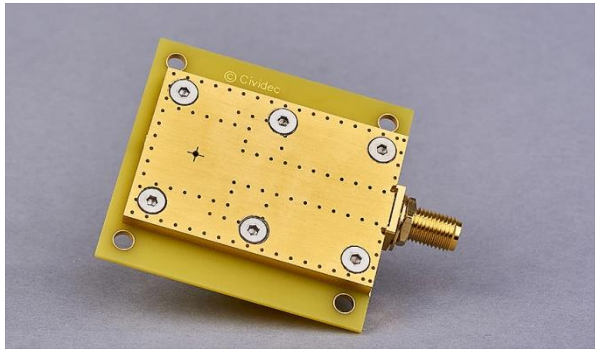
Must tune directly at IP (luminosity…)

Two complementary techniques for fast luminosity measurements

- compare / collaborate / mutually supporting
- share simulation, mechanics, some data…
- since 2012

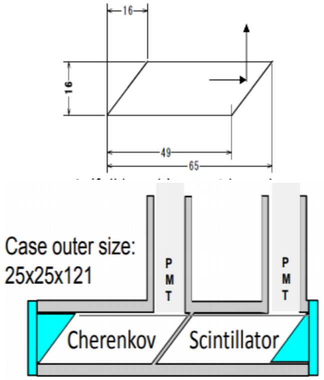
LumiBelle2 / IJCLab

- single crystal CVD diamond sensors
- $4 \times 4 \times 0.5/0.14\ mm^3$
- Fast charge/current amplifiers
- Digital electronics and processing



ZDLM (Zero Degree Luminosity Monitor) / KEK

- Cherenkov and scintillator detectors
- $15 \times 15 \times 64\ mm^3$ LGSO non-organic scintillator and ES-crystal (quartz)
- Photomultipliers
- Analog & digital processing



What for / specs ?

➢ "Dithering" feedback

- Correct for few Hz horizontal motion
- 79 Hz orbit "dithering" + luminosity sampling @ 1 kHz → reconstruct baseline freq. + 2nd harmonic
- Efficient separation from other "slow" variations
- 1% relative precision @ 1 kHz sufficient (cf. C.-G. Pang et al., J.Phys.Conf.Ser. 1067 (2018) no.7, 072023)
- Provide analog signal as input to lock-in amplifier

➢ Bunch by bunch luminosity diagnostic

- Nominally 4 ns bunch separation → need short signal pulses, ideally < 4 ns
- 1% or better relative precision @ 1 Hz

➢ IP vertical beam size measurement + tuning at very low currents

1. Single beam orbit + optics corrections in two rings
2. Vertical e+ and e- beam size optical tuning → suppress local aberrations in nanobeam final focus

   ⬆ Very low current → avoid confusion from beam-beam induced blowup

3. Control of beam-beam blowup → find best spot in tune diagram

- Dynamic range $L \approx 10^{32} \rightarrow 10^{36}$ cm^{-2} s^{-1}
- Non luminosity scaling contamination < 1% (e.g. beam gas bremsstrahlung and Touschek losses)
- Manage radiation damage at highest luminosity

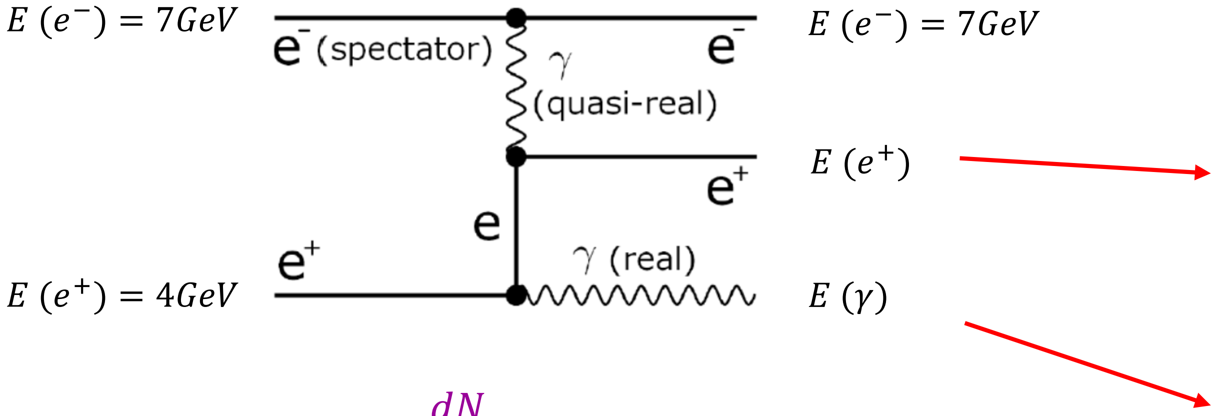
Bhabha process at vanishing scattering angle

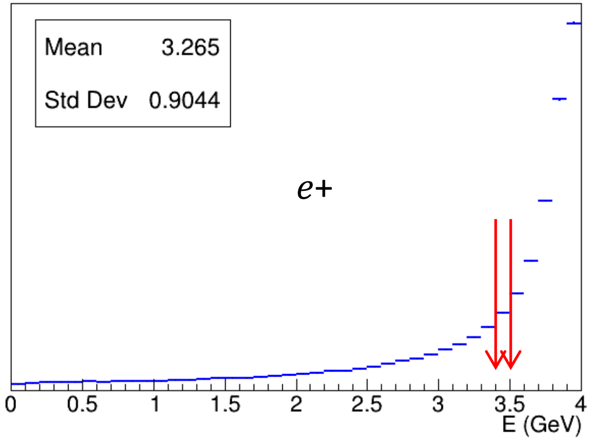
a.k.a. Single Bremsstrahlung

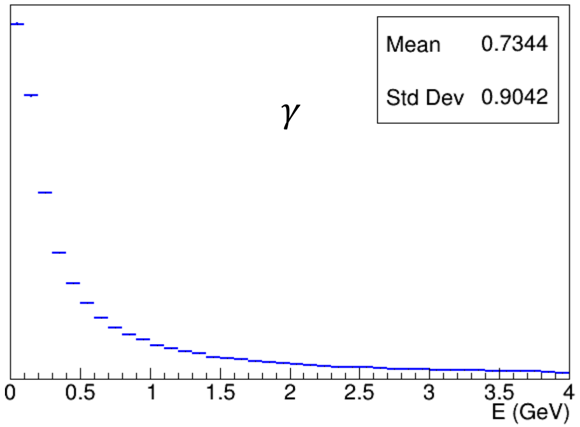
Dima El Khechen et al., PRAB 22, 062801 (2019)

Large cross section $\sigma \approx 150 - 200\ mbarn$ for $E\ (\gamma) > 1\%\ E\ (beam)$

1) $e+$ rate in LER 10 m after IP (part of energy spectrum near E(e+) ≈ 3.5 GeV after large bend)
2) γ rate in HER 30 m after IP (part of 0.1-0.3 mrad IP beam angular spread due to geometry)







Only relative luminosity → $L \propto \frac{dN}{dt}$ with certain conditions…

1. Acceptance depends on choice of sensor / location
2. Also some variation with beam parameters…
3. $\sigma_{\text{Bhabha@zero-degree}}$ not precisely computed in QED

➔ OK for usage on “short” enough time-scales
➔ care for beam parameter dependence

Theoretical prediction for small transverse beam size and large beam offset

- Finite scattering angle interaction cross-section does not dependent on beam size and offset ⇒ ECL measurements
- Zero scattering angle interaction can occur over a range extending beyond beam size ⇒ ZDLM and LB2 measurements
  - ZDLM/ECL and LB2/ECL cross section ratios are suppressed for typical beam sizes of SuperKEKB, (**Fig -1-*)
  - ZDLM and LB2 counting rates decrease more slowly than ECL when beams are separated, (***Fig -2-*)

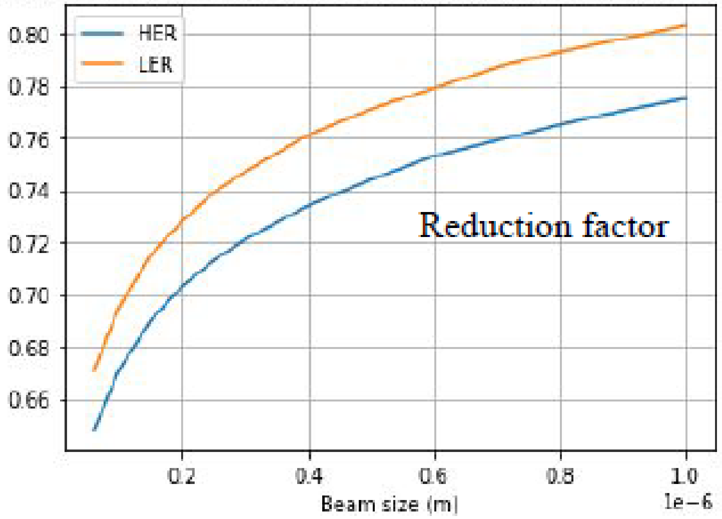


Fig -1- Plots of the ratio of the reduced and classical cross section with the beam size variation for positron (LER) and electron (HER) beams.

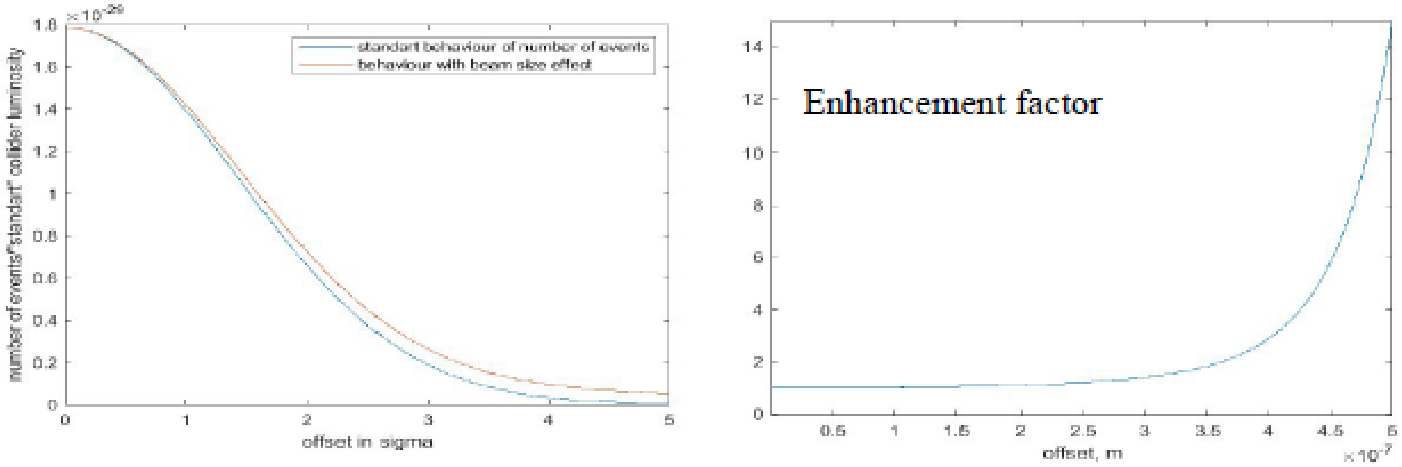


Fig -2- Left : Plots of the number of events for relative luminosity compared to absolute luminosity. Right : Plots of the ratio of number of events for LB2/ZDLM over number of events for ECL.

- Experimental study :
  - Comparing ZDLM and LB2 counting rate with respect to ECL during vertical beam offset scan
- Previously this effect has been studied at VEPP***

** Made by Thibaut OTTMANN, based on : "Beam-size effect and particle losses at B-factories KEKB and PEP-II, G.L. Kotkin, V.G. Serbo, NIM B 227 (2005) 137–142"*
*** Made by Vladyslav VINNICHENKO, based on : " V.N. Baier, V.M. Katkov and V.M. Strakhovenko, pre-print INP 81-59 (Novosibirsk, 1981) https://inp.nsk.su/images/preprint/1981_059.pdf"*
****LARGE IMPACT PARAMETER CUT-OFF IN THE PROCESS $e^+e^- \rightarrow e^+e^-\gamma$, VEPP, Yury Eidelman et al. , Physics Letters B, 1982*

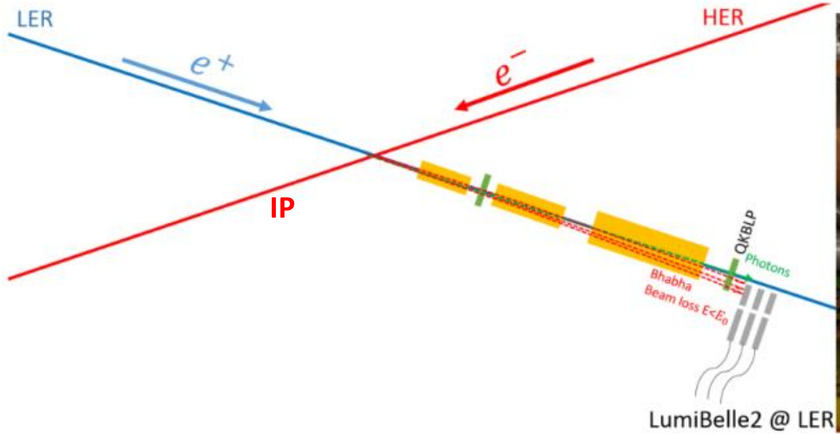
Maroua Benhatchi, *Master Intership Report, 2022*

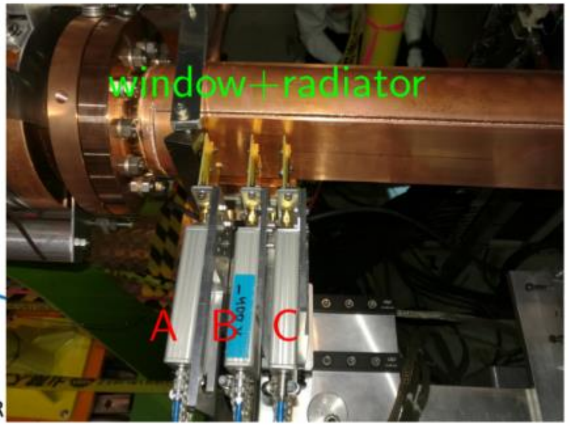
Implementation in LER and HER

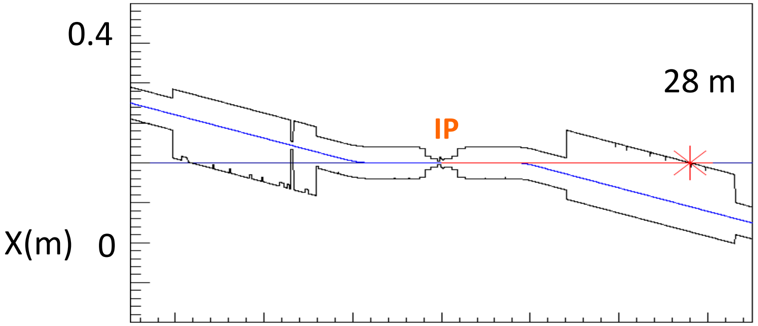
Cheng Guo Pang et al., Nucl.Instrum.Meth. A931 (2019) 225-235

POSITRON RING (measure e+)

