# Status of Early SuperKEKB Phase-3 Commissioning

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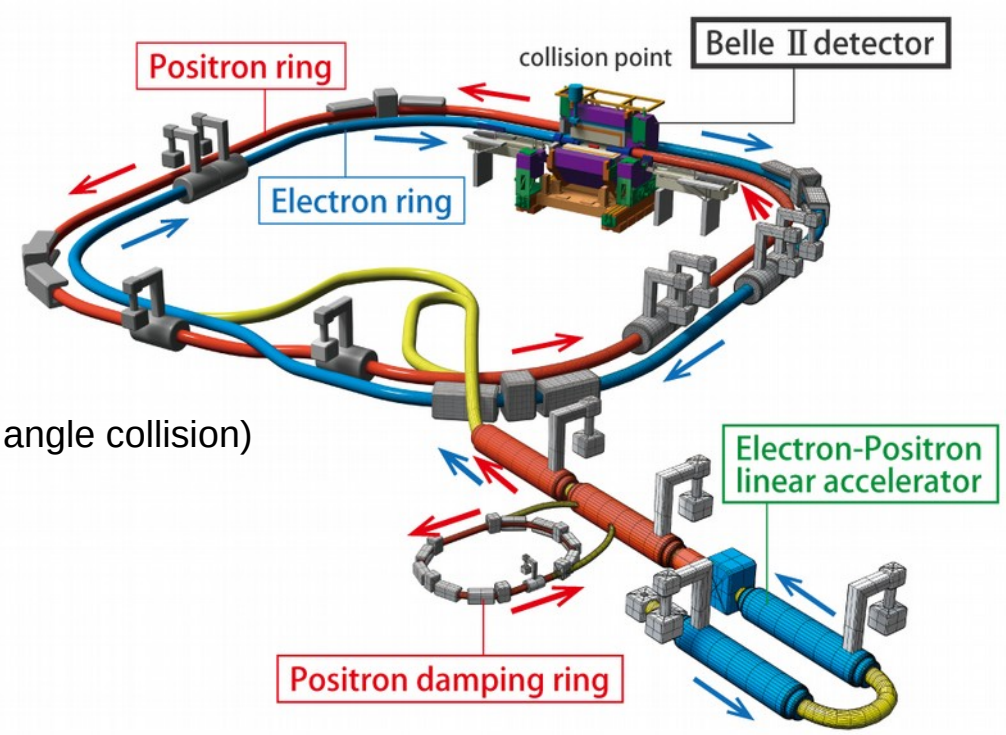
# SuperKEKB Accelerator

- Double ring collider for Belle 2 experiment (B-meson Physics)
  - Main rings
    - 7GeV electron storage ring (HER)
    - 4GeV positron storage ring (LER)
  - Injector complex
    - electron/positron linac
    - 1.1GeV positron damping ring (DR)
  - Design Parameter
    - Target Luminosity: 8 x $10^{35}$ $cm^{-2}s^{-1}$
    - Collision Scheme: “nano-beam” (Large Piwinski angle collision)
    - Beam Current: 3.6/2.6A (LER/HER)
    - Crossing Angle: 83mrad
    - σ*x ~ 10μm, σz ~ 6mm
    - β*y ~ 300μm




