The SuperKEKB Has Broken the World Record of the Luminosity

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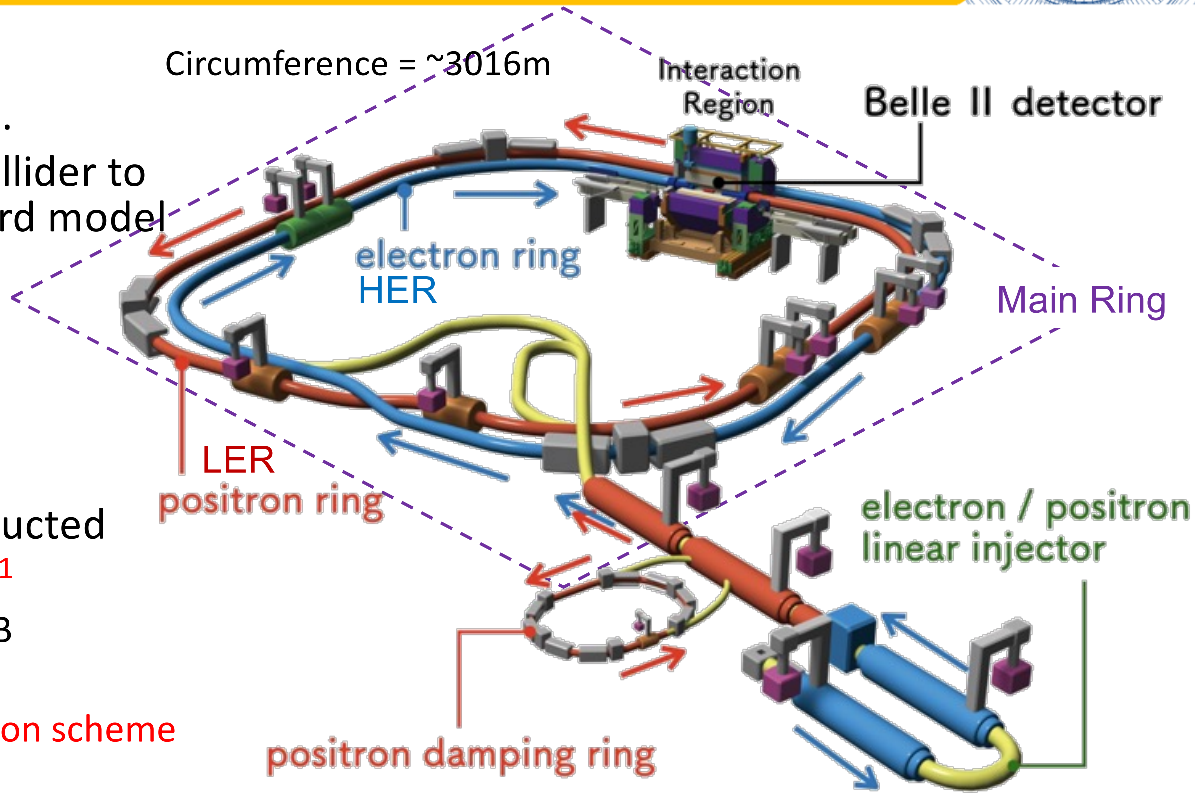
On behalf of SuperKEKB Commissioning Group

SuperKEKB

- SuperKEKB;
  - An upgrade of KEKB B-factory (KEKB).
  - High-luminosity electron-positron collider to seek out new physics beyond standard model
  - Main ring (MR) is composed of
    - Low Energy Ring (LER);
      - 4.0 GeV Positron, 3.6 A(design)
    - High Energy Ring (HER);
      - 7.0 GeV electron, 2.6 A(design)
  - Positron damping ring: newly constructed
  - Design Luminosity : 8.0×10^{35} $cm^{-2}\cdot s^{-1}$
    - ✓ 40 times maximum luminosity of KEKB
    - ✓ Twice beam current of KEKB (×2)
    - ✓ Squeezing βy^* with nano-beam collision scheme (×20)
    - ✓ Over a period of 10 years, a 50-fold increase in integrated luminosity relative to the original KEKB is expected.



SuperKEKB

SuperKEKB project history

- Phase1 operation (2016.Feb. ~ June);
  - Vacuum scrubbing, low emittance beam tuning, and background study for Belle II detector installation
  - w/o final focusing system (QCS) and Belle II detector
- Phase2 operation (2018.Mar. ~ July);
  - Damping ring for positron was introduced.
  - Pilot run of SuperKEKB and Belle II w/o pixel vertex detector (PXD)
  - Demonstration of nano-beam collision scheme
  - Study on background larger than at KEKB due to much lower beta functions at IP.

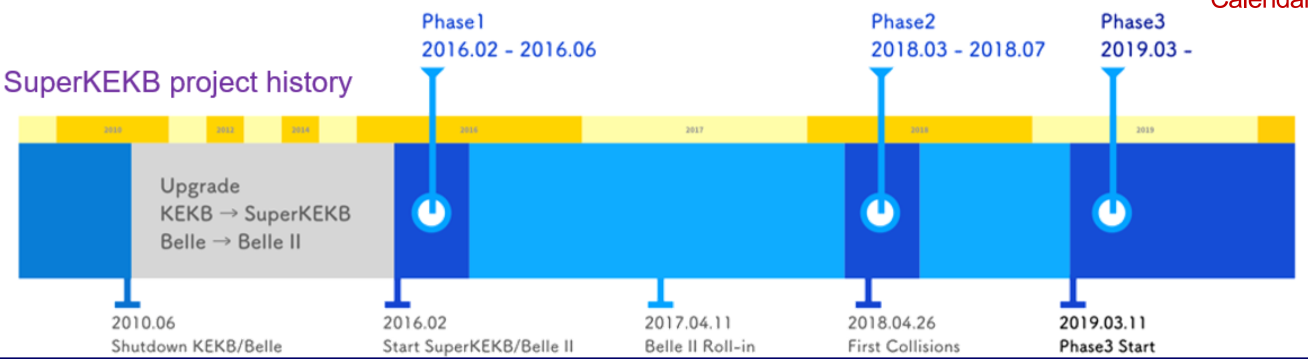
- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector.
    - Top-up injection in both rings
  - Phase3 2019ab (2019.3~7)
    - "Status of Early SuperKEKB Phase-3 Commissioning" by A.Morita (WEYYPLM1) @ IPAC'19 (2019.5.22)
  - Phase3 2019c (2019.10~12)
  - Phase3 2020ab (2020.2~)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

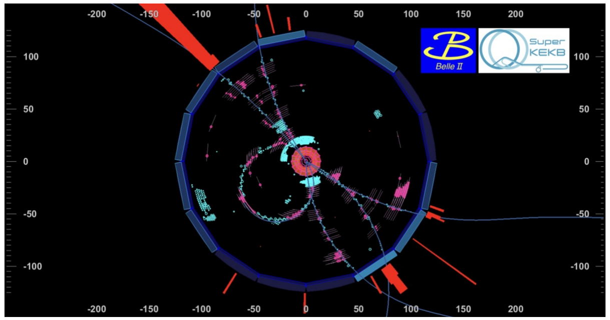
✓ New nomenclature of each run of Phase3

"Phase3 YYYYxx"

