Overview and prospects of the SuperKEKB commissioning

—Overview of Phase 3 commissioning

—Critical issues at present and after LS1 (Long-shutdown 1)

What limits the SuperKEKB performance at present?

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for the SuperKEKB commissioning team

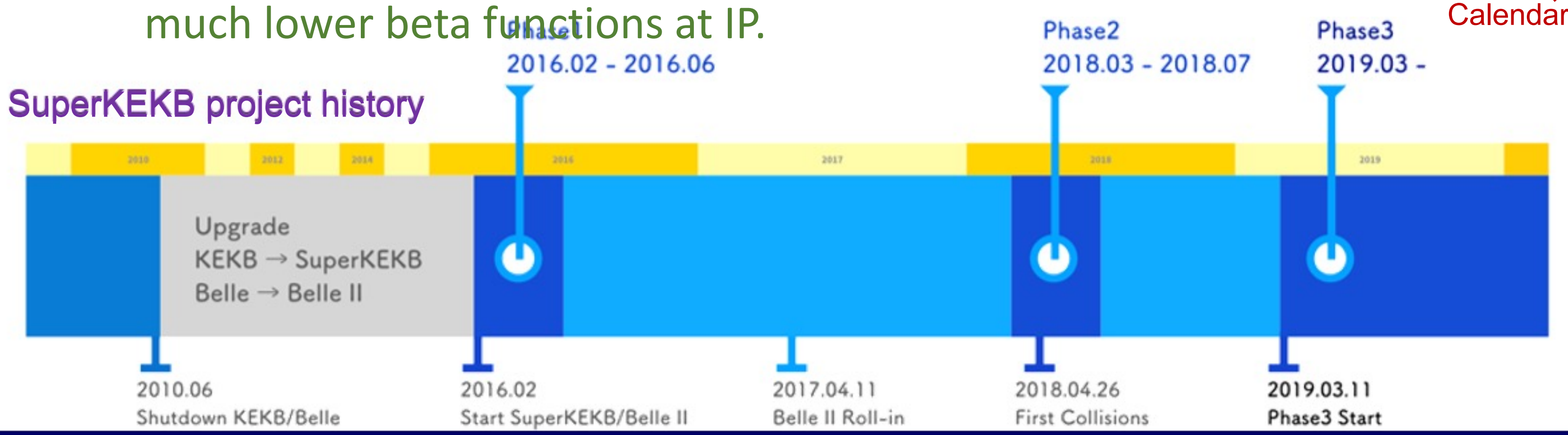
eeFACT'22 2022.09.14

Focus on the most essential issues for SuperKEKB
More comprehensive reports on SuperKEKB commissioning
---Y. Funakoshi *et al.*, "THE SUPERKEKB HAS BROKEN THE WORLD RECORD OF THE LUMINOSITY", in Proc. IPAC'22, Bangkok, Thailand, June 2022
---Y. Ohnishi, in this workshop

Overview of Phase 3 commissioning

SuperKEKB project history

- **Phase1 operation（2016.Feb. ~ June)；**
  - Vacuum scrubbing, low emittance beam tuning, and background study for Belle II detector installation
  - w/o IR and Belle II detector
- **Phase2 operation（2018.Mar. ~ July)；**
  - Pilot run of SuperKEKB and Belle II w/o pixel vertex detector (PXD) nor silicon vertex detector (SVD)
  - Demonstration of nano-beam collision scheme
  - Study on background larger than at KEKB due to much lower beta functions at IP.



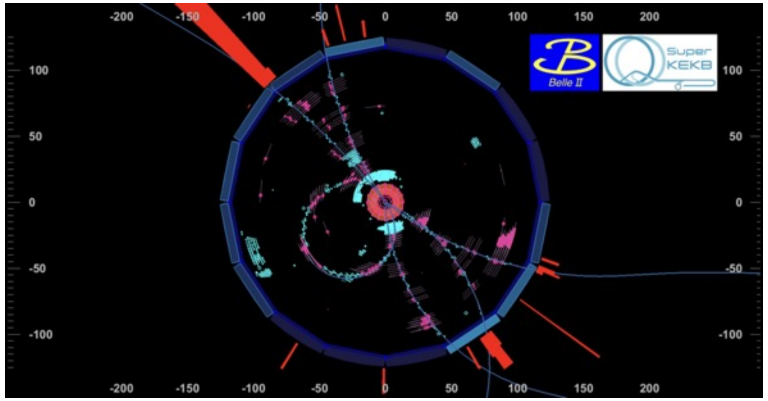
- **Phase3 operation（2019.March~)；**
  - Physics run with fully instrumented detector.
  - Phase3 2019ab (2019.3~7)
    - "Status of Early SuperKEKB Phase-3 Commissioning" by A.Morita (WEYYPLM1) @ IPAC'19 (2019.5.22)
  - Phase3 2019c (2019.10~12)
  - Phase3 2020ab (2020.2~)
    - "Highlight from SuperKEKB Beam Commissioning" by K. Shibata @ IPAC2020 (2020 May)

