Fast Luminosity Monitoring at SuperKEKB

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on behalf of LumiBelle2 and ZDLM groups
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Collaboration

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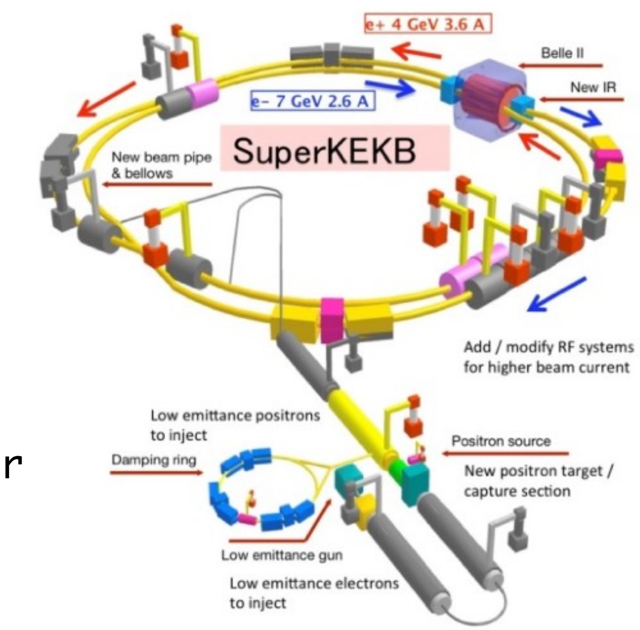
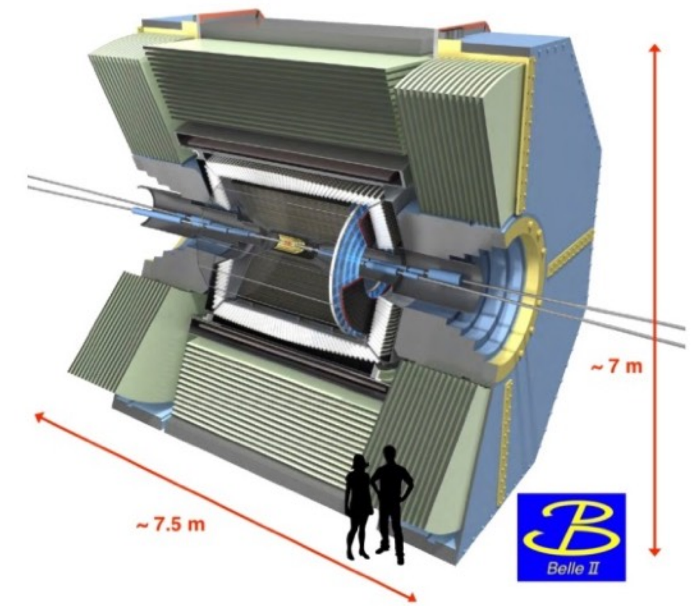
SuperKEKB & Belle II

- Luminosity monitoring & tuning
- Beam induced backgrounds monitoring

1) Phase 1 : 2016/Feb. ~ Jun.
   - single beam commissioning, vac. scrubbing
   - no luminosity (no final focus), no detector
2) Phase 2 : 2018/Mar. ~ July
   - colliding beam commissioning, no vertex detector
3) Phase 3 : from 2019/Mar. ~ ?
   - full luminosity for physics running

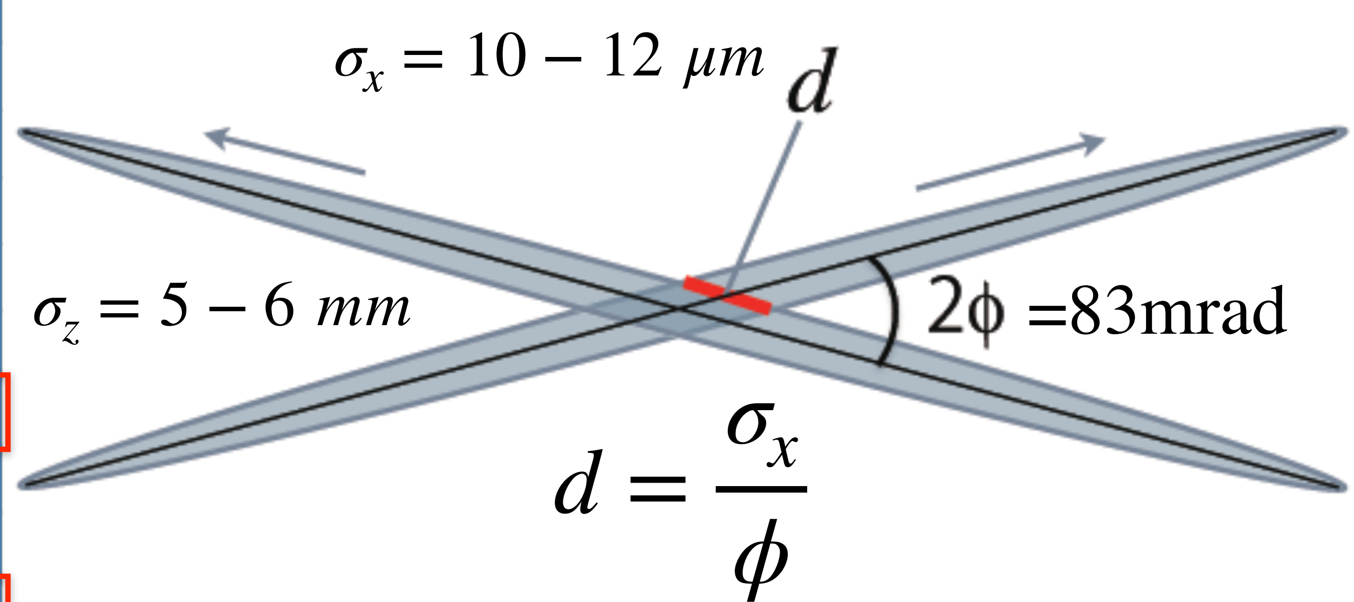




parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Half crossing angle	φ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.088	0.081	
Bunch Length	σ_z	6.0	6.0	6.0	5.0	mm
Horizontal Beam Size	σ_x^*	150	150	10	11	um
Vertical Beam Size	σ_y^*	0.94		0.048	0.062	um
Luminosity	**L**	**2.1 x 10^{34}**		**8 x 10^{35}**		**$cm^{-2}s^{-1}$**

Luminosity: increased by a factor of 40

Nano-Beam Scheme SuperKEKB

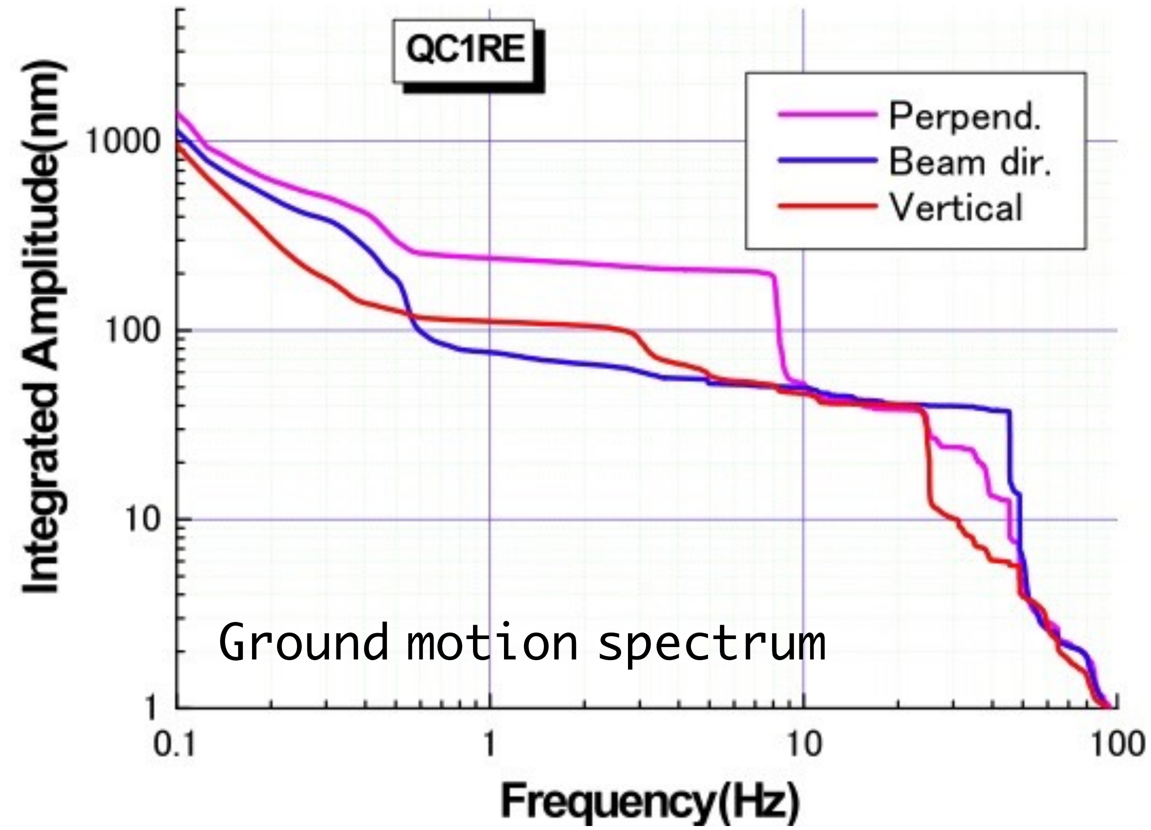


β_y = 0.3mm   *half crossing angle :* ϕ d ~ 300 μm

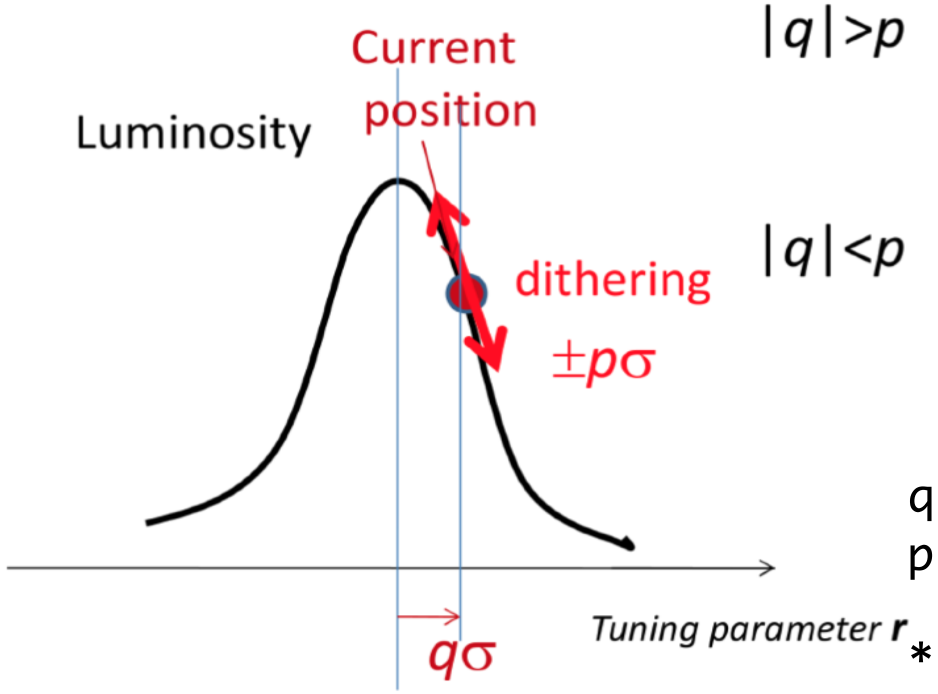
mitigates beam-beam and hour-glass effects…

Why fast luminosity monitoring ?

- Horizontal drift and ground motion can cause luminosity degradation
- Horizontal beam-beam deflection is too weak due to large crossing angle
- A dithering feedback system which uses fast luminosity signals as input is used to stabilise the horizontal beam orbit
- Beam-beam deflection method is used for orbit feedback in vertical plane



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

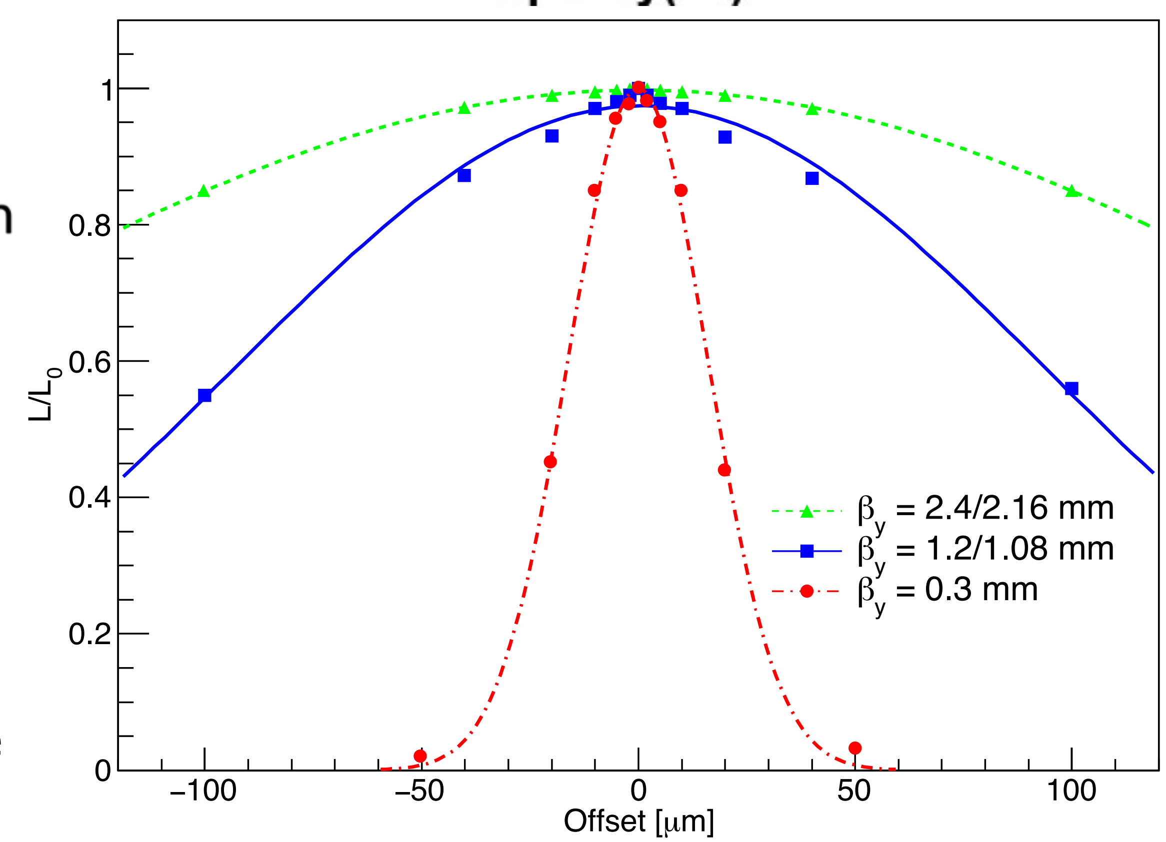


$|q|>p$ goes up and down on a side of slope

$|q|<p$ goes over across the peak

q: beam-beam offset
p: dithering amplitude

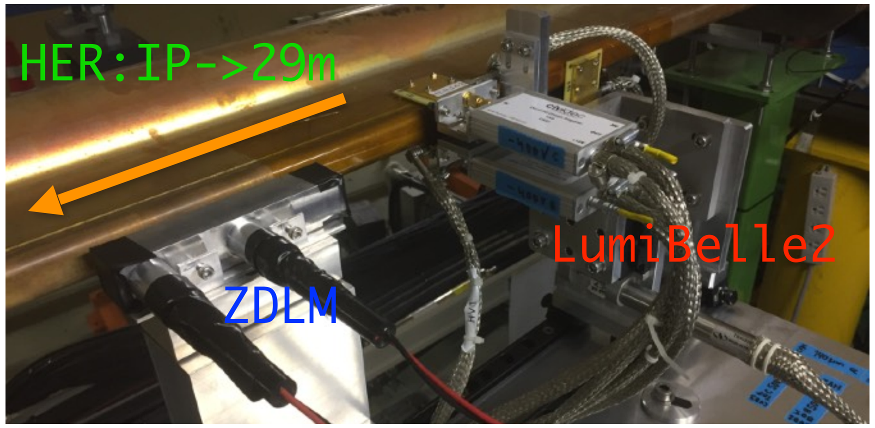
*normalised to Σ_x



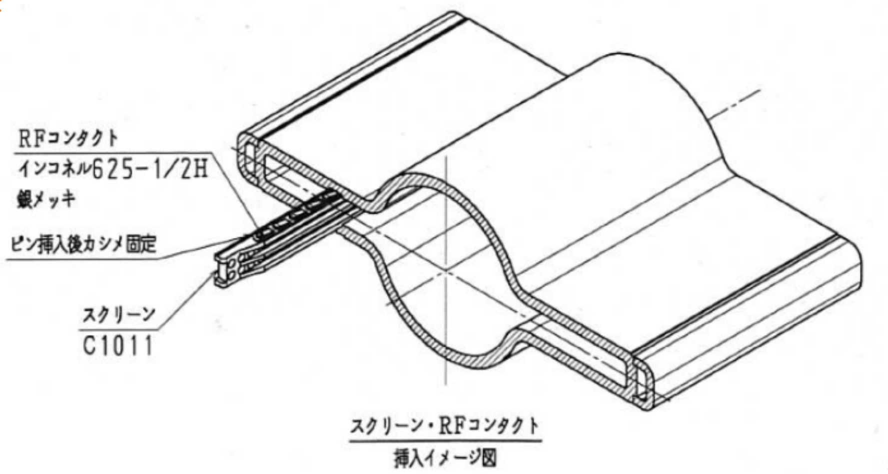
Luminosity degradation vs horizontal offset

Fast luminosity monitoring

- **Goal: fast relative luminosity monitoring based on radiative Bhabha scattering as input to SuperKEKB IP dithering orbit feedback system** (and for machine tuning and backgrounds studies)
  - **Train Integrated Luminosity (TIL)**: $\Delta L/L \sim 1\%$ @ 1 kHz
  - **Bunch Integrated Luminosity (BIL)**, 2500 bunches/train, 4 ns, ~ 1% @ few Hz

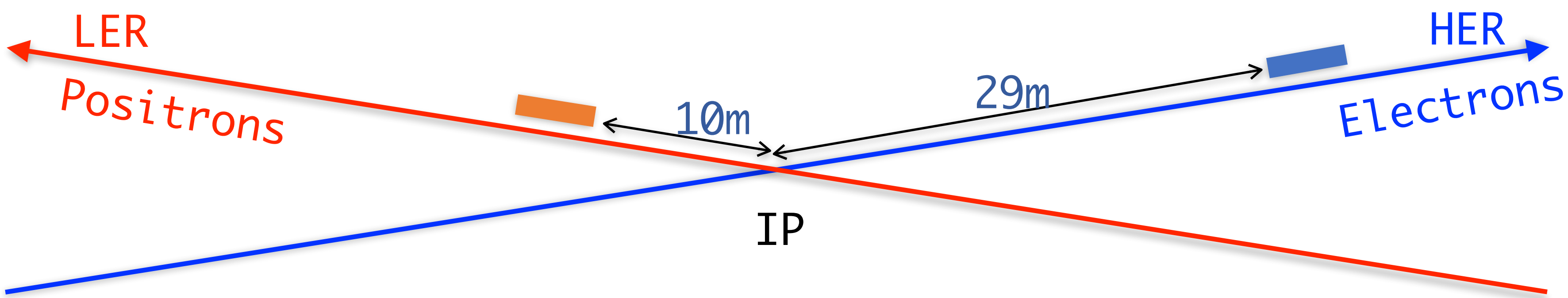


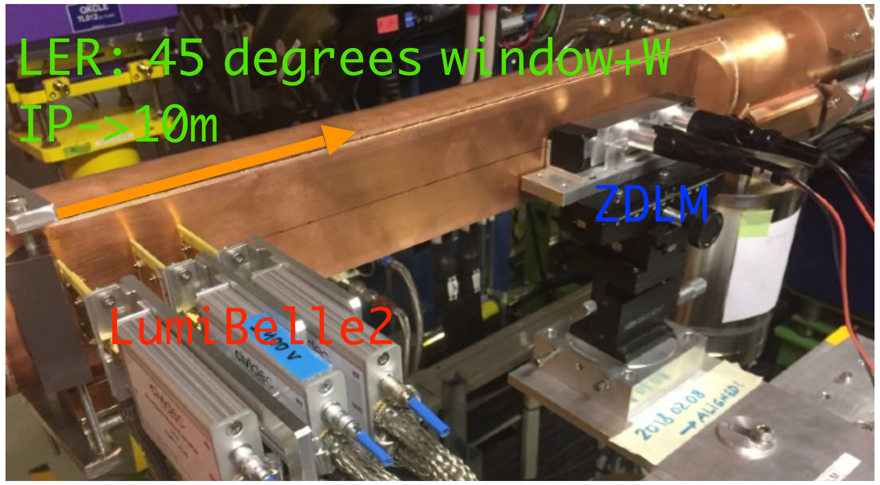
- **Radiative Bhabha process at vanishing photon scattering angle**
  - Rate proportional to Luminosity
  - Large cross section ~ 0.2 barn



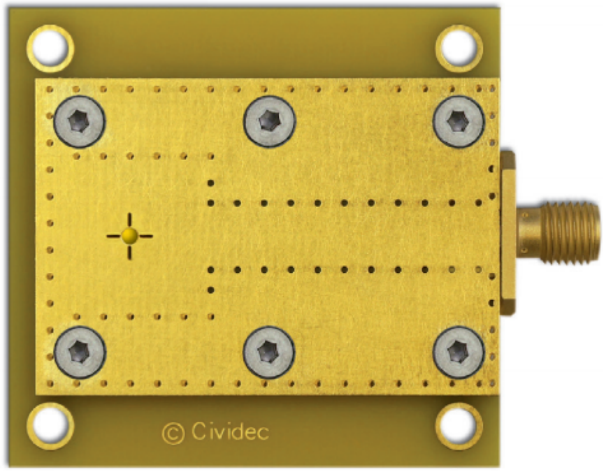
- **Two complementary techniques from LAL and KEK:**
  - **LumiBelle2 (LAL): sCVD diamond detector ~ 4.5x4.5x0.5/0.14 mm³**
  - **ZDLM (KEK) Cherenkov detector + scintillator + PMT**

- **Two commonly optimised locations:**
  - 10m downstream of IP in LER ⟶ Bhabha positrons
  - 29m downstream of IP in HER ⟶ Bhabha photons

