SuperKEKB as test and demonstrator of future e^+e^- circular colliders

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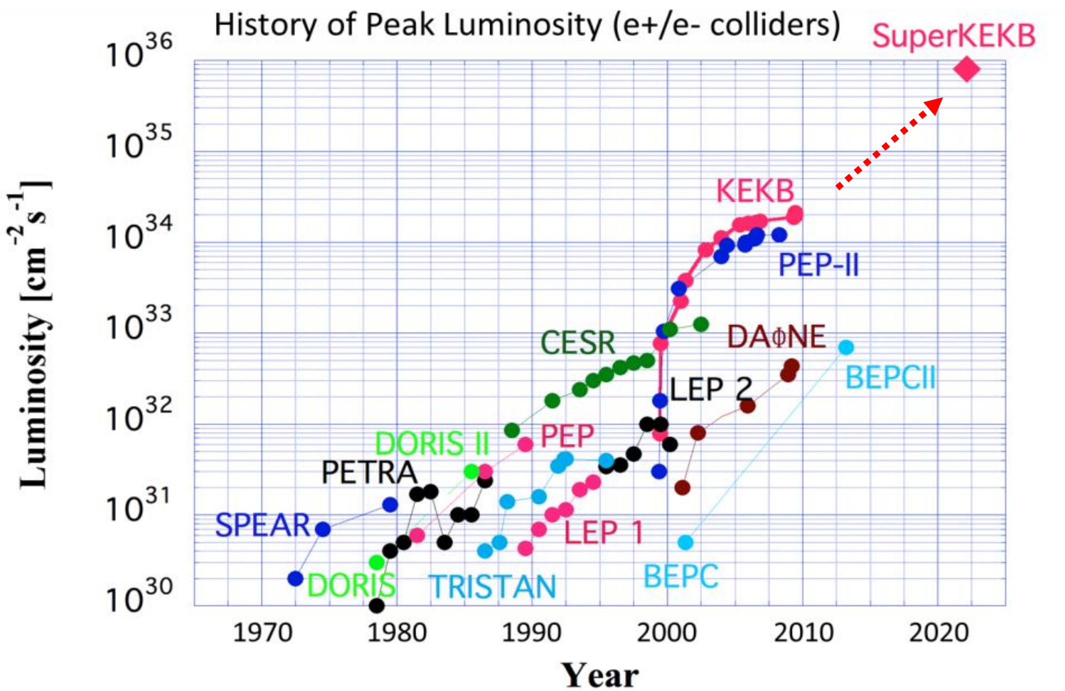
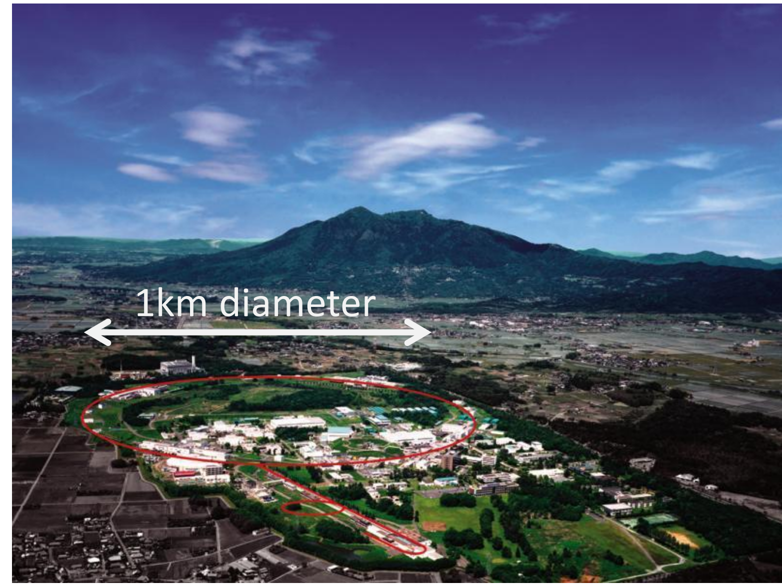
R. Yang (CERN, CLIC & SuperKEKB)

Material: 1st SuperKEKB Beam Dynamics Mini-Workshop, 17/7 2019: https://kds.kek.jp/indico/event/31793/

Exploring the luminosity frontier with SuperKEKB





KEKB
$2 \times 10^{34}/cm^2/s$

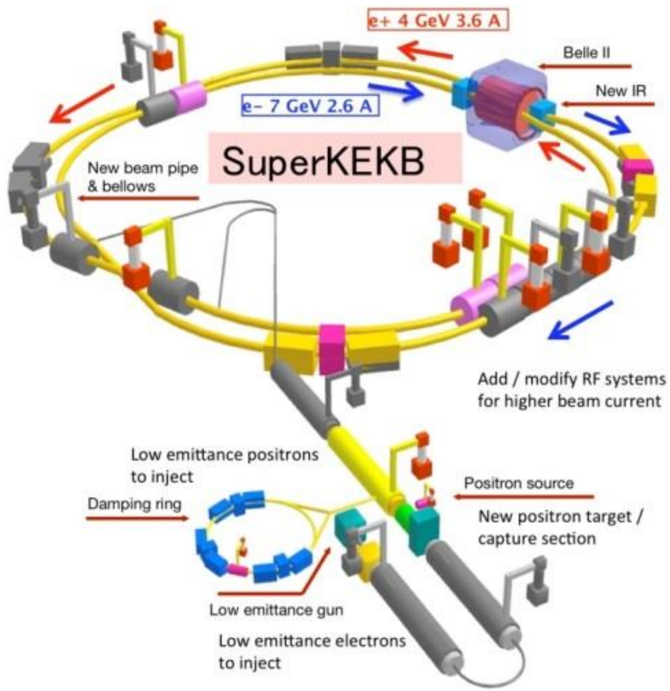
SuperKEKB
$8 \times 10^{35}/cm^2/s$

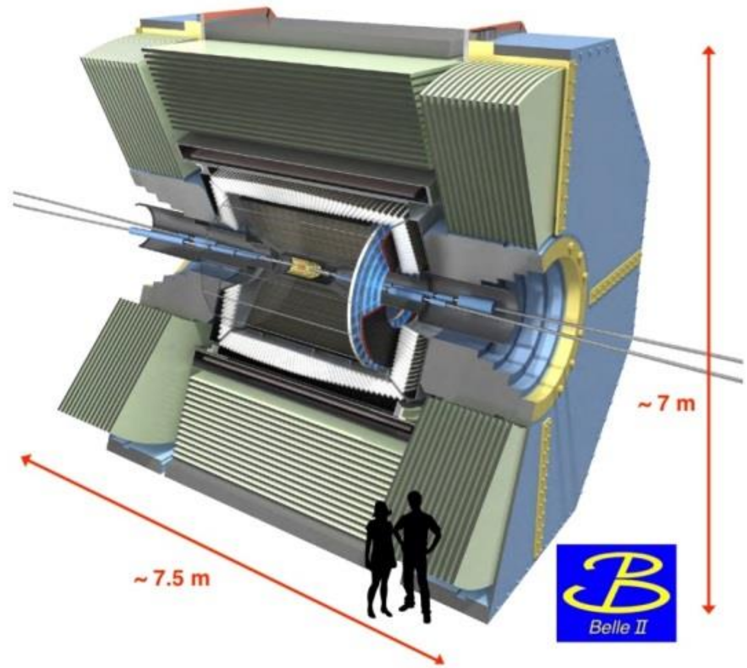
- Future e^+e^- circular colliders (FCCee, CEPC) use concepts tried for 1st time at SuperKEKB, e.g. nanobeam collision scheme
- Maximize luminosity ↔ mitigate beam induced detector* backgrounds → major SuperKEKB challenge

Relevant to test / validate future collider designs !

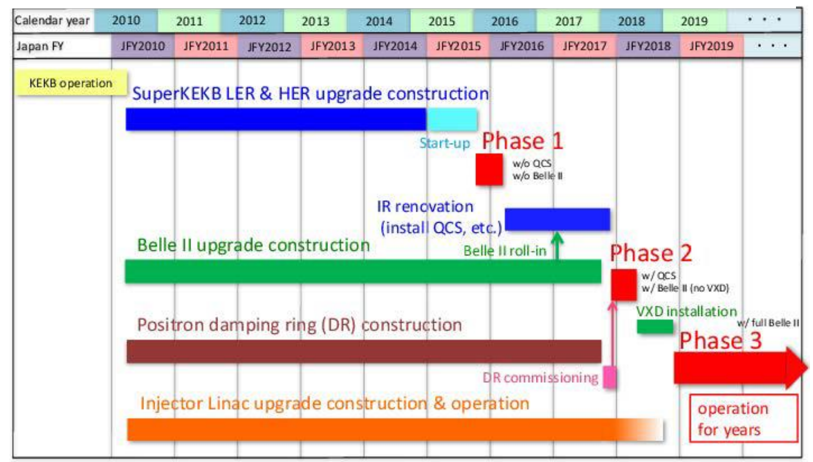
* also some accelerator components

SuperKEKB & Belle-II projects





Schedule



1) Phase 1 : February → June, 2016
   - single beam commissioning, vacuum scrubbing
   - no luminosity (no final focus), no Belle II
2) Phase 2 : February → July 2018
   - colliding beam commissioning, Belle II w/o vertex detector
   - first collisions + pilot run (0.5 fb^{-1})
3) Phase 3.1 : March 27 → July 1, 2019
   - Physics run with full detector (6.5 fb^{-1}), resume in October-December

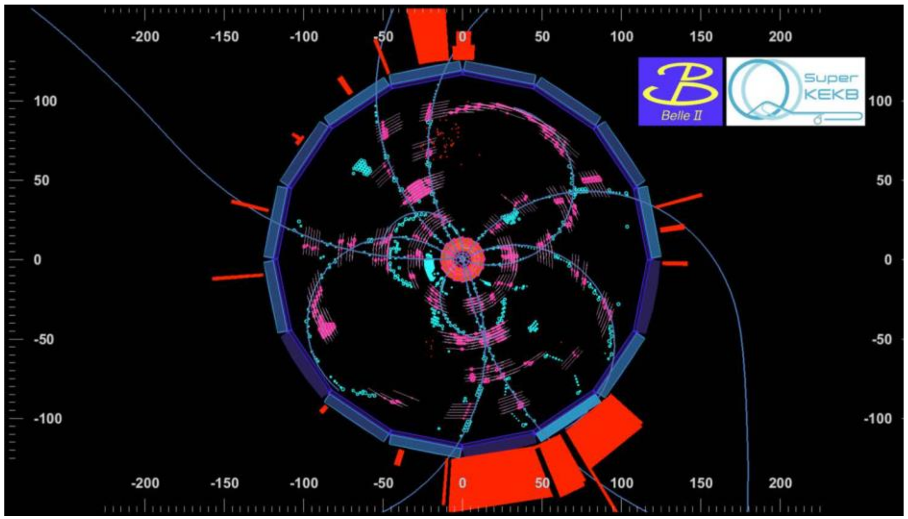
Belle-II @ SuperKEKB physics motivation

Discover new physics via precision search for deviations from SM predictions induced by new particles appearing in higher order quantum corrections

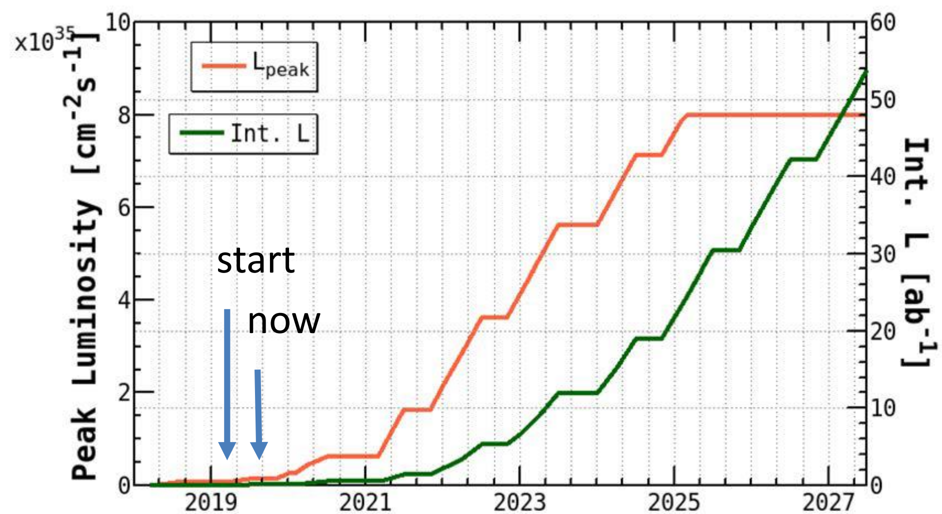
- Precision measurements of CKM matrix elements
- Rare / forbidden B, D, τ decays
- Dark sector searches
- ….

specification: × 40 peak luminosity of KEKB → 50 ab^{-1}

1st B-B like event during 1st physics run



Luminosity projection



[Talks on Belle II detector & physics at ICNFC 2019]

1. P. Goldenzweig, "First look at CKM parameters from early Belle II data"
2. I. Komarov, "Dark sector physics with Belle II: first results and prospects"
3. L. Vitale, "Belle II experiment: status and prospects"

KEKB ↔ SuperKEKB parameters

		KEKB LER (e^+)	KEKB HER (e^-)	SuperKEKB LER (e^+)	SuperKEKB 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)