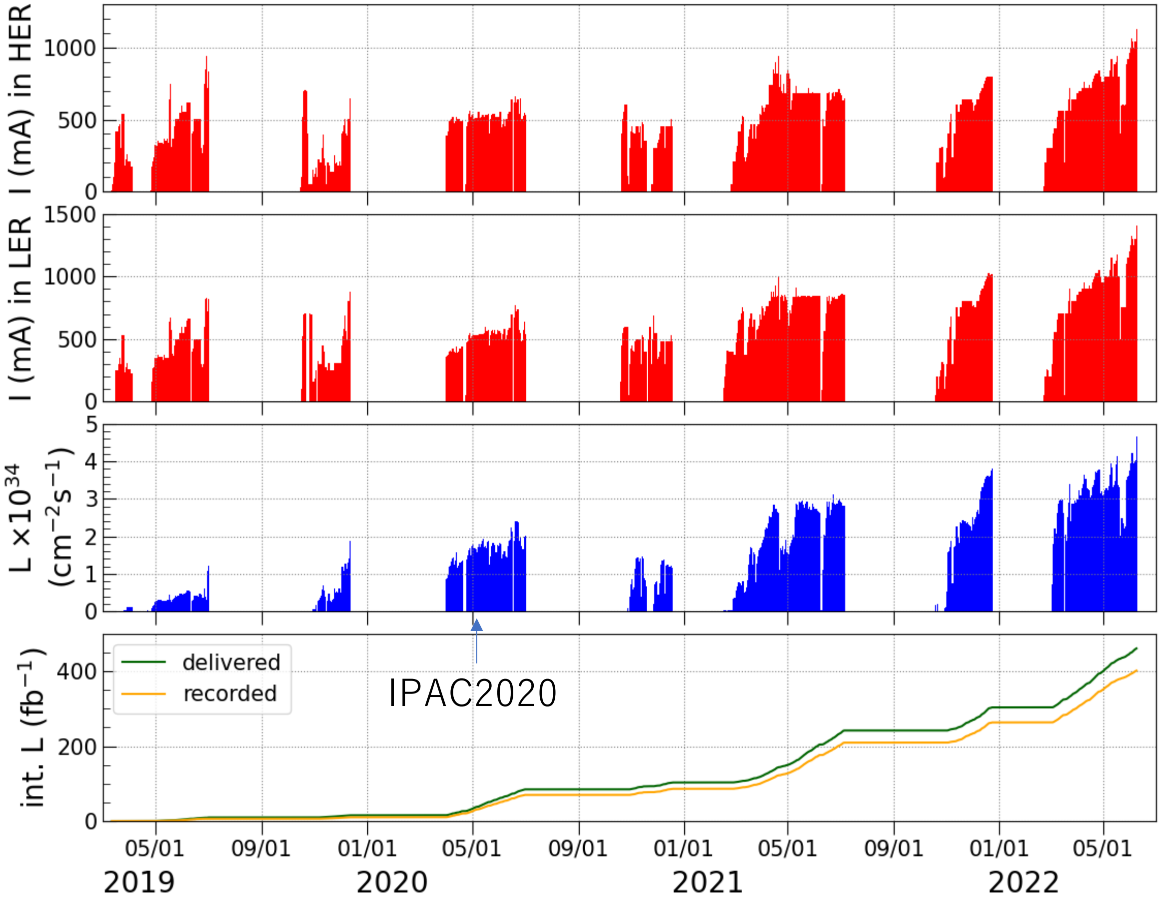
Calendar year

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





History of beam operation



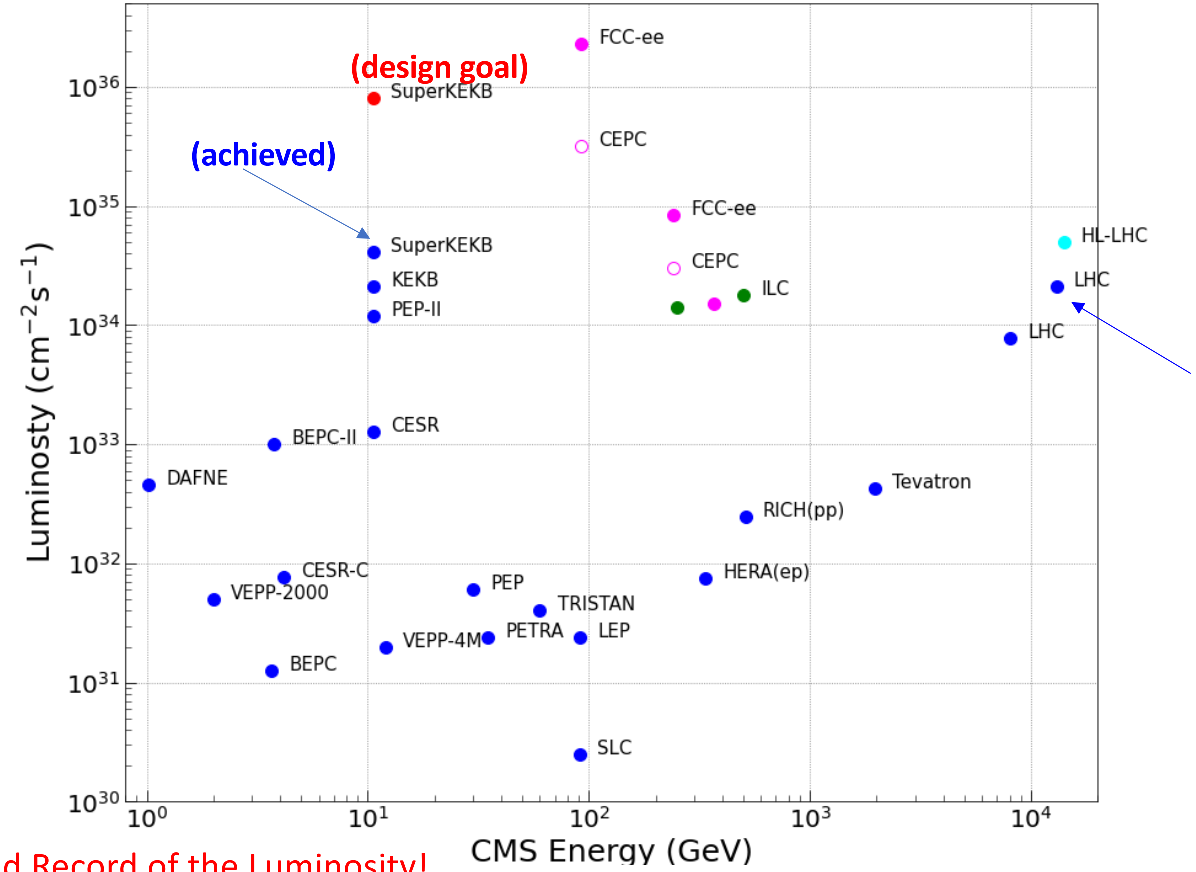
Comparison of machine parameters

	KEKB achieved		SuperKEKB 2020 May 1st (IPAC2020 K. Shibata)		SuperKEKB 2022 June 8th (IPAC2022 at present)		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
βy^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξy	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

Comparison of Luminosity



The SuperKEKB Has Broken the World Record of the Luminosity!