http://www-superkekb.kek.jp/

http://www.kek.jp/en/newsroom/2016/03/02/1630/

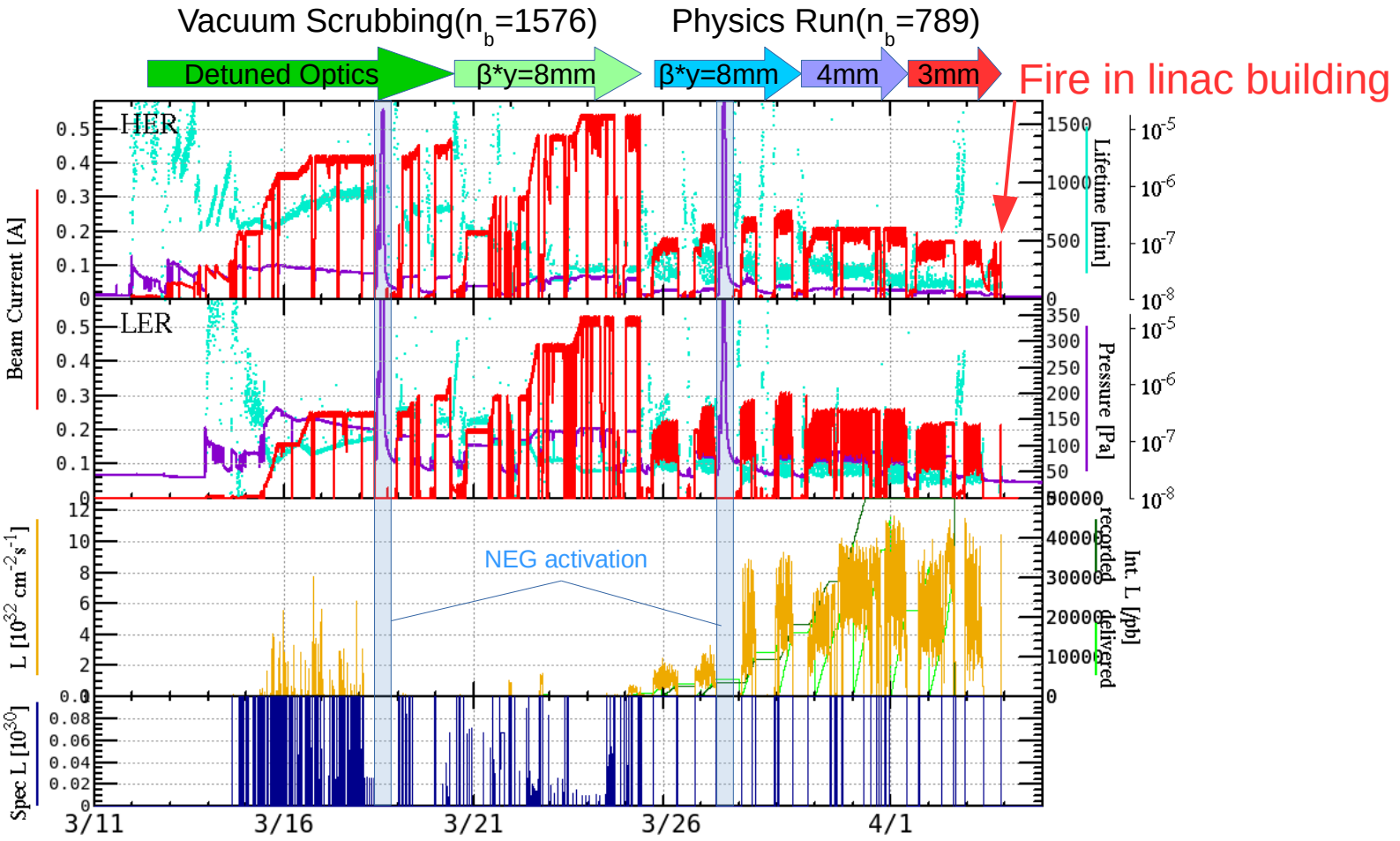
# Staging of SuperKEKB Commissioning

- Phase-1 2016/02/01 ~ 06/28
  - For low emittance operation test & vacuum scrubbing without final focus system
- Phase-2 2018/03/16 ~ 07/17
  - For “nano-beam” collision test with final focus system & Belle 2 detector except vertex detector
- Phase-3 2019/03/11 ~
  - For full-scale collider experiment with full Belle 2 detector