→ × 40 peak luminosity

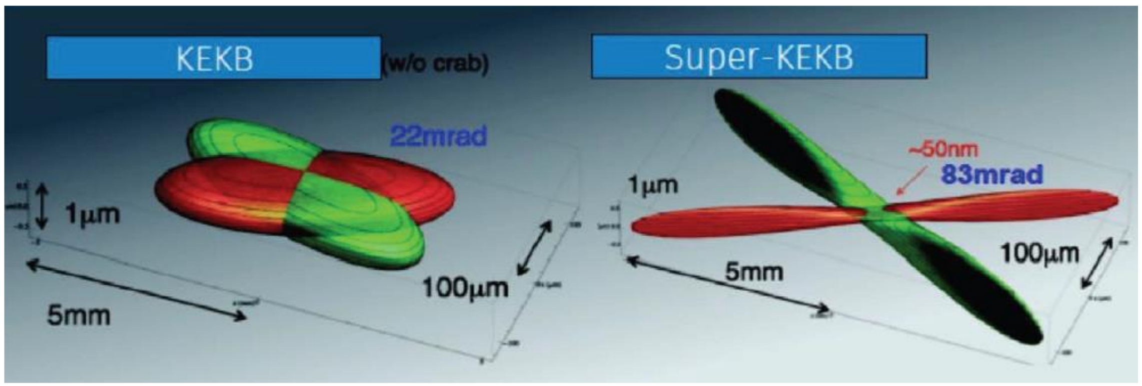
Nanobeam collision scheme

opportunities

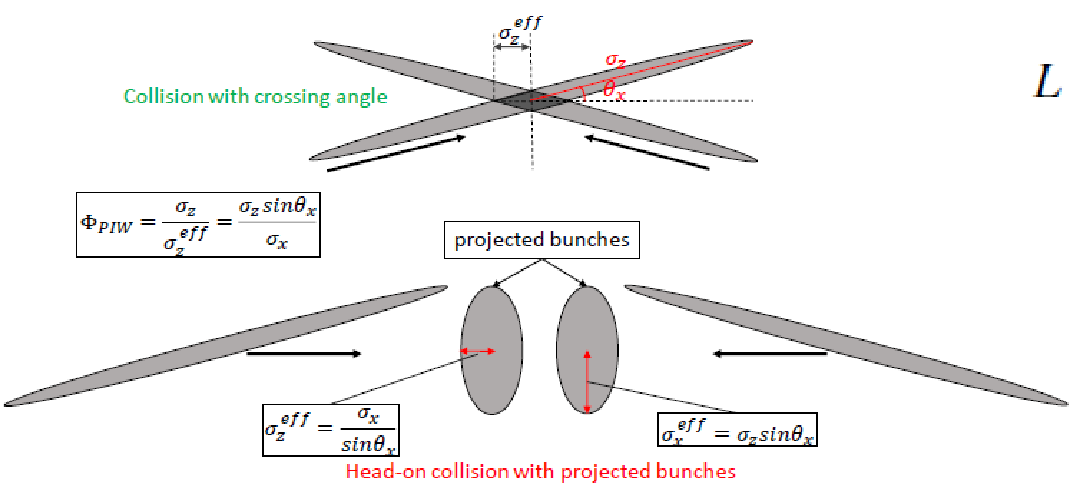
- ✓ very small β_y avoiding "hour-glass" limitation (effective bunch length ≈ depth of field of the optics)
- ✓ collide more charge @ tiny vertical beam size with similar beam-beam tune-shift strength parameter

challenges
@ SuperKEKB

1. IP tuning to cancel optical aberrations essential to maintain tiny beam sizes (linear collider like ?)
2. control beam-beam tune-shift with more complex beam-beam dynamics + IP optics aberrations
3. continuously injected intense beams & strong IP optical magnification → backgrounds (linear collider like ?)



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



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

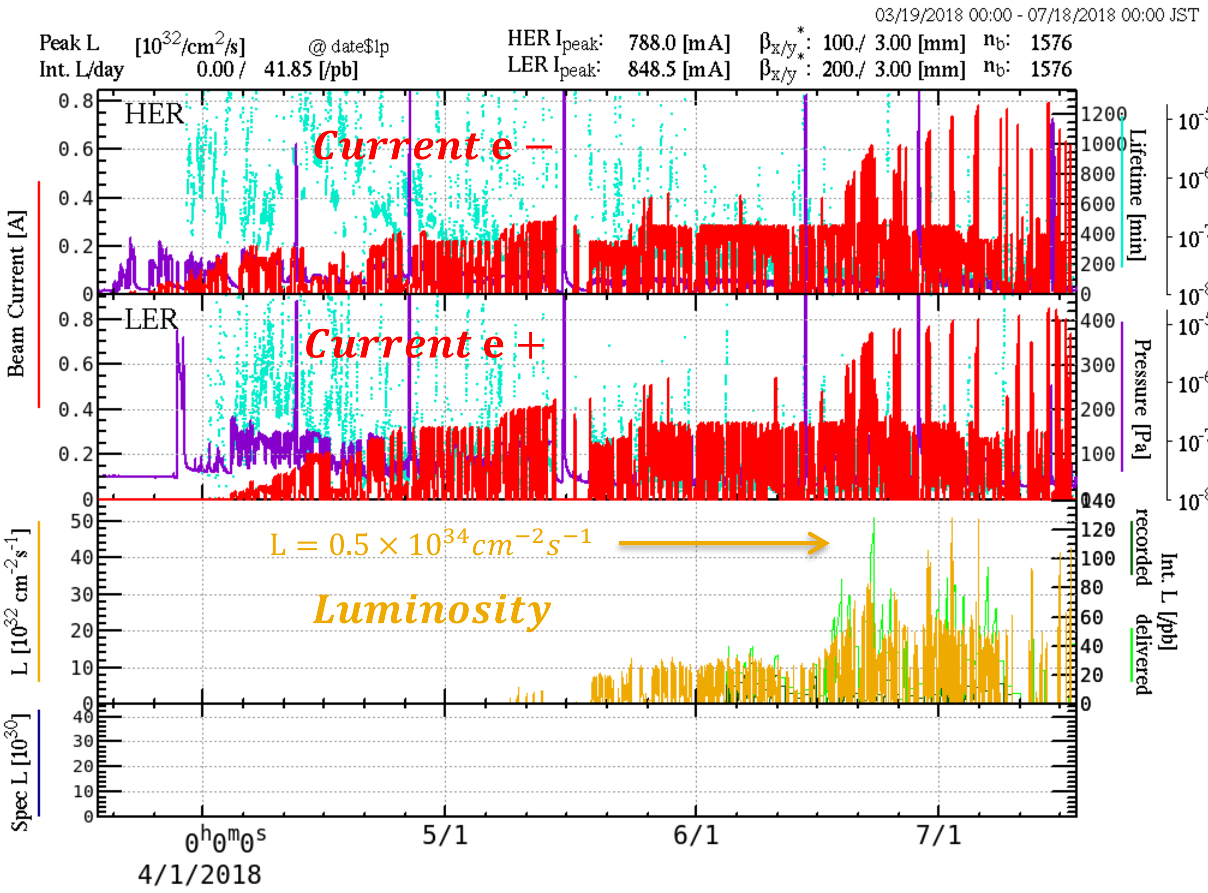
× 1/20 β_y × 2-3 beam currents

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

× 1/20 σ_y

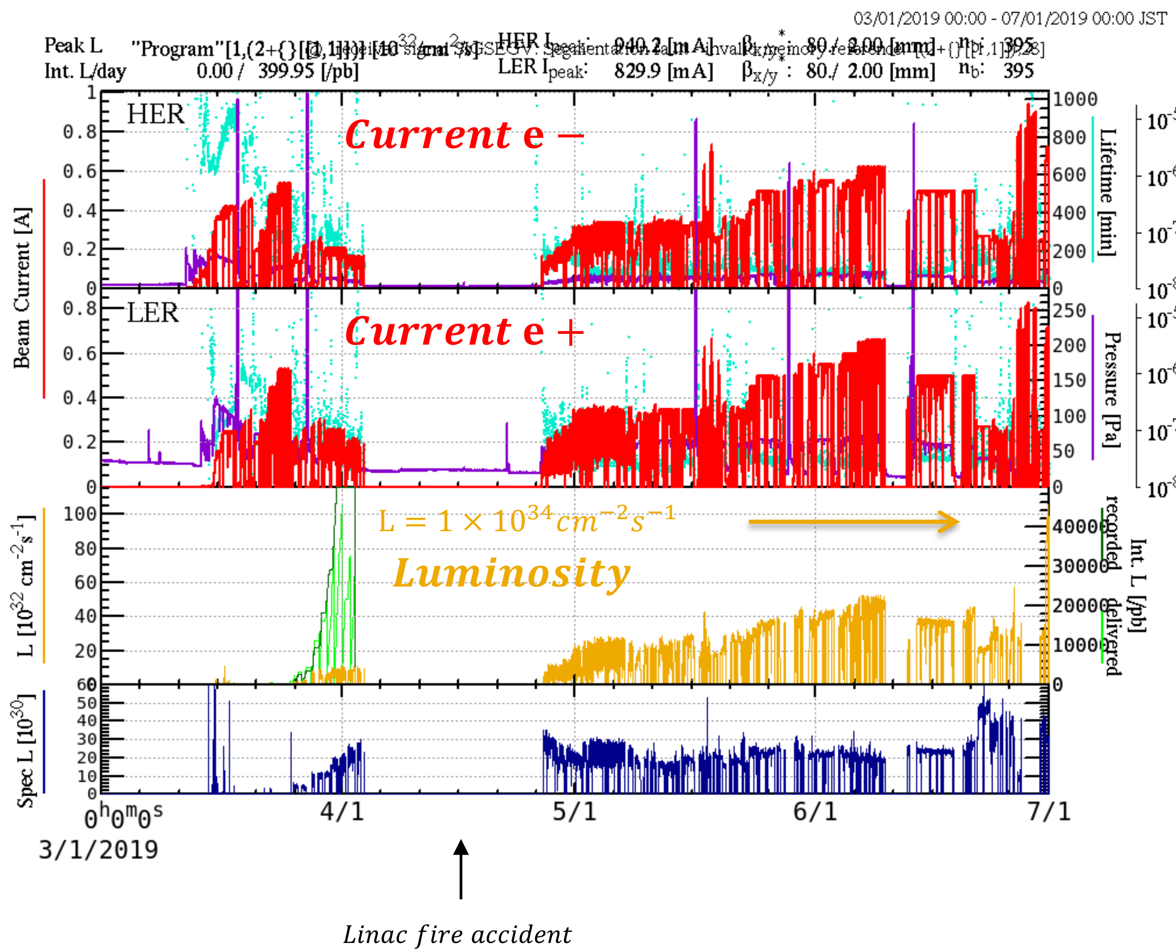
SuperKEKB commissioning history: Phase 2 (March => July 2018)

- Belle II detector rolled in and first physics events measured
- Colliding beam commissioning, no vertex detector
- Progressively reducing β_y^* from $8\ mm$ to $3\ mm$ (design value is 0.3 mm)
- Smallest beam size (at low intensity) $\sigma_y^* \approx 0.4\ \mu m$
- Maximum luminosity: $\mathrm{L} \approx 0.5 \times 10^{34} cm^{-2} s^{-1}$



SuperKEKB commissioning history: Phase 3 (March => June 2019)

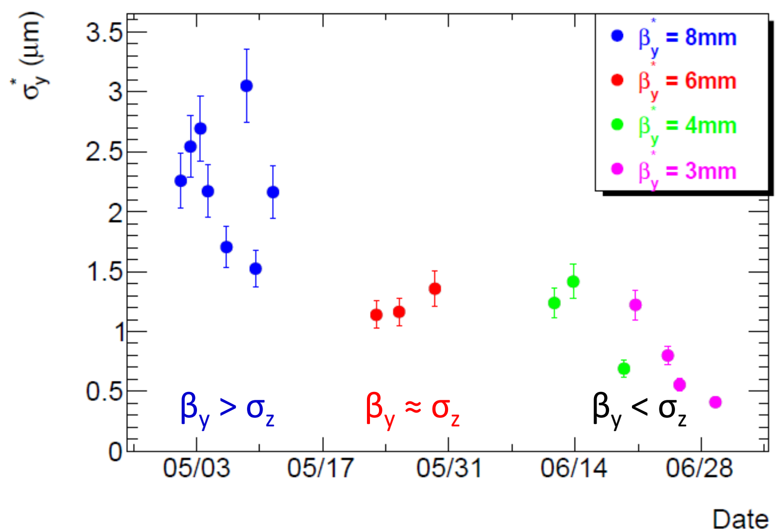
- Belle II vertex detector installed
- Background decreased by factor 10 with improved collimation
- Lost one month due to linac fire accident (unrelated to SuperKEKB)
- Maintained stable operation with continuous injection and currents at $I \approx 500\ mA$
- Belle II data taking most of the period: accumulated $\sim 6.5\ fb^{-1}$ for early Belle II physics analyses
- Squeezed beta β_y^* to 2 mm
- Luminosity milestone: $\mathrm{L} = 1.0 \times 10^{34} cm^{-2} s^{-1}$

