Realizing high luminosity at SuperKEKB

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on behalf of the SuperKEKB commissioning group

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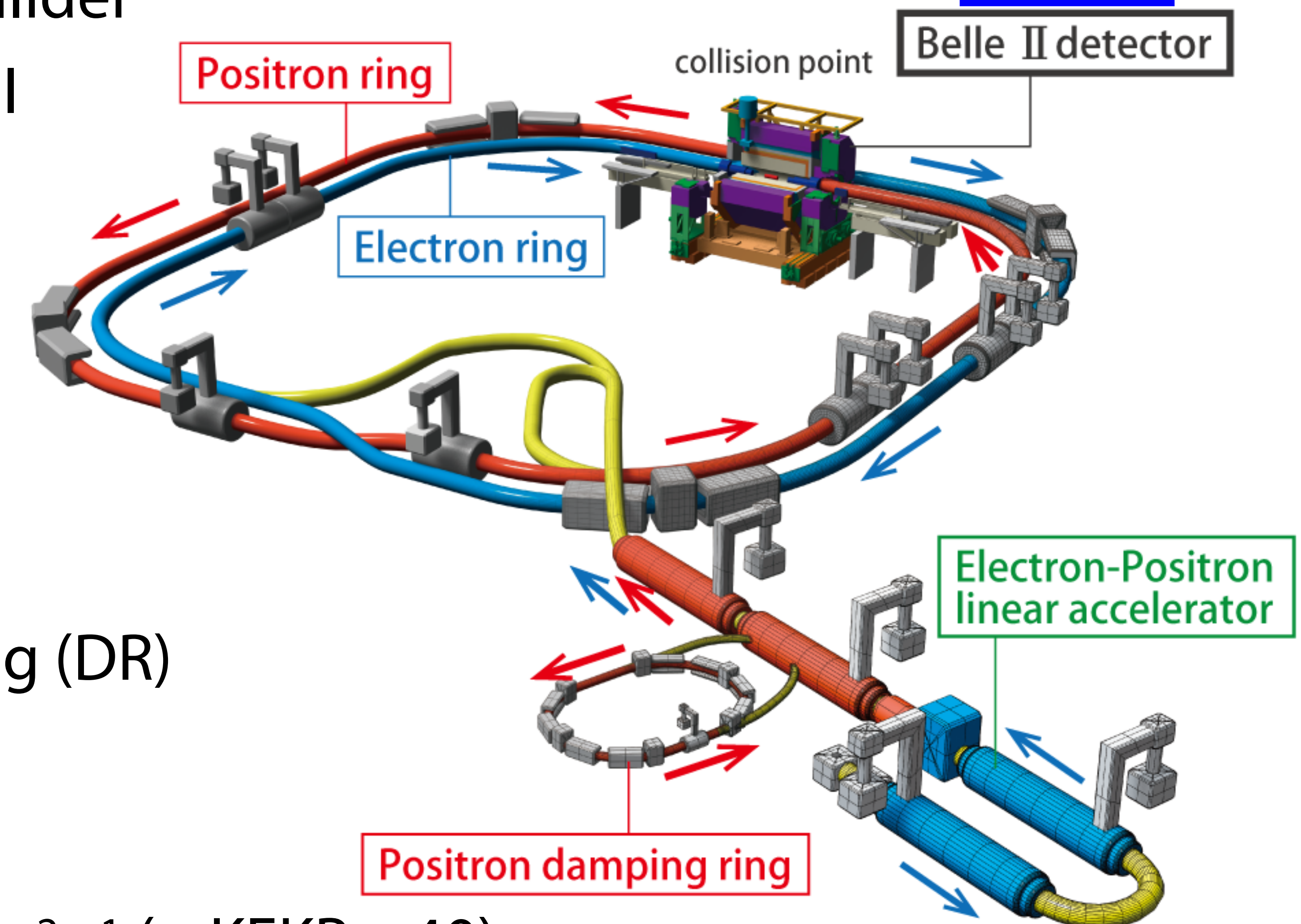
Outline

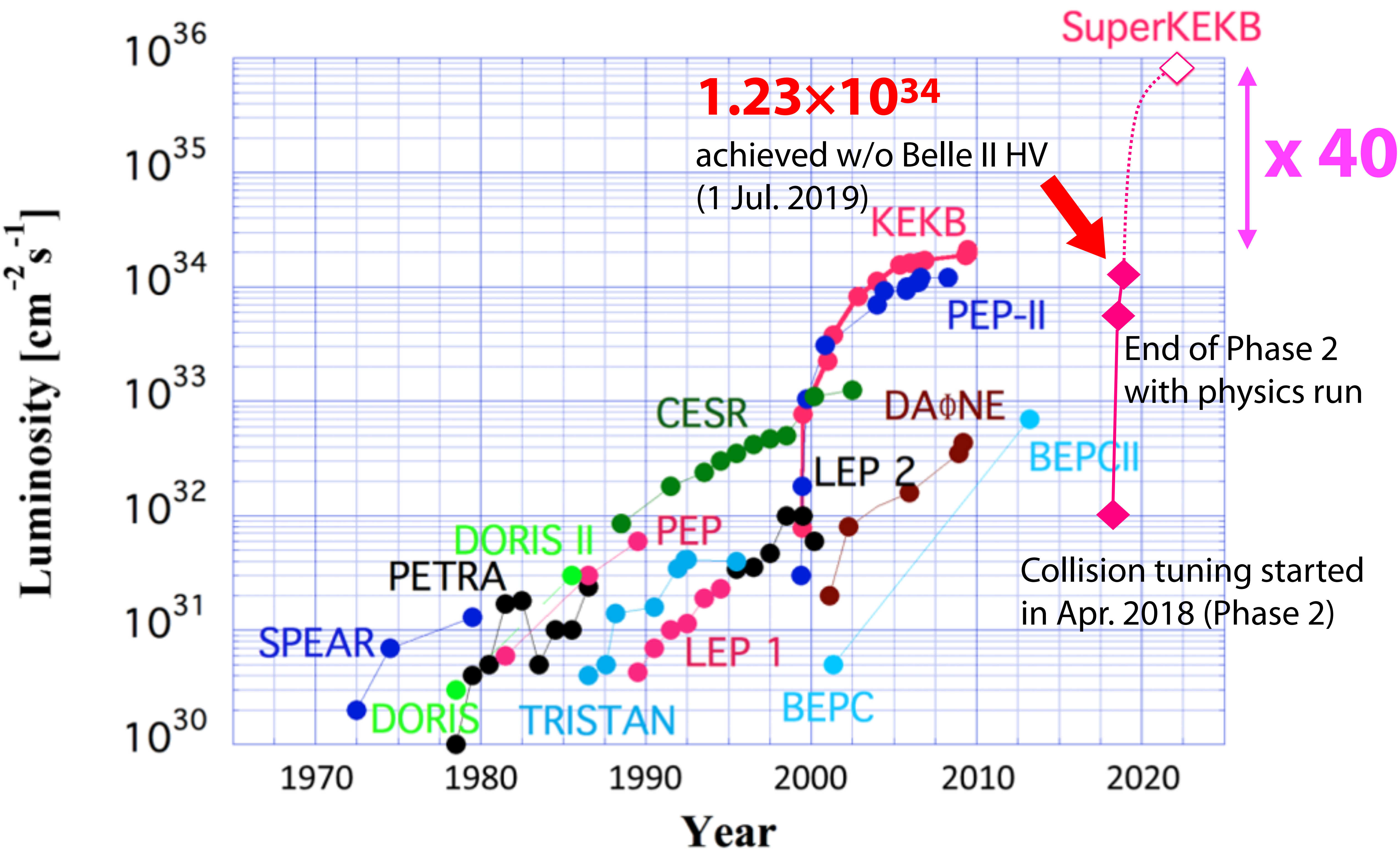
- Introduction to the SuperKEKB e^+e^- collider
- Phase 2 commissioning summary
- Phase 3 commissioning summary
- Commissioning plan in coming years
- Summary

The SuperKEKB e^+e^- collider

- Major upgrade to the KEKB e^+e^- collider providing tons of B, τ, etc. to Belle II
- Main rings
  - 7 GeV e^- storage ring (HER)
  - 4 GeV e^+ storage ring (LER)
- Injector complex
  - Electron/positron linac
  - 1.1 GeV positron damping ring (DR)
- "Nano-beam" collision scheme
- Design parameters
  - Target Luminosity: 8 x 10^{35} $cm^{-2}s^{-1}$ (= KEKB x 40)
  - Beam Currents: 3.6 A (LER) and 2.6 A (HER)
  - Horizontal crossing Angle: 41.5+41.5 mrad
  - β_y^* ~ 0.3 mm
  - σ_x^* ~ 10 μm, σ_y^* ~ 50 nm, σ_z ~ 6 mm

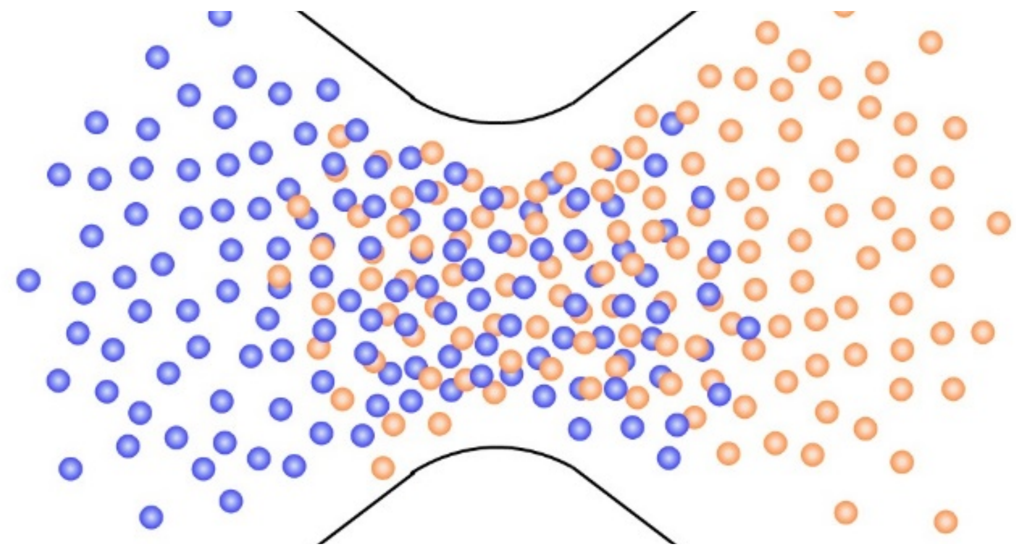


History of peak luminosity (e^+e^- collider)



What is the nano-beam collision scheme?

Luminosity increases in general as β_y^* decreases. But, increase in luminosity will be tamed at $\beta_y^* < \sigma_z$ due to hourglass effects.



Nano-beam collision scheme [Raimondi, 2007]

With finite crossing angle ϕ_x, effective bunch length becomes $\sigma_{z,eff} = \dfrac{\sigma_x^*}{\phi_x}$.

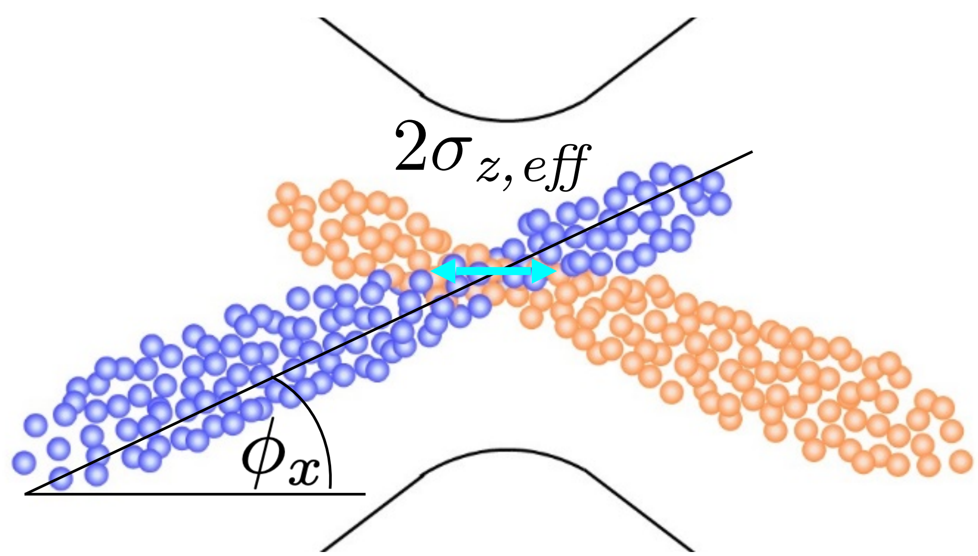
Condition to avoid hourglass effects

$$\beta_y^* > \frac{\sigma_x^*}{\phi_x} = \frac{\sigma_z}{\Phi} \quad \left(\Phi = \frac{\sigma_z \phi_x}{\sigma_x^*} \sim 20 \right)$$

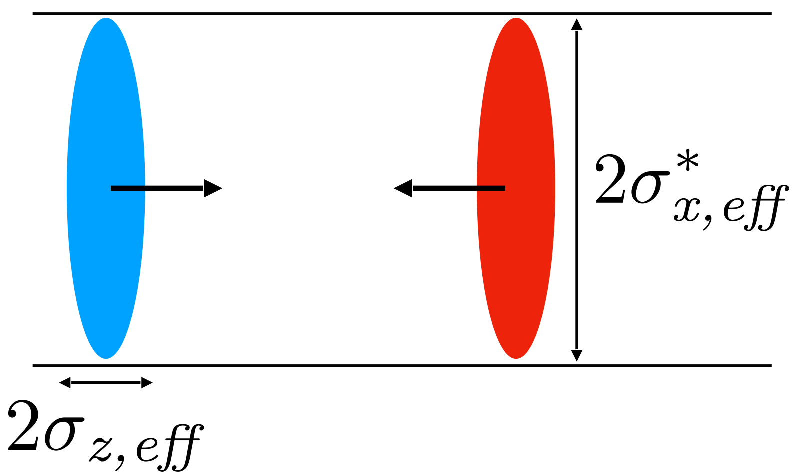
enables squeezing β_y^* by $1/\Phi$

(Φ is called Piwinski angle.)

Not too large Φ to avoid synchro-beta coupling



Luminosity in the nano-beam scheme



Beam-beam collision in the nano-beam scheme can be represented using the effective beam sizes.

Horizontal beam size: $\sigma^*_{x,\mathit{eff}} = \sigma_z \phi_x$

Bunch length: $\sigma_{z,\mathit{eff}} = \sigma^*_x / \phi_x$

Luminosity: $L = \dfrac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \dfrac{\gamma_\pm}{2er_e} \dfrac{I_\pm \xi_{y\pm}}{\beta^*_y}$

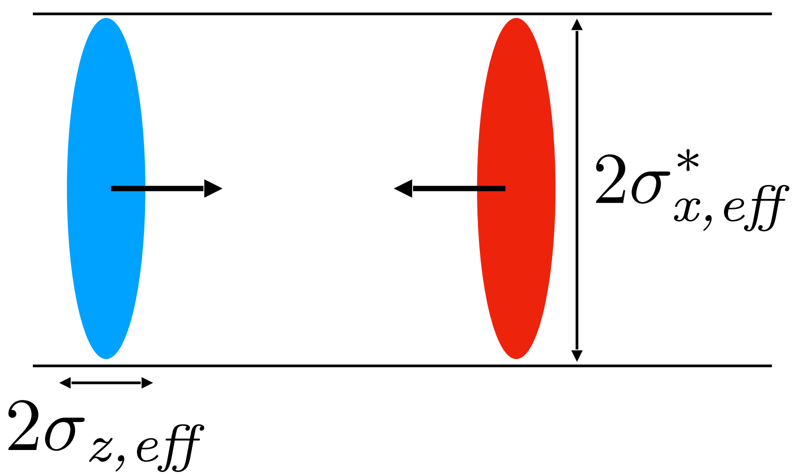
Beam-beam parameter: $\xi_{y\pm} = \dfrac{r_e N_\mp}{2\pi\gamma_\pm(\sigma^*_{x,eff})}\sqrt{\dfrac{\beta^*_y}{\varepsilon_y}}$

Strategy towards KEKBx40 luminosity:

$$I_\pm \nearrow 2 \;\wedge\; \beta^*_y \searrow 1/20 \;\wedge\; \xi_y \to 1 \quad \Rightarrow \quad L \nearrow 40$$

(important to reduce ε_y proportional to β_y^* to leave ξ_y constant)

Luminosity in the nano-beam scheme



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Staging of the SuperKEKB commissioning

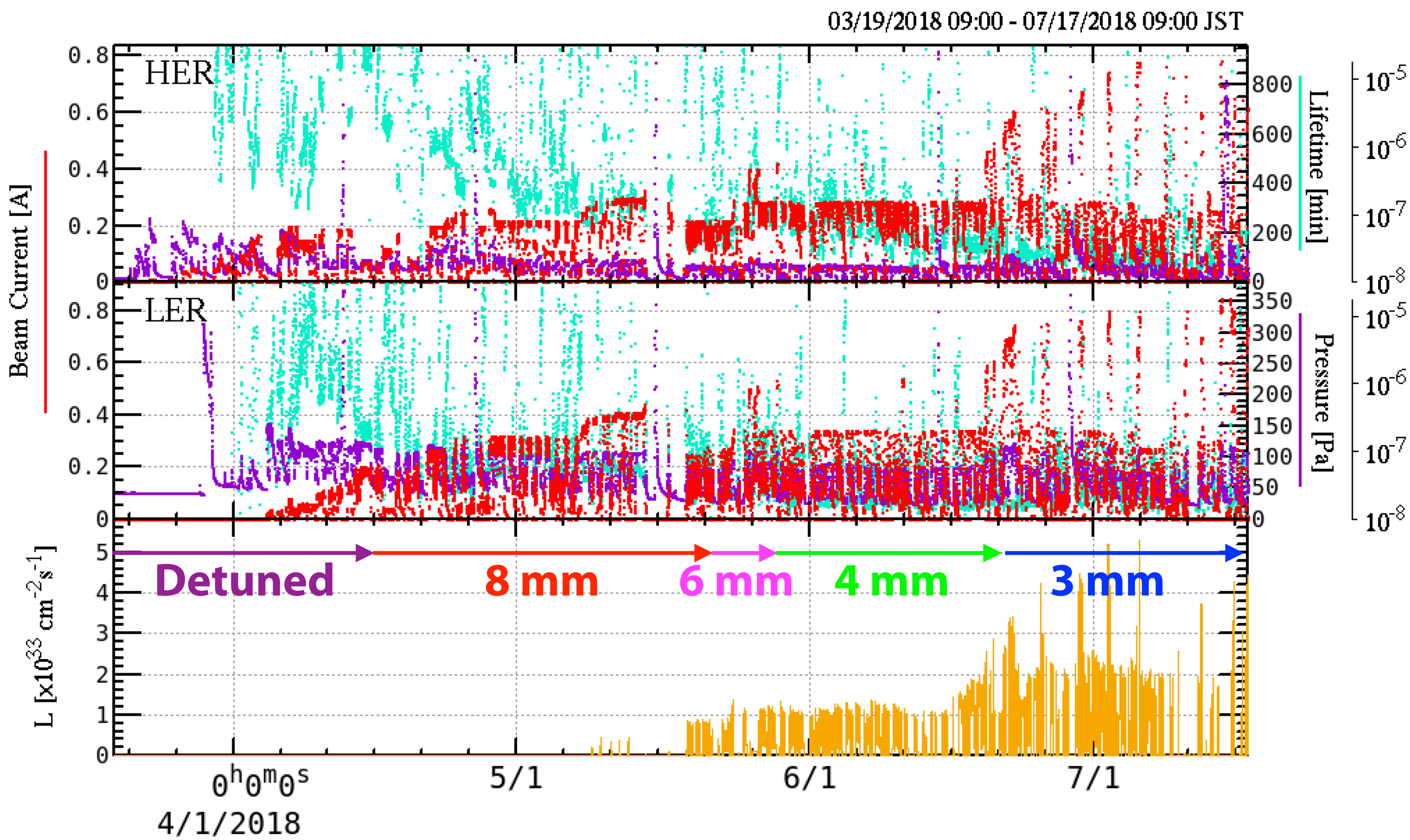
- **Phase 1: 1 Feb. 2016 - 28 Jun. 2016**
  - Vacuum scrubbing without final focus system (QCS)
  - Basic parameter tuning with no beam collision

- **Phase 2: 16 Mar. 2018 - 17 Jul. 2018**
  - With e^+ damping ring (DR) and QCS
  - With the Belle 2 detector except for vertex detectors (VXD)
  - Beta squeezing and beam collision
  - Verification of the nano-beam collision scheme

- **Phase 3: 11 Mar. 2019 - 1 Jul. 2019 and 15 Oct. 2019 -**
  - The “full-scale" Belle II experiment with VXD
  - Beam collision tuning
  - Additional beam collimators

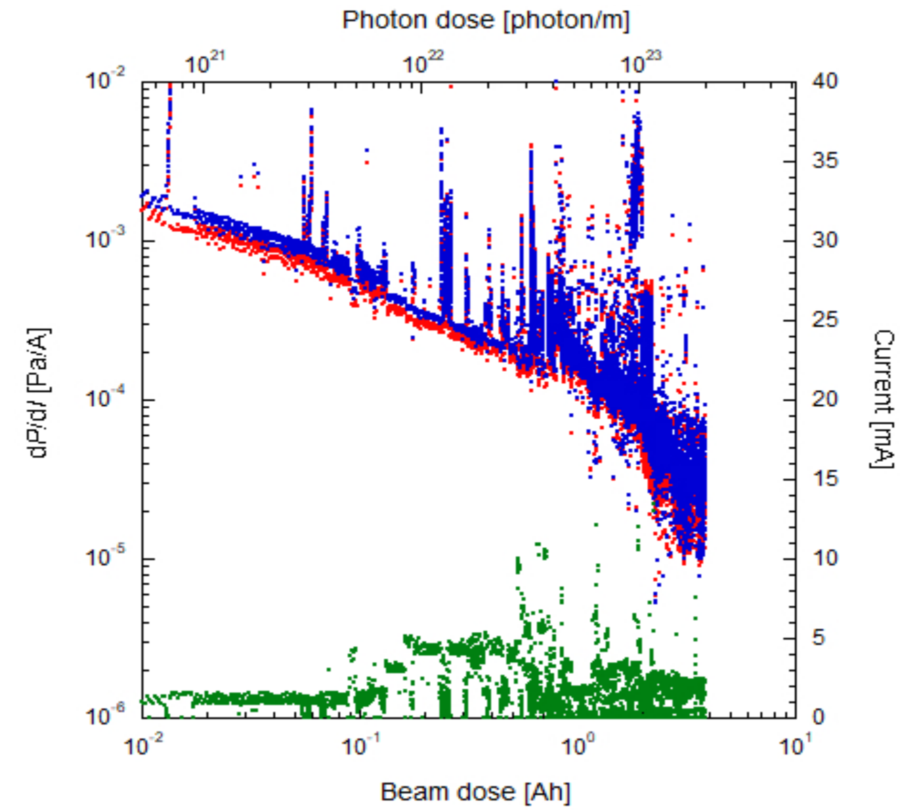
Aims of the Phase 2 commissioning

- Positron beam injection through the DR
- Collision tuning with QCS and the Belle II detector (except for VXD)
- Sustain beam backgrounds at a tolerable level to install VXD in Phase-3
- Demonstrate the nano-beam collision scheme.