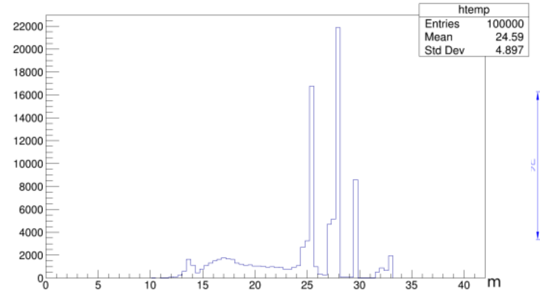
- Optimal position found at 10 m behind IP using SAD
- Over-bent Bhabha positrons → vacuum chamber
- Special beam pipe with window + Tungsten radiator
- Start-to-end simulation (GuineaPig++, SAD, GEANT4)





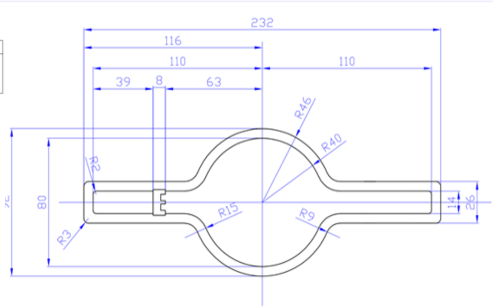


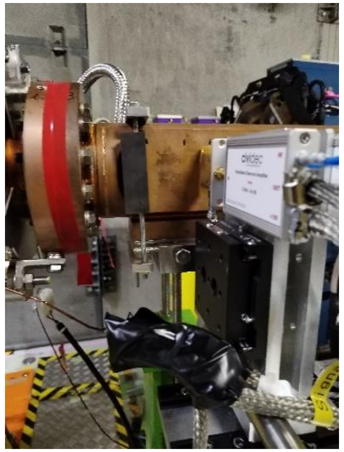
loss position distribution

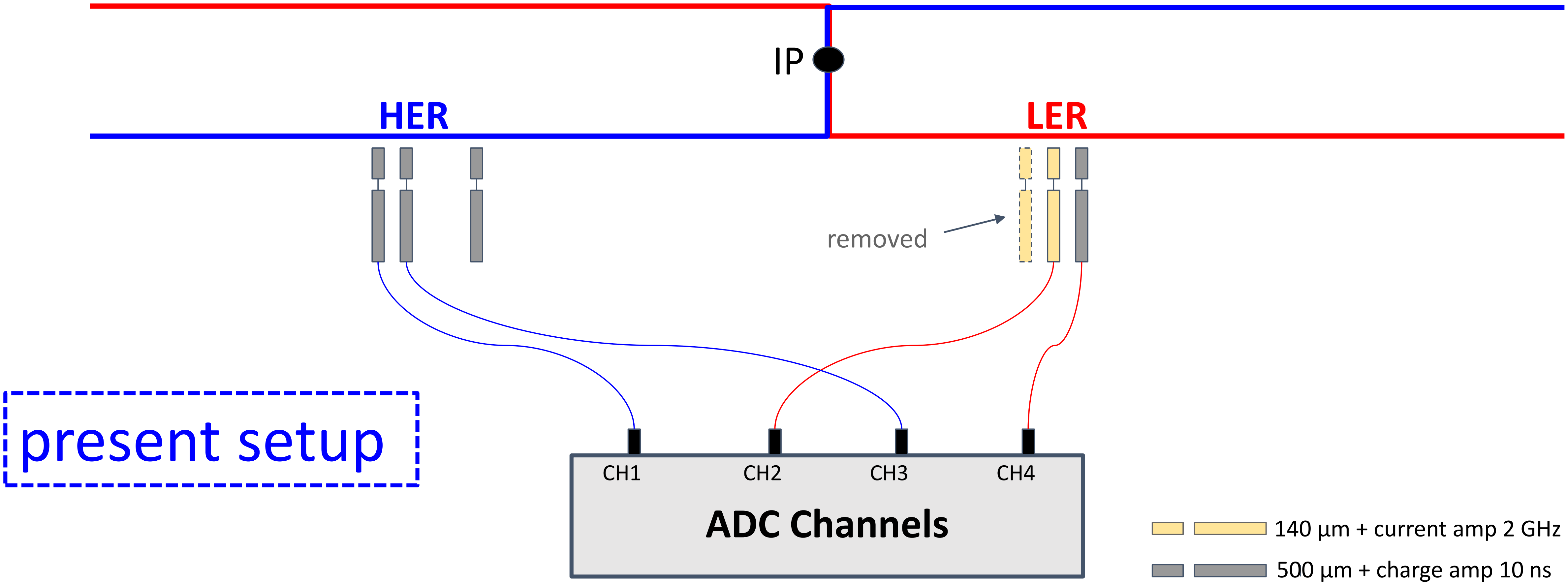


ELECTRON RING (measure γ)

- Photon ray-tracing in detailed vacuum chamber geometry + GEANT4
- Original position at 30 m (2018)
- New optimal position found at 28 m with ≈ 10 times higher rate






IP
HER
LER
removed
present setup
CH1
CH2
CH3
CH4
ADC Channels
140 μm + current amp 2 GHz
500 μm + charge amp 10 ns

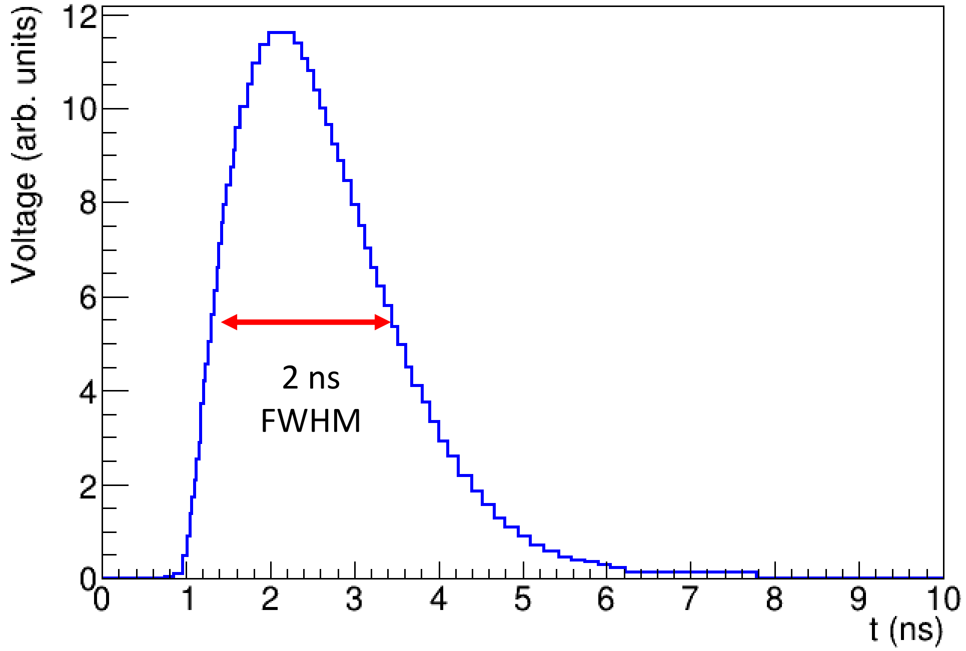
LumiBelle2 diamond sensor signals

High charge carrier mobility → fast signal formation

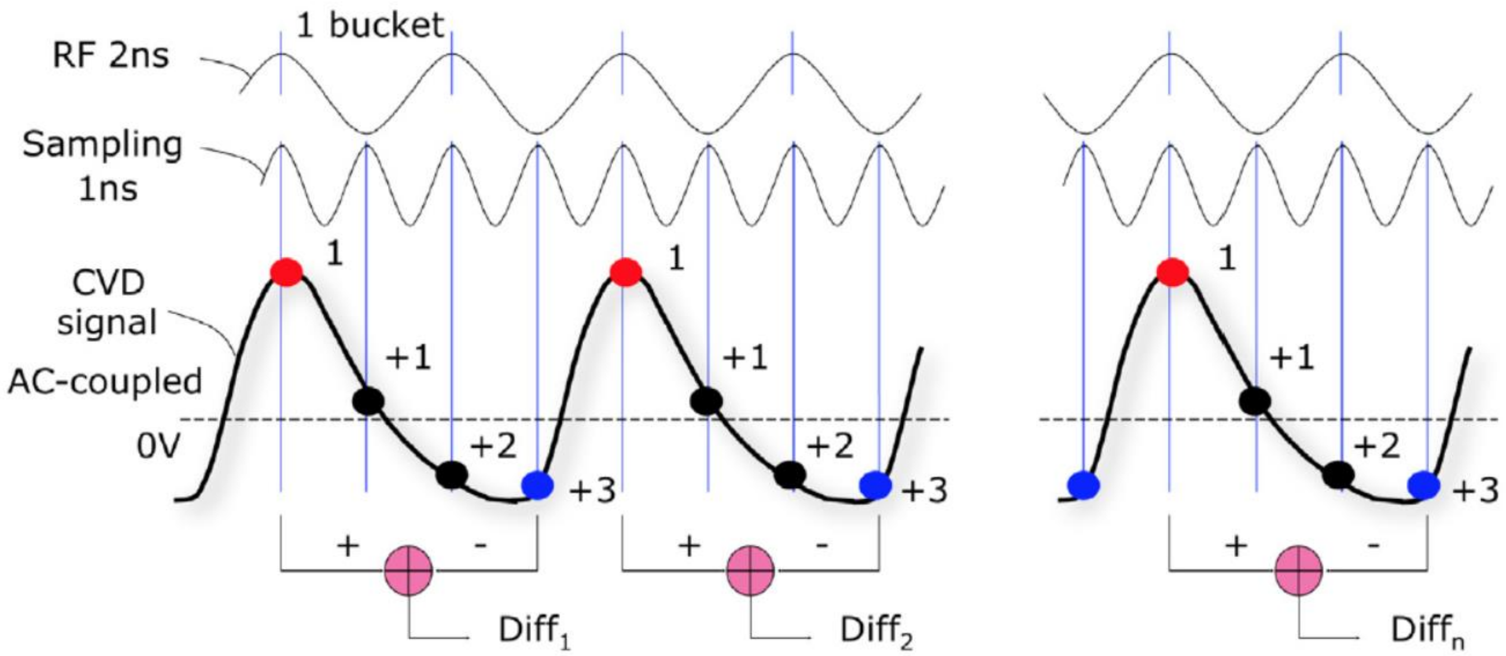
Wide band-gap (5.5 eV) → good radiation tolerance

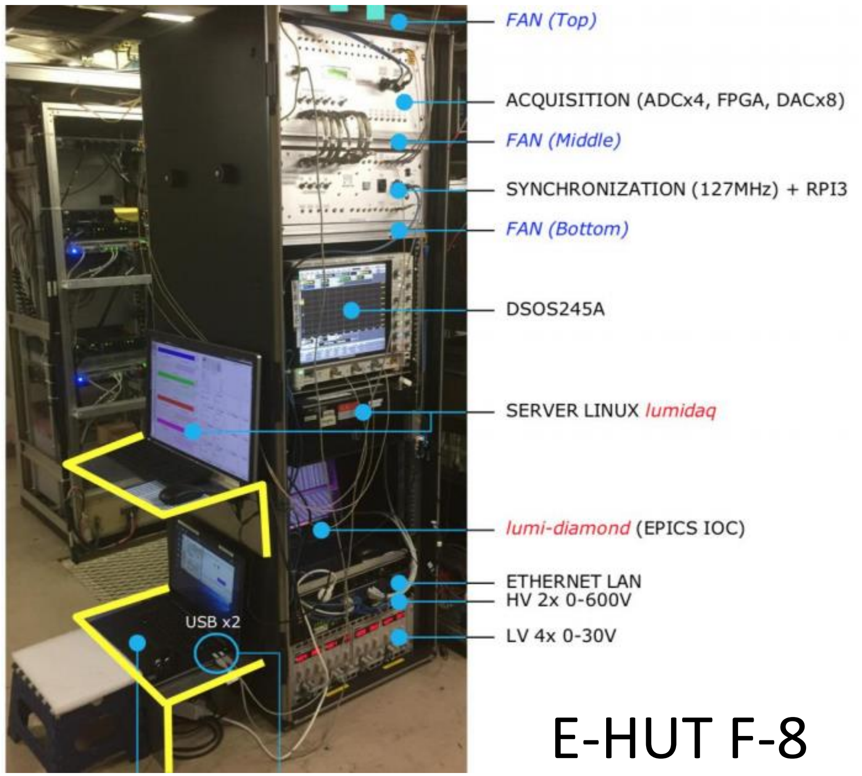
SuperKEKB nominal collision spacing = 4 ns

- Monitor bunch-by-bunch luminosity → easier with pulse width < 4 ns
- 140 μm thick diamond + fast 2 GHz current amplifier → 2 ns FWHM



LumiBelle2 signal processing





E-HUT F-8

- 2 / 10 ns FWHM signals from 140 / 500 µm with 2 GHz current / low noise charge amp sampled every 1 ns
- Synchronized to RF clock → continuous monitoring, averaging at 1 kHz and 1 Hz (bunch by bunch and all bunches together)
- Luminosity proportional to amplitude of signal peaks
  1. ADC is AC-coupled → record difference between peak and baseline → **"TIL" & "BIL"**
  2. Raw sum of all samples also ∝ luminosity and recorded → **"RAWSUM"**
  3. Number of peaks also recorded (constant fraction discriminator) → **"COUNT"**

$$BIL[j] = \sum_{0}^{1\,s} Diff_{n,j}, \quad if\ Diff_{n,j} > Threshold_1$$

$$TIL = \sum_{0} Diff_i, \quad if\ Diff_i > Threshold_1$$

$$Count = Count + 1, \quad if\ Diff_i > Threshold_1$$

$$RAWSUM = \sum_{0}^{1\,ms} (Sample_i - Threshold_2), \quad if\ Sample_i - Threshold_2 > 0$$

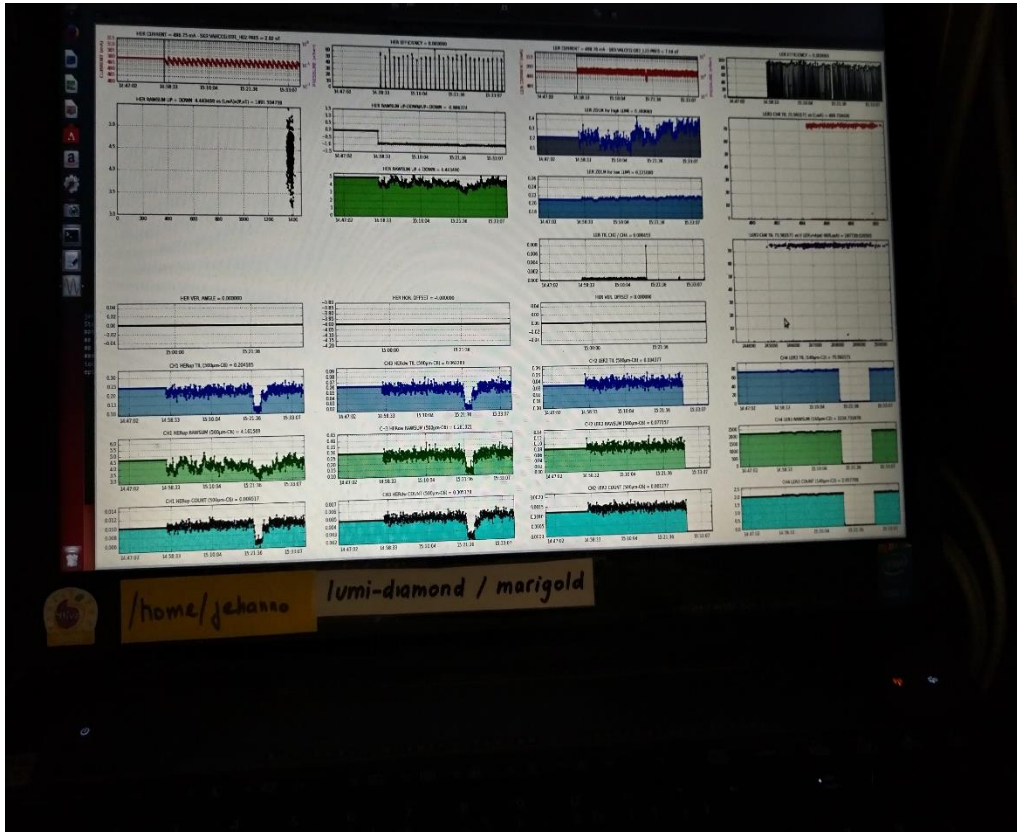
→ EPICS broadcasting @ 1 Hz → "1 Hz, 1 KHz, bunch-by-bunch, bunch-current" data streams transferred daily for archiving