✓ New nomenclature of each run of Phase3

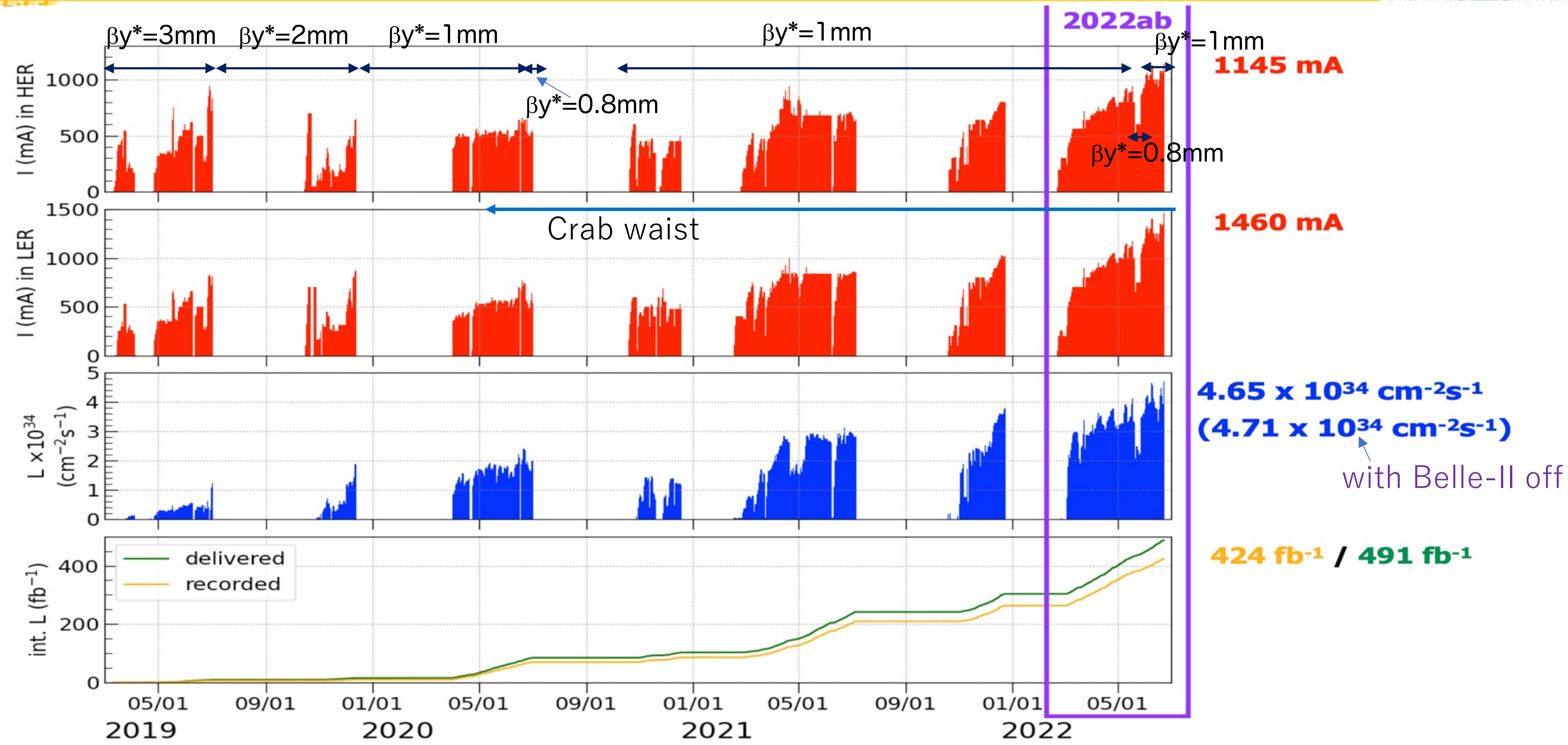
"Phase3 YYYYxx"

YYYY: Calendar year

- a : Winter shutdown - March
- b : April - Summer shutdown
- ab : Winter shutdown – Summer shutdown
- c : Summer shutdown – Winter shutdown



History of SuperKEKB Phase 3 operation



Comparison of machine parameters

	IPAC2020 K. Shibata		IPAC2022 at present					
	KEKB achieved		**SuperKEKB 2020 May 1st**		**SuperKEKB 2022 June 8th**		**SuperKEKB design**	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.321	1.099	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.5873	0.4887	1.440	1.040
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξ_y	0.129	0.090	0.0236	0.0219	0.0407 (0.0565)[a]	0.0279 (0.0434)[a]	0.0881	0.0807
Luminosity [$10^{34}cm^{-2}s^{-1}$]	2.11		1.57		4.65		80	
Integrated Luminosity [ab^{-1}]	1.04		0.03		0.40		50	