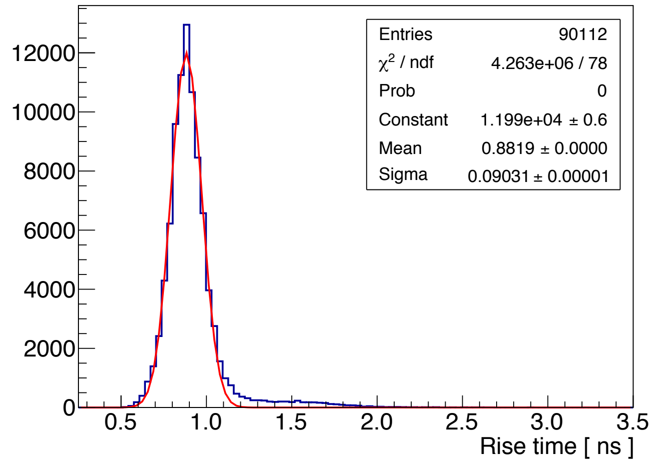


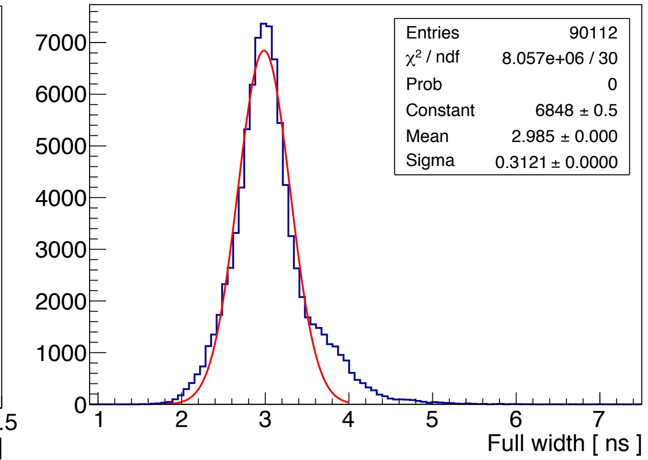


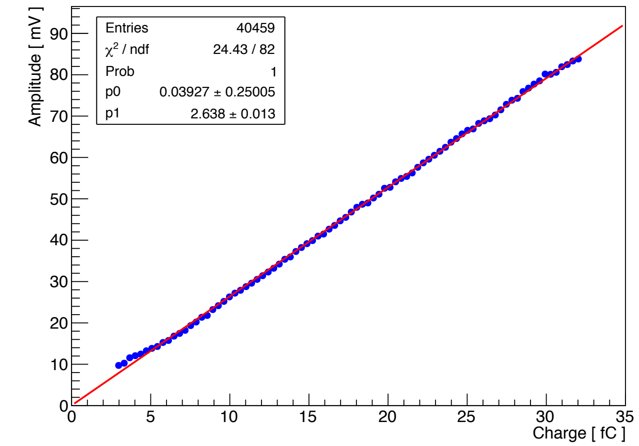
Detectors



sCVD diamond detector

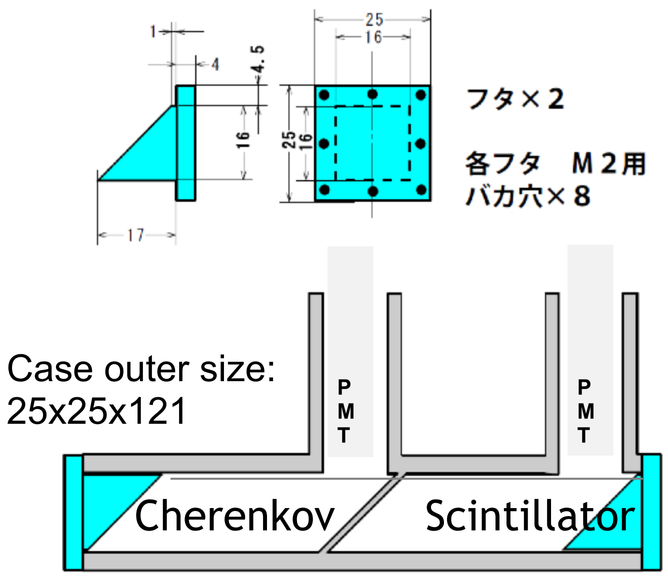


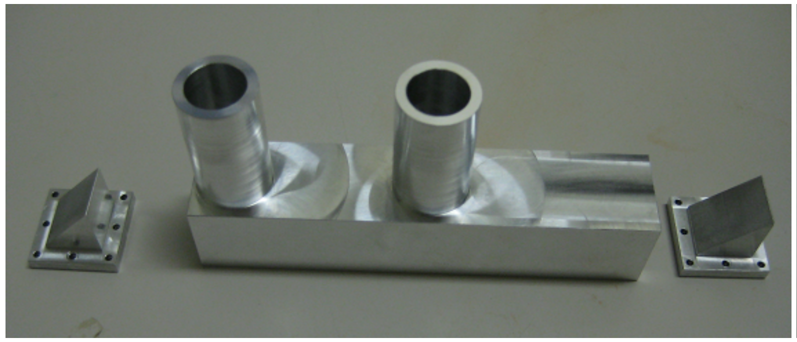


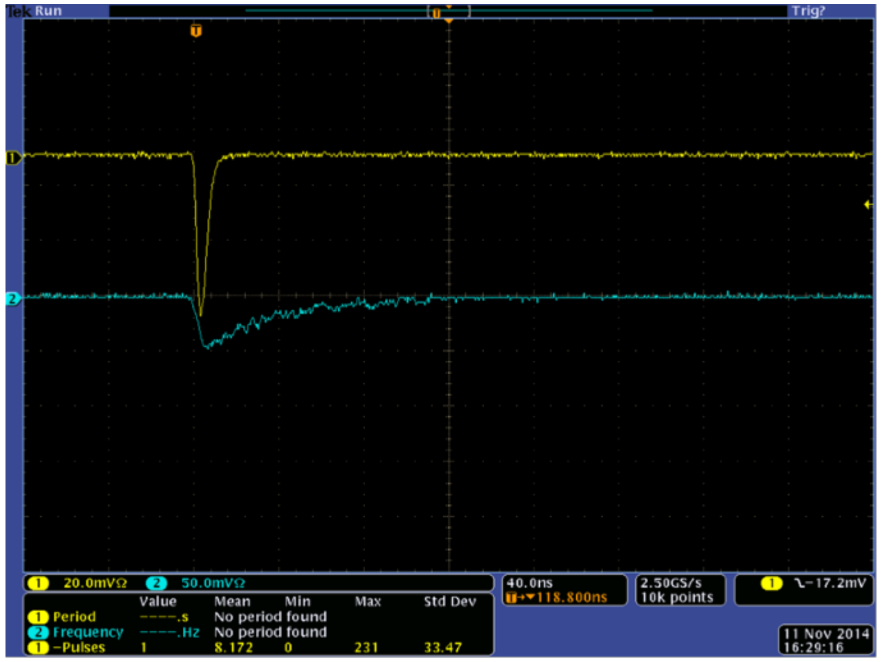


- Wide band-gap (5.5 eV) semiconductor devices;
- Strong atomic bond (radiation resistant);
- Fast charge/current amplifiers
- High drift velocity (fast detector).

LumiBelle2



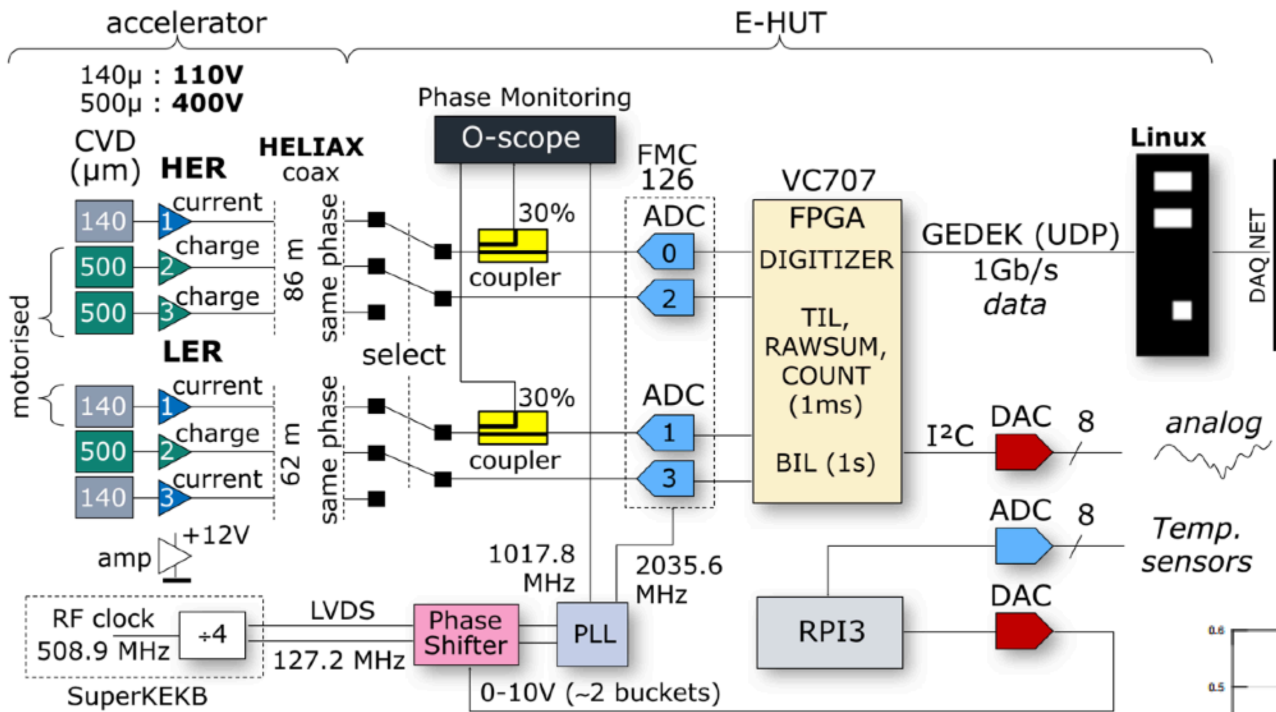


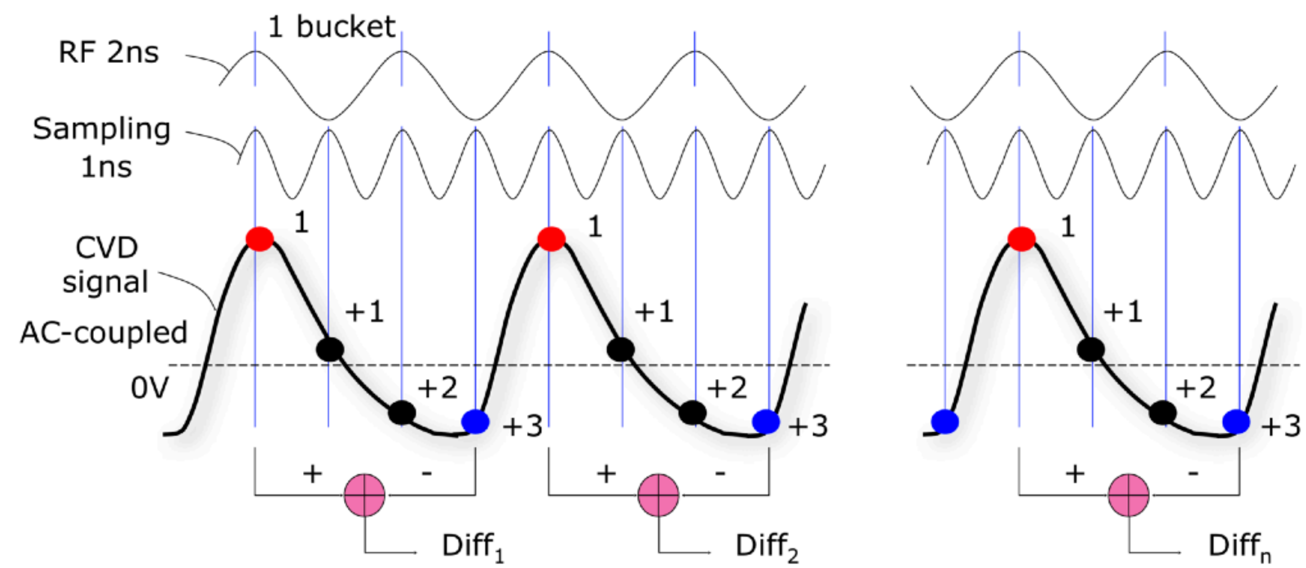


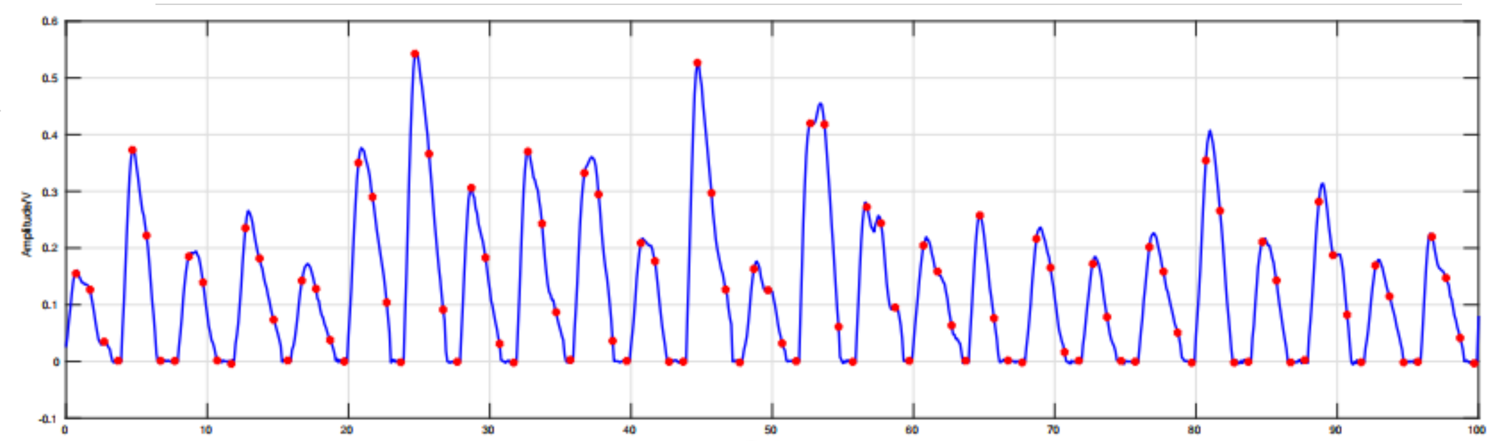
Cherenkov and **LGSO** scintillator
σ = 1.31 ns for 2 counters
Time resolution < 1 ns is achieved for one counter.

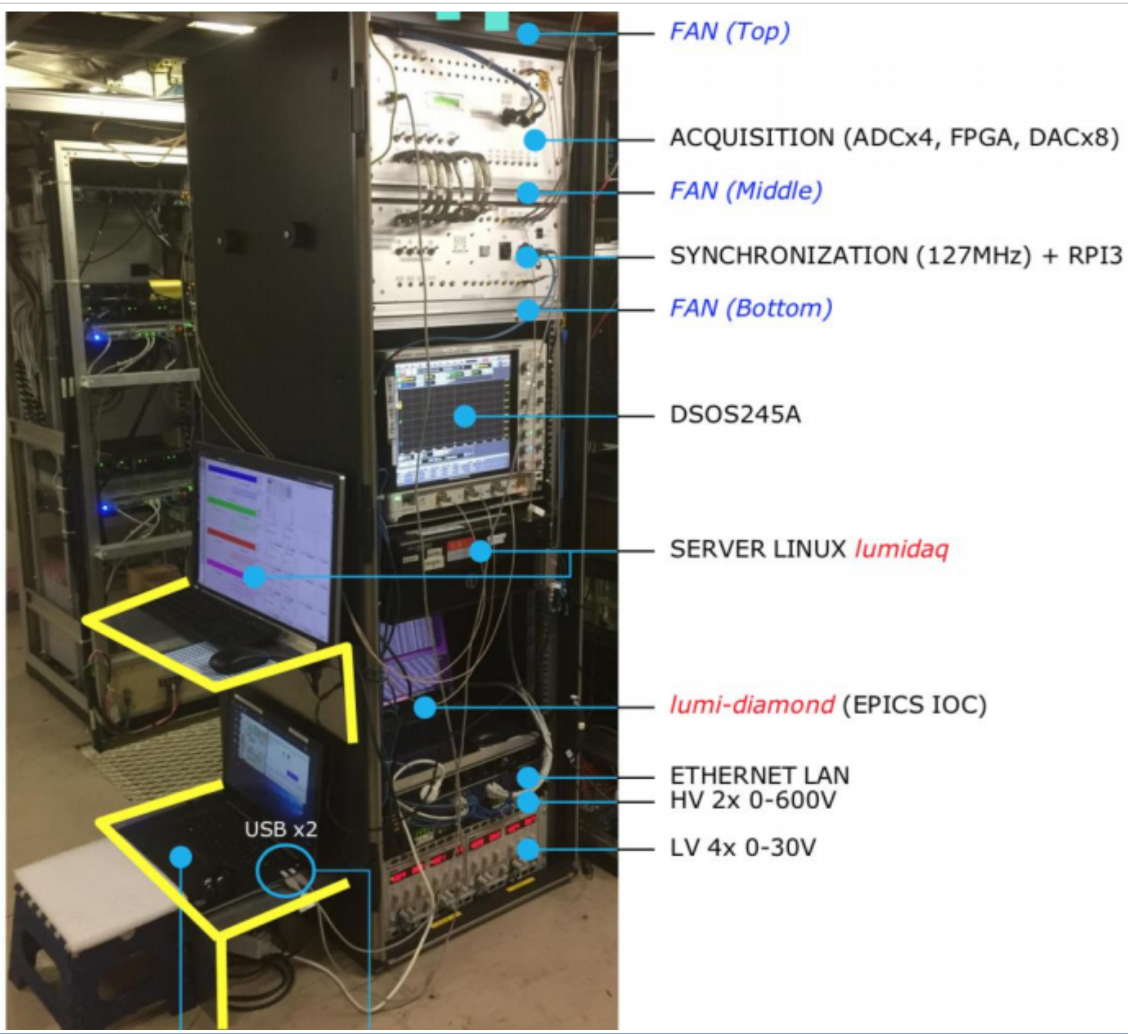
ZDLM

Data acquisition system (LumiBelle2)





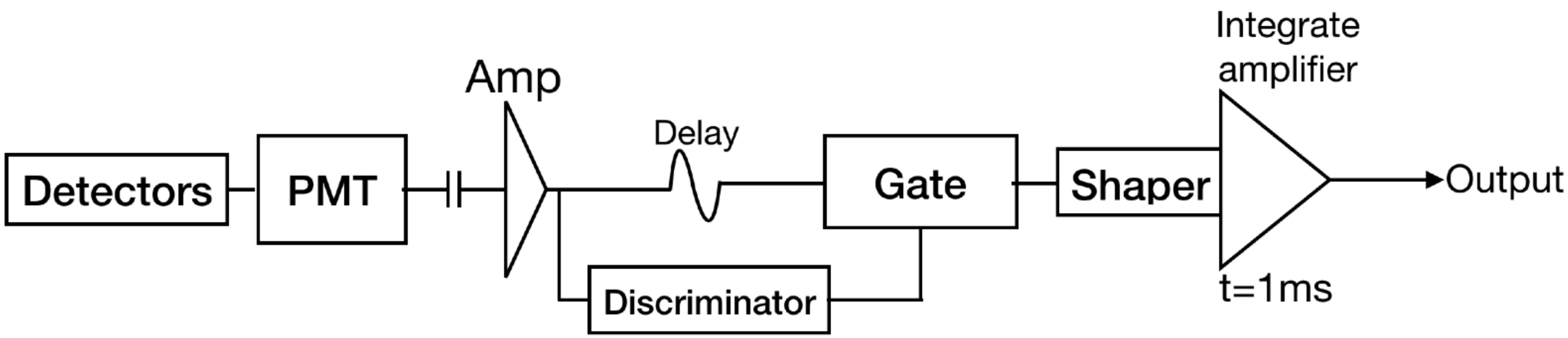


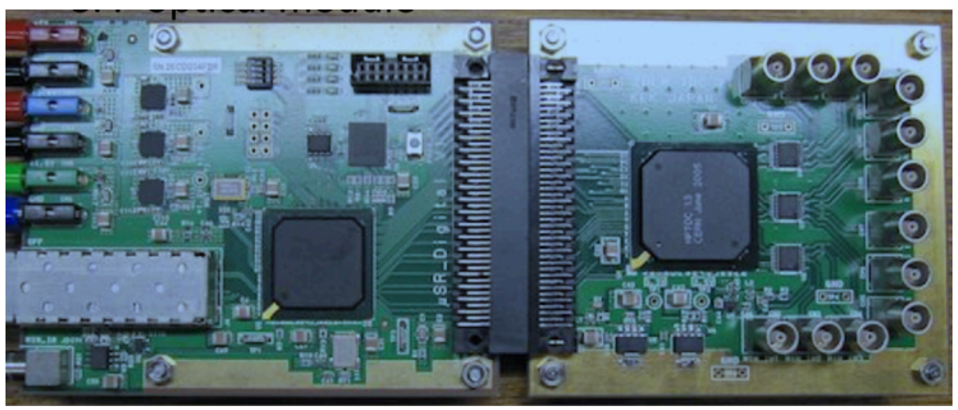


LumiBelle2:

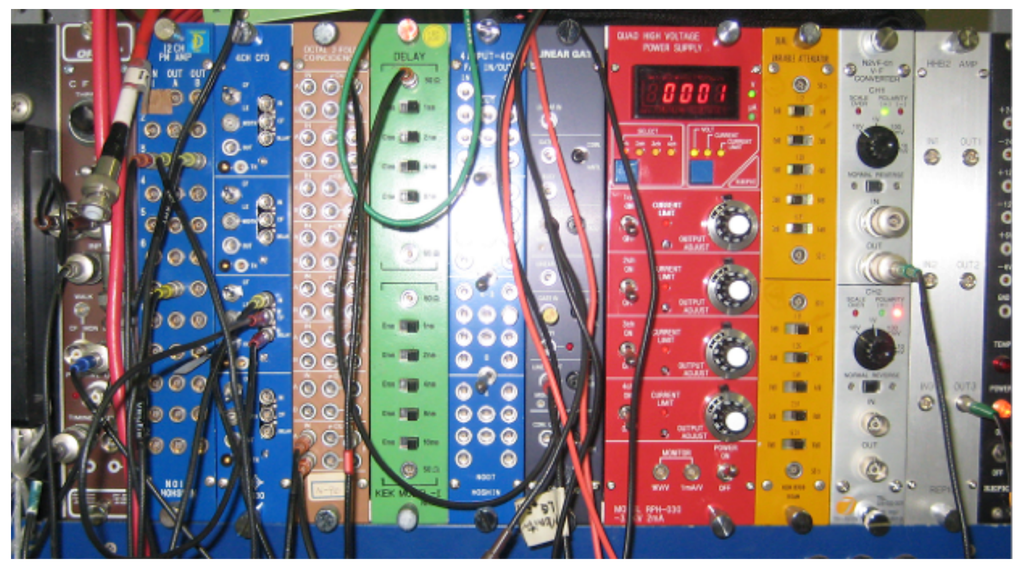
- **No trigger**
- **Synchronised to RF**
- **Continuous monitoring**
- **Digital**
- **TIL and BIL**
- **Bucket resolution (2ns)**