Machine Parameters of SuperKEKB

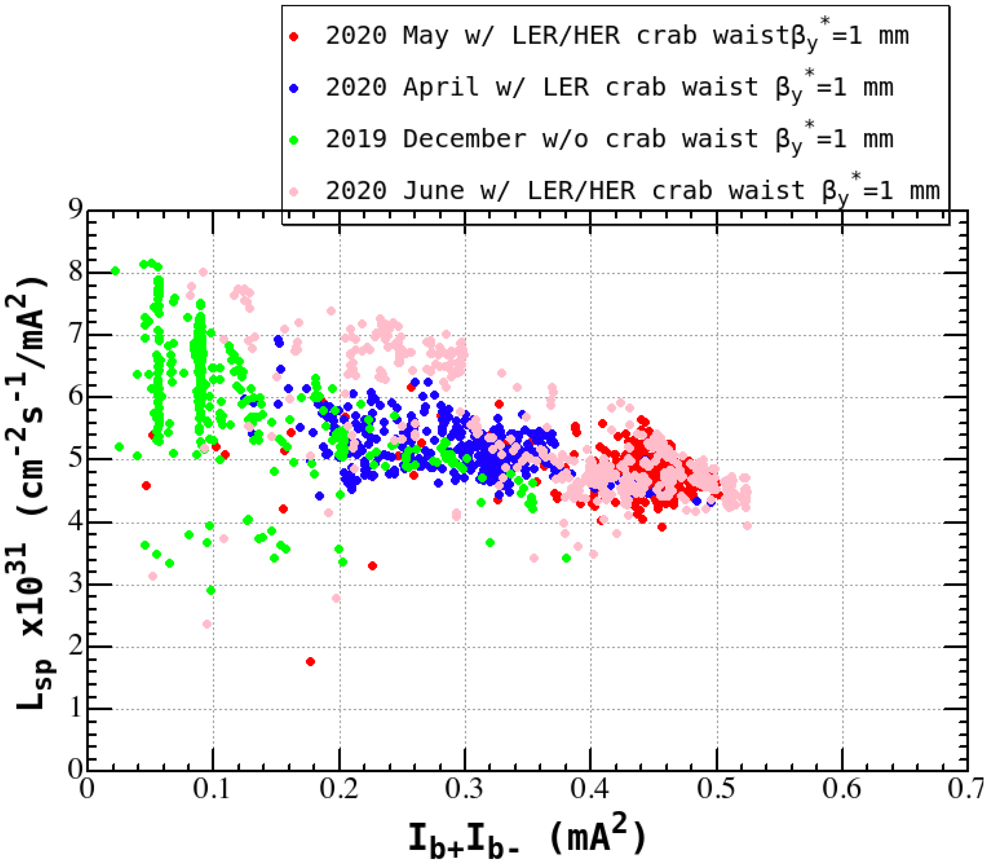
	LER	HER	
Beam Energy	4.0	7.0	GeV
Circumference	3016		m
Crossing angle	83		mrad
Crab waist ratio	80	40	%
Beam current @Maximum Luminosity	1.321	1.099	A
Number of bunches	2249		
Bunch current @Maximum Luminosity	0.5873	0.4887	mA
Total RF voltage V_c	9.12	14.2	MV
Synchrotron tune ν_s	-0.0233	-0.0258	
Bunch length σ_z	5.69	6.03	mm
Momentum compaction α_c	2.98E-4	4.54E-4	
Betatron tune ν_x / ν_y	44.524/46.592	45.532/43.575	
Beta function at IP β_x^* / β_y^*	80/1	60/1	mm
Measured vertical beam size (XRM) @IP σ_y^*	0.224	0.224	μm
Vertical beam-beam parameters ξ_y	0.0407	0.0279	
Beam lifetime	8	24	min.
Luminosity (Belle 2 CsI)	4.65		10^{34} cm^{-2} s^{-1}

← Touschek dominant (beam lifetime)

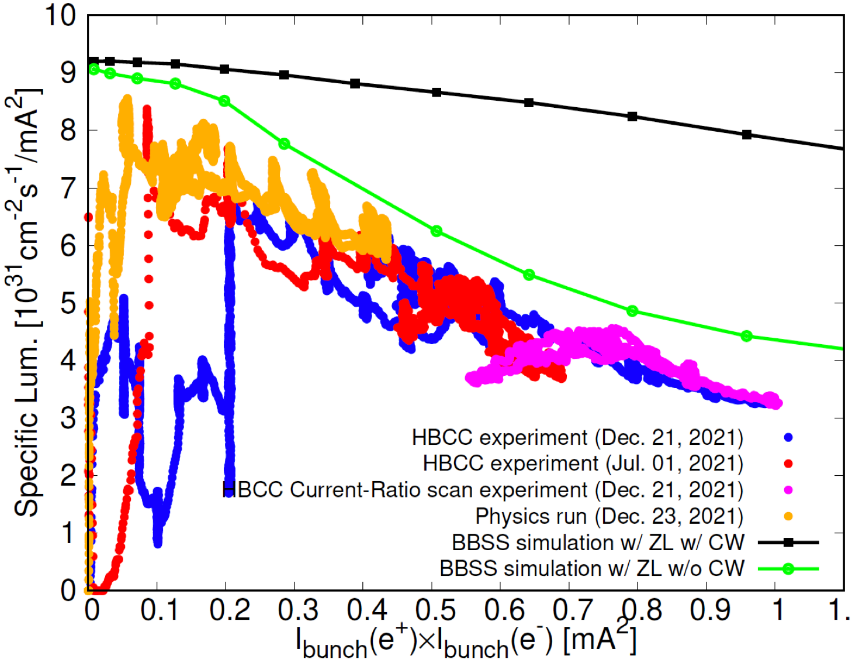
Luminosity improvement [1/4] Crab waist

- Introduction of crab waist at SuperKEKB
  - Motivations
    - The beam-beam performance was poor in spite of all of knob tunings for improving it. It was limited by beam-beam resonances which can be suppressed by crab waist.
  - Method
    - FCC-ee type scheme: use of imbalance sextupoles in the vertical local chromaticity correction section.
  - Time table
    - 2020 March 16th : LER crab waist (40%)
    - 2020 March 24th : LER crab waist (60%)
    - 2020 April 24th : HER crab waist (40%)
    - 2020 June 1st : LER crab waist (80%)

Specific luminosity w/ and w/o crab waist



Strong-Strong Beam-Beam simulation

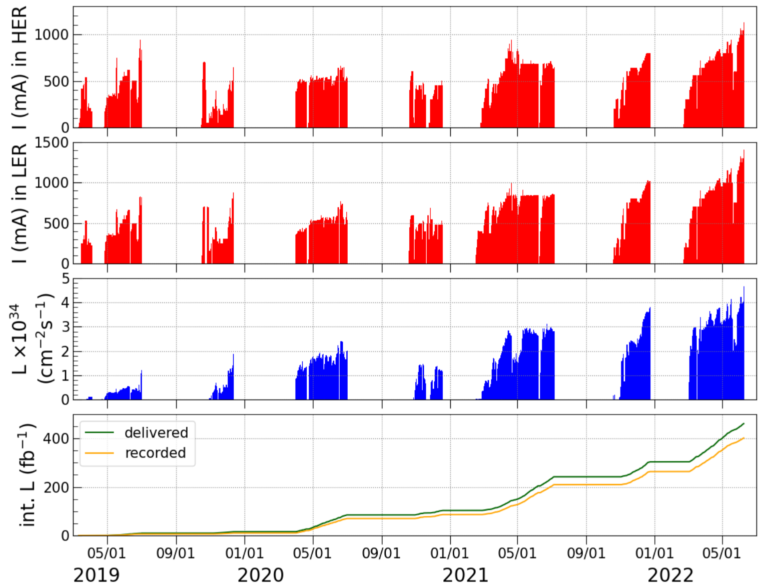


Summary of crab waist scheme

- 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, 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.

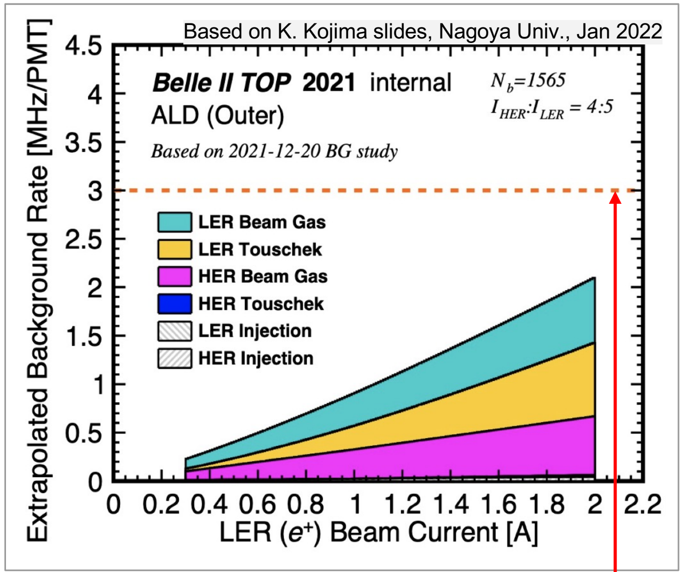
Luminosity improvement [2/4] Higher beam currents