LER 400 mA single beam vacuum scrubbing – 17/02/2024

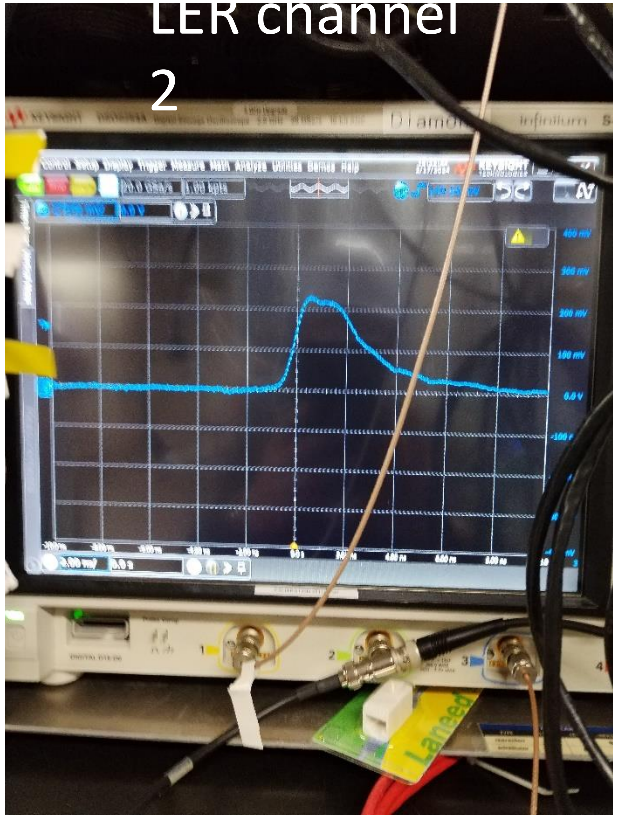
(beam gas Bremsstrahlung events)

E-HUT / lumi-diamond PC

E-HUT / Keysight digital scope

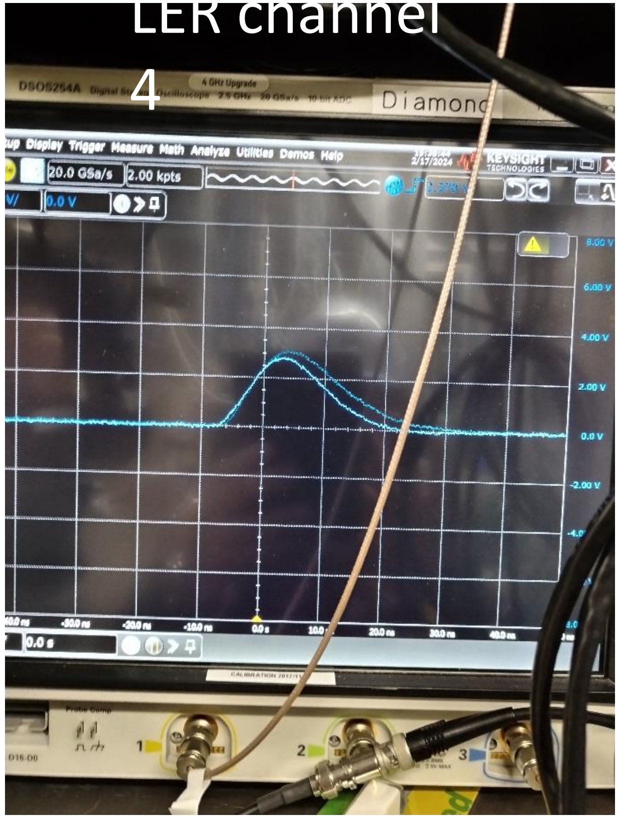


On-line EPICS data plotter



140 μm diamond

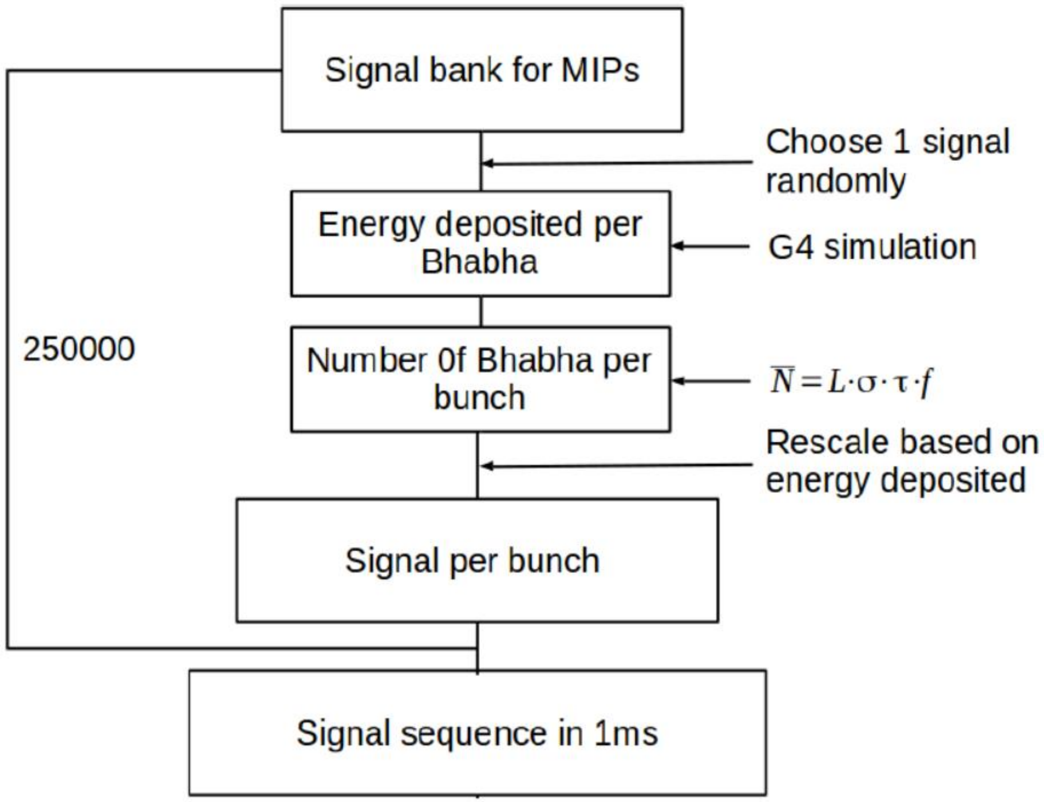
2 GHz current amp



500 μm diamond

10 ns charge amp

Signal formation and DAQ simulation



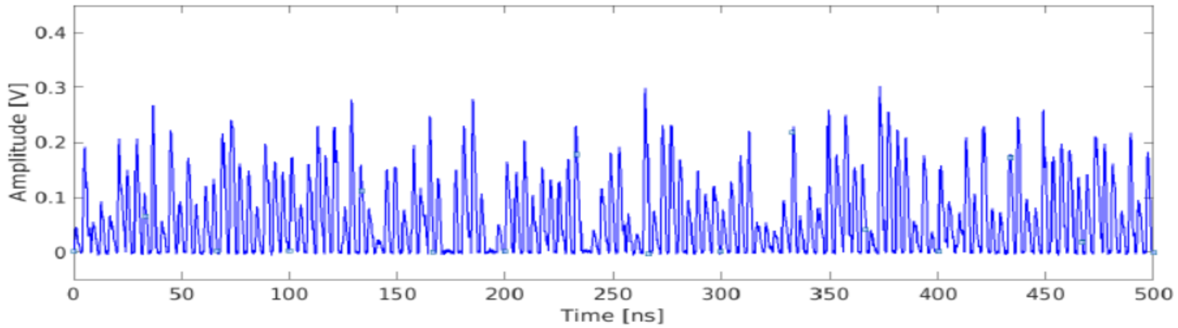


Figure 4.20: Example of signal sequence for the diamond detector with thickness of 140 μm coupled with the C2 broadband current amplifier in the nominal luminosity case.

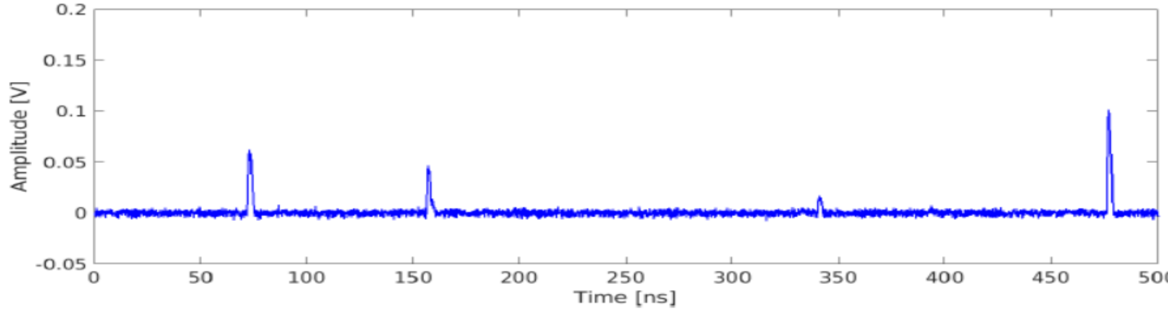
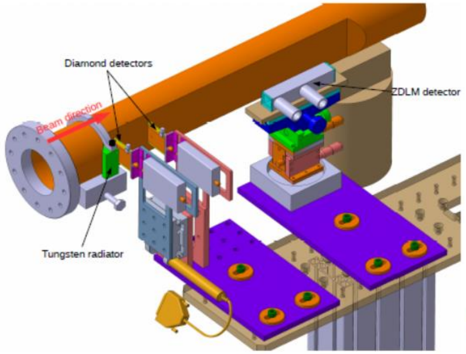


Figure 4.21: Example of signal sequence for the diamond detector with thickness of 140 μm coupled with the C2 broadband current amplifier for Phase-2 target luminosity case: $1 \times 10^{34}\ cm^{-2}s^{-1}$.



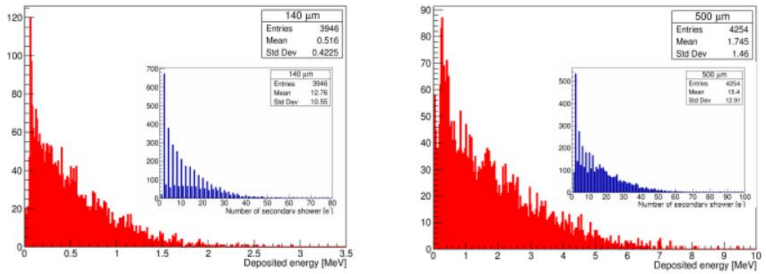


Figure 4.17: Histogram of deposited energy and number of secondary electrons for the diamond detector with thickness of 140 μm on l.h.s and 500 μm on r.h.s.

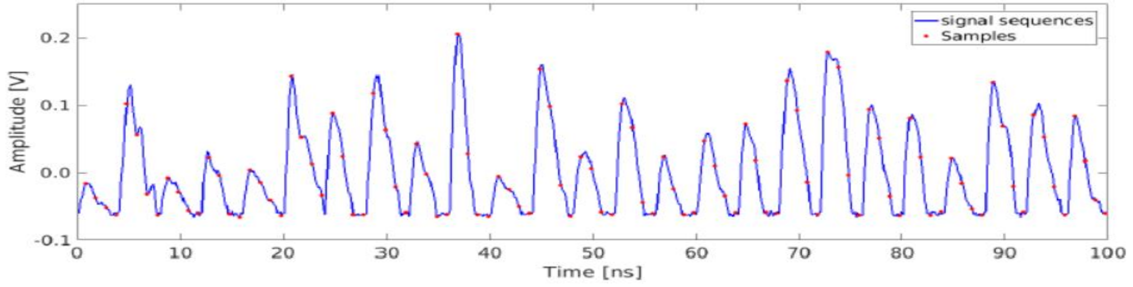


Figure 4.22: Example of sampling of constructed signal sequences for the expected fill pattern at the nominal luminosity of SuperKEKB after phase adjustment to get the maximum amplitude for each signal (the first 100 ns of the 1 ms sequence are shown).