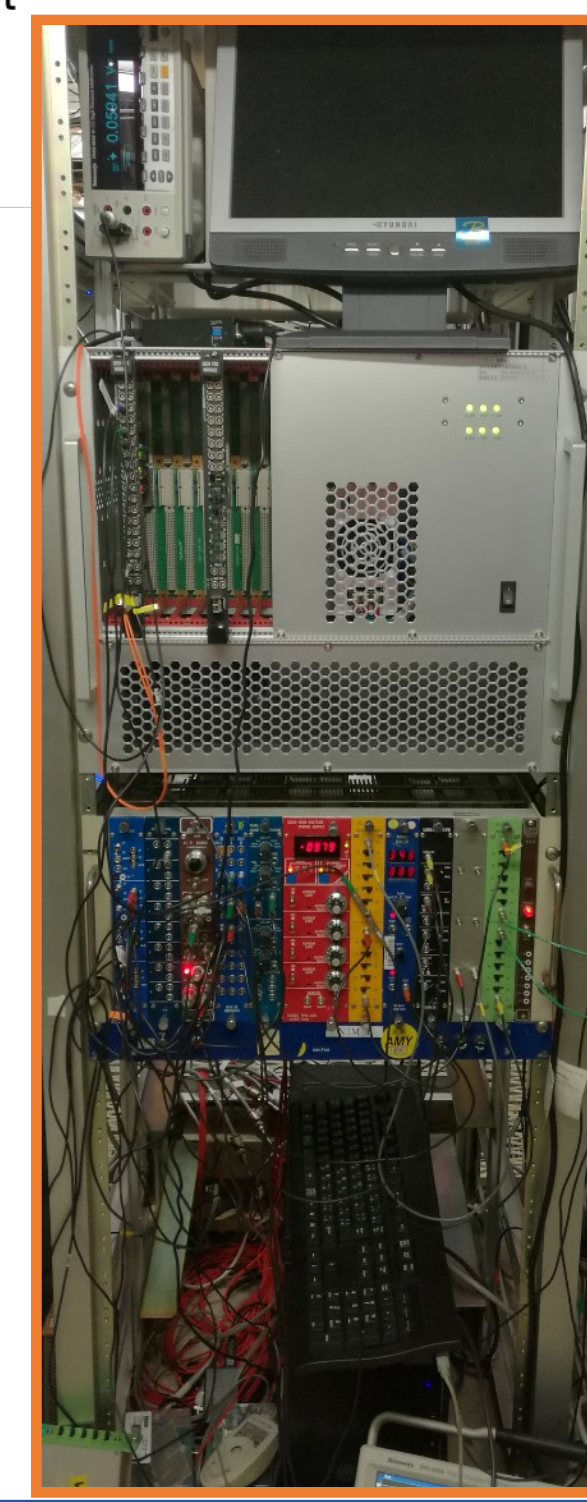
Data acquisition system (ZDLM)





Prototype of TDC module





ZDLM:

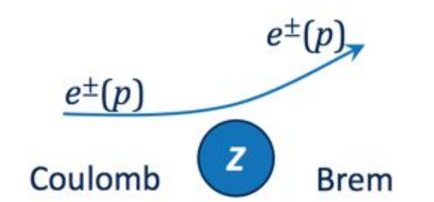
Luminosity measurement with pulse integration

- **Integration/counting**
- **Trigger mode**
- **Analog**
- **TIL and BIL**

Signal sources

Coulomb:

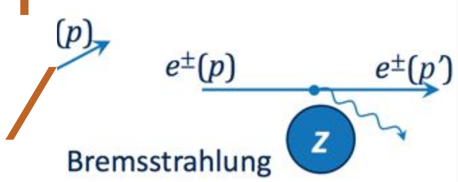
- ➡ Proportional to vacuum pressure and beam current
- ➡ Important globally but negligible for luminosity monitoring



Bremsstrahlung:

- ➡ Proportional to vacuum pressure and beam current
- ➡ Largest source of background in phase 2
- ➡ Photons measured at HER side
- ➡ Positrons measured at LER side

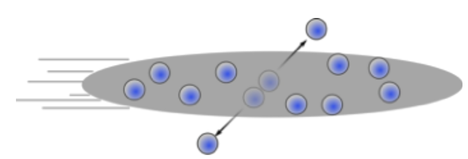
Dominant in LumiBelle2/ ZDLM



Touschek:

- ➡ Proportional to square of beam current
- ➡ Inversely proportional to beam size

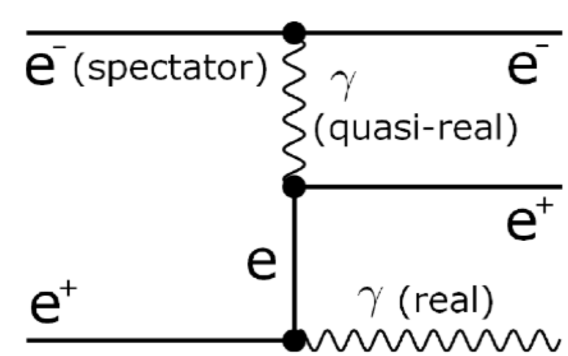
Background



Radiative Bhabha process:

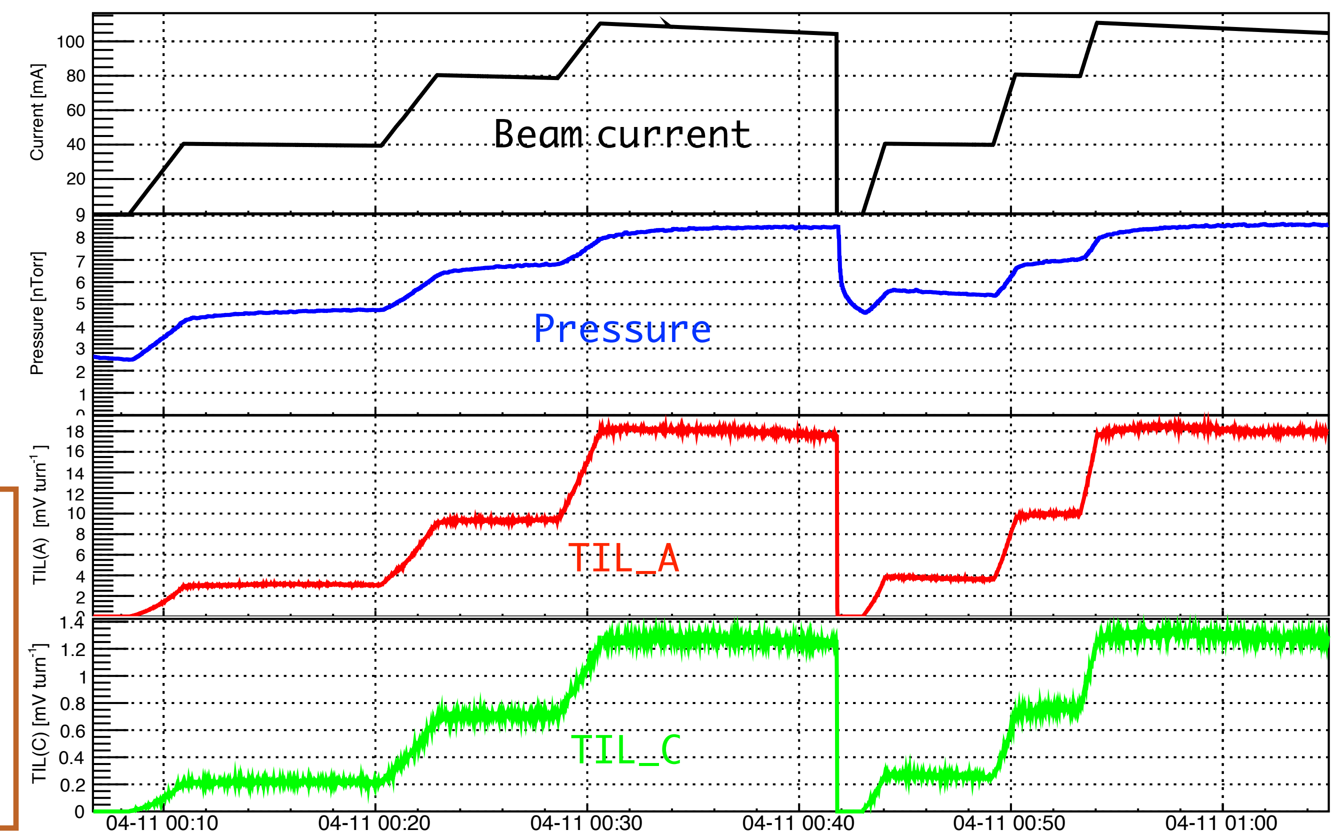
- ➡ Scattered @ IP
- ➡ Proportional to luminosity
- ➡ Large cross-section

Luminosity signal

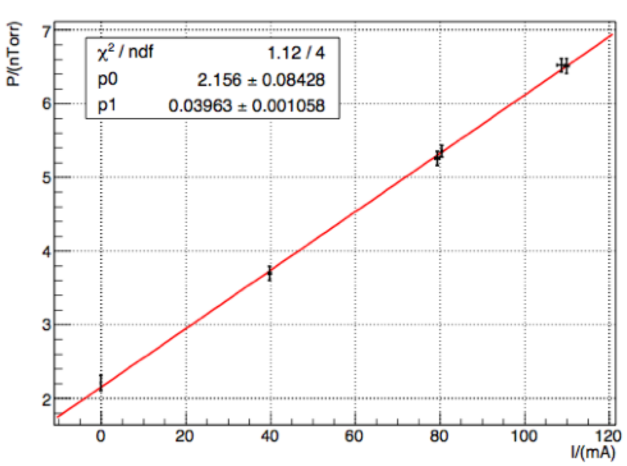


Background study

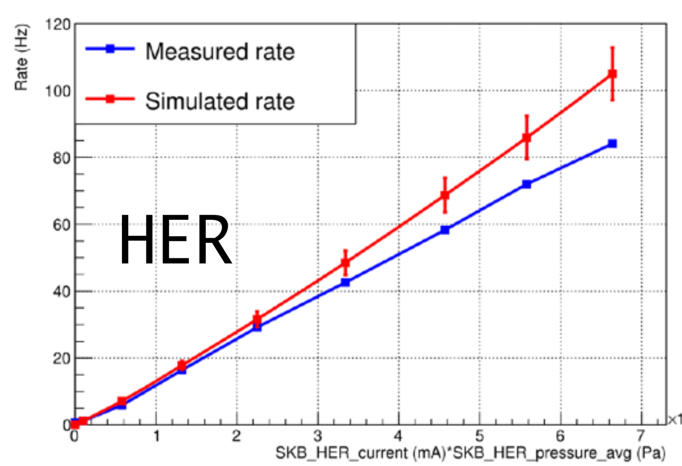
- **Background measurement:**
  - ✦Bremsstrahlung ∝ I*P
    Dominant
  - ✦Touschek ∝ $I^2/(\sigma_x\sigma_y\sigma_z)$
  - ✦Coulomb ∝ I*P



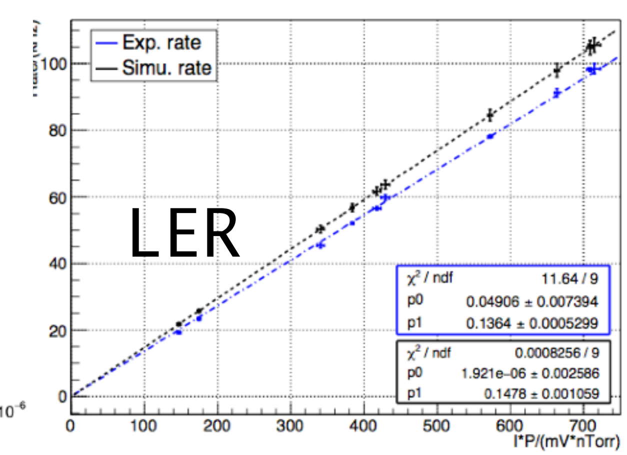
- ➡ Beam gas desorption: pressure ∝ current (in some range?)
- ➡ Background signal: ∝ I*P
- ➡ Simulation are about 10%-25% larger than experiment



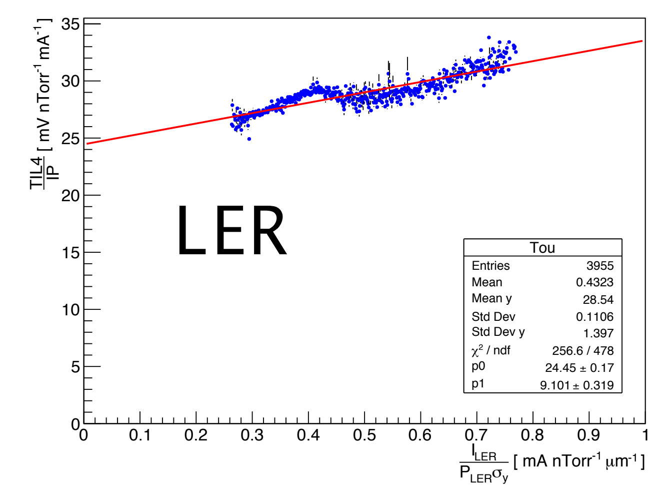
Beam gas desorption



Simulated results are about 25% larger than measurement

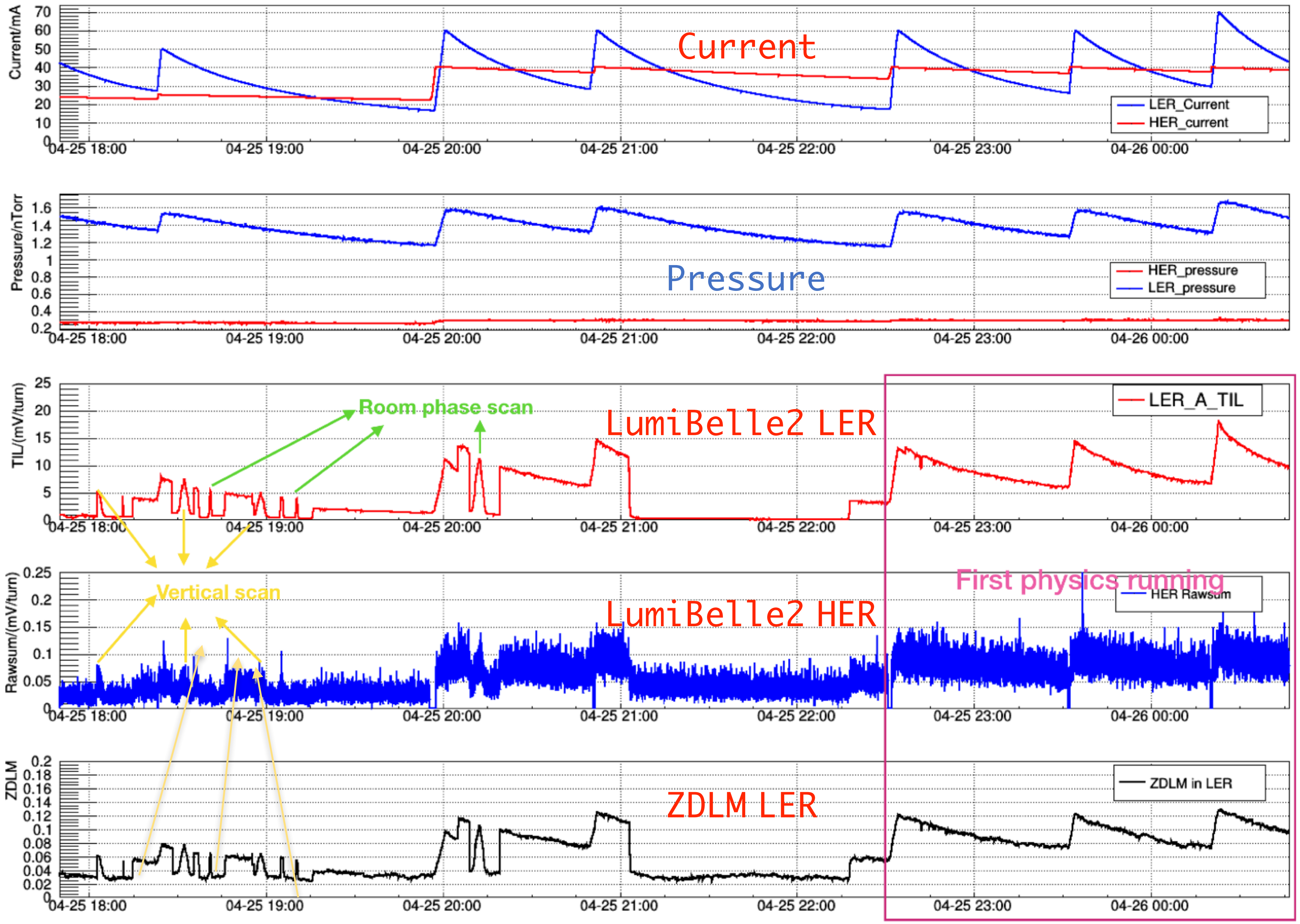


Simulated results are about 11% larger than measurement

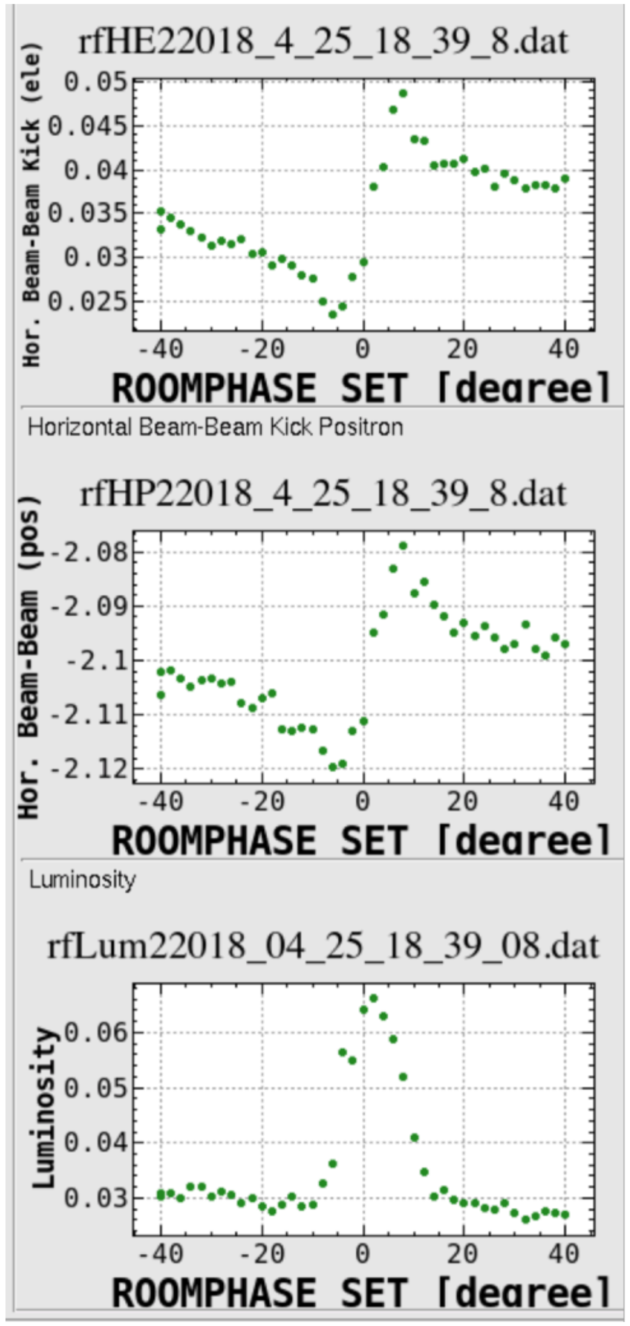


In Phase-2, Touschek has a fraction of 13% and Bremsstrahlung about 87%

First collision observed @ 04-25



Luminosity monitoring system



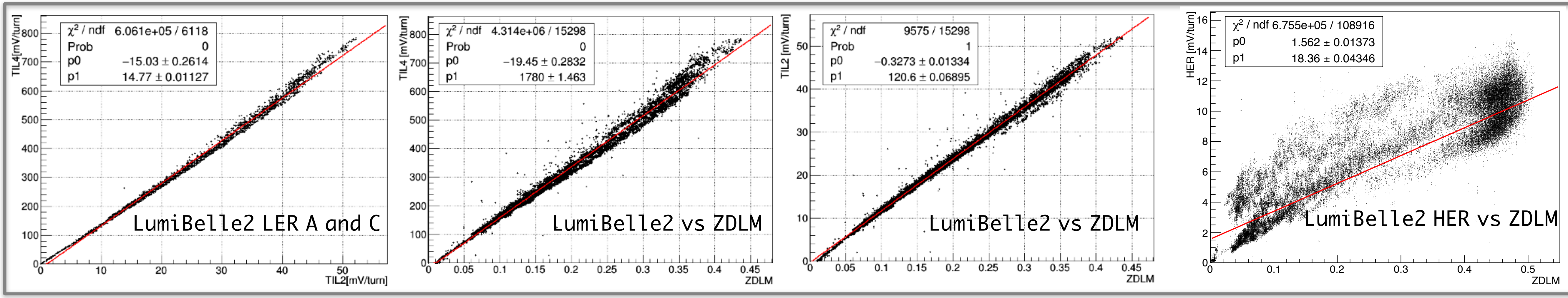
Beam-beam deflection

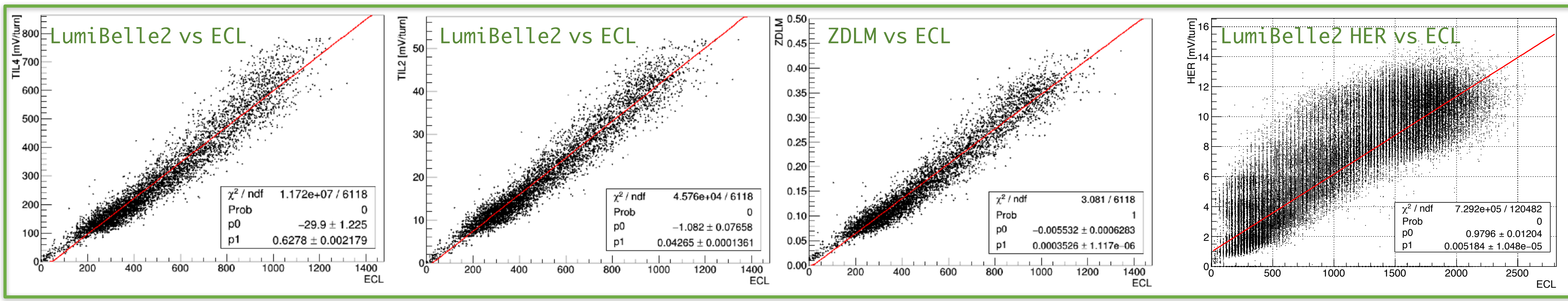
- Both luminosity monitoring and beam-beam deflection technologies are used to search for collision with horizontal, vertical and longitudinal scans
- Both LumiBelle2 and ZDLM observed the Bhabha scattering signal

Luminosity signals cross check

- Cross check among LumiBelle2, ZDLM and ECL

*ECL is the Belle II absolute measurement of luminosity, based on recording coincident signals from back-to-back Bhabha events in the angular acceptance of the forward (“end-caps”) calorimeters.





