LUMIBELLE2: FAST LUMINOSITY MONITORING USING DIAMOND SENSORS AT SUPERKEKB

APEC 2018
Frankfurt, Germany
11 December 2018

LumiBelle2
Luminosity Monitoring for Belle II

Salvatore Di Carlo (LAL)

LAL group:

P. Bambade, D. Jehanno, V. Kubytskyi, C.Pang, Y. Peinaud, C. Rimbault

Collaborators:

- SuperKEKB: Y. Funakoshi, K. Kanazawa, M. Masuzawa, Y. Ohnishi, Y. Suetsugu, M. Tobiyama, D. Zhou, K. Ohmi
- Belle II: Sadaharu Uehara + BEAST team

SuperKEKB

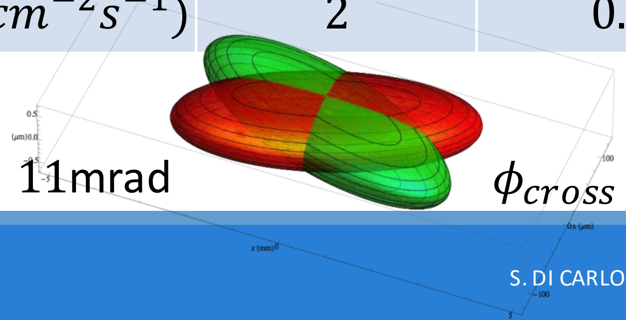
LumiBelle2
Luminosity Monitoring for Belle II

- SuperKEKB is an asymmetric-energy and double-ring electron-positron collider.
- Upgrade of KEKB with a luminosity 40 times larger than its predecessor.

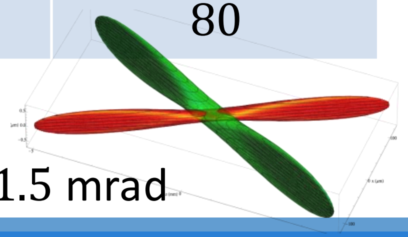
FIGURES OF MERIT:
- $E_{e^+} = 4\ GeV$
- $E_{e^-} = 7\ GeV$
- $L = 8 \times 10^{35} cm^{-2} s^{-1}$

UPGRADES:
- Nano-beam scheme (x20)
- Doubled currents (x2)

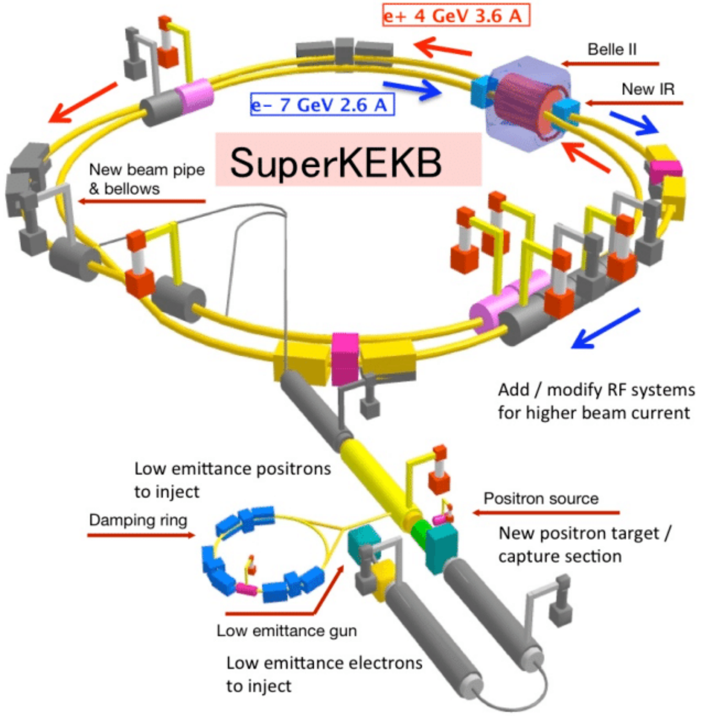
$LER(e^+)$ $HER(e^-)$	KEKB (world's highest luminosity machine)		SuperKEKB Commissioning Phase 2, 2018		SuperKEKB Design	
	LER	HER	LER	HER	LER	HER
$\sigma_x^*\ (\mu m)$	103	116	20	20	10.1	10.7
$\sigma_y^*\ (\mu m)$	1.9	1.9	0.8	1.0	0.048	0.062
$I\ (A)$	1.6	1.2	0.9	0.8	3.6	2.6
$L\ (10^{34} cm^{-2} s^{-1})$	2		0.6		80	



$\phi_{cross} = 11\text{mrad}$



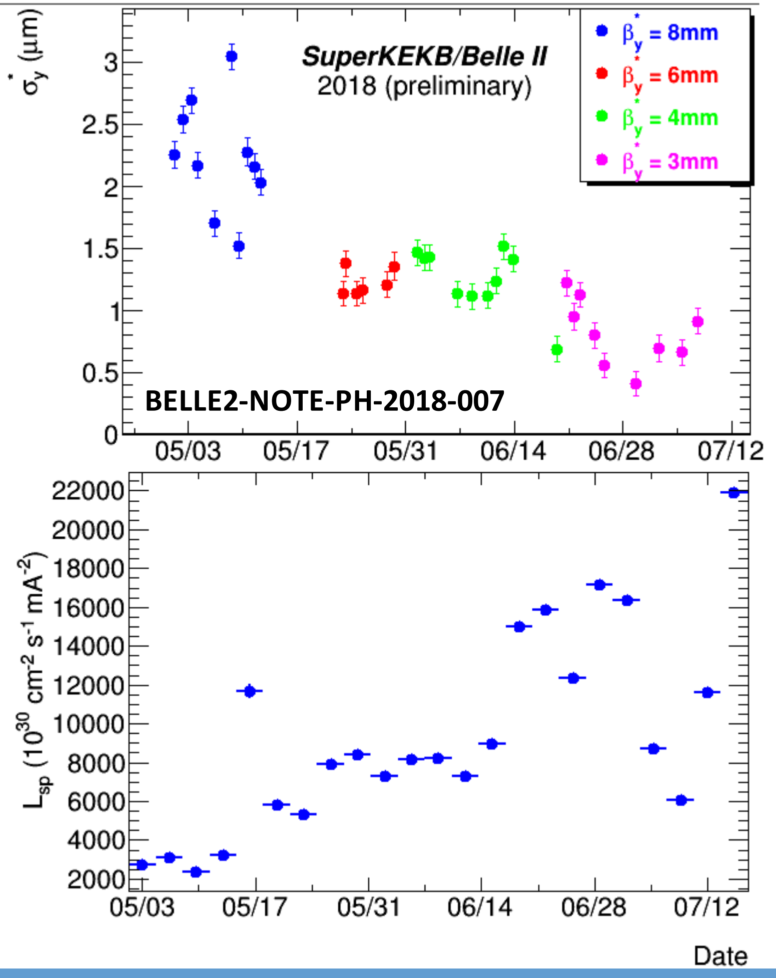
$\phi_{cross} = 41.5\ \text{mrad}$



Commissioning history (Phase 2, 2018)

Luminosity Monitoring for Belle II

- SuperKEKB collisions started at the end of April 2018, while operations ended in July 2018;
- The vertical beta function was progressively reduced from $\beta_y^* = 8mm$ to $\beta_y^* = 3mm$;
- The smallest beam size achieved (at low intensity) was $\sigma_y^* \approx 0.4\ \mu m$;
- The maximum vertical beam-beam parameter achieved was $\xi_y = 0.021$;
- The maximum stored beam currents were $I = 0.9/0.8\ A$ for LER/HER beams;
- The maximum luminosity achieved was $\mathrm{L} = 0.6 \times 10^{34} cm^{-2} s^{-1}$;
- Phase 3 of commissioning will start in 2019 and the plan is to reach $\mathrm{L} = 1 - 1.5 \times 10^{34} cm^{-2} s^{-1}$ in 2019 and $\mathrm{L} = 4 - 6 \times 10^{34} cm^{-2} s^{-1}$ in 2020.