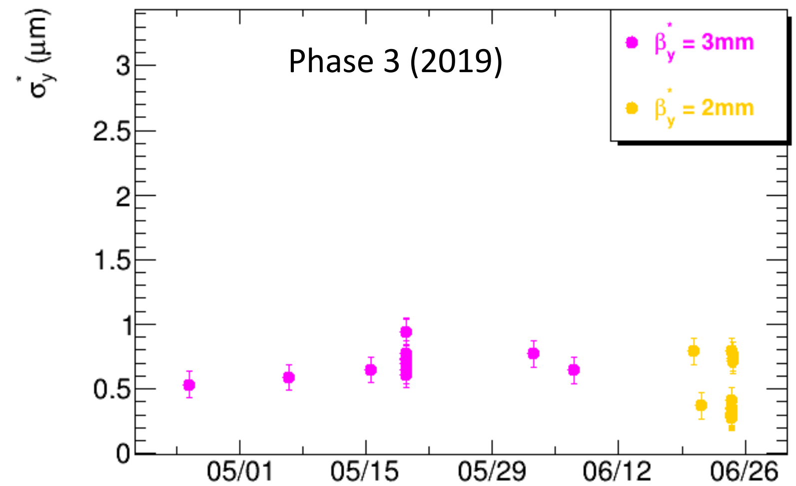


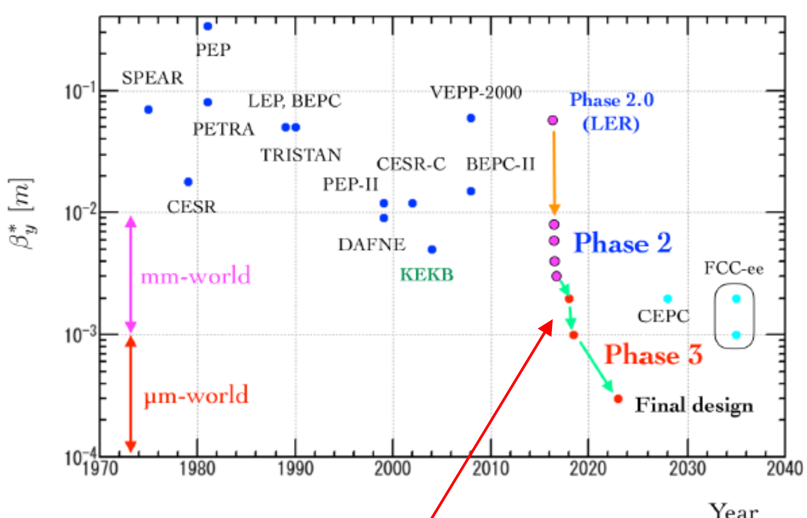
Good progress squeezing σ_y with $\beta_y < \sigma_z$

→ shows "hour-glass" effect mitigated in nanobeam scheme

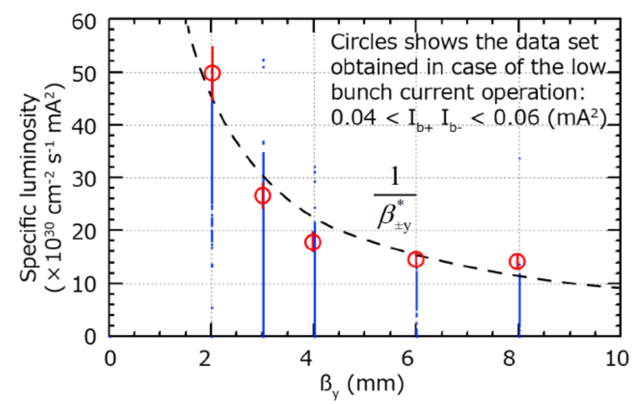
→ smallest β_y achieved in storage ring







β_y = 2 mm achieved in June 2019

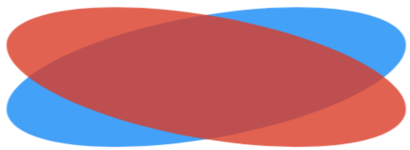


L_{sp} is increased by squeezing βy*.
($\xi_{\pm y}$ can be kept while squeezing)

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

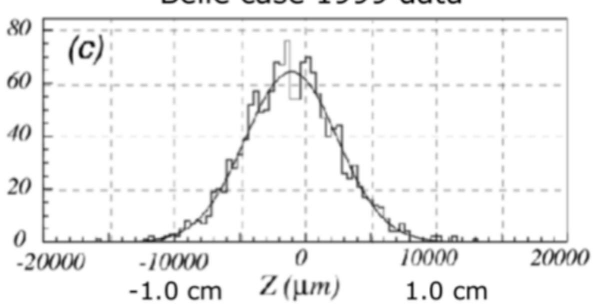
Reduced bunch overlap in nanobeam scheme also visible on Z distribution of reconstructed track vertices

Ordinary collision KEKB



Z vertex distribution

Belle case 1999 data



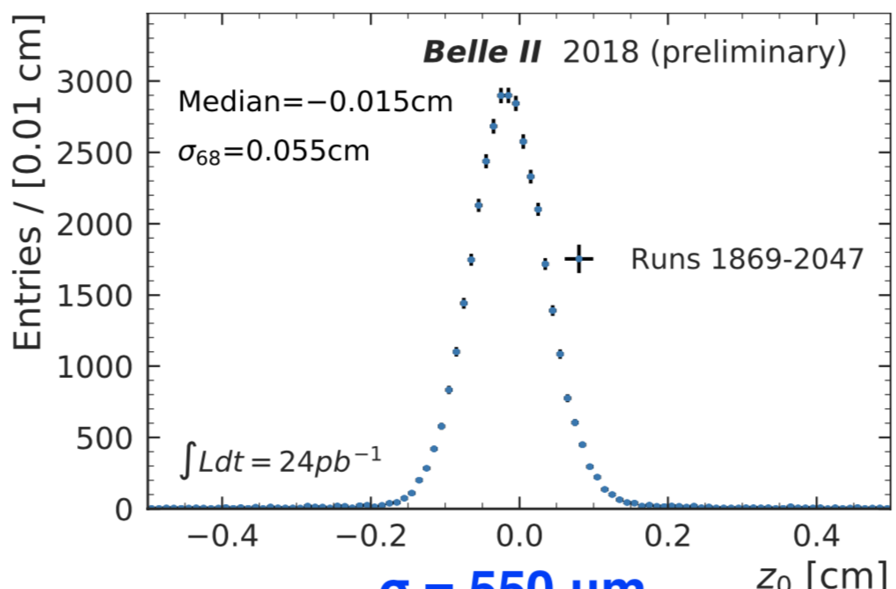
σ = 4.5 mm

Nano-Beam (SuperKEKB)

$2\phi = 83$ mrad

Z vertex distribution

Belle II case 2018 data



σ = 550 μm

IP optical aberrations blowing up the beam size are unavoidable

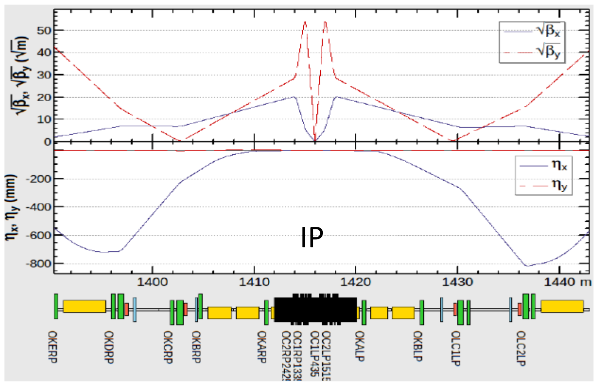
→ reliable measurement for correction only at the IP…

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

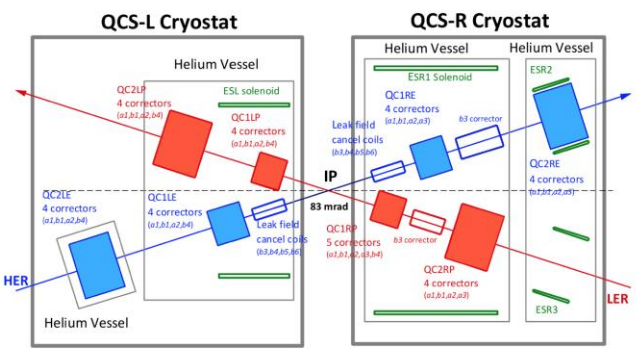
+ higher order terms
(geometric & chromo-geometric)

ideal spot waist shift linear x-y coupling linear dispersion

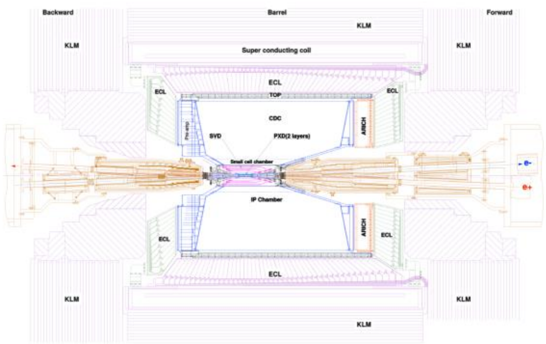
Optical functions in LER ±27 m around IP



SC final focus system



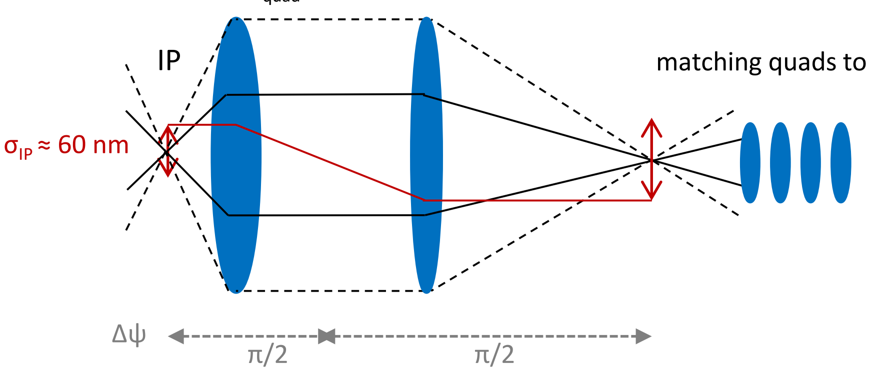
integration with Belle II



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

σ$_{quad}$ ≈ 0.2 mm

matching quads to select β*



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

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

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

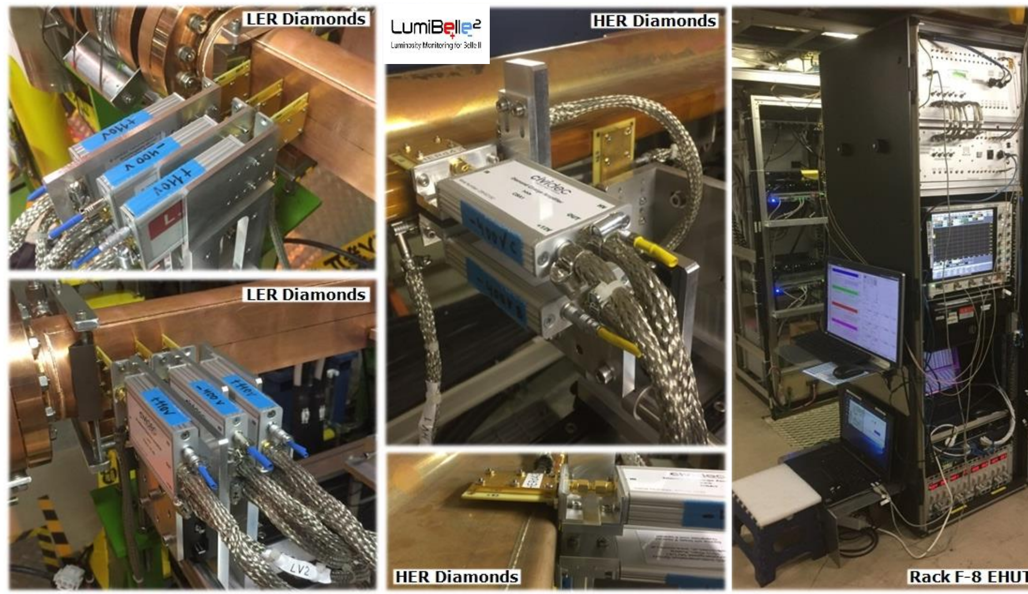
Must tune directly at IP (luminosity…)

LumiBelle2

Luminosity monitor that measures recoiling electrons, positrons, and photons from forward radiative Bhabha scattering

FEATURES:

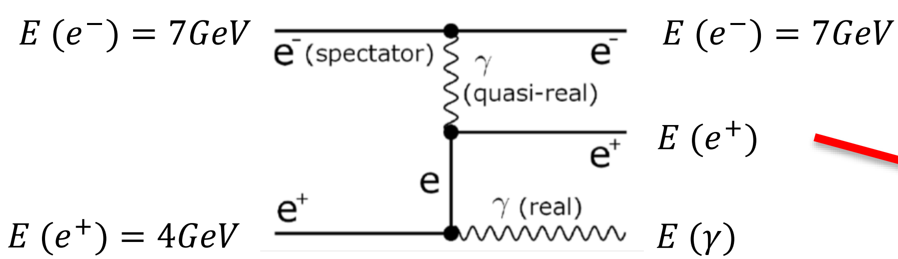
- Single crystal CVD diamond sensors
- $4 \times 4 \times 0.5/0.14\ mm^3$
- Fast amplifiers;
- Digital electronics.
- 4 of 6 channels online

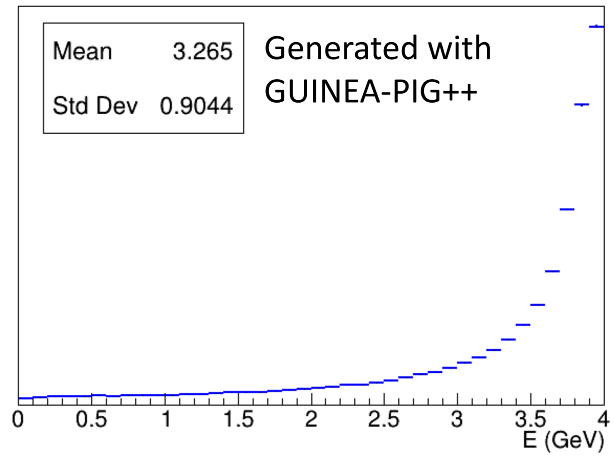


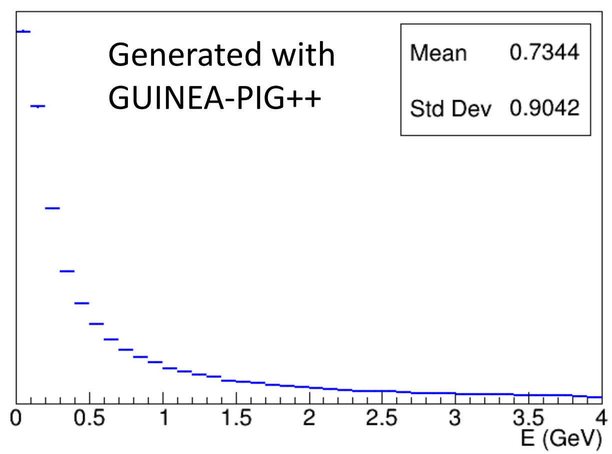
GOALS:

