SuperKEKB Ring operation status and plan

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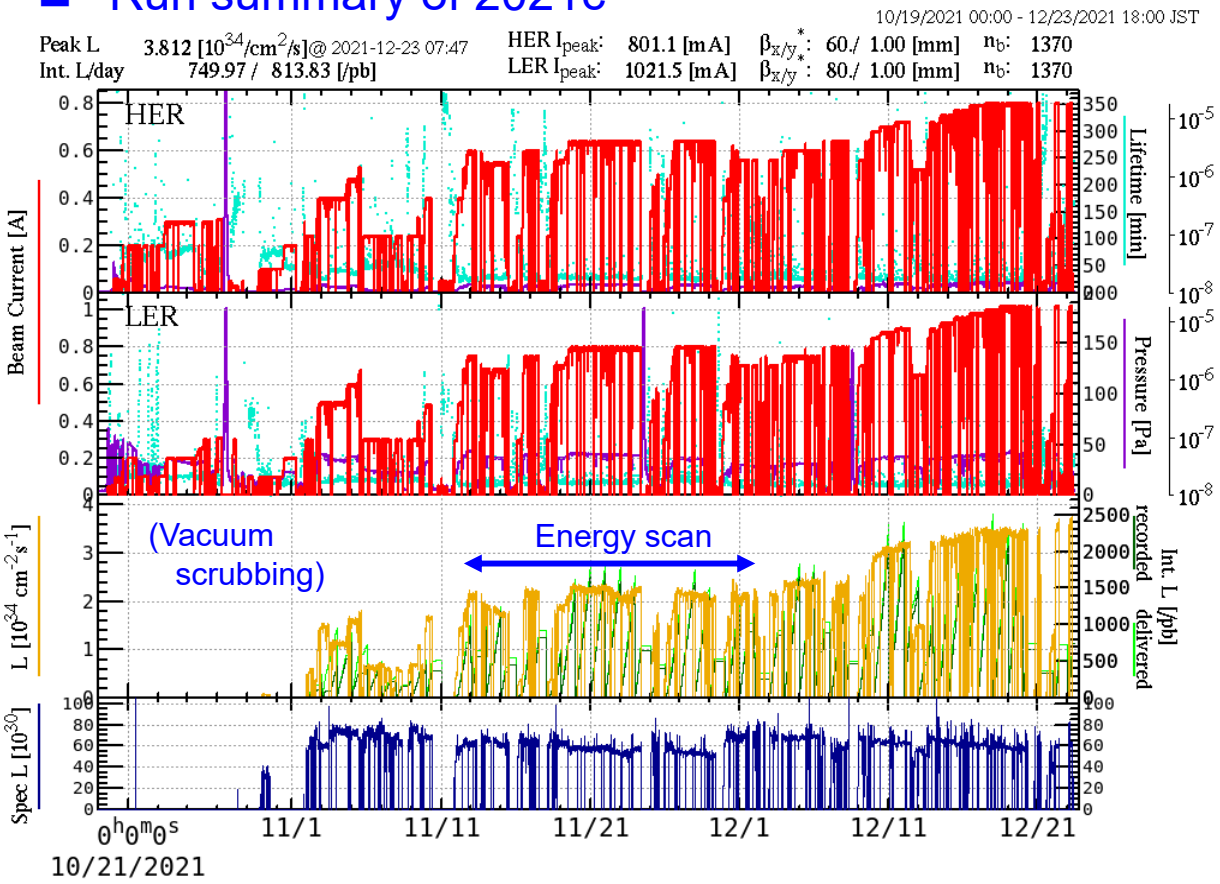
KEK Accelerator Laboratory
@BPAC 21/Feb/2022

SuperKEKB 2021c run (2021/10/19～12/23)

Run summary of 2021c



10/19 – 10/27
- Vacuum scrubbing and machine studies at β_y^* = 8 mm

10/28 – 11/5
- Accidental firing of LER injection kicker. I < 300 mA.