- We have been increasing beam currents with fighting with obstacles
  - Obstacles
    - Hardware damages due to fast beam losses
      - Frequency hardware troubles on collimators (and Belle II sub-detectors) happened when the bunch current in LER is larger than 0.7 mA. The recent increase in beam currents was achieved by increasing the number of bunches while respecting the limit from bunch current limit (<~0.7mA/bunch). (to be addressed later)
    - Detector beam background
    - Beam aborts
    - Beam instability
    - Beam injection



Current background level in Belle II

One of the most vulnerable sub-detectors is
the Time of Propagation (TOP) particle ID system



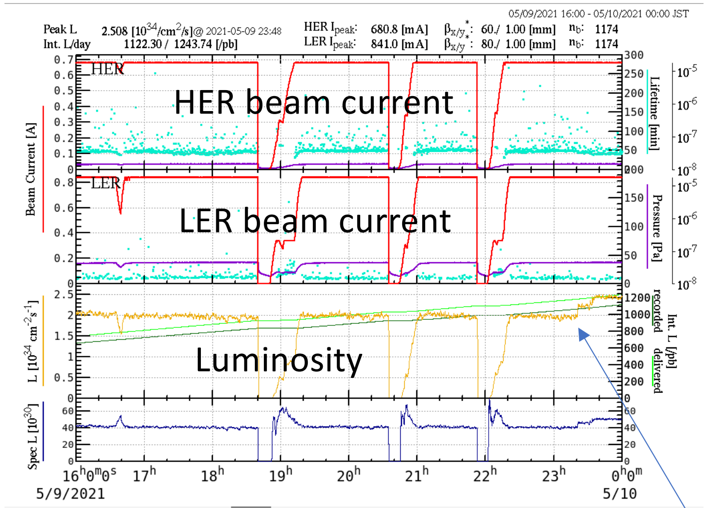
Current background limit for the TOP PMT rate

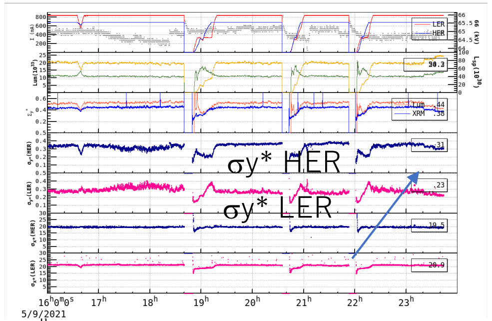
- Current background rates in Belle II are acceptable and well below limits
- Belle II did not limit beam currents in 2021 and 2022
  - It will limit SuperKEKB beam currents eventually, without further background mitigation
- To reach the design luminosity an upgrade of crucial detector components is foreseen (e.g. TOP short lifetime conventional PMTs)

In view of replacement of a vulnerable part of PMTs in LS1 (Long Shutdown 1), the BG limit of TOP PMT was raised to 5 MHz in 2022.
Beam Gas BG in LER is expected to be lowered in the process of vacuum scrubbing. We also expect that BG will be lowered by IR radiation shield reinforcement done in LS1. On the other hand, luminosity related BG will increase with a higher luminosity.

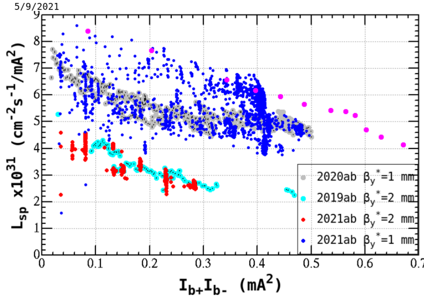
Luminosity improvement [3/4] Bunch-by-bunch feedback gain

- In May 2021, the luminosity increased by lowering gain of the bunch-by-bunch feedback system in HER.
- Noise mixed in FB system affected the luminosity.
  - The noise was caused by a troubled module. Since the noise frequency was near the betatron tune, its effect was large.





Beam sizes

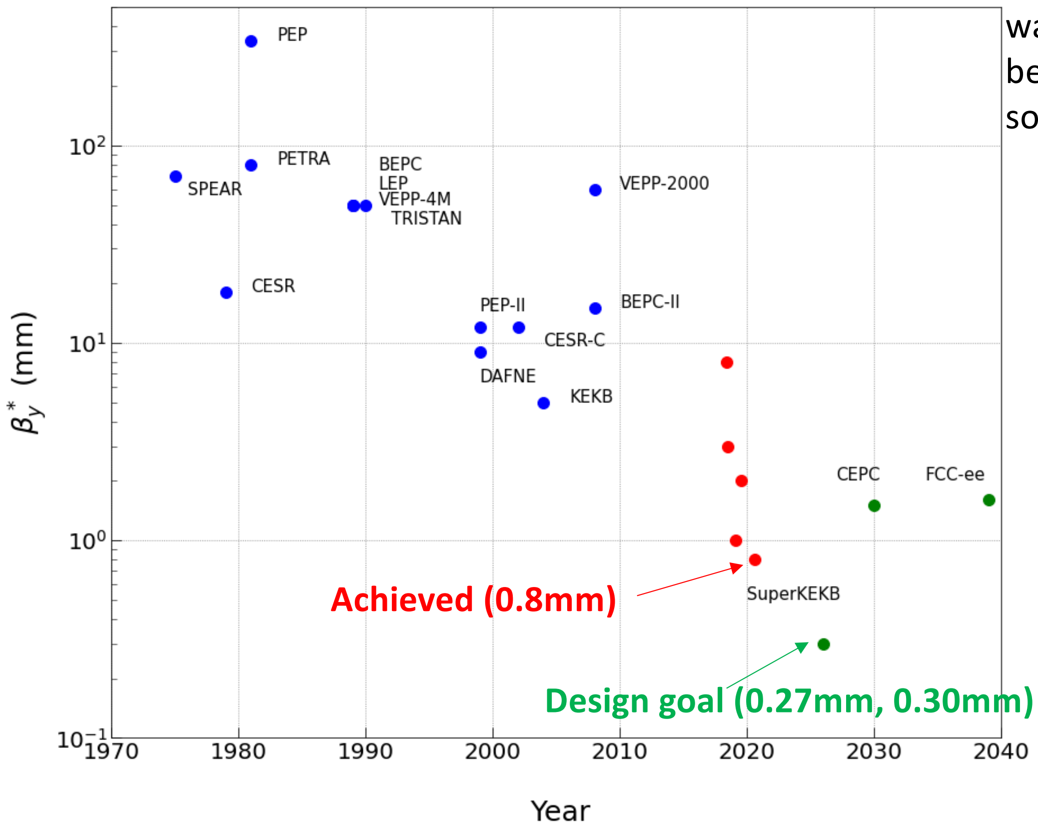


Specific luminosity

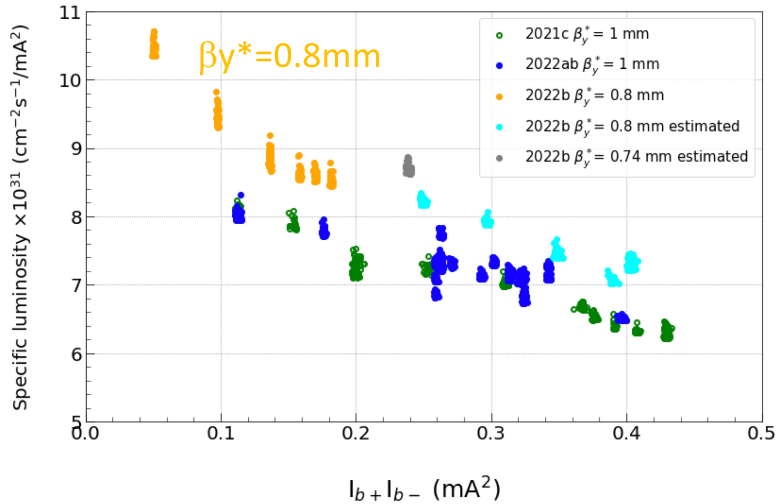
The luminosity increased by lowering HER vertical FB gain by 4dB + 4dB.