1. Train integrated luminosity): 1% precision at 1kHz;
2. Bunch-by-bunch integrated luminosity): 1% precision at 1 Hz;
3. Cover SuperKEKB large luminosity range with high SNR : $L = 10^{30} - 10^{36} cm^{-2} s^{-1}$

Zero degree radiative Bhabha scattering







- Complementary reaction for e^+ spectator
- Large cross section $\sigma \approx 250\ mbarn$ for $E\ (\gamma) > 1\%\ E\ (beam)$
- LumiBelle2 measures rates dN/dt of e^+ in the positron ring and γ in the electron ring

ABSOLUTE LUMINOSITY

$$L = \frac{1}{\sigma}\frac{dN}{dt}$$

σ not known with precision + acceptance varies over time

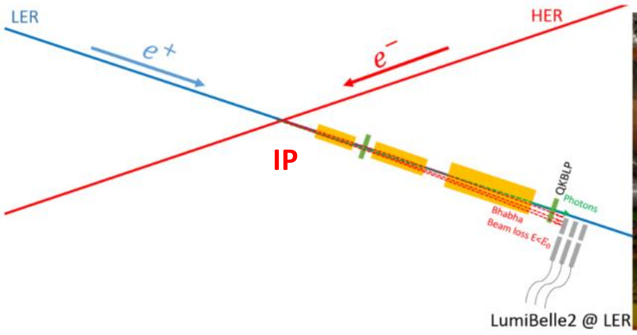
RELATIVE LUMINOSITY

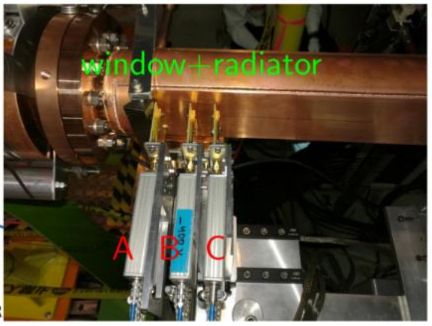
$$L \propto \frac{dN}{dt}$$

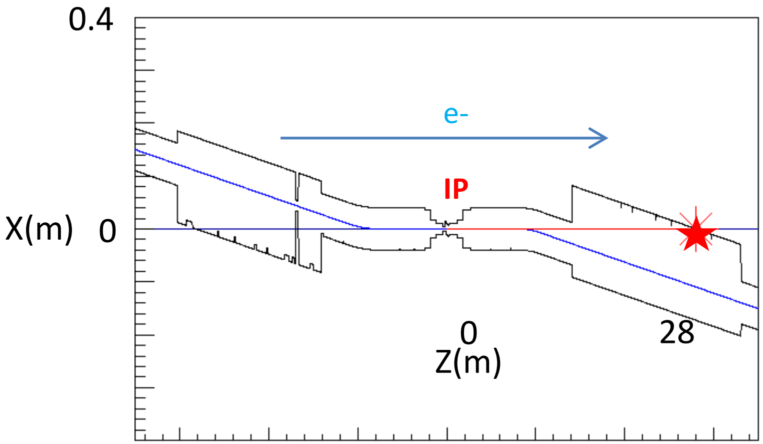
Detectors position

POSITRON RING (measure e+)

- Optimal position found at 11 m downstream of IP using SAD
- Bhabha positrons are over-bent and hit the vacuum chamber
- Special beam pipe with window + Tungsten radiator







ELECTRON RING (measure γ)

- Originally position at 30 m (2018)
- I designed an original simulation to track photons inside the vacuum chamber. Photons generated with GUINEA PIG ++
- Optimal position found at 28 m
- New position has rate $\sim$10 times higher (2019);

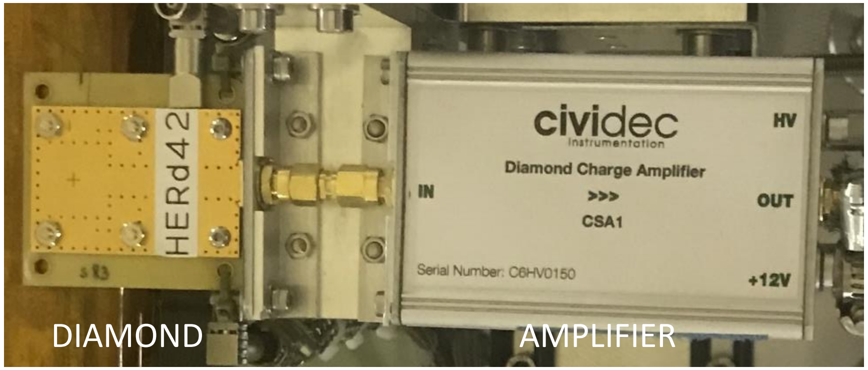
Fast monitoring with diamonds

High charge carrier mobility

→ fast signal formation

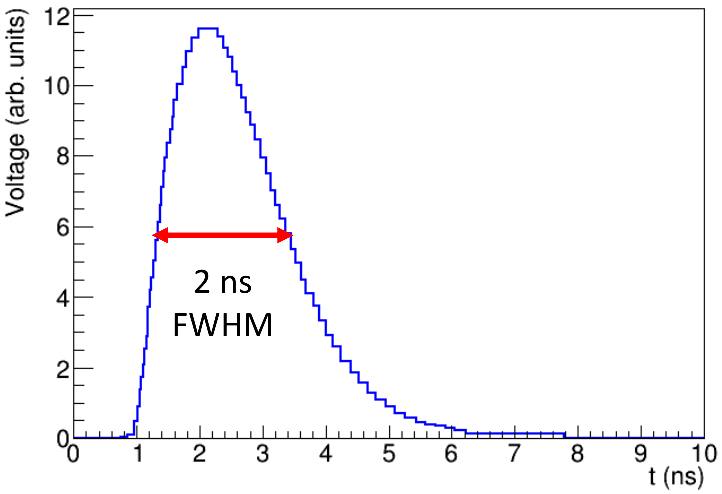
Wide band-gap (5.5 eV)

→ good radiation tolerance

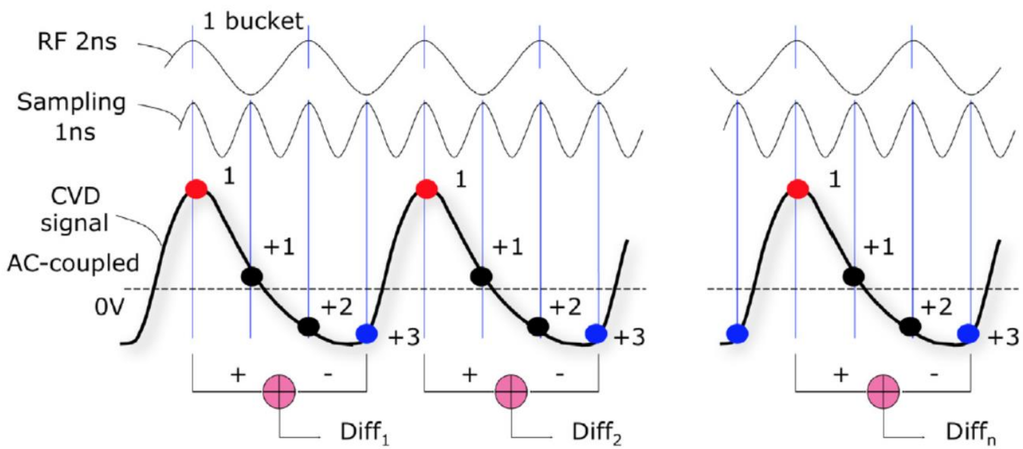


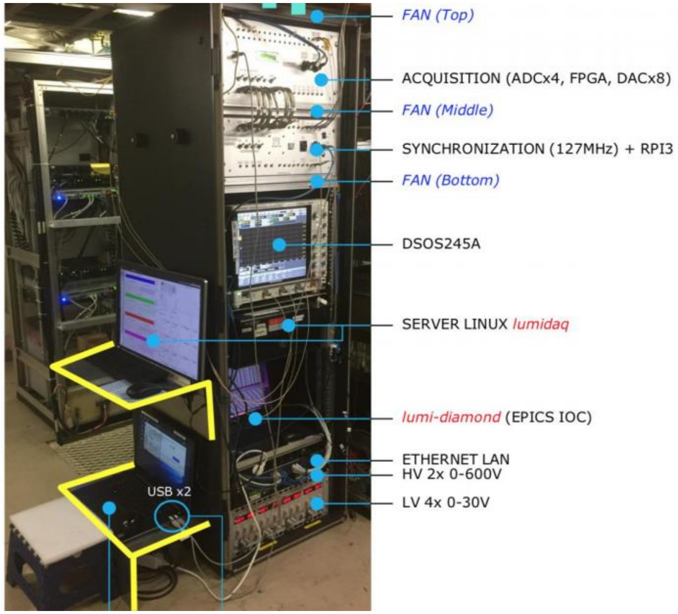
SuperKEKB collision period = 4 ns

- To monitor bunch-by-bunch luminosity we need a pulse width smaller than 4 ns
- 140 μm thick diamond + fast current amplifier provides 2 ns FWHM



Signal processing algorithms





- 2ns FWHM signals are sampled every 1 ns
- Synchronization to RF clock -> continuous monitoring, averaging at 1 kHz
- Luminosity proportional to amplitude of signal peaks
  1. ADC is AC-coupled -> difference between peak and baseline recorded
  2. Raw sum of signal peaks is also recorded

ZDLM (Zero Degree Luminosity Monitor)

S. Uehara (KEK, IPNS/Belle II)

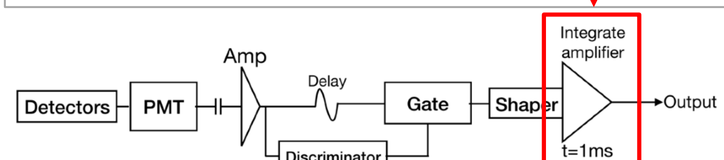
Improved version of KEKB fast luminosity monitor

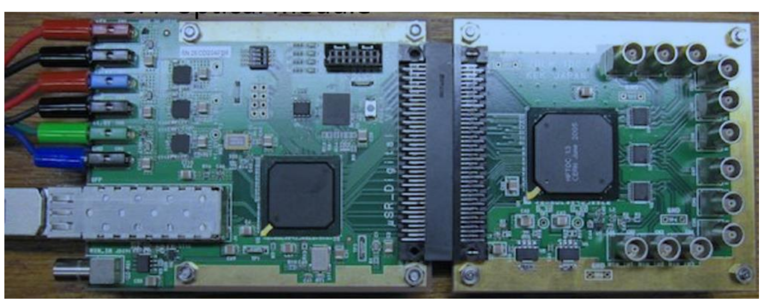
- used as benchmark for many studies ↔ LumiBelle2

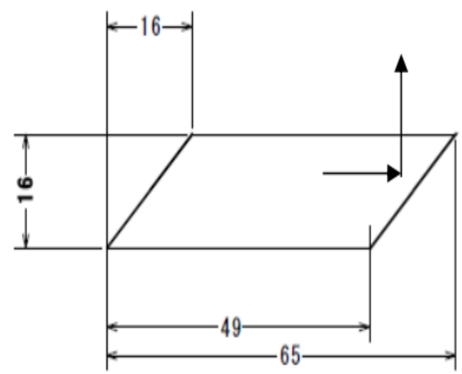
Shared supports and many activities for optimisation and evaluation

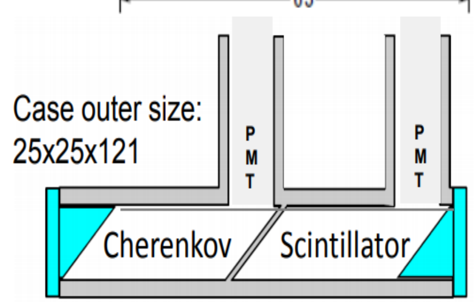
Different, complementary techniques (sensors, electronics and DAQ,…)

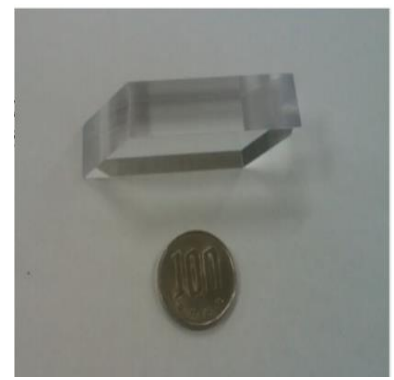
- Cherenkov and scintillator detectors + PMT
- $15 \times 15 \times 64\ mm^3$ LGSO non-organic scintillator and ES-crystal (quartz)
- Miniaturized versions
- Provides bunch-by-bunch and train integrated luminosities
- Analog electronics