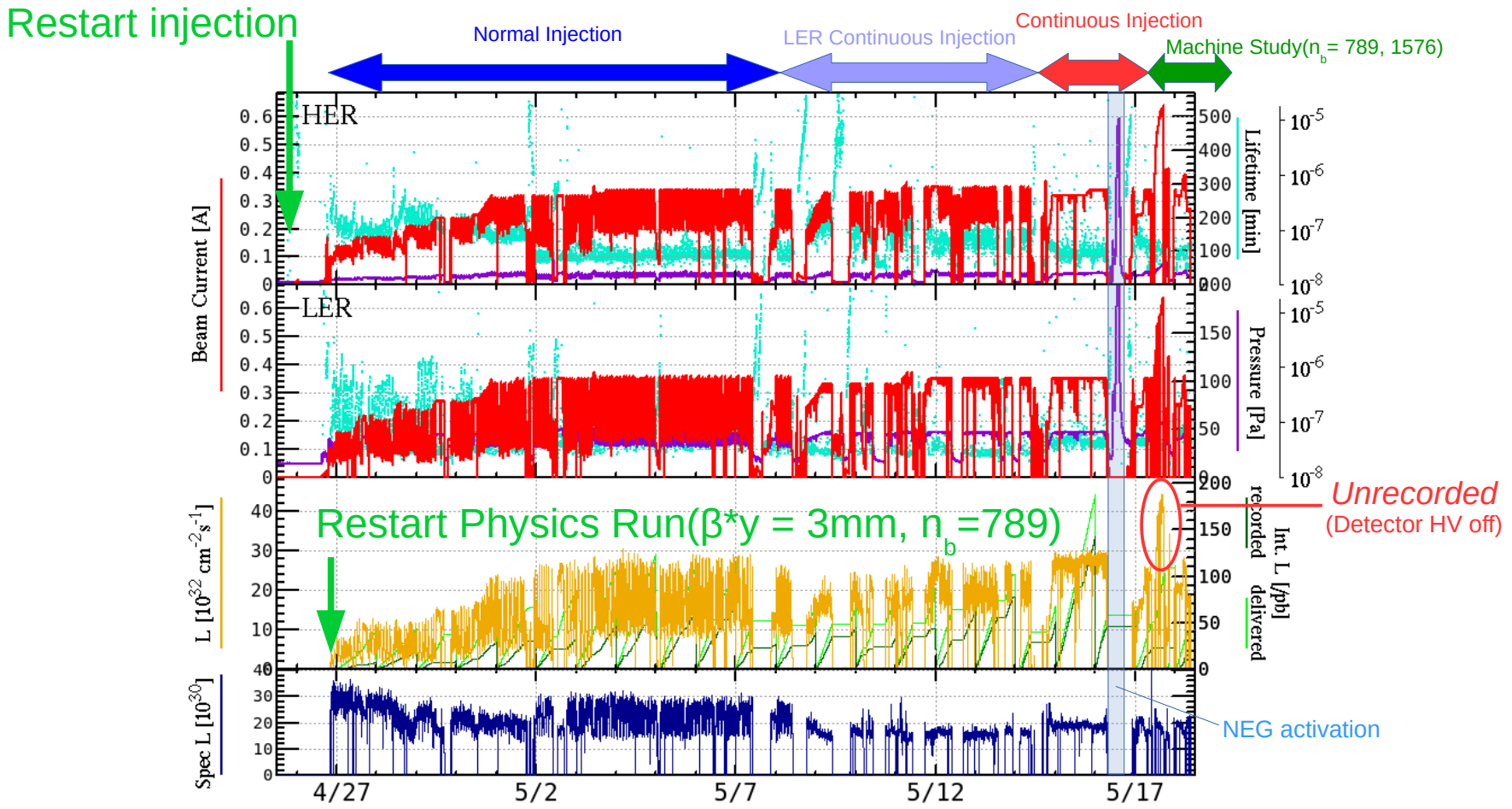
# Hardware Updates since Phase-2

- Interaction Region(IR) Disassembly & Reassembly
  - IR is reassembled to install Belle 2 vertex detector(PXD & SVD).
  - Signal cables of L-side QC1 BPMs(QC1LP for LER, QC1LE for HER) are damaged during QCS cryostat insertion process.
    - **Not critical** because 3 signal cables are still available for 4 electrode BPM.
    - BPM gain calibration & consistency check for QC1LP & QC1LE become impossible.
    - IP orbit feedback accuracy will be degraded.
- Beam Collimator
  - HER & LER vertical beam collimator head damaged during Phase-2 commissining are replaced.
  - Additional 4 horizontal collimators are installed(1 for HER, 3 for LER).
  - Additional vertical collimator is installed for LER.
- Skew Quadrupole Correctors
  - IR skew quadrupole magnet excitation range is extended x2.23 by adding extra winding(10 magnets for HER, 6 magnets for LER).
  - Number of arc skew quadrupole correctors is almost doubled by installing additional power supply for skew quadrupole winding for SF-family chromaticity corrector sextupoles.

# Operation Overview(1)



# Operation Overview(2)



# Initial Optics & Orbit for Phase-3

- Initial Optics & Correction Fudge
  - Optics: Detuned Optics operated in Phase-2
    - $(\beta^*x, \beta^*y) = (384\text{mm}, 48.6\text{mm})_{\text{LER}}, (400\text{mm}, 81\text{mm})_{\text{HER}}$
  - Fudge: Phase-2 Latest Fudge except final focus quadruple(QCS) Waist & R2*
    - For changing QCS waist & R2* knob parameter handling
    - IP waist & R2* knob tuning(most efficient luminosity tuning knob) by QCS is cleared.
- Initial Reference Orbit & Steering Parameter
  - Use Phase-2 data-set during Detuned Optics Operation.
    - IP V-offset for collision & H-offset for adjusting vertex position during Phase-2 are cleared.

# Beta Squeezing

- Squeeze β* down to β*y=3mm collision optics by tracing way-point optics used in Phase-2.
  - Beam collimator setting & detector loss monitor abort are important for avoiding QCS quench.
  - Linac injection charge limiting workaround is useful to prevent loss monitor abort during 1st injection to squeezed optics before xy-coupling correction.

| (β*x, β*y) | Established Date in Phase-3 (2019) | | Established Date in Phase-2 (2018) | |
|---|---|---|---|---|
| | LER | HER | LER | HER |
| Detuned | 3/13 | 3/11 | 3/31 | 3/20 |
| (200mm, 8mm) | 3/18 | 3/18 | 4/16 | 4/10 |
| (200mm, 6mm) | 3/25 | 3/25 | 5/14 | 5/10 |
| (200mm, 4mm) | 3/26 | 3/26 | 5/24 | 5/24 |
| (200/100mm, 3mm) | 3/28 | 4/1 | 6/5 | 6/20 |