doubled

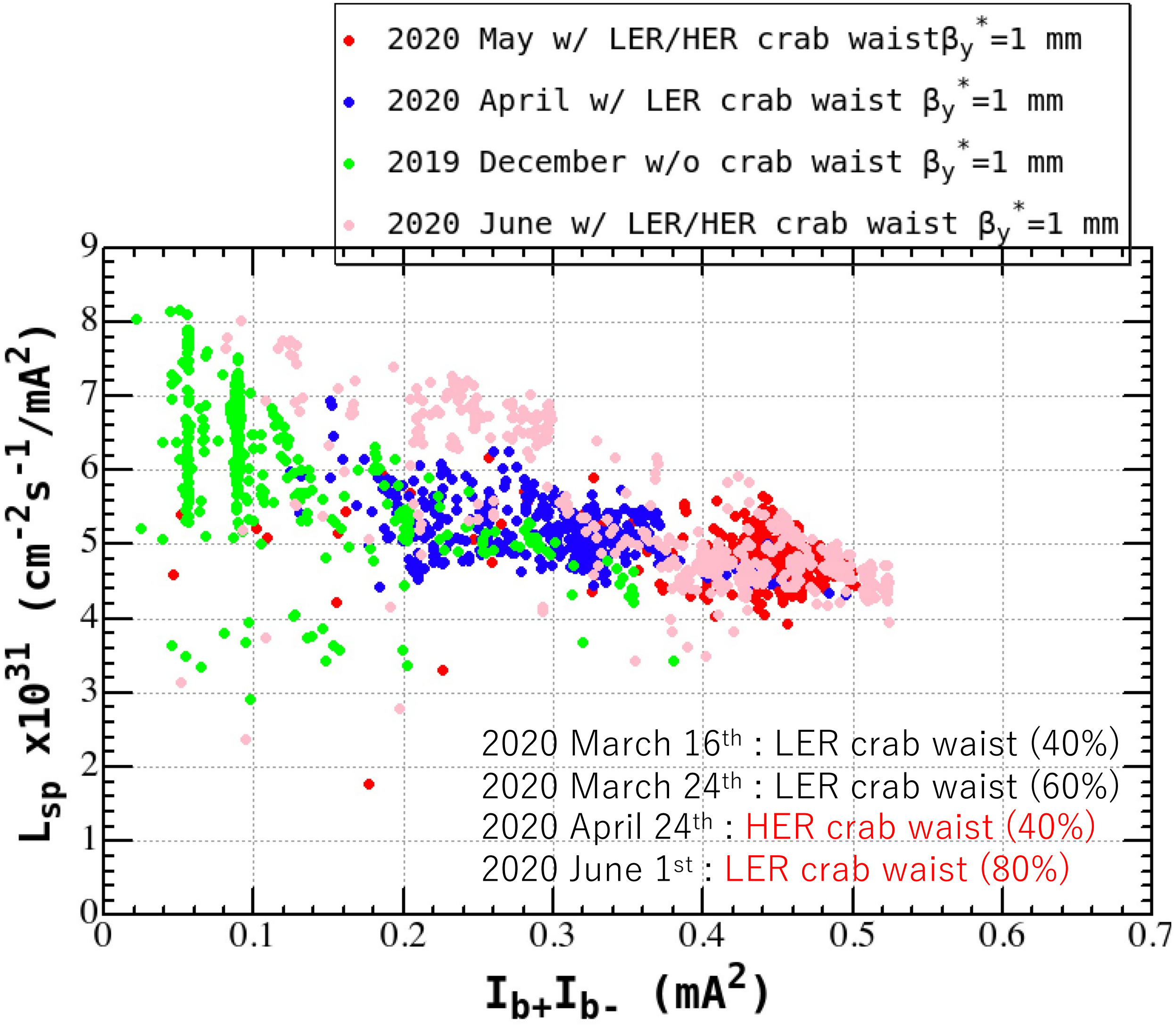
a) High bunch current collision study

Summary of luminosity improvement in Phase 3

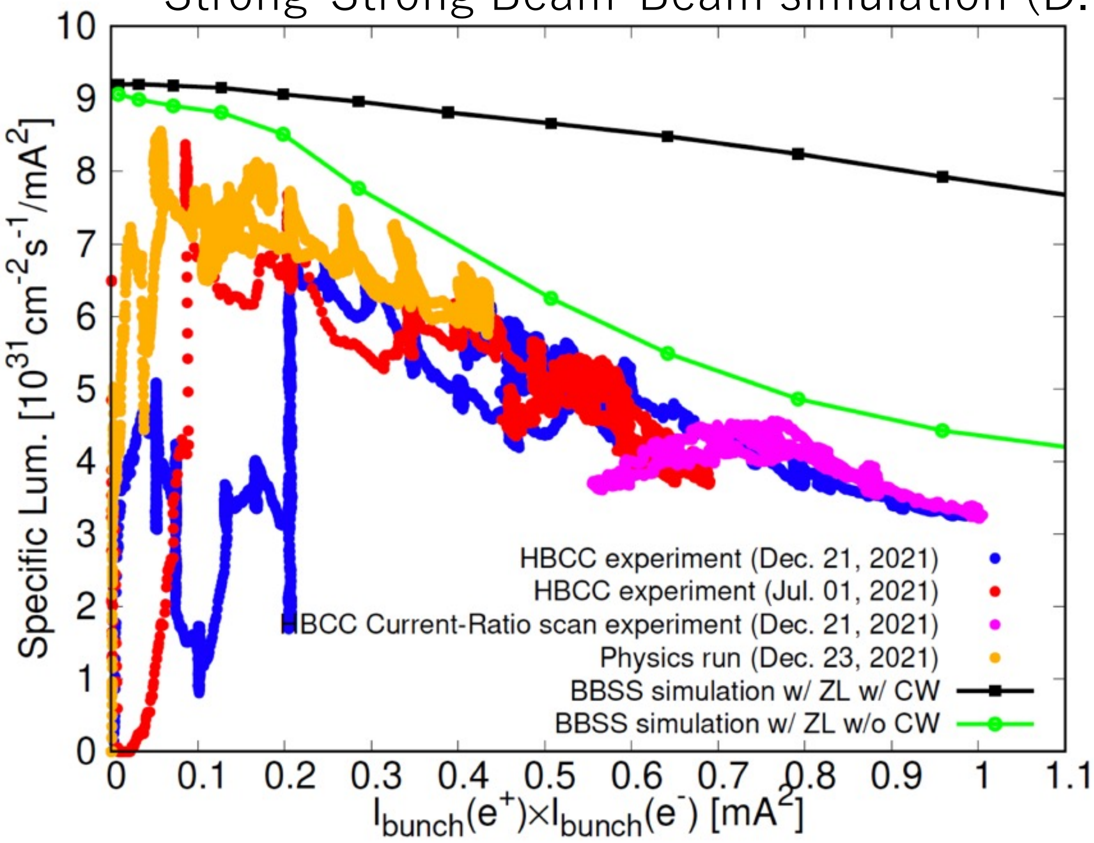
- Squeezing β_y^*
  - Squeezing down to 1 mm has been successful and luminosity has increased accordingly.
    - 2019 (β_y^*=3mm, 2mm), 2021(β_y^*=1mm)
  - Squeezing down to 0.8 mm was tried twice (June 2020 and May 2022).
    - Short-time trial (~ 1 week for each trial).
    - Optics setting and optics corrections were successful. Beam lifetime in both rings was not so bad compared with that with β_y^*=1mm.
    - Beam injection was poor particularly in LER and we could not store the beam current up to the same value as that with β_y^*=1mm. (<- maybe serious problem)
- Beam Currents
  - From 2020 to 2022, the total beam currents have been increased mainly by increasing the number of bunches with keeping the bunch currents at the similar level.
    - We have refrain from increasing the bunch current mainly in LER beyond 0.7mA/bunch to avoid the sudden beam loss events. (This is a very strong constraint.)
    - We have almost reached the maximum number of bunches with design bunch spacing (2 RF bucket spacing) and then we will have to increase the bunch currents in order to increase the beam current further from now on.
- Beam-beam parameters
  - Benefits of crab waist
    - Improvement in specific luminosity and increase of bunch current
  - Achieved vertical beam-beam parameters
    - Limited by the bunch currents
    - Still low compared with the beam-beam simulations

Specific luminosity w/ and w/o crab waist

Crab waist ratio:
from June 2020 up to now
LER: 80%, HER: 40%



Strong-Strong Beam-Beam simulation (D. Zhou)



Summary of crab waist scheme

- Benefits of use of crab waist scheme
  - Suppression of beam-beam blowup
    - Specific luminosity was improved.
  - Increase of the bunch currents of both beams
    - Without crab waist, beam injections was limited due to beam blowup.
- Beam lifetime issue
  - Dynamic aperture shrinks w/ crab waist and the lifetime decrease w/ crab waist was expected.
    - But in βy^*= 1mm case, almost no lifetime decrease was observed in LER and HER.
      - The narrow physical apertures at collimators determine the lifetime.
    - In the case of lower βy^*, simulations showed the lifetime w/ crab waist will set a strong limit.

Critical issues at present and after LS1 (Long-shutdown 1)

What limits the SuperKEKB performance at present?

Example of parameters for L= 1 x 10^{35} $cm^{-2}s^{-1}$

	LER	HER
# of bunches	2345+1	
Luminosity	1.0 x 10^{35} $cm^{-2}s^{-1}$	
I_{total}	2.35 A	1.64 A
I_{bunch}	1.0mA	0.7mA
βy*	0.8mm	0.8mm
εy [pm]	43	
εx [nm]	3.8	
Lifetime [min]	3.86	
Loss rate [mA/s]	10.2	
Required injection charge [nC/s]	102	
Required Injection efficiency [%]	68%	

—Parameters based on a high-bunch-current collision study with βy* = 1mm
—An achieved beam lifetime with βy* = 1mm is assumed.
—A 25% increase in specific luminosity with βy* = 0.8mm is assumed.