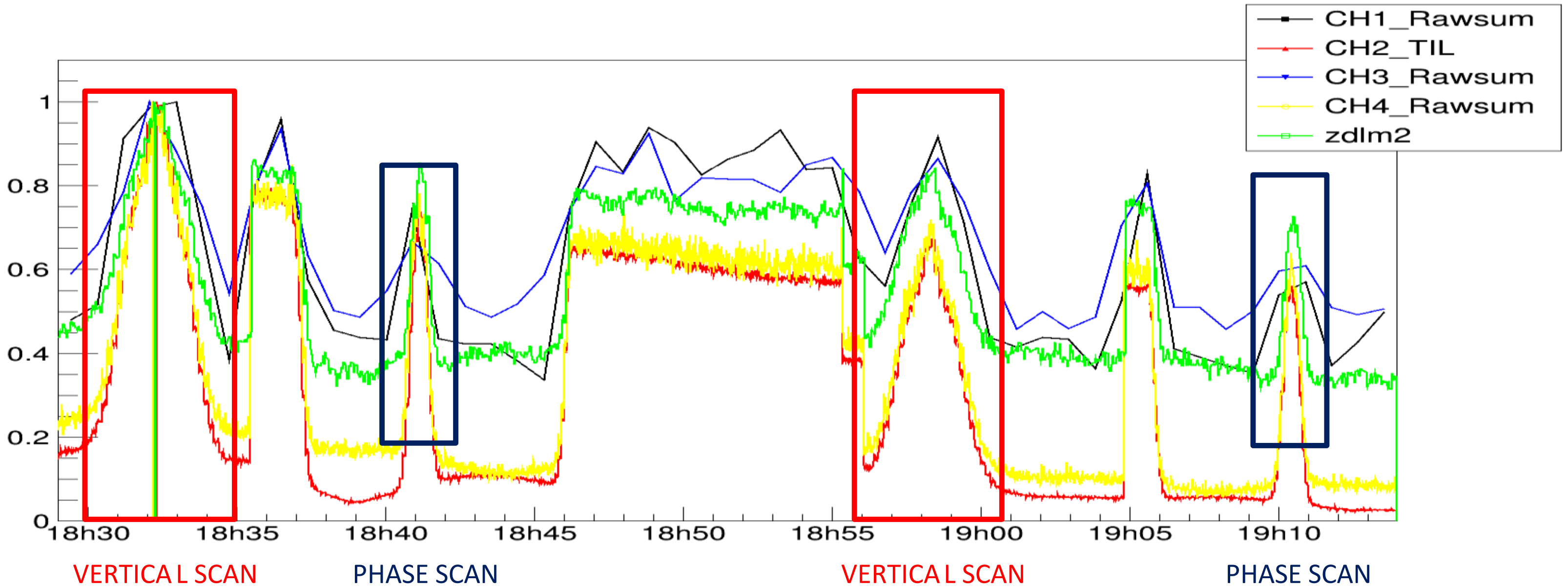








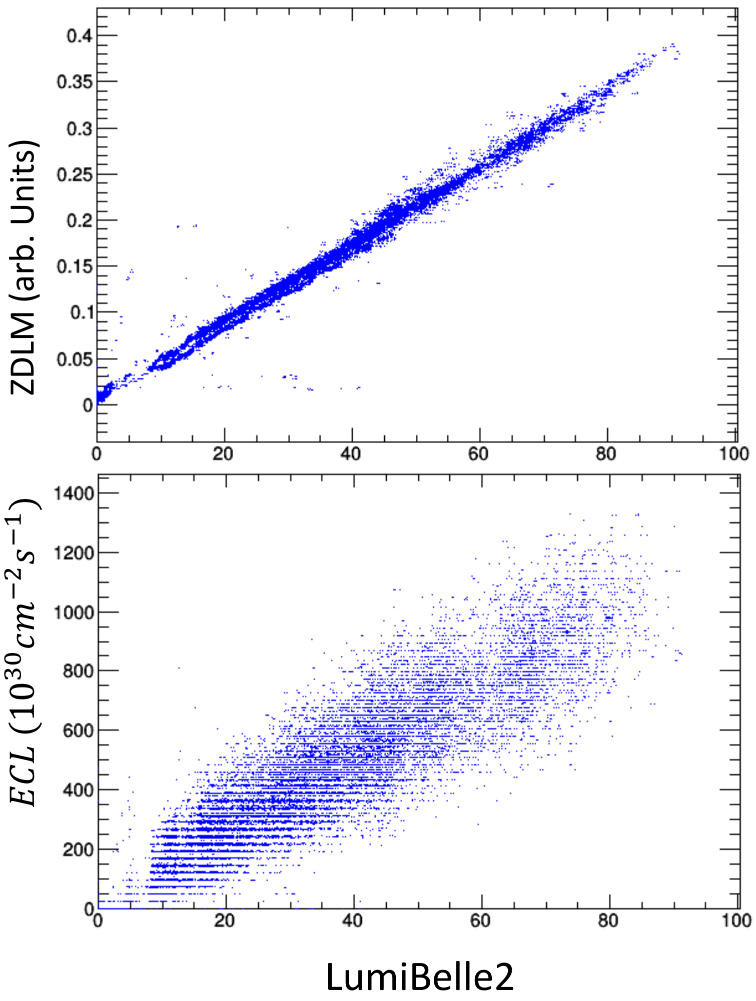
First collisions (luminosity): 25 April, 2018



- Vertical and phase (longitudinal) scans were performed to find the optimal position of the beams
- Zero Degree Luminosity Monitor (ZDLM), present since KEKB, used as benchmark
- The 4 LumiBelle2 channels and the ZDLM work well and are in agreement
- Successfully measured and provided the luminosity on-line from the first collision up to this date

Correlation with other monitors: ZDLM and ECL

- The ZDLM is a relative luminosity monitor located close to the LumiBelle2 diamonds.
- The Electromagnetic Calorimeter (ECL) is part of the Belle II detector and can measure the absolute luminosity.
- We observe good correlation on a day-by-day basis or shorter time scales;
- Long term variations in slopes (sensitivities) due to changes in beam conditions and setups: gains, position of the sensors, thresholds, etc.



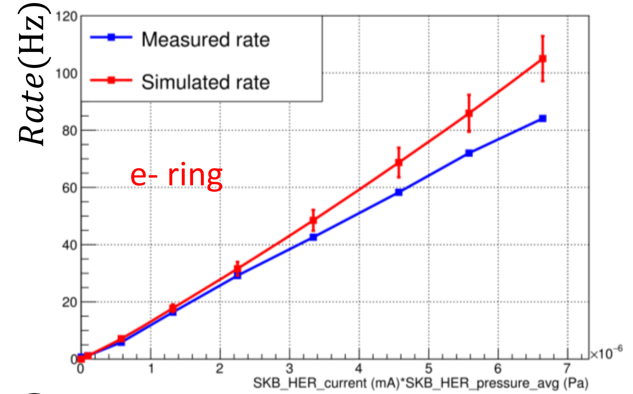
Background study

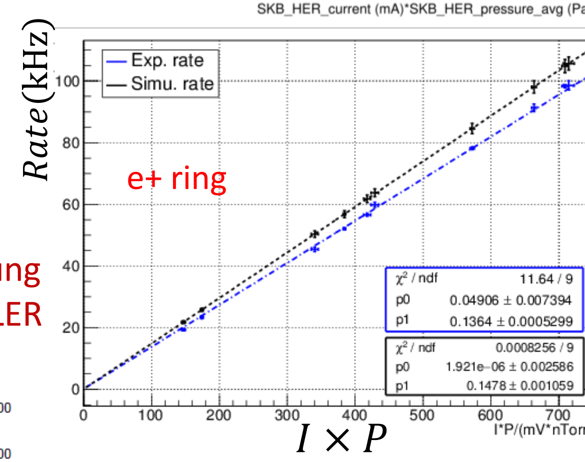
SIMULATION FEATURES:
- Bremsstrahlung, Coulomb, and Touschek scattering included
- Use of SAD for tracking and Geant4 for particle detection
- Detailed simulation of pressure profile and chemical composition of vacuum gas ($Z_{eff} \approx 4.2 - 4.5$) from previous study (J.Carter, M.Ady)

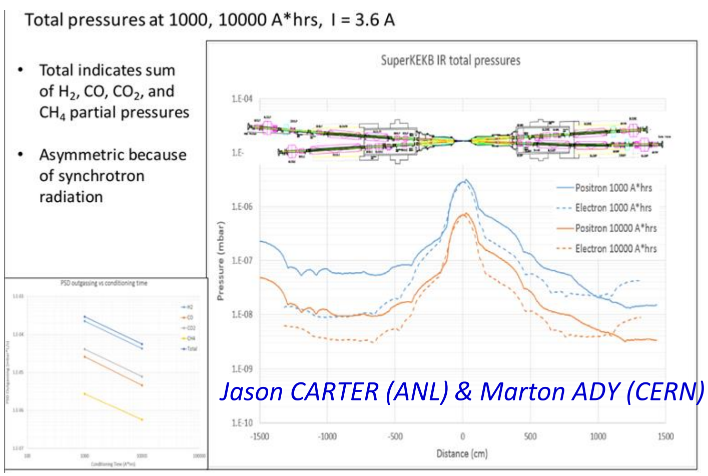
HER (e- ring):
- Dominant rate from Bremsstrahlung photons
- Electron rates from Bremsstrahlung, Coulomb, and Touschek scattering are negligible($\ll 1Hz$)

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

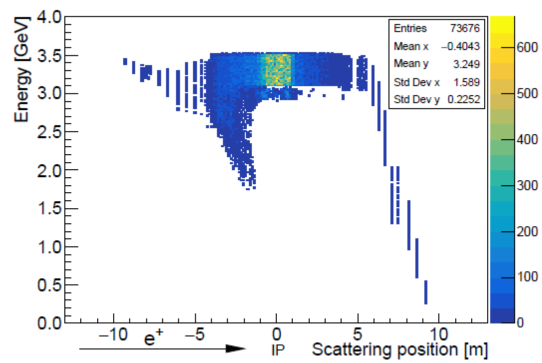


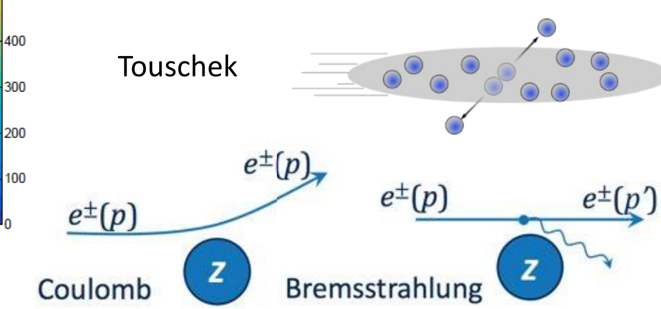




Simulated vacuum profile in IR

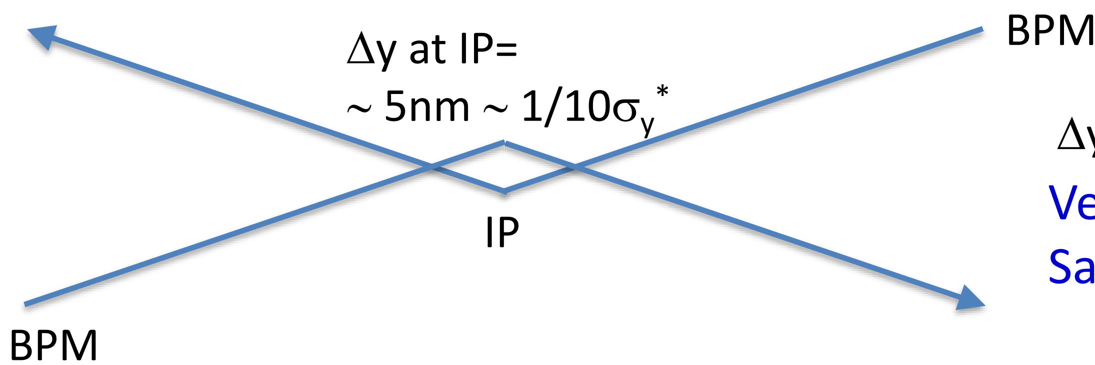
Scattering position of Bremsstrahlung particles detected in LumiBelle2 / LER





Fast & slow beam position variations at IP require feedback corrections

- Beam-beam deflection for fast vertical motion



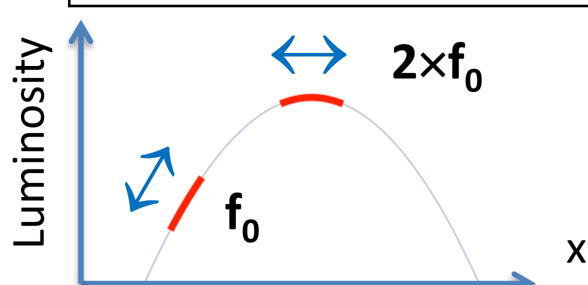
Δy at BPM= ~ 1.3μm

Vertical vibration ~ 25-100 Hz

Sampling (BPMs) ~ 32 kHz

- Luminosity feedback by "dithering" for slower horizontal motion

Cf. WEXBA04 by Yoshihiro Funakoshi, Wednesday, 11:20 am



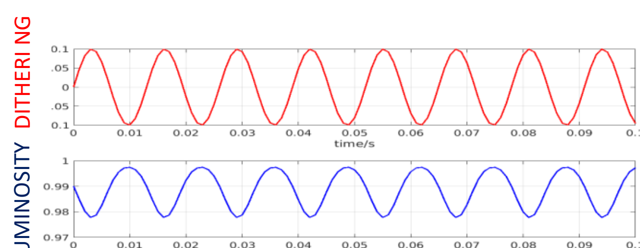
Horizontal motion ~ few Hz

Modulation freq. f_0 ~ 79 Hz

Sampling (lumi. meas.) ~ 1 kHz

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

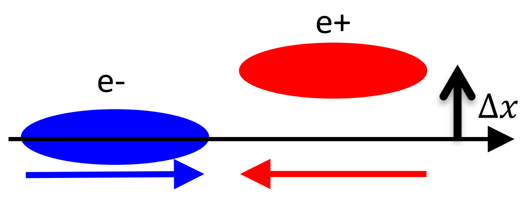
$$L(t) = \frac{f_{rev} N_1 N_2}{4\pi\sigma_x\sigma_y} e^{-(\frac{[q+psin(2\pi ft)]^2}{4})}$$