Beam H-V offset and luminosity degradation

LumiBelle2
Luminosity Monitoring for Belle II

HORIZONTAL OFFSET FEEDBACK

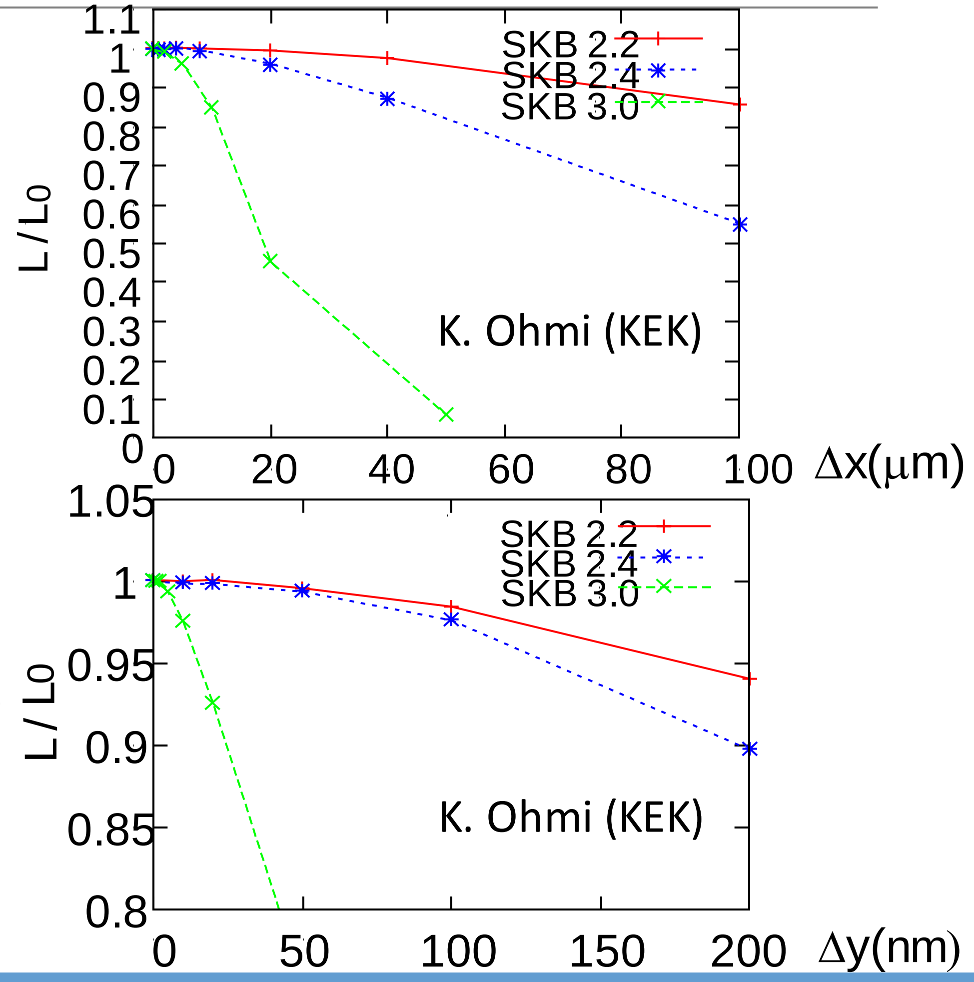
- Dithering system inherited from PEP-II;
- 8 sets of coils (H/V) on LER, dithering at f=79 Hz, max horizontal bump $5\sigma_x^*$;
- **Fast luminosity monitors (LumiBelle2), 1 kHz;**
- Lock-in amplifier to extract luminosity component at driving frequency f;

VERTICAL OFFSET FEEDBACK

- 4 beam position monitors (BPMs) at 51 cm from the IP in HER/LER, 32 kHz;
- 4 electrodes for each BPM at 10.5 mm from orbit;
- 25 Hz vibration → $\Delta y = 18.6nm\ (rms)$ → luminosity drop 4.6%;

OFFSET CORRECTION (Feedback cycle H: 1 Hz; V: 100 Hz)

- 12 corrector magnets (8V, 4H) on HER with max kick $50\ \mu rad$;
- Ultimate goal: suppression of luminosity loss to below 1% in both H and V.



Luminosity monitoring:
three complementary techniques

Luminosity Monitoring for Belle II

LumiBelle2 (Rel.)	ZDLM (Rel.)	ECL LOM (Abs.)

Both measure photons, recoiling electrons or positrons from the extremely forward-angle radiative Bhabha scattering, which has a large cross section ($\sigma \approx 200\ mbarn$).

LumiBelle2 (Rel.)

- Single crystal CVD diamond sensors;
- $4 \times 4 \times 0.5/0.14\ mm^3$;
- Fast charge/current amplifiers;
- Digital electronics.

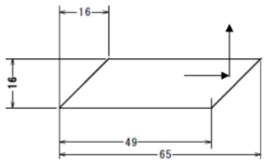
GOALS:

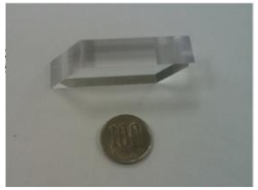
- TIL (Train Integrated Luminosity): 1% relative precision at 1kHz;
- BIL (Bunch Integrated Luminosity): monitoring with 1 % precision at 1 Hz;
- Large dynamic range with high SNR :

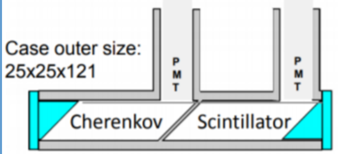
$L = 10^{30} - 10^{36} cm^{-2} s^{-1}$

ZDLM (Rel.)

- Cherenkov and scintillator detectors;
- $15 \times 15 \times 64\ mm^3$ ES-crystal (quartz) and LGSO non-organic scintillator ;
- Photomultipliers;
- Analog electronics.





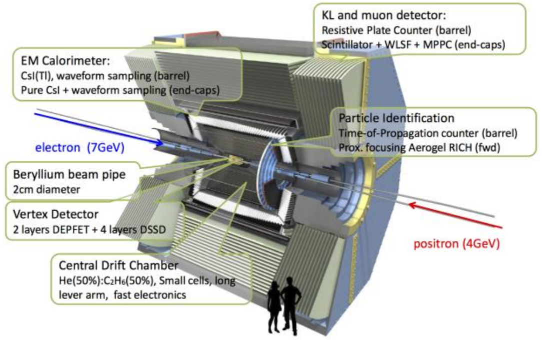


ECL LOM (Abs.)

Measures coincidence rates in opposite sectors for Bhabha events at $\theta > 13°$, cross section $\sigma \approx 29\ nb$.

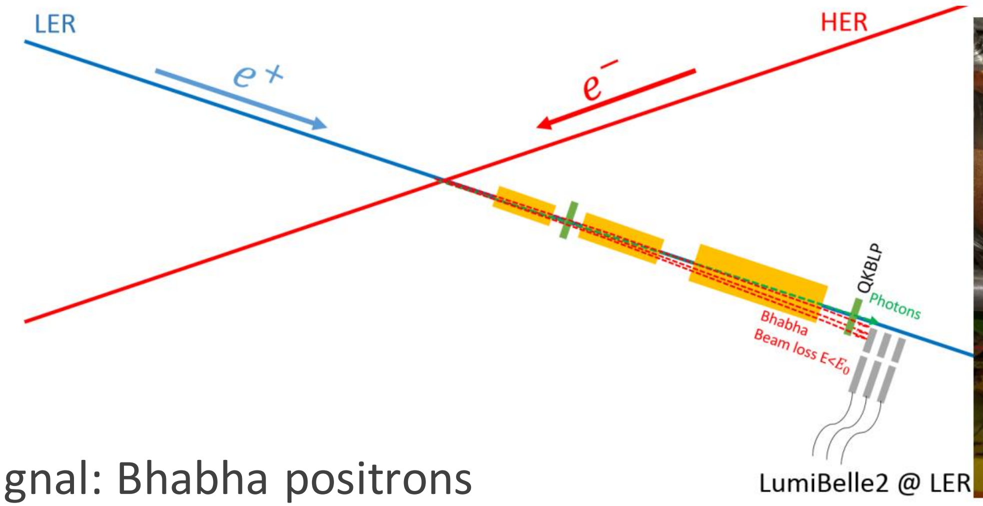
- Installed in the backward and forward end-caps of the Belle2 detector;
- Provides an absolute value of the luminosity at 1-10Hz with precision 0.1-5%, depending on the luminosity.