Is this possible? (→ I_{bunch})

25% increase in specific luminosity? (→ βy*)

Equal beam size in LER/HER is assumed. (→ εy)

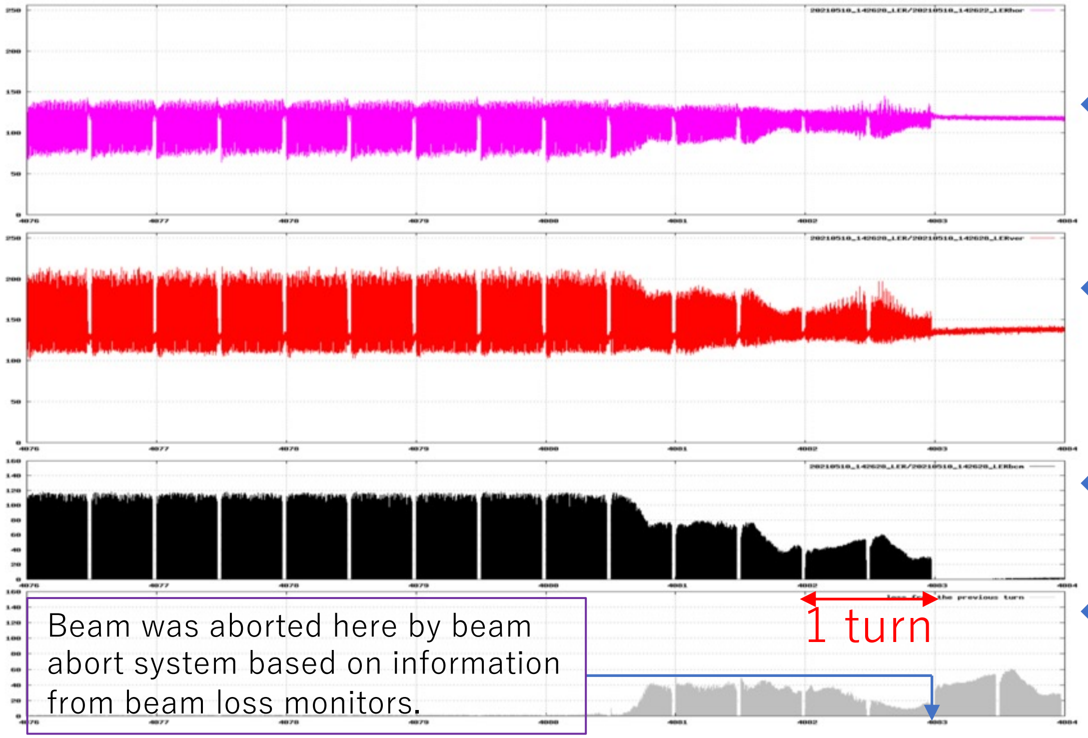
One or two years after LS1 (Long Shutdown 1), we want to achieve the luminosity of 1 x 10^{35} $cm^{-2}s^{-1}$.

Assumed injection charge 3 + 3 nC with 25Hz injection (→ Required Injection efficiency)

Sudden beam loss events

- Observations
  - Very fast and large beam loss (< 3 turns) (particularly in LER)
  - The loss causes damage of collimators and Belle II inner sensors, and QCS quench
  - Empirical rule: Bunch current must not exceed 0.7mA.
- Obstacle to machine operation
  - We have been conservative in increasing beam currents (particularly bunch currents).
  - This issue determines the speed of increasing beam currents and then slows down increase of luminosity.
- Mechanism of sudden & large beam loss
  - Still has not understood well
    - A "fire ball" hypothesis was proposed by T. Abe.
      - A microparticle heated by the beam-induced field causes a macroscopic vacuum arc.
      - We will continue to study this hypothesis
  - A joint Belle2-SuperKEKB team has been working to identify the original places of fast beam losses. Recent progress shows collimators near the injection region are the most possible candidates.
  - Investigations are ongoing to fully understand this issue and countermeasures are being sought.

Typical sudden beam loss events (LER)



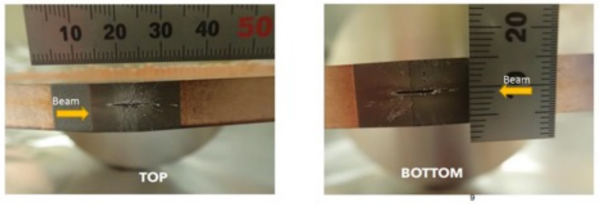
Bunch oscillation recorder (BOR)
Horizontal oscillation

Bunch oscillation recorder (BOR)
Vertical oscillation

BOR amplitude
= oscillation amplitude × bunch current

Bunch current monitor (BCM)

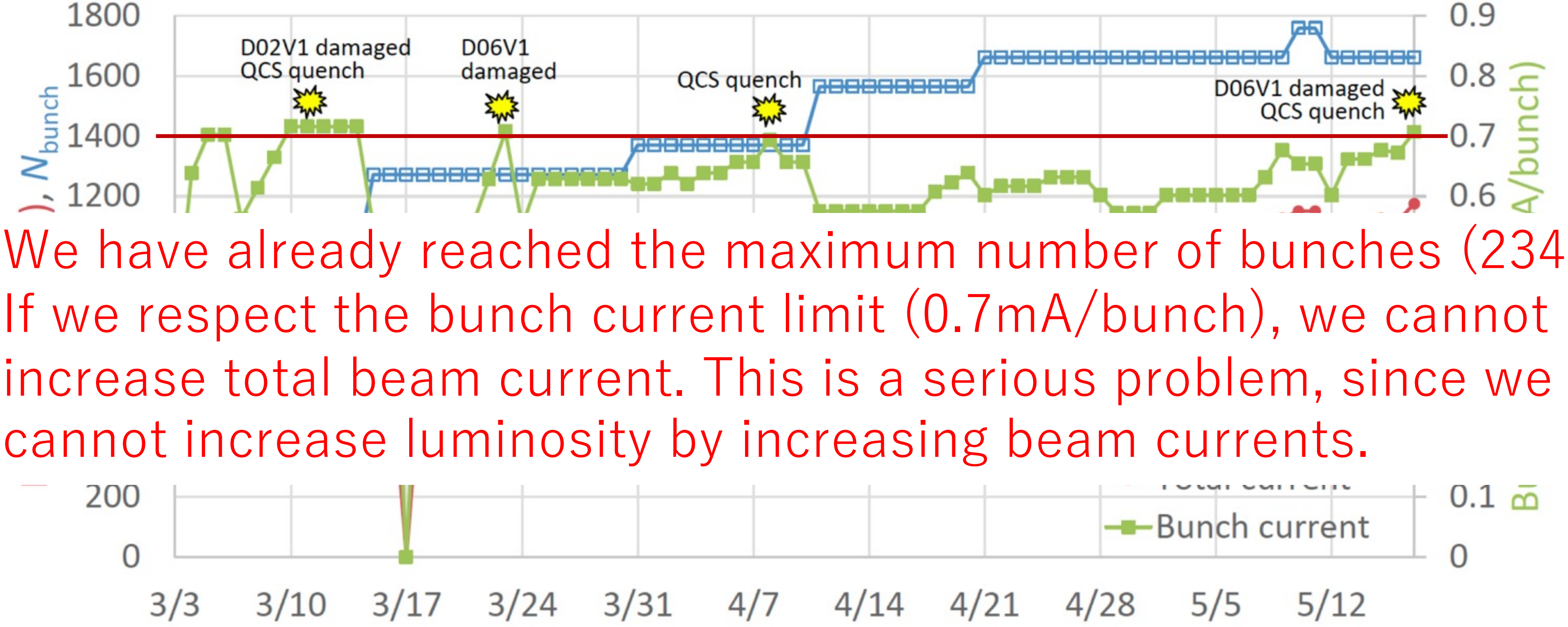
Amount of beam loss (from BCM)



Broken collimator heads

- Very fast beam loss: within 3 turns
- Almost no bunch (dipole) oscillations were observed before beam loss.
  - In some cases, beam oscillation in the previous turn of beam loss was observed.
- No beam size blowup is observed before beam loss.