Background study

SIMULATION FEATURES:

- Bremsstrahlung, Coulomb, and Touschek scattering included
- Use of SAD for tracking and Geant4 for particle detection
- Detailed simulation of pressure profile and chemical composition of vacuum gas ($Z_{eff} \approx 4.2 - 4.5$) from previous study (J.Carter, M.Ady)

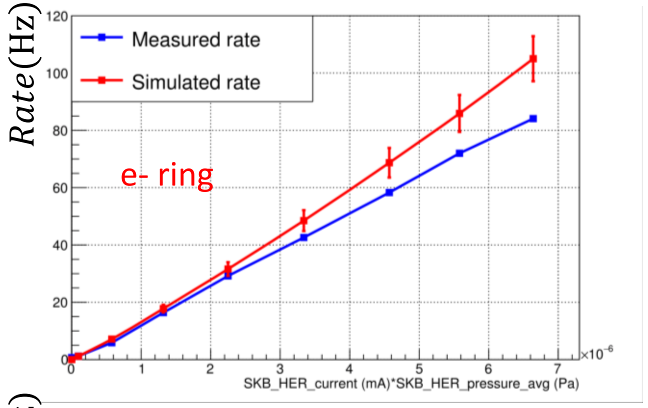
HER (e- ring):

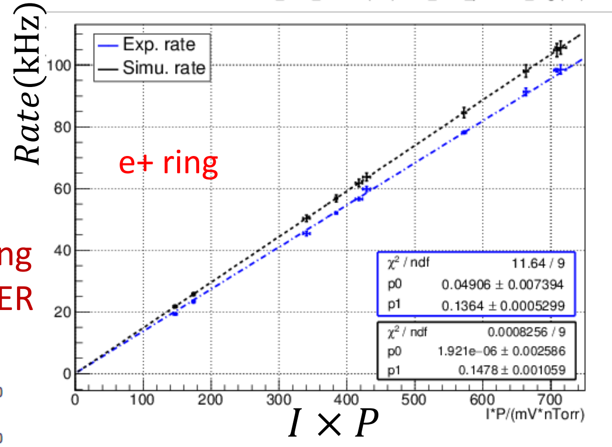
- Dominant rate from Bremsstrahlung photons
- Electron rates from Bremsstrahlung, Coulomb, and Touschek scattering are negligible($\ll 1Hz$)

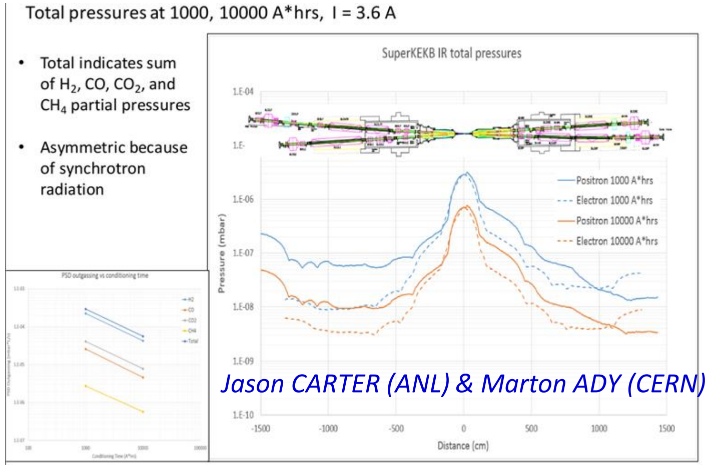
LER (e+ ring):

- Dominant rate from Bremsstrahlung positrons
- $\sim 10\%$ of the rate from Touschek scattering
- Positron rate from Coulomb scattering is negligible

Measurement vs Simulation

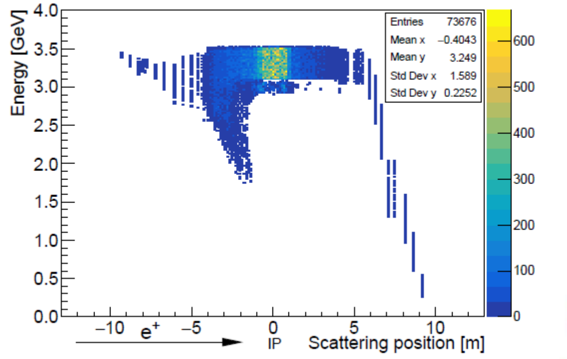


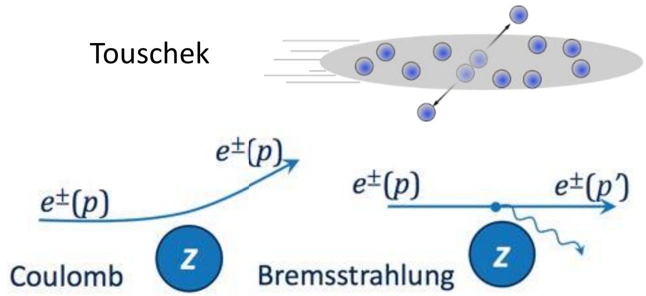




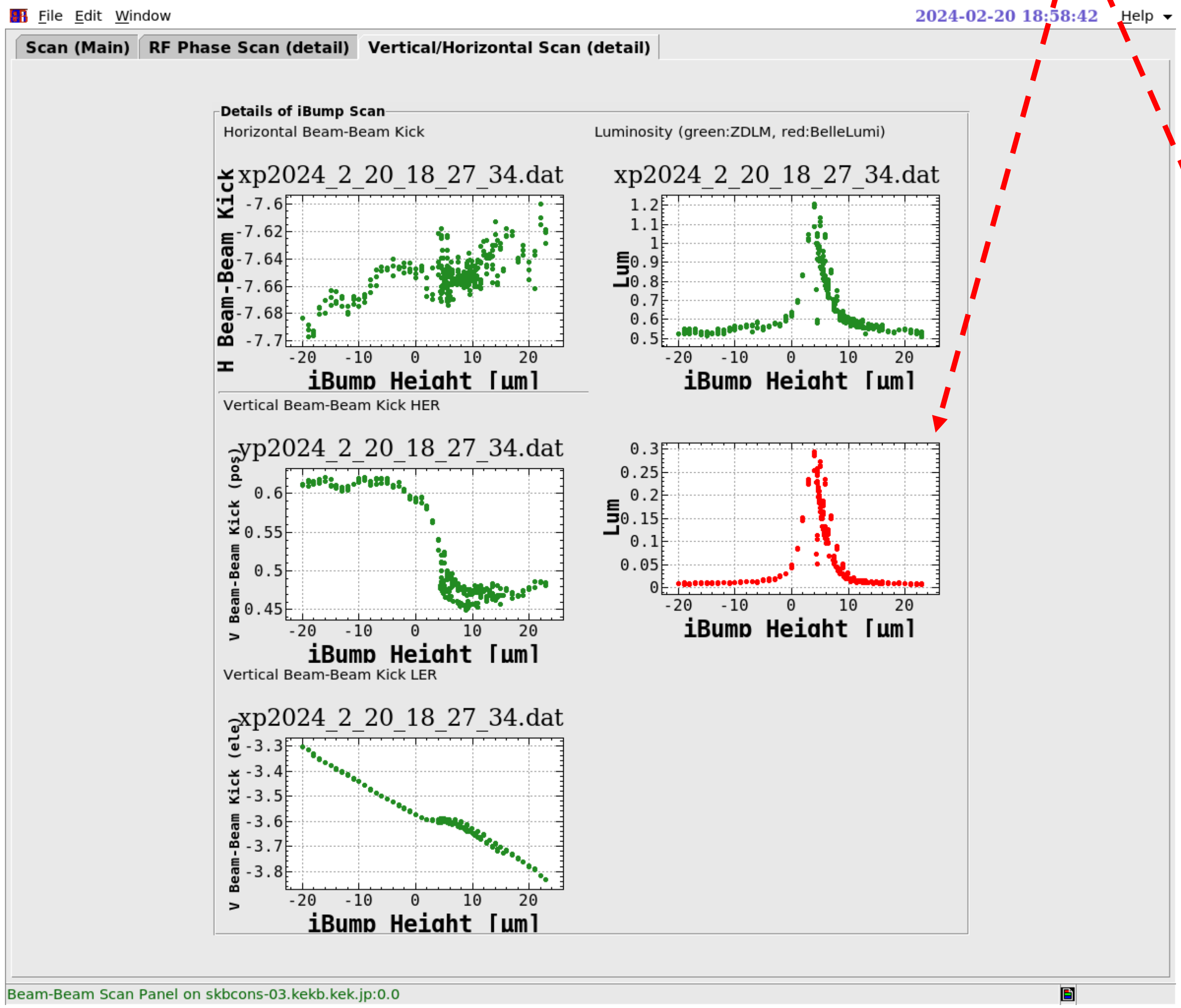
Simulated vacuum profile in IR

Scattering position of Bremsstrahlung particles detected in LumiBelle2 / LER

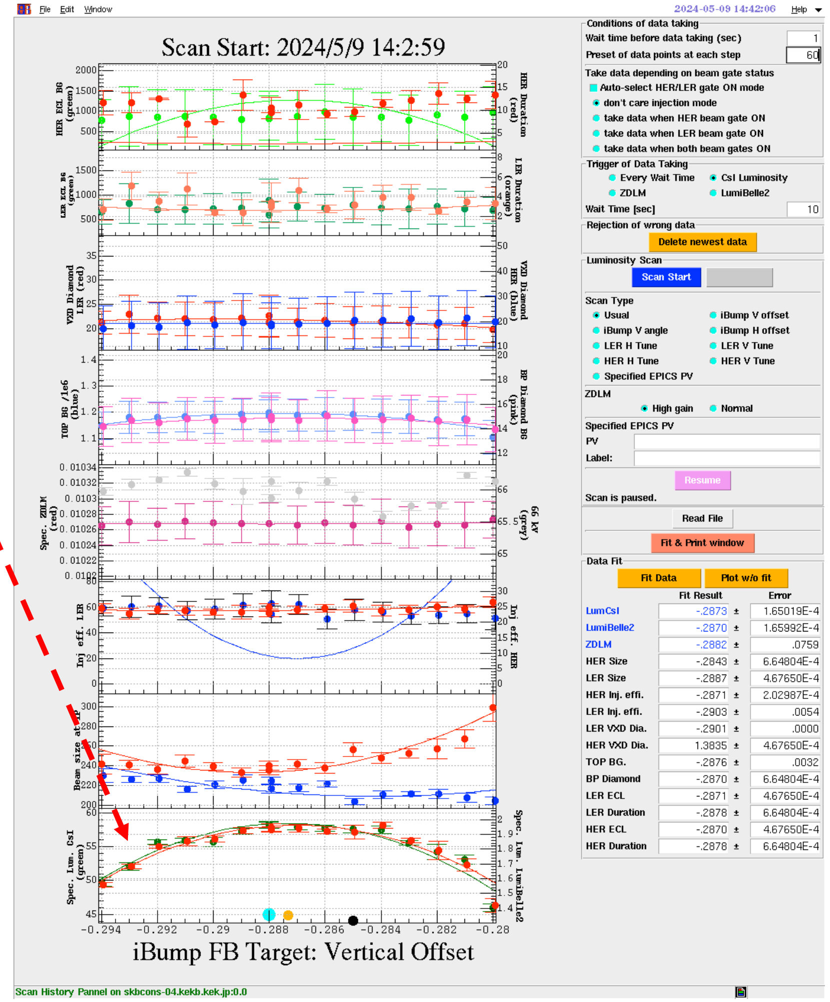




Setting up and optimizing beam collision with LumiBelle2

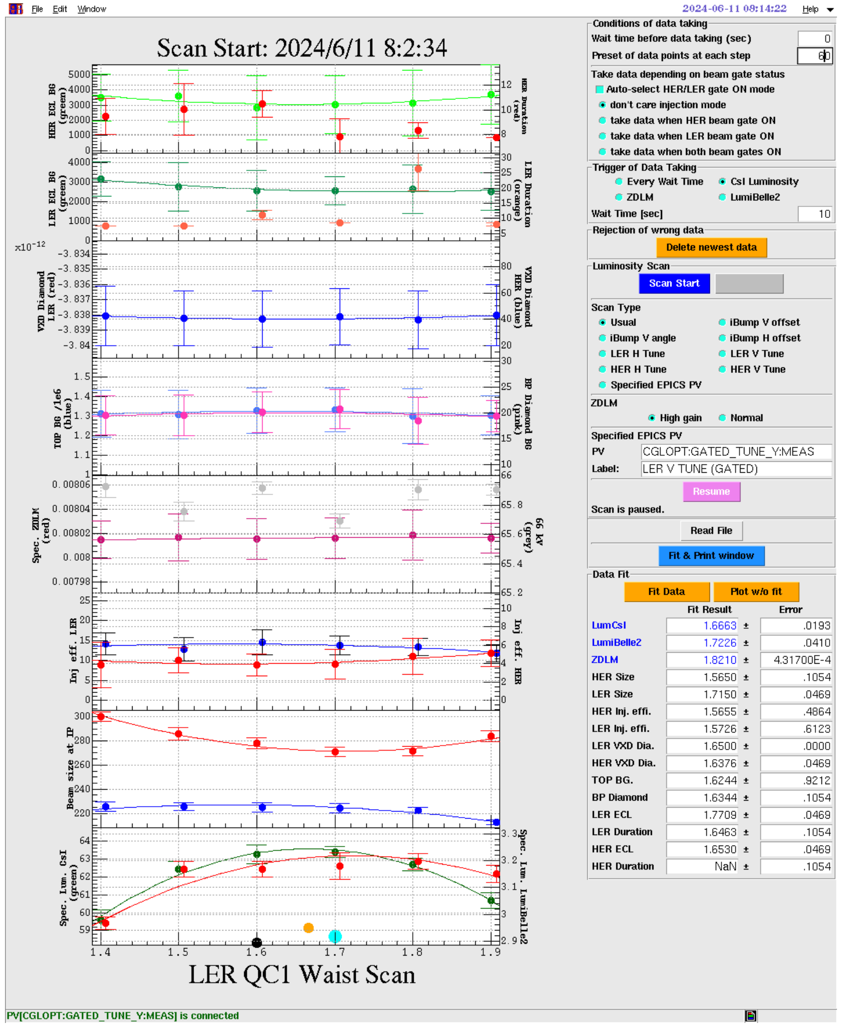


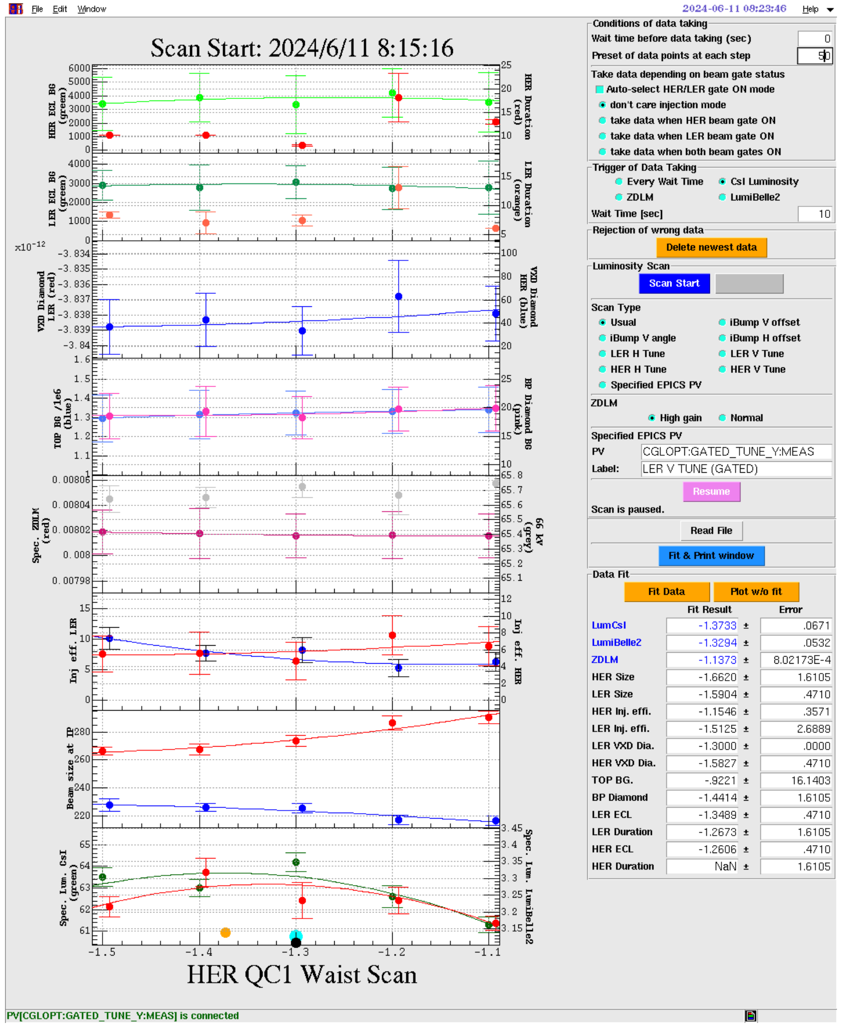
Initial scanning of IP beam offset to enable collisions at very beginning of the run…