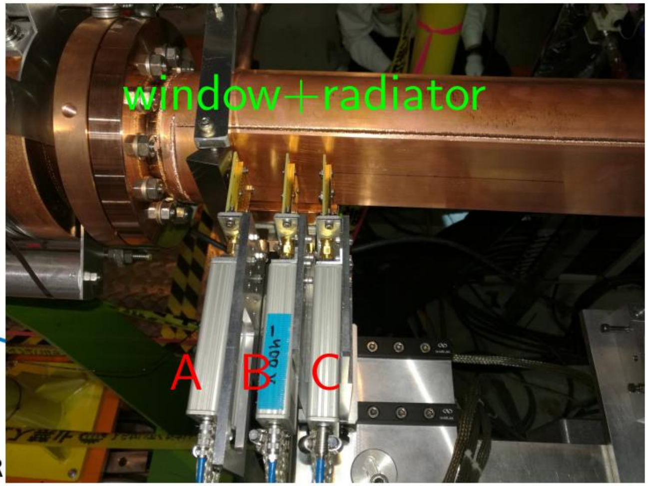
Belle II Detector

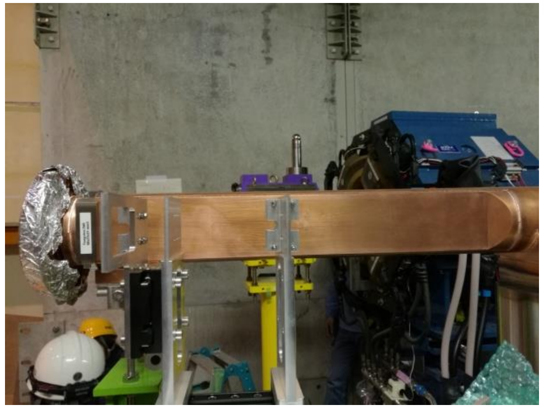


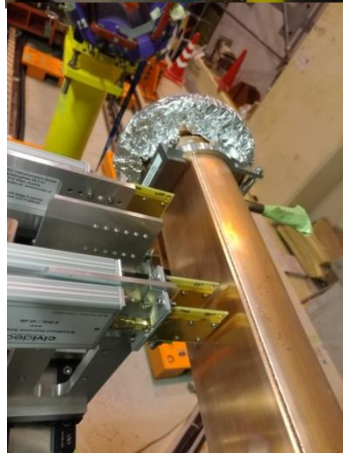
LER (positron) side experimental setup

LumiBelle2
Luminosity Monitoring for Belle II







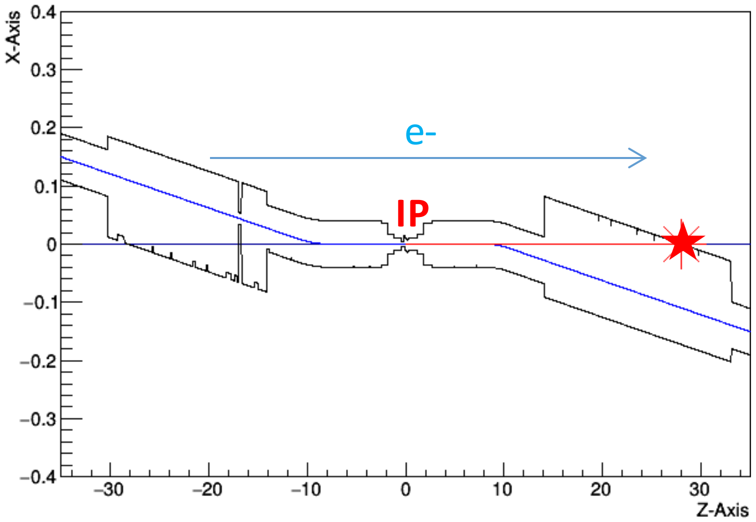


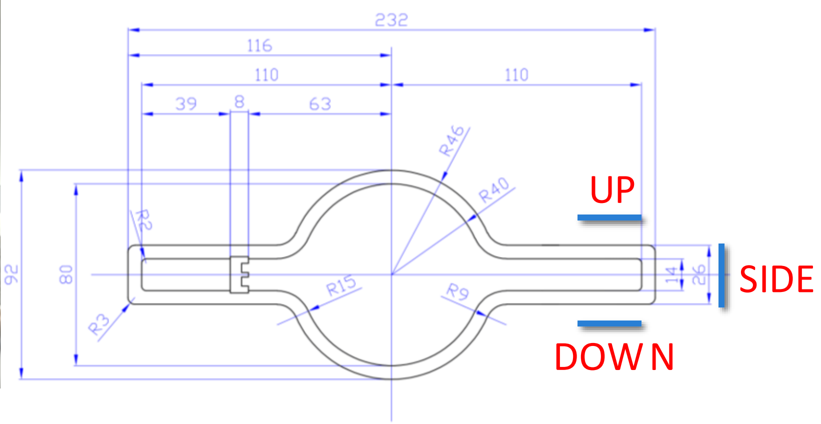
- Signal: Bhabha positrons
- Background: Bremsstrahlung positrons, Touschek positrons
- Platform: 11 m downstream of IP
- 3 sensors aligned
- Special beam pipe with window + Tungsten radiator

HER (electron) side experimental setup

LumiBelle2
Luminosity Monitoring for Belle II

- Signal: Bhabha photons
- Background: Bremsstrahlung photons, Touschek electrons
- Platform: 30.5-30.8 m downstream of IP
- 3 sensors: up, down, side

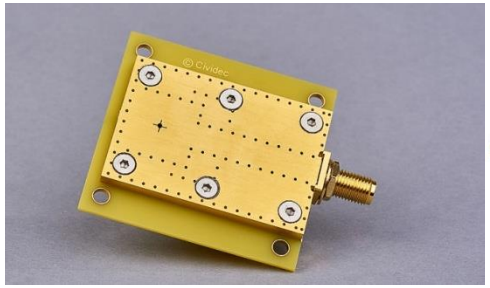




Diamonds sensors and amplifiers

Luminosity Monitoring for Belle II

- Wide band-gap (5.5 eV) semiconductor devices;
- Strong atomic bond (radiation resistant);
- Radiation damage above $\approx 1MGy$;
- High drift velocity (fast detector).

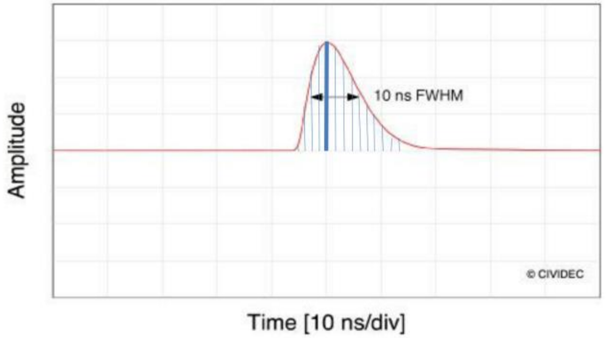


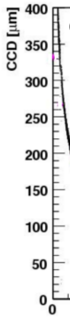
	CVD Diamond	Potential device application benefit
Bandgap (eV)	5.47	High temperature
Breakdown field (MVcm^{-1})	10	High voltage
Electron saturation velocity (x10^{7} cm s^{-1})	2	High frequency
Hole saturation velocity (x10^{7} cm s^{-1})	0.8	
Electron mobility (cm^{2} V^{-1} s^{-1})	4500	
Hole mobility (cm^{2} V^{-1} s^{-1})	3800	
Thermal conductivity (Wcm^{-1} K^{-1})	24	High power

SUPERKEKB COLLISION PERIOD = 4ns

140/500 μm diamond + CURRENT/CHARGE AMPLIFIER:

- Shaping time: 4/10 ns
- Threshold: 10/5 mV



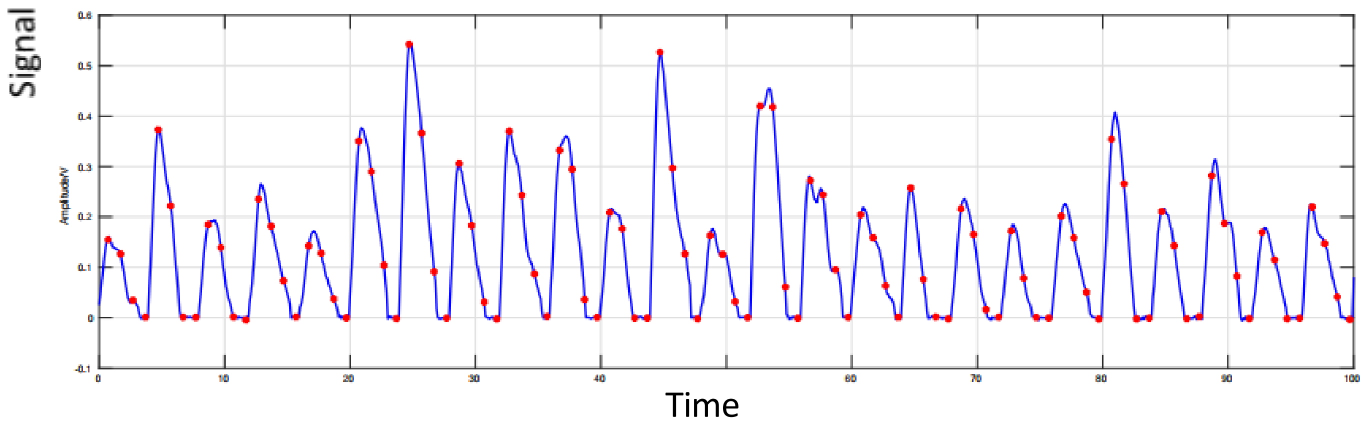


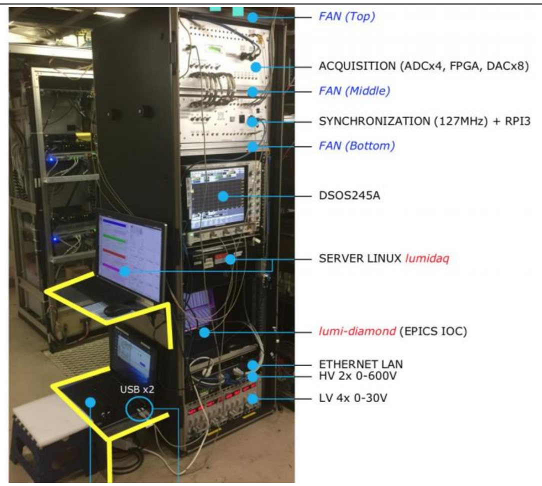
CHARGE COLLECTION EFFICIENCY
(S. Schuwalow, DESY)

Signal processing algorithms

LumiBelle2
Luminosity Monitoring for Belle II

Sampling on the signal sequences at 1GHz:





- TIL:

if $S[(i-1)\times 2+1]-S[(i-1)\times 2+4] > threshold$:

TIL $+= S[(i-1)\times 2+1]-S[(i-1)\times 2+4]$

- RAWSUM:

if $S(j) > threshold$:

Rawsum $+= S(j)$

- TIL and RAWSUM represent different ways to calculate the luminosity from the measured signal .
- Synchronization , no trigger -----> Continuous monitoring, averaging at 1 kHz.
- EPICS PV with measured luminosity are continuously provided to the SuperKEKB control room.