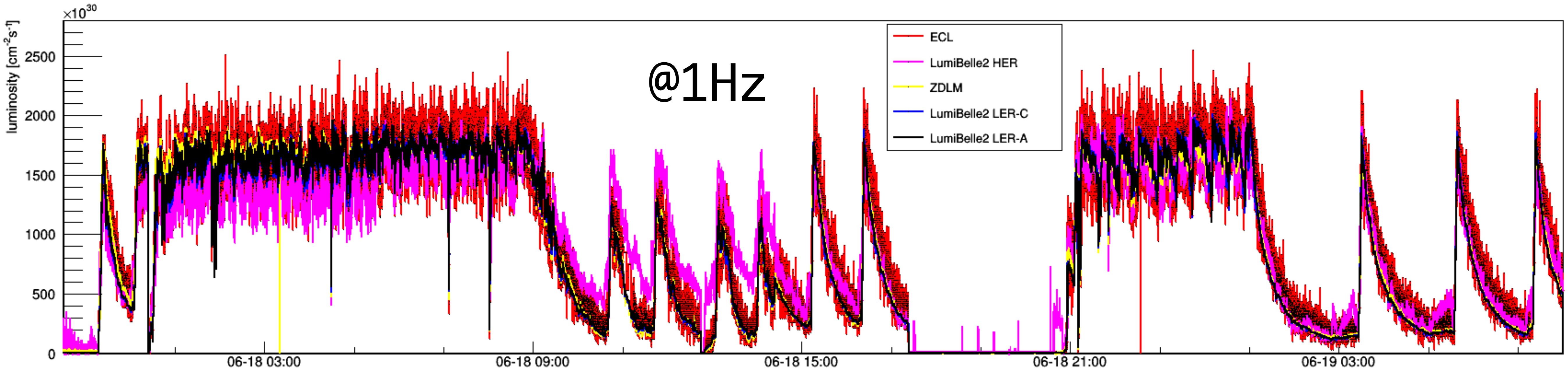
➡ Signals between different channels of LumiBelle2 are proportional to each other

➡ Signals from LumiBelle2 are proportional to signals from ZDLM

➡ LumiBelle2 HER signals are weaker, consistent with others in principle

➡ LumiBelle2 and ZDLM are proportional to ECL luminosity signals

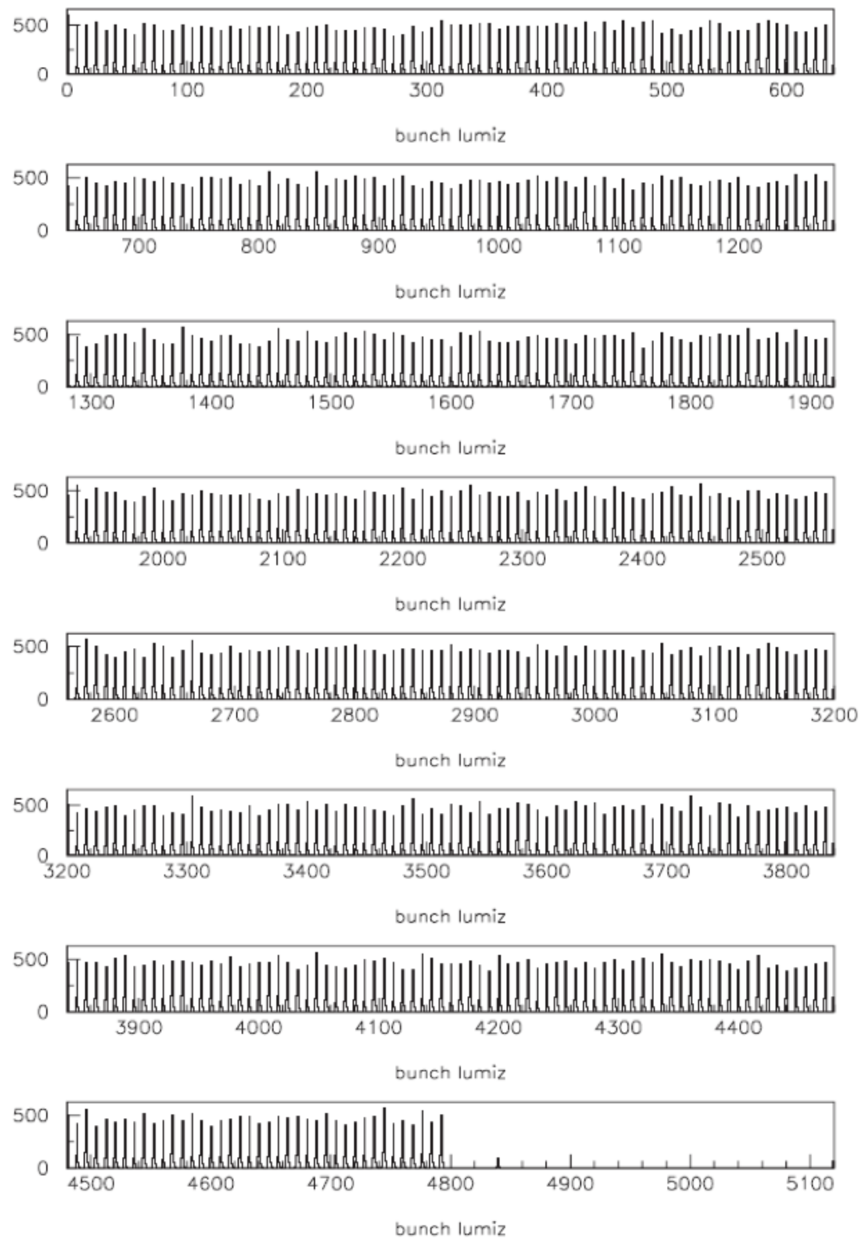
Luminosity signals vs ECL

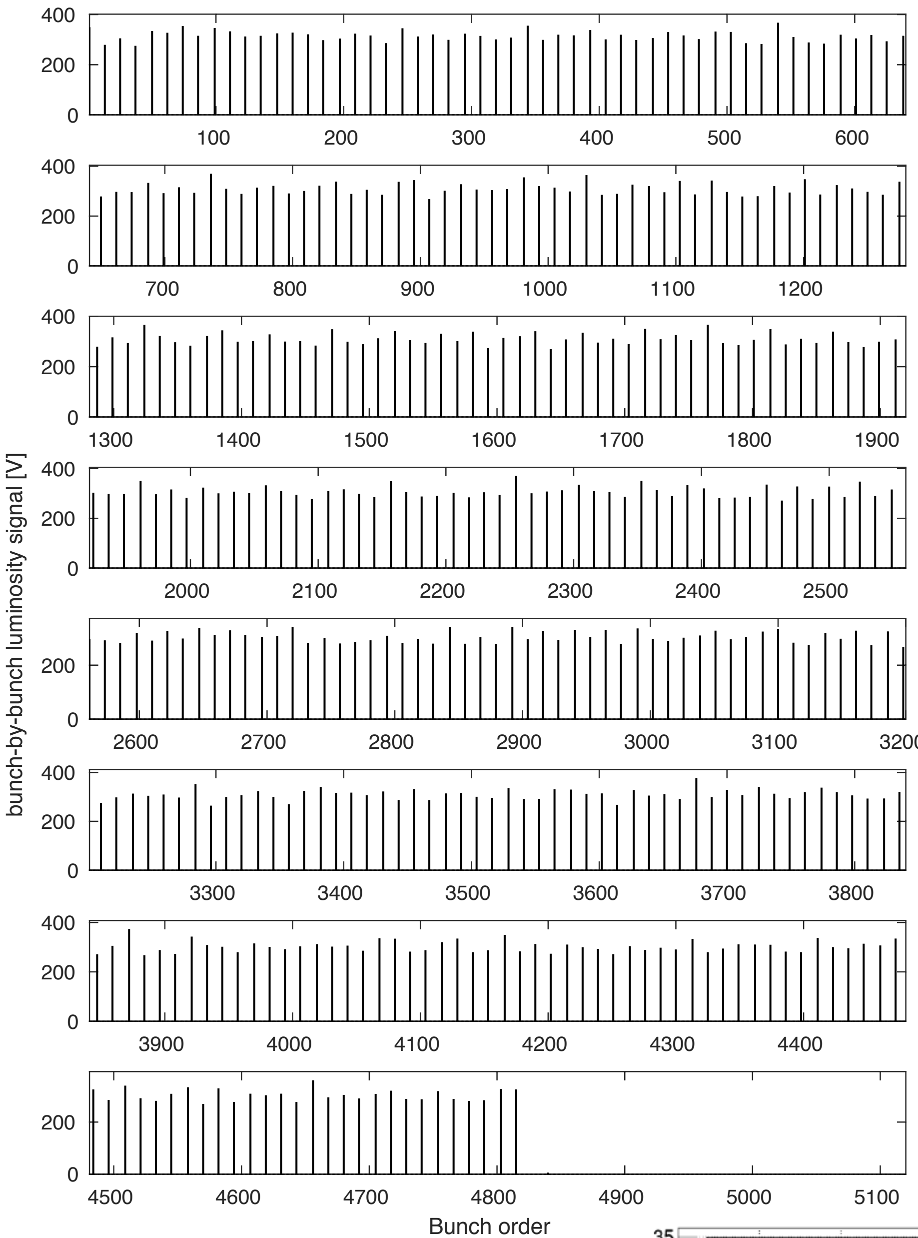


- LumiBelle2 and ZDLM agree well with ECL after normalisation
- LER is much more precise than HER
- Much more statistics than ECL: 2~5 orders of magnitude for HER → LER
  - LumiBelle2 and ZDLM rates depend on channels/configuration
  - LumiBelle2 signals have some sensitivity to vertical angle @ IP
- Relative luminosity measurements

Bunch-by-bunch luminosity

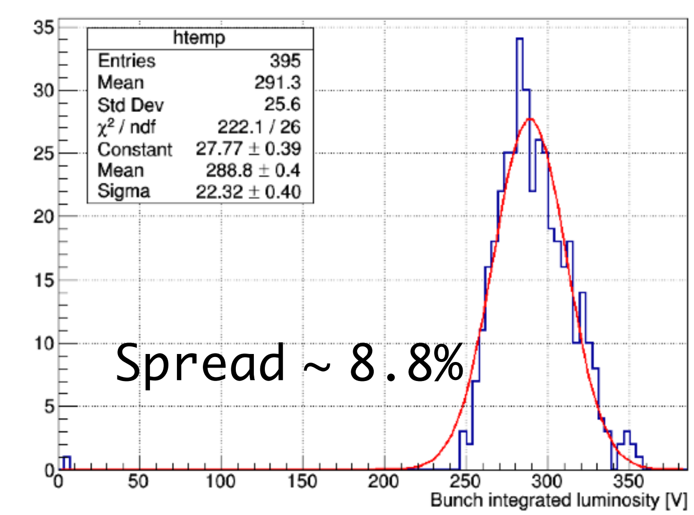
ZDLM



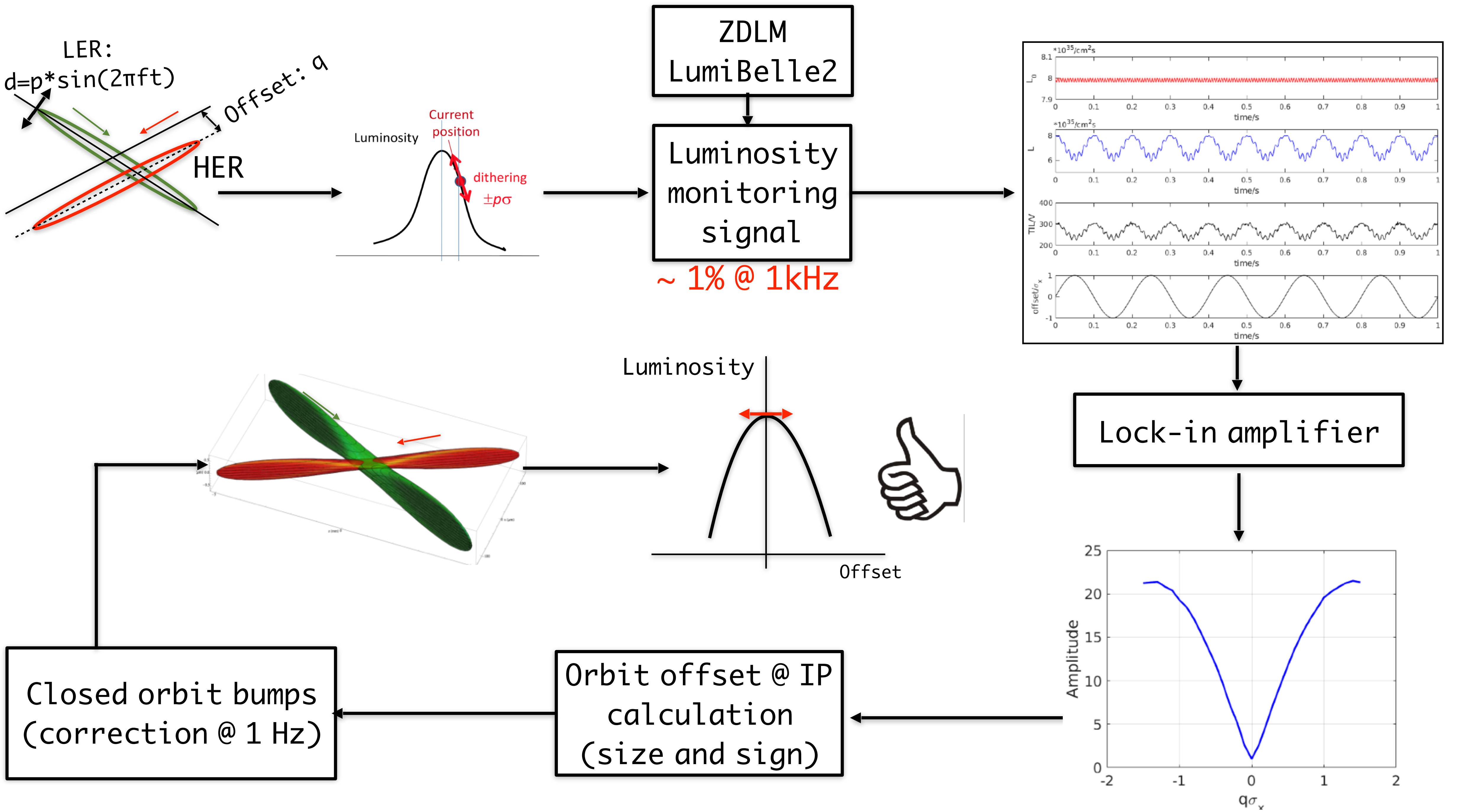


LumiBelle2

- Bunch-by-bunch luminosity signals @ 1Hz are available
- Bunch-by-bunch variations mainly from bunch current differences (measured bunch currents: 8.1%)
- Online display

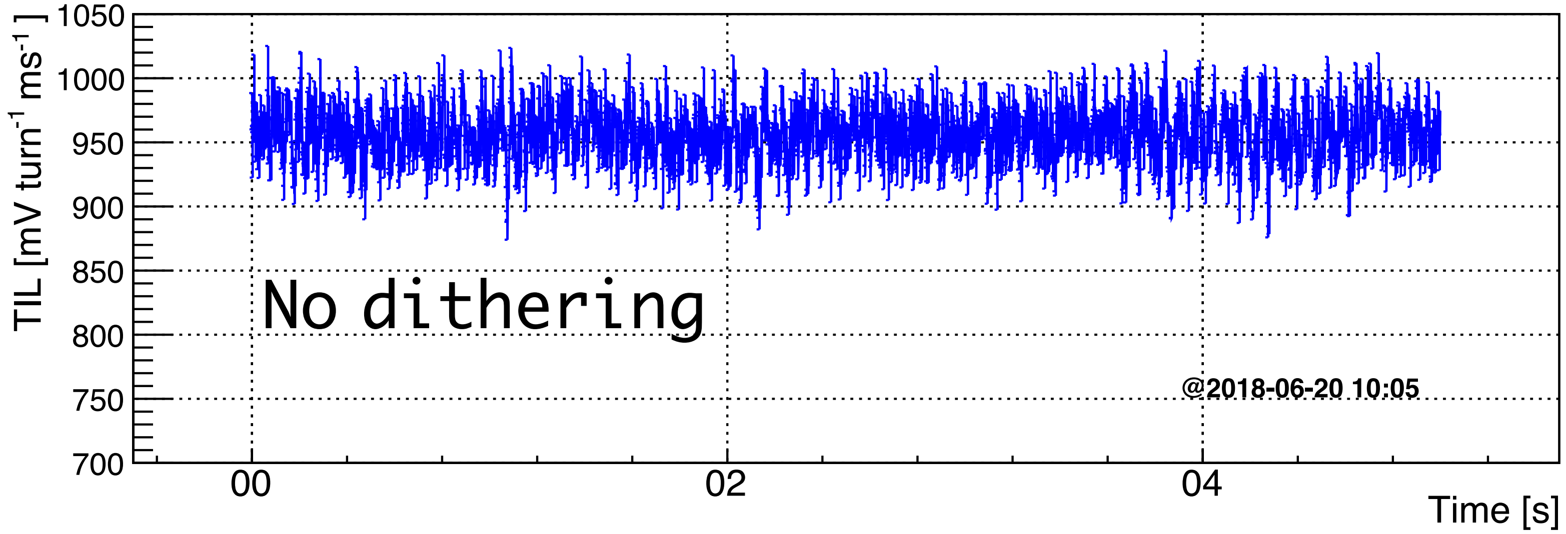


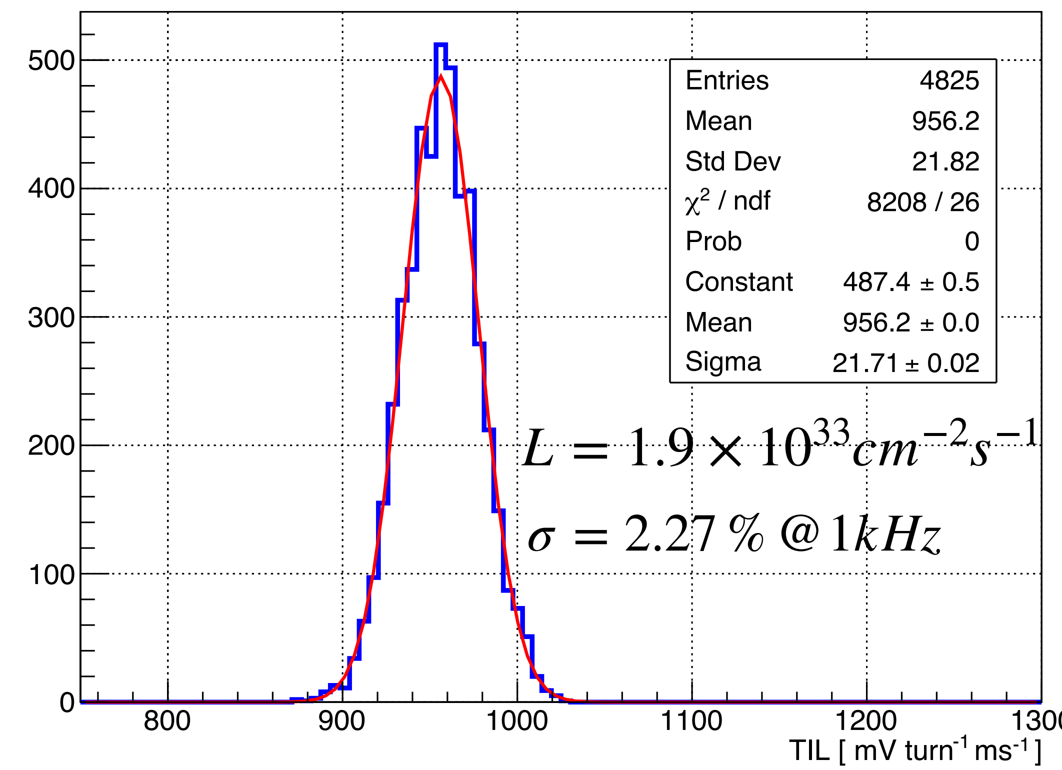
Dithering feedback algorithm



- Modulate the LER beam position at IP at a known frequency (79Hz) with horizontal orbit bump
- Observe the luminosity modulation with a lock-in amplifier
- Luminosity reaches maximum when output of lock-in amplifier are minimum
- Newton method search for zero are used for feedback control algorithm