***Phase-2 Collision Optics***

LER/HER

**No QCS Quench**

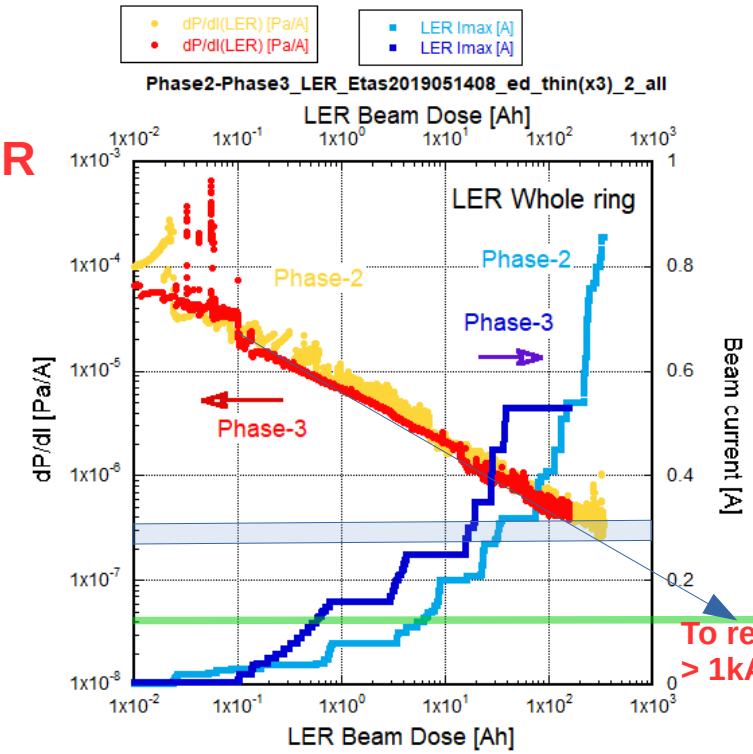
27 QCS Quenches to complete Squeezing

Detuned → 3mm Collision ~3weeks (22days) ~3months

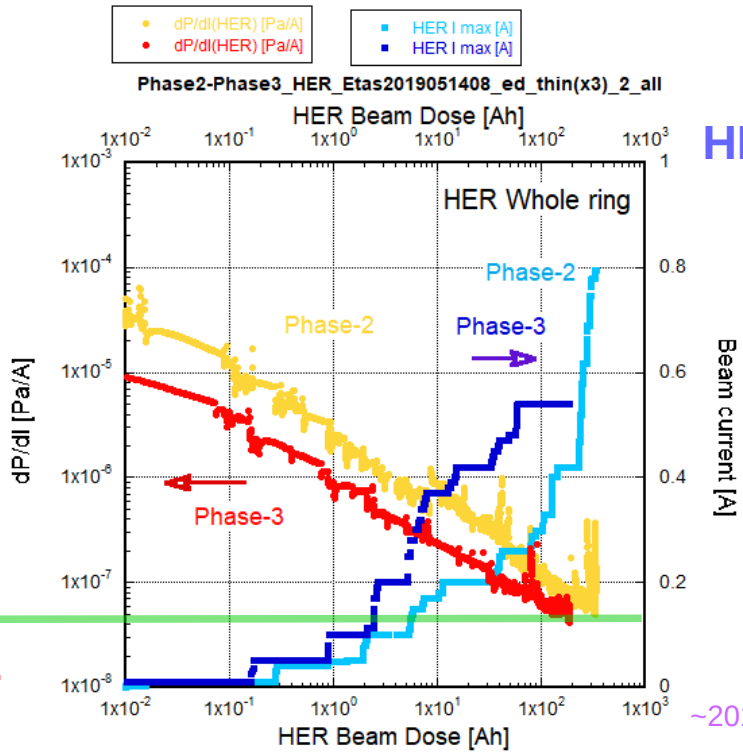
# Whole Ring Vacuum Pressure

- HRE vacuum pressure is already reached phase-2 level.
- LER vacumm pressure is still higher than phase-2.
  - Further scrubbing is required to reduce beam-gas detector background.

LER




HER




**To reach HER level,**
**> 1kAh dose is required.**

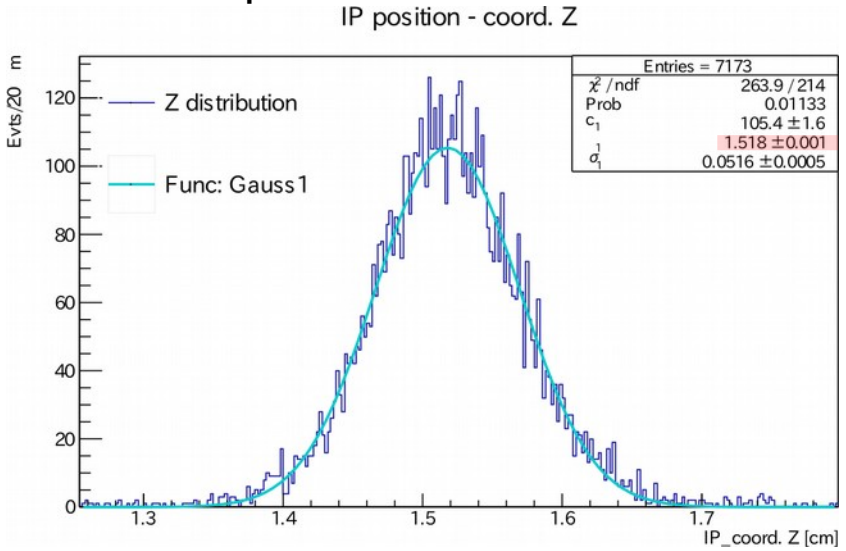
~2019/05/14

# IP Orbit for Collision

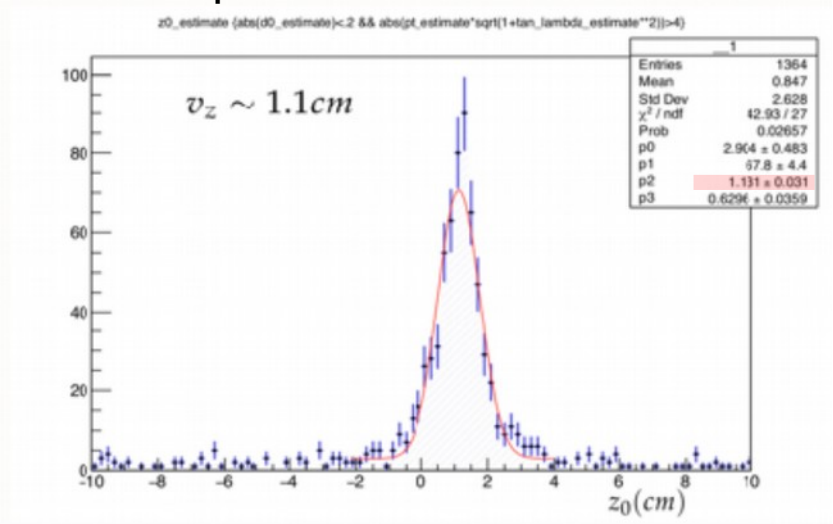
Comparison of measured longitudinal vertex position
determined by relative horizontal orbit at IP.