History of sudden beam loss events 2022



We have already reached the maximum number of bunches (2346). If we respect the bunch current limit (0.7mA/bunch), we cannot increase total beam current. This is a serious problem, since we cannot increase luminosity by increasing beam currents.

The three big accidents of LER beam loss in 2022 happed at I_b>~0.7mA/bunch within a day after increasing the beam current at the three different N_{bunch} -> Empirical rule: we must not exceed 0.7mA/bunch.

In the case of a small number of bunches (N_{buch} = 793, 61, 31), we haven't observed the large beam loss with a higher bunch currents.

Occasionally, large beam loss in LER happened with bunch currents lower than 0.7 mA but the total current was high (For example, on June 3rd, I_b=~0.62mA/bunch with a high total current (1325mA)).

How to confront sudden beam loss

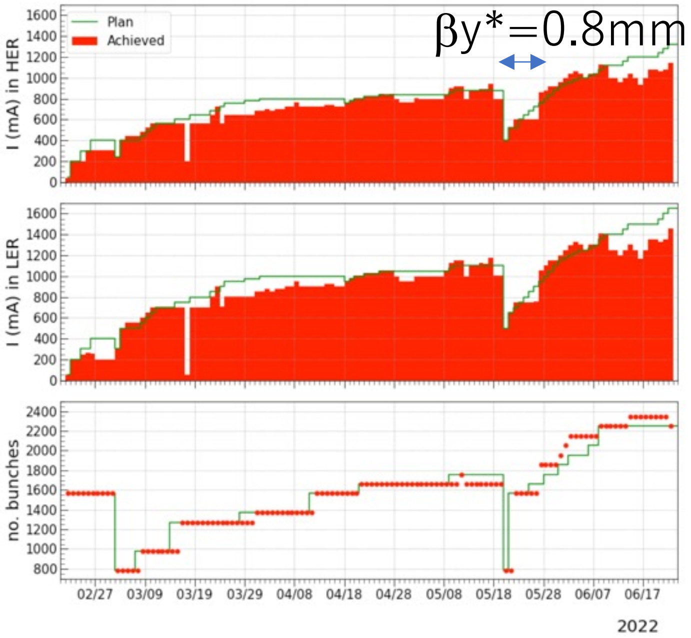
- Fundamental countermeasures
  - Identification of mechanism of sudden beam loss events is essential.
    - International task force on sudden beam loss events was formed in July 2022.
    - More observations on the events
    - More study on “fire ball” hypothesis
- Tentative countermeasures
  - Development of robust collimator against the large beam loss.
    - Typically, collimator replacement work and the baking runs take 3~4 days and gives a serious impact on the physics experiment.
    - Low-Z (Ti ?) and short length collimator (spoiler) + main collimator (D05V1(NLC)?)

Beam injection

- SuperKEKB injection scheme
  - Injector Linac provides e+ and e- beams.
  - Synchronization between injection and rings allows 1-bunch or 2-bunch injection per pulse.
  - Top-up injection is achieved for e+ and e- beams at 50Hz at maximum(25 Hz for e+ and 25 Hz for e-).
- Beam current limitation
  - The maximum stored beam currents in the rings are determined by the balance between the charge sent from Linac and the charge loss due to beam lifetime particularly in the case of βy^*=0.8mm.
  - The injection efficiency is a very important issue.
    - Depends on βy^*, bunch currents, machine tuning, collimator setting…
    - Typical values of injection efficiency with βy^*=1mm: ~50%(LER), ~40%(HER)
    - With βy^*=0.8mm, the injection efficiency became much worse and the achievable total beam currents were much lower than that with βy^*=1mm.
      - We tried squeezing βy^* down to 0.8mm twice and in both cases beam injection limited the luminosity.

LER beam injection parameters

	2022/5/26 in collision	2022/5/26 single beam	2022/6/22 in collision
β_y^* [mm]	0.8	0.8	1
I_{total} [mA]	747	746	1403
I_{bunch} [mA]	0.477(1565bunch)	0.477(1565bunch)	0.624 (2246bunch)
Lifetime [min.]	6.7	4.8	7.5
BT charge 1 [nC]	2.05	2.03	2.16
BT charge 2 [nC]	1.67	1.58	1.86
Rep. rate [Hz]	23	23	21
Ratio (2bunch : 1bunch)	4:1	4:1	4:1
DCCT inj. Rate [mA/s]	0.660	0.558	1.03
Inj. Eff. (PV) [%]	7.98	6.97	12.6
Inj. Eff. (lifetime corr.) [%]	32.6	47.0	54.4
εx [nm]	3.8	3.8	4.4
εy [pm]	40	25	60
C_T (Touschek life coeff.)	9.10e10	8.24e10	9.44e10



Ignore vacuum life

$$\tau_{Touschek} = C_T \frac{n_b}{I_{beam}} \sqrt{\varepsilon_x \varepsilon_y} \sigma_z$$

LER Injection: bunch current dependence

	2022/5/26 In collision	2022/5/26 In collision	2022/5/26 In collision
β_y^* [mm]	0.8	0.8	0.8
I_{total} [mA]	186	247	292
I_{bunch} [mA]	0.473(393bunch)	0.6295 (393bunch)	0.744 (393bunch)
Lifetime [min.]	7.6	7.2	6.4
BT charge 1 [nC]	2.00	2.03	1.98
BT charge 2 [nC]	1.75	1.77	1.73
Rep. rate [Hz]	12.5	12.5	23
Ratio (2 bunch : 1 bunch)	4:1	4:1	4:1
DCCT inj. Rate [mA/s]	1.17	0.472	0.446
Inj. Eff. (PV) [%]	25.8	10.3	5.4
Inj. Eff. (lifetime corr.) [%]	37.4	24.3	15.7
εx [nm]	3.3	3.8	4.5
εy [pm]	35	45	60
C_T (Touschek life coeff.)	1.2e11	1.1e11	9.0e10