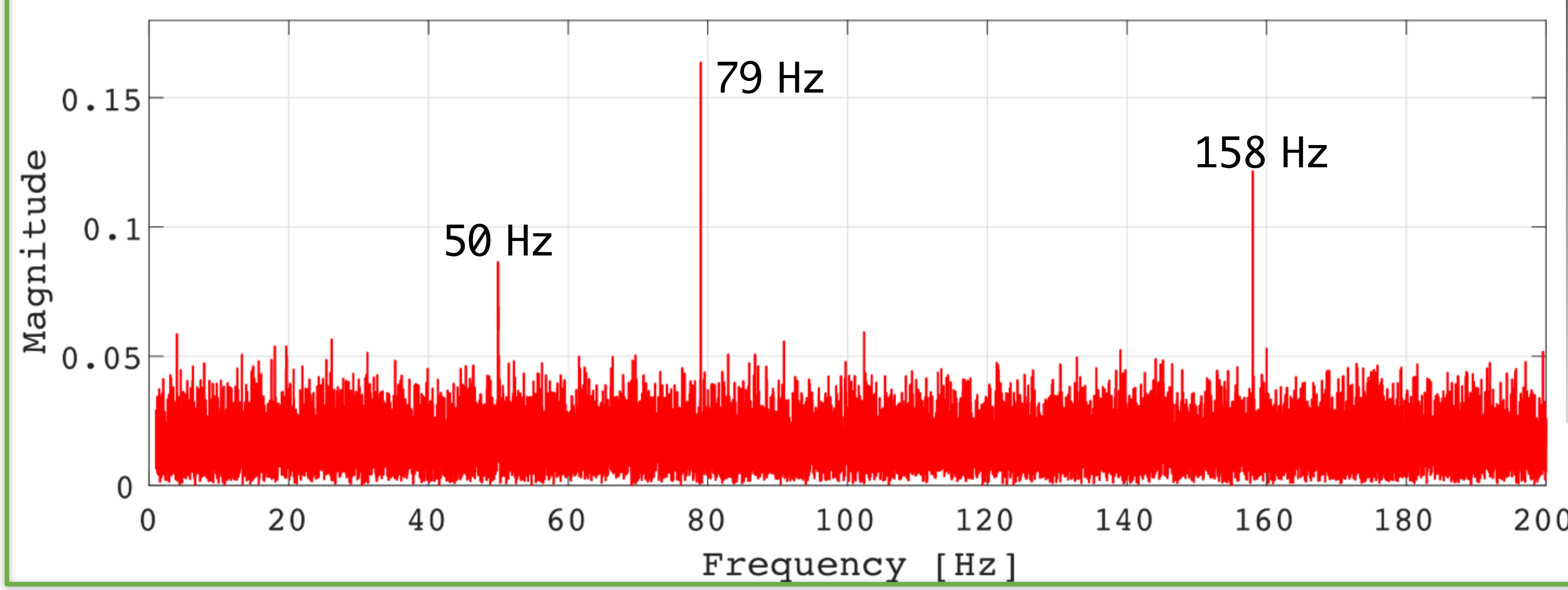
Luminosity signals @ 1kHz

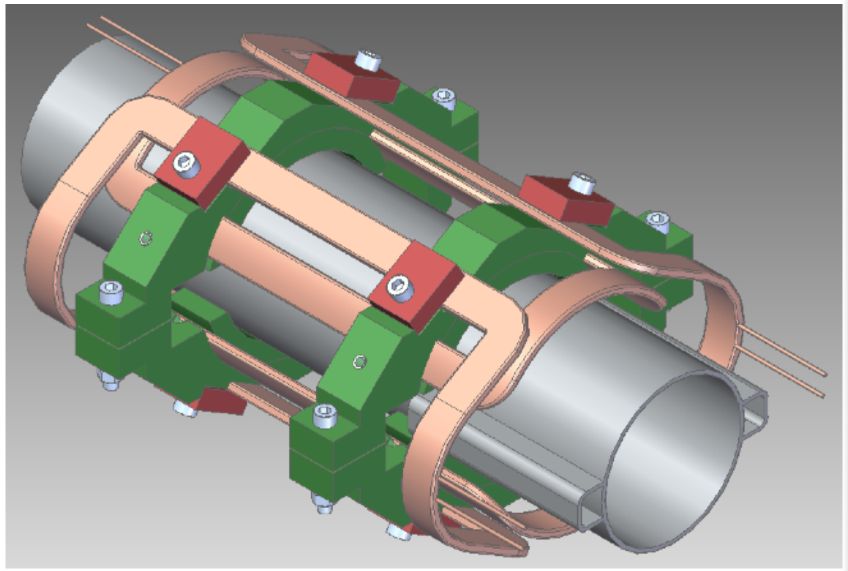




1% at 1 kHz can be expected: L=$10^{34} cm^{-2} s^{-1}$

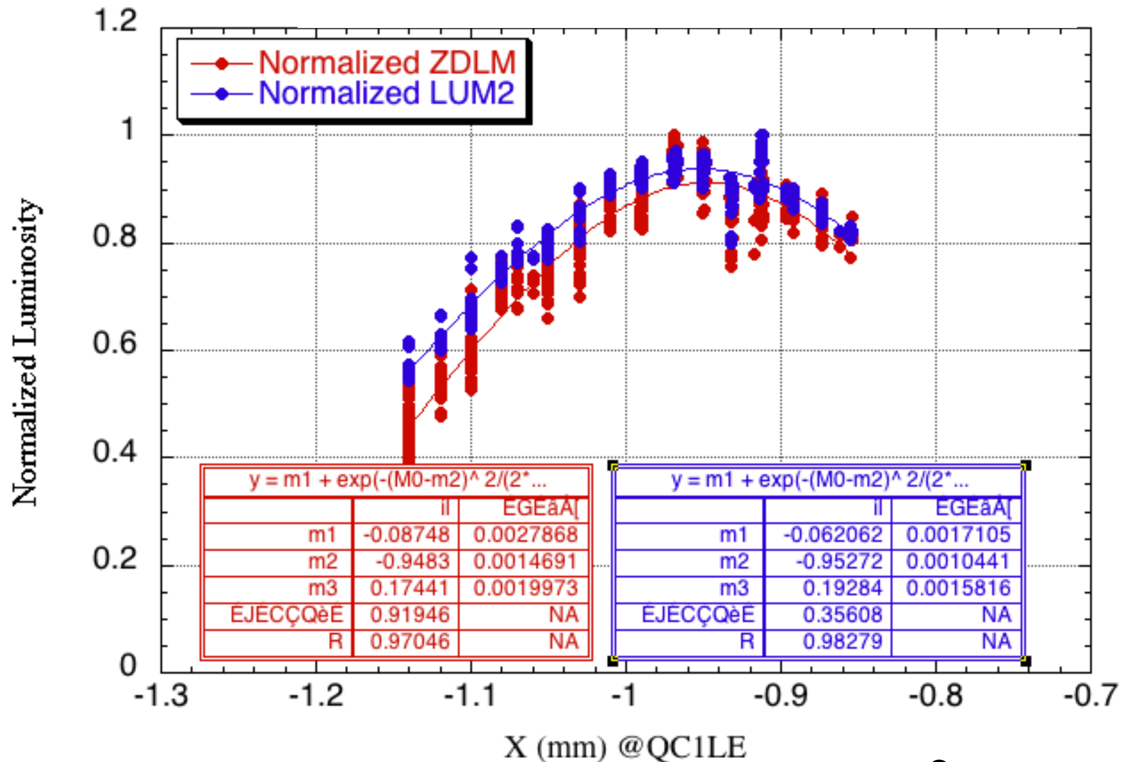
Dithering @ 79 Hz





Dithering coil X 12

Dithering feedback test



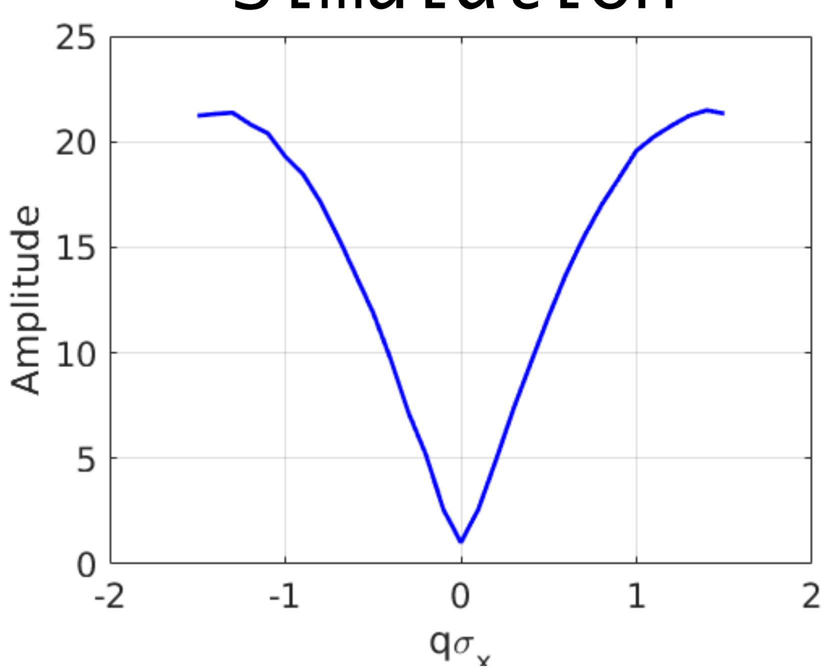
- Phase obtained by mixing dithering driving and luminosity monitoring signals
- Slope information can be obtained by several successive corrective moves
- Newton method is used to correct the beam orbit at 1 Hz

* f: dithering frequency 79Hz

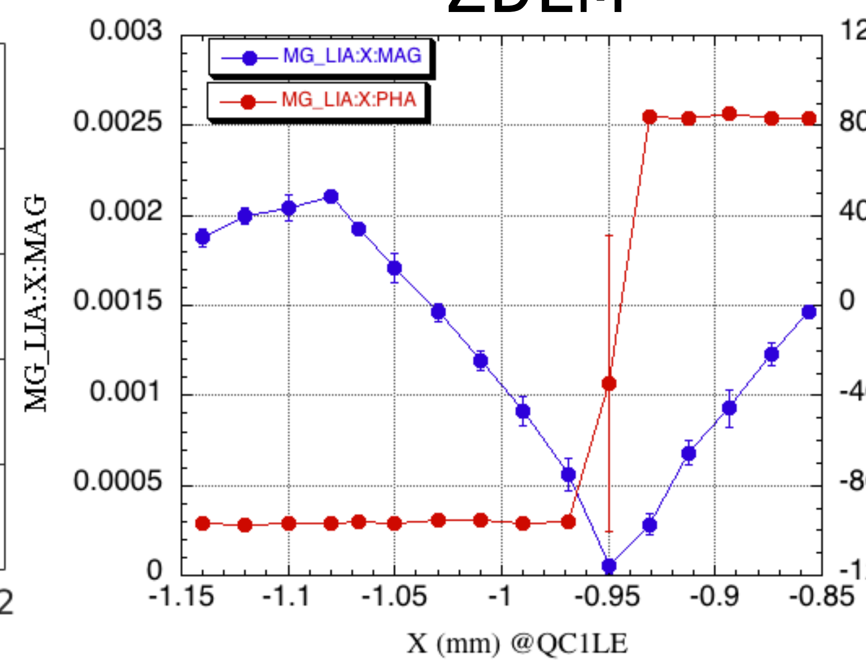
$$L \sim m_1 + e^{\frac{(x-m_2)^2}{2m_3^2}}$$

$$V_{x1} = -\frac{1}{2\sqrt{2}} G_L \frac{L}{L_{max}} \frac{x_0 x}{\Sigma_x^2} exp(-\frac{x_0^2}{2\Sigma_x^2})$$

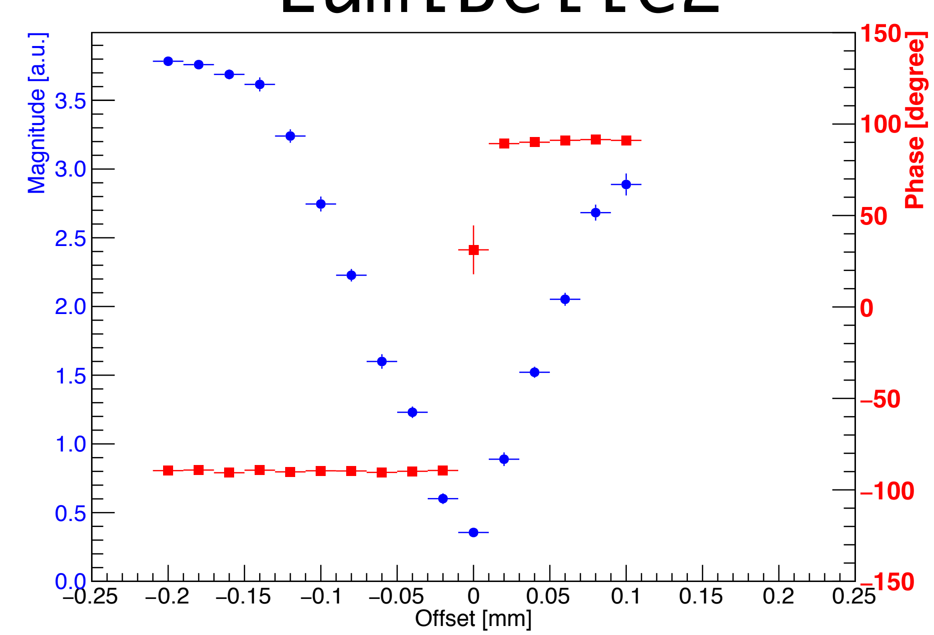
Simulation



ZDLM

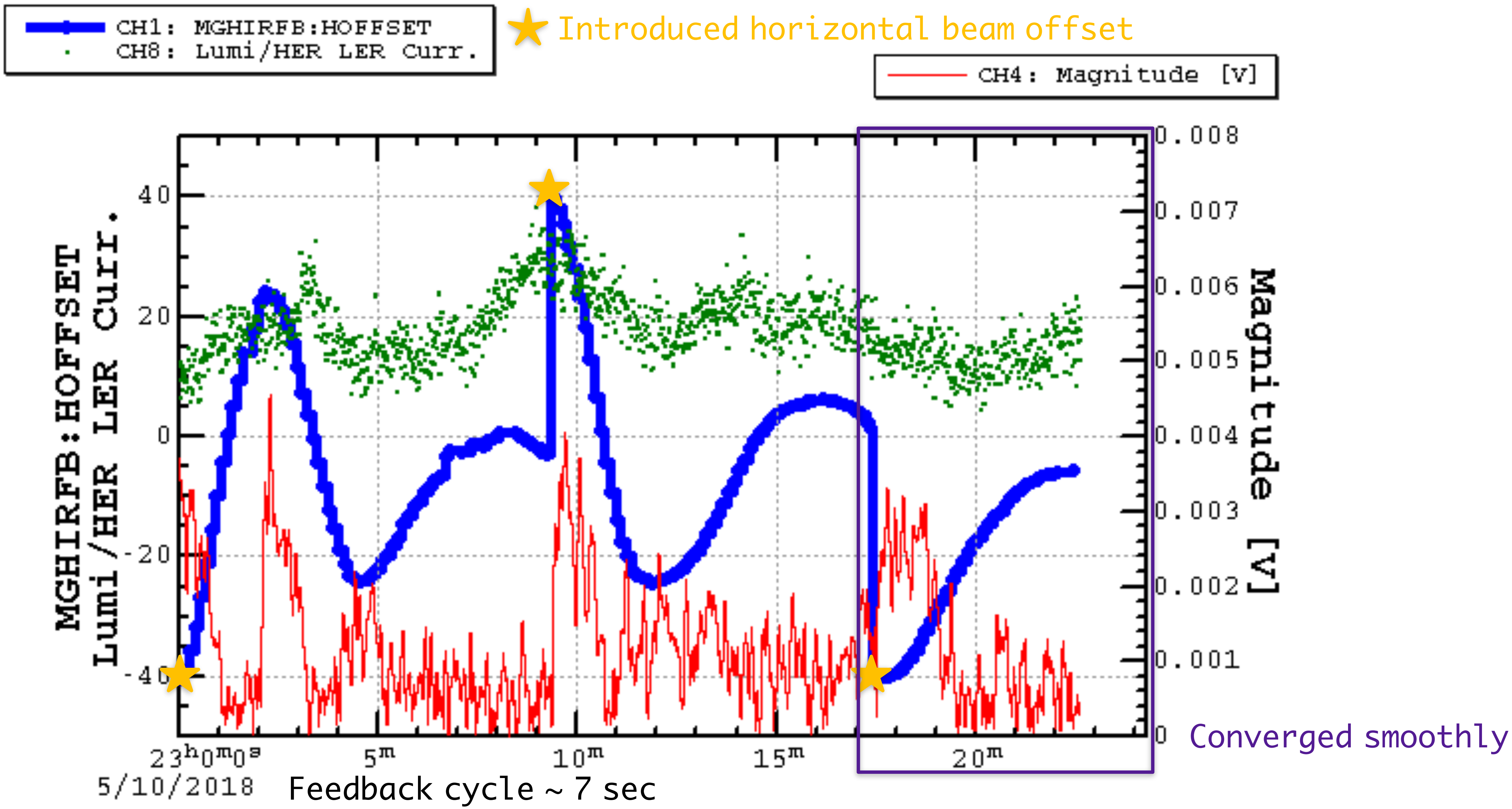


LumiBelle2



Dithering feedback test

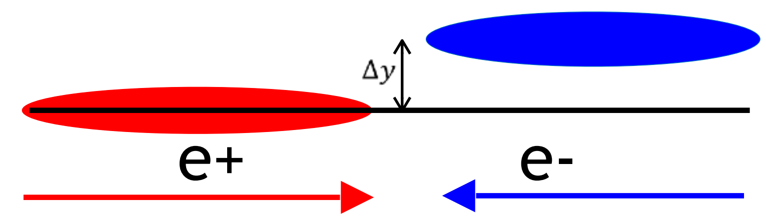
- Feedback test with deliberately introduced horizontal offset



- Dithering orbit feedback system worked well
- Luminosity is not sensitive to the horizontal offset and fluctuated for other reasons during this test
- No vertical orbit feedback has been used yet

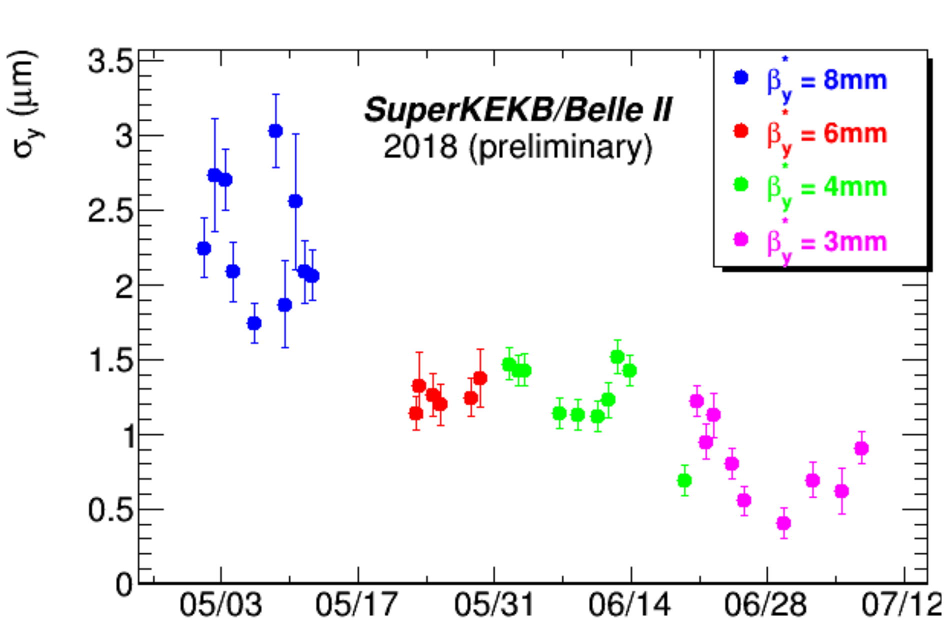
Vertical offset scan

- Vertical offset scan is used to optimise vertical beam position and estimate vertical beam size
- SNR are estimated based signals w/o collision
- Vertical beam size decreases with squeezing of β_y^*
- Luminosity calculated based on fitted σ_y^*

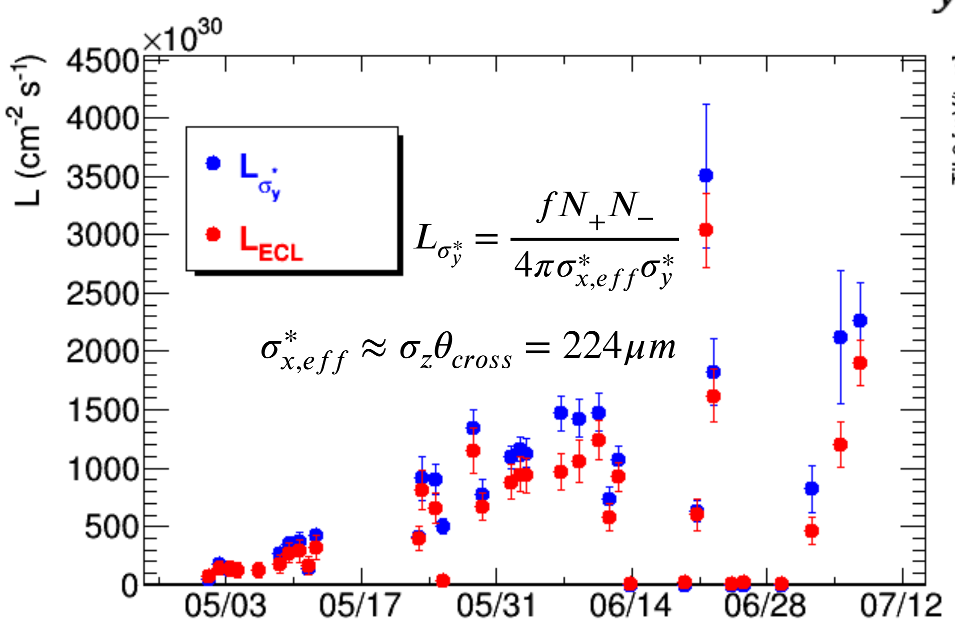


$$\frac{L}{L_0} = exp\left(-\frac{\Delta y^2}{2\Sigma_y^2}\right)$$

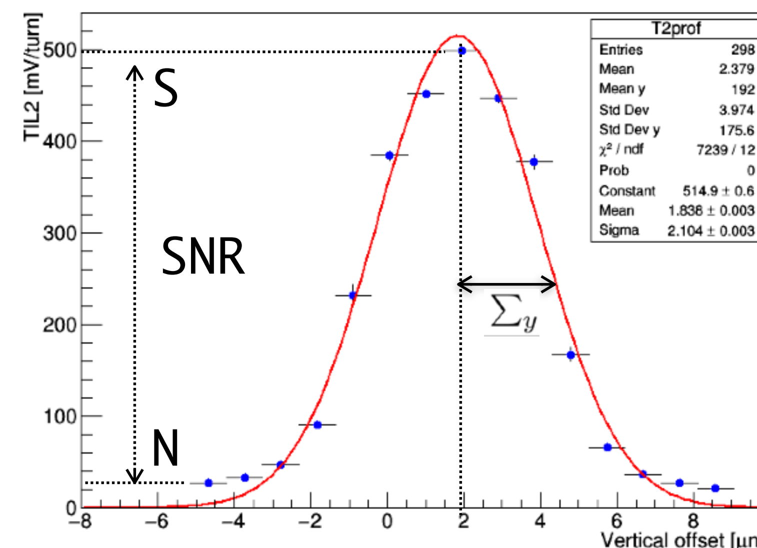
$$\Sigma_y^2 = \sigma_{1,y}^2 + \sigma_{2,y}^2 \approx 2\sigma_y^2$$



Fitted vertical beam size



Luminosity



Monitor	SNR
ZDLM LER-IntI	28.6
ZDLM LER-Count	28.3
ZDLM HER-Count	2.3
LumiBelle2 LER-A	28.45
LumiBelle2 LER-C	17.45
LumiBelle2 HER-A	3.95

Luminosity @ $8.71\times10^{32}cm^{-2}s^{-1}$

➡ In general, beam size goes down with β_y^* squeezing

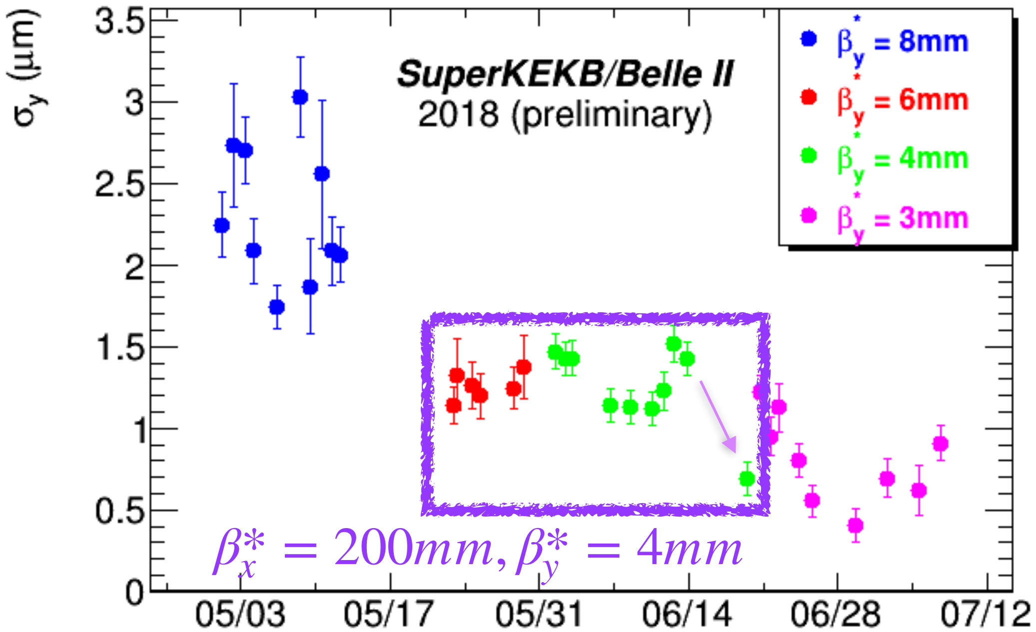
➡ Beam-beam blow up was observed for β_y^*=3/4 mm

➡ Luminosity calculated based on geometry is always larger than ECL luminosity ➞ beam-beam blow up

➡ Beam-beam simulation is under study right now

Vertical offset scan

- Adjustment of XY coupling with QC1 Skew quadrupoles



σ_y^* estimation at IP:

- Estimation from X-Ray beam size monitor:

σ_y^* =0.4/0.5 um (LER/HER) No change after adjustment of X-Y coupling (R2) at IP!