Note: Phase-3 initial data-set for orbit & steering is based on Phase-2 detuned optics operation.

Phase-3 1st measurement
reported at 2019/03/27.




Phase-2 1st measurement
reported at 2018/05/09.

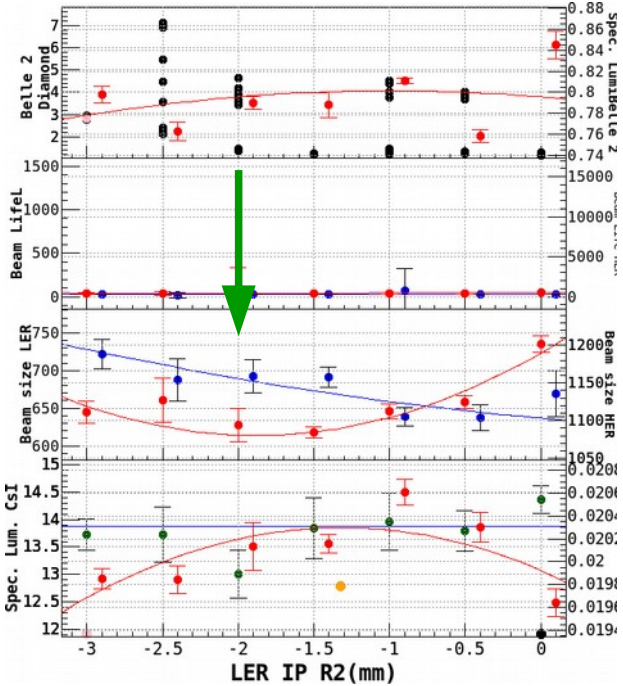


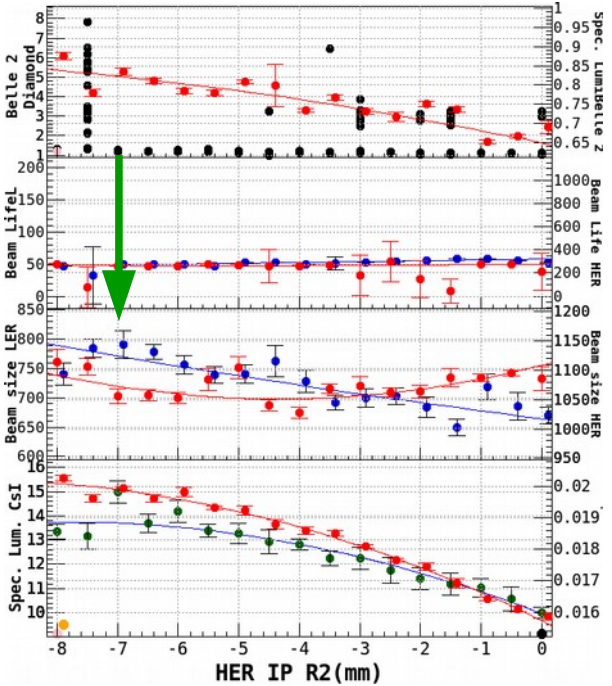

By Eugenio Paoloni

- Good agreement with Phase-2 measurement.
- Relative location of QCS magnets seems to be preserved after IR reassembly.

# IP Coupling for Collision

First R2* (IP xy-coupling) knob scan on β*y = 4mm optics at 2019/03/30.
(R2* is most important knob for SuperKEKB luminosity tuning.)
Initial R2* tuning knob of Phase-3 is 0. (Cleared due to QCS knob cleanup)