Background study

LumiBelle2
Luminosity Monitoring for Belle II

SIMULATION FEATURES:

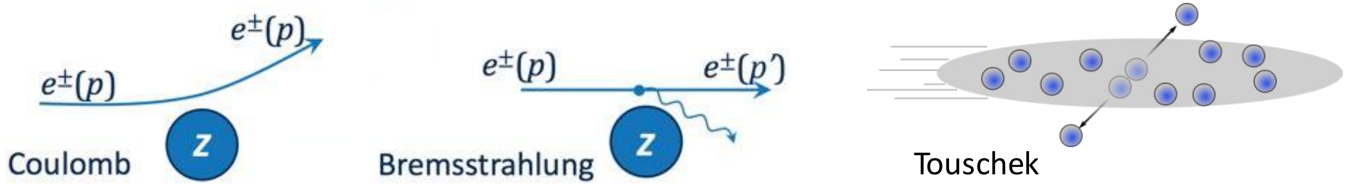
- Bremsstrahlung, Coulomb, and Touschek scattering;
- Detailed simulation of pressure profile and chemical composition of vacuum gas ($Z_{eff} \approx 4.2 - 4.5$);

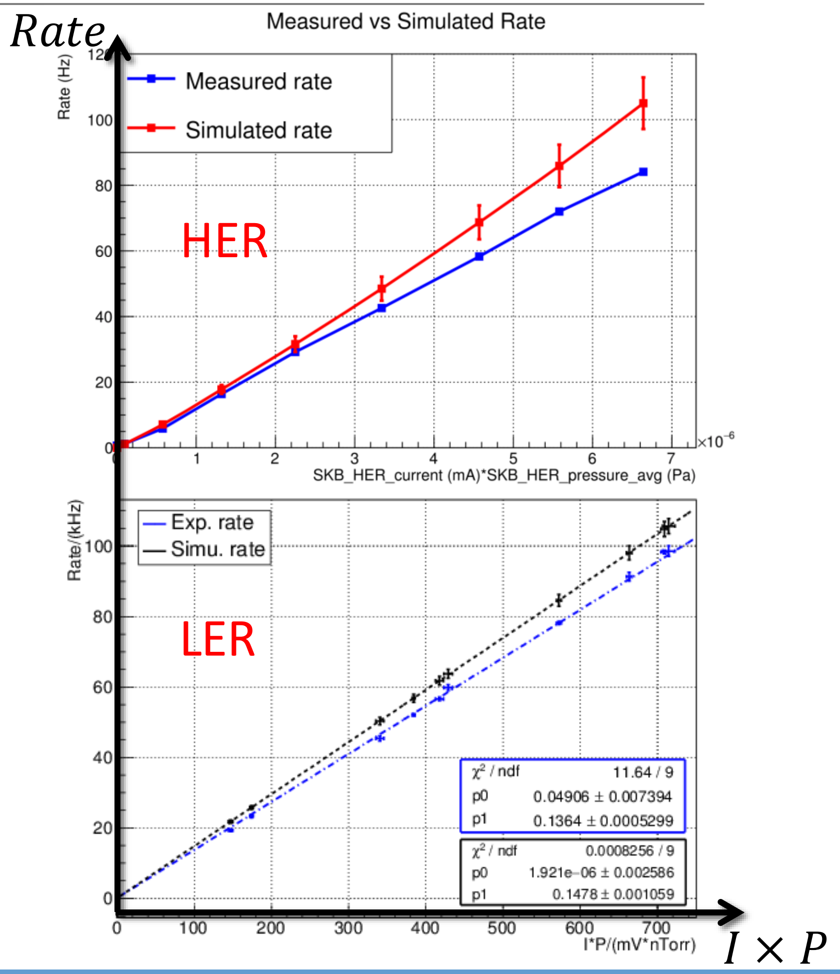
HER (e- ring):

- 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 effect;
- Positron rate from Coulomb scattering is negligible.



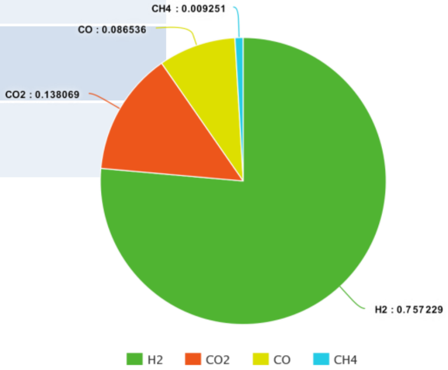


Pressure profile around the IP

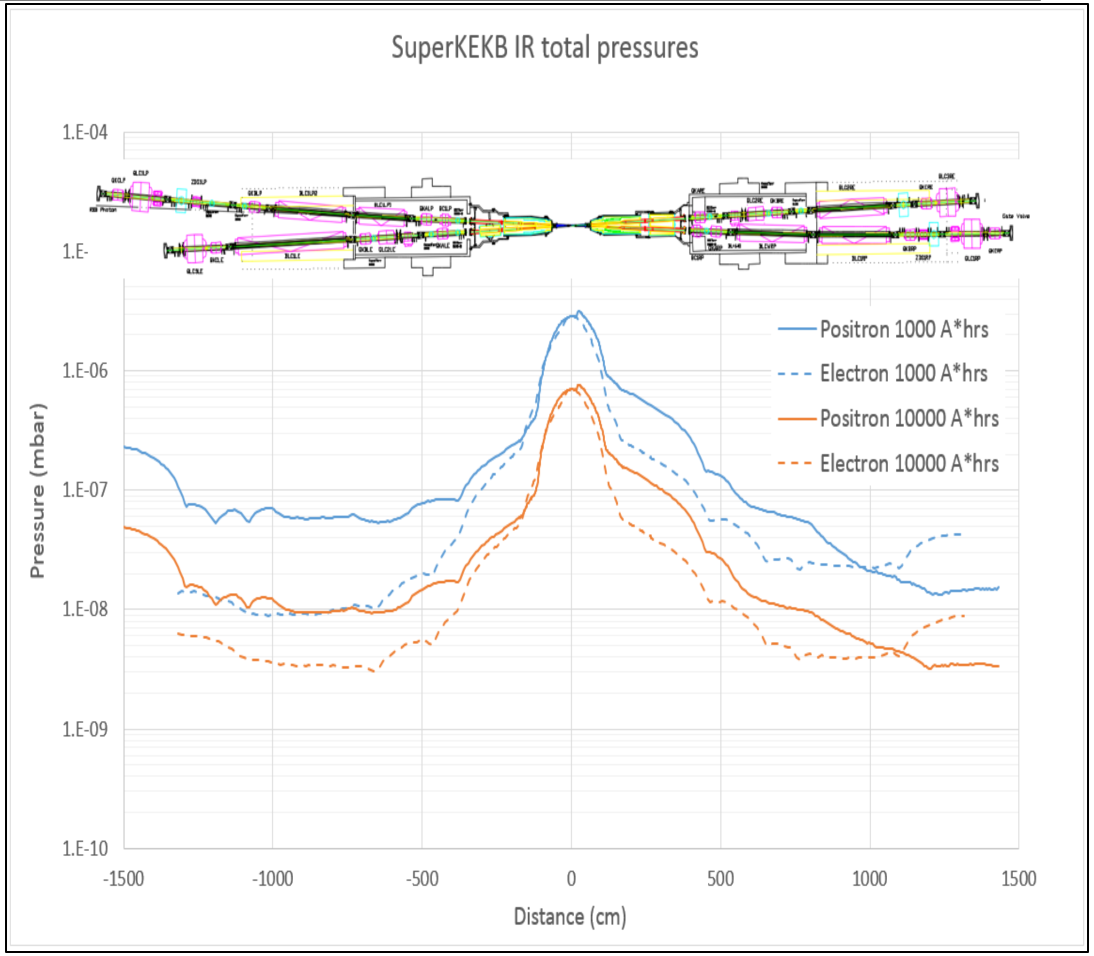
LumiBelle2
Luminosity Monitoring for Belle II

- Total indicates sum of H_2, CO, CO_2, and CH_4 partial pressures
- Asymmetric because of synchrotron radiation
- Total pressures at $10^3, 10^4\ A \times hrs,\ I = 3.6\ A$

Molecule	Partial pressure: $p_i = P_i/P_{tot}$
H2	0.757229
CO2	0.138069
CO	0.086536
CH4	0.009251