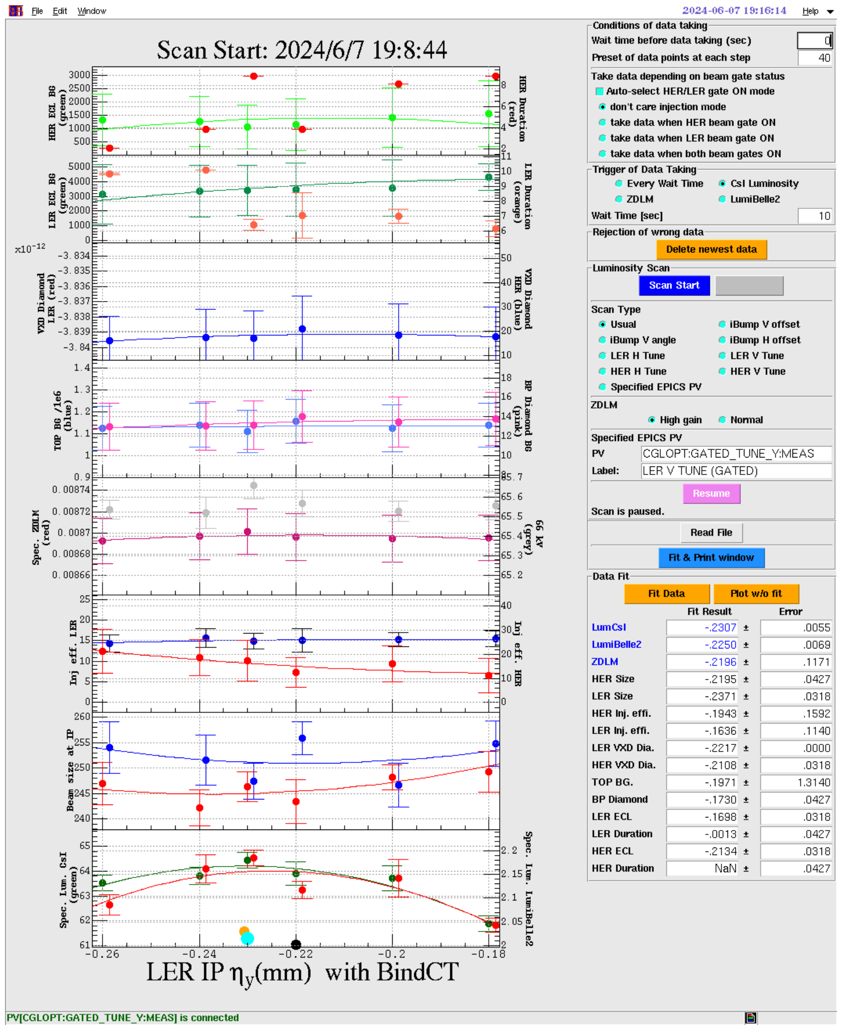


Regularly optimizing IP beam offset to maximize luminosity…

Minimising electron and positron IP beam sizes with LumiBelle2…







Comparing luminosity measuring channels in 24 hour period

2024-10-25:08:00 – 2024-10-26:08:00

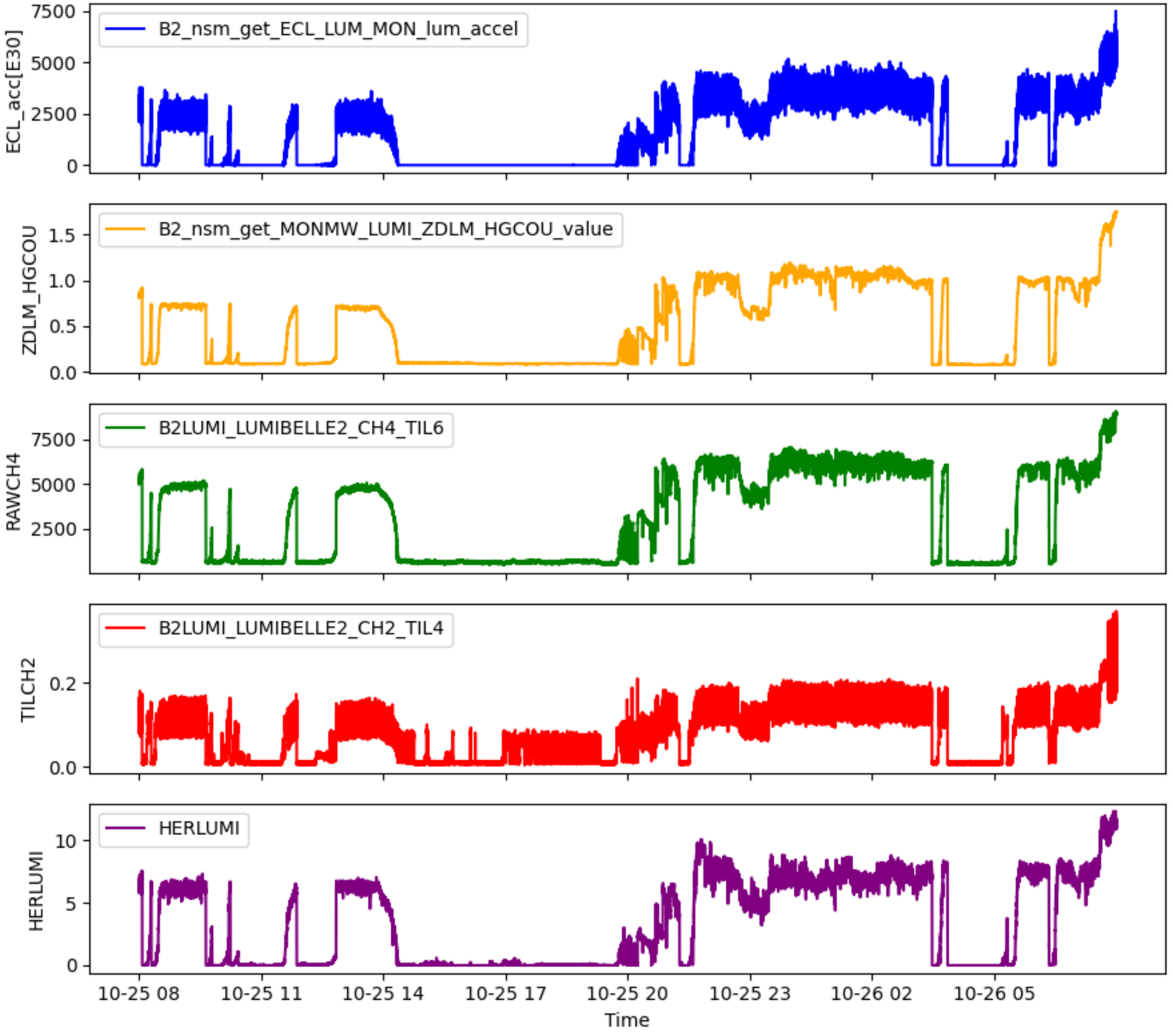
Belle II ECL end-caps

Belle II ZDLM

Belle II LumiBelle2 LER CH4

Belle II LumiBelle2 LER CH2

Belle II LumiBelle2 HER CH1+3

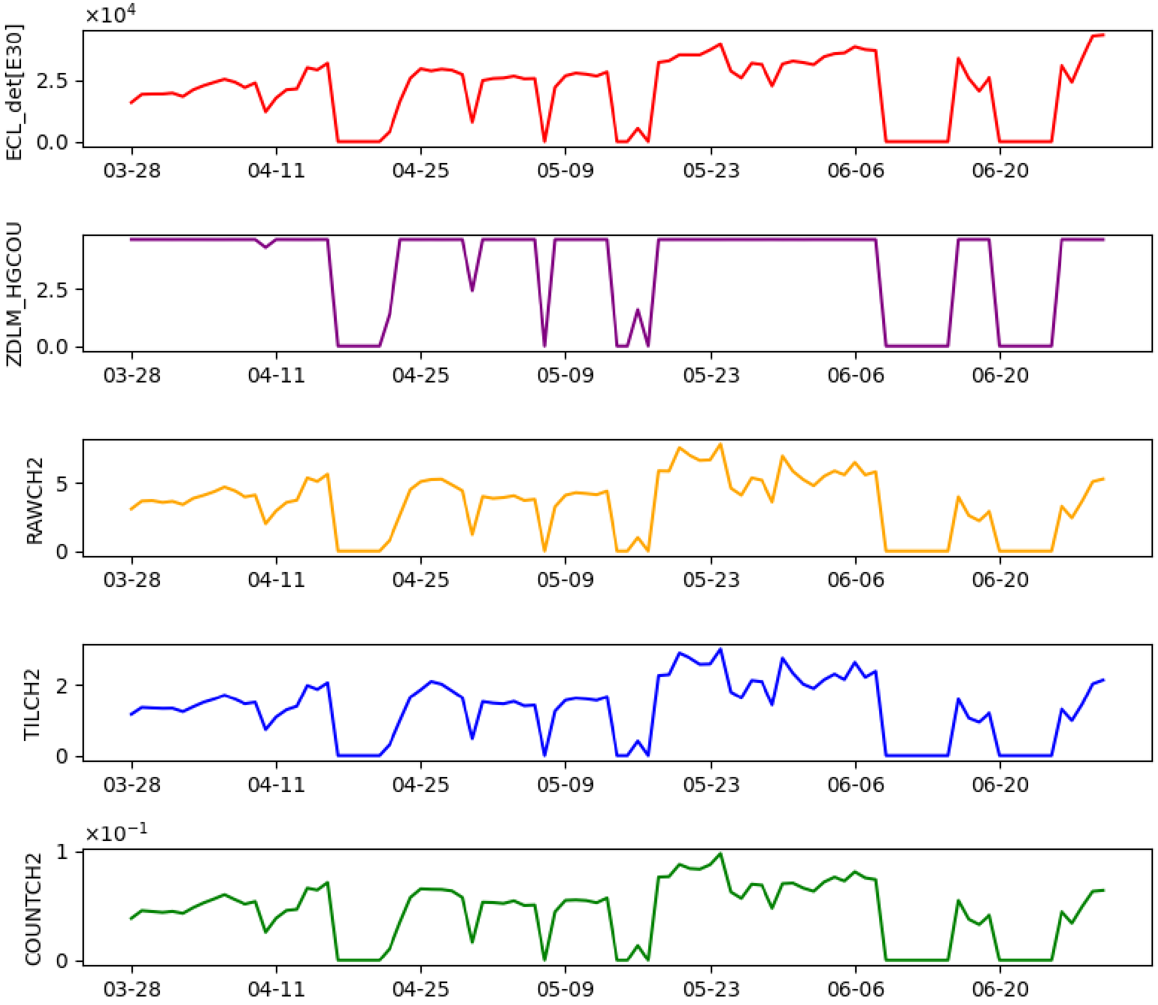


Luminosity sampled history from ECL, ZDLM and LumiBelle2 LER 140 µm channel

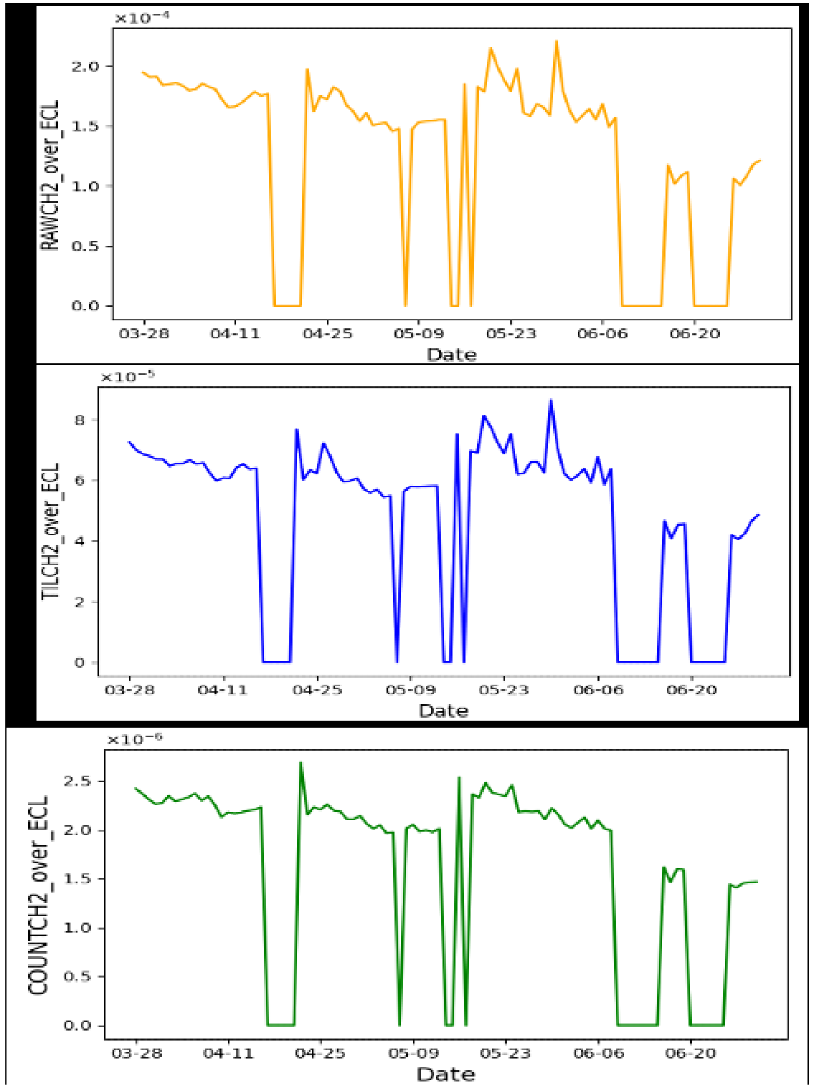
26/03/2024 → 31/07/2024

Meng Li et al., “Status and performance of LumiBelle2 in the 2024 beam operation of SuperKEKB”, IBIC2024 THP16

AI “forest method”