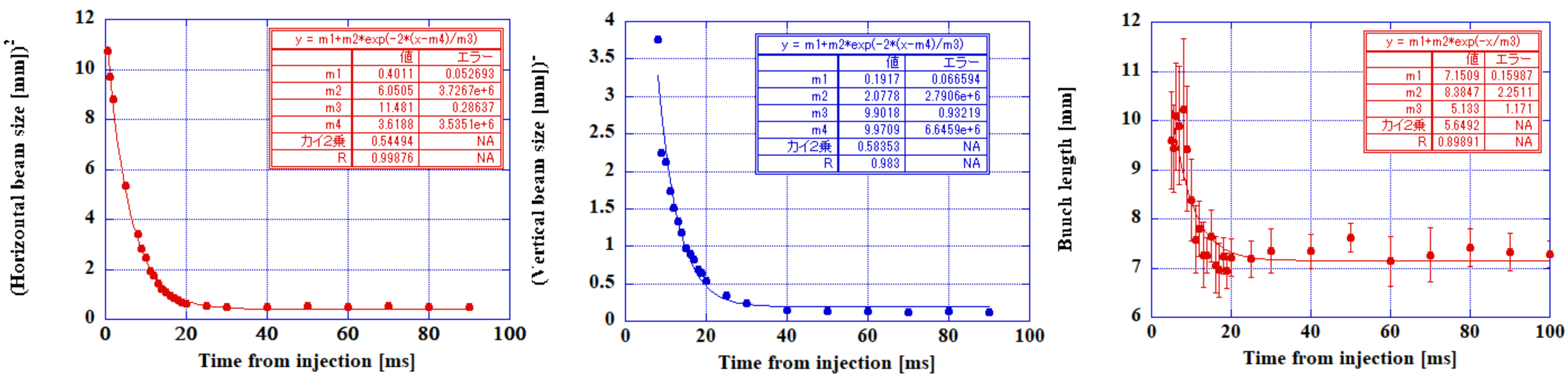


Positron damping ring

- Commissioning starts in Phase 2 (March 2018).
- Injection, storage, and extraction were smoothly commissioned within the first 3 days.
- Beam sizes agree well with the designed values:
  - Design $(\tau_x, \tau_y, \tau_z) = (11.5, 11.7, 5.8)$ [ms]
  - Measured $(\tau_x, \tau_y, \tau_z) = (11.5, 9.9, 5.1)$ [ms]
- Pressure (dP/dI) at the arc section smoothly decreases.
- 2 pulse and 2 bunch modes ready for high-A operation
- No big issue so far



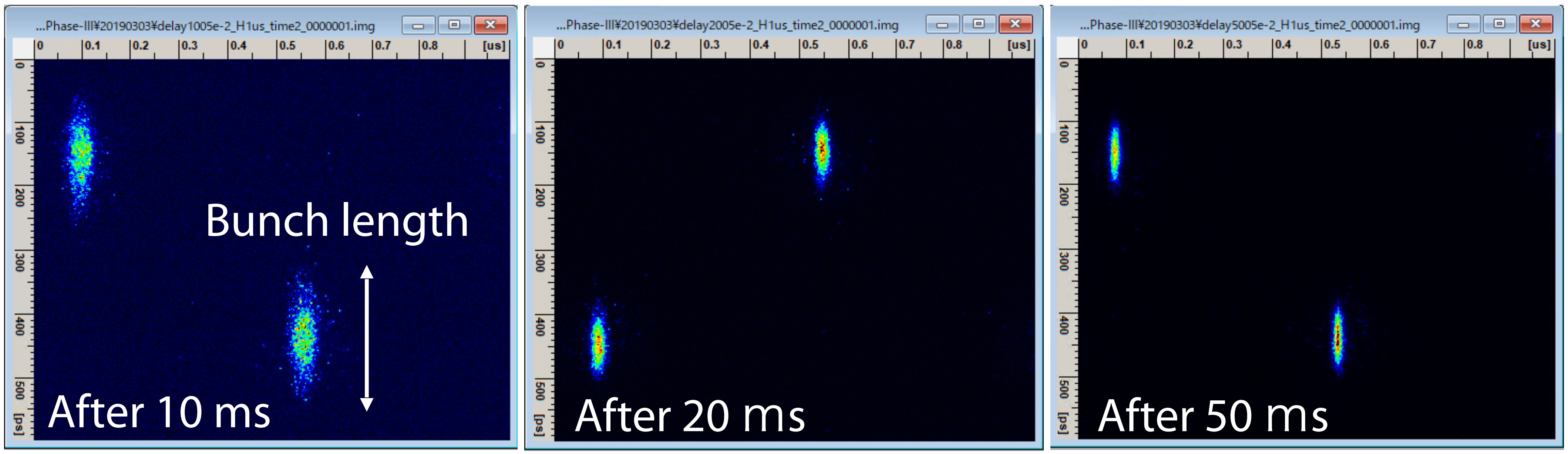
Pressure (dP/dI) at damping ring



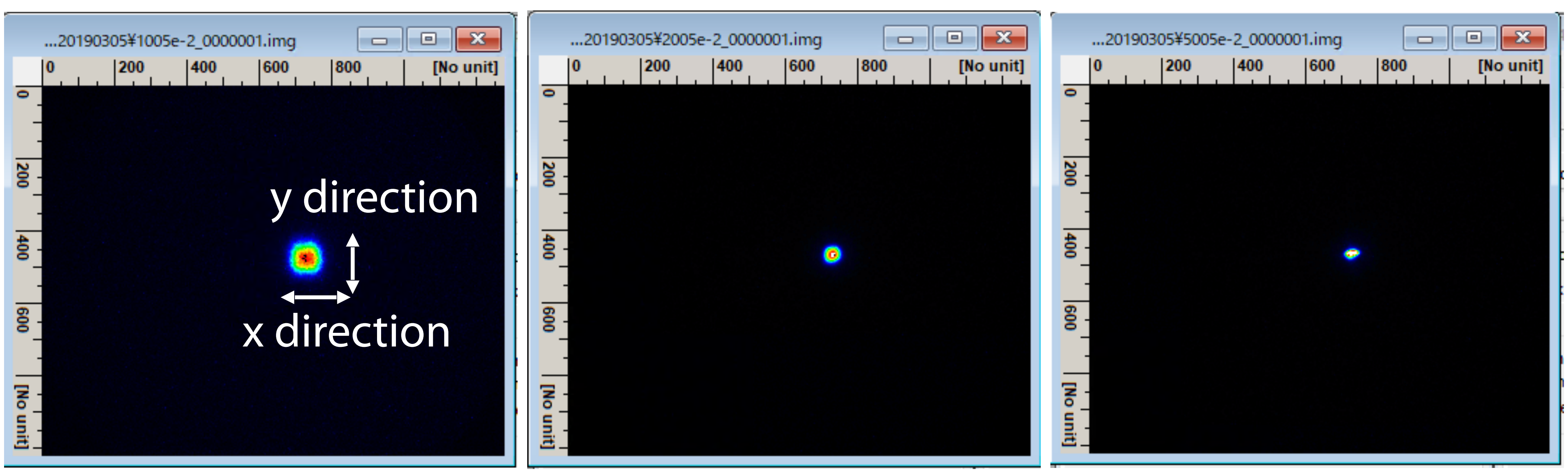
Damping of X, Y, and Z beam sizes in Phase 3

Positron damping ring (DR)

Bunch length measurements with a streak camera

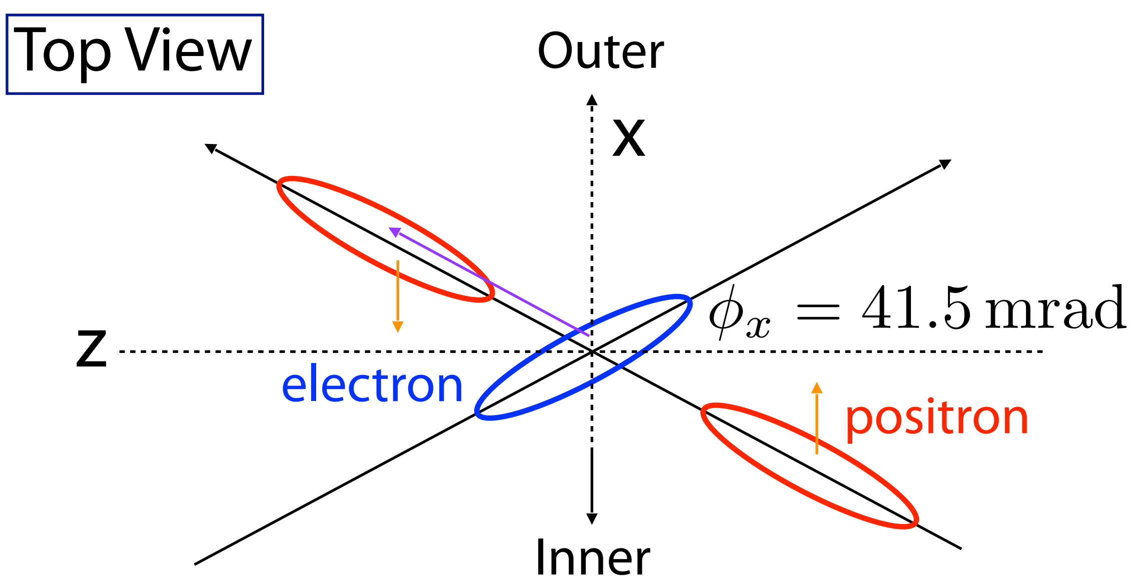


Beam size measurements with a gated camera



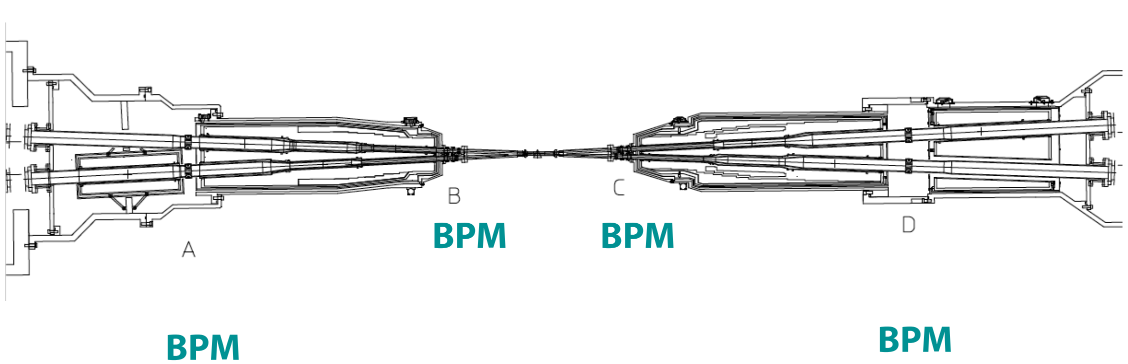
Beam collision search by RF-phase scan

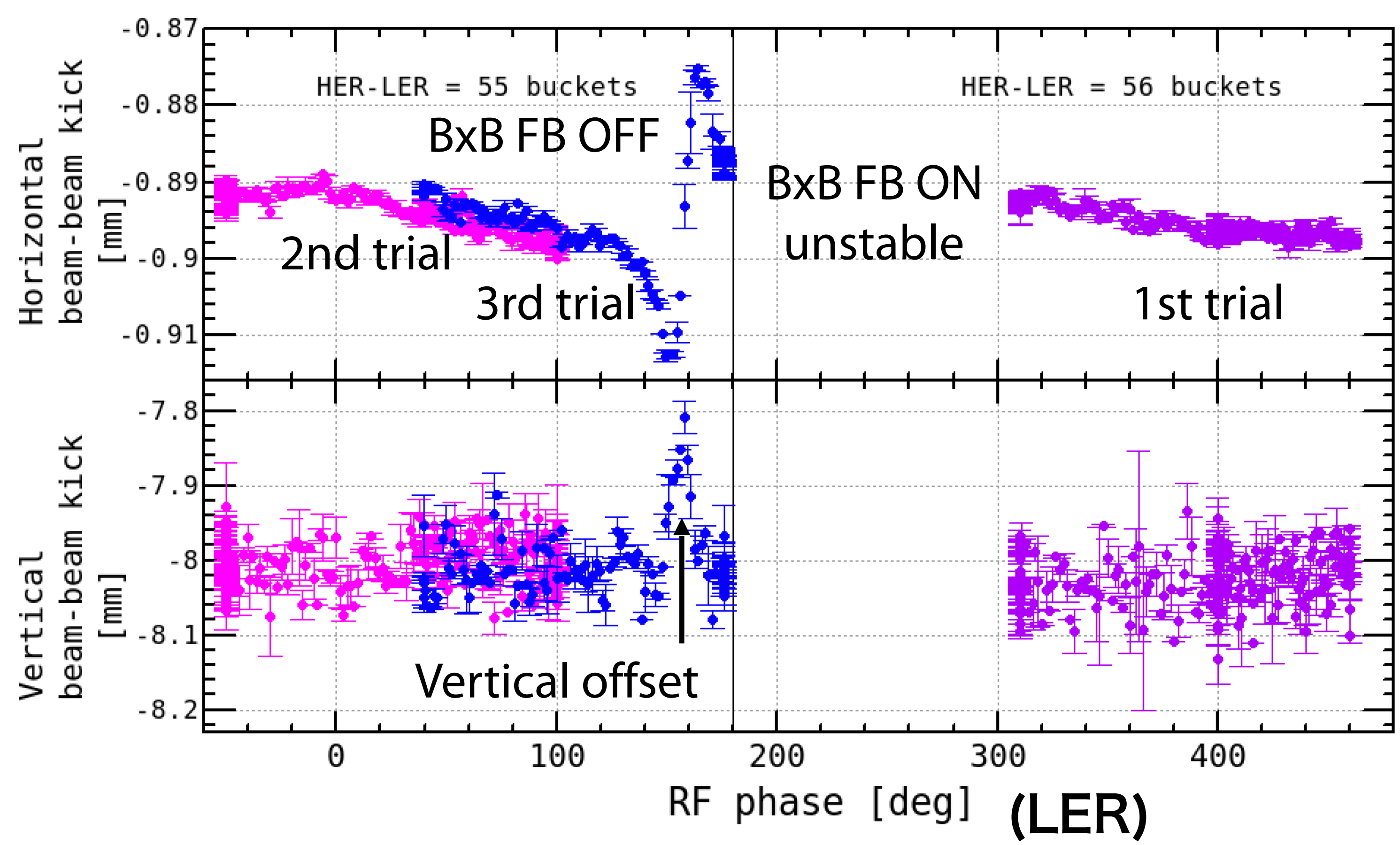
- Adjusted the RF phase to find characteristic beam-beam kick indicating beam-beam collision
- Horizontal kick owes to finite crossing angle.
- Vertical kick owes to vertical-orbit-offset between HER and LER.



$$\Delta z = \frac{\varphi - \varphi_0}{360^\circ} \times \left(\frac{C}{h}\right)$$