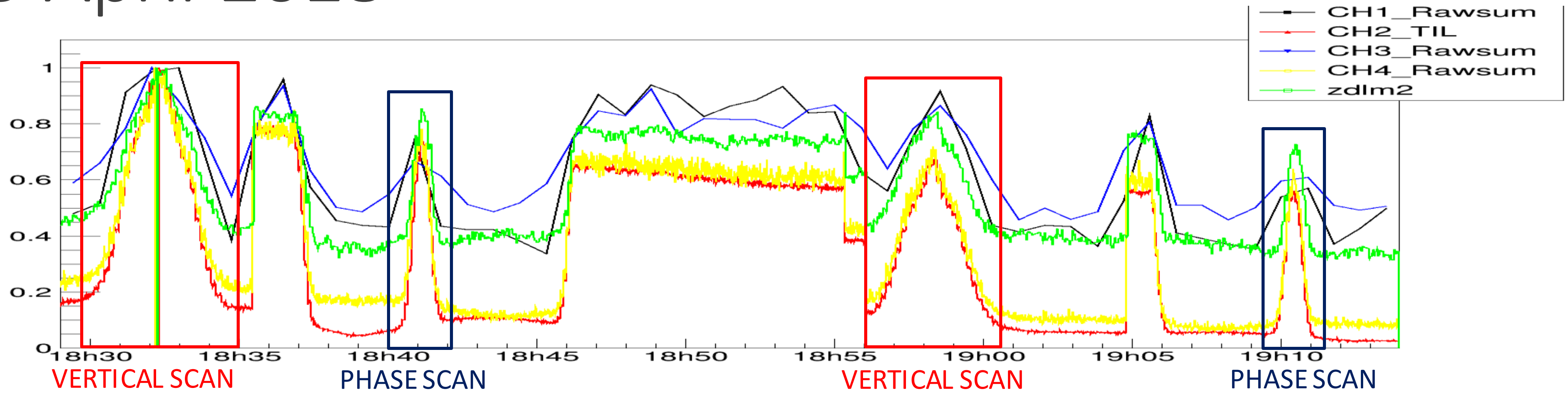


Jason CARTER – Argonne National Laboratory
Marton ADY - CERN



First luminosity measurements 25 April 2018

LumiBelle2
Luminosity Monitoring for Belle II



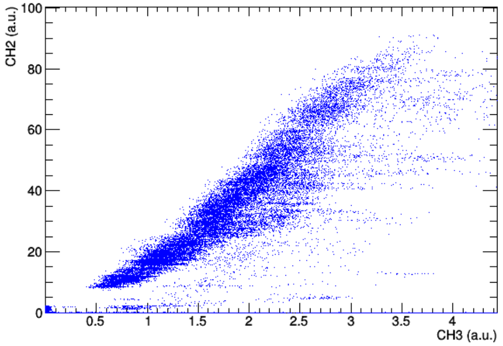
- First Bhabha events measured on April 25, 2018;
- Vertical and phase (longitudinal) scans were performed to find the optimal position of the beams;
- The 4 detectors LumiBelle2 and the ZDLM work well and are in agreement;
- We successfully measured and provided the luminosity from the first collision to the end of Phase 2 (July 18, 2018).

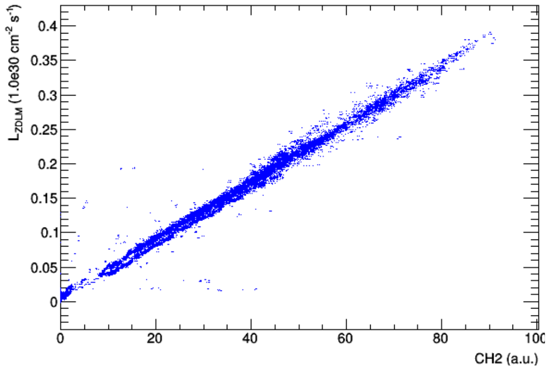
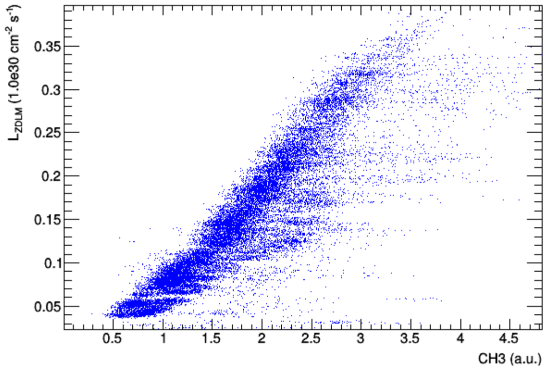
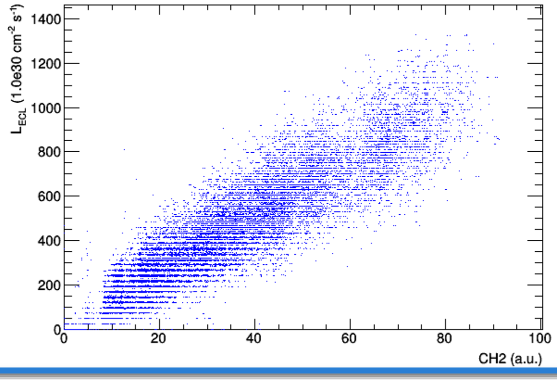
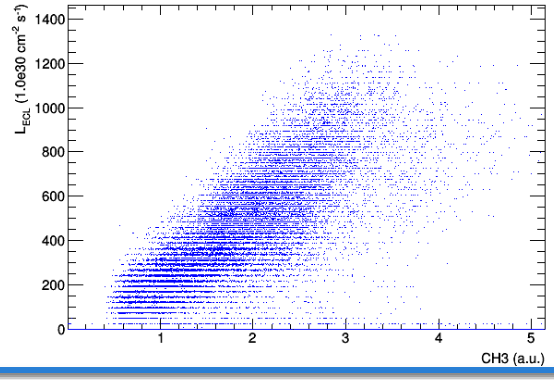
Correlation with other monitors: ZDLM and ECL

LumiBelle2
Luminosity Monitoring for Belle II

- We observe good correlation between our channels and with other luminosity monitoring devices on a day-by-day basis or shorter time scales;
- Long term variations in SNR and relative sensitivities are seen and can be explained by changes in beam conditions and changes in setups in terms of gains, position of the sensors, thresholds, etc.

LumiBelle2: LER vs HER



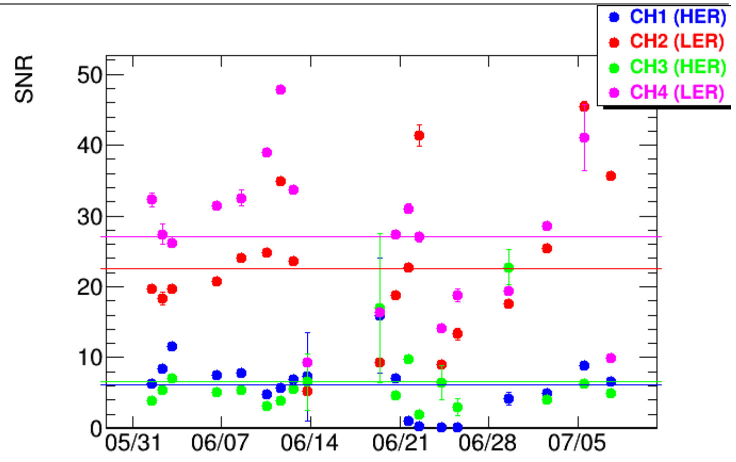
	LumiBelle2 LER	**LumiBelle2 HER**
ZDLM		
ECL		

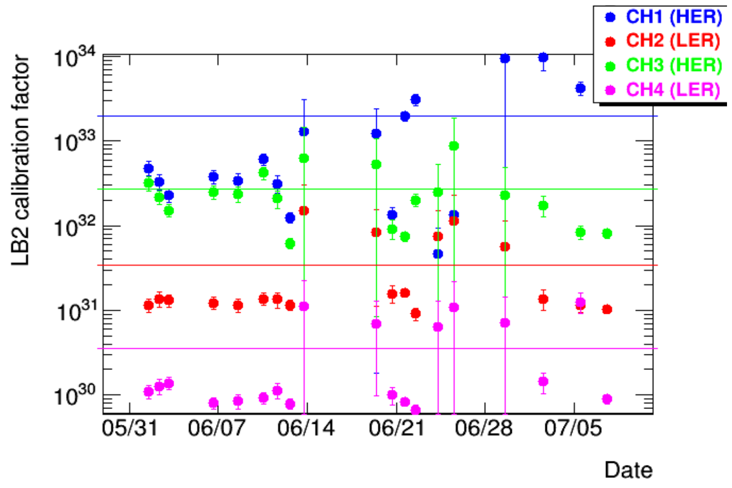
Long term SNR and absolute calibration stability

Luminosity Monitoring for Belle II

- The SNR is large for LER, while small for HER. The LER was the most performing side during Phase 2;
- The fluctuations in SNR are due to changes in pressure and beam conditions, which result in changes of beam-gas background rates, and LumiBelle2 setup;
- The LumiBelle2 is designed to measure relative luminosity but it can be calibrated using the ELC LOM absolute luminosity;
- The calibration has to be performed frequently (every day), since it depends on beam conditions and changes in our setups in terms gains, position of the sensors, thresholds, etc.