11/01 – 11/10
- QCS quench due to earthquake
- Thyratron replacement on Nov. 8

11/11 – 11/29
- Energy scan
- Thyratron replacement on Nov. 24

11/30 – 12/8
- Increasing beam currents up to 800 mA / 640 mA

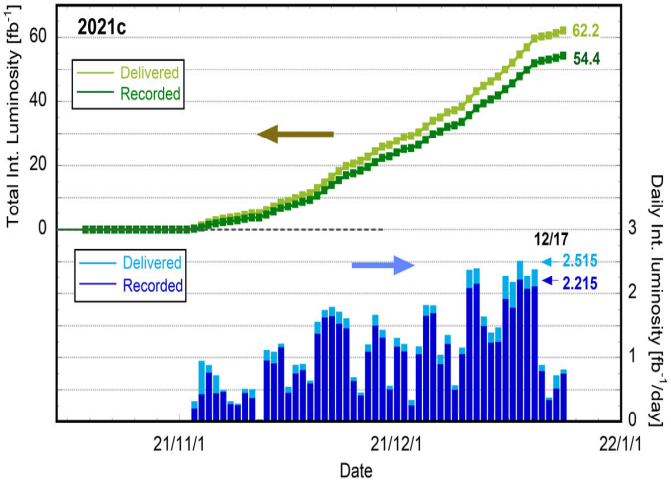
12/10 -12/19
- Extremely large HER σ_y after earthquake
- Mini energy scan (+4 MeV) on Dec. 1
- QCS quench due to human error
- Increasing beam currents up to 1020 mA / 820 mA. n_b = 1370.

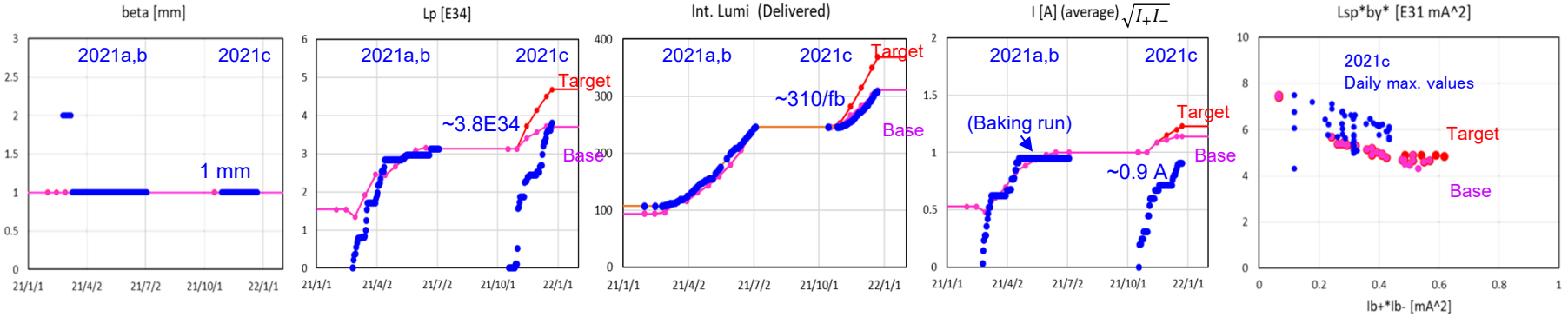
12/20 – 12/23
- Machine studies
- Chromatic X-Y couplings, resonance structures, TMCI, beam-beam, injection performance, collimators, optics, etc.

SuperKEKB 2021c run (2021/10/19～12/23)

Major results -1

- Luminosity records
  - Luminosity: 3.81x10^{34} cm^{-2}s^{-1} @1370 bunches.
  - Int. luminosity: 2.52 fb^{-1}/day (Delivered), 2.22 fb^{-1}/day (Recorded). ~310 fb^{-1} in total, which is close to the base profile
- Energy scan (11/10～11/29)
  - Physics run at 10.657, 10.706, 10.751, 10.810 GeV.
  - Sufficient data was successfully obtained in each energy.
- Protocol to stably and safely increase beam currents
  - The protocol including “baking run” was established and almost worked well from 12/10.
  - The maximum beam currents of 1020 mA in SuperKEKB era was achieved (LER, 1370 bunches, during physics run).
  - No severe rapid beam loses and damages to vertical-type collimators and detectors have happened, although the reason is not so clear.