- Measurement by luminosity monitor with beam-beam scan:

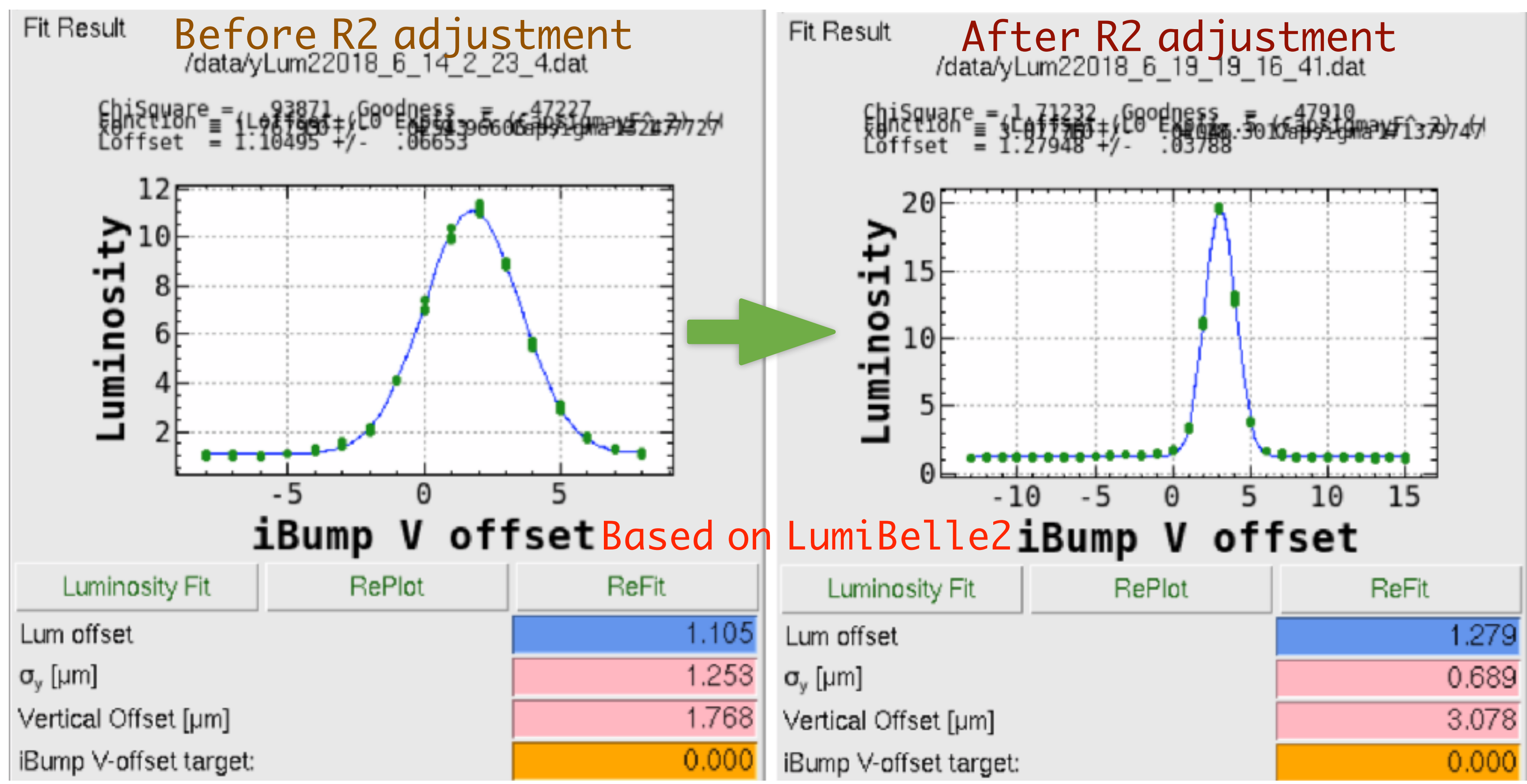
σ_y^* =1.253 um → 0.689 um Effective tool to measure the beam size at IP!

<u>Sensitive luminosity monitor is quite essential for local IP optical tuning !</u>

Extremely low bunch current: 15.8 mA/1576 bunches ~0.1mA/bunch: avoid beam-beam blowup geometrical luminosity.

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

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



Conclusion and prospects

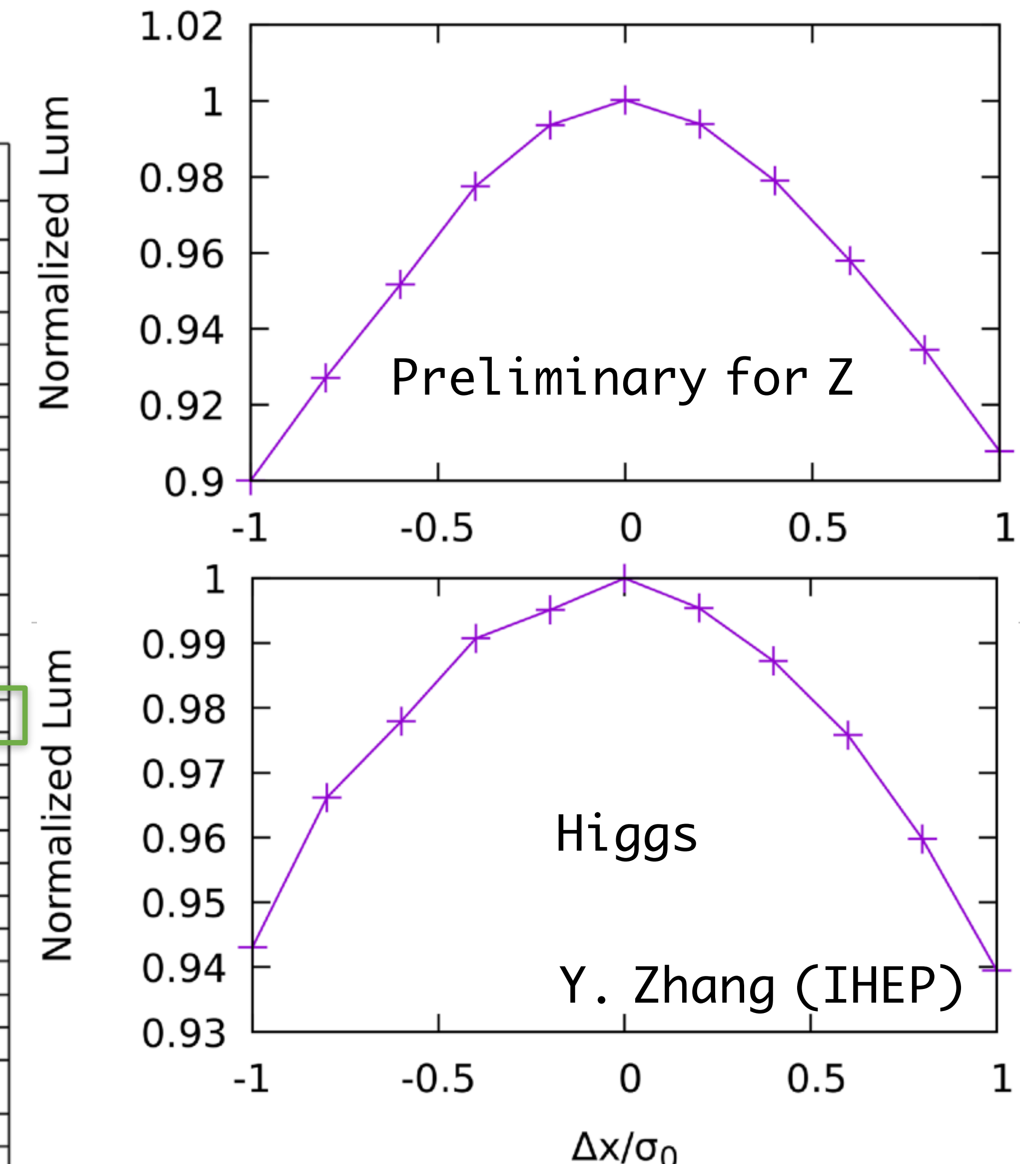
- LumiBelle2 and ZDLM were operating as expected during Phase-2
  - Useful real time luminosity information for SuperKEKB
  - Compatible results with simulation for single beam backgrounds
  - Good correlation with other luminosity monitors
  - Successful 1th test as input to horizontal IP orbit dithering feedback
  - Vertical beam size evaluation at IP from vertical offset scanning
- Plans:
  - Increase HER signal rate (new better location)
  - Faster charge amplifiers & lower current amplifier
  - Long-term DAQ, more channels ?
  - Keep good sensitivity and cover large luminosity range of 10^{32}~10^{36}cm^{-2}s^{-1}
  - Shielding / protection to mitigate activation & limit accumulated radiation dose

➡ More test on horizontal IP orbit dithering feedback

Conclusion and prospects

- Possible application to CEPC ?

	Higgs	*W*	*Z (3T)*	*Z (2T)*
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	**0.36/0.0015**	**0.36/0.0015**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	**1.35**	**0.4**	**0.23**	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	**0.67**	**1.4**	**4.0**	**2.1**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* (10^{34}cm^{-2}s^{-1})	**2.93**	**10.1**	**16.6**	**32.1**



Luminosity degradation @ CEPC

- Sensitive luminosity monitoring may be very important for local IP optical tuning with extremely low beam currents to avoid beam-beam blow-up and get geometrical luminosity
- Horizontal beam sizes all are a few um, like SuperKEKB, but will geological conditions for CEPC candidate sites be better than KEK?
- Luminosity is not so sensitive to horizontal beam-beam offset, while for long-term drift, luminosity-driven orbit dithering feedback might also be useful and effective ?

Thank You

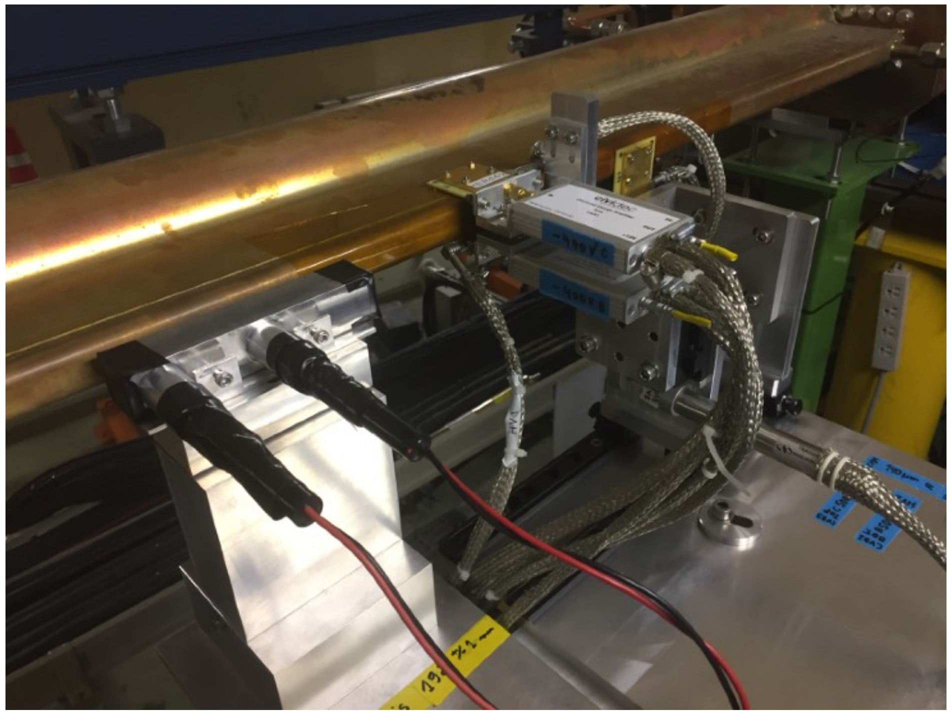
SuperKEKB Phase-2 key machine parameters

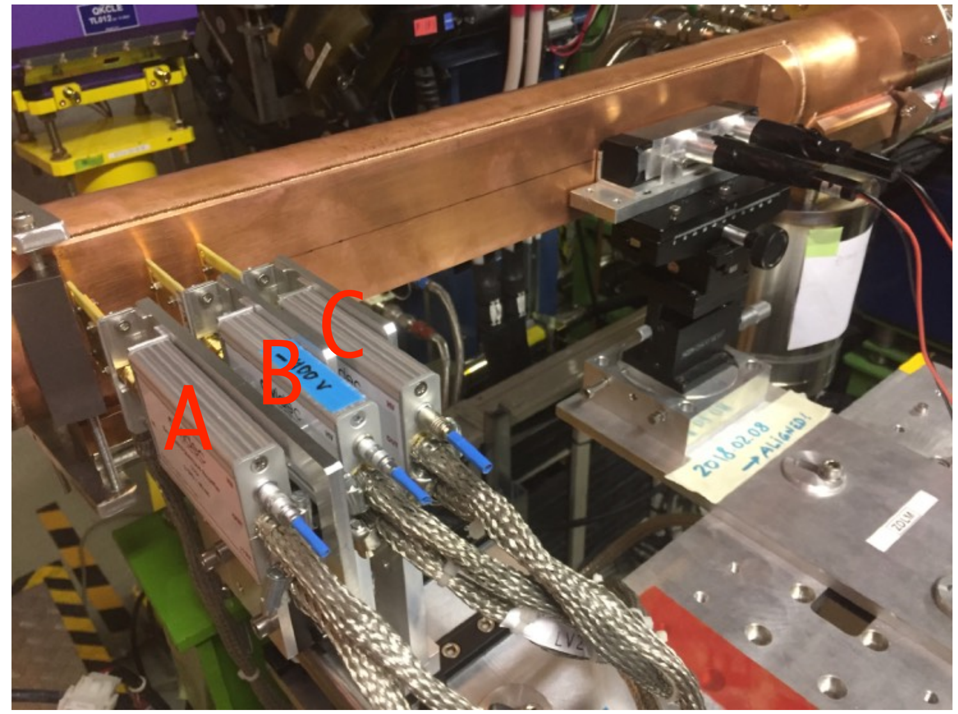
	KEKB (2006)		Phase 2.1		Phase 2.2		Phase 2.3		Phase 2.4	
	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER
β_x [mm]	590	560	200	200	256	200	128	100	128	100
β_y [mm]	6.5	5.9	8	8	2.16	2.40	2.16	2.40	1.08	1.2
ε_x [nm]	18	24	2.1	4.6	2.1	4.6	2.1	4.6	2.1	4.6
$\varepsilon_y/\varepsilon_x$ [%]	**3**	**2.5**	**10**		**5.0**		**1.4**		**0.7**	
σ_x^* [μm]	103	116	20	30	23.2	30.3	16.4	21.4	16.4	21.4
σ_y^* [nm]	1900	1900	1296	1918	476	743	252	393	126	197
σ_z [mm]	7	7	6	6	6	5	6	5	6	5
ϕ_x [mrad]	11		41.5		41.5		41.5		41.5	
Φ	**0.75**	**0.66**	**12.5**	**8.3**	**10.7**	**8.2**	**15.2**	**9.7**	**15.2**	**9.7**
Remark	1.72×10^{34} cm^{-2}s^{-1}		10^{33} cm^{-2}s^{-1}		10^{34} cm^{-2}s^{-1}		2×10^{34} cm^{-2}s^{-1}		4×10^{34} cm^{-2}s^{-1}	

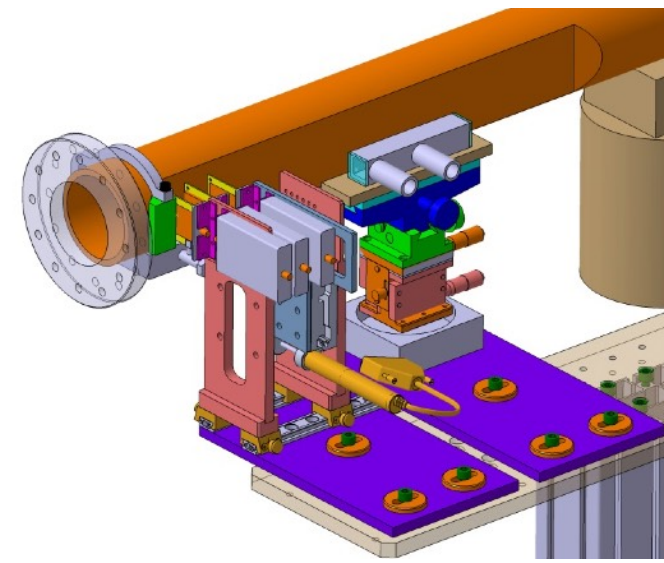
Summary of Beta squeezing at IP

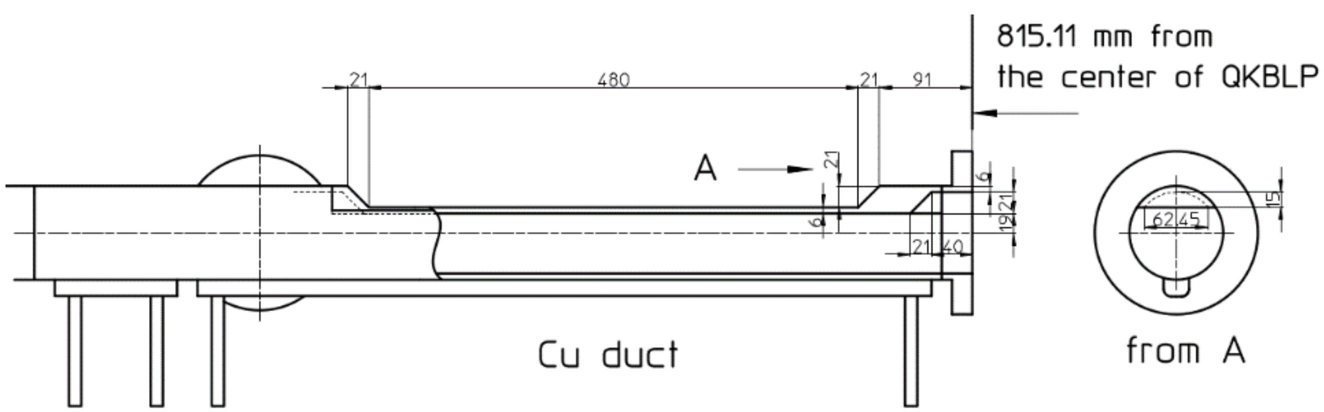
Phase	β_x^* [mm]		β_y^* [mm]		comment	L_{peak} x10^{33} [$cm^{-2}s^{-1}$]	I_{LER} / I_{HER} , n_b [mA]	Start Date
	LER	HER	LER	HER				
2.1.0	200		8		Luminosity Run	0.93	250 / 220, 600	April 16
2.1.1	200		6		Luminosity Run	1.37	340 / 285, 789	May 22
2.1.2	200		4		Luminosity Run	1.36 no improve	340 / 285, 789	May 28
2.1.3	200		4	3	Luminosity Run	1.32	340 / 285, 789	June 8
2.1.4	200		3		Luminosity Run	1.05	320 / 265, 789	June 11
2.1.5	100		4		Luminosity Run	1.09	340 / 285, 789	June 12
2.1.6	200	100	4		Luminosity Run	2.04 improve !	350 / 295, 789	June 13
2.1.7	200	100	3		Luminosity Run	2.6	340 / 285, 789	June 20
2.2.0	200		2		Optics correction 50 mA	N/A	50 / 50, 1576	June 7
2.3.1	-	100	-	1.5	Optics correction 50 mA	N/A	- / 50, 1576	July 9