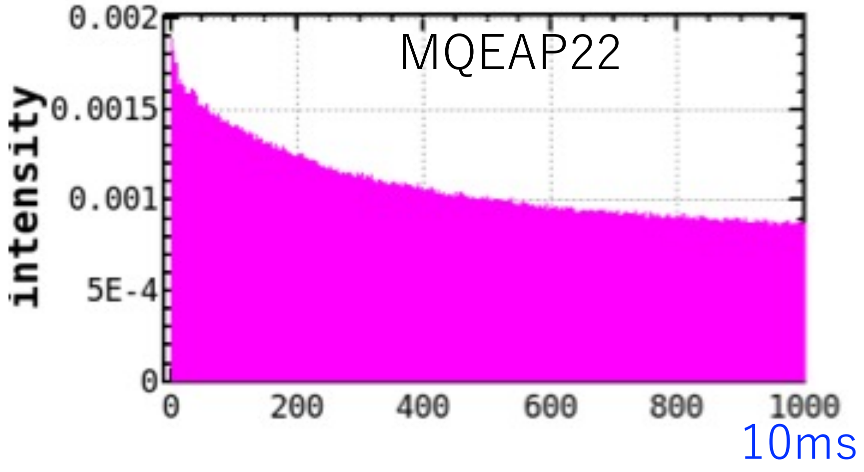
← Very large current dependence

← Ignore vacuum life

Beam loss of injecting beams with βy^*=1mm

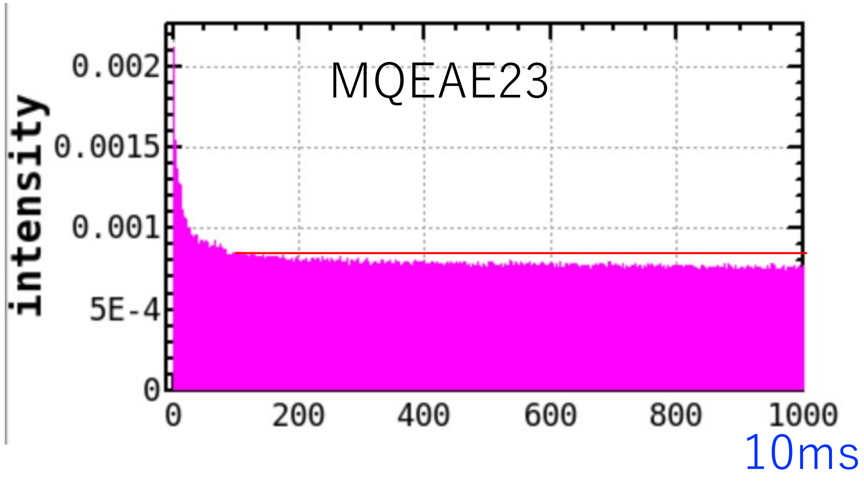
Observation with Turn-by-Turn BPMS

LER



Injection efficiency: ~50%

HER



Injection efficiency: ~36%

Relatively slow beam loss compared with that of HER

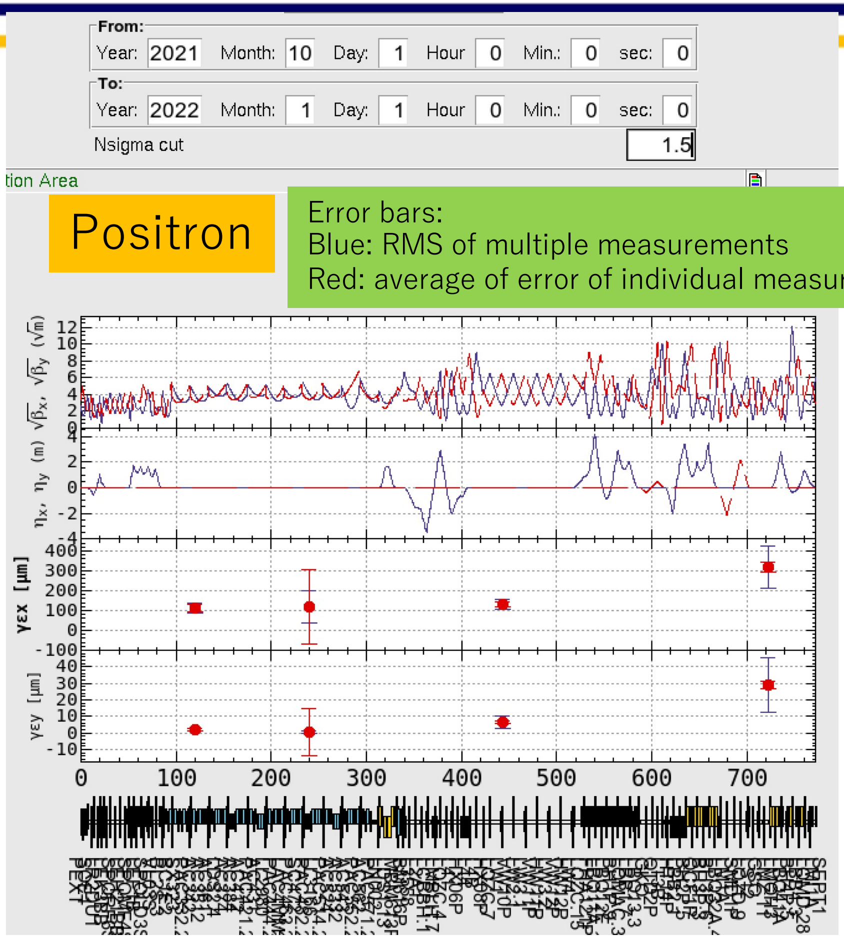
Summary of injection efficiency

- Observation
  - Typical injection efficiency with βy*=1mm in the physics experiment
    - LER: ~50%, HER: ~40%
  - Injection efficiency with βy*=0.8mm
    - Lower injection efficiency than that with βy*=1mm
    - Single beam injection efficiency is higher than that in the collision.
    - Injection efficiency depends strongly on the bunch current.
    - We could not store the same beam currents as the case with βy*=1mm.
    - Trials of βy*=1mm are short periods and there might be some room for improvements.
  - Necessary injection efficiency in LER with assumed beam parameters for the luminosity of 1 x 10^{35} cm^{-2} s^{-1}.
    - ~70% in LER with the bunch charge of 3nC/bunch for the injecting beam
    - Fundamental improvement in the injection efficiency will be needed.
- Countermeasures
  - Understanding of the reasons for poor injection efficiency is essentially important.
    - Simulations on the beam injections during LS1 should be done.
    - More intensive machine study should be done in the beam operation after LS1.
      - Reducing injection oscillations, injecting beam emittance (CSR), tune survey etc.
  - Other efforts related to beam injection
    - Efforts to increase Linac bunch charge
    - Improving beam lifetime (dynamic aperture and collimator setting)

Linac, BT Emittance measurement (2021c)