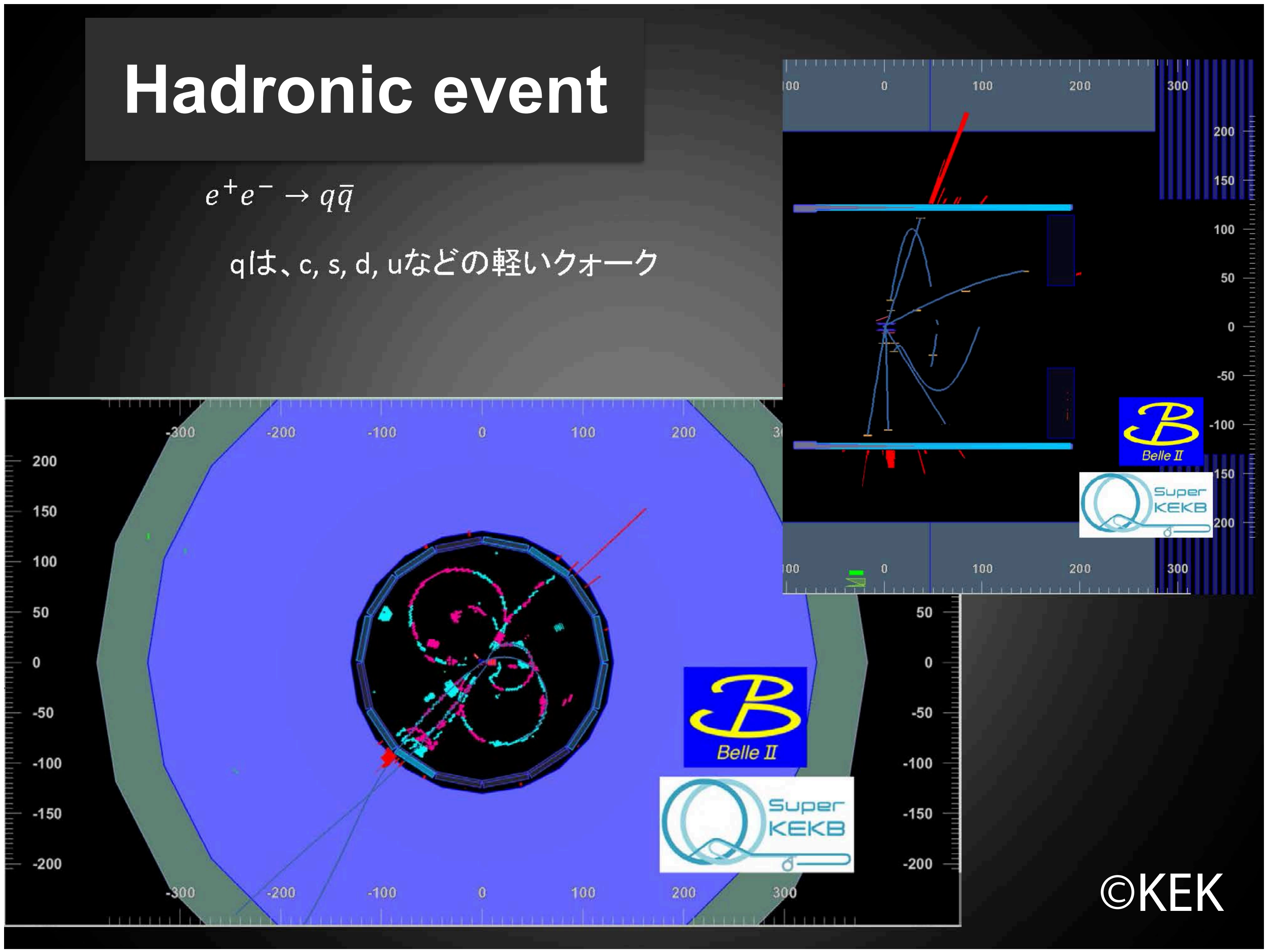
C = 3016.3 m
h = 5120





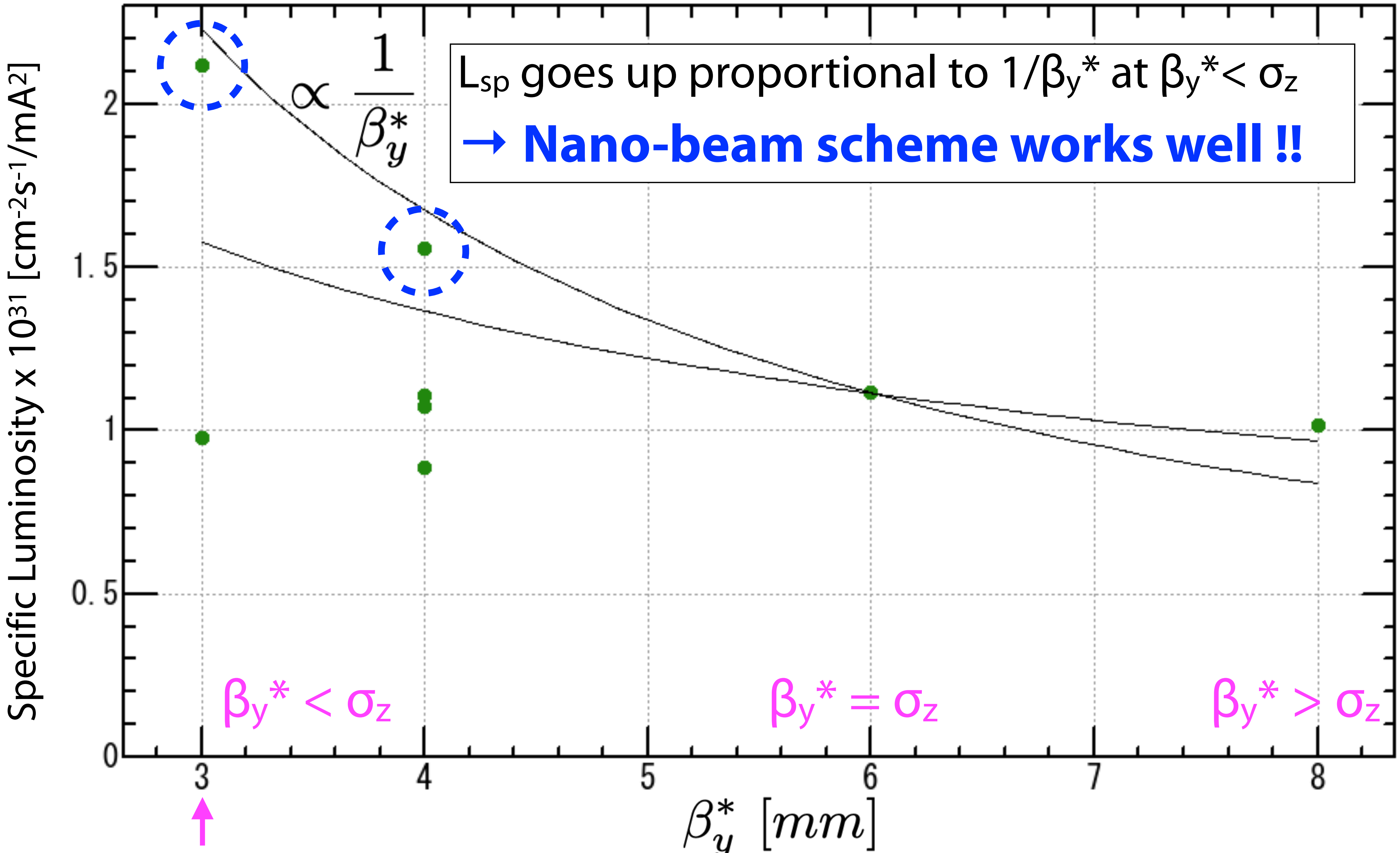
First collision at SuperKEKB & Belle II

26 April 2018 0:38



Verification of the nano-beam scheme

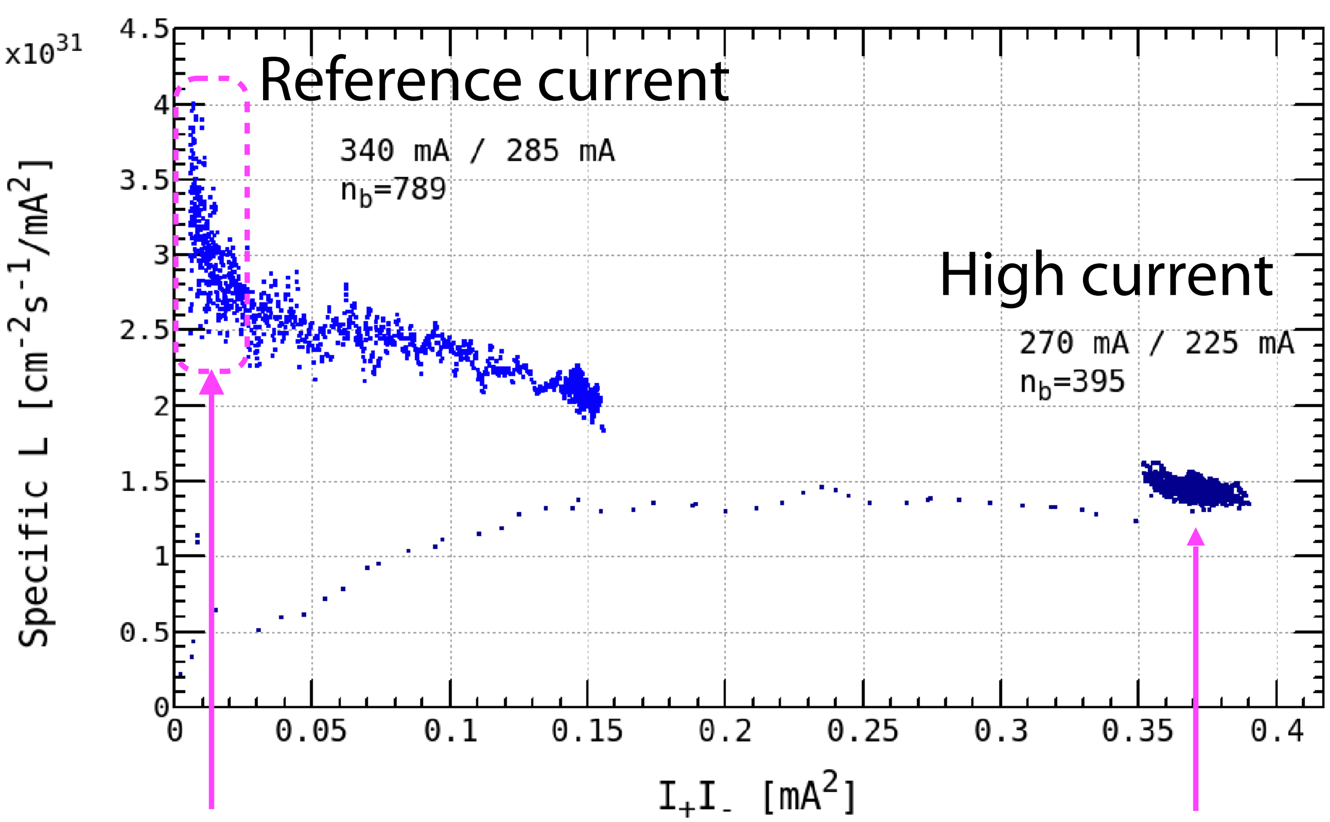
$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y} \Rightarrow L_{SP} = \frac{L}{n_b I_{b+} I_{b-}} \propto \frac{1}{\beta^*_y}$$

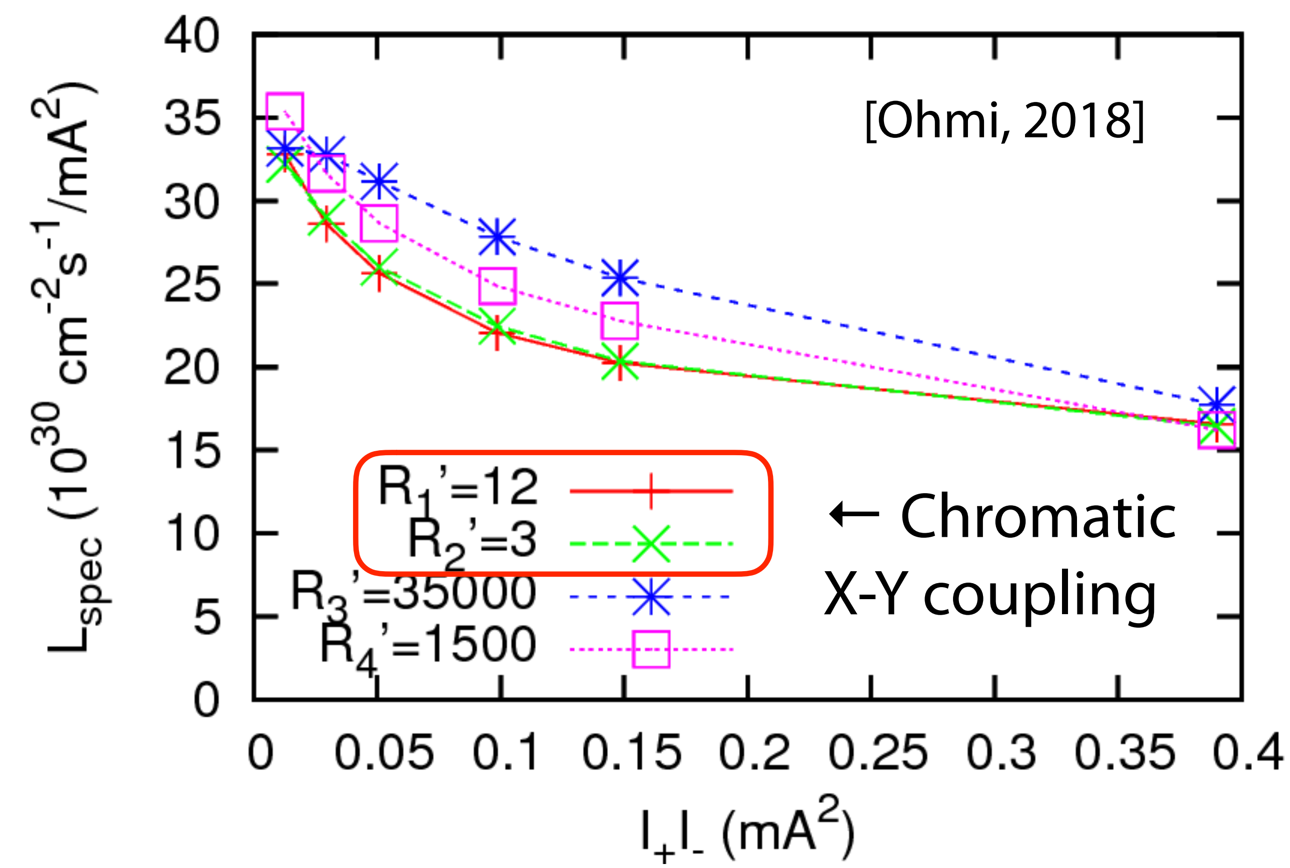


Lowest β_y^* in the world
(as of July 2018)

L_{sp} degradation as a function of I_+I_-

- L_{sp} rapidly decreases as I_+I_- increases even at low-current operation.
- Maximum L_{sp} is consistent with the expectation using single-beam sizes.
- Possible source is chromatic X-Y coupling at the IP [Ohmi, 2018].





L_{sp} rapidly degrades as I_+I_- increases.

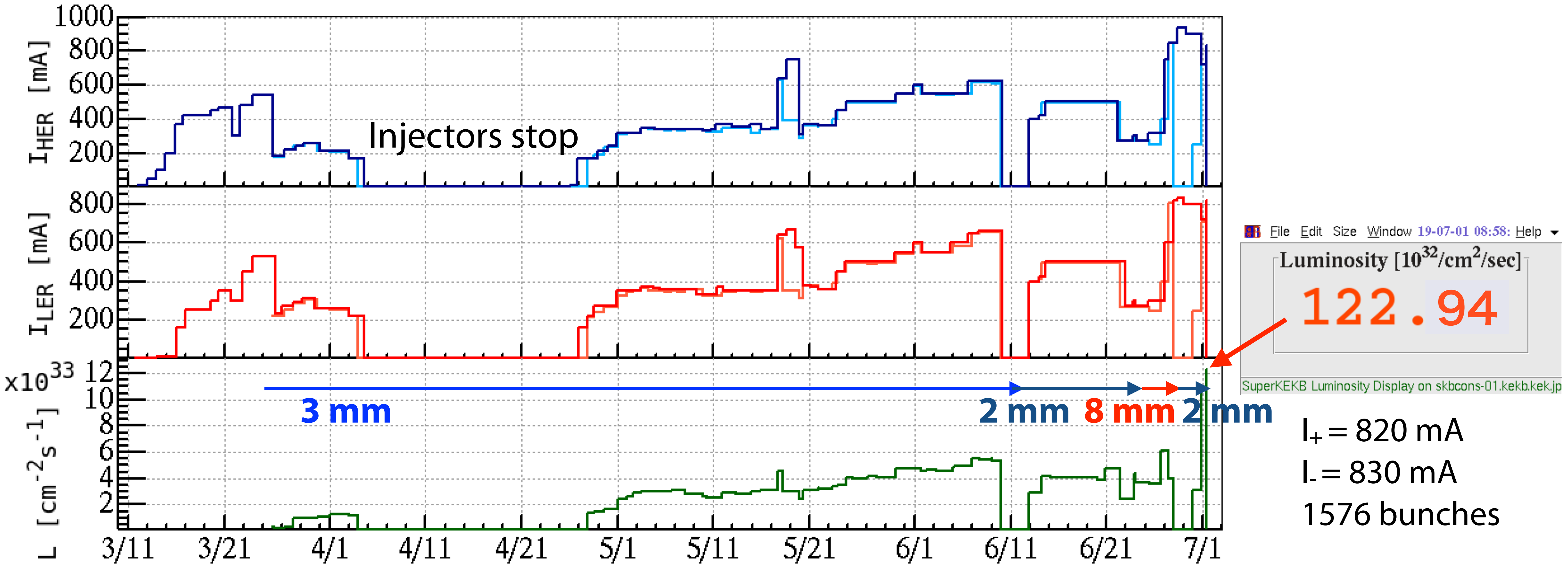
Beam-beam blowup Collective effect

L_{sp} is especially sensitive to R1′ and R2′.

Investigation and correction for chromatic X-Y coupling are left for Phase 3.

Aims of the Phase 3 commissioning

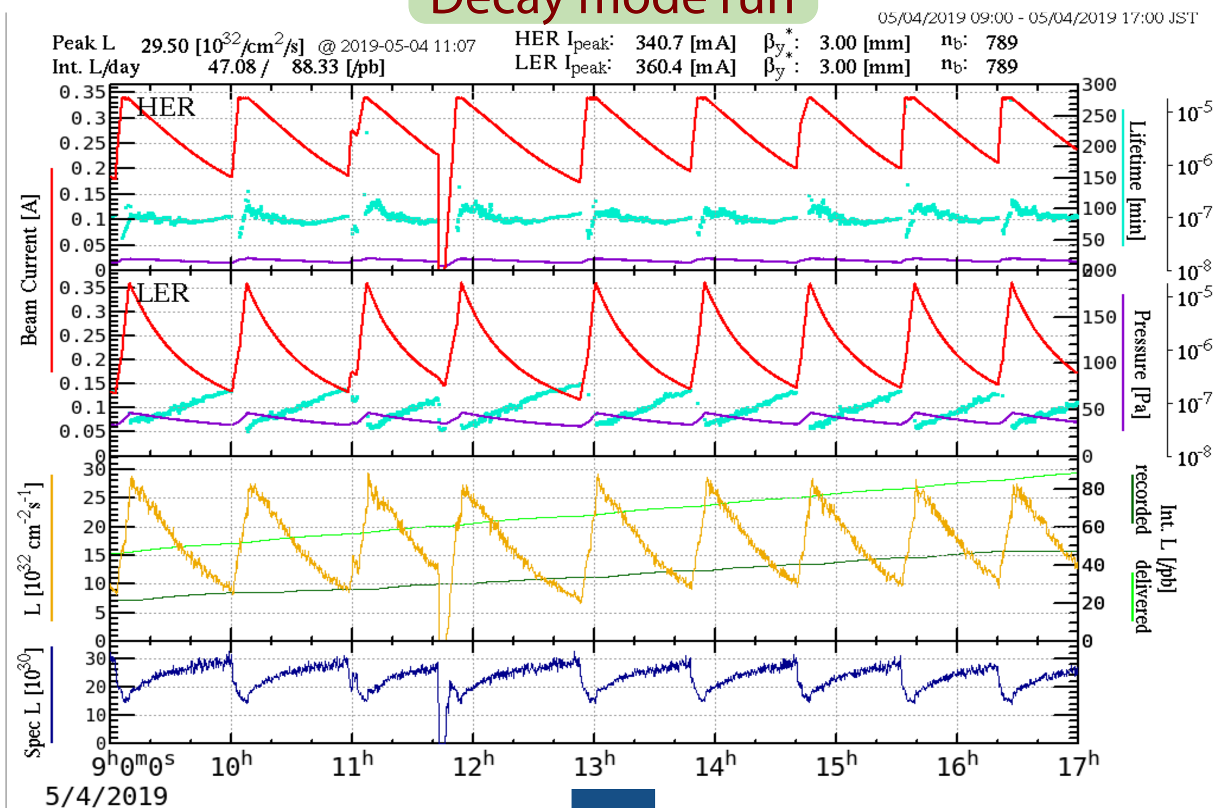
- Continuous beam injection
- Further $\beta_{x,y}^*$ squeezing
- Understanding linear/non-linear beam optics
- High-current operation
- Reduction of the beam-induced backgrounds to the Belle2 detector



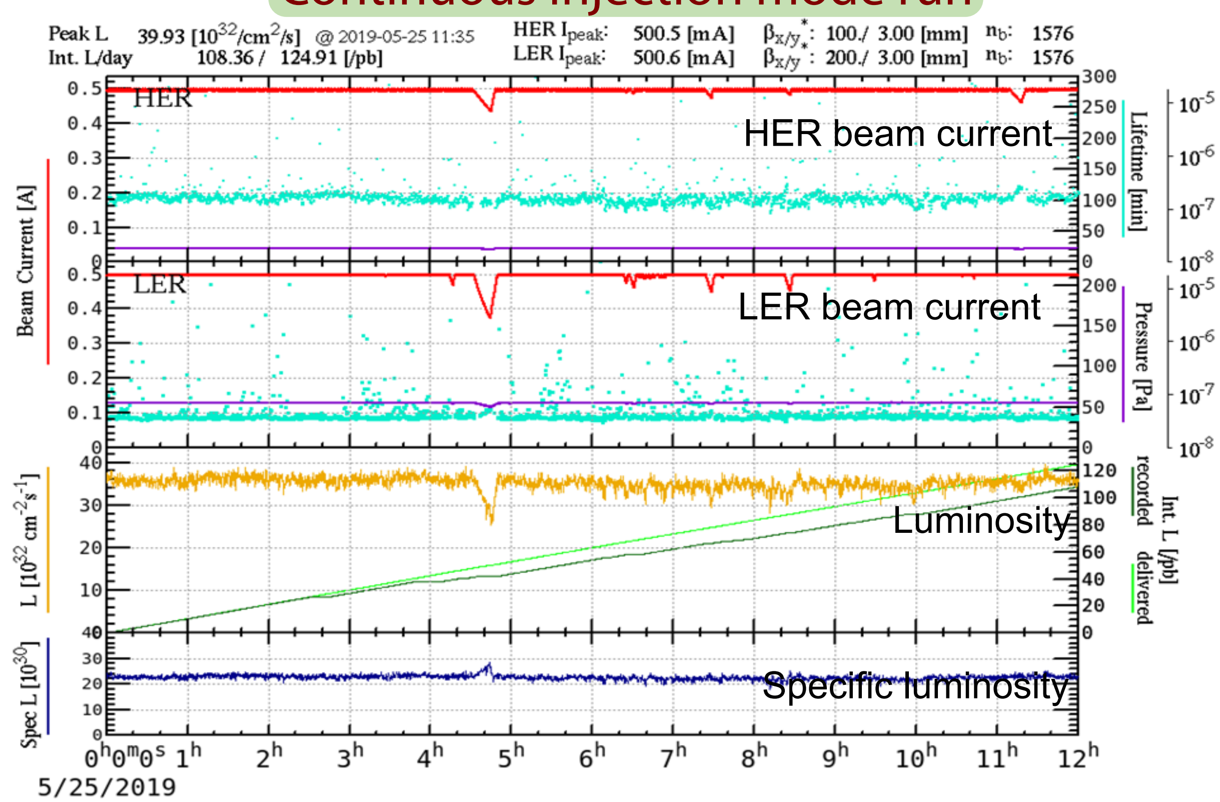
$I_+ = 820$ mA
$I_- = 830$ mA
1576 bunches