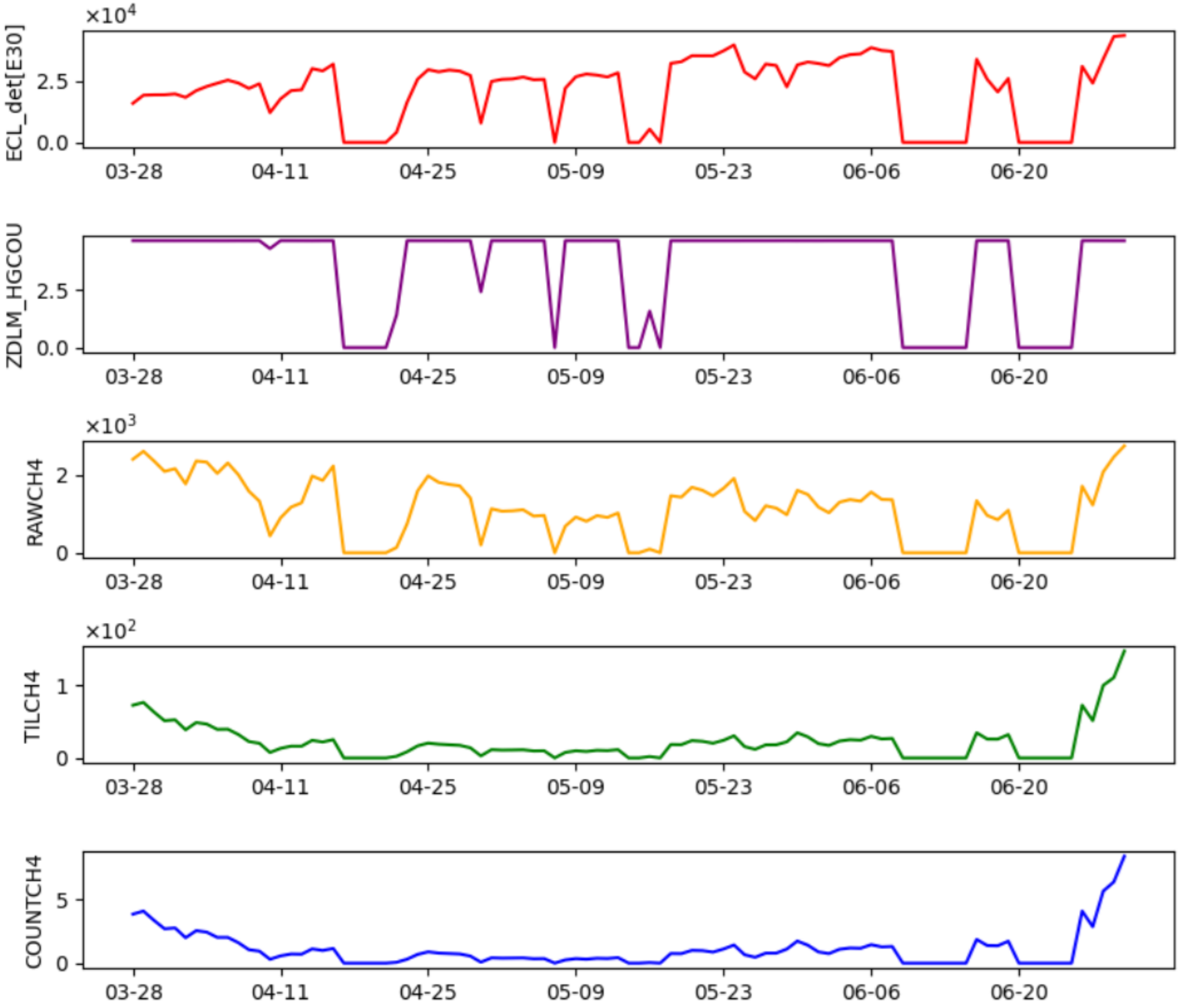
LumiBelle2 / ECL



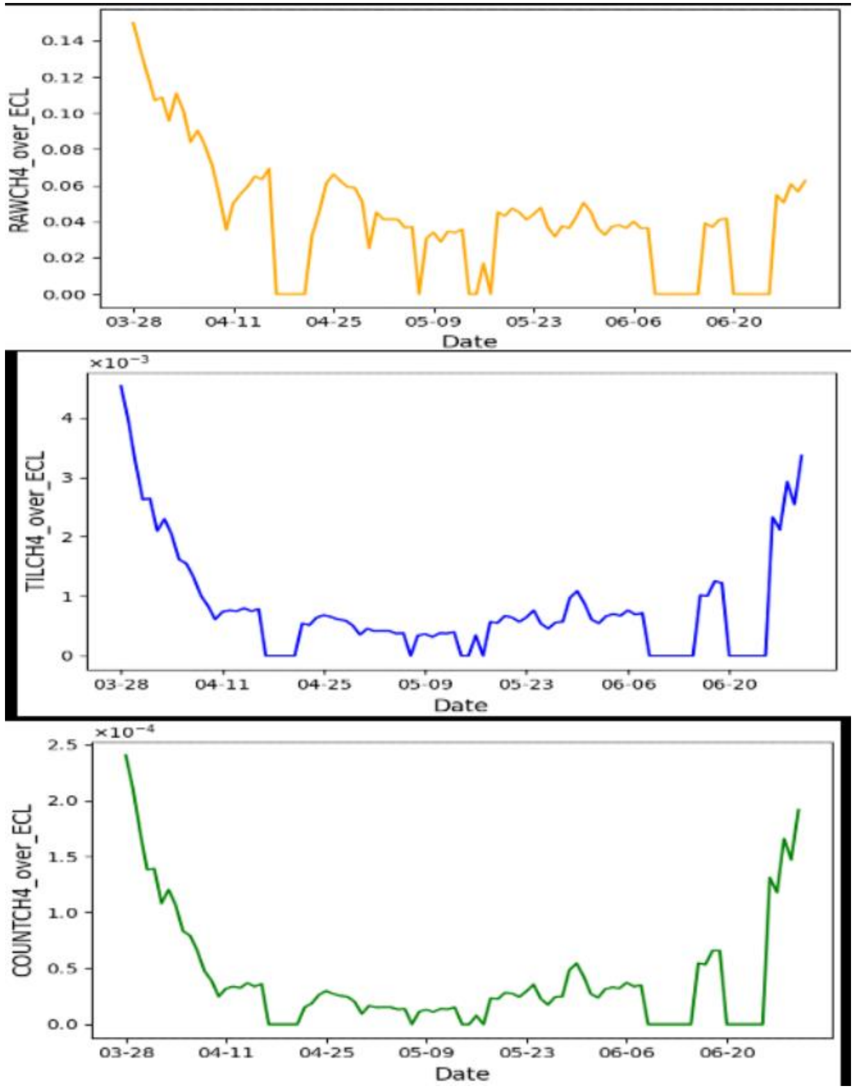
Luminosity sampled history from ECL, ZDLM and LumiBelle2 LER 500 μm channel

26/03/2024 → 31/07/2024

AI "forest method"



LumiBelle2 / ECL



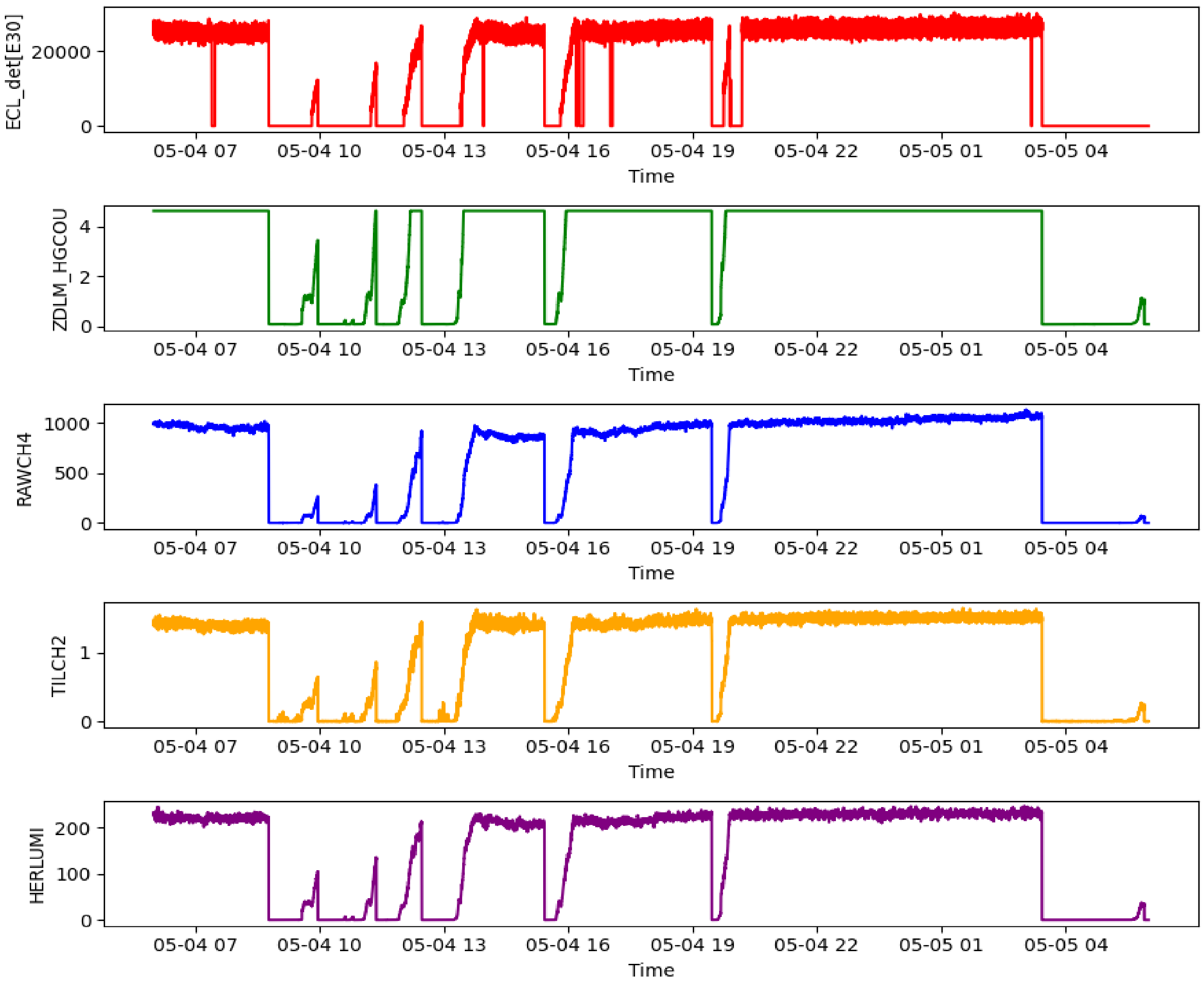
Further prospects

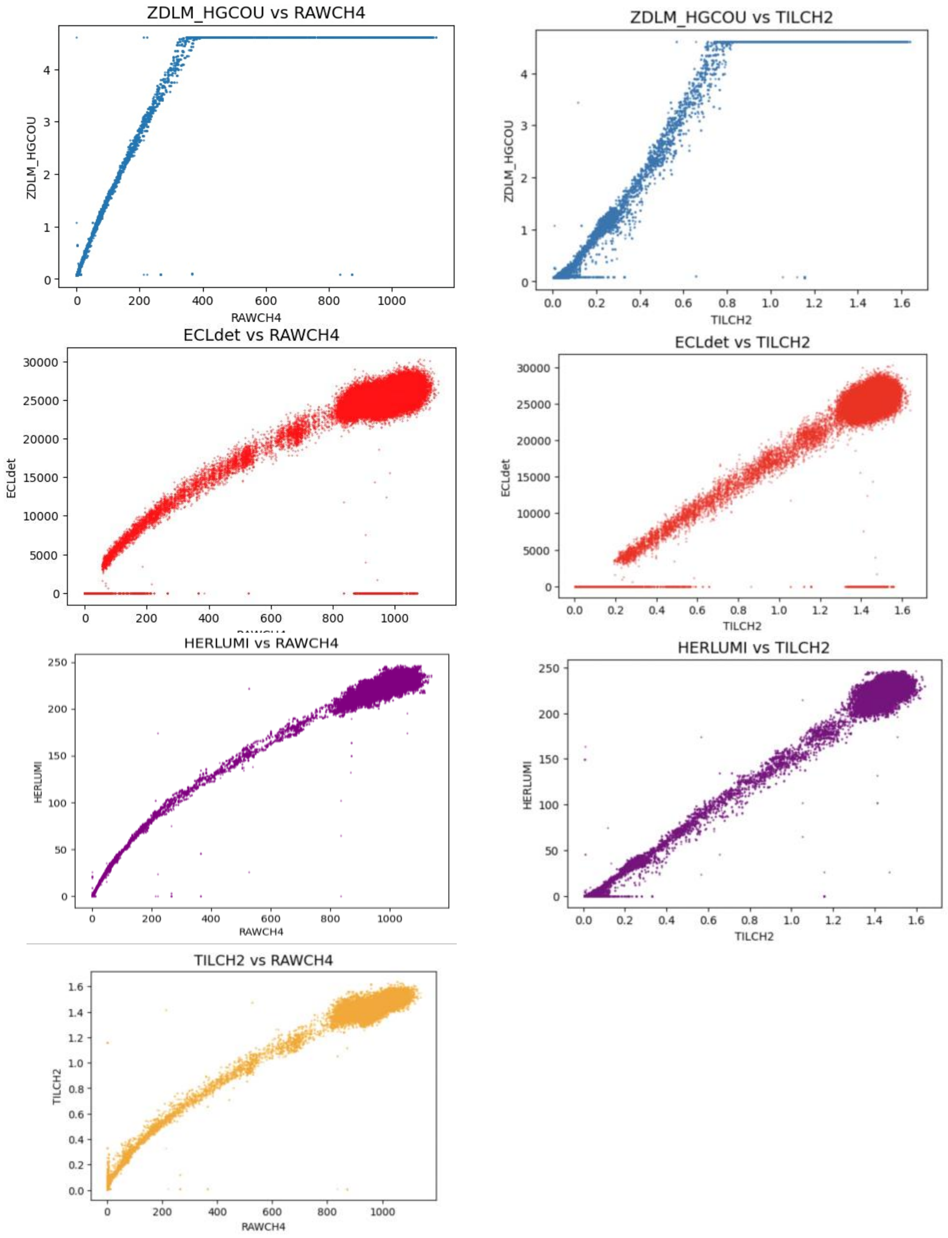
- LumiBelle2 provides useful input to the performance optimization of SuperKEKB
- Issue of radiation tolerance need further study
- Prospect of installing LGAD sensors in LumiBelle2 → radiation hardened version from IHEP-Beijing used in Atlas
- LumiBelle2 @ KEK operated by IJCLab partly remotely and with help from KEK, but very understaffed
  ➔ collaboration & contributions from IFG PAN would be highly welcome

Extra slides

1Hz luminosity from ECL, ZDLM and LumiBelle2 LER 500/140 µm & HER 500 µm channels