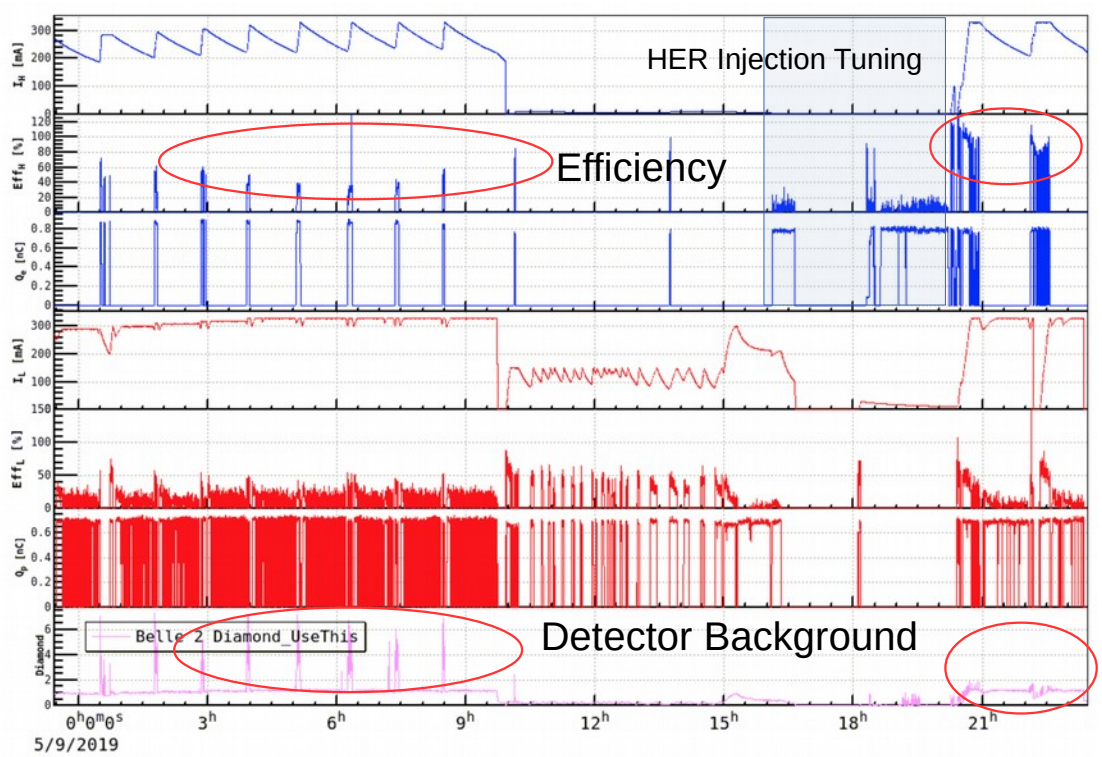




Expected optimum R2* from Phase-2 tuning: -2/-7mm(LER/HER)

- Good agreement with Phase-2 optimum.
- Relative rotation of QCS magnets seems to be preserved after IR reassembly.

# Systematic Injection Tuning

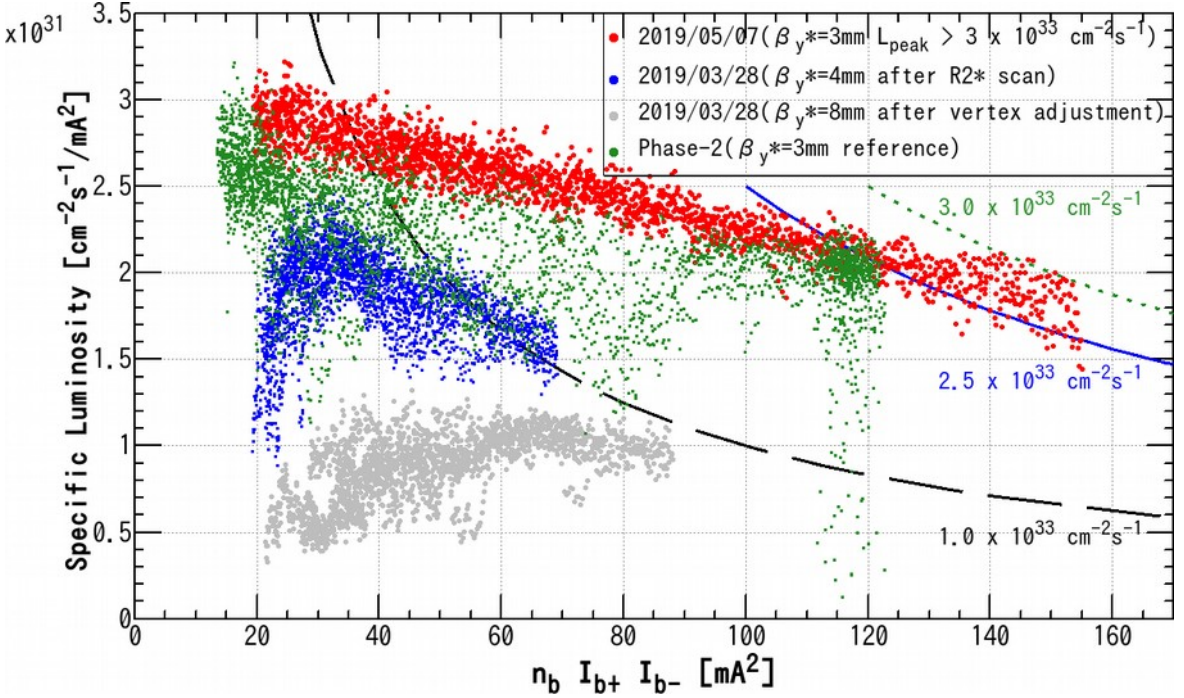
- Tuning to minimize betatron & synchrotron oscillation of injection beam measured by using TbT ring BPMs & 1-turn injection mode.
  - Longitudinal tuning items
    - Linac & BT energy feedback
    - Linac energy spread
    - Injection phase
  - Transverse tuning items
    - BT end orbit feedback
    - Septum position & angle
    - Kicker height & jump
    - Vertical steering