The increase in the luminosity was ~25%.

Luminosity improvement [4/4] β_y^*



In 2022b run, we tried βy*=0.8mm. The specific luminosity was higher than βy*=1mm case. We could not store higher beam currents due to poor injection efficiency. We will re-try soon.



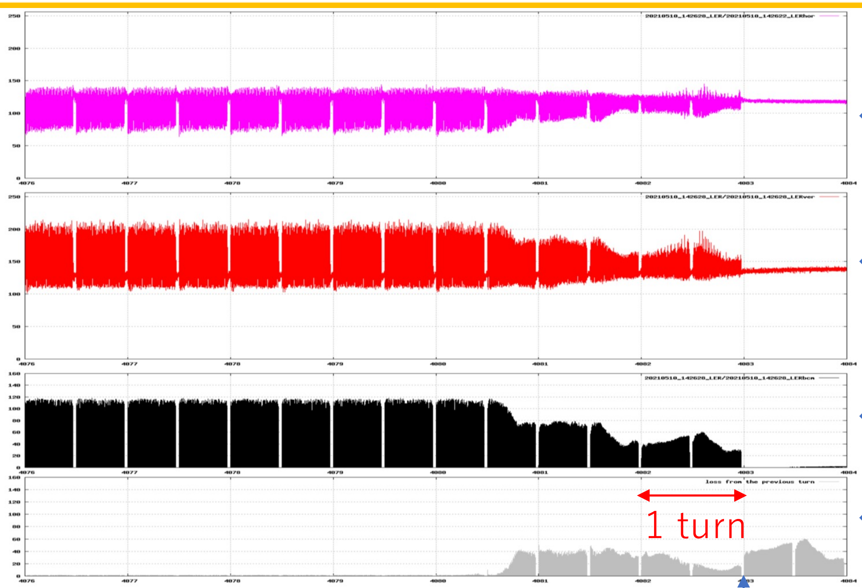
In the data in cyan and blue, estimated values of βy* in HER were less than 1mm(setting value) due to horizontal orbit change in SLY depending on total beam current.

SLY: Sextupoles at local chromaticity correction

Performance limiting issues [1/4] Fast & large beam loss

- Observations
  - 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 fast & large beam loss
  - Still not understood well
    - A 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. (https://kds.kek.jp/event/41394/contributions/209334/attachments/154298/195935/16aA561-03.pdf)
  - Investigations are ongoing to fully understand this issue and countermeasures are being sought.

Typical large beam loss events (LER)



Bunch oscillation recorder (BOR)
Horizontal oscillation

Bunch oscillation recorder (BOR)
Vertical oscillation

BOR amplitude
= oscillation amplitude × bunch current

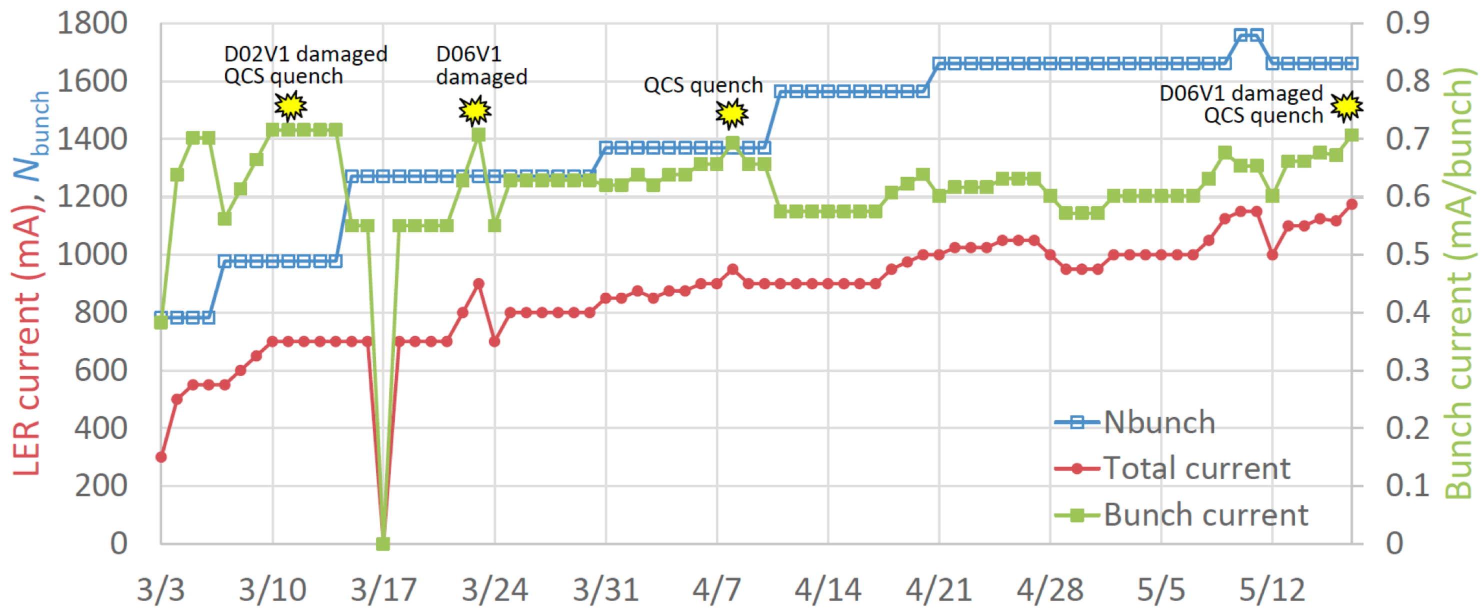
Bunch current monitor (BCM)

Amount of beam loss (from BCM)

Beam was aborted here by beam abort system based on information from beam loss monitors.

- Very fast beam loss: within 3 turns
- 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 large beam loss events 2022



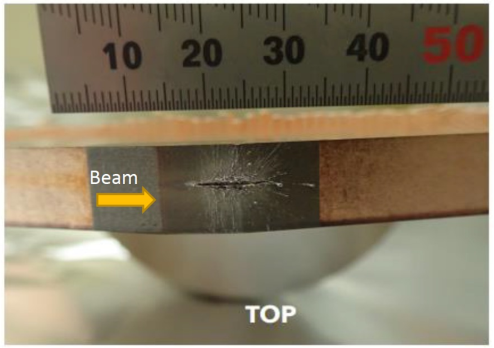
K. Matsuoka

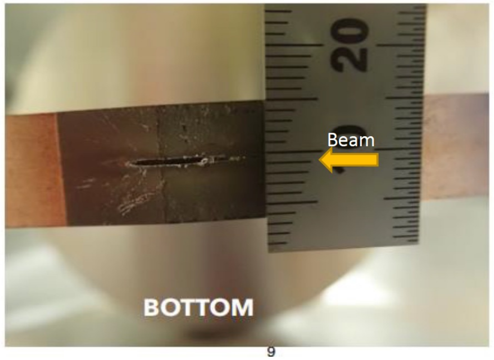
The three big accidents of LER beam loss in 2022 happed at I_b>~0.7mA/bunch within a day after increasing the beam current at the three different N_{bunch} -> Empirical rule: we must not exceed 0.7mA/bunch.

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)).

Severe damage on LER vertical collimator





- After a huge beam loss event on June 6th in 2021, LER BG increase significantly.
- D02V1 collimator jaws were severely damaged (deep scar on the bottom jaw).
- Typically, collimator replacement work and the baking runs take 3~4 days.