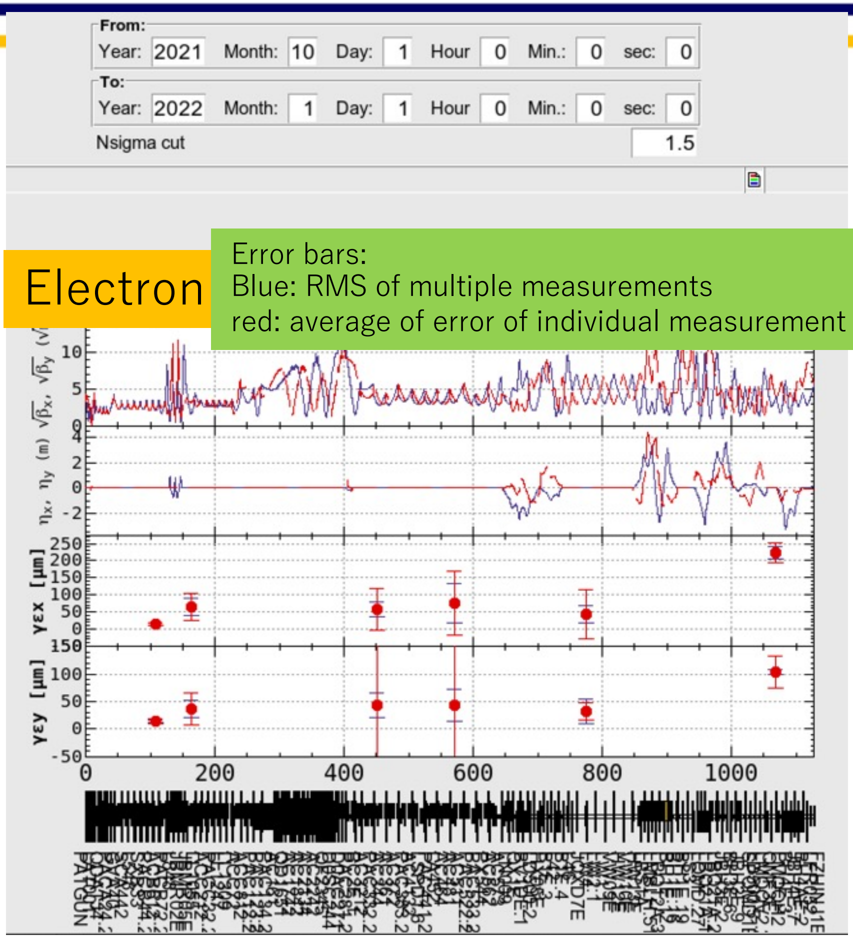
Positron

Error bars:
Blue: RMS of multiple measurements
Red: average of error of individual measurement



Electron

Error bars:
Blue: RMS of multiple measurements
red: average of error of individual measurement

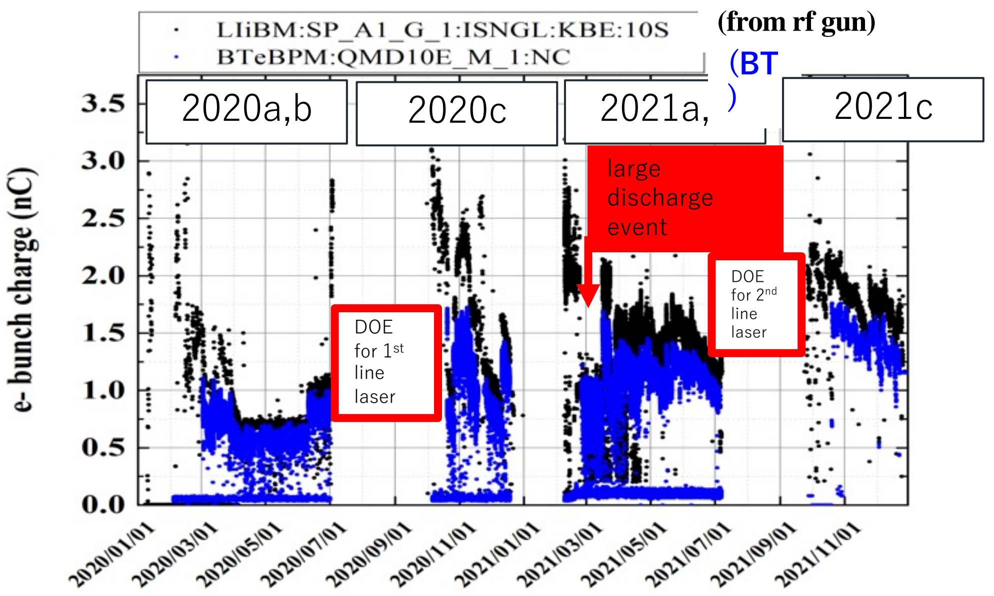


Target (design) values	e+	e-
Normalized emittance (H/V) [μm]	100/15	40/20

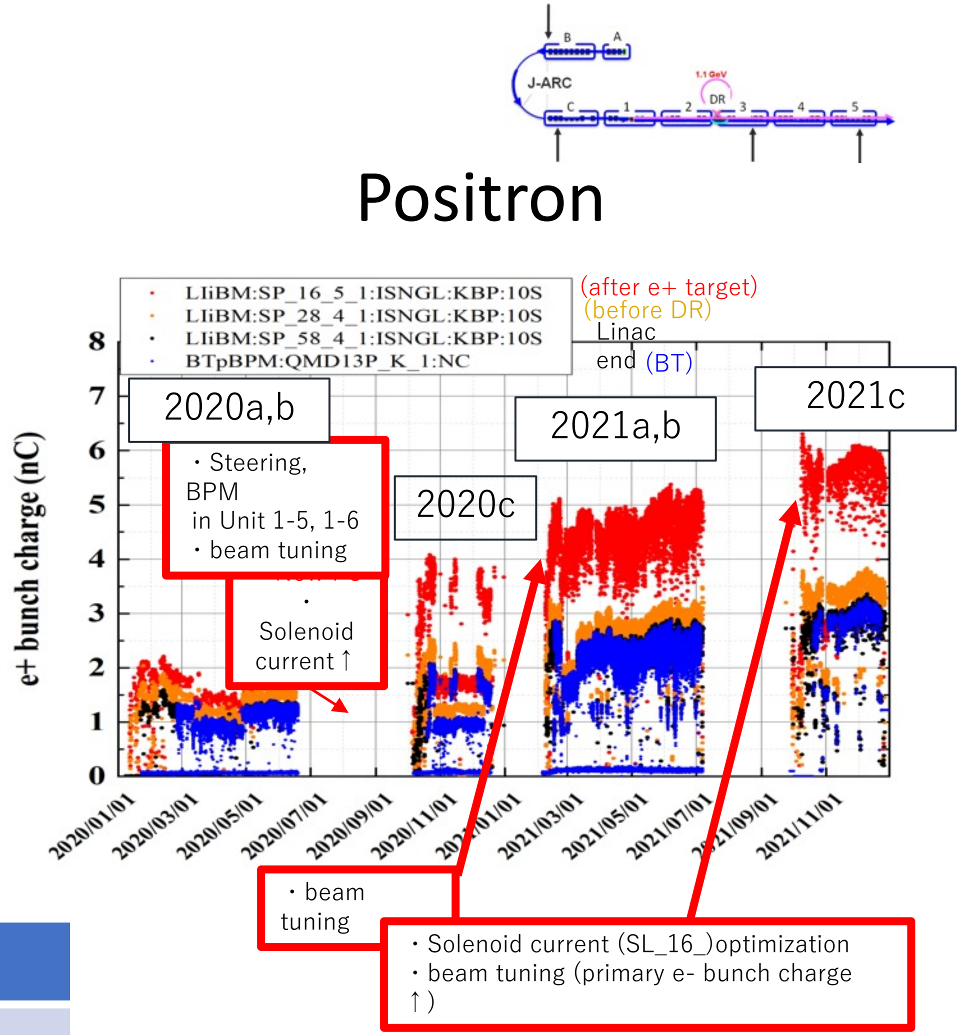
For better injection efficiency, suppression of emittance growth in BT lines is important.
The emittance is bunch charge dependent and the CSR effects are being studied actively.