LumiBelle2 CH#	SNR	Calibration factor
CH1 (HER)	6 ± 4	$2 \pm 3 \times 10^{33}$
CH2 (LER)	23 ± 10	$3 \pm 4 \times 10^{31}$
CH3 (HER)	7 ± 5	$3 \pm 2 \times 10^{32}$
CH4 (LER)	27 ± 10	$4 \pm 4 \times 10^{30}$



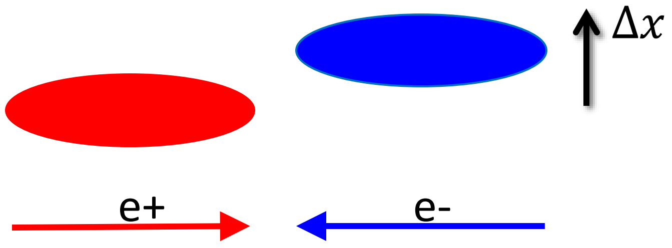


Horizontal dithering feedback system

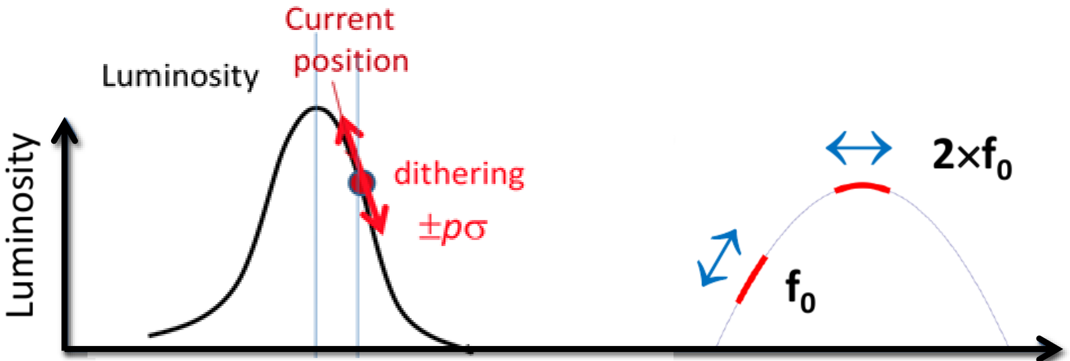
LumiBelle2

Luminosity Monitoring for Belle II

- The dithering system makes one beam to oscillate around its orbit as Δx_{dith}= p sin(2πft) with frequency f =79Hz ;
- Luminosity oscillates and Fourier components give information about the relative position of the beams;
- If $|q| > p$ FT peaks at f, if $|q| < p$ FT peaks at 2f;
- Relative phase dithering-luminosity gives sign of Δx;

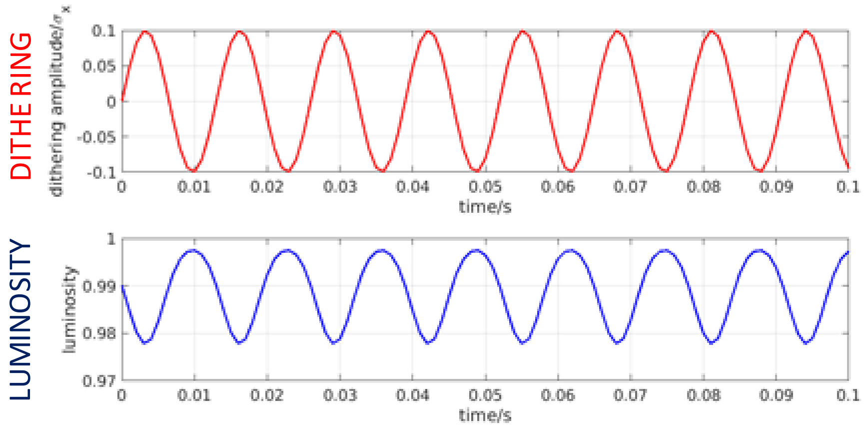


$$L(t) = \frac{f_{rev} N_1 N_2}{4\pi\sigma_x\sigma_y} e^{-(\frac{[q+psin(2\pi ft)]^2}{4})}$$



$\|q\|>p$	goes up and down on a side of slope
$\|q\|<p$	goes over across the peak

$$\Delta x = q + p\sin(2\pi ft)$$

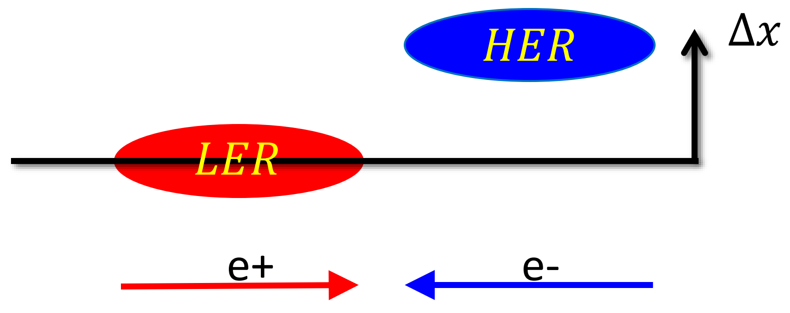


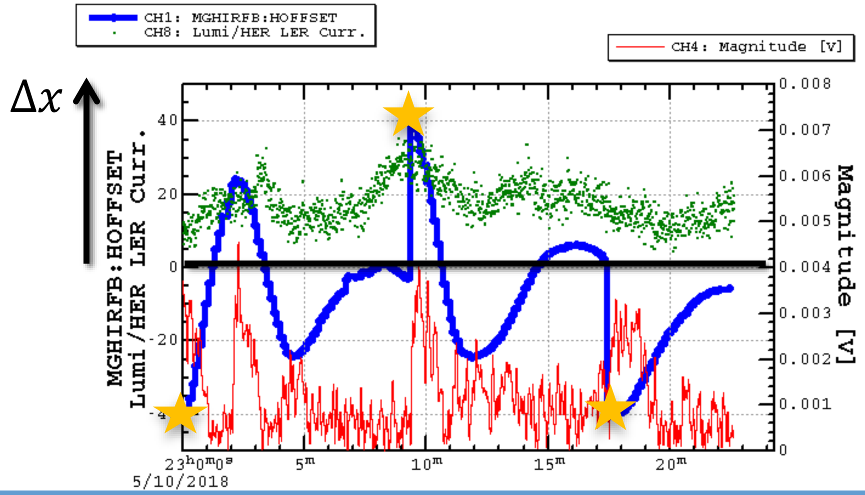
Dithering feedback test Phase 2

Luminosity Monitoring for Belle II

- The dithering feedback system was first tested in May 2018;
- The HER beam was artificially given an offset, while the LER beam was dithered;
- The task of the feedback was to bring the beams back to the optimal position (zero offset);
- The feedback algorithm tries to minimize the Magnitude [V] of the luminosity FT calculated at the driving frequency f;
- The algorithm runs in the main computer system (SuperKEKB control room);
- It determines the amplitude and sign of the offset at the IP;
- These parameters are then sent to the magnet contol system via EPICS to create a bump in the HER;
- The first two attempts resulted in an overshoot;
- After optimization of the algorithm parameters, the feedback was able to smoothly minimize the offset.

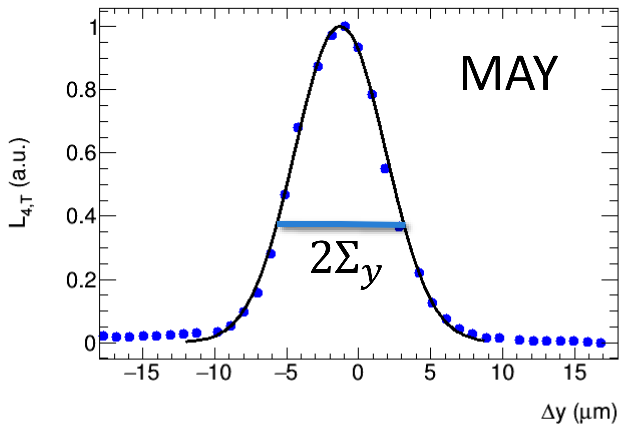
$$\Delta x = q + \mathrm{p}\sin(2\pi \mathrm{f} t)$$

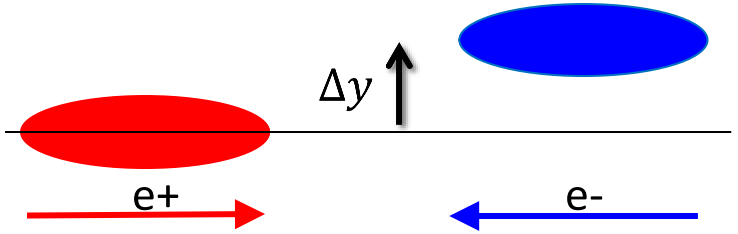




Beam size estimation through vertical scans

Luminosity Monitoring for Belle II





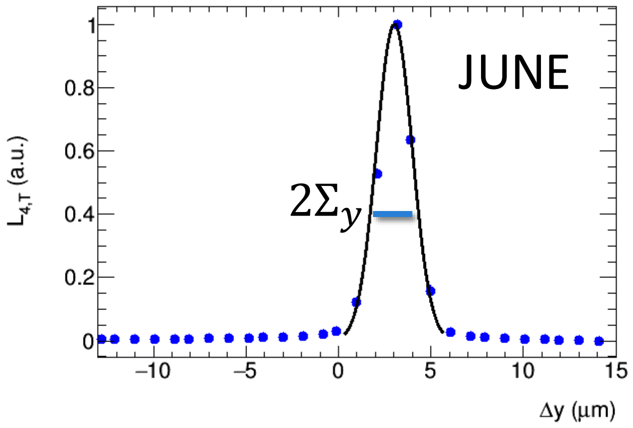
Simple geometrical result obtained integrating Gaussian distributions with vertical offset