Detectors installation



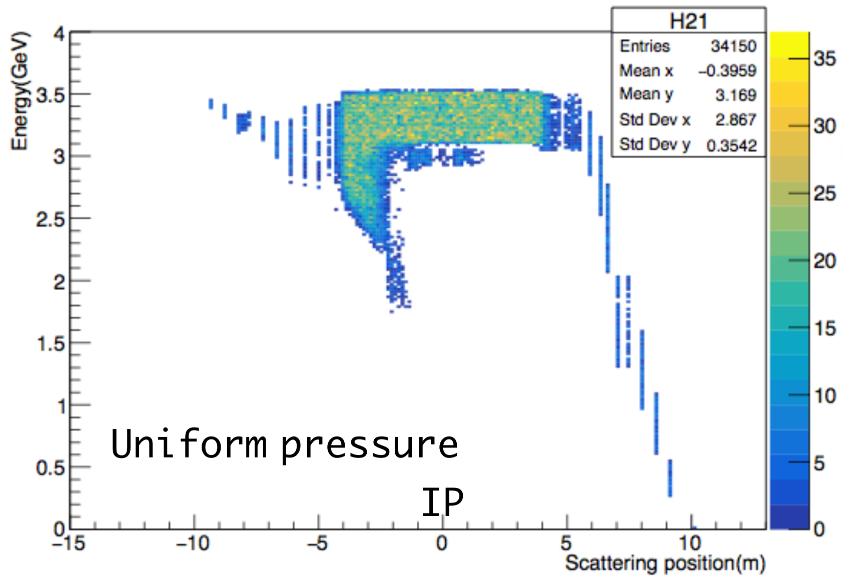


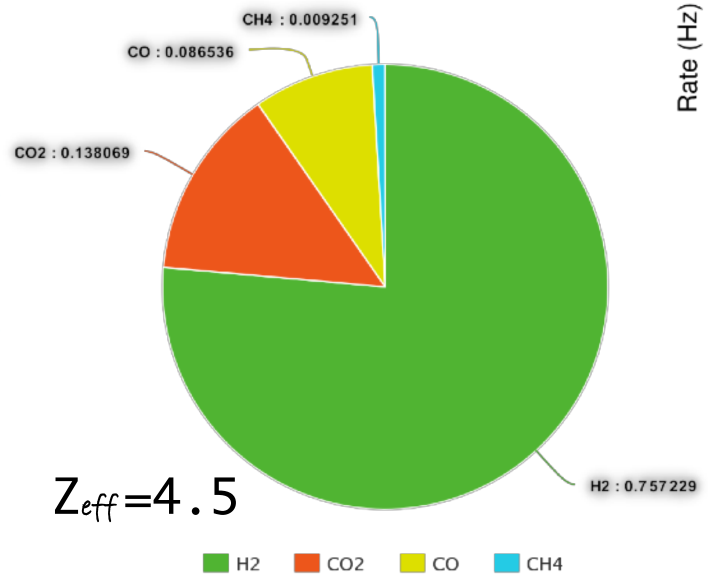




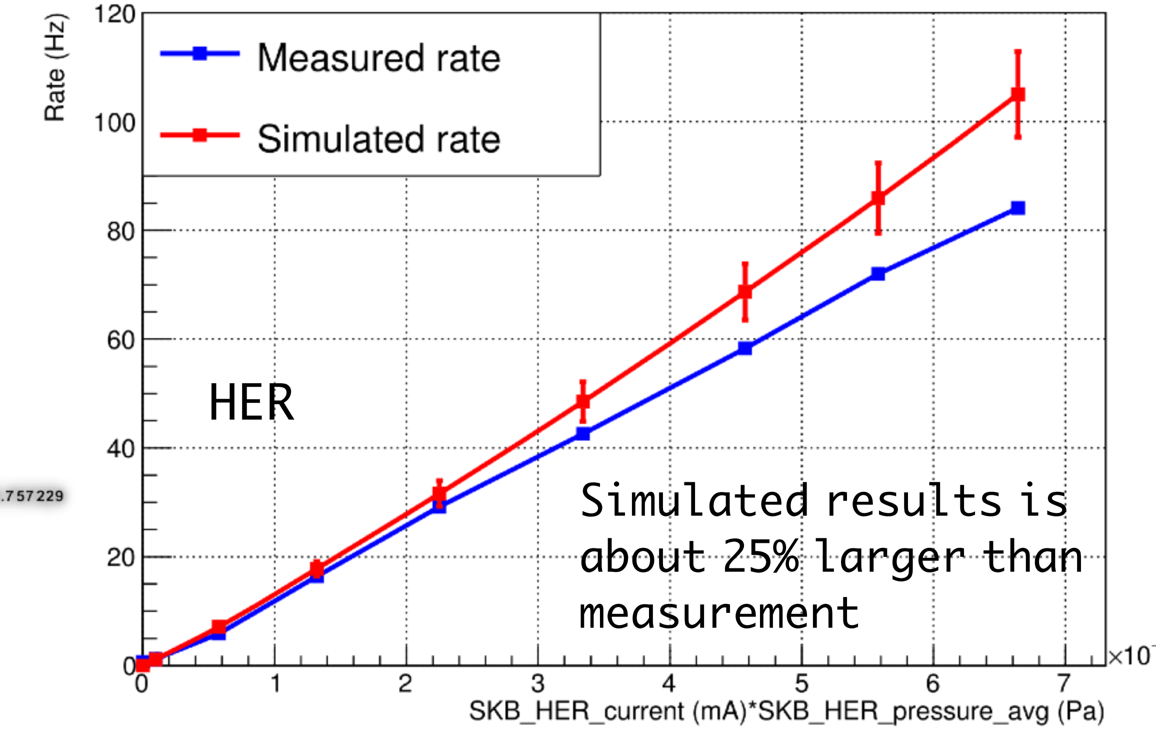
Background study

•Comparison with simulation



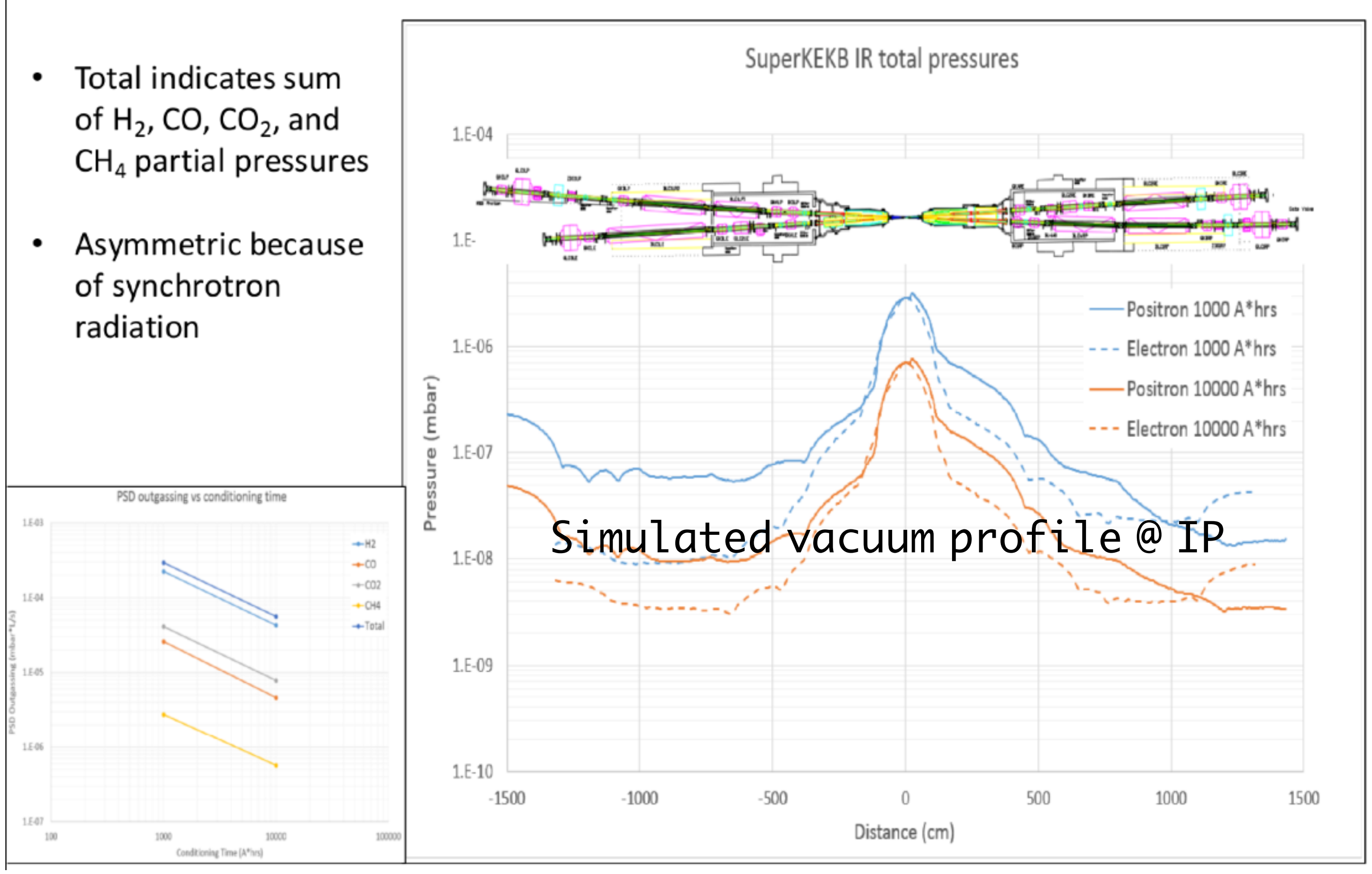


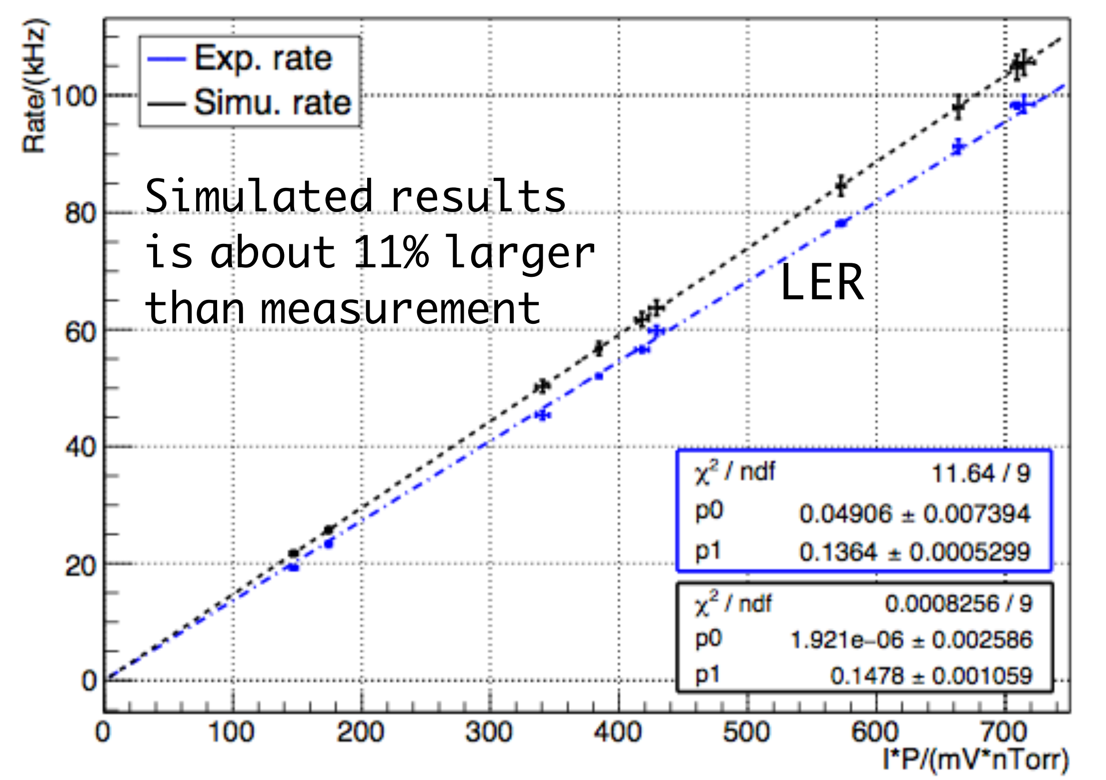
Scattering position of lost particles



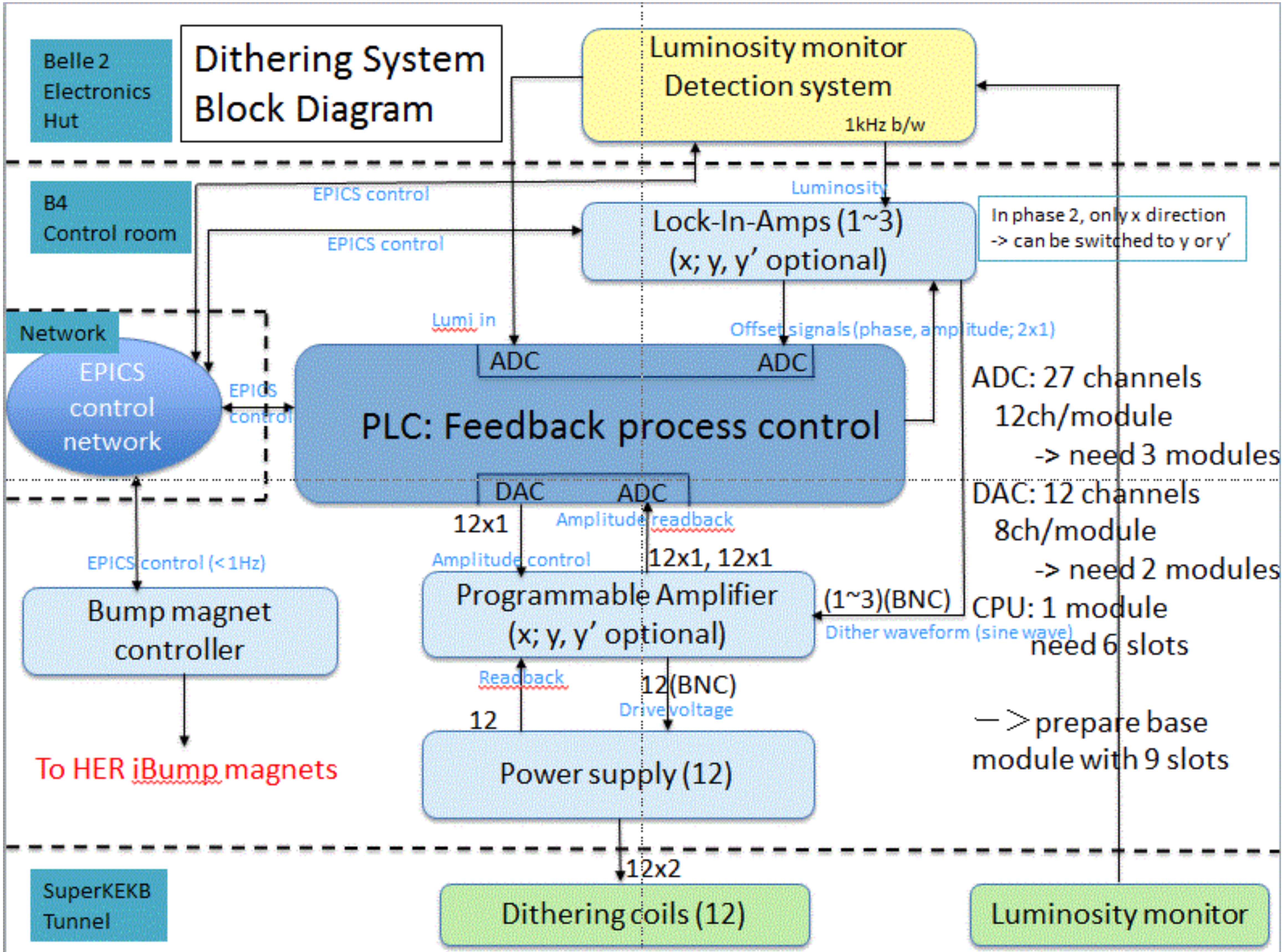
Total pressures at 1000, 10000 A*hrs, I = 3.6 A

- Total indicates sum of H_2, CO, CO_2, and CH_4 partial pressures
- Asymmetric because of synchrotron radiation

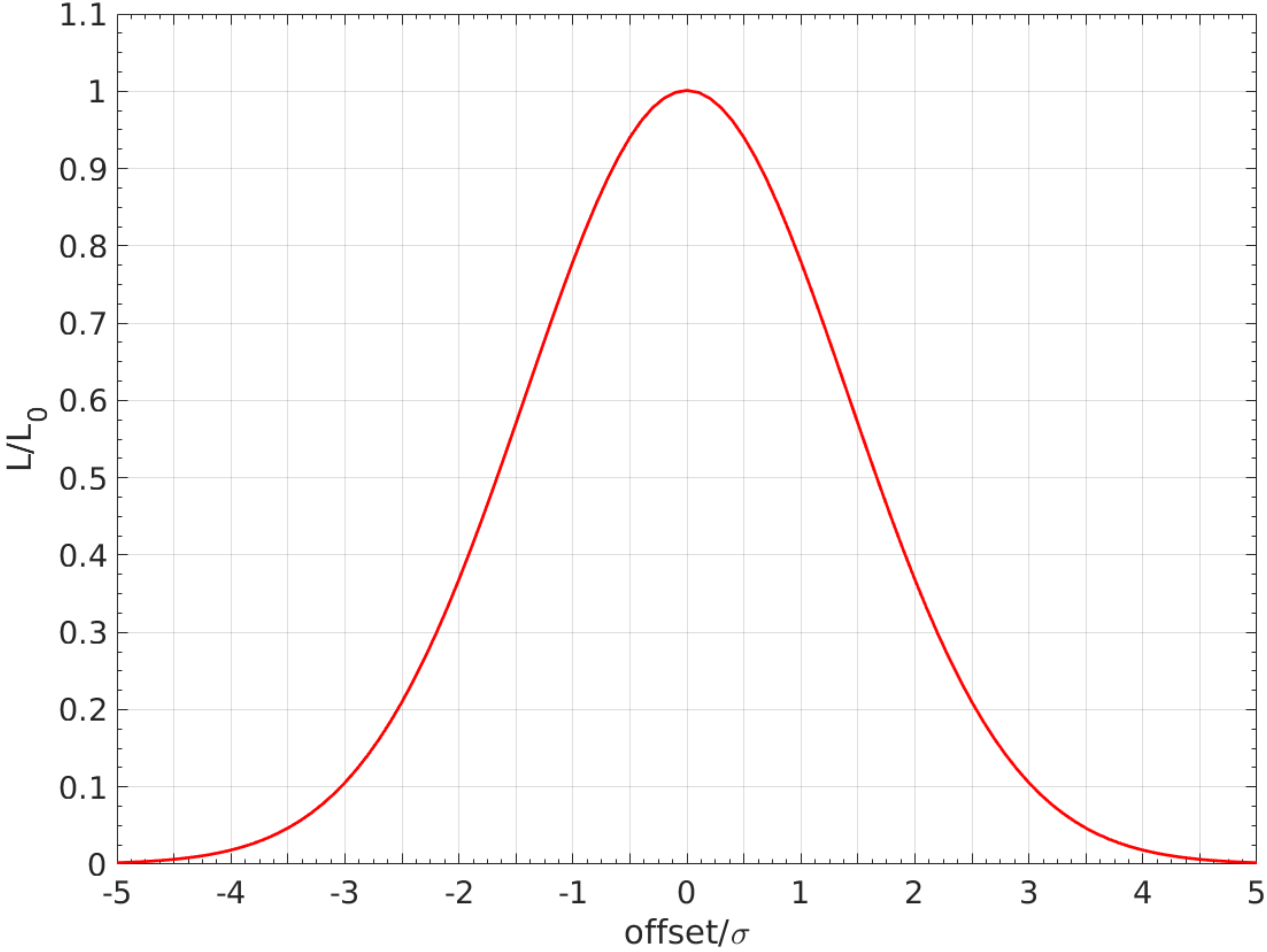




Detailed algorithm of dithering feedback



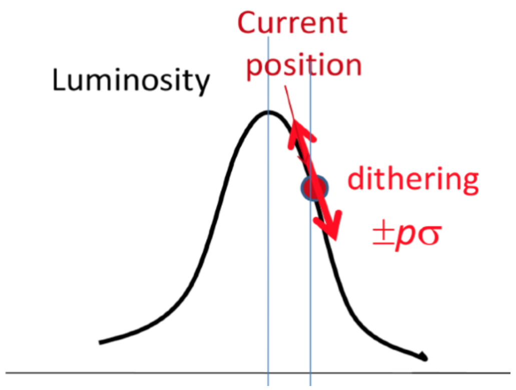
Luminosity vs offset (geometrical)

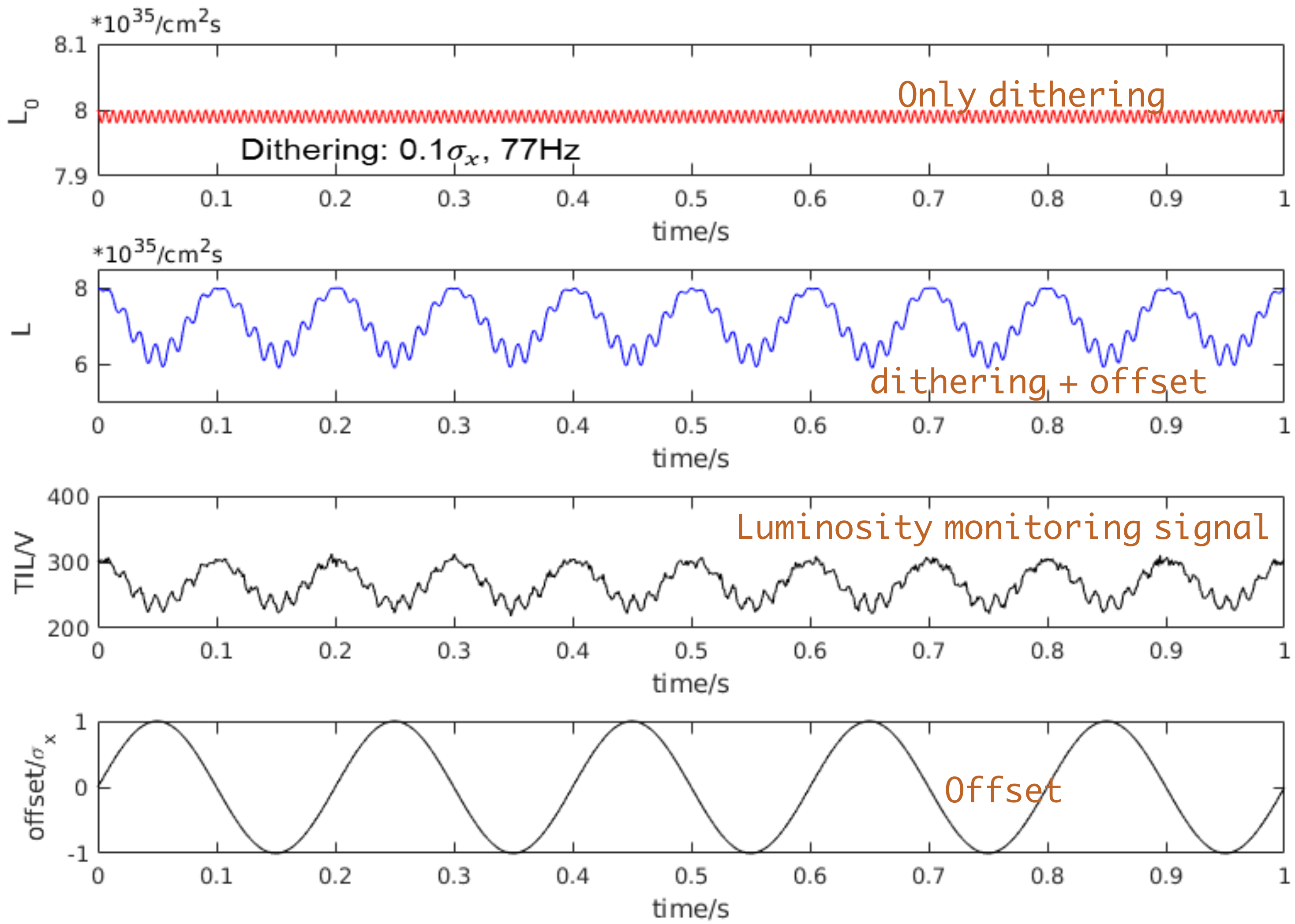


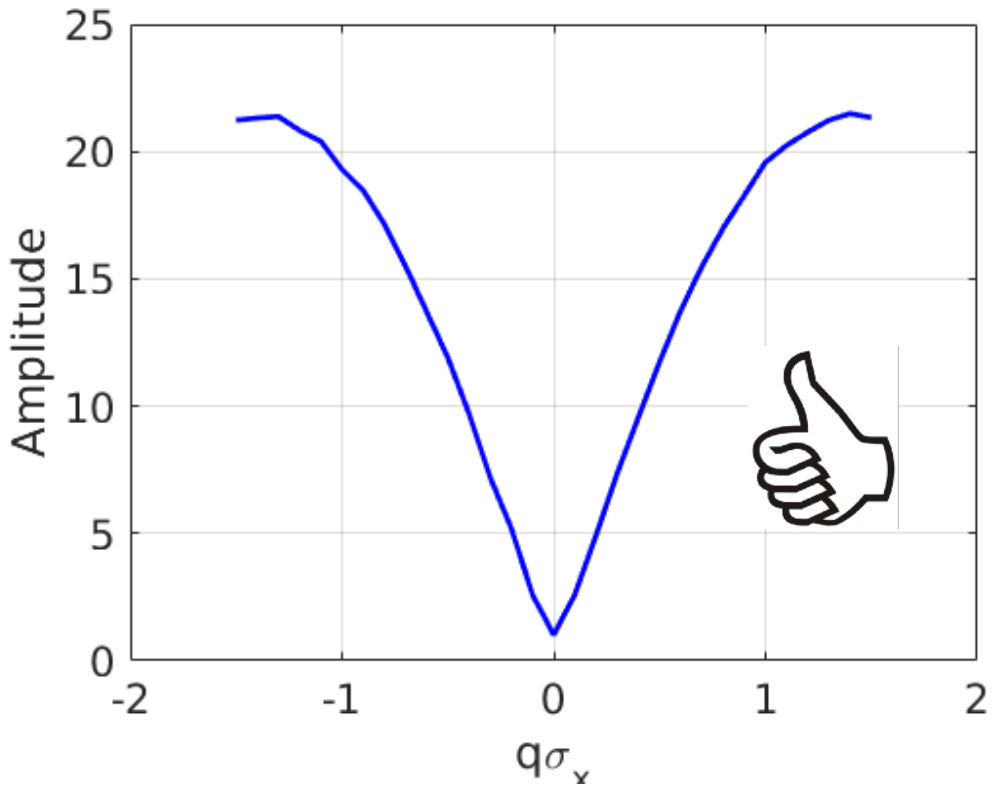
- Lock-in amplifier model

Lock-in amplifier: extract a signal with a known carrier wave from an extremely noisy environment.