Linac bunch charge history

Electron



Positron



Target (design) values	e+	e-
Charge / bunch [nC]	4	4

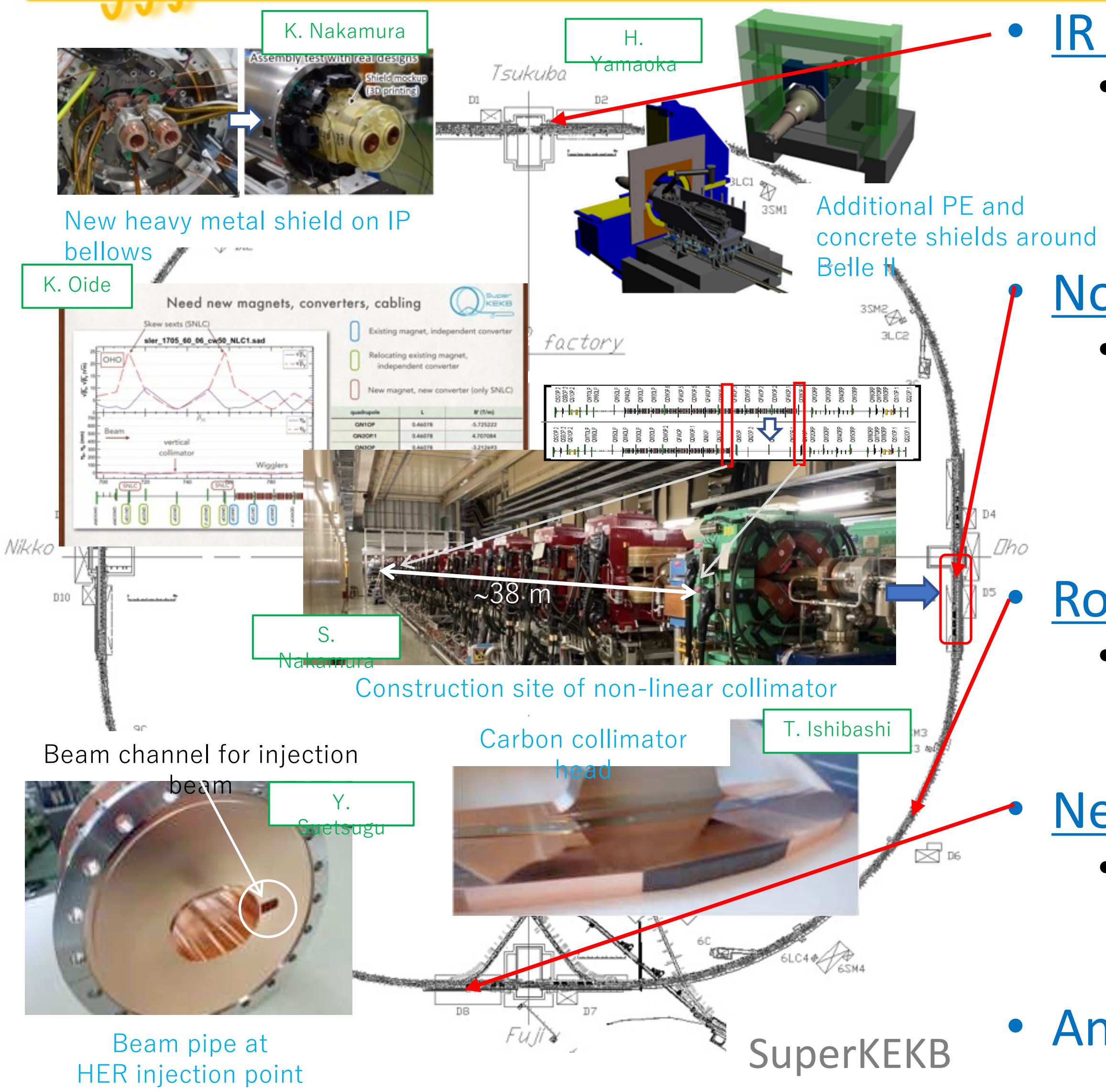
Summary

- To reach $L = 1 \times 10^{35}\ cm^{-2}\ s^{-1}$,
  - Countermeasures against the sudden beam loss is very important.
    - Finding its mechanism is our first priority. <- International task force was formed last month.
    - Tentative countermeasure is to install robust collimators to the sudden beam loss.
  - Injection efficiency
    - Finding reasons for low injection efficiency and taking effective countermeasures are very important. More simulations and machine studies will be needed.
    - If we can improve the
    - Improving the quality
  - Other issues
    - Improvement in the specific luminosity.
      - Improvement in the beam-beam performance. <-D. Zhou san's talk
      - Total beam current dependent optics deformation <– H. Sugimoto san's talk.

I have a strong sense of crisis on those issues.

- Toward design luminosity
  - To squeeze βy^* down to design values (0.27mm in LER and 0.30mm in HER), further upgrade works will be required, including an extensive IR upgrade to improve beam lifetime. We have a plan to do those upgrade works in Long Shutdown 2 (LS2) in around 2027. The upgrade plan will need to be studied.

Major upgrade items during LS1 (Long shutdown 1)



- [IR radiation shield modification]
  - For BG reduction
    - New heavy metal shields around IP bellows
    - Additional concrete & polyethylene shields around Belle II
    - Material change from W to SUS of QCS cryostat front plate
- [Non-linear collimator (LER)]
  - For impedance and BG reduction
    - New collimation scheme less likely to cause TMCI
    - Removal of 50 wiggler magnets
    - Installation of 2 skew sextupole and 5 quadrupole magnets
    - Installation of new vertical collimator with wider aperture
- [Robust collimator head (LER)]
  - As countermeasure against kicker-pulser misfiring and resulting destruction of collimator
    - Replacement with carbon head of horizontal collimator D06H3
- [New beam pipes with wider aperture at HER injection point]
  - For improvement of injection efficiency
    - New beam pipes with wider aperture
    - New BPM for precise measurement of injected beam
- And so on…

LS1 started in June 2022. The SuperKEKB operation will resume in October 2023.