Continuous beam injection

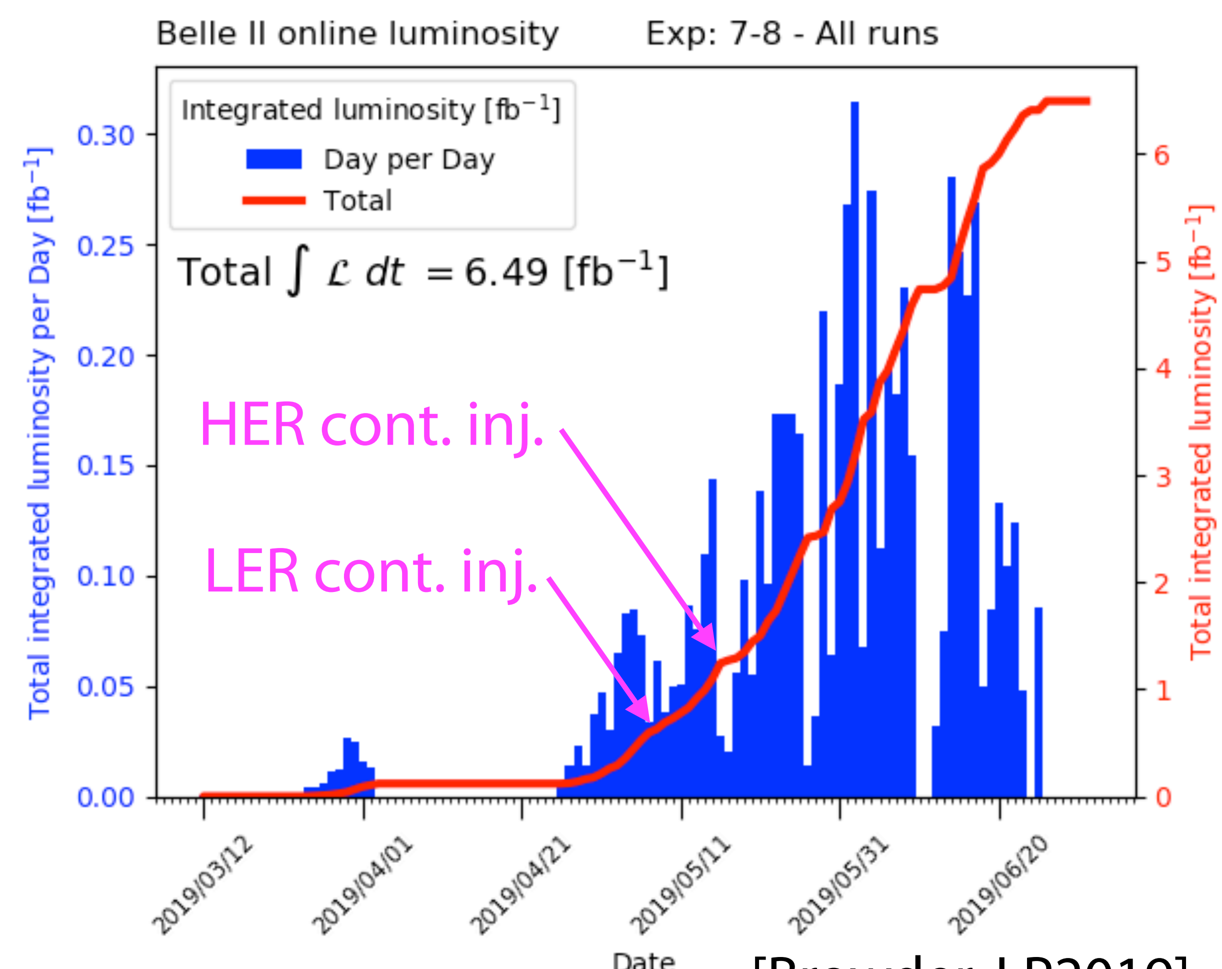
Decay mode run



Continuous injection mode run



- Successful background reduction thanks to elaborate tunings on injection parameters and collimators
- Continuous injection contributes to increase in ∫luminosity



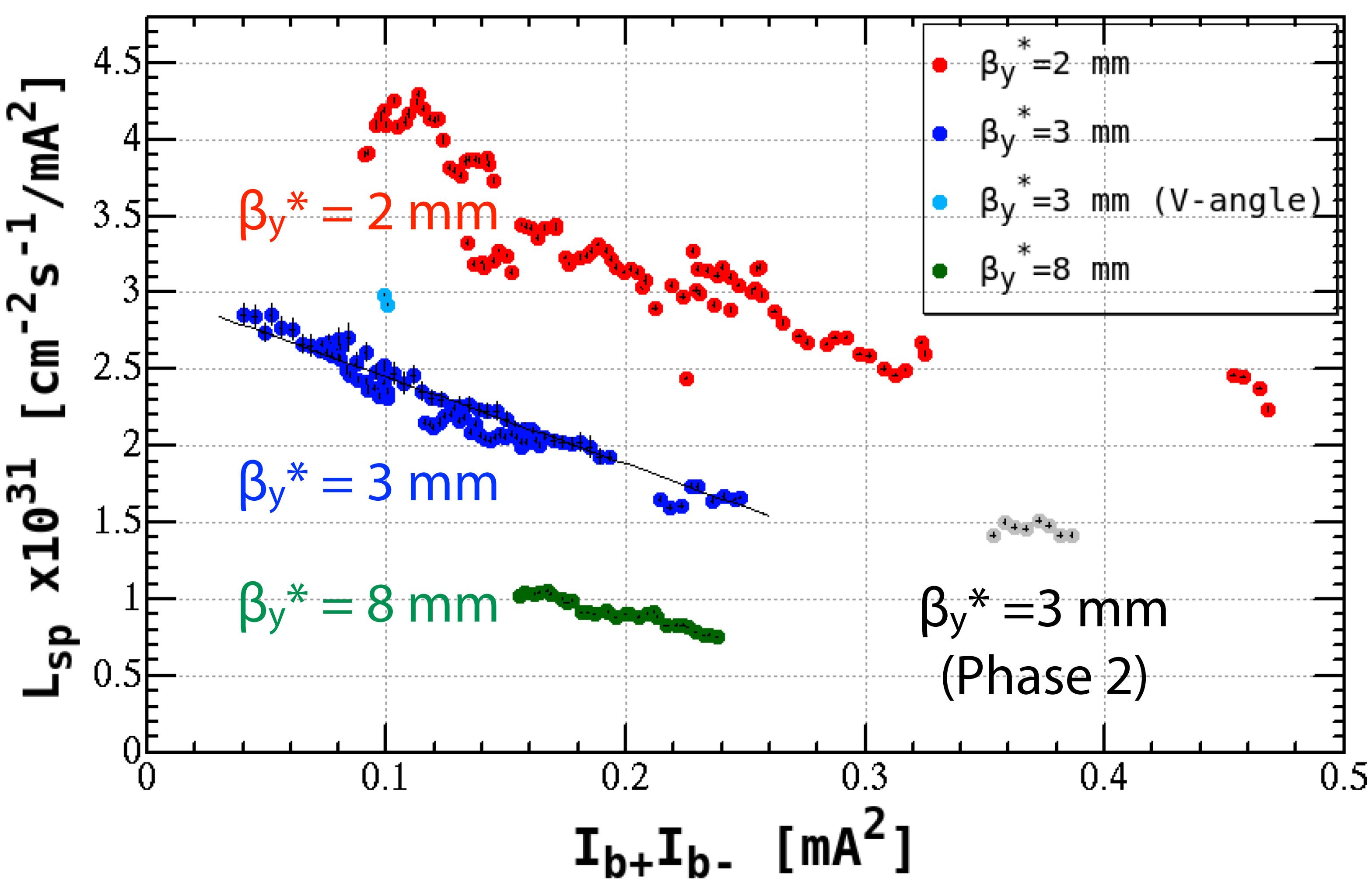
[Browder, LP2019]

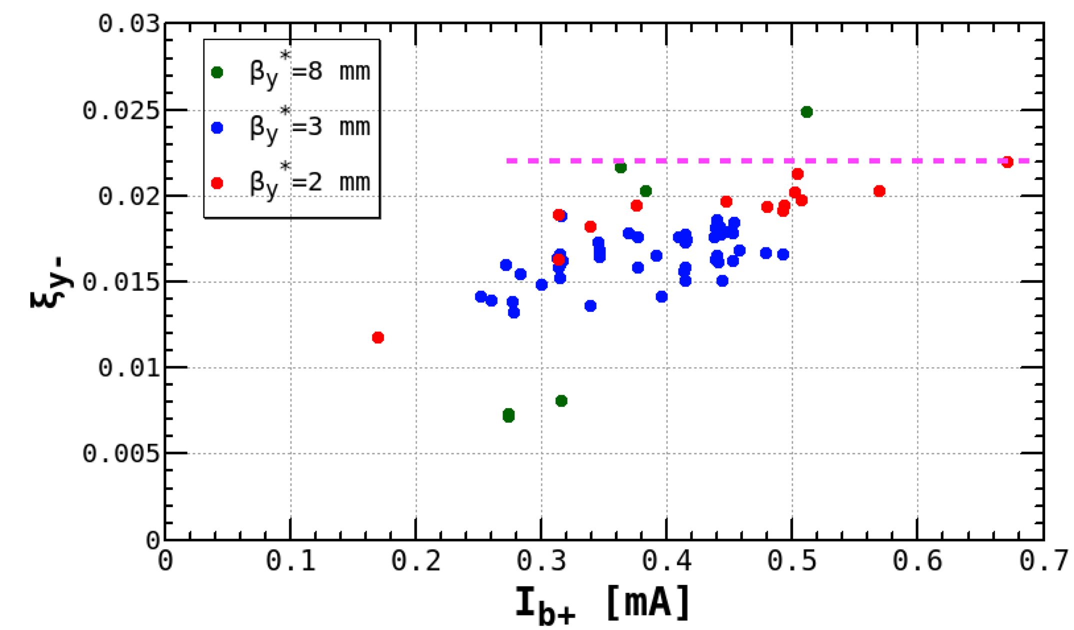
β_y* squeezing and specific luminosity

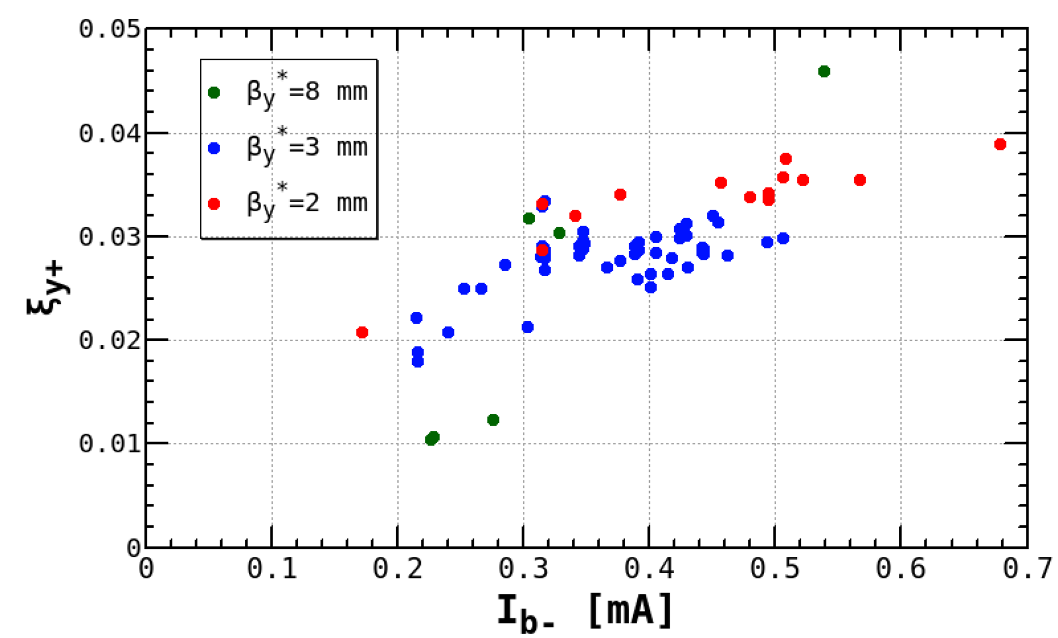
- Specific luminosity increases as β_y* squeezed from 8 to 2 mm.
- Beam-beam parameters sustain ~0.022 for β_y* = 2 mm, but is still smaller than the design value ξ_{y-} ~ 0.04 at 0.7 mA.

$$\xi_{y\pm} = \frac{r_e N_\mp}{2\pi\gamma_\pm \phi_x \sigma_{z\mp}} \sqrt{\frac{\beta_y^*}{\varepsilon_{y\mp}}}$$

ξ_y=constant indicates ε_y decreases ~$1/\sqrt{\beta_y^*}$.

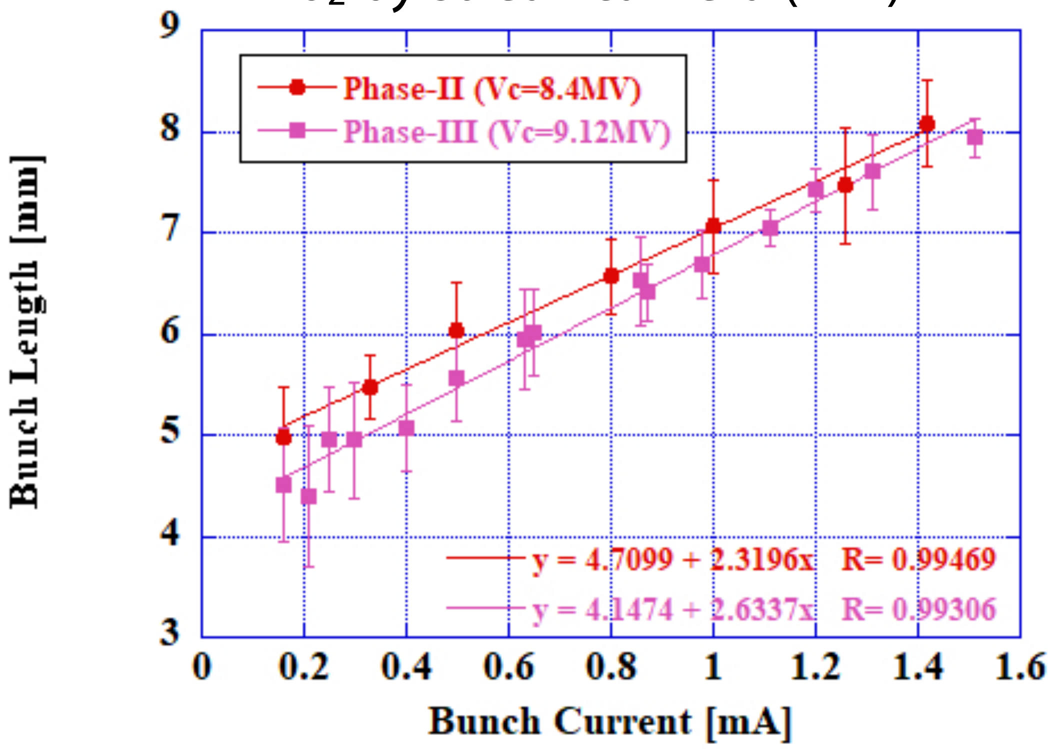




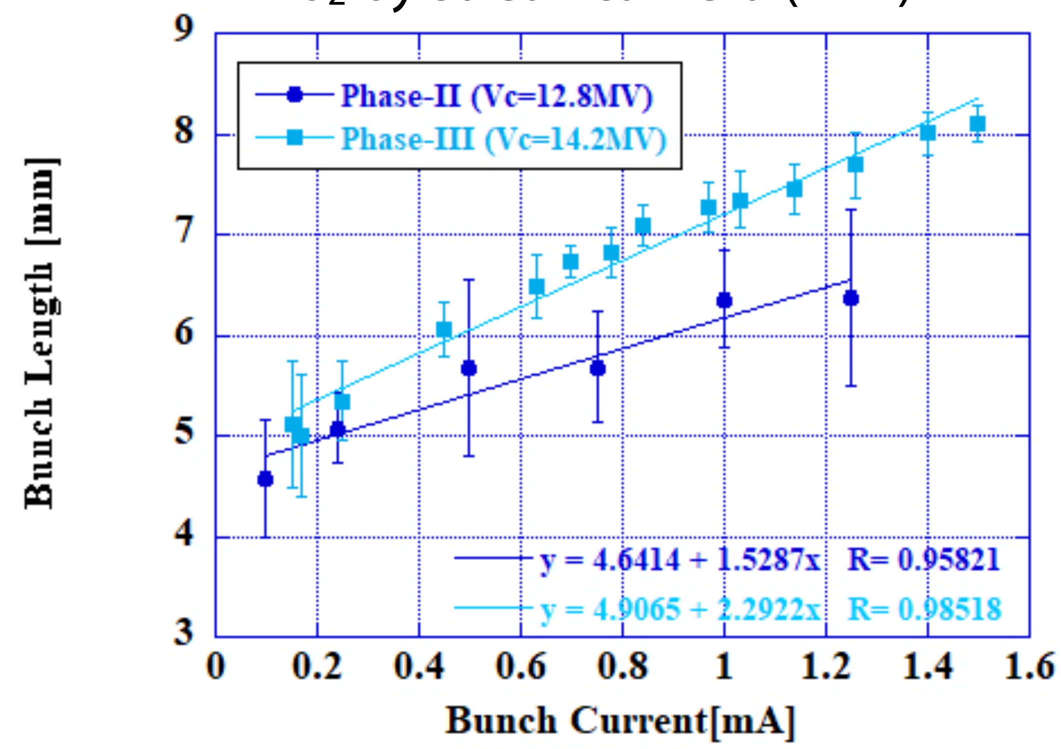


Cross-check on bunch length measurement

σ_z by streak camera (LER)



σ_z by streak camera (HER)



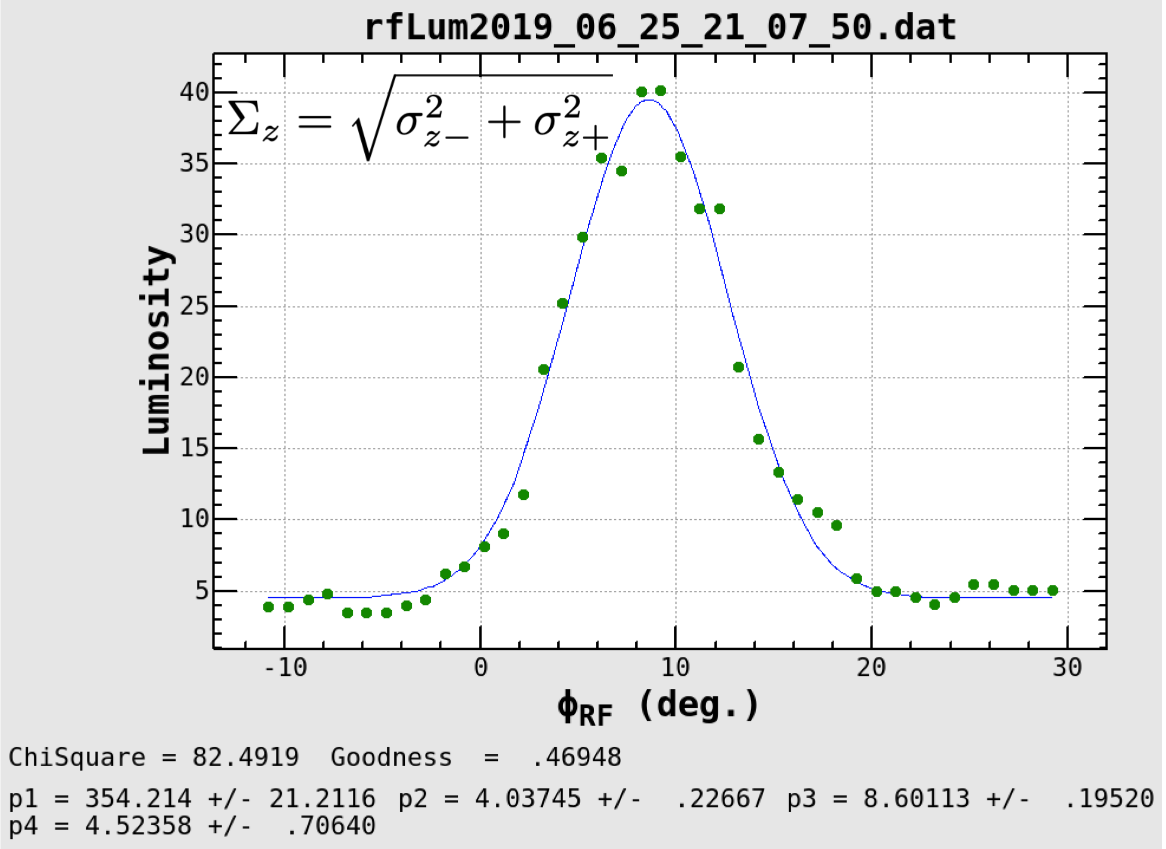
Luminosity measurements as changing the RF phase enables the bunch length Σ_z measurements.