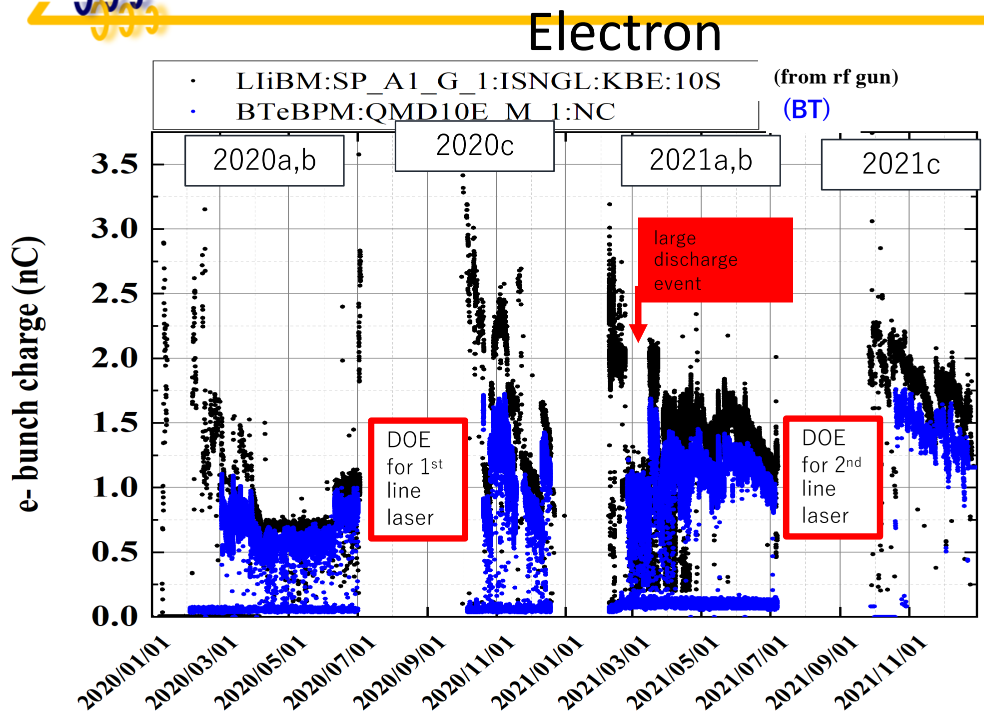
Performance limiting issues [2/4] Beam injection

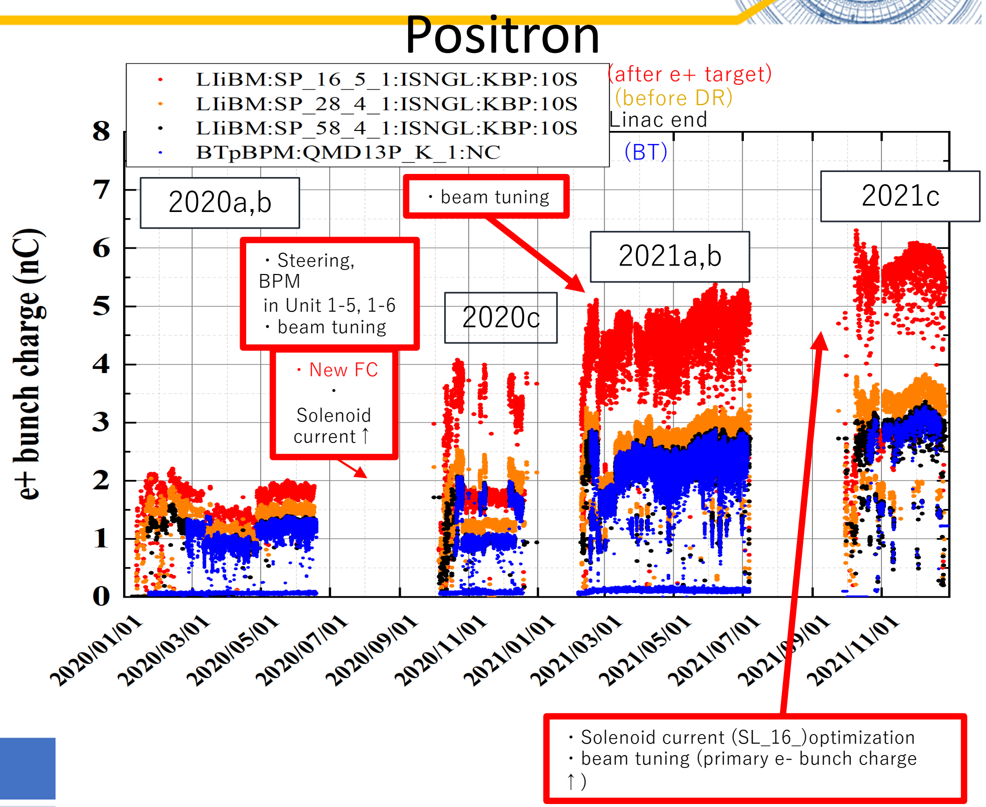
- SuperKEKB injection scheme

K. Furukawa et al, Poster, THPOST011

  - Injector Linac provides e+ and e- beams. (e+: thermionic gun, DR, e-: RF gun)
  - Synchronization between injector 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(sum of e- and 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.
    - Increasing linac charge is important.
  - The shorter beam lifetime at smaller βy^* (dynamic aperture) requires a more powerful injection. Conversely, injection sets a limit on the achievable βy^*.
    - Machine operation with the optics of $\beta y^* = 0.8$mm is being tried in this run.
  - The injection efficiency is also 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)
    - Emittance preservation in Linac and BT is important.

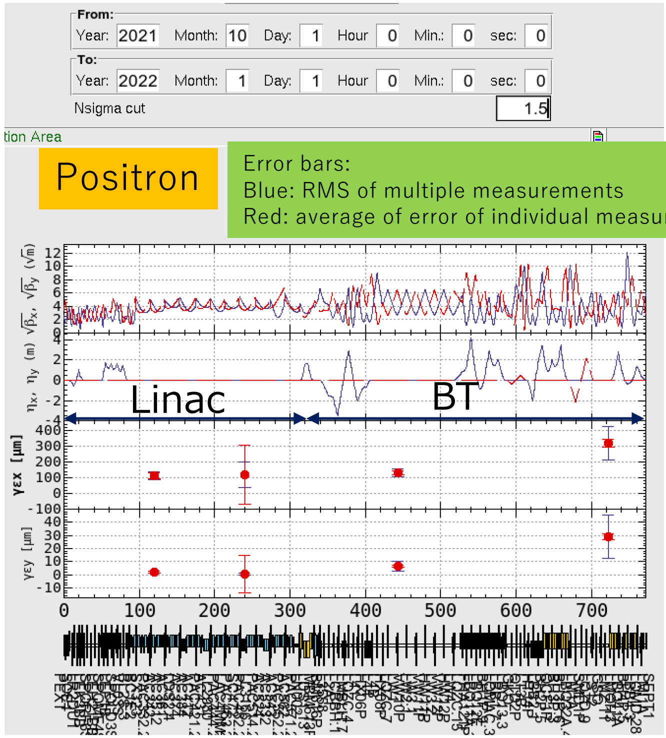
Linac bunch charge history

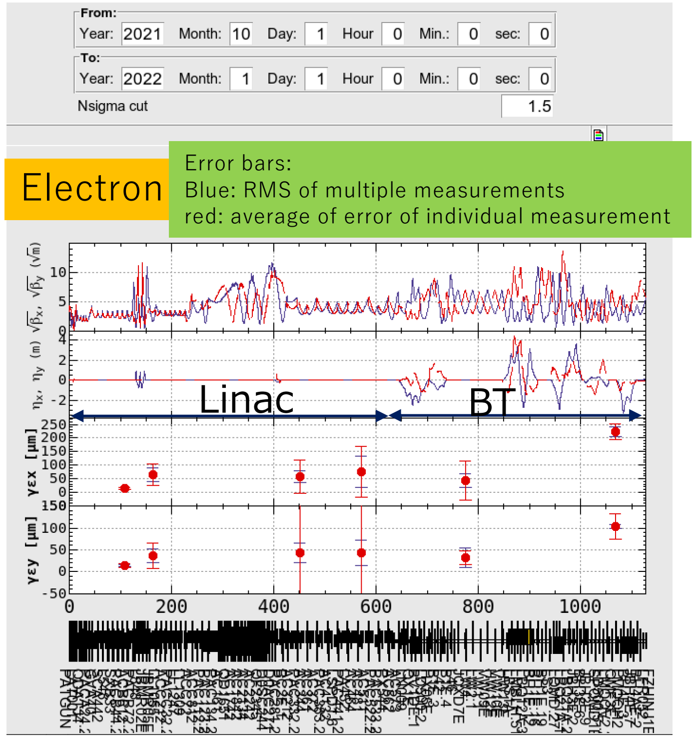




Target (design) values	e+	e-
Charge / bunch [nC]	4	4

Linac, BT Emittance measurement using wire scanners (2021c)





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 growth is bunch charge dependent and may be caused by CSR effect.