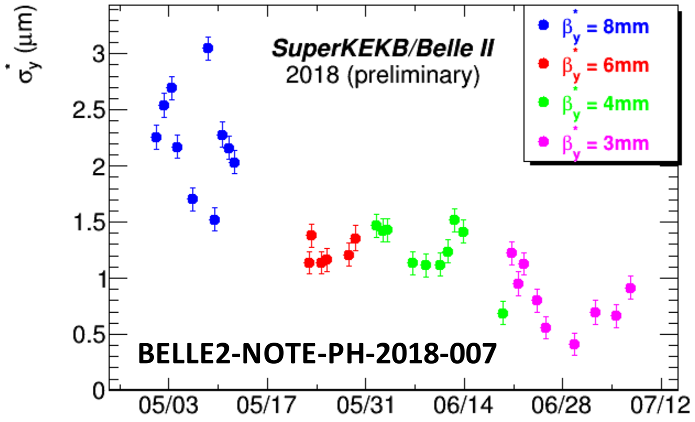
$$\frac{L}{L_0} = exp\left(-\frac{\Delta y^2}{2\Sigma_y^2}\right)$$

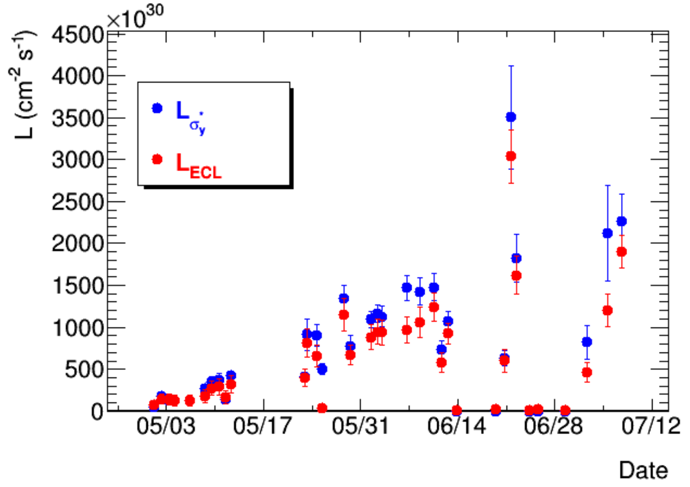
$$\Sigma_y^2 = \sigma_{1,y}^2 + \sigma_{2,y}^2 \approx 2\sigma_y^2$$

$$L_0 = \frac{fN_+N_-}{4\pi\sigma_{x,eff}^*\sigma_y^*} \quad \longrightarrow L_{\sigma_y^*}$$

$$\sigma_{x,eff}^* \approx \sigma_z\theta_{cross} = 224\mu m$$







LumiBelle2 use for SKB optical corrections

Luminosity Monitoring for Belle II

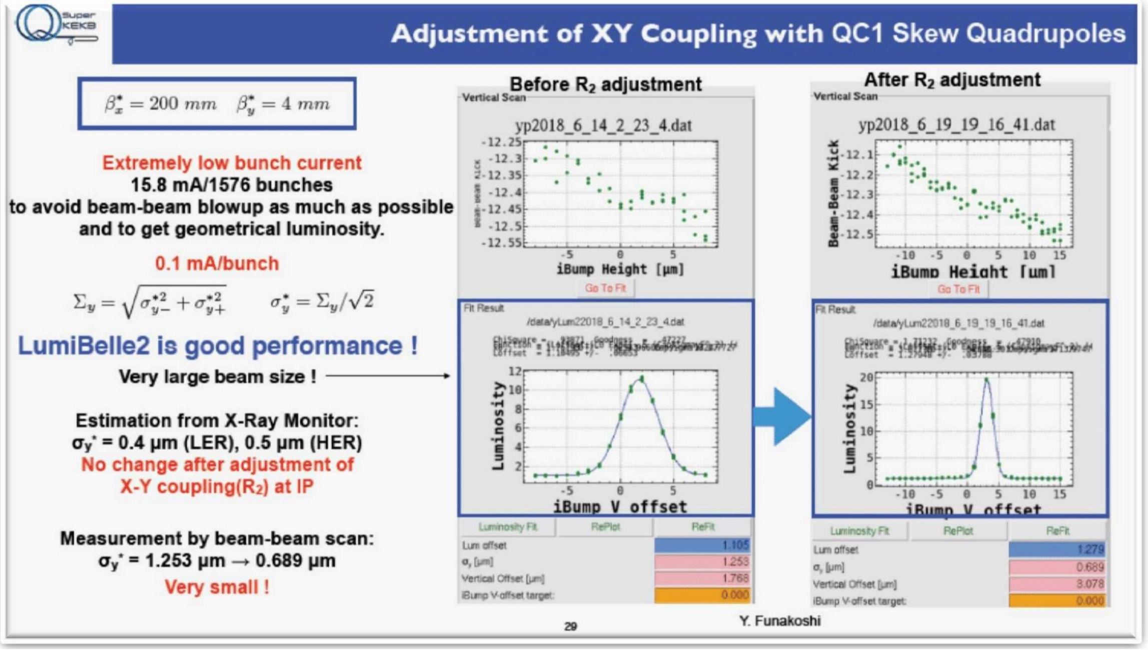
- SuperKEKB machine group relies on LumiBelle2 for beam tuning operations;
- Optical corrections are applied at very low intensity to separate the beam-beam blow-up effect from the beam enlargement caused by optical aberrations;

- The ECL LOM monitor, which measures the SKB absolute luminosity, does not work well at low intensities;
- In the example, after the R_2 adjustment, $L = 3 \times 10^{30}\ cm^{-2}s^{-1}$;
- For the ECL to have statistical error of at least about 10% at such L, one should integrate the measurements over 1000 s, while LumiBelle2 has a 2% error in 1 second!

- LumiBelle2 is important for optical correction at low intensities!

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

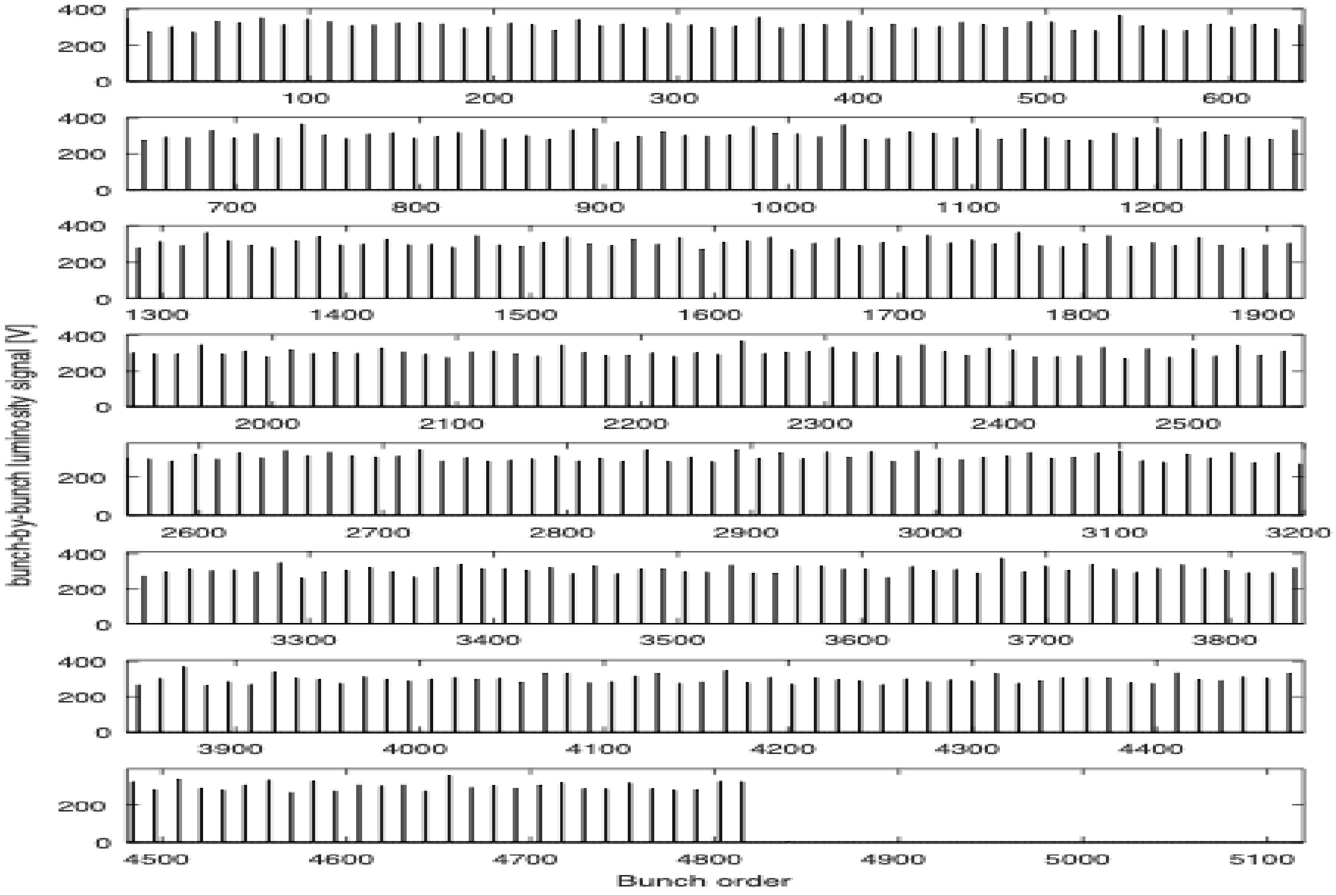
→ *must do at very low intensity to avoid confusion from beam-beam blow-up*