$$\Delta z = \frac{\varphi - \varphi_0}{360°} \times \left(\frac{C}{h}\right)$$

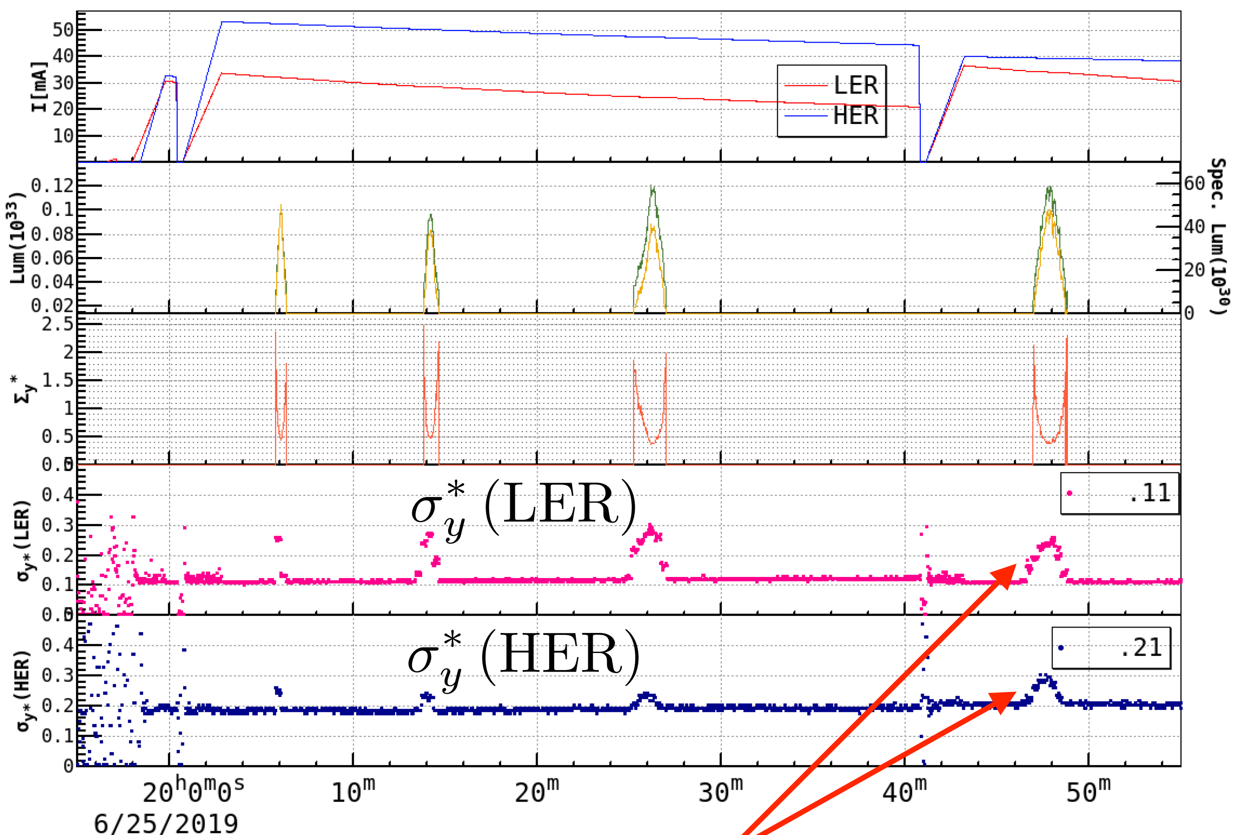
C = 3016.3 m
h = 5120

Σ_z (BB scan)	Σ_z (Streak)	σ_{z+} (Streak)	σ_{z-} (Streak)
6.61 mm	6.58 mm	4.25 mm	5.02 mm

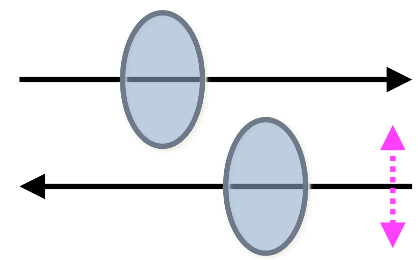
Independent measurements give consistent bunch length.



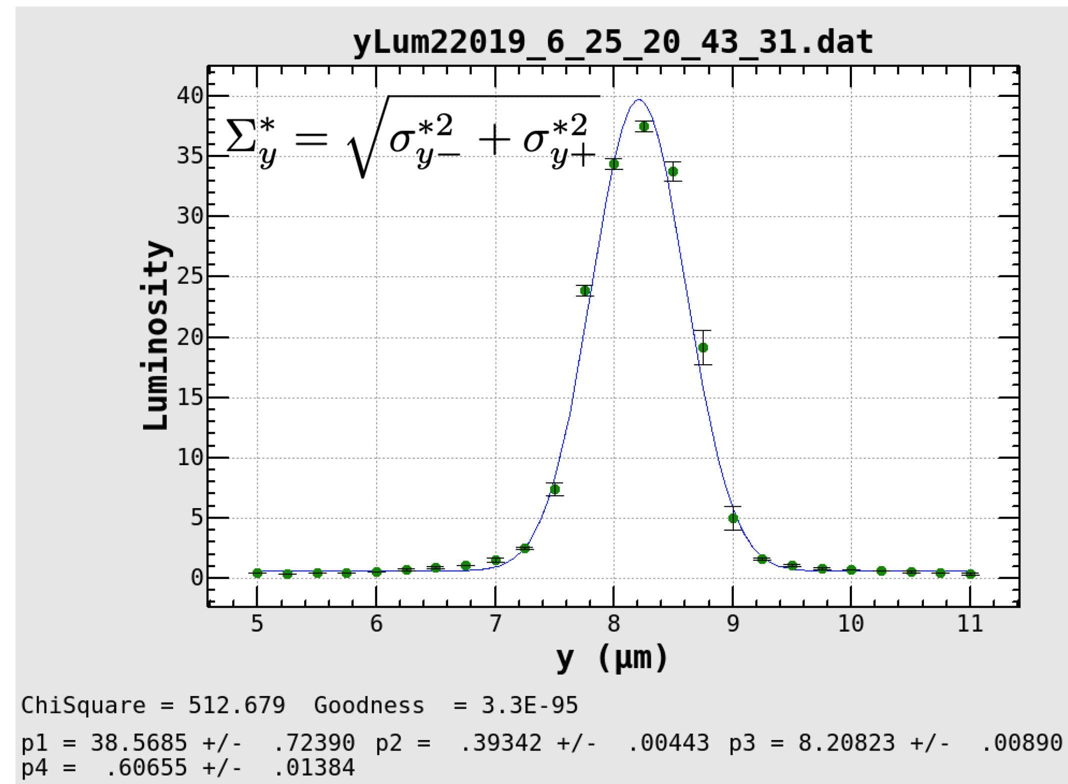
Cross-check on ver. beam size measurement



σ_y^* blows up even at 0.04 mA/bunch



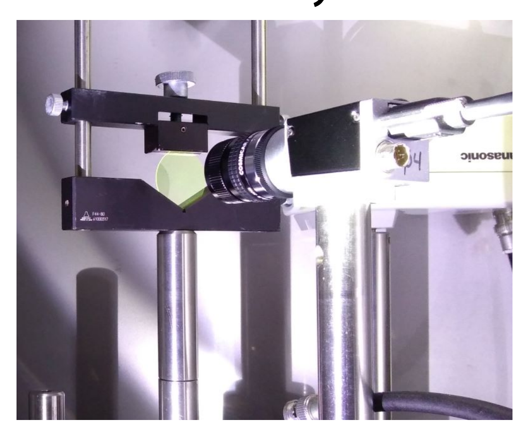
Luminosity measurement by a fast luminosity monitor "LumiBelle2" while modulating the vertical-beam-orbit-offset

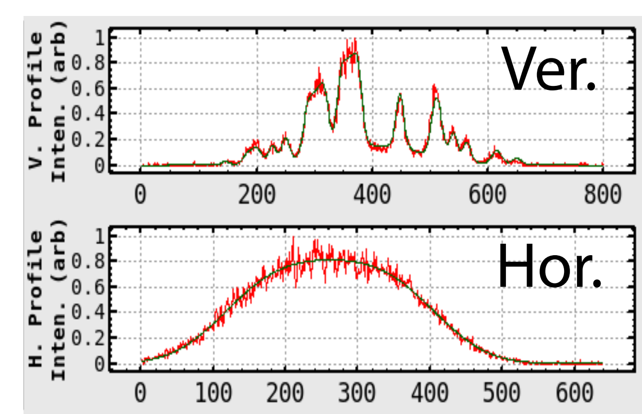


Σ_y^* (BB scan)	Σ_y^* (Lum)	Σ_y^* (XRM)	σ_{y+}^* (XRM)	σ_{y-}^* (XRM)
0.393 µm	0.38 µm	0.378 µm	0.234 µm	0.297 µm

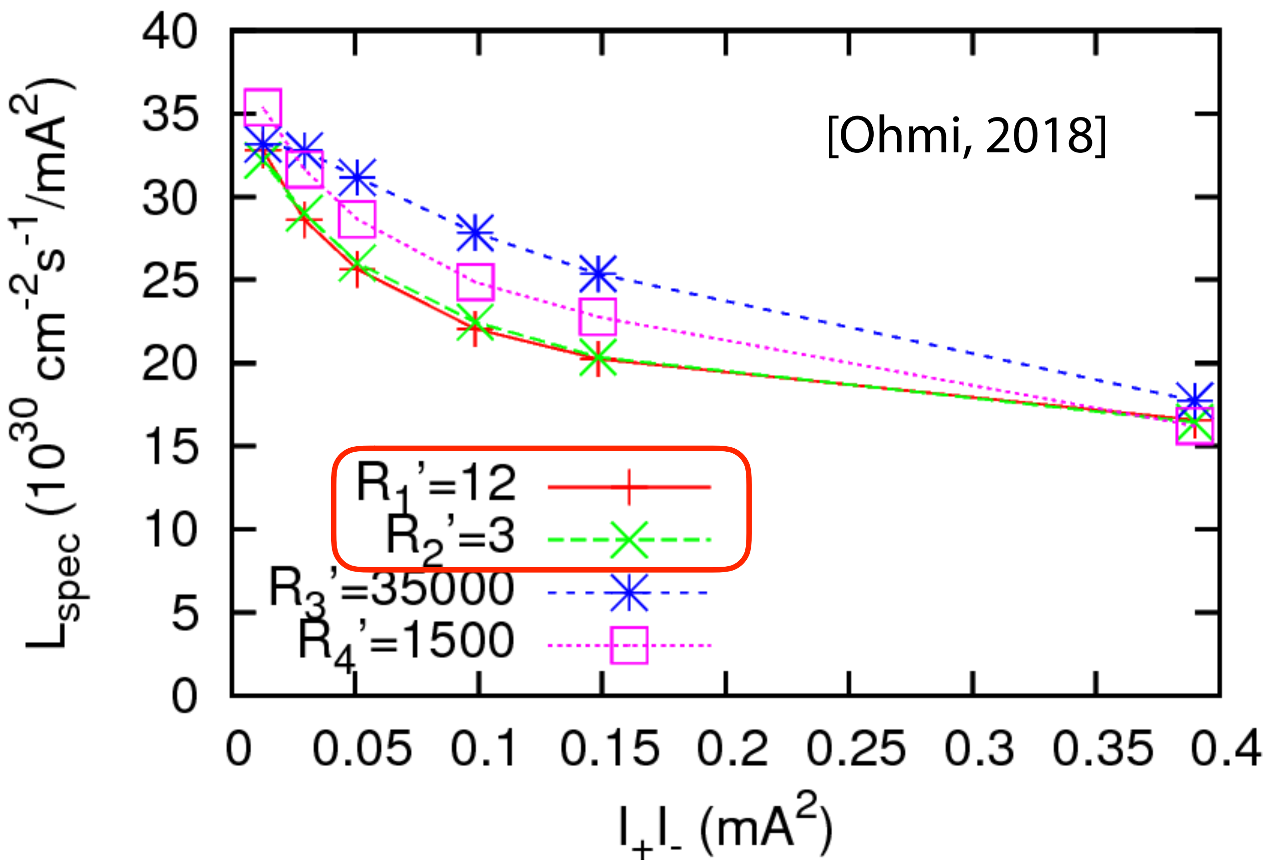
Independent measurements give consistent vertical beam size.

X-ray beam-size monitor (XRM)





Chromatic X-Y coupling



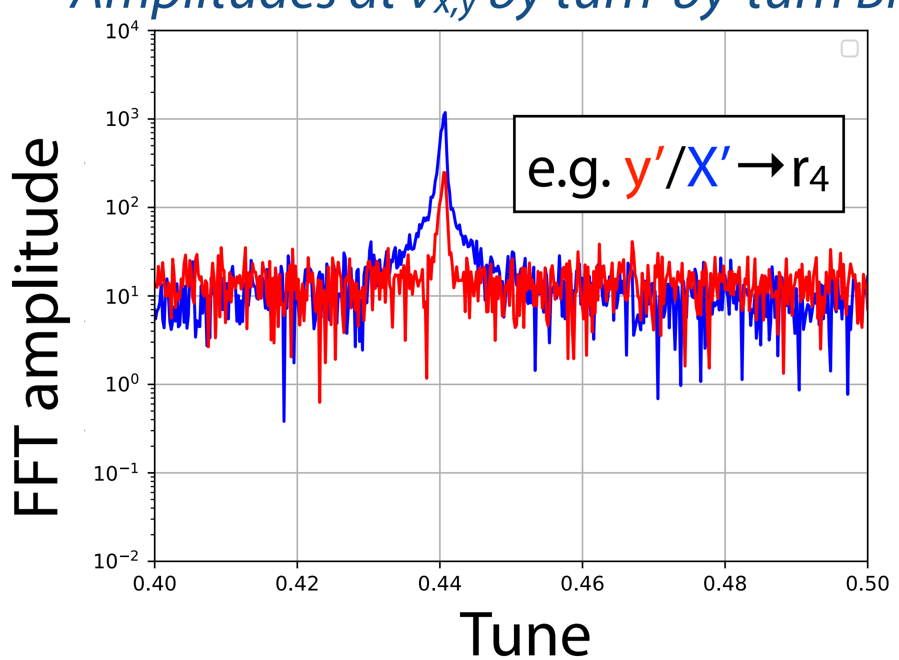
In Phase2, a suspected reason for the L_{sp} degradation was chromatic X-Y coupling.

Coupled coordinates — Coupling coefficients — Decoupled coordinates

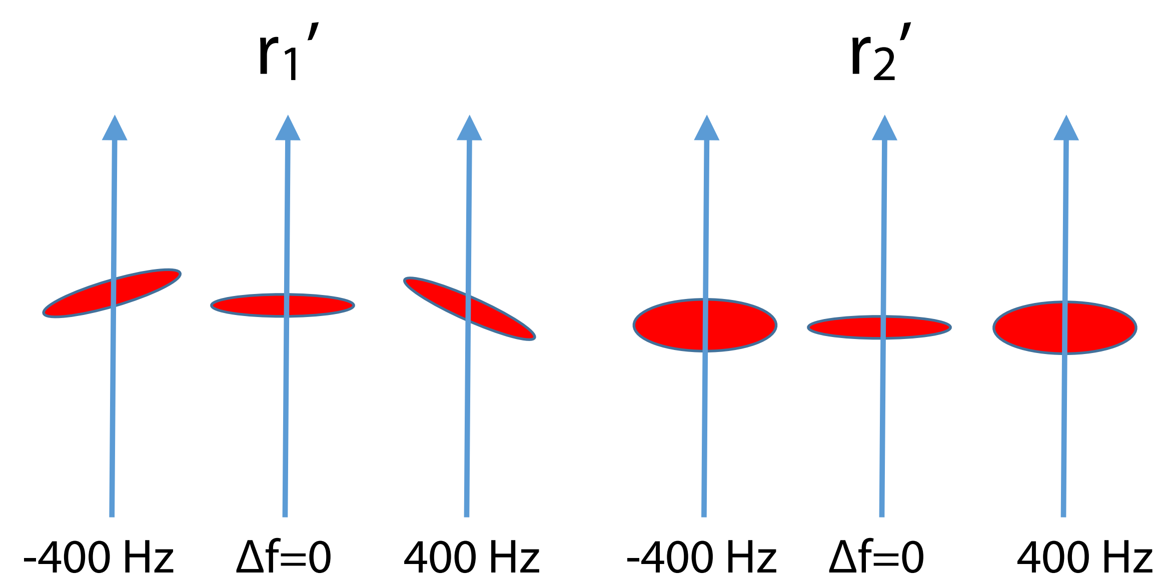
$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} \mu & 0 & r_4 & -r_2 \\ 0 & \mu & -r_3 & r_1 \\ -r_1 & -r_2 & \mu & 0 \\ -r_3 & -r_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} X \\ X' \\ Y \\ Y' \end{pmatrix}$$

Coupling at shifted frequencies (±400, ±200, and 0 Hz) extract chromatic terms r_i'.