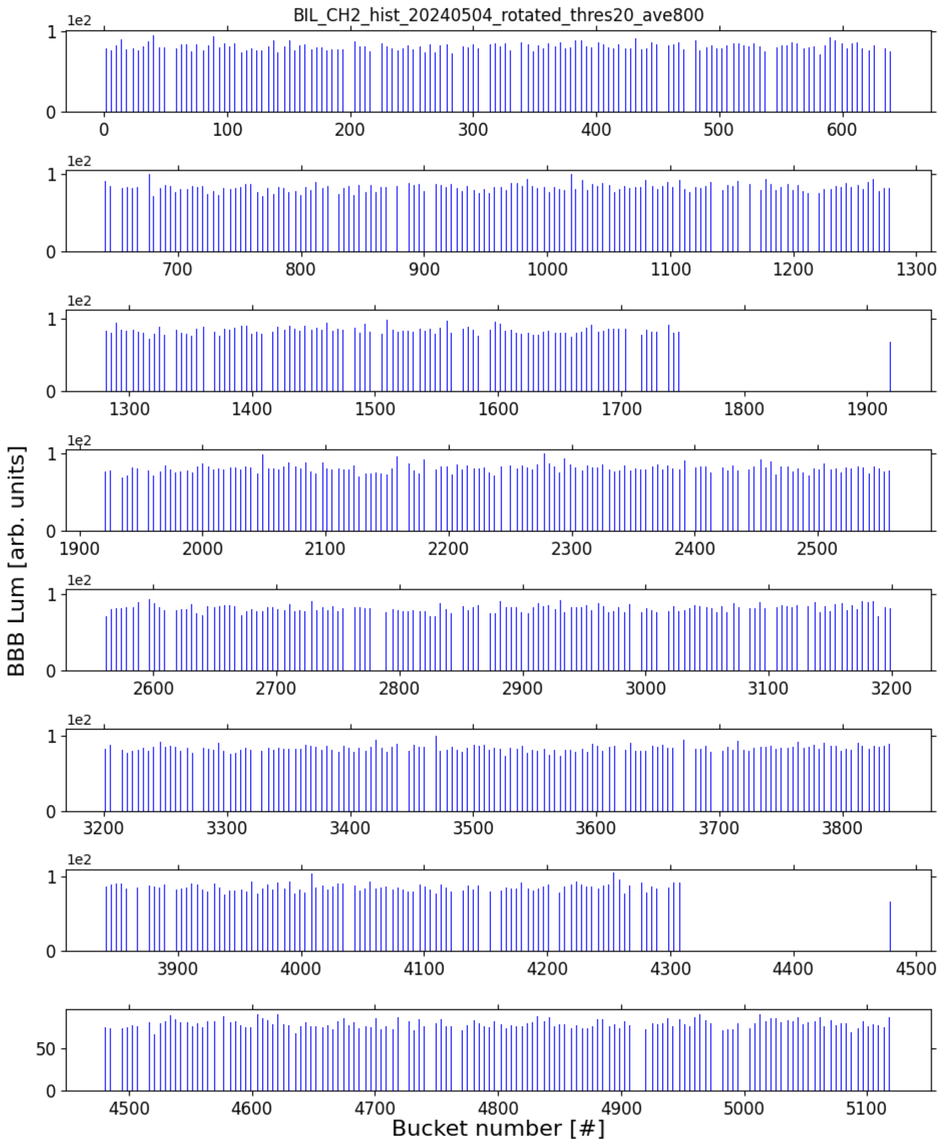
04-05-2024





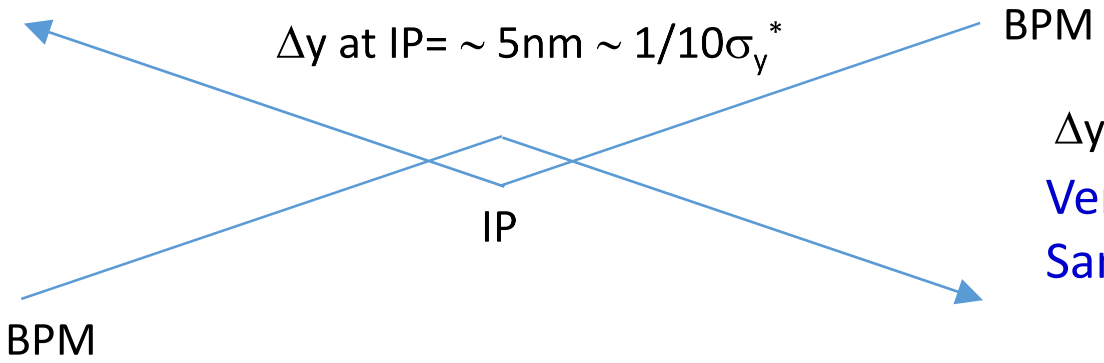
LumiBelle2 1Hz bunch-by-bunch luminosity

2346 bunches on 04-05-2024



Fast & slow beam position variations at IP require feedback corrections

- Beam-beam deflection for fast vertical motion

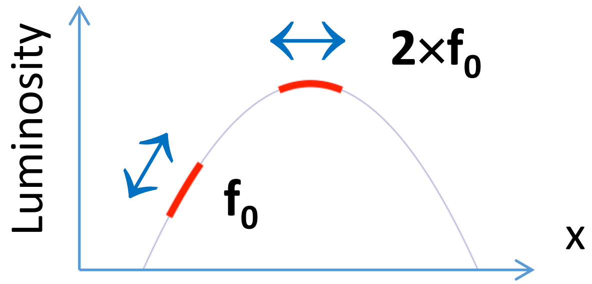


Δy at BPM= ~ 1.3μm

Vertical vibration ~ 25-100 Hz

Sampling (BPMs) ~ 32 kHz

- Luminosity feedback by "dithering" for slower horizontal motion



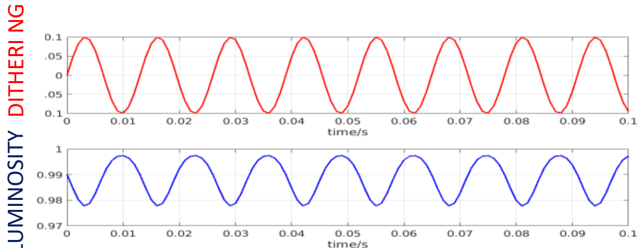
Horizontal motion ~ few Hz

Modulation freq. f_0 ~ 79 Hz

Sampling (lumi. meas.) ~ 1 kHz

- minimize f_0 output component
- dithering × lumi. signal → phase

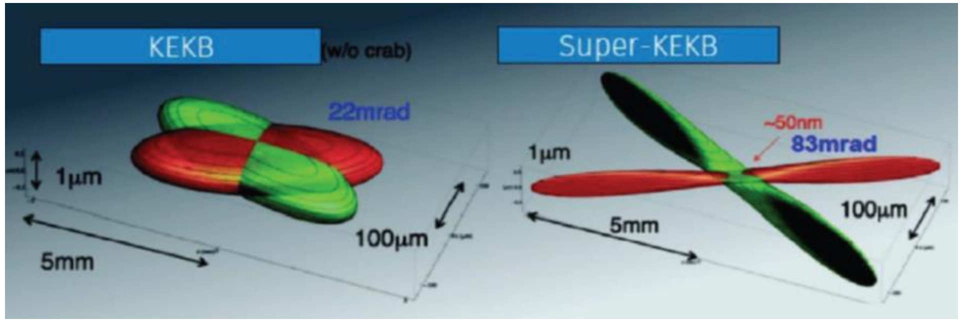
$$L(t) = \frac{f_{rev} N_1 N_2}{4\pi\sigma_x\sigma_y} e^{-\left(\frac{[q + p\sin(2\pi f t)]^2}{4}\right)}$$



Dithering coil x 12

Luminosity degradation with horizontal offset

nanobeam collision geometry



Sensitivity similar to head-on collisions for $\beta_y \rightarrow 0.3$ mm

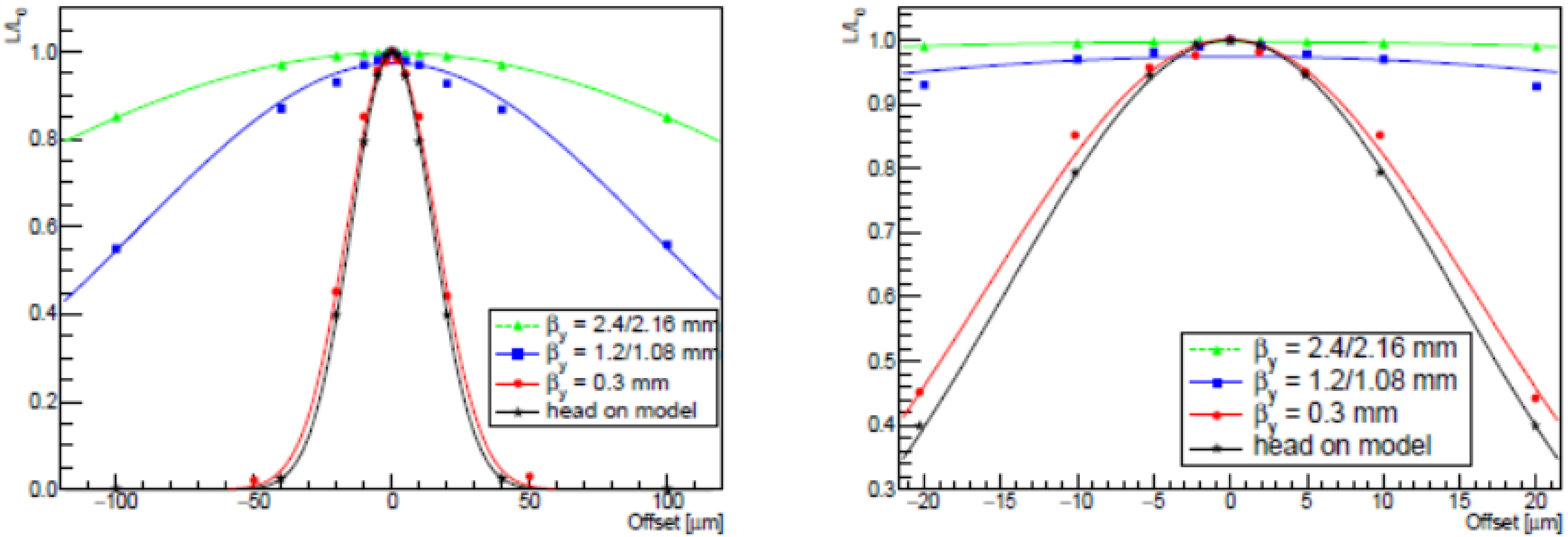


Figure 4.40: Luminosity degradation as function of beam-beam offset simulated with different β_y at the IP for the nano-beam collision geometry, and for the head-on model (with $\beta_y^* = 0.3$ mm).

Horizontal orbit dithering feedback simulation

basic ingredients & setup

Cheng Guo Pang, Doctoral thesis, https://theses.hal.science/tel-03092297

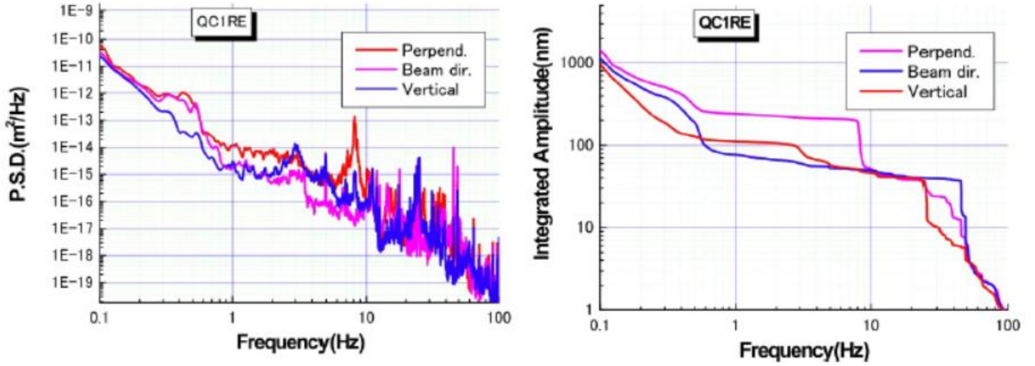


Figure 4.38: PSD (on l.h.s) and integrated amplitude (on r.h.s) of the QC1RE magnet vibration: the horizontal direction (labeled Perpend.) is shown in red on the l.h.s. plot and in pink on the r.h.s. plot.

Inverse FFT of measured GM spectra

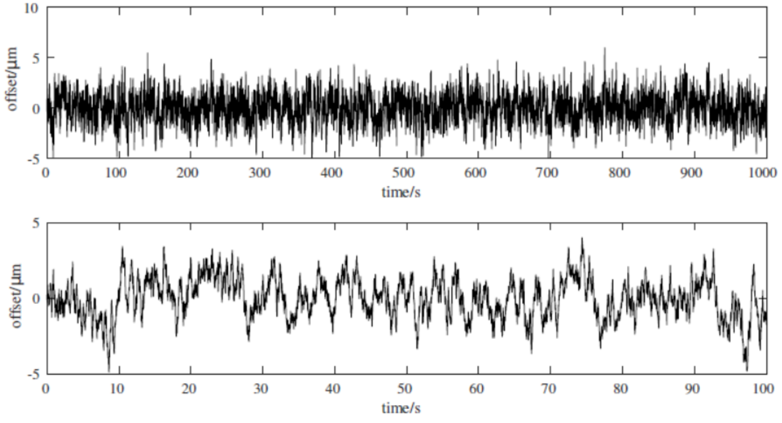


Figure 4.39: Example of ground motion induced vibration in the time domain obtained from the measured PSD spectrum (Figure 4.38) by application of iFFT.

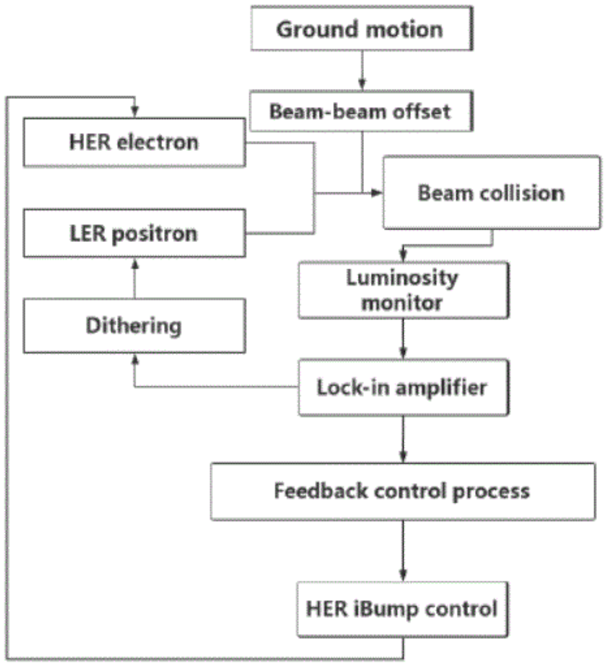


Figure 4.37: Flow-chart of the start-to-end simulation for the dithering orbit feedback system to maintain very high luminosity in the presence of mechanical vibration caused by ground motion.

$$\mathscr{L} = \mathscr{L}_0 exp\left[-\frac{[x_0 + \Delta x sin(2\pi f t)]^2}{2\Sigma_x^2}\right], \quad \Sigma_x^2 = \sigma_{x+}^2 + \sigma_{x-}^2$$