$$R = \sqrt{X^2 + Y^2}, \quad \theta = arctan(\frac{Y}{X})$$
$$X = \sum V_i \times cos(2\pi f t_i), \quad Y = \sum V_i \times sin(2\pi f t_i)$$







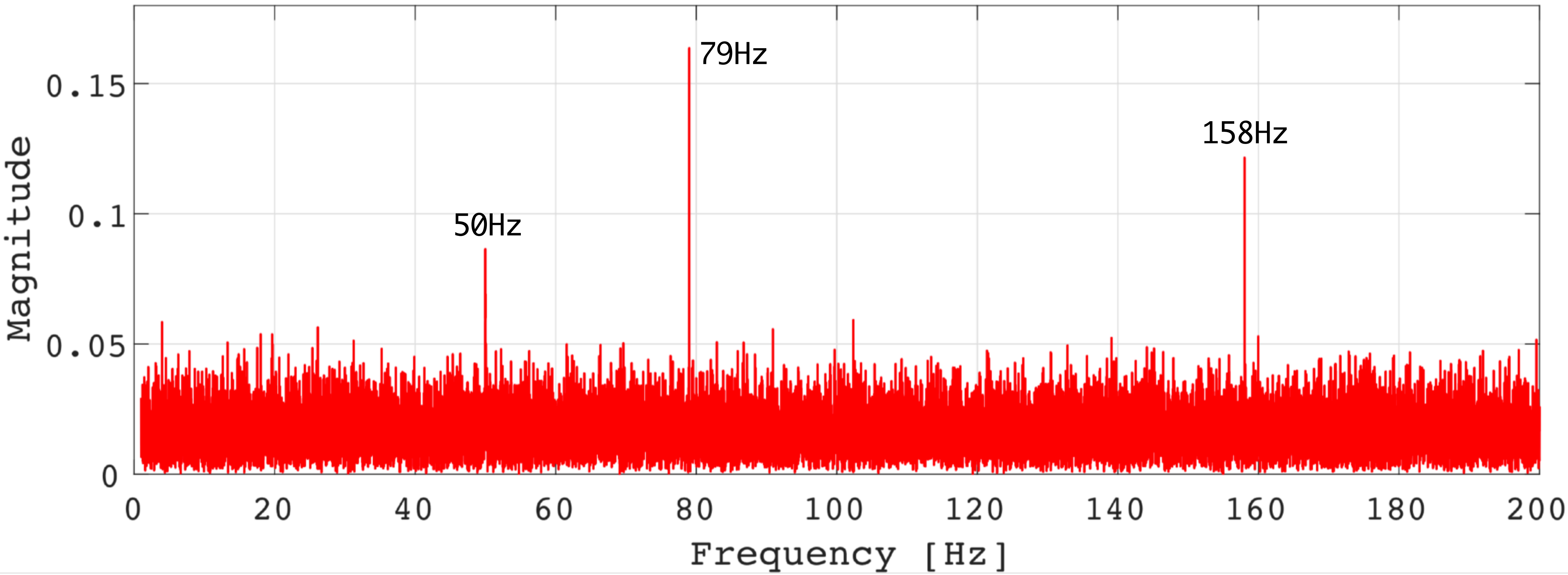
Magnitude of base-frequency

Magnitude of double-frequency

Maximise the magnitude of double frequency
Minimise the magnitude of base frequency

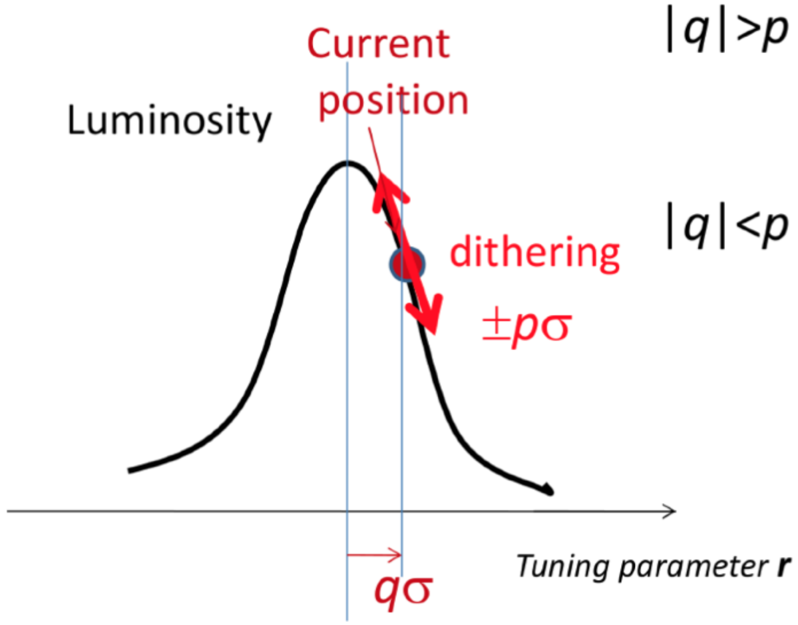
Dithering study

- Measurement with spectrometer



- Peaks at dithering frequency were observed for both detectors
- LumiBelle2 failed to observe the peak at double frequency because it is currently operated with a higher threshold than foreseen
- Dithering algorithm is validated

Offset phase



$|q|>p$ goes up and down on a side of slope

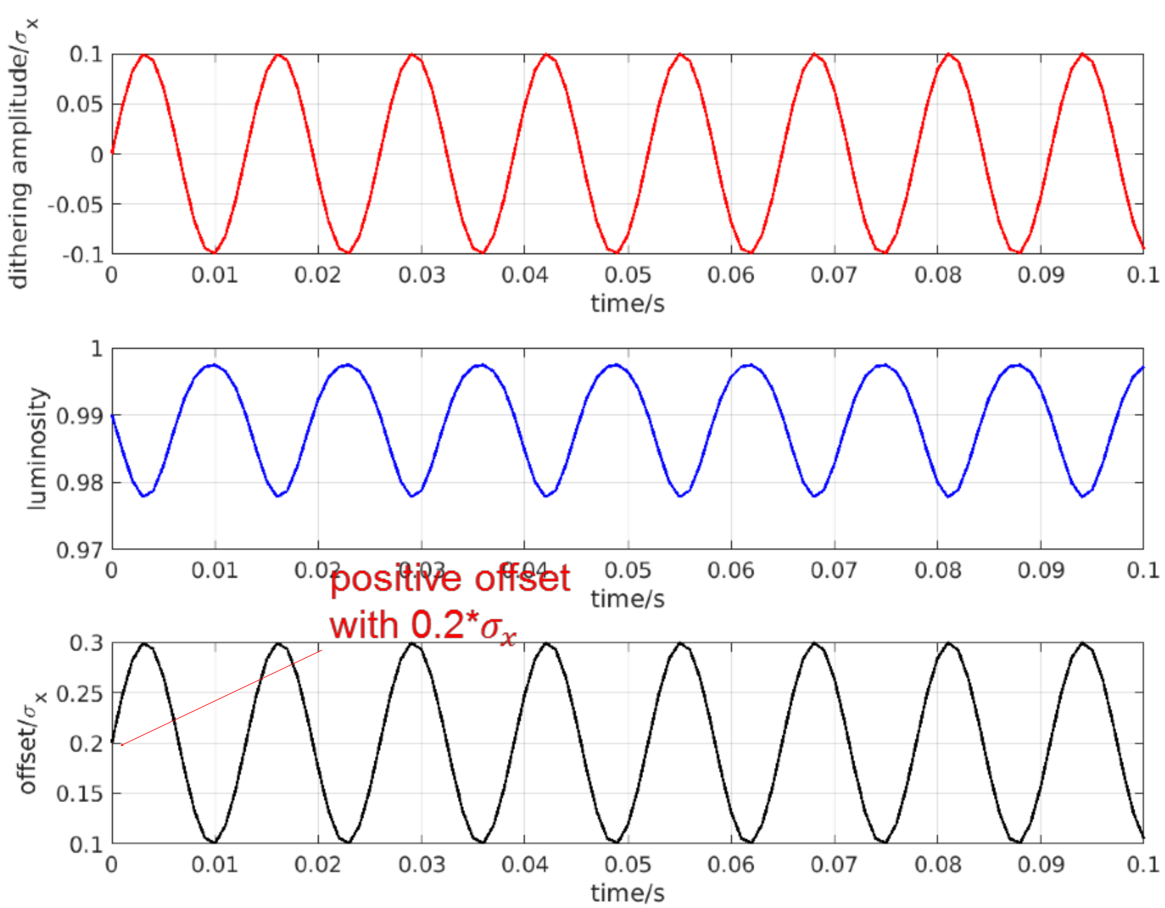
$|q|<p$ goes over across the peak

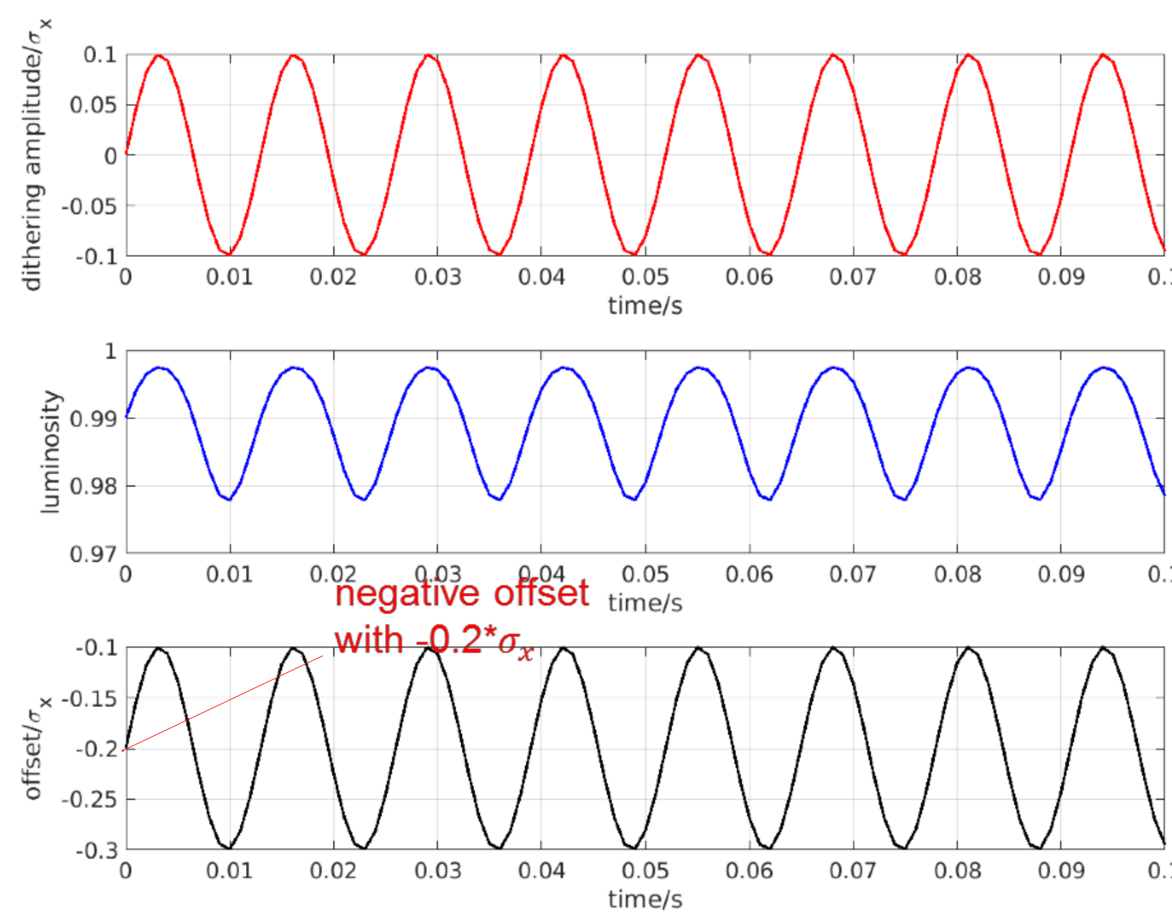
Assuming the dither driving is sine wave with frequency of 77Hz:

positive offset ⇒ inverse phase

negative offset⇒ same phase

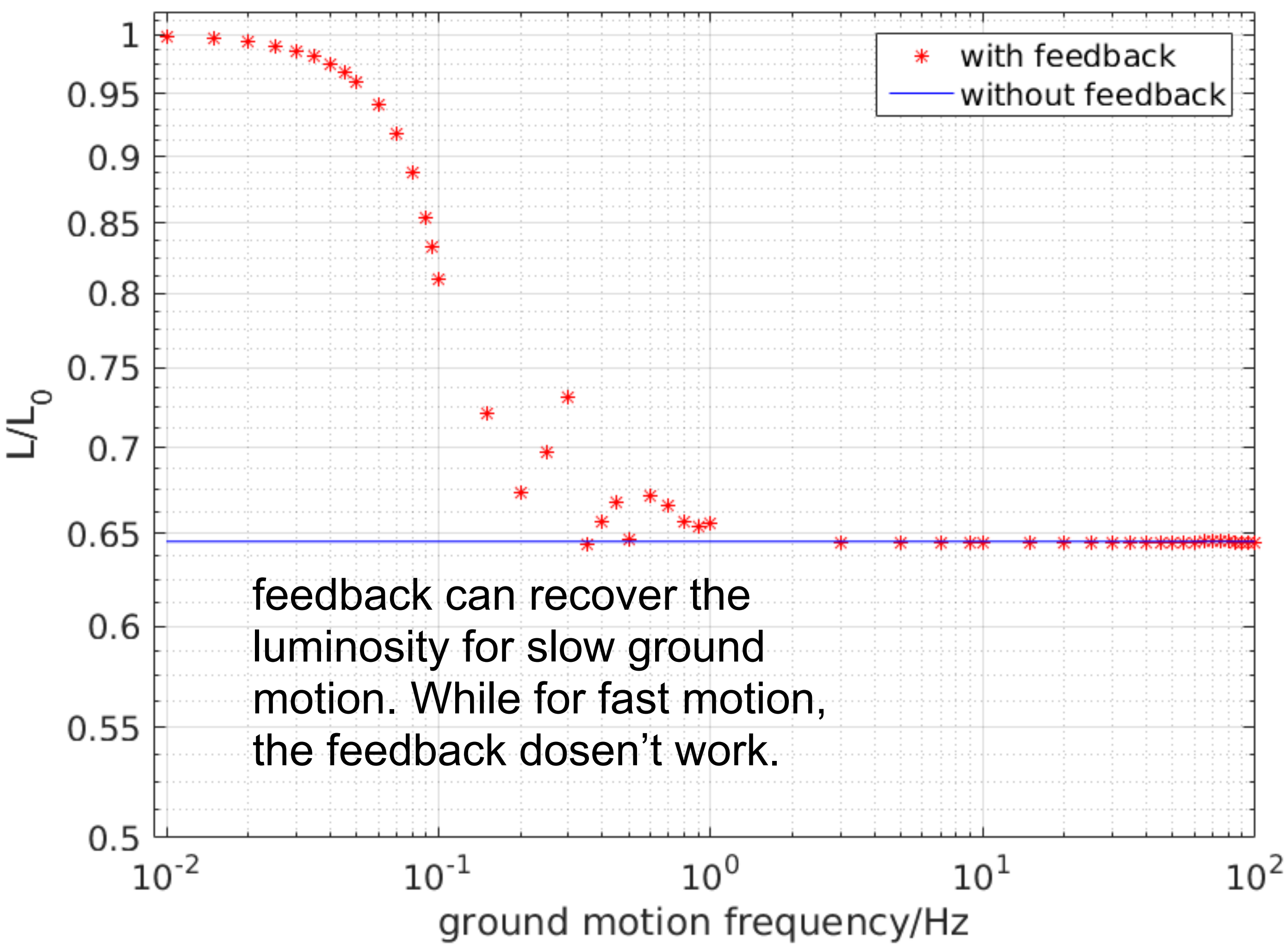
*Care must be taken with the phase difference between dither driving and luminosity measurement.
Offset sign can get at the last dithering cycle before correction.

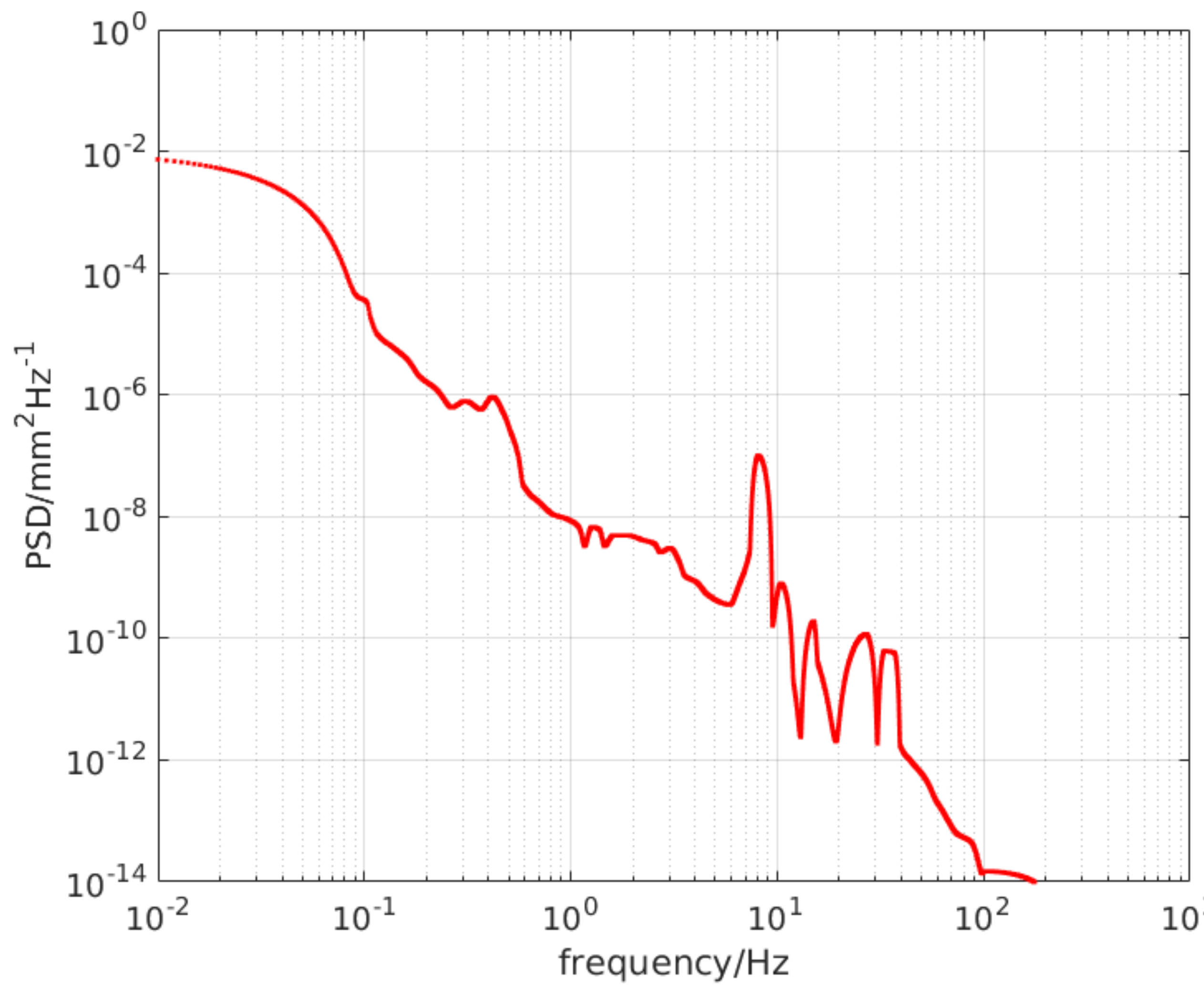




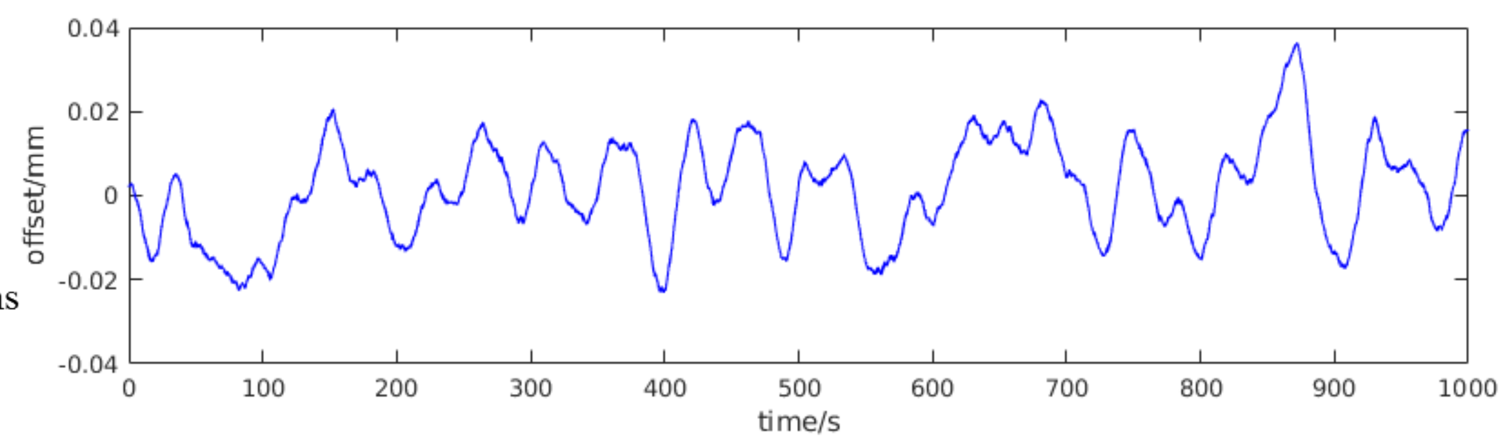
Dithering feedback simulation

- Ground motion data in time domain can be gotten from measured PSD with iFFT , and is used to represent beam-beam offset





- Head-on collision
- σ_x: 10 μm
- Dithering: 0.1*σ_x, 77Hz
- Correction frequency: 1Hz
- Lock-in amplifier input: luminosity monitoring data in last 1s
- Relative precision of luminosity monitoring signal: 0.01 in 1ms
- GM amplitude: 2*σ_x



Dithering feedback simulation

- Ground motion data in time domain can be gotten from measured PSD with iFFT , and is used to represent beam-beam offset

Example of dithering feedback simulation with Phase-3 parameters