Dithering coil x 12

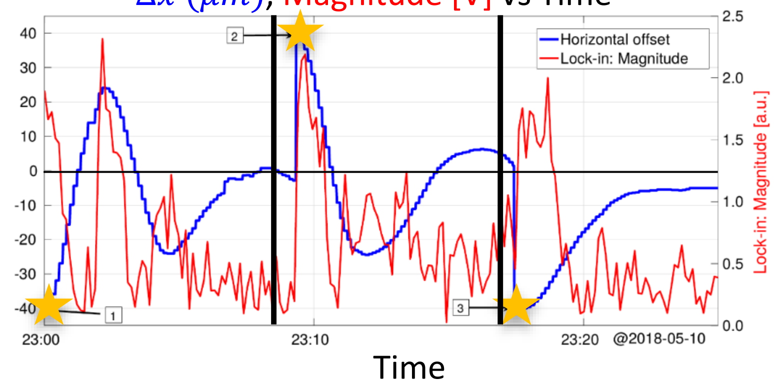
1st dithering feedback test in Phase 2

- The e- beam was artificially given an offset, while the e+ beam was dithered
- The algorithm tries to minimize the Magnitude [V] of the luminosity FT calculated at the driving frequency f_0 to bring the beams back to the optimal position (unwanted offset o=0)
- These parameters are then sent to the magnet control system via EPICS to create a bump in the e- beam
- After first two attempts, optimization of the algorithm parameters, in the third one the feedback was able to smoothly minimize the offset



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

$\Delta x\ (\mu m)$, Magnitude [V] vs Time



Further tests in Phase 2 & 3 have exhibited some coupling effects between X and Y feedback systems → to be solved for operation at design parameters

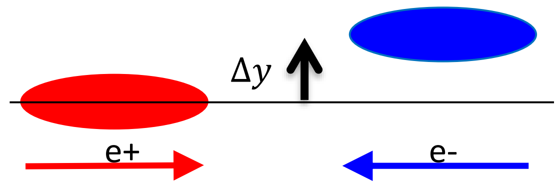
Beam size estimation with vertical offset scans

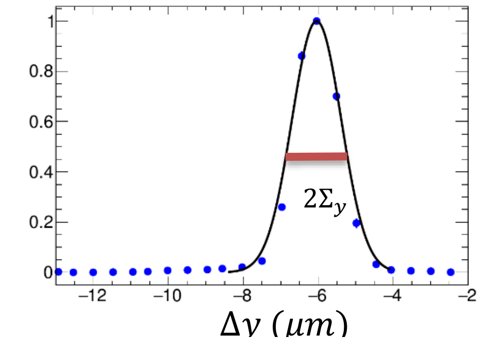
Analytical result integrating Gaussian distributions with vertical offset:

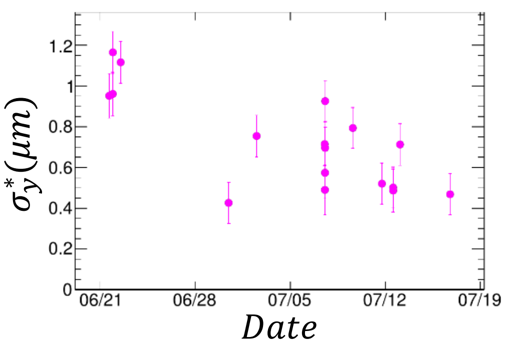
$$\frac{L}{L_0} = exp\left(-\frac{\Delta y^2}{2\Sigma_y^2}\right)$$

$$\Sigma_y^2 = {\sigma_{1,y}^*}^2 + {\sigma_{2,y}^*}^2 \approx 2{\sigma_y^*}^2$$

assumes rigid beams



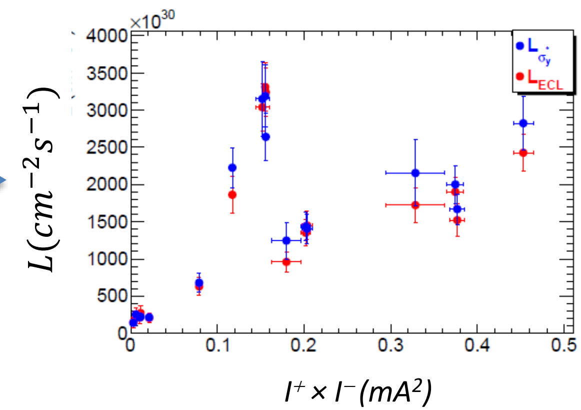




Benchmark vs ECL

$$L_{\sigma_y^*} = \frac{f N_+ N_-}{4\pi \sigma_{x,eff}^* \sigma_y^*}$$

$$L_{\sigma_y^*}/L_{ECL} > 1$$

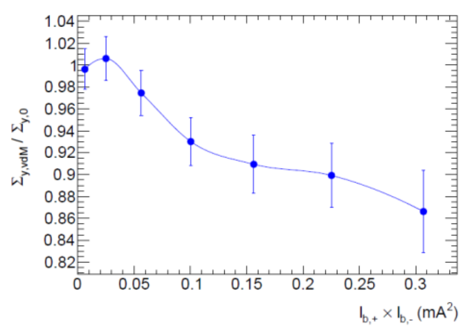


σ_y^* estimation slightly biased due to non constant beam-beam blow-up during the scan

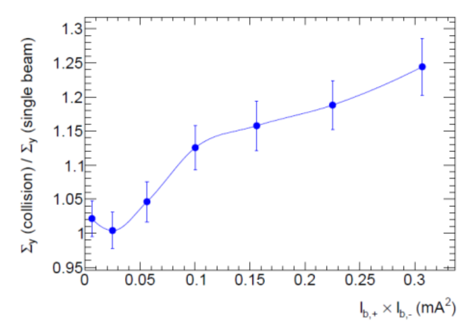
beam-beam simulation

(S. Di Carlo & D. Zhou)

Bias



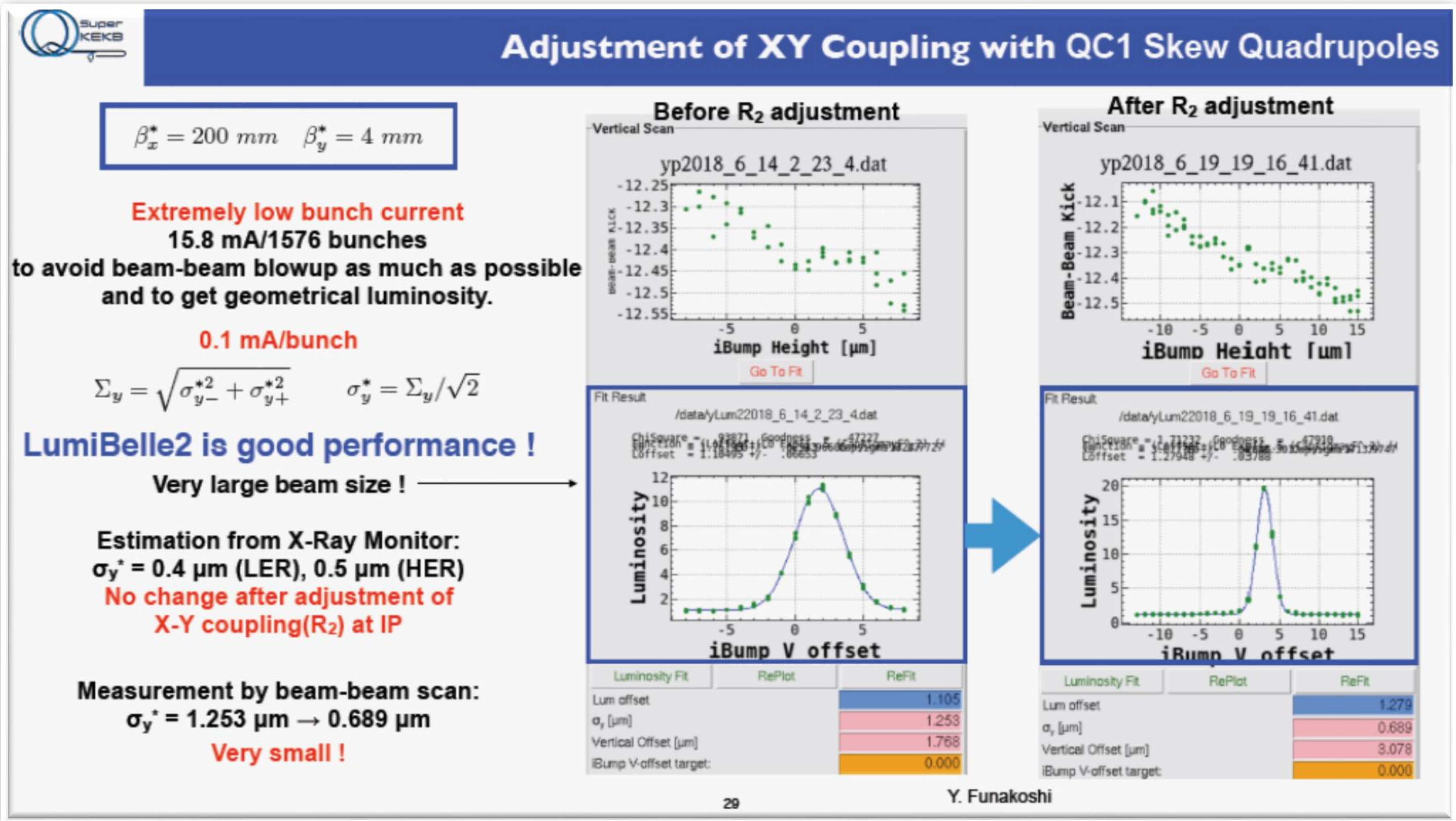
Blow-up



Sensitive luminosity monitor important to correct optical aberrations in vertical IP beam size

Phase 2
$\beta_y^* = 4$ mm

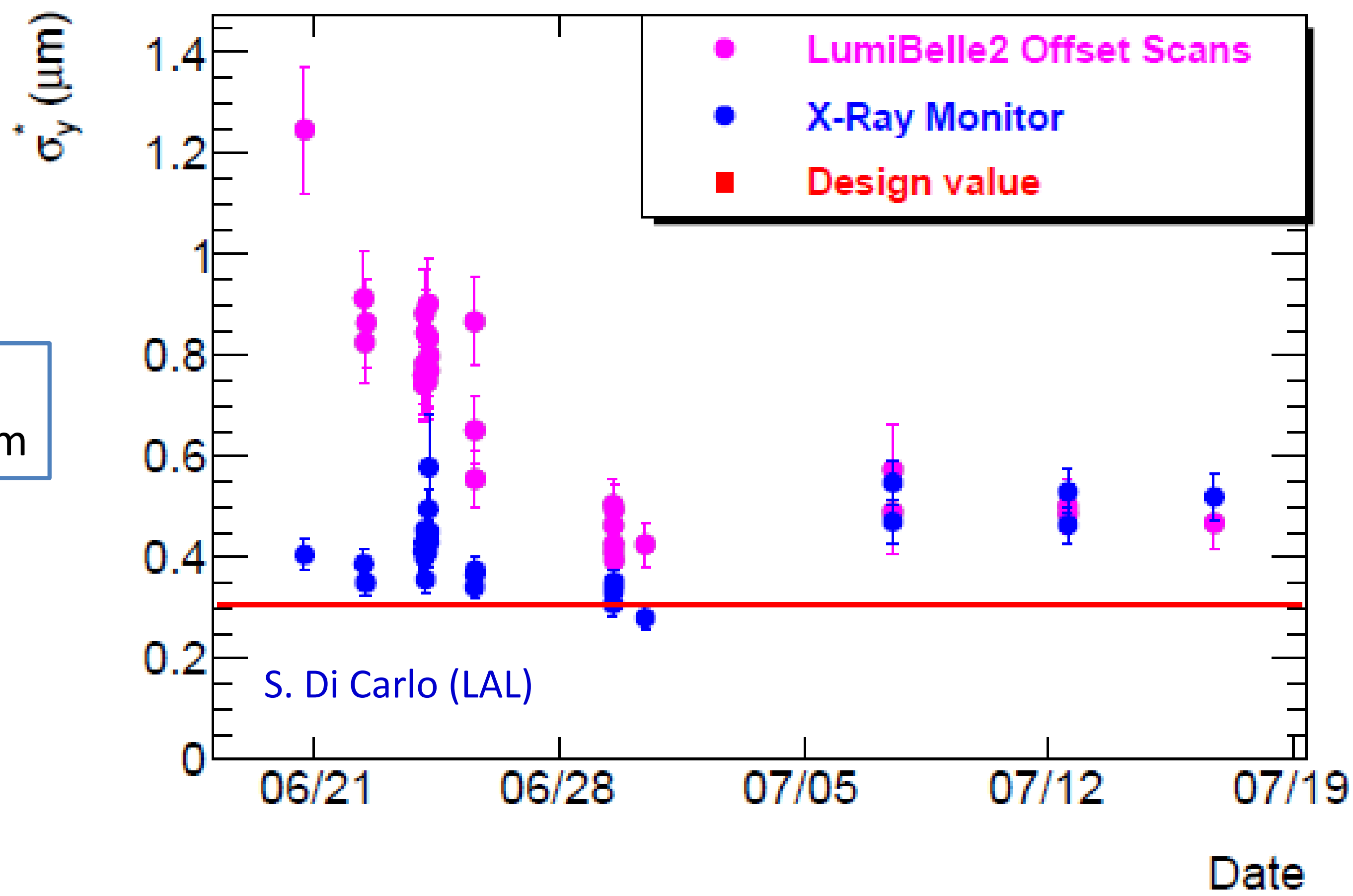
very low intensity essential to avoid beam-beam effects:
(1) confusion from blow-up, (2) biased beam size estimates



Sensitive luminosity monitor important to correct optical aberrations in vertical IP beam size

very low intensity essential to avoid beam-beam effects:
(1) confusion from blow-up, (2) biased beam size estimates