Horizontal dithering orbit feedback simulation

response to fixed offset

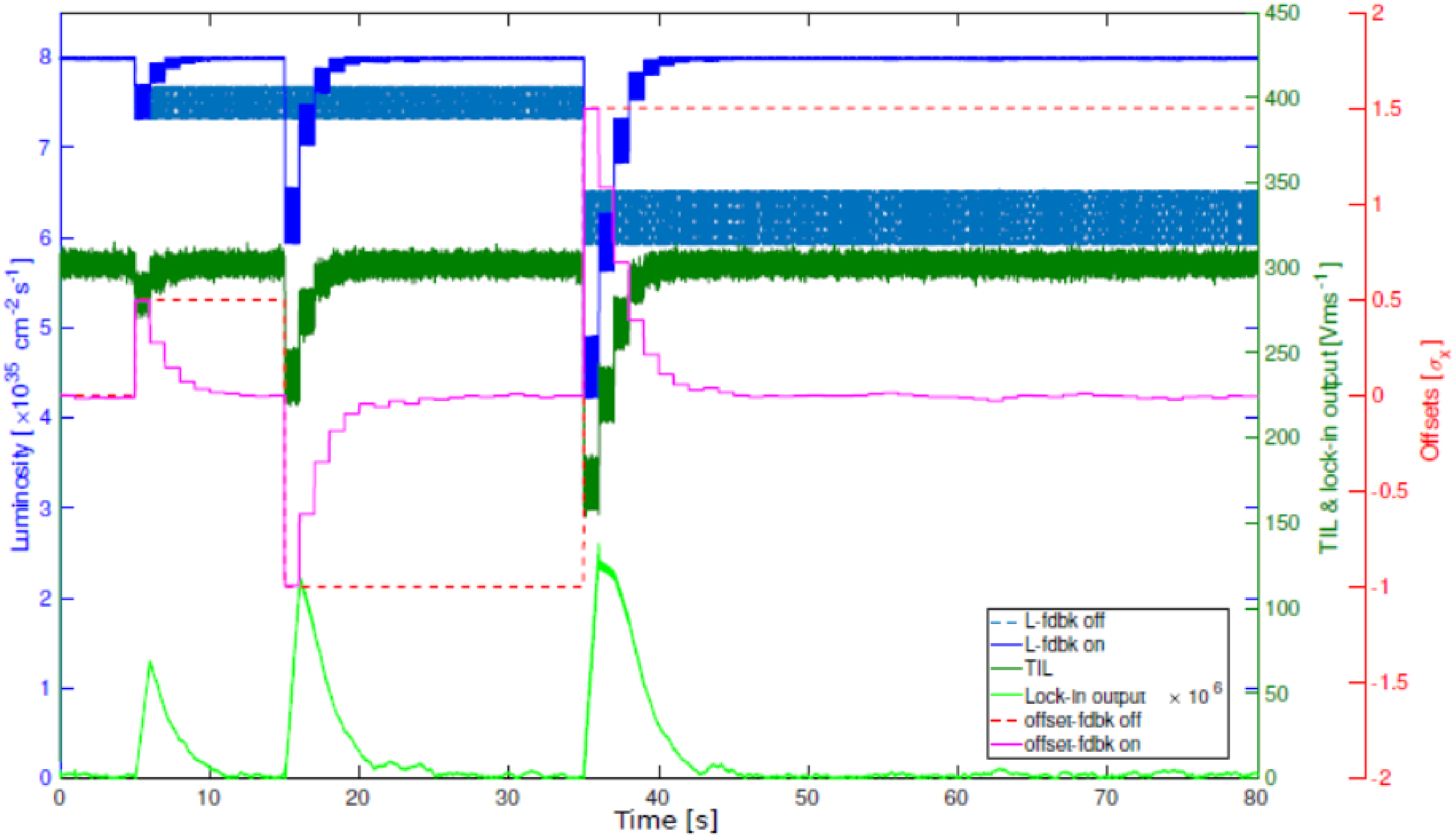
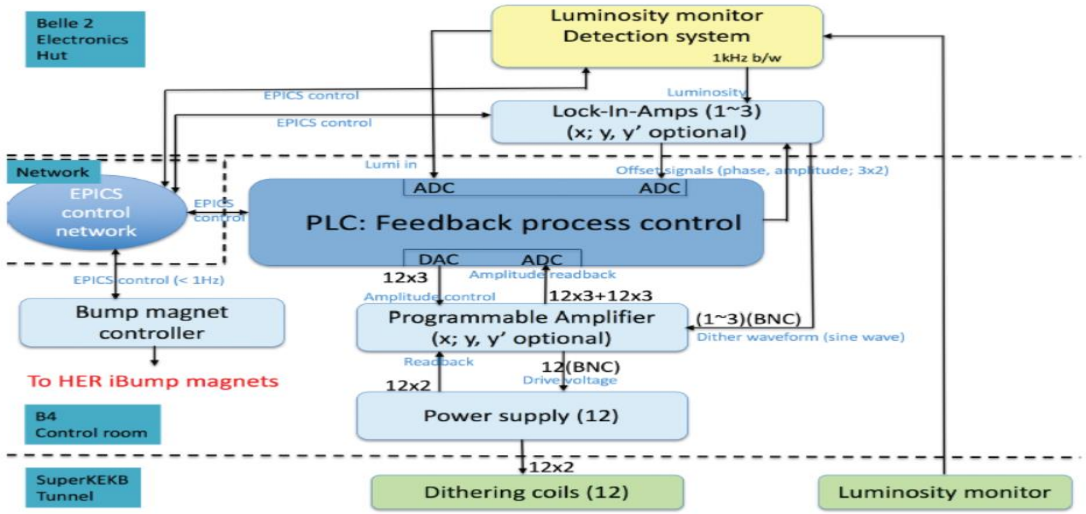
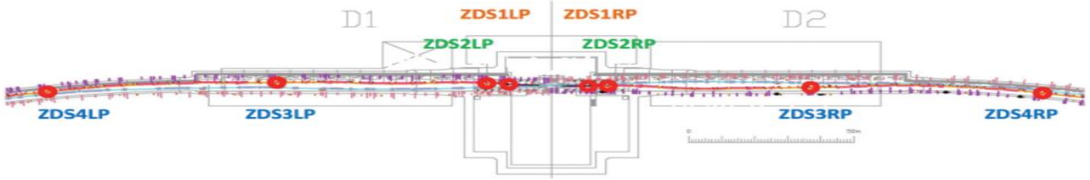


Figure 4.42: Simulated performance of feedback algorithm with several successive offsets. The luminosity is plotted in blue (with and without feedback), the simulated fast luminosity signal TIL in dark green, the magnitude of Fourier component at 79 Hz of the simulated fast luminosity signals in light green, and the offset between the two beams in red (without feedback) and pink (with feedback).

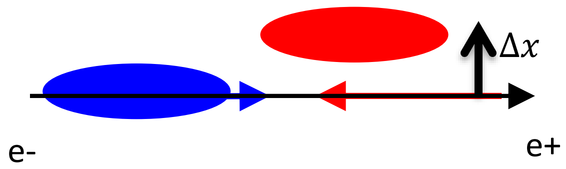
1^{st} dithering feedback test in Phase 2

Mika Masuzawa et al., "Early Commissioning of the Luminosity Dither Feedback for SuperKEKB ", IBIC2018 MOPA13
Yoshihiro Funakoshi et al., "Early Commissioning of the Luminosity Dither Feedback for SuperKEKB ", eeFACT2018 WEXBA04

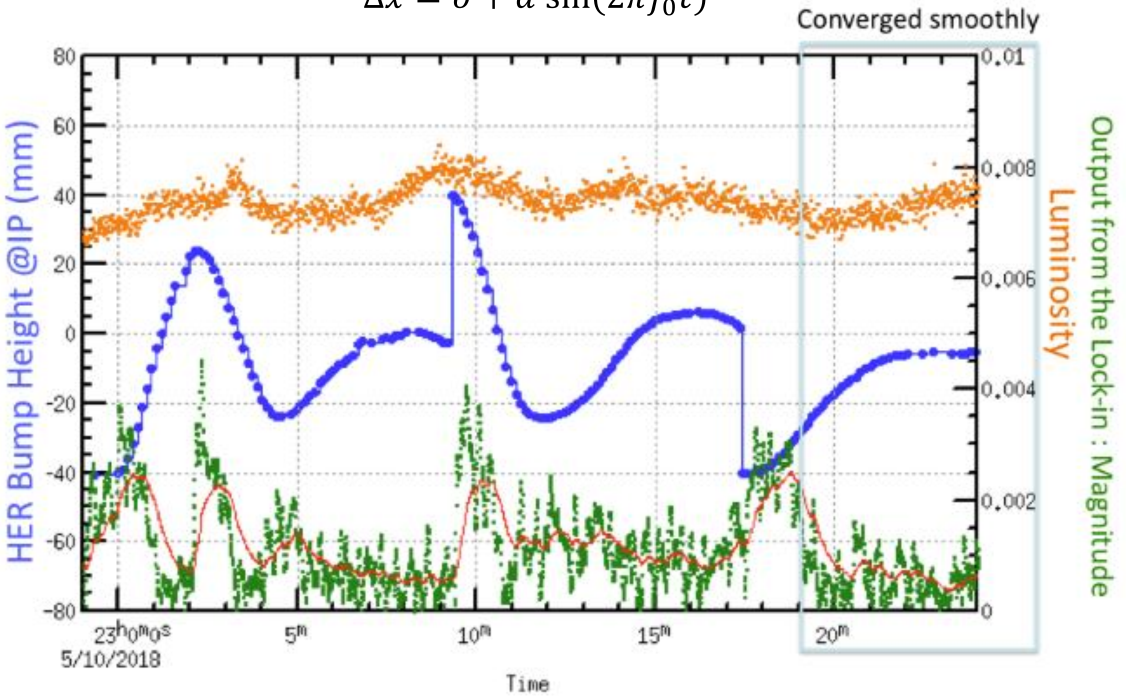




4 dither coils on each side of IP



$$\Delta x = o + d\sin(2\pi f_0 t)$$



- e- beam artificially given an offset, while e+ beam was dithered
- Compute beam offset magnitude to cancel magnitude [V] of luminosity FFT component at dithering driving frequency f_0
- Beams brought back to optimal position (remove unwanted offset o=0) applying this offset with
  - **sign set by relative phase of input dithering and induced luminosity variation**
  - **damping factor (depends on precision / noise levels)**
- Corresponding bump parameters sent to magnet control system via EPICS
- After first 2 attempts + PI algorithm parameter optimization, the 3^{rd} feedback test could smoothly minimize the induced offset

Horizontal dithering orbit feedback simulation

response to ground motion

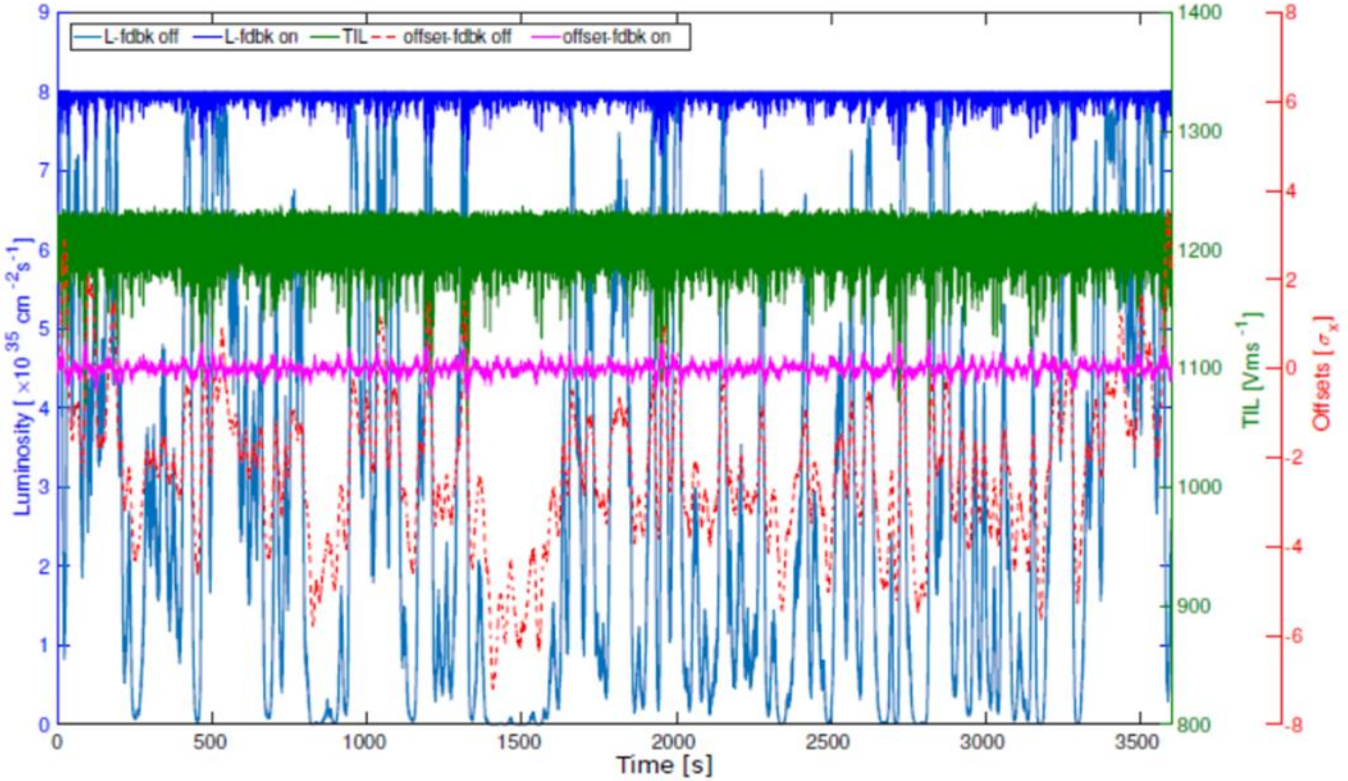


Figure 4.44: Luminosity, train integrated luminosity signal provided by diamond detector and the beam-beam offset with and without feedback for Phase-3 optics over a period of 3600 s.

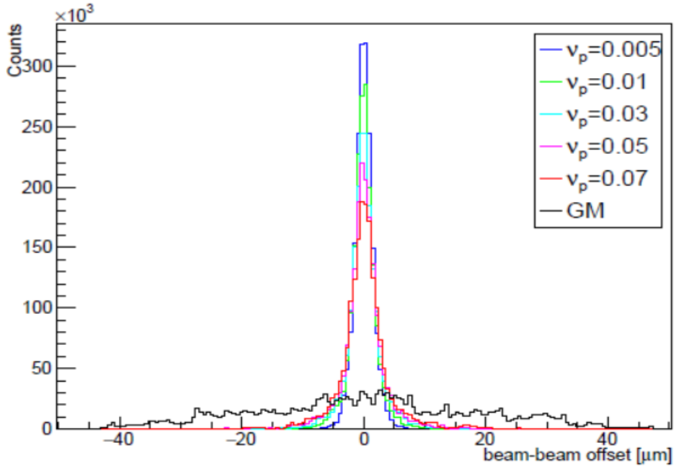


Figure 4.46: Residual beam-beam offset with feedback for different values of the relative luminosity precision.

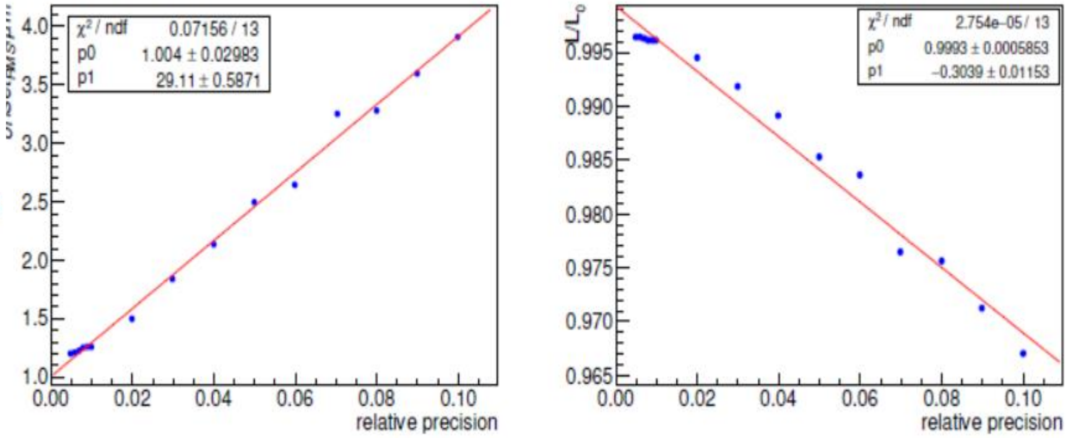


Figure 4.47: Residual RMS offset(l.h.s) and the ratio of luminosity with feedback with respect to the ideal luminosity as function of the train integrated luminosity signal's relative precision at 1 kHz.

Luminosity precision 2-3% @ 1 kHz

➔ Luminosity loss < 1%