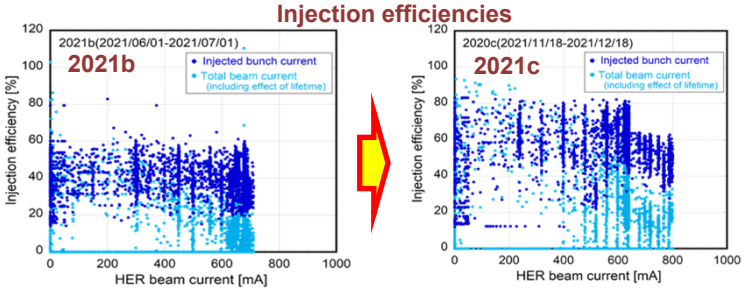


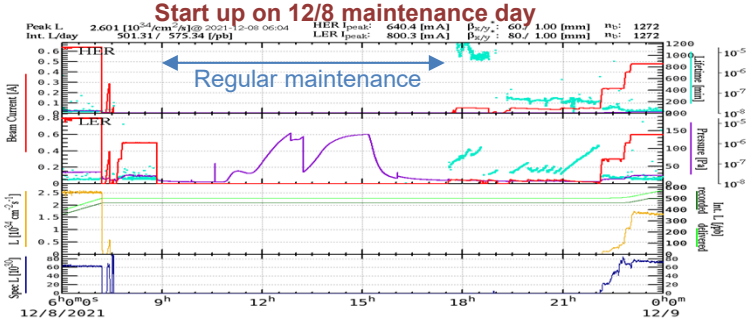


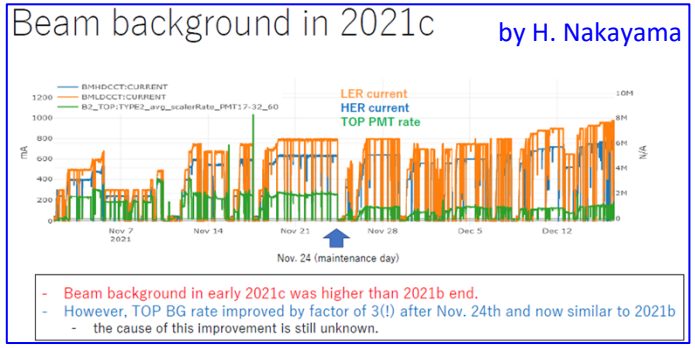
SuperKEKB 2021c run (2021/10/19～12/23)

Major results -2

- Improvement in the injection efficiency of HER
  - Injection efficiency improved to approximately 60 %.
  - Low emittance injection beam, optics matching at BT considering the fringe-field of septum magnets, improvement in the tuning methods, etc.
- Smooth startup after maintenance work
  - Startup protocol was established.
  - Injection veto of CLAWS abort system reduces beam aborts during injection tuning (12/1~).
- Improvement in background
  - Beam background was drastically reduced after the maintenance on 11/24, although the reason has not been so clarified.
  - The effect of D02_V1 collimator relocations seems to be almost as expected (for outer detectors).
- Beam studies
  - The last three days' day and swing shifts were dedicated to beam studies (β_y^* = 1 mm).
  - Various studies were done, including studies proposed by sub-groups of ITF.
  - Fruitful results were obtained and reported in the summary meeting held on 13 and 14, January. (https://kds.kek.jp/event/40680/, sorry in Japanese)



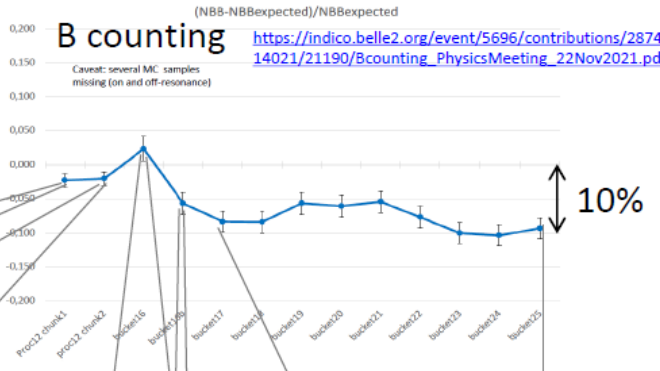




Slow drift of collision energy

Collision energy

Indication of a shift in the collision energy by ~6 MeV 1.5 years ago



https://indico.belle2.org/event/5696/contributions/28741/attachments/14021/21190/Bcounting_PhysicsMeeting_22Nov2021.pdf