Amplitudes at $\nu_{x,y}$ by turn-by-turn BPMs

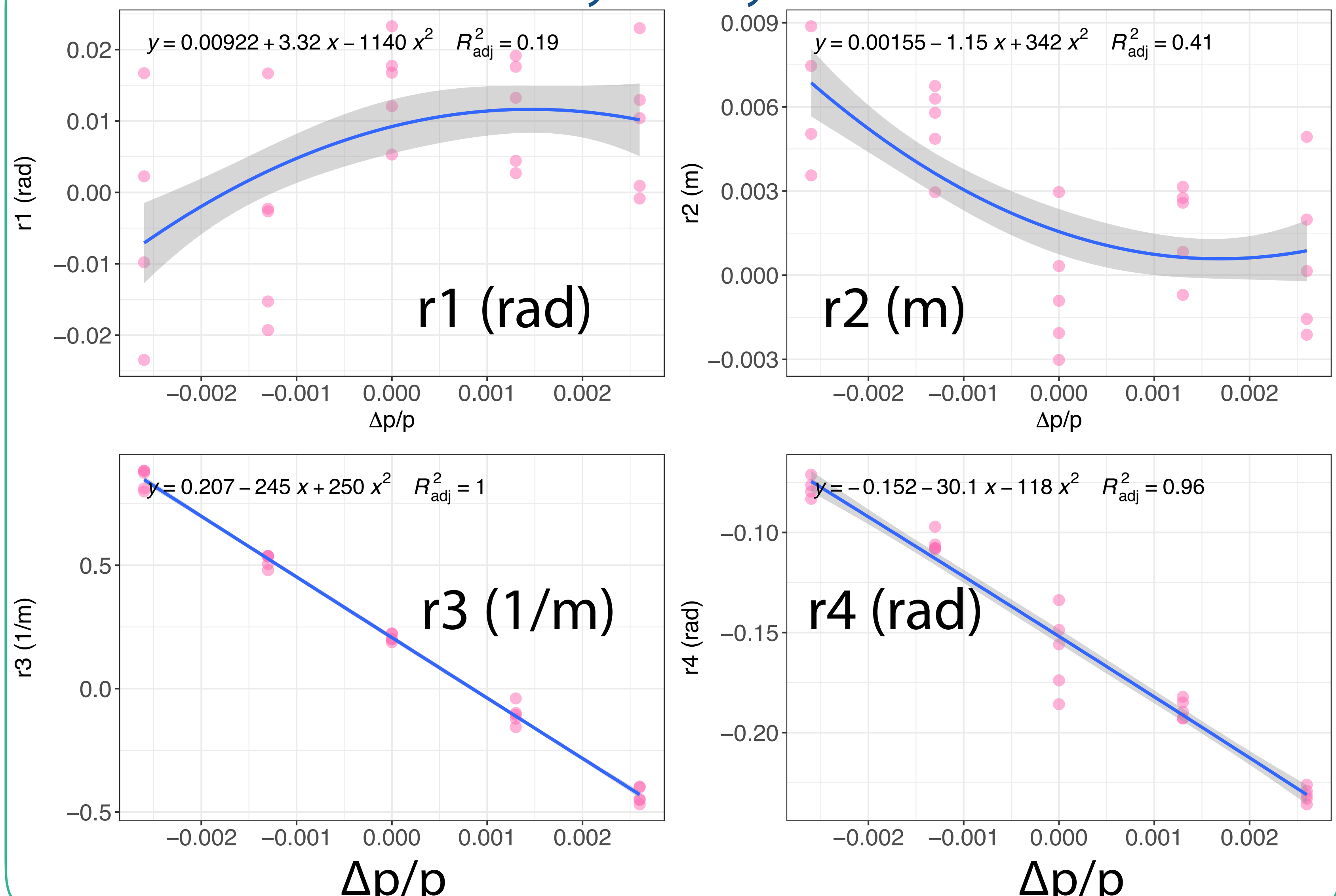


Beam sizes by scanning the beam-orbit offset

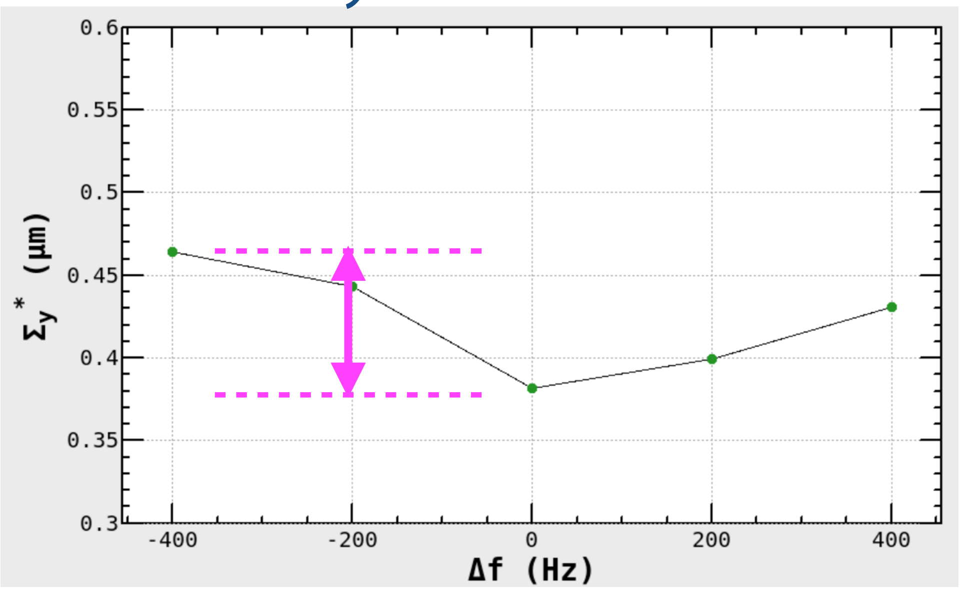


Chromatic X-Y coupling

Measured by turn-by-turn BPMs



Measured by ver. beam-orbit scan



$$\Delta\sigma_y^* = \sqrt{(\sigma_{y,max}^*)^2 - (\sigma_{y,min}^*)^2} = 0.26\,\mu\mathrm{m}$$

$$r_1(\delta) = 12\,\mathrm{rad} \times 0.17\,\% = 20.4\,\mathrm{mrad}$$

$$r_2(\delta) = 3\,\mathrm{m} \times 0.17\,\% = 5.1\,\mathrm{mm}$$

r1′: $\Delta\sigma_y^* = r_1(\delta)\sigma_x^* = 0.50\,\mu\mathrm{m}$

r2′: $\Delta\sigma_y^* = \frac{r_2(\delta)}{\beta_x^*}\sigma_x^* = 0.62\,\mu\mathrm{m}$

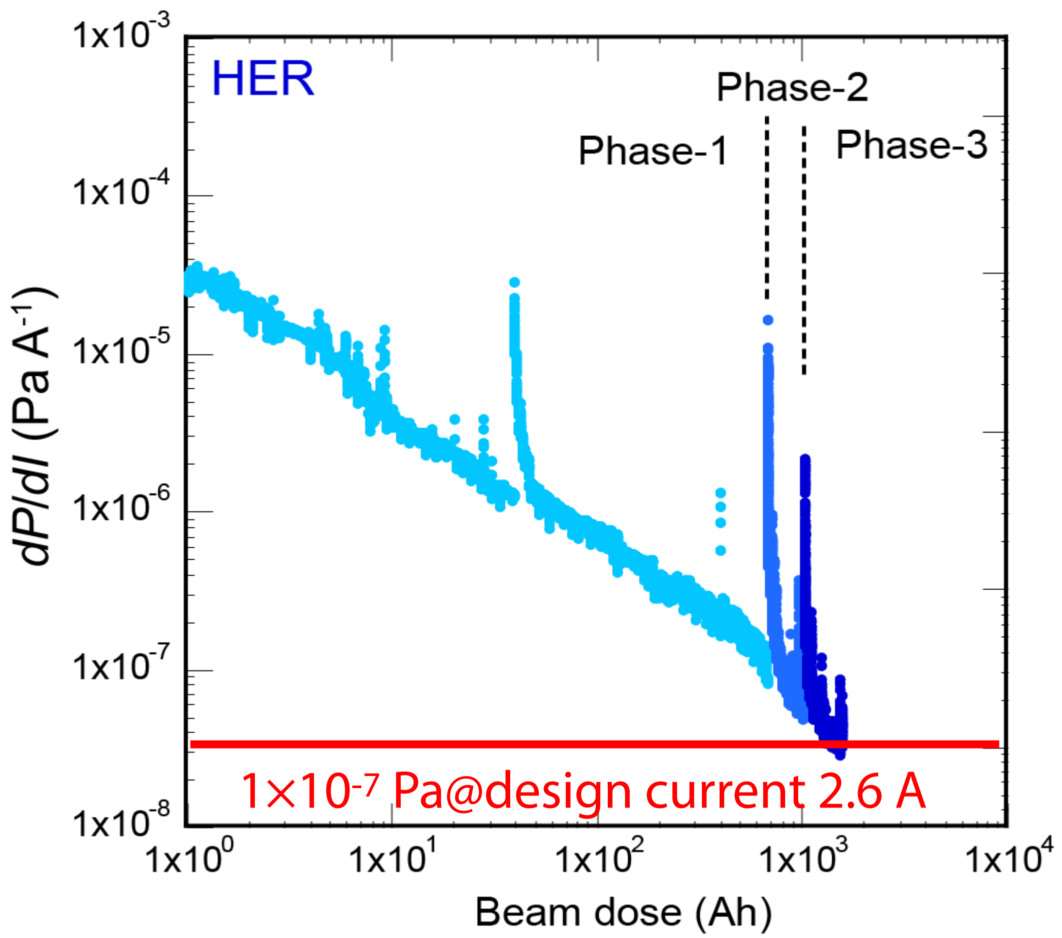
$(\varepsilon_x = 3\,\mathrm{nm}, \beta_x^* = 0.2\,\mathrm{m})$

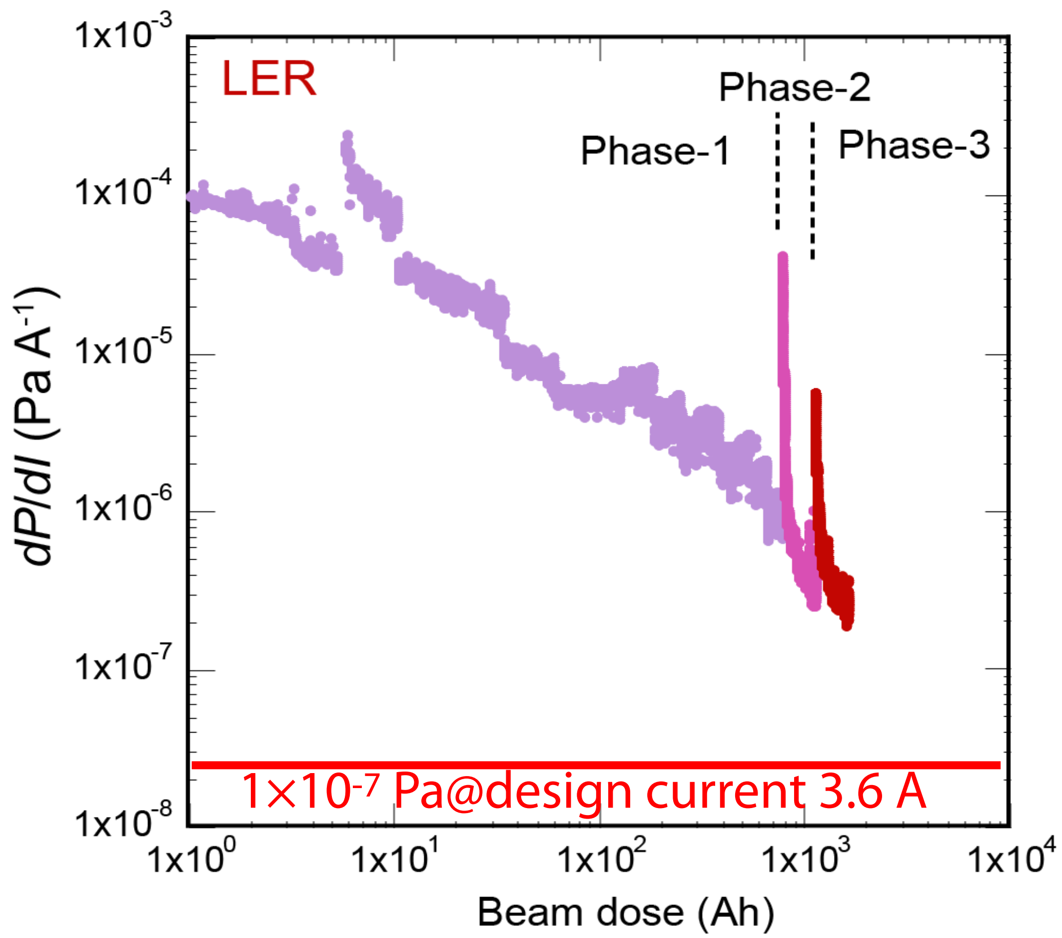
→ ~1/2 of r1′=12 rad and r2′=3 m

- Nonzero chromatic X-Y coupling are observed by both turn-by-turn BPMs and vertical beam-orbit scan.
- r1′ ~ 3-6 rad and r2' ~ 1 m
- Correction using rotatable sextupoles is under discussion.

Internal pressure in the main rings

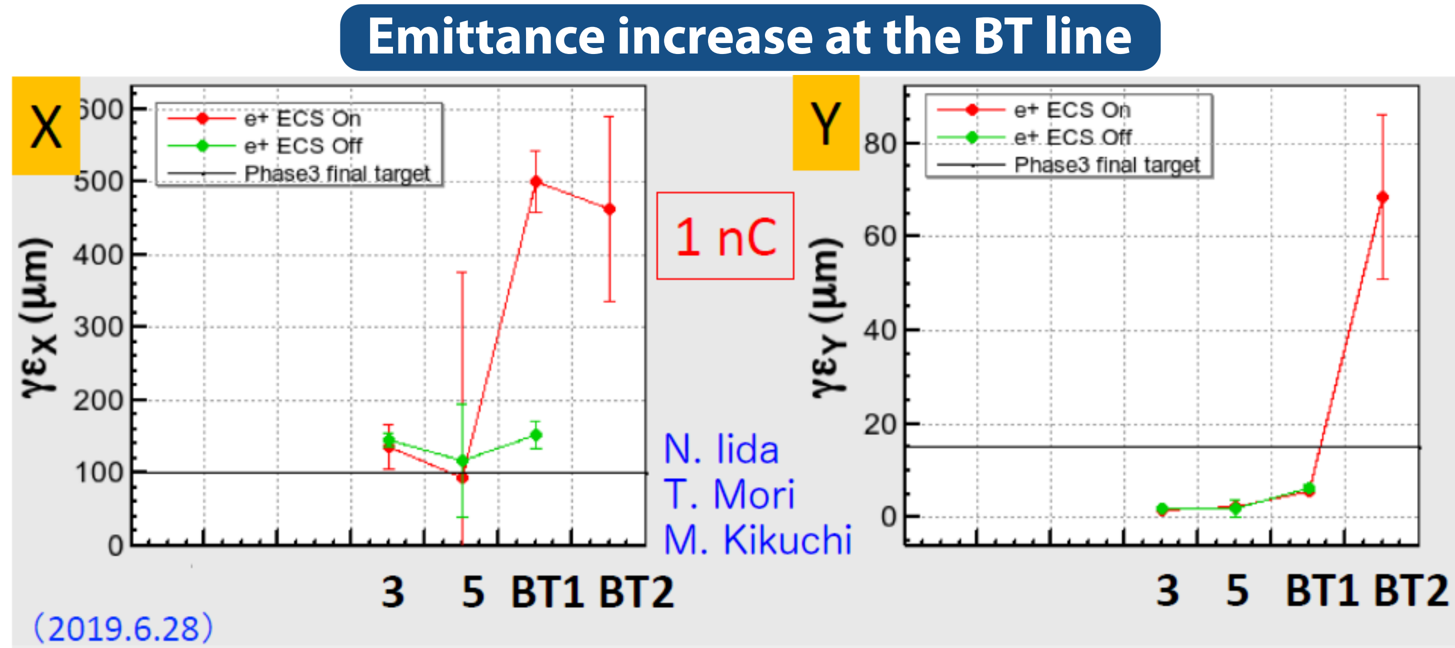
- Need vacuum pressure < 1×10^{-7} Pa at the designed current (e^{-} 2.6 A and e^{+} 3.6 A)
  - to make beam lifetime longer
  - to reduce beam-gas scattering backgrounds to the Belle II detector
- Pressure goes down almost linearly with the accumulated dose.
- HER (same beam pipe as KEKB) achieved the target value in Phase 3.
- LER (newly installed at SuperKEKB) needs more vacuum scrubbing until ~5 kAh.



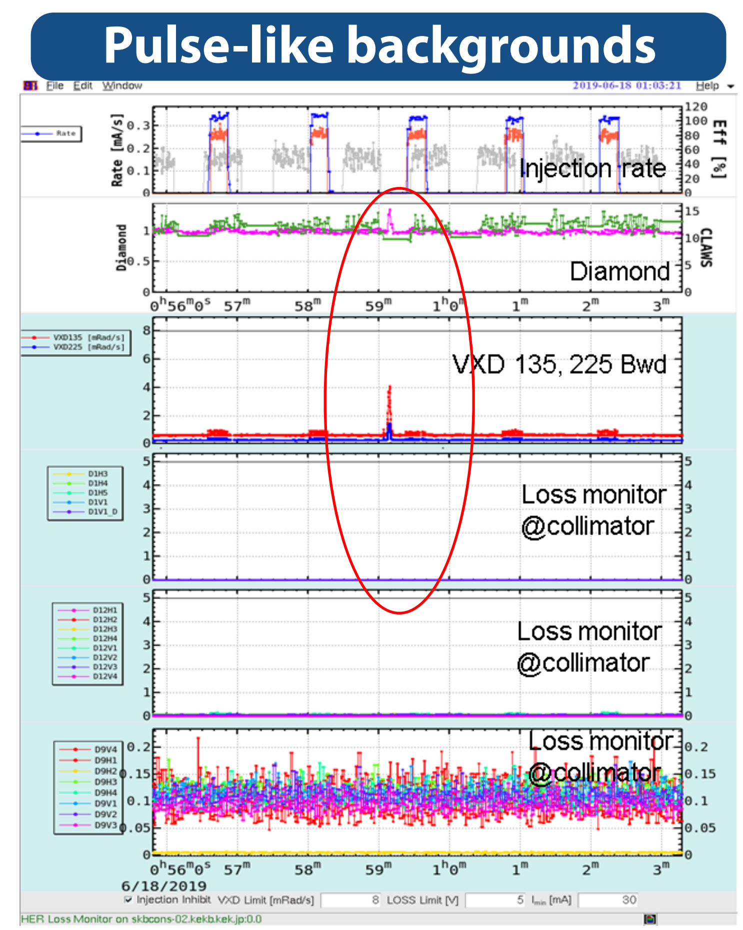


Other challenges

- **Injector, damping ring, and beam transfer line**
  - Keep low emittance at BT line
  - Increase charge/bunch

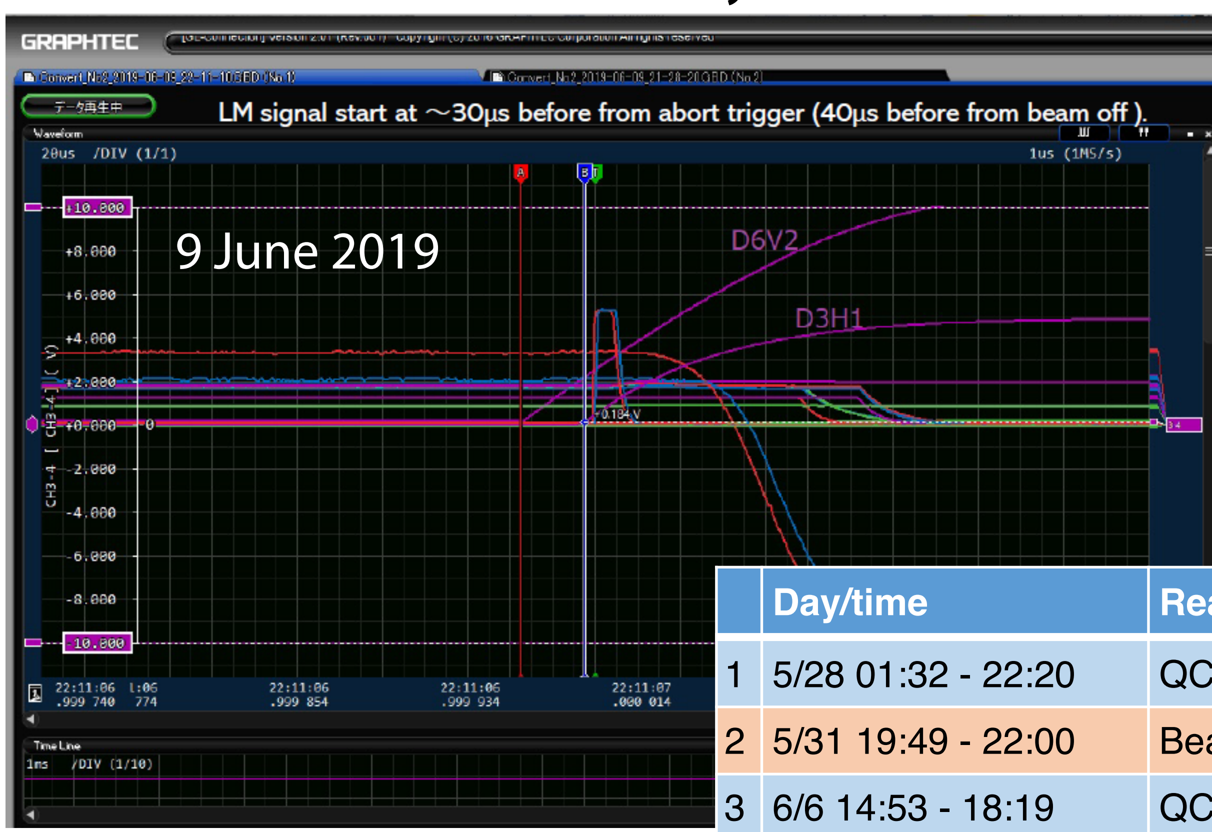


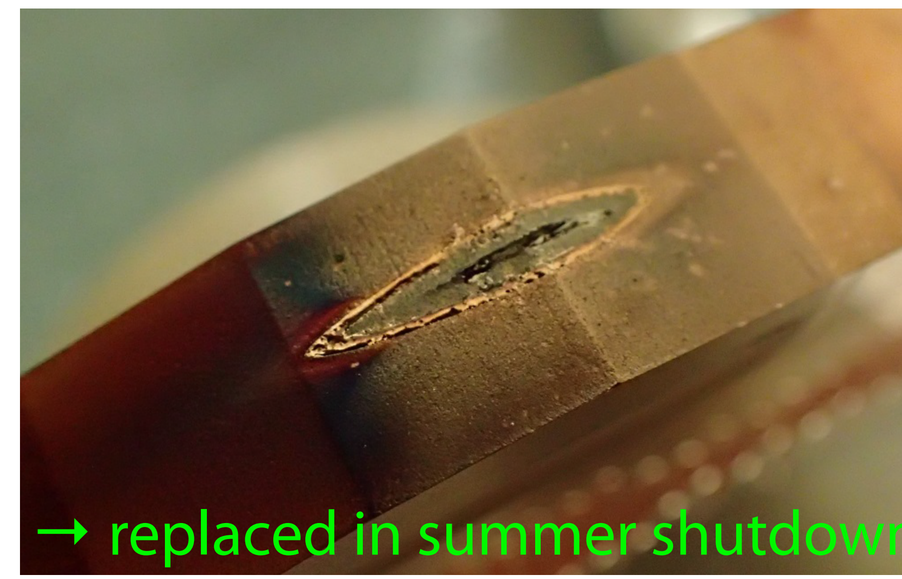
- **Injector and main rings**
  - Pulse-like backgrounds
    - occurred by injection and storage beams
    - additional beam monitors and FB in BT
  - Beam-gas Coulomb scatterings
    - install more beam collimators (D06V1)
    - vacuum scrubbing towards 5 kAh in LER, baking of vacuum components



Other challenges

- **Rapid beam loss within few turns made QCS quench and collimator damage**
  - Beam loss ~ 150 mA/30 μs simultaneously damaged the collimator head and quenched the QCS system, followed by 4 days beam stop.
  - Needs correct understanding on a mechanism (scattering off dusts?)
  - Improvements of beam collimators (head, structure, add more collimators)
  - Fast beam abort system





	Day/time	Reason	Ring	Vacuum Spike	1st Abort trigger
1	5/28 01:32 - 22:20	QC2LE PS	HER	-	LM@D1H5 collimator
2	5/31 19:49 - 22:00	Beam loss	LER	D06_L07 3.98E-7 Pa (B2P_65)	LM@D6V2 collimator
3	6/6 14:53 - 18:19	QC2LE PS	HER	-	Belle2 VXD diamond
4	6/9 22:11 - 6/13 19:01	Beam loss (155mA)	LER	D02_L18 3.64E-5 Pa (D02_V1 collimator) D05_L20 9.64E-8 Pa (D05 ARES and wiggler) D06_L25 4.86E-7 Pa (D06_V2 collimator) D11_L22 8.35E-7 Pa (NIKKO D11wiggler)	Belle2 VXD diamond
5	6/27 11:41 - 12:34	Beam loss	LER	D03_L20 1.17E-7 Pa (B2P_96)	Belle2 VXD diamond

Commissioning plan

Summer shutdown (1 Jul. 2019 - 15 Oct. 2019)

- Replacement of the bellows and the QC1L BPM cables at the IP
- Many other work at the machine and the Belle II.