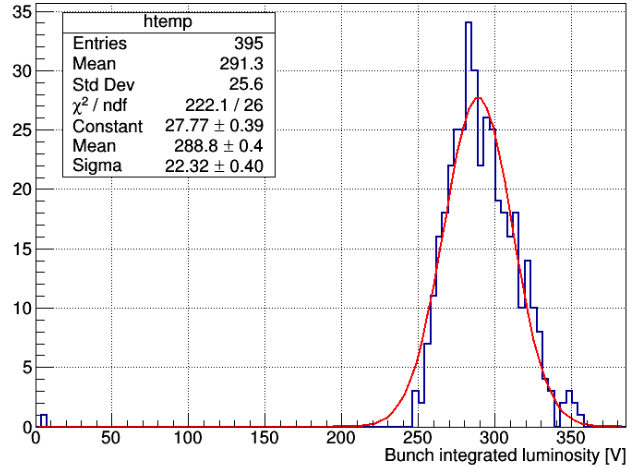
*Yukiyoshi Ohnishi's opening plenary talk at ICFA eeFACT'18

Bunch-by-bunch luminosity

LumiBelle2
Luminosity Monitoring for Belle II



8% spread in bunch luminosities



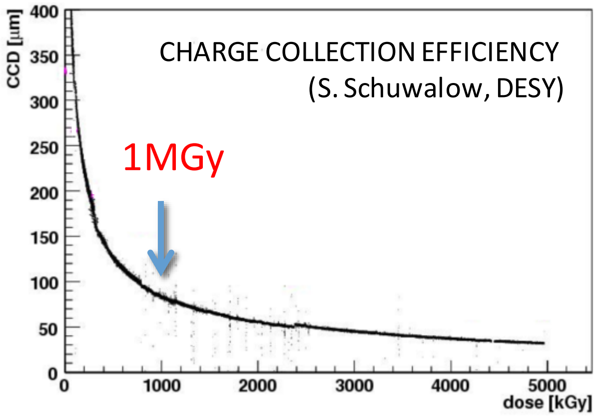
- Bunch-by-bunch luminosity signals @1Hz are available through EPICS PV;
- Bunch luminosity precision: 1-2%;
- 8% spread mainly depends on bunch current differences;
- Online display in SKB control room.

LumiBelle2 precision/dose and luminosity

LumiBelle2 Luminosity Monitoring for Belle II

HER:
- Initially low precision;
- Position change in Phase 3.
- Low dose expected in Phase 3;

LER:
- High precision;
- Noise issue in Phase 2;
- Potential high dose issue in Phase 3.



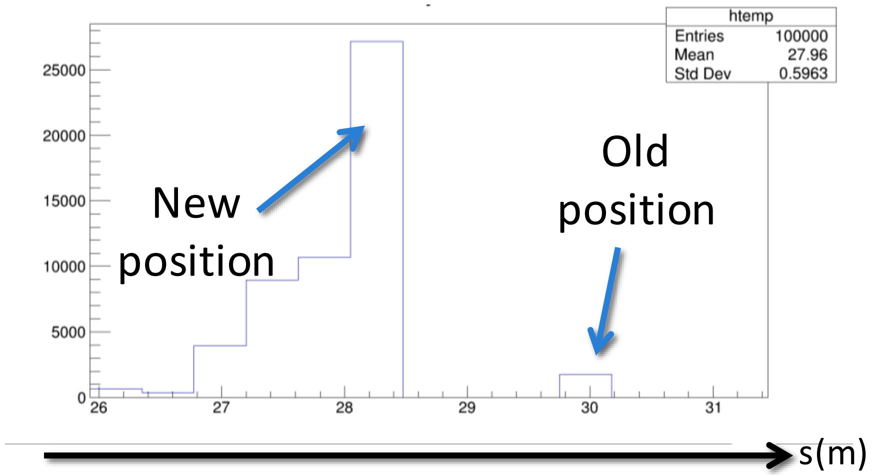
- We need both HER and LER to cover the whole range of SKB luminosities (10^{32} => 10^{36}) and cope with the accumulated dose and any unexpected issues (noise,...);
- HER precision will be improved by changing the position of the diamond sensors;
- LER diamond is motorized and can be moved to receive a lower dose;
- Simulation study shows that 1% level precision is enough for horizontal IP orbit feedback with dithering technique;
- Fraction of cross section intercepted is 1%/0.001% for LER/HER.

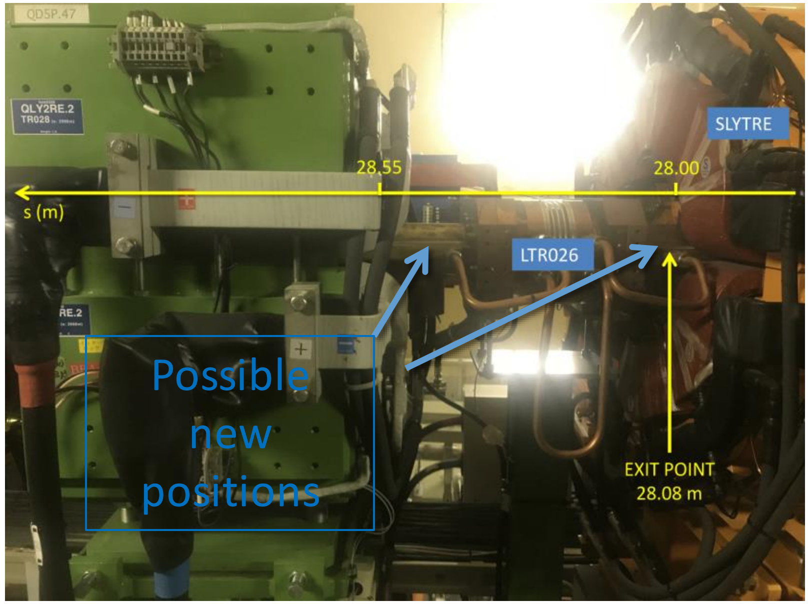
	Phase	Luminosity	ΔL/L % 1ms HER/LER	Dose (Mgy/h) HER/LER
Experimental →	Phase 2	$2 \times 10^{33} cm^{-2} s^{-1}$	60/2	4e-7/4e-4
Prediction →	Phase 3	$1 \times 10^{34} cm^{-2} s^{-1}$	30/1	2e-6/2e-3
Prediction →	Design	$8 \times 10^{35} cm^{-2} s^{-1}$	3/0.1	1e-4/0.1

HER Phase 3 update

LumiBelle2
Luminosity Monitoring for Belle II

- A potentially better position was found by detailed tracking simulation of photons inside HER beam pipe;
- The new position is expected to have a rate ~10 times higher;
- To place the sensors in the new position, new special holders were designed at LAL (*Y. Peinaud*);
- Fraction of cross section intercepted after update is 1%/0.01% for LER/HER;
- After upgrade, 1% precision for HER is expected at design luminosity.





Phase	Luminosity	ΔL/L % 1ms HER/LER	Dose (Mgy/h) HER/LER
Phase 3	$1 \times 10^{34} cm^{-2} s^{-1}$	10/1	2e-5/2e-3
Design	$8 \times 10^{35} cm^{-2} s^{-1}$	1/0.1	1e-3/0.1

Conclusions and plans

Luminosity Monitoring for Belle II

Conclusions

- Good agreement with simulation for single beam backgrounds;
- Good correlation with other luminosity monitors (ZDLM, ECL);
- Provide online 1kHz luminosity as input to horizontal IP orbit dithering feedback: 1st test was successful;
- Provide estimation of effective σ_y^* of beams at IP by vertical offset scans;
- Provide online luminosity at low intensity for SKB machine tuning (e.g. IP beam size tuning);
- Provide online 1Hz bunch-by-bunch luminosities.
- Ability to vary signal acceptance to keep few % precision @ 1 kHz over $10^{32} - 10^{36}\ cm^{-2}s^{-1}$;

Plans

- Increase HER signal rates, we have identified and will use better location for Phase 3;
- Faster charge amplifiers & lower noise current amplifiers;
- Long term DAQ solution, possibly with a few more channels (now we have 4);
- Shielding / protection to mitigate special beam-pipe activation on LER side is under study;
- It will be important to limit accumulated radiation dose in the diamonds;
- After intensive on site activity and presence during SuperKEKB commissioning phases 1&2, we will progressively develop the software needed to remotely operate LumiBelle2 and monitor its performance.