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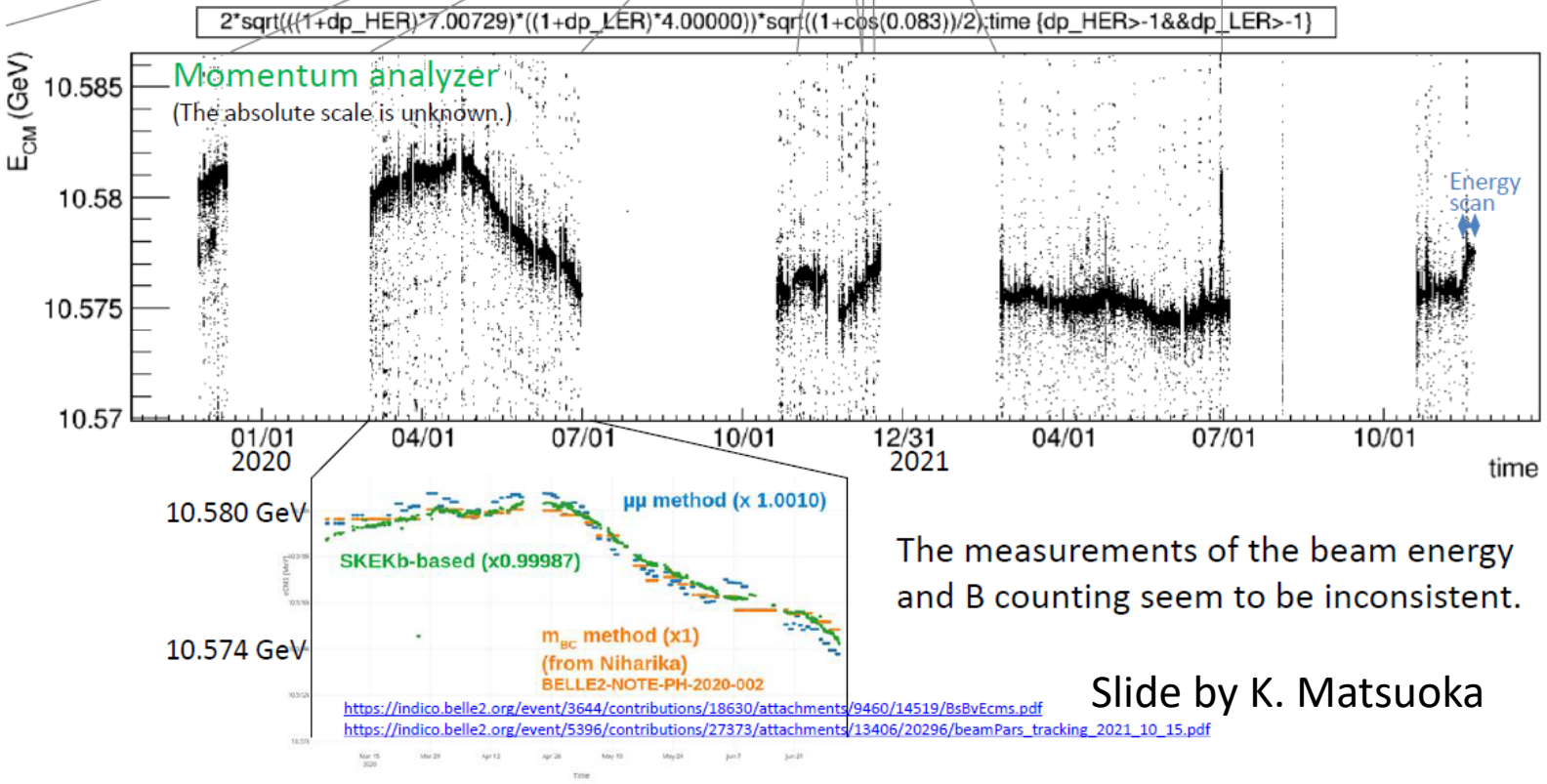
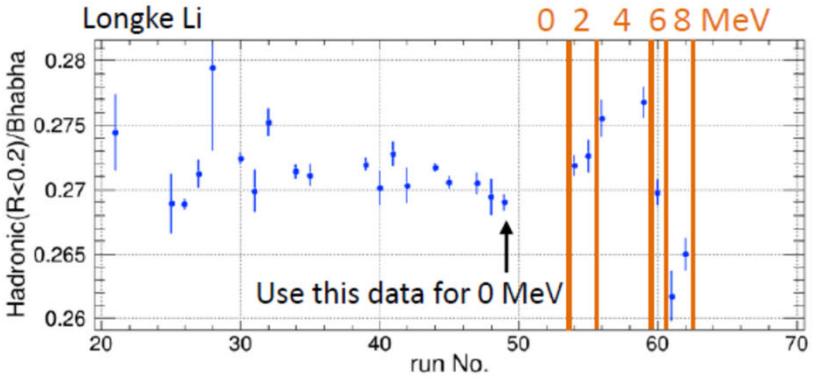