2019 autumn run (15 Oct. 2019 - 12 Dec. 2019)

- Continue physics run and machine tunings.

Winter shutdown (12 Dec. 2019 - 16 Jan. 2020, to be fixed)

- 150 kV power line work by TEPCO, power in KEK was restricted to less than 50 MW
- MR needs to be stopped, while can operate Linac, DR, and BT
- A vertical-type collimator will be installed in LER (D06V1).

2020 spring run (16 Jan. 2020 - 30 Jun. 2020, under consideration)

- Operation in January will be for mainly BT tuning and vacuum scrubbing.
- Continue physics run and machine tunings

Summary

- SuperKEKB is a major upgrade to KEKB and aims at x40 luminosity.
- Many components have been improved over 5 years construction. Commissioning started in 2016 and physics run with full Belle II in 2019.
- Nono-beam collision scheme is employed and β_y^* is squeezed to 2 mm.
- Continuous injection in both rings gains integrated luminosity.
- Achieved peak luminosity 1.23×10^{34} $cm^{-2}s^{-1}$ on 1 July 2019 (Integrated luminosity = 6.5 fb^{-1})
- Collider performance has been improved day-by-day.

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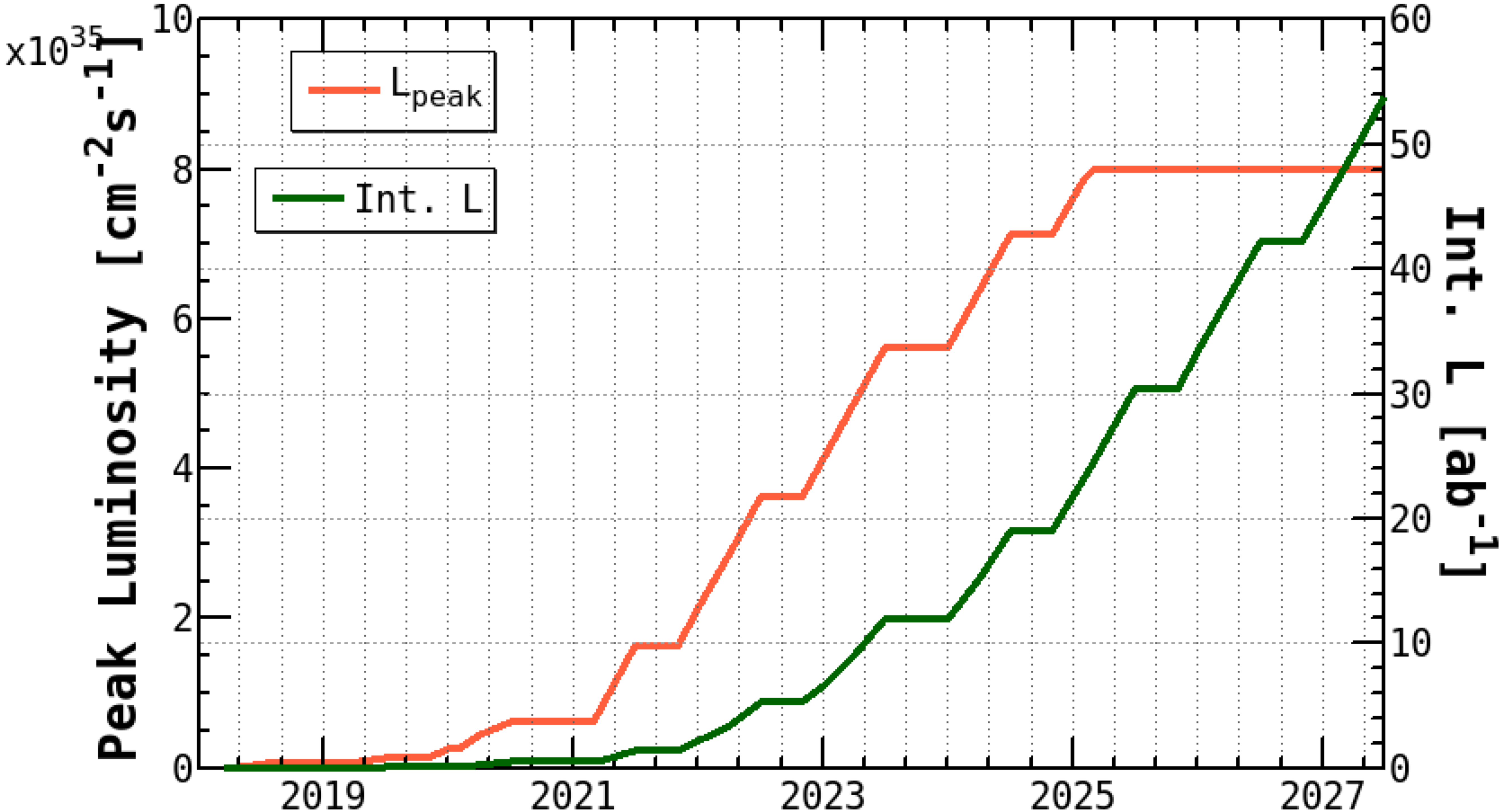
Stay tuned!!

Backup

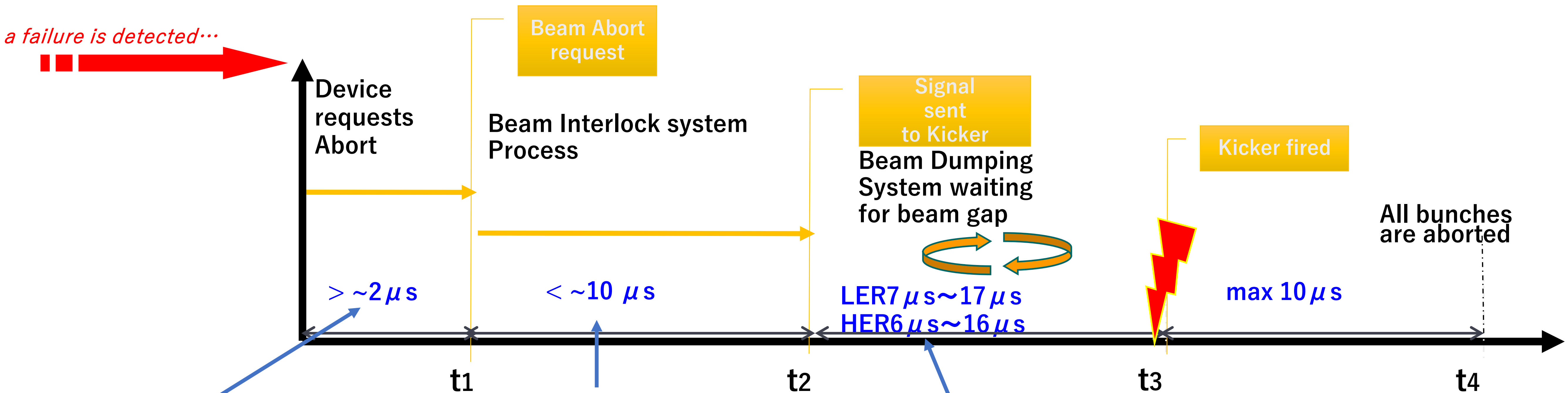
Projected luminosity



Detailed operation strategy is under discussion with Belle II.

[Ikeda, MAC 2019]

Beam Abort Delays



Hardware dependent

To summarize the abort request on the beam abort system.

Depends on the optical cable length from the local control room to CCR.

10μs for D1, D2(near Belle-II),

2μs for D7 or D8

Synchronization of the abort request signal with revolution in FPGA. : Max delay=10μs
Delay to synchronize to the abort gap(fixed delay) : 4.2μs for LER, 2.8μs for HER
Delay from CCR to kicker (400m) : 2μs
Thyratron ON :1μs
Rise time for the kicker : 200ns

[Ikeda, MAC 2019]

3. Speedup of the abort

1. Minimize t1(Detector response time)
   ① QCS magnet
   - Quench detector : Shorter checking time 10ms→2ms for stronger protection of QCS magnet. ： (Done)
   - QCS PS I/L : Remodel the PS module to take out abort signal directly from FPGA without conventional PLC when there is a failure in a power supply. (start from main magnet)

   ② Beam loss detection
   - Make the threshold of the detectors severe and keep redundancy.
   - Loss Monitor : Set lower threshold
     - Use PIN at the place besides collimator.
     - Make the injection veto system for collimator PIN. (from D6V2 as a trial)
   - RF D5F arc sensor : Set lower threshold and shorter checking time (6μs→). : Use temporarily.
   - Belle : Make shorter sampling time (10μs→<5μs)
2. Shorten t2-t1(Distance from CCR)
   - Detect the beam loss by the detector near CCR.
     - D6V2 collimator PIN signal send to D7 in stead of D4.
3. Shorten t3-t2
   - Increase the number of abort gap (1→2)
     - Shortened time ＜ 5μs

We perform all of these before autumn run.

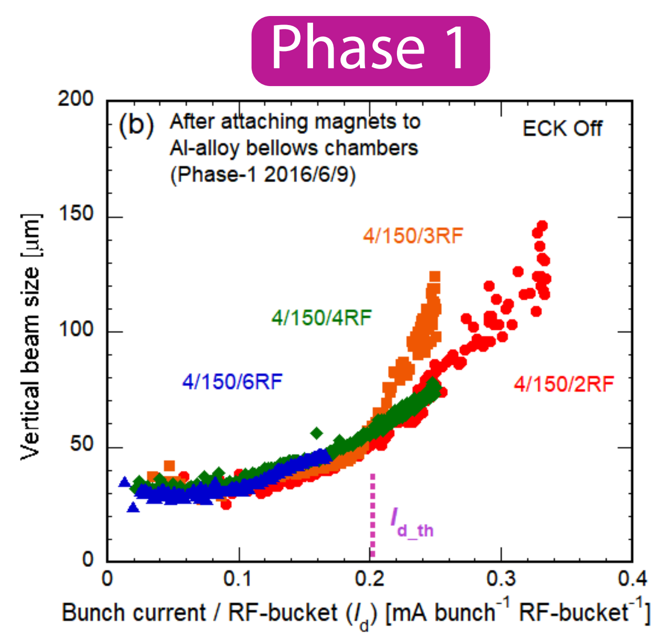
[Ishibashi, MAC 2019]

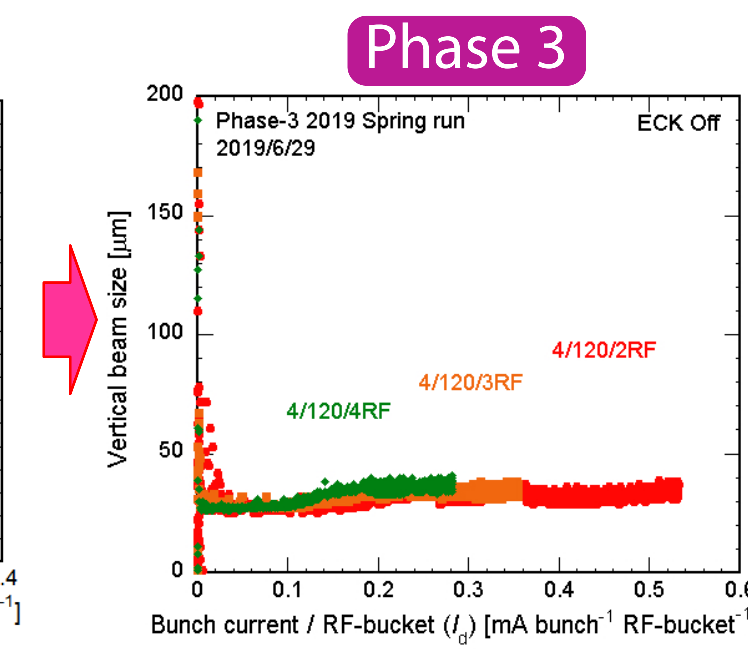
Summary and plans

- Vacuum scrubbing is going well.
- Countermeasures for ECE in LER are quite effective.
- Problems:
  - Collimator damage
  - Dust events
  - BG in derived from vacuum
  - IP bellows chamber heating
- Near Future Plans:
  - Change the damaged collimator(D02V1 bottom) in the summer/winter.
  - Knock beam pipes in LER.
  - Try baking collimators in tunnel.
  - Change IP bellows chamber in this summer shutdown.
  - Add a vertical collimator at D06V1 in LER in the winter shutdown.

Electron cloud effects

- Beam size blowup was observed in Phase 1.
- After Phase 1, permanent magnets were attached to the beam pile to add magnetic field to beam incident direction.
- No apparent beam size blowup in Phase-III until 0.53 mA/bunch/RF-bucket.





Summary

[Kobayashi, MAC 2019]

- Steady operation has been continued without serious problem in RF systems.
- ARES cavity and DR cavity has also operated without trouble and the trip-rate is enough low at present.
- In SCC operation, piezo actuator frequently failed with electric breakdown. From our study, it was found that the moisture degrades its insulation, and that drying piezo with silica gel is effective to prevent from the degradation.
  We ill continue to study moisture control around the piezo in the tunnel.
- Newly developed digital LLRF control systems, applied to 9 stations at OHO section, is properly working without fatal trouble.
- New LCBI damper system with new digital filters has been developed. It can suppress the μ=-1, -2 and -3 modes in parallel. In Phase-2, successful damping of μ=-1 and -2 was demonstrated by the new damper.

MR Magnet System Summary

[Masuzawa, MAC 2019]

- The IR construction went well, which lead to a smooth 1st collision in Phase 2.
- The IR re-construction for Phase 3 also went well, with good reproducibility of the IR orbit.
- Additional coils in the IR skew quads made it possible to scan a wider range in the IR coupling knob scans.
- A water leak from a ~20-year-old flow switch led us to start replacing the flow switches used in the KEKB magnets.
    - This could be a very costly operation so we will do it over time.
    - Flow switch is just one of the magnet subsidiary components.
    - What about rubber hoses? Will they last for the next ~10 years? Everybody ages.

- The # of power supply failures decreased from Phase 1 to Phase 3.
- Investigation of the QCS (QC2LE) power supply failure due to distorted gate signals is on-going. This is one of our highest priority items for the summer shutdown.
- Adding a fast abort signal from the QCS power supplies looks feasible, and we will try to implement a fast abort signal from the QCS PS for the fall run.

- The south arc of the MR continues to sink, at an average rate of 1.9 mm/year.
- A correlation is seen between the HLS, the cryostat motion and the steering currents.
- Some correlation is seen between the fast luminosity signal and vibration data. We will keep looking into the vibration issues.

[Mitsuka, MAC 2019]

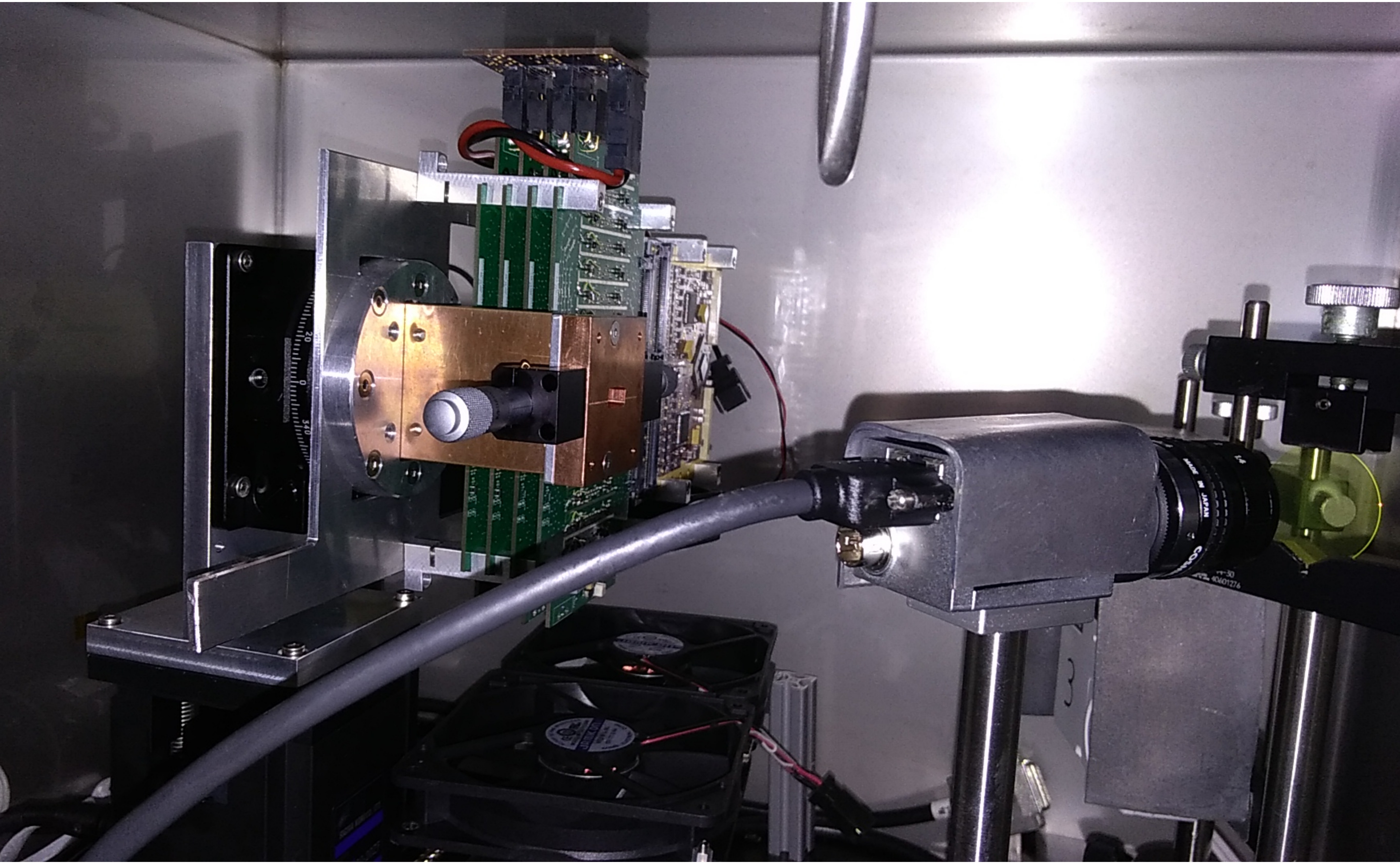
Summary

- 1 out of 4 channels of each MQC1LE/LP seems damaged, although no significant effect to operation. Replacement with new cables in August.