**Injection efficiency(rate) & detector background are improved.**

# Specific Luminosity(1)

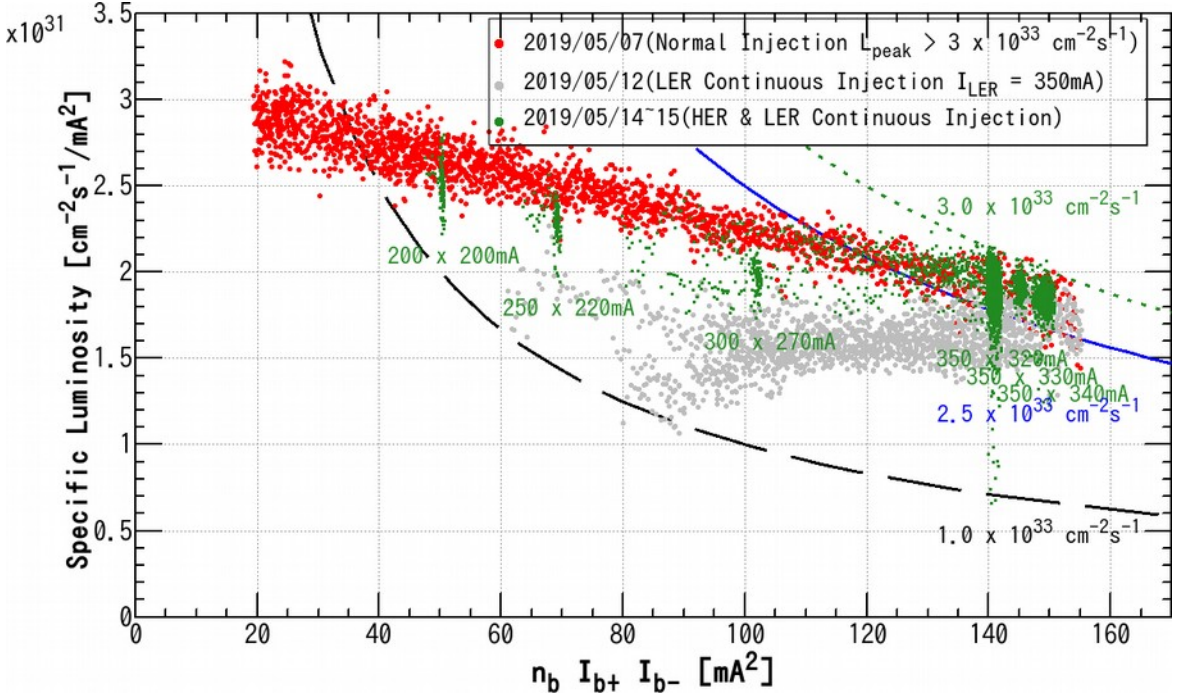
6.12 spacing 789 bunch operation(decay mode)




- Improvements by squeezing β*y & Luminosity Tuning are reconfirmed.
- Lsp in 370/350mA(LER/HER) decay mode reaches almost same level of Phase-2.
- Current dependent V-offset feedback target improves Lsp during decay.

# Specific Luminosity(2)

6.12 spacing 789 bunch operation(decay mode & continuous injection mode)

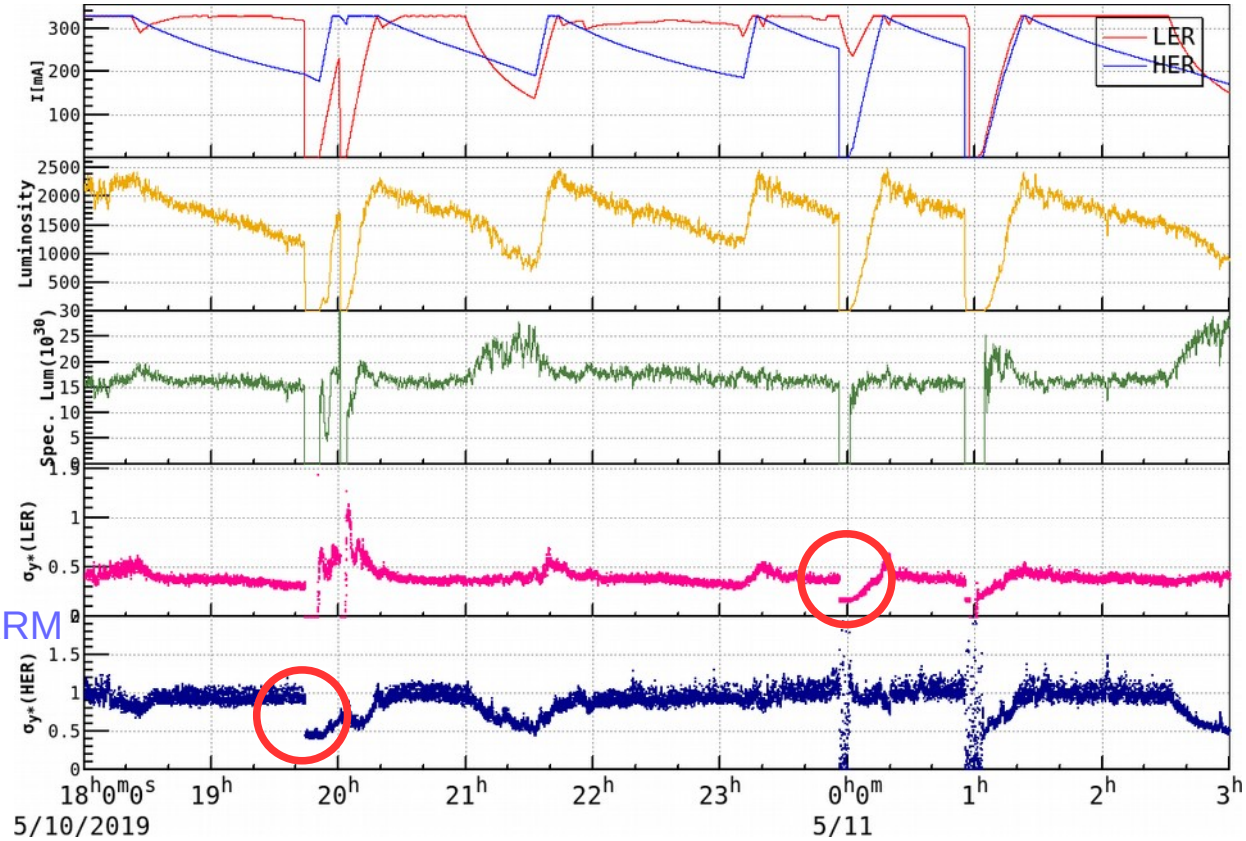



- By using continuous injection, collision & luminosity tuning become easier because of stable beam current.