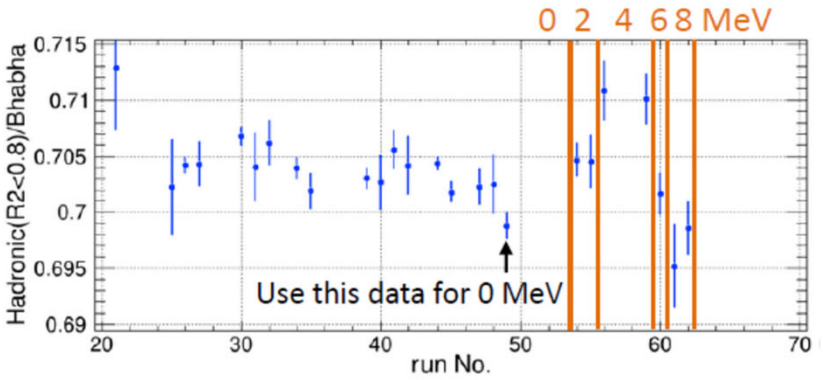
The measurements of the beam energy and B counting seem to be inconsistent.

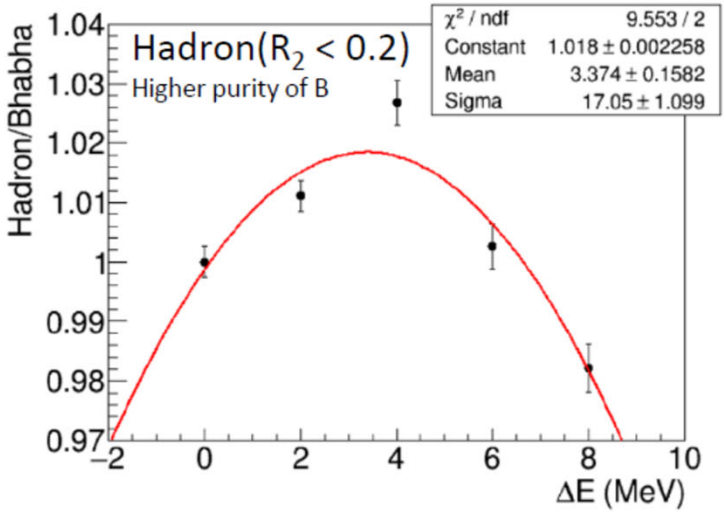
Slide by K. Matsuoka

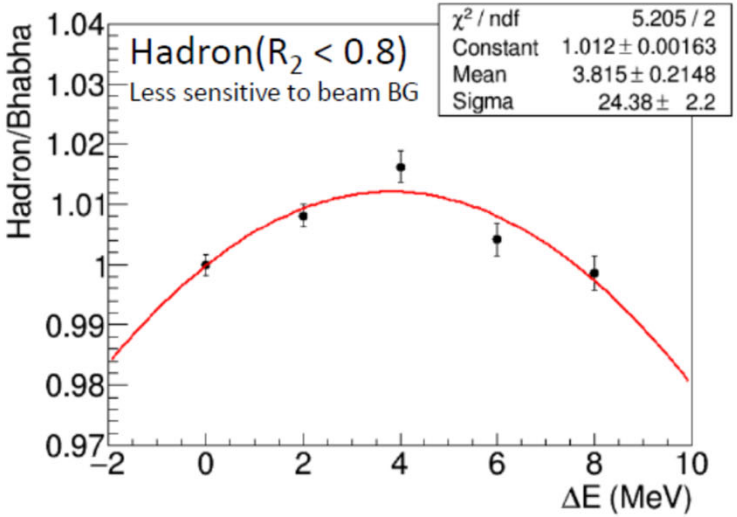
https://indico.belle2.org/event/3644/contributions/18630/attachments/9460/14519/BsBvEcms.pdf
https://indico.belle2.org/event/5396/contributions/27373/attachments/13406/20296/beamPars_tracking_2021_10_15.pdf