Performance limiting issues [3/4] Beam-beam performance

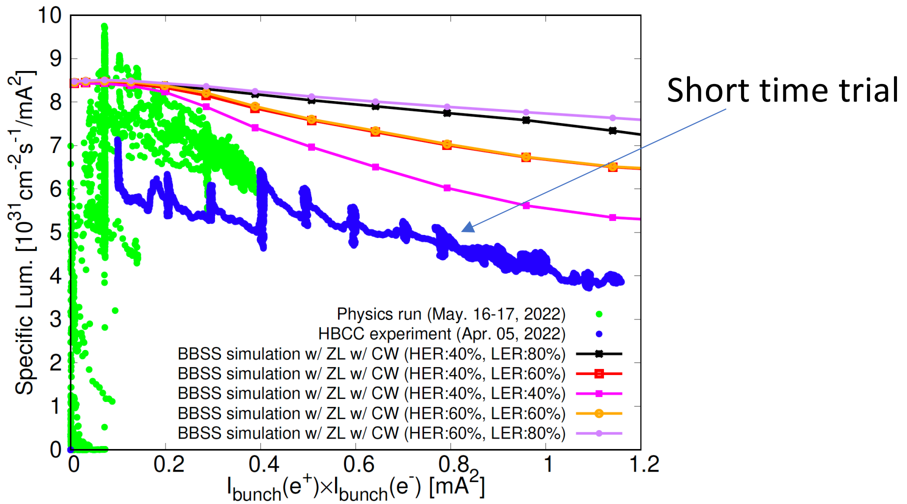
- Observed luminosity performance is much lower than simulations with BBSS (Beam-Beam Strong-Strong). This has been and will be a challenge at SuperKEKB.

D. Zhou, et al, Poster, WEPOPT064

- Candidates of causes
  - Machine imperfections: Non-zero linear and chromatic coupling (**M. Masuzawa, Contributed Oral, TUOZSP2**) and dispersions at IP, beam-current dependent optics distortion due to orbit change at QCS* and SLY*, etc.
  - Imperfect crab waist scheme; Interplay of beam-beam interaction and beam coupling impedance.
  - Beam oscillation excited by injection kickers at LER causes luminosity loss by ~10%.

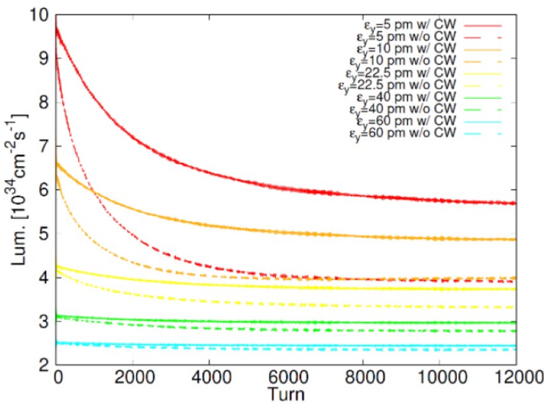
Operation parameter set for BBSS simulation

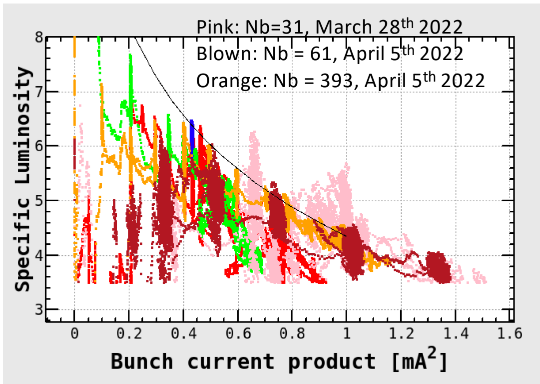
	2022.04.05		Comments
	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	
# bunch	393		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	35	30	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design



Beam-beam issues [contn'd]

- Ways to better beam-beam performance
  - Beam-beam simulations predict better beam-beam performance with
    - Smaller vertical emittance in single beam (matter of optics corrections)
    - Higher crab waist ratio in HER (strength)
  - Identification of causes of discrepancy between simulations and experiments
  - Better working points
- Beam-beam parameters
  - Achieved values in physics runs: : ξy(LER) =0.0392 , ξy(HER) = 0.0269
  - Achieved values in high bunch collision study: ξy(LER) =0.0565 , ξy(HER) = 0.0434
  - By increasing bunch currents in physics run, higher ξy and then a higher luminosity is expected.



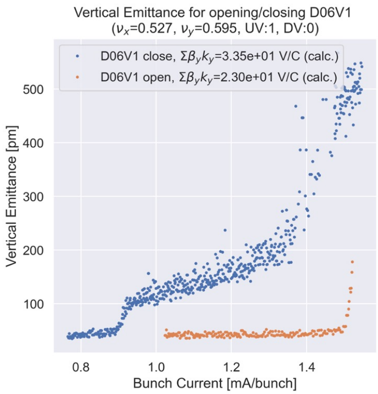


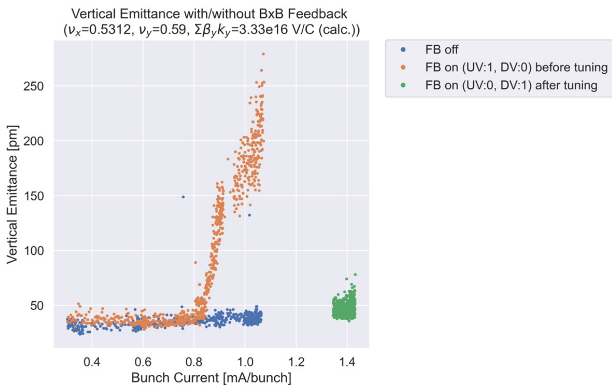
Performance limiting issues [4/4] Impedance related issues

- Single bunch effect
  - LER TMCI (Transverse Mode Coupling Instability)
    - The apertures of vertical collimators scale as βy*, TMCI will set a limit on the bunch current. Extensive machine studies have been done on this issue.
      - With the use of 2 vertical collimators and taking into account the impedance from the high-β region around final focus quadrupoles, the TMCI threshold will be lower than the design bunch current of 1.44mA when βy*<0.6mm.
      - By introducing a nonlinear collimator (NLC), we can use more vertical collimators and meanwhile reduce Belle II BG.
  - Single bunch beam blowup in LER (-1 mode instability)
    - Beam blowup has been observed with a threshold ~0.8mA/bunch, .
    - This blowup has been intensively studied. The interplay of the feedback system and vertical impedance was identified to be the main source of beam blowup. Fine-tuning of FB system helped suppress the blowup.
- Multi-bunch (coupled bunch) instability
  - Low-frequency resistive wall (RW) impedance gives the fastest growth time (1.6ms@600mA in HER, 3.6ms@600mA in LER). This instability has been well suppressed by the bunch-by-bunch feedback system so far.
  - The longitudinal coupled bunch instability caused by fundamental mode impedance of RF cavities has been well suppressed by -1 mode dumpers in both rings.
- Electron clouds
  - In the current beam condition (4 or 6 ns bunch spacing, <0.7 mA/bunch), no significant beam size blowup due to the electron clouds effect has been observed in LER.