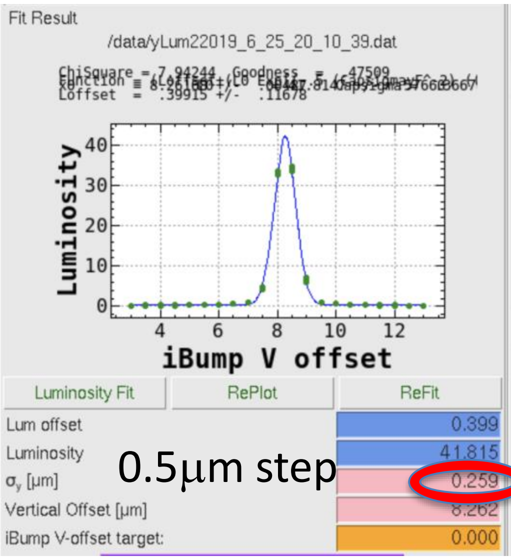
Phase 2
$\beta_y^* = 3$ mm

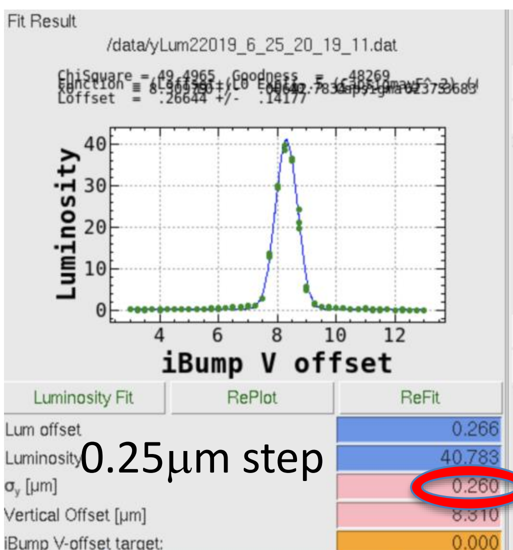


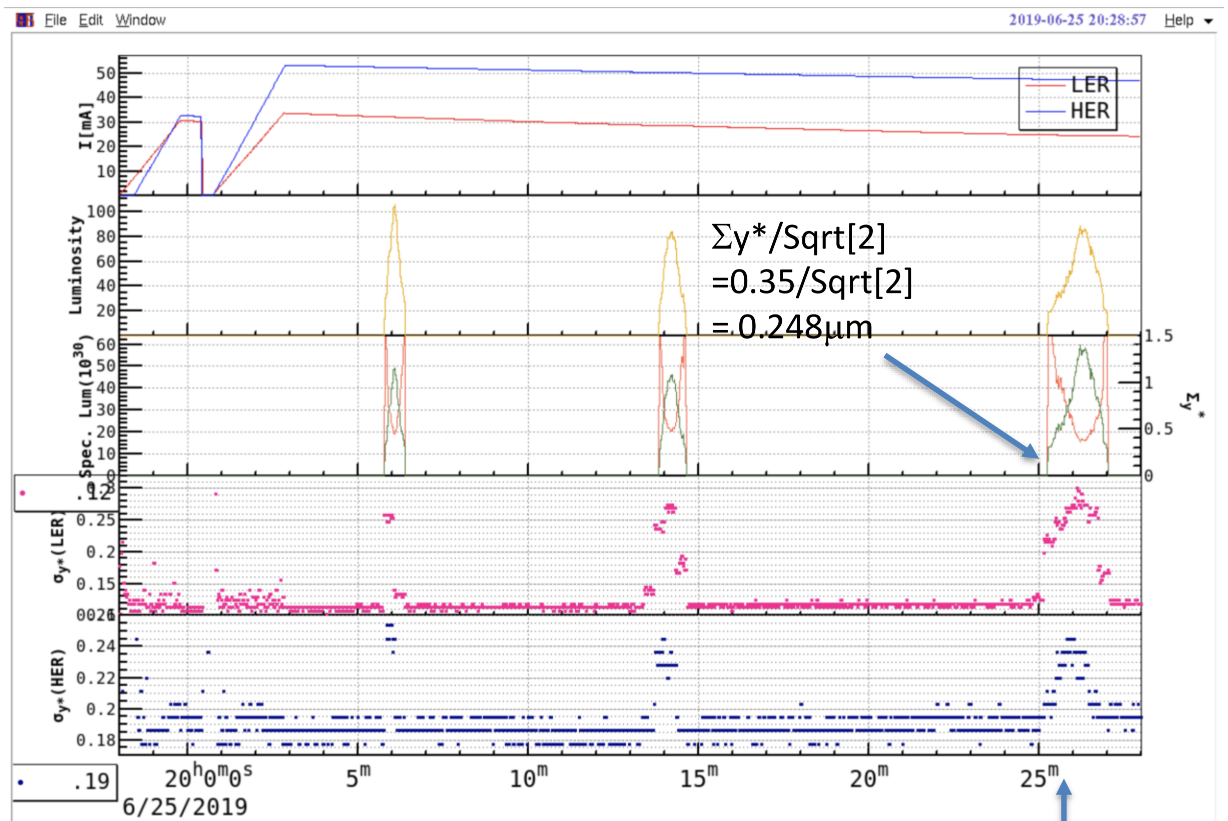
Vertical offset scan

Y. Funakoshi (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

Phase 3
$\beta_y^* = 2$ mm



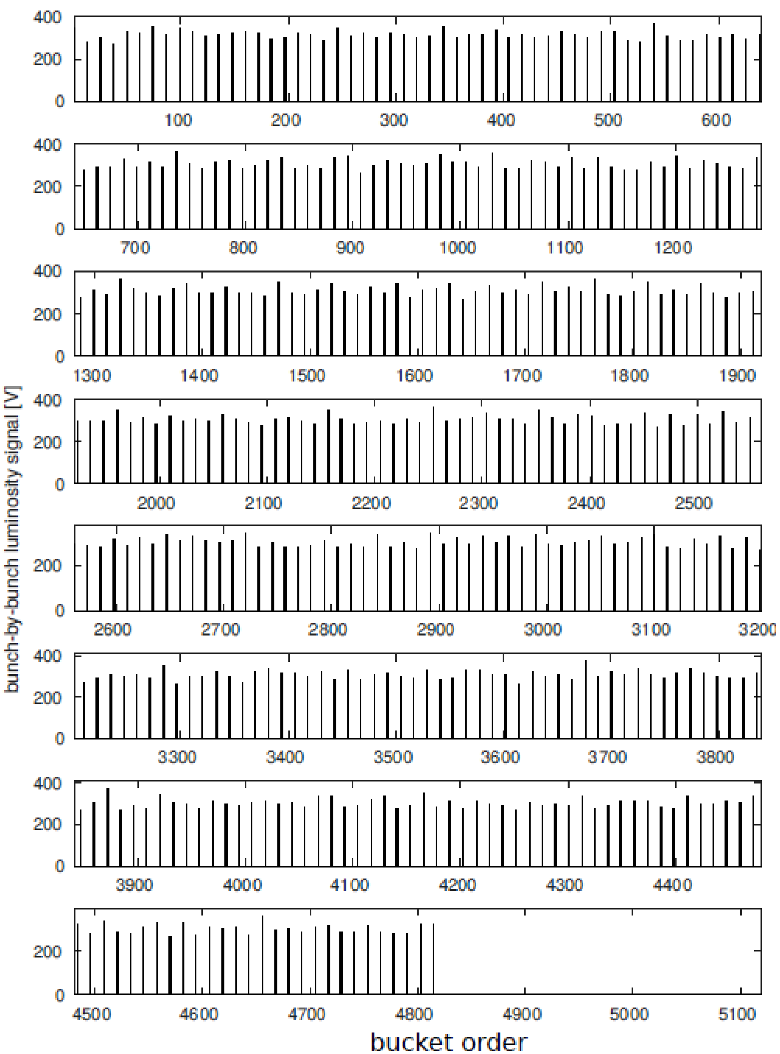




$\Sigma y^*/\mathrm{Sqrt}[2]$ (XRM) $=\mathrm{Sqrt}[0.3\hat{}2+0.25\hat{}2]/\mathrm{Sqrt}[2]= 0.276$µm

XRM & beam-beam scan beam size match → IP has no big x-y coupling

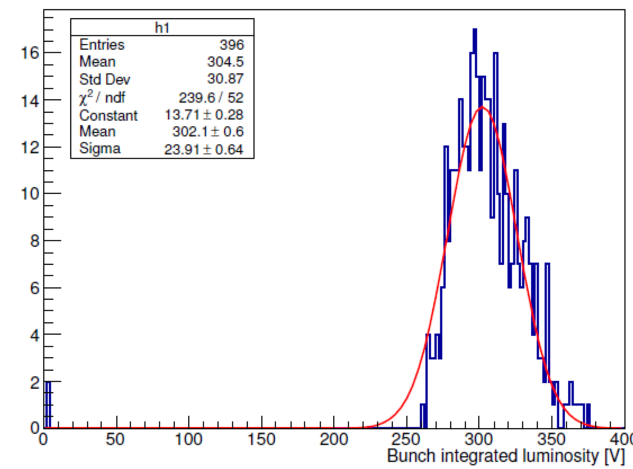
Bunch-by-bunch luminosities, folded vertical bunch sizes and relative offsets

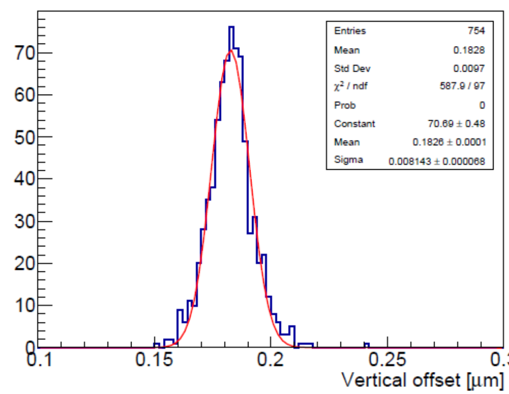


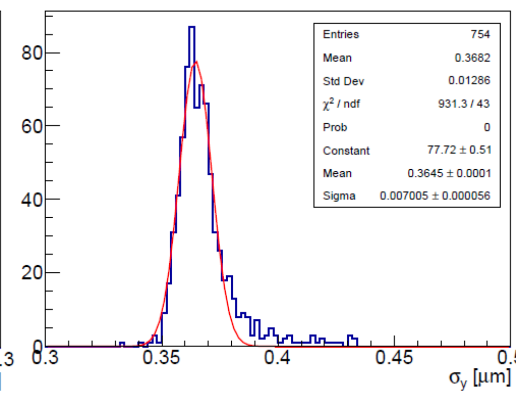
8% spread mainly depends on bunch current differences

Bunch-by-bunch luminosity precision: 1-2% at 1Hz

dominated by spread in bunch-by-bunch currents







8nm RMS spread in bunch-by-bunch vertical offsets (2.3% of average bunch size)

2% RMS spread in bunch-by-bunch vertical beam sizes

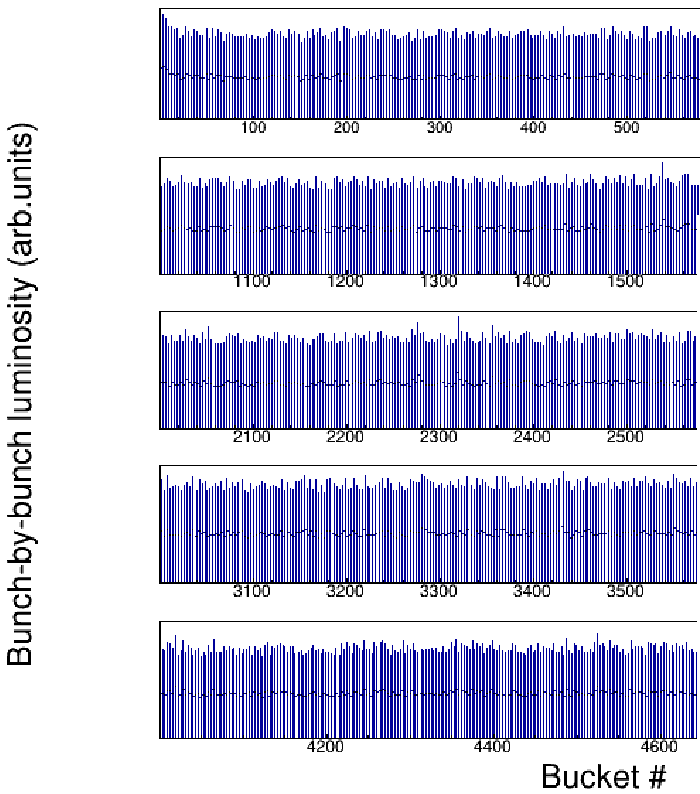
Bunch-by-bunch luminosities at high current :

enhanced values for 1st bunches in the train

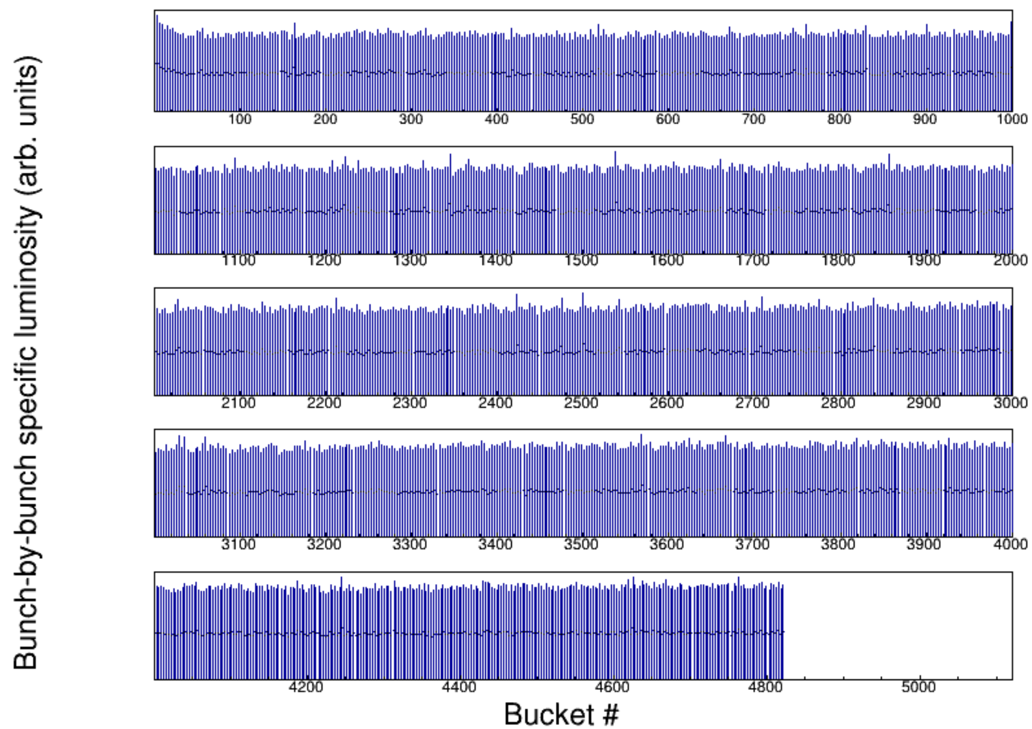
→ transient beam loading effect, other ???