Mini energy scan around Y(4S)









Lost 5-7% of $B\bar{B}$ for 1.5 years

The energy was set to ΔE = 4 MeV

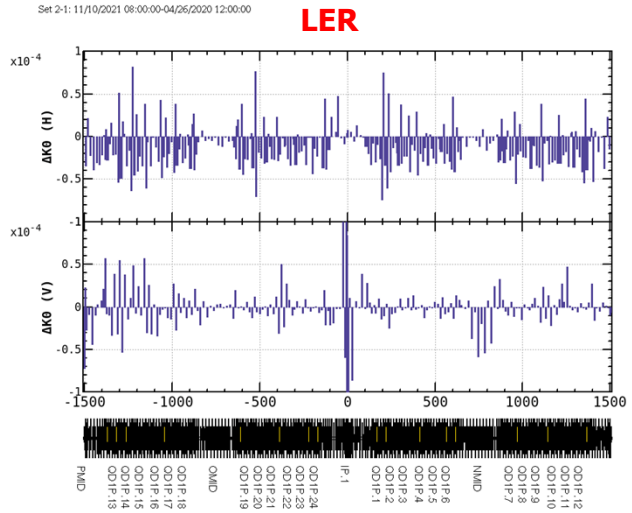
The recovery of $B\bar{B}$ and the absolute energy have to be confirmed by offline analyses.

Slide by K. Matsuoka

Beam Energy for Y(4S) difference between 2020 Apr. 26 and 2021 Nov. 10

Y. Ohnishi
Nov. 25 2021

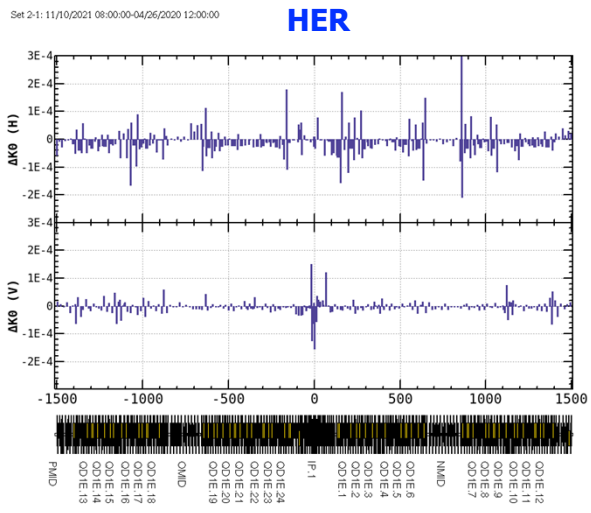
LER



Hor. steering kick angle

Ver. steering kick angle

HER



$\delta = -5.95 \times 10^{-4}$

E_L = 3997.620 MeV

E_L = 4000.000 MeV (design)

expected

ΔE_{cm} : -5.9 MeV

$\delta = -5.17 \times 10^{-4}$

E_H = 7003.66 MeV

E_H = 7007.29 MeV (design)

Energy at 2020 is not sure whether on the exact Y(4S) or not.

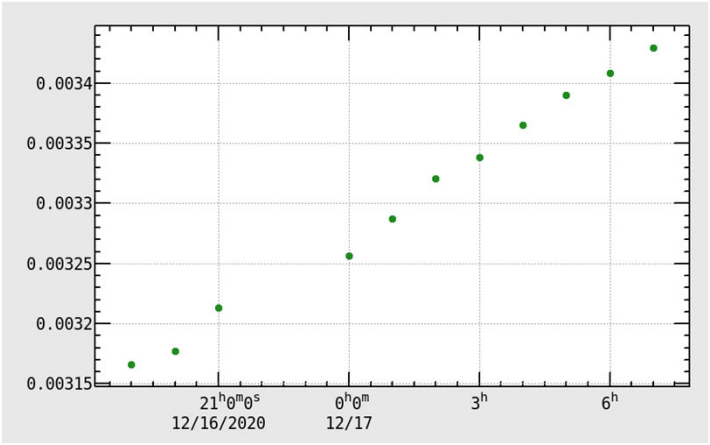
Sum of kick angles of horizontal dipole correctors was not kept well before 2020c.
The closed orbit correction (CCC) algorithm was improved to keep the energy.