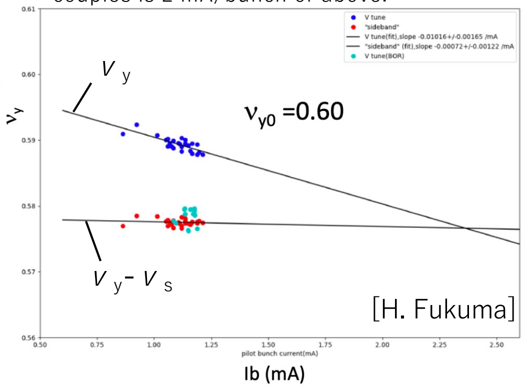
Study on TMCI and -1 mode blowup

- We've observed vertical beam-size blow-ups around 0.8 mA/bunch in LER with single-beam operations, and this value is about 50% or more lower than an expected TMCI threshold.
- When the beam-size blow-ups have been observed, a peak corresponding to ν_y-ν_s appears (so we call this "-1 mode instability").
- The impedance in vertical collimators contributes to this instability, and opening apertures of them can increase the threshold.
- The vertical bunch-by-bunch feedback system with a standard setting enhances this instability, and its tunings can suppress the instability.
- The mechanism of the -1 mode instability is under investigation (**S. Terui et al., Poster, WEPOTK050**), but we've found two ways to deal with this instability.
  1. Tuning of the vertical bunch-by-bunch feedback
  2. Reducing the impedance in the vertical direction by opening vertical collimators
  - ✓ The second point is one of motivations to introduce the nonlinear collimator.





Peaks in a tune spectrum and a Bunch Oscillation Recorder (BOR). The expected bunch current when the 0- and -1-mode couples is 2 mA/bunch or above.

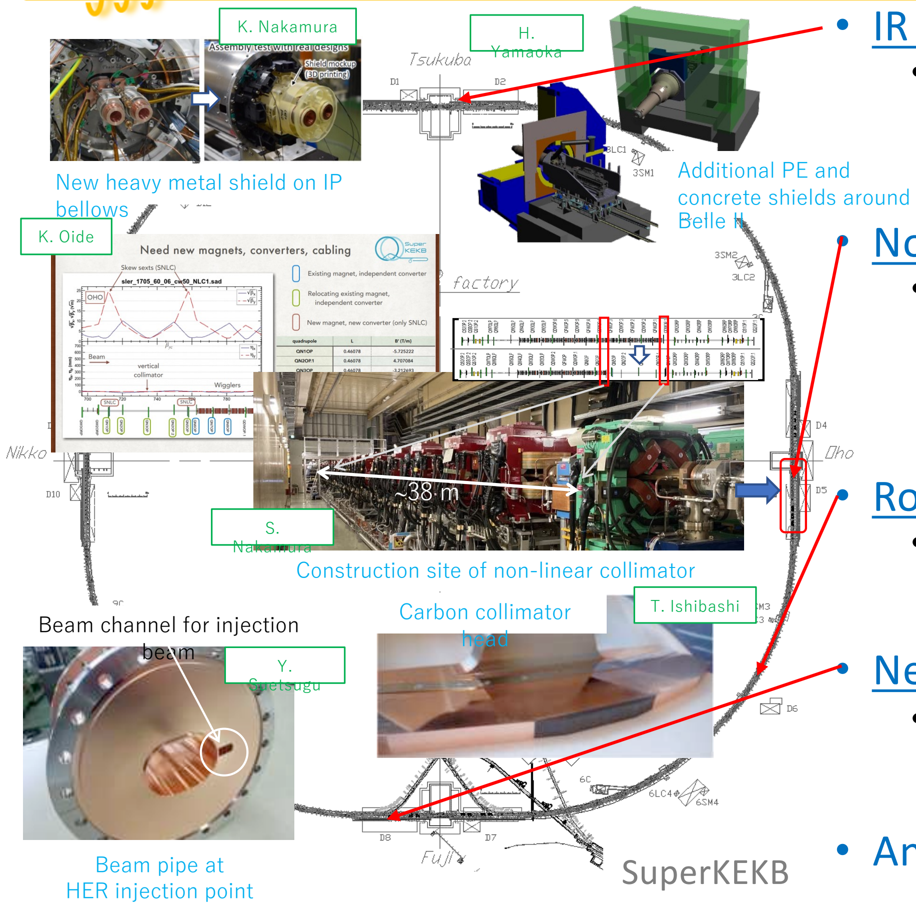


T. Ishibashi

Upgrade plan

- Long Shutdown 1 (LS1): July 2022 – September 2023
  - Belle II: additional VXD detector installation, TOP counter PMTs replacement
  - SuperKEKB: Upgrade works in this opportunity
- Medium term plan for increasing luminosity
  - We will aim at the luminosity of 1 x 10^{35} cm^{-2} s^{-1} within 1 or 2 years after LS1 with βy^* = 0.8mm.
  - The operation with βy^* = 0.6mm will also be tried.
- Long term plan for luminosity upgrade
  - 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 is being studied.

Major upgrade items during LS1



- 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…

Example of parameters for L= 1 x10^{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

- This parameter list was made based on a high bunch current collision study.
  - We will need higher bunch currents.
- We will aim to achieve the parameter list.
- In the process of aiming at the parameter set, we will need to study various issues and aim at the luminosity with solving issues found and with modifying the parameter set.

International Task force for SuperKEKB upgrade

Mission

- Bring ideas and exchange notes to solve various problems we face as a luminosity frontier machine, to achieve SuperKEKB design luminosity.
  - Short term
    - Working together on a to-do list with priority for LS1 to achieve luminosity of the order of 10^{35} cm^{-2} s^{-1} without any large-scale modification of accelerator components.
  - Longer-term
    - Searching for ideas to achieve the design luminosity.

Four working groups (sub-groups) organized

- Optics
- Beam-beam
- TMCI
- Linac

History

- Started with the Initial members recommended by ARC members
- The first kick-off meeting was held in July, 2021
- More people joined us.
- There have been 6 ITF general meetings many more sub-group meetings held so far.
- ITF working in close collaboration with KEKB commissioning team.

International Task force for SuperKEKB upgrade

Examples of activities

- Lattice translation and repository for SuperKEKB; Optics optimization and simulations with independent codes.
- Dynamic aperture optimization, new optics design.
- Beam-beam simulation, impedance calculation, instability theories.
- Deep discussions on the simulation results and new ideas.
- Proposed many machine study items and discussion on the results.

You are welcome to join us!

International Task Force members

2021/7/27

International members

Maria Enrica Biagini	INFN
Georg Hoffstaetter	Cornell
Evgeny Levichev	BINP
Mark Palmer	BNL
Yunhai Cai	SLAC
Rogelio Tomas	CERN
Pantaleo Raimondi	ESRF
Katsunobu Oide	CERN/KEK

KEK ACCL members

Mika Maszawa (Chair)	SKEKB
Yukiyoshi Ohnishi	SKEKB
Akio Morita	SKEKB
Hiroshi Sugimoto	SKEKB
Renjun Yang	SKEKB
Haruyo Koiso	SKEKB
Yoshihiro Funakoshi	SKEKB
Tsukasa Miyajima	SKEKB
Kazuhito Ohmi	SKEKB
Demin Zhou	SKEKB
Kentaro Harada	KEK-PF

Belle II members

Hiroyuki Nakayama	Belle II
Francesco Forti	Belle II

BPO members

Masanori Yamauchi	KEK		
Tadashi Koseki	ACCL	Naohito Saito	IPNS
Makoto Tobiyama	SKEKB	Shoji Uno	Belle II
Hiroyasu Ego	SKEKB	Yutaka Ushiroda	Belle II
Kyo Shibata	SKEKB	Toru Iijima	Belle II
Mika Masuzawa	SKEKB	Kodai Matsuoka	Belle II

We will continue to make every efforts to improve SuperKEKB performance toward design goal.

Fin.

Thank you for your attention.