- No other major problem in the beam monitors, work well over Phase 2&3
  - Promising capability of GTBTs for optics measurements
  - Well calibrated beam size monitors provide fundamental information to the beam commissioning, and may contribute to beam dynamics study.
  - Bunch-by-bunch FB system stably operated
  - Tuning of the fast IP-orbit FB underway, will be involved into daily operation if necessary

- R&D of new detectors are running in parallel.

Si-XRM



[Iida, MAC 2019]

(1) Injection beam

TBI: To be introduced

Improvements for stabilizing the injection beam

		Tool	Place	Achievement	Feedback	Talk
A	Energy	(A) Energy feedback	Jarc, DR, BT	○		
B	Energy spread	(B) Sub Hermonic Buncher 1 (SHB1) for LER beam	Thermionic Gun	○	—	
		SHB2		TBI	—	
		RF Phase monitor	LINAC	○	TBI	T. Miura
		RF Induced wave monitor	LINAC	△	—	
		OctoPos BPM monitor	Jarc	○	TBI	F. Miyahara
			BT	△	TBI	
C		(C) Temperature control	LINAC	△		
	Orbit	Orbit feedback	LINAC	○		Y. Seimiya
			End of BT	○		
D	Orbit jitter	(D) Pulsed magnet PS	Sector 3-5	△	—	Y. Seimiya
	Energy jitter	(D) Energy knob phase	Sector B, 2, 5	TBI	—	
		(D) RF phase	LINAC	△	—	T. Miura
	Injection phase	FB of Master oscillator	LINAC and MR	○		
E	Emittance	(E) e- RF gun	RF Gun	△(Stability)	TBI	R. Zhang
		e+ DR	DR	○	—	
		(E) Wire scanner	LINAC, BT	○	—	Y. Seimiya
			End of BT	△	—	T. Mori

Summary

I. Injection background

(0) Tuning method with TBT BPM on one-pass mode is established.

(1) Injection beam

- Improvement for stabilising the injection beam will be continued.

(2) Injection tuning

- HER
  - Some parameters such as the septum angle, the vertical steerings should be tuned to keep the low BG.
  - The tunes or collision tunings sometimes affects to the BG.
- LER injection is very stable. Thanks to the DR.

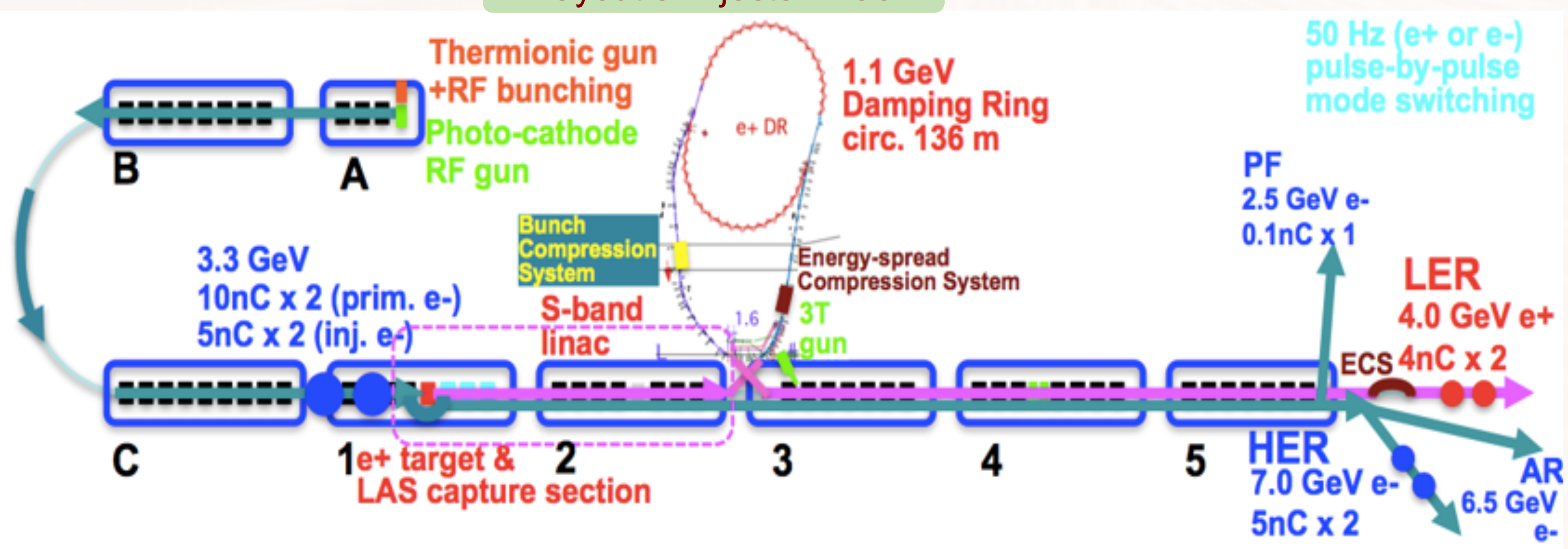
II. Beam aborts during the injection can be monitored

- ~10% of the aborts during injection were caused by the abnormal orbit or energy in LINAC.
  - The abnormal beam will be cut by the new collimators.
  - The other causes are still unknown.

Highlights in Phase-2

- The injector linac has been working stably.
- Simultaneous bean injection to five rings (HER, LER, Damping ring, PF, and PF-AR) was realized in Phase-2.
  - Pulsed magnet system is working well.

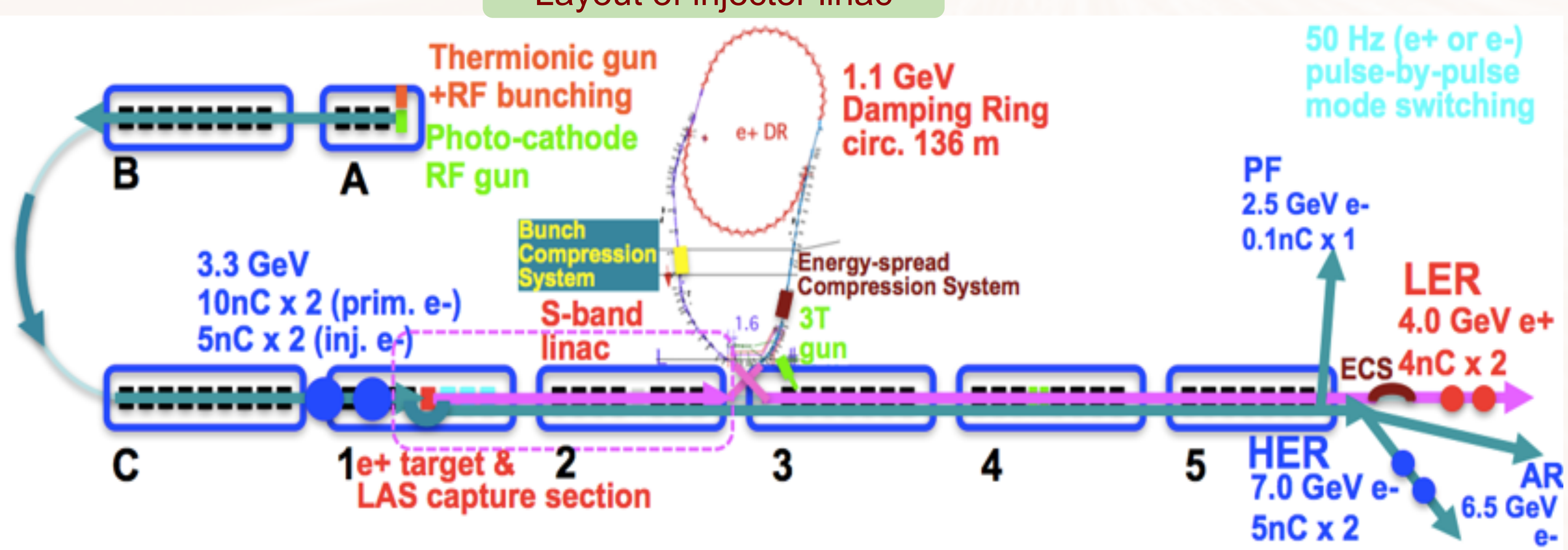
Layout of injector linac



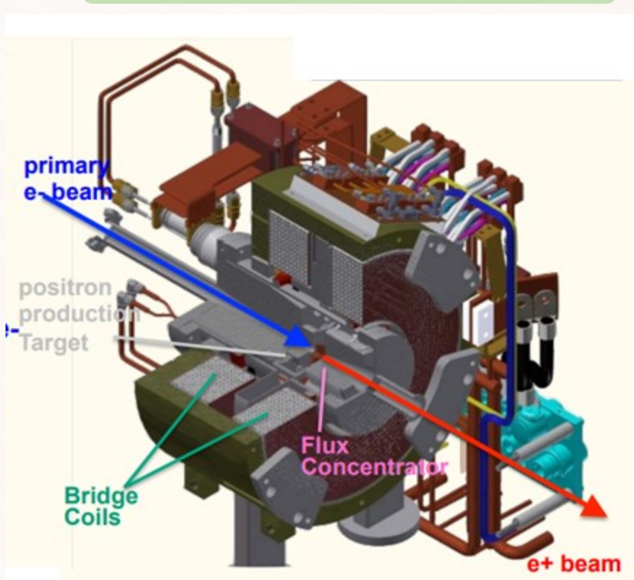
Highlights in Phase-2

- The injector linac has been working stably.
- Simultaneous bean injection to five rings (HER, LER, Damping ring, PF, and PF-AR) was realized in Phase-2.
  - Pulsed magnet system is working well.
- Photo-cathode RF gun has been regularly used for HER injection.
- Flux concentrator has been also functioning as expected.
  - These will be reported by Satoh-san, Zhang-san, and Enomoto-san.

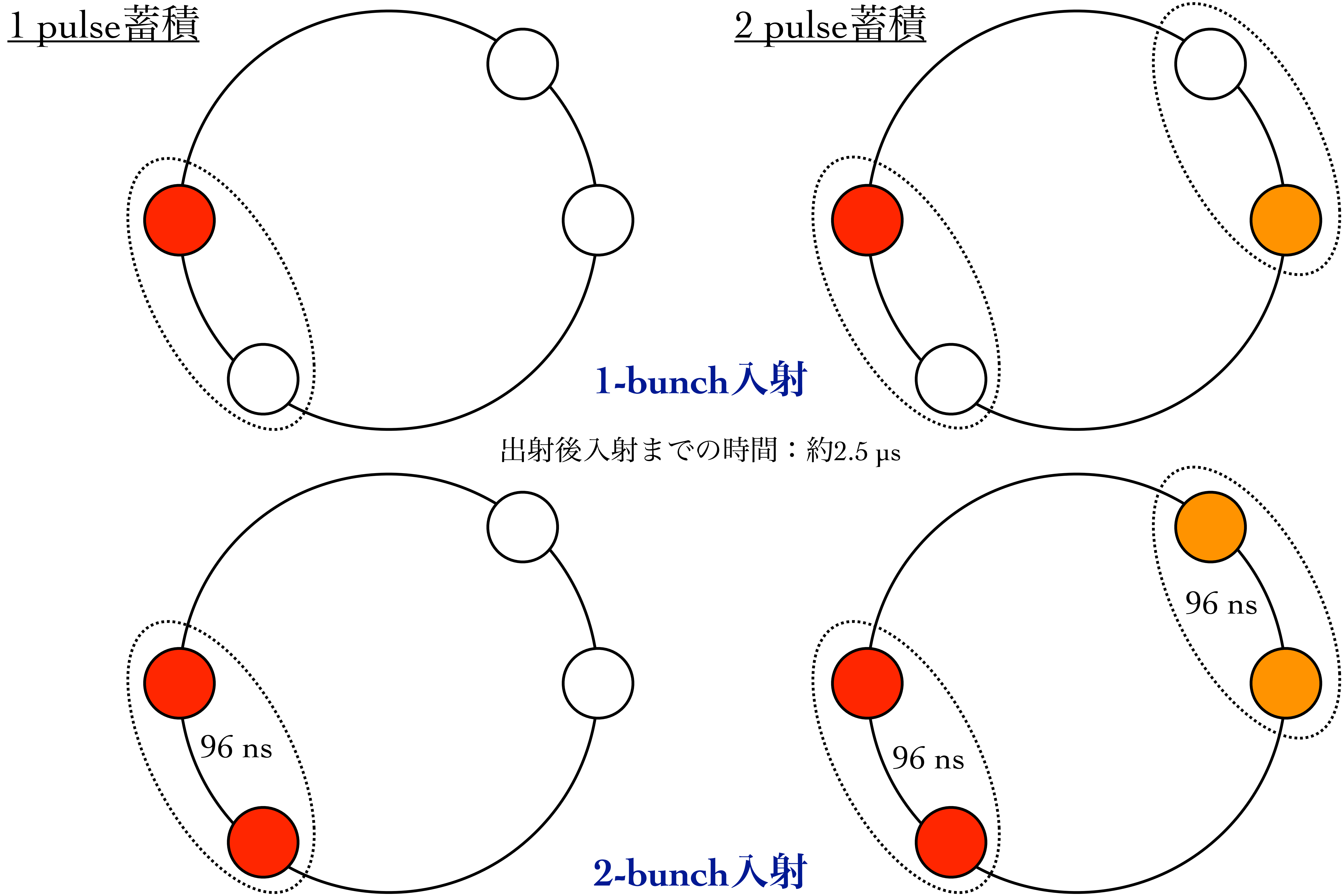
Layout of injector linac



Flux concentrator for e^+



Damping Ring: 最大4バンチの蓄積



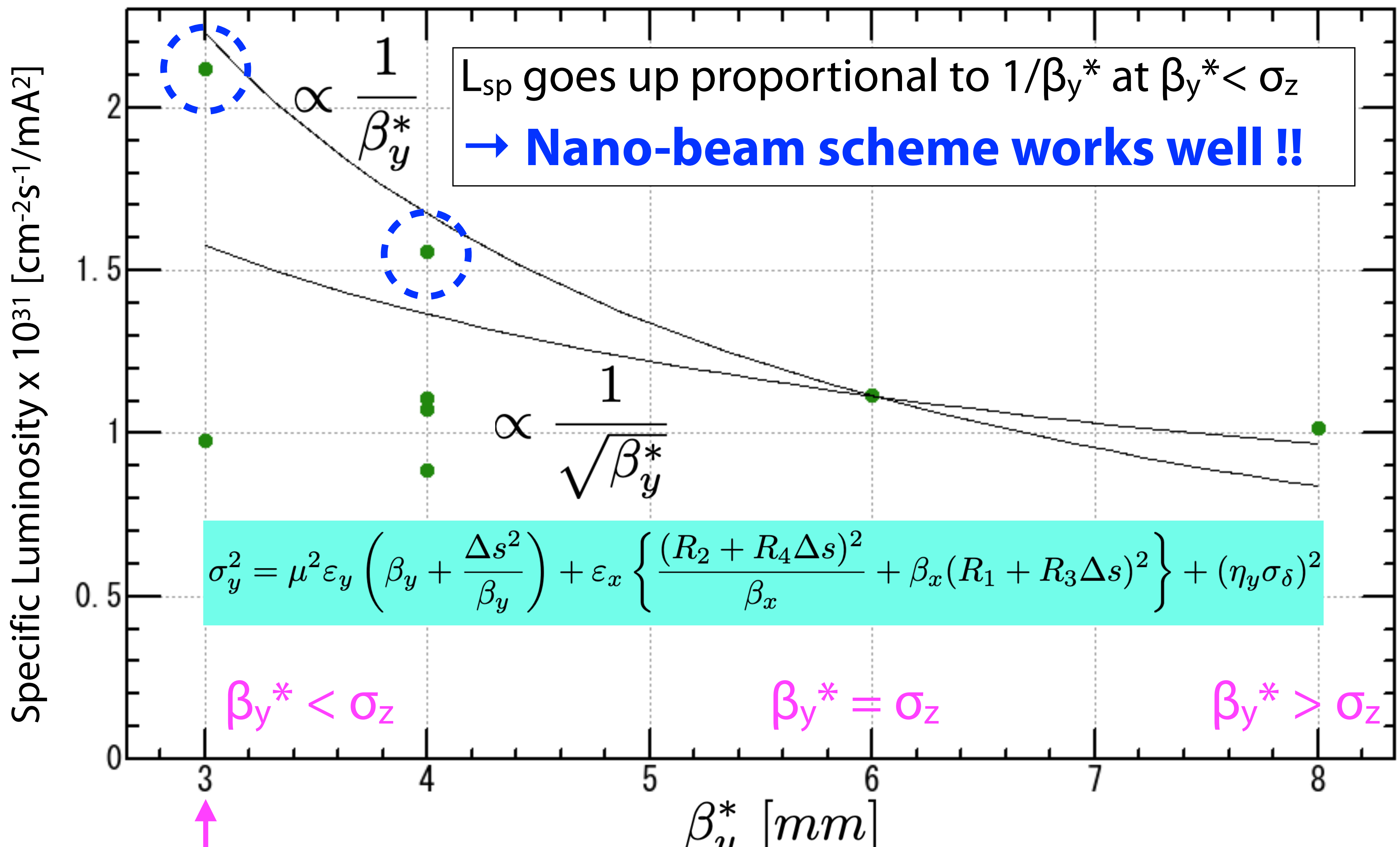
[Nakayama, MAC 2019]

Summary

- Status
  - Horizontal collimators are added after Phase2, and they suppress Touschek bkg
  - LER beam gas bkg now dominates (>= 70% of total background)
  - CDC and TOP limit max beam currents
  - Injection bkg bursts are a persistent problem, causing CDC HV trips
  - QCS and (we think) beam-dust related background bursts endanger detectors
- Recommendations
  - LER beam gas reduction: beam steering study, optics modification, new vertical collimators, intense LER vacuum scrubbing
  - Improve HER simulation for improved long-term bkg prognosis
  - Check beam-gas normalization with gas injection study
  - Improve injection further, especially for HER
  - Improved / faster / redundant abort system (See Ikeda-san's talk later)

Verification of the nano-beam scheme

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y} \Rightarrow L_{SP} = \frac{L}{n_b I_{b+} I_{b-}} \propto \frac{1}{\beta^*_y}$$



Lowest β_y^* in the world
(as of July 2018)

Highlights in Phase-3 2019 Spring

- Summary of major results

Major results in Phase-1, Phase-2 and Phas-3 2019 Spring run						
Parameters	Phase-1 (3/2/2016–6/30/2016)		Phase-2 (3/19/2018–7/17/2018)		Phase-3 2019 Spring run (3/11/2019–7/11/2019)	
	LER	HER	LER	HER	LER	HER
Max. beam current [mA]	~1010	~870	~860	~800	~830	~940
Beam dose [Ah]	775.0	661.5	337.5	340.2	500.4	539.1
Min. β_x^*/β_y^* in physics run (non phys.) [mm/mm]	-	-	200/3 (200/2)	100/3 (100/1.5)	100/3 (80/2)	100/3 (80/2)
Min. ε_x / ε_y [nm/pm]	~-/10 . (single)	~-/10 (single)	~1.7/160 (in col.)	~4.6/80 (in col.)	~2.0/88 (in col.)	~3.8/61 (in col.)
Max. bam beam param.			0.0244	0.0141	0.0355	0.0197
Max. lumi. L [$\times 10^{33}$ cm^{-2} s^{-1}]			5.55 (@1/1576/3.06)		12.3 (@1/1576/3.06, β_y^*=2mm)	
Specific lumi. @Max. L [$\times 10^{31}$ cm^{-2} s^{-1} mA^{-2}]			1.43		2.9	

Table 1. Machine parameters. * indicates values at the IP.

	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
N_b	2500		
C	3016.315		m
ε_x	3.2	4.6	nm
ε_y	8.64	11.5	pm
β_x^*	32	25	mm
β_y^*	270	300	µm
$2\phi_x$	83		mrad
α_p	3.25×10^{-4}	4.55×10^{-4}	
σ_δ	8.08×10^{-4}	6.37×10^{-4}	
V_c	9.4	15.0	MV
σ_z	6	5	mm
ν_s	−0.0247	−0.0280	
ν_x	44.53	45.53	
ν_y	44.57	43.57	
U_0	1.87	2.43	MeV
τ_x/τ_s	43.1/21.6	58.0/29.0	msec
ξ_x	0.0028	0.0012	
ξ_y	0.0881	0.0807	
L	8×10^{35}		$cm^{-2}\ s^{-1}$