Horizontal Steerings in LER

Y. Ohnishi
Feb. 3, 2021

EPICS PVs (KRB)

sum of horizontal kick angle (rad)

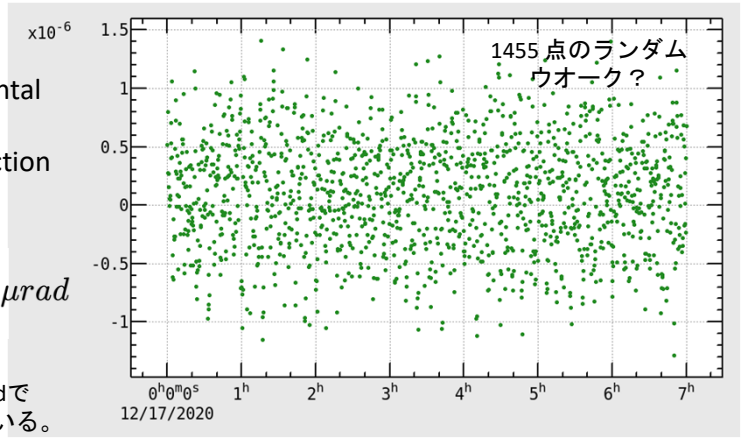


CCCで設定しょうとしたキック角の総和

sum of horizontal kick angle for each correction at CCC (rad)

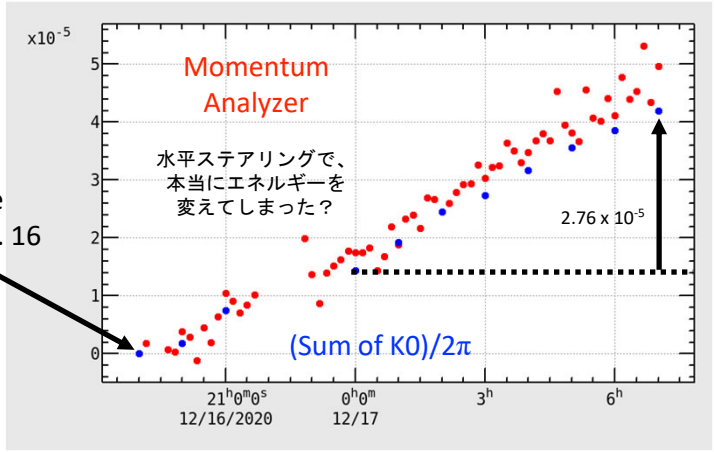
$$\sum_i^n \theta_{xi} < \pm 1\ \mu rad$$

CCCでは
$|\theta_x|$>4x10^{-8} radで
足切りを行っている。
(~24 bit)



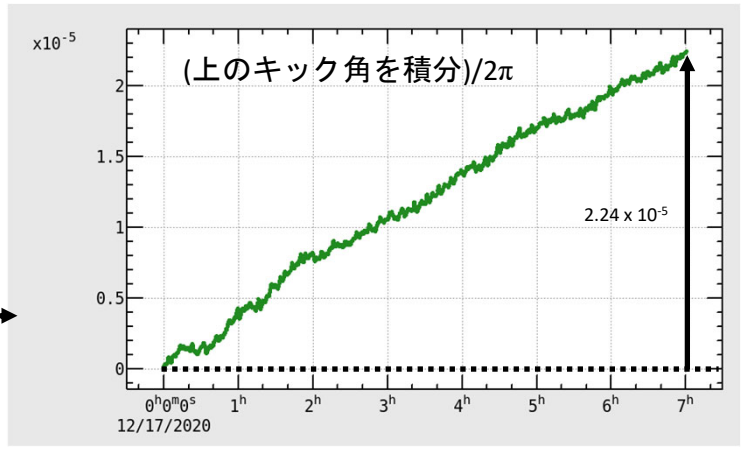
$\frac{\Delta p}{p_0}$

Reference is 19:00, Dec. 16



両者の違いは、
設定精度の問題?