$L = 1.1 \times 10^{34}\ cm^{-2}\ s^{-1}$

1576 bunches



Bunch-by-bunch lu

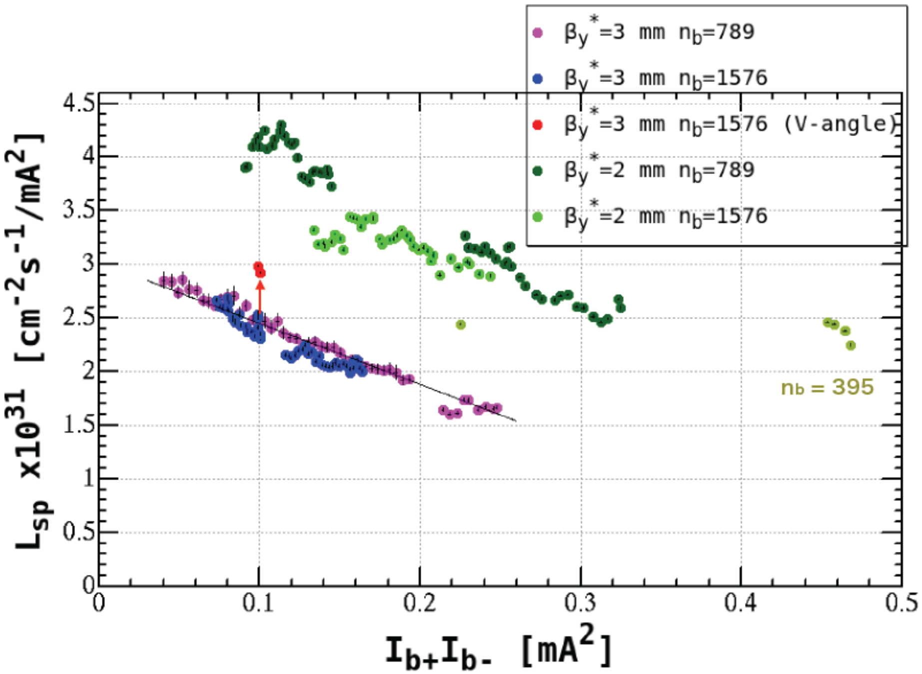


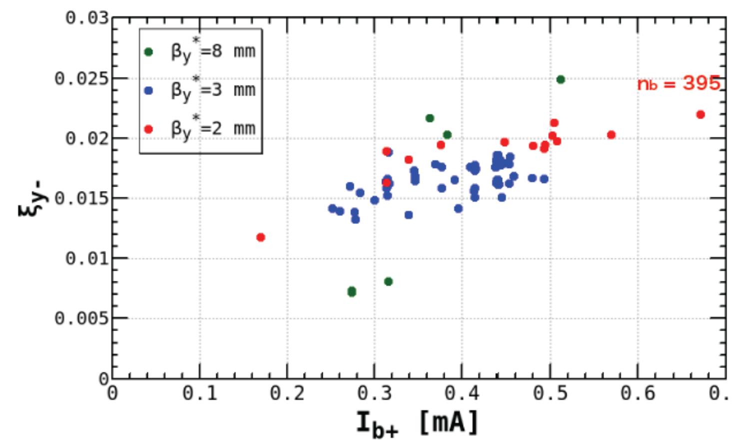
Specific bunch-by-bunch luminosities

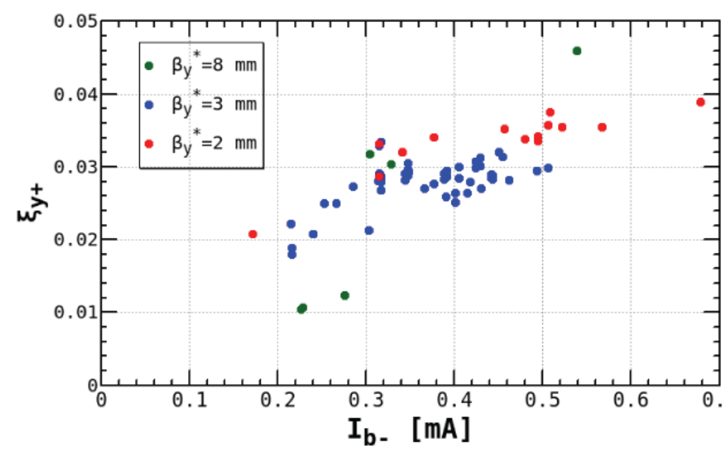
Present beam-beam performance

Y. Ohnishi (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

Specific Luminosity and Beam-Beam Parameter







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

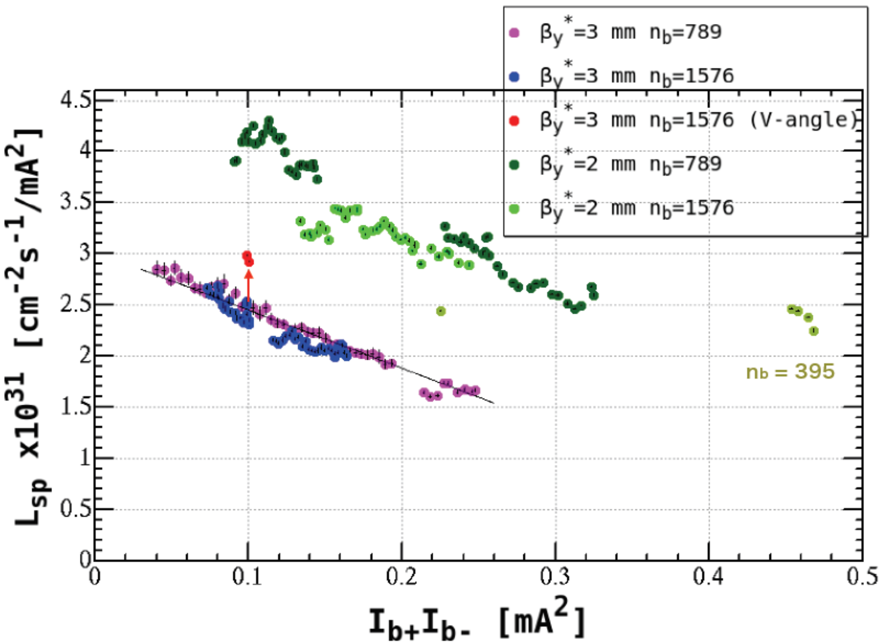
- Luminosity improves squeezing β_y
- Beam-beam parameter remains constant ~ 0.025

→ need ξ_y ~ 0.08 @ 1.4 mA ⇔ ξ_y ~ 0.04 @ 0.7 mA

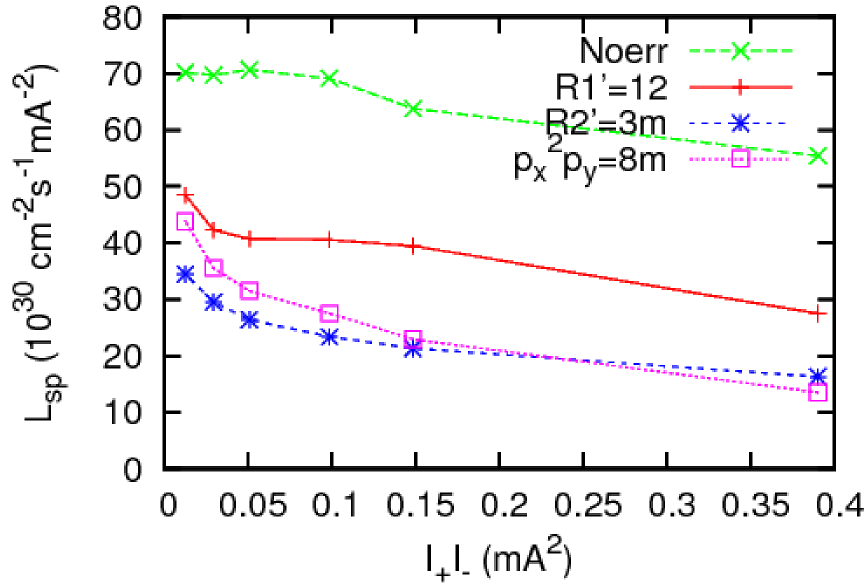
$$\xi_{xy\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp\beta_{xy}^*}{\sigma_{xy}^*(\sigma_x^*+\sigma_y^*)}R_{\xi_{xy}} \quad \rightarrow \quad \xi_y \pm \sim \sqrt{\frac{\beta_y}{\varepsilon_y \mp}}$$

Example of simulated effect of high-order / chromatic optical aberrations on beam-beam performance

based on K. Ohmi (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019



R1’ = 12 rad
R2’ = 3 m
$C(p_x^2 p_y)$ = 8 m



Magnitude of aberrations needed to explain beam-beam blow-up seems very / too large…

- Realism of simulation to quantitatively fully represent the beam-beam interaction and its interplay with optical aberrations, including the full non-linear ring lattice ?
- Other effects specific to nanobeam scheme (large crossing angle) → “crab-waist” solution ?

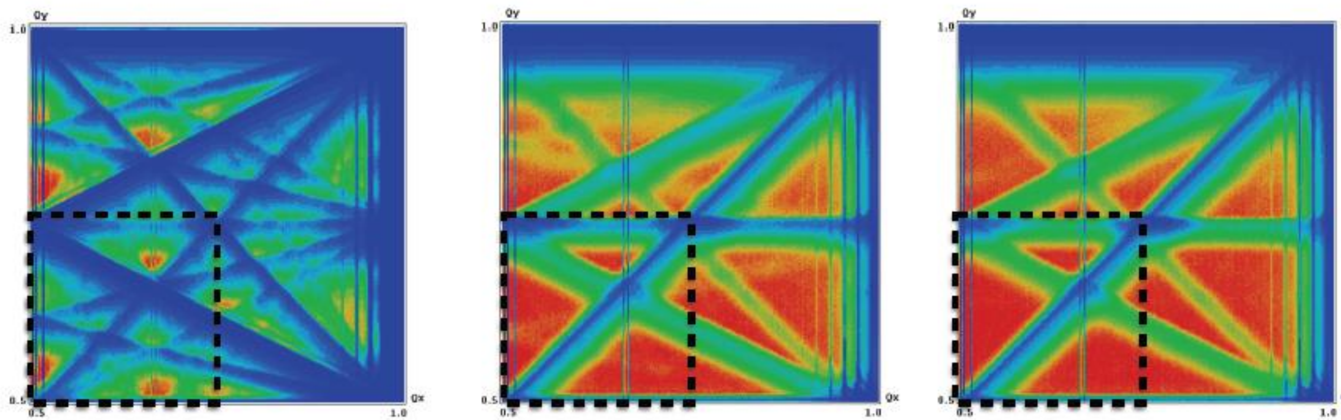
Is crab-waist the solution ?

D. Zhou (KEK), 1st SuperKEKB Beam Dynamics Mini Workshop, 17/7/2019

2. BBWS simulation: Tune scan

➤ **Tune scan to detect the beam-beam resonances**

- $\pm\nu_x+4\nu_y+\alpha=N$ was recognized and respected in the choice of operational working point from Phase-2
- $\pm\nu_x+4\nu_y+\alpha=N$ plays an important role only without crab waist, which is the baseline design of SuperKEKB
- $\pm\nu_x+4\nu_y+\alpha=N$ was found to be important in SuperKEKB by D. Shatilov [Talk presented at IHEP, China on Apr.11, 2014]



$\beta_y = \sigma_z/\phi$ | Strong beam is not crabbed | Both beams are crabbed

This plot approximately corresponds to the scheme currently adopted for SuperKEKB

No crab waist

The power of crab waist is demonstrated.

10

Thanks to Y. Zhang for sending the slides

Investigation of beam-beam effects in the nano-beam scheme → central topic at SuperKEKB

Conclusion and prospects

- SuperKEKB is the only electron-positron collider operating with new concepts to reach very high luminosity
- Initial commissioning and operation shows good progress, also considerable challenges
  - tuning of many optical aberrations at the IP
  - beam-beam effects/limits and interplay with optical aberrations
  - beam induced background and trade-off wrt luminosity / β^*
  - ……
- Essential instrumentation to directly probe the beam size and luminosity performance at the IP
- Application to future high energy colliders: FCC-ee / CEPC, also ILC/CLIC…
  - ✓ unique training ground to prepare, test, validate future designs…

Backup slides