# Beam Size during Collision

Current

IP beam size estimated from XRM

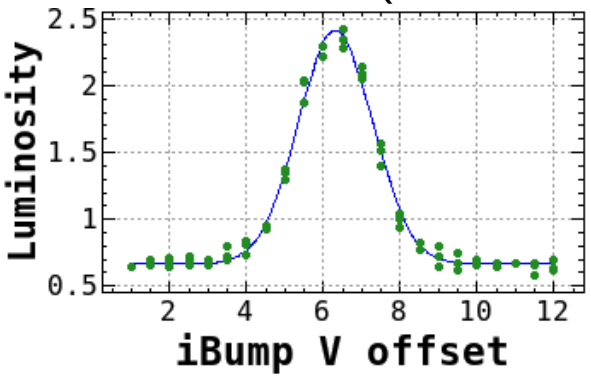



β*y = 3mm Collision
with LER Continuous Injection

- We HAVE TO control beam-beam blowup for getting higher luminosity.
- HER single beam size is larger than LER's one. ($\varepsilon_{y,HER} \sim 4\varepsilon_{y,LER}$)

# Low Bunch Current Beam Size measured by Beam-Beam Scan

Phase-3 (2019/04/02)
I =21.4/18.4mA(LER/HER)




| Luminosity Fit | RePlot | ReFit |
|---|---|---|
| Lum offset | | 0.669 |
| Luminosity | | 1.743 |
| $\sigma_y$ [μm] | | 0.685 |
| Vertical Offset [μm] | | 6.313 |

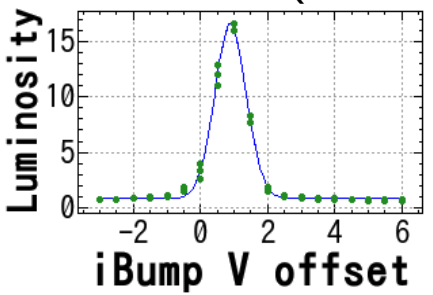
Σ*y / √2

This measurement is larger than expected value from typical single beam size: $\sigma^*y_{LER,HER}$.

β*y = 3mm, $n_b$ = 1576
(same optics & fill pattern)

**Inconsistent with Phase-2**

Phase-2 (2019/06/29)
I = 15.8/15.8mA(LER/HER)




| Luminosity Fit | RePlot | ReFit |
|---|---|---|
| Lum offset | | 0.827 |
| Luminosity | | 15.811 |
| $\sigma_y$ [μm] | | 0.333 |

Further investigation is required.

- Optics distortion(xy-coupling/dispersion)
- Lack of IP xy-coupling/dispersion tuning
- iBump(Collision V-Bump) calibration error

# Operation Summary

- IR orbit & optical function are consistent with Phase-2 after IR (final focus system) reassembly.
- 789-bunch(6.12spacing) luminosity performance on β*y=3mm optics is reconfirmed.
  - Lp = 3.07 x $10^{33}$ $cm^{-2}s^{-1}$ 346/335mA(LER/HER) @ 2019-05-07 07:07 JST (decay mode)
  - Lp = 3.13 x $10^{33}$ $cm^{-2}s^{-1}$ 347/338mA(LER/HER) @ 2019-05-15 20:30 JST (continuous injection)

    (New “recorded” luminosity record in this fill pattern during SuperKEKB commissioning)
- Beam operation is continuing without QCS quench.
  - Beam collimator tuning and detector loss monitor abort works well to protect QCS.
- Linac/Injection tuning & beam collimator tuning improve Belle2 detector background.
  - HER & LER continuous injection operation is started since May 14. +50% ~ +60% for integral
  - Belle2 recordable luminosity is improved compared with phase-2.
    - Belle2 detector runs with 3 x $10^{33}$ $cm^{-2}s^{-1}$ luminosity. +50% for integral
      - Phase-2 recordable limit is almost 2 x $10^{33}$ $cm^{-2}s^{-1}$.

**x2 improvement of integrated luminosity compared with Phase-2.**

# Major Issues

- High current operation
  - 1A is required for $10^{34}cm^{-2}s^{-1}$ luminosity on β*y=3mm optics.
  - LER beam instability found at >800mA operation in Phase-2 HAS TO be reconfirmed & resolved.
- Beam-beam blowup
  - Specific luminosity degrades because of beam-beam blowup. (Achieved $\xi_y < 0.03$)
  - Big IP chromatic aberration is suspected, however, it is not confirmed by measurement.
  - Vertical beam size measured by beam-beam scan on ultra low bunch current collision is different with phase-2 study result. (Further investigation is required)
- Single beam blowup in HER
  - Beam size measured by X-ray Radiation Monitor is too large compared with expected size from xy-coupling & dispersion measurement. (Further investigation is required)