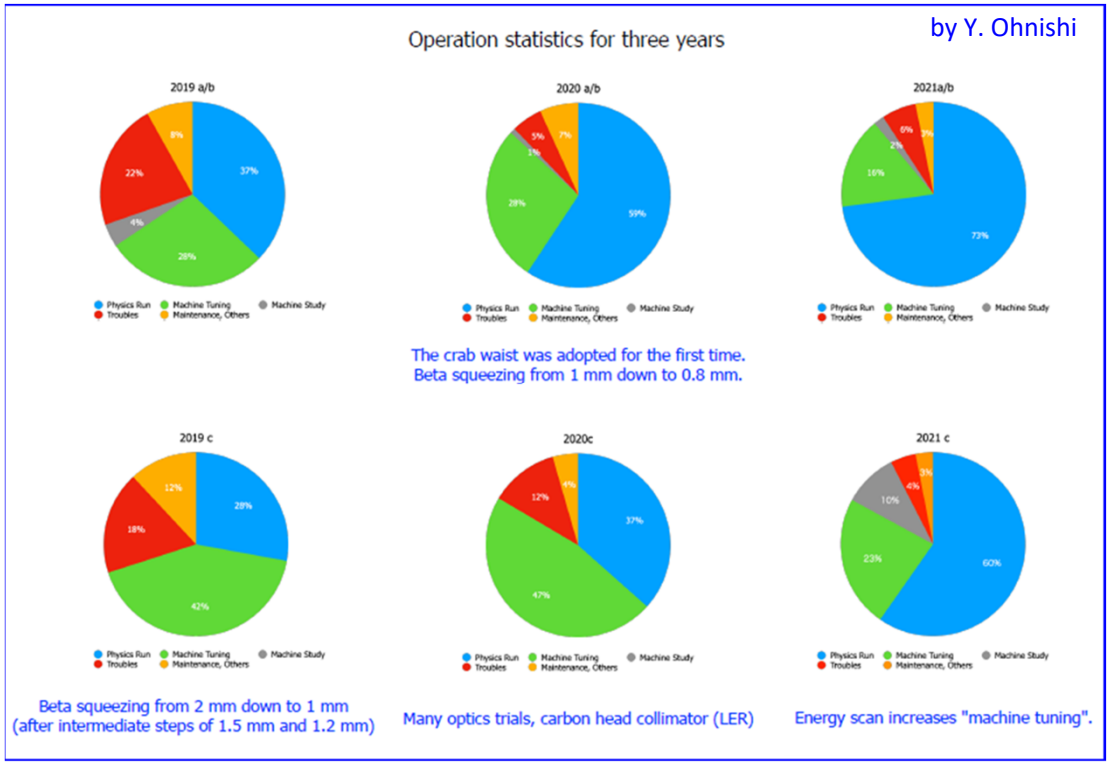
$\frac{\Delta p}{p_0}$

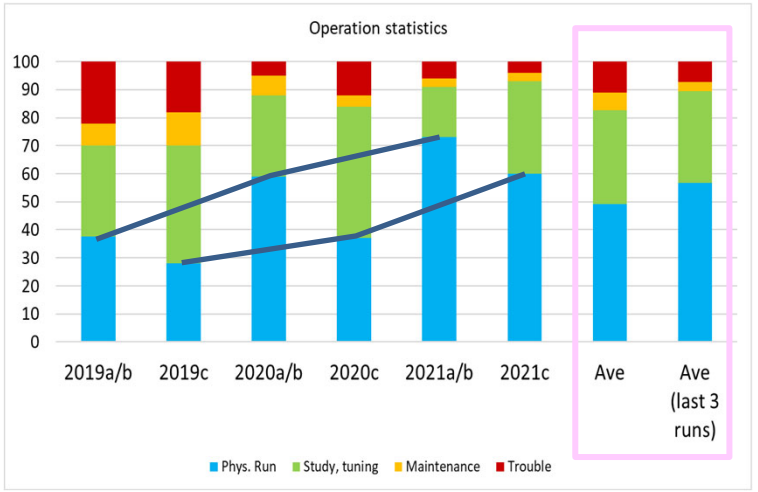


- In the COD correction algorithm used in SuperKEKB, in order to maintain beam energy, the sum of the total kick angle of the horizontal steering magnets were kept below a certain amount.
- We have found the poor convergence (10^−7) before 2020c. After 2021a, the correction algorithm was improved to have better convergence (10^−18).
- The energy drift is suspected to be caused by the poor convergence.
- Even with the current correction algorithm, slow drift of the energy might happen. Monitoring the energy drift by Belle II detector and/or periodic mini-energy scan will be needed.

Slide by K. Matsuoka

SuperKEKB 2021c run (2021/10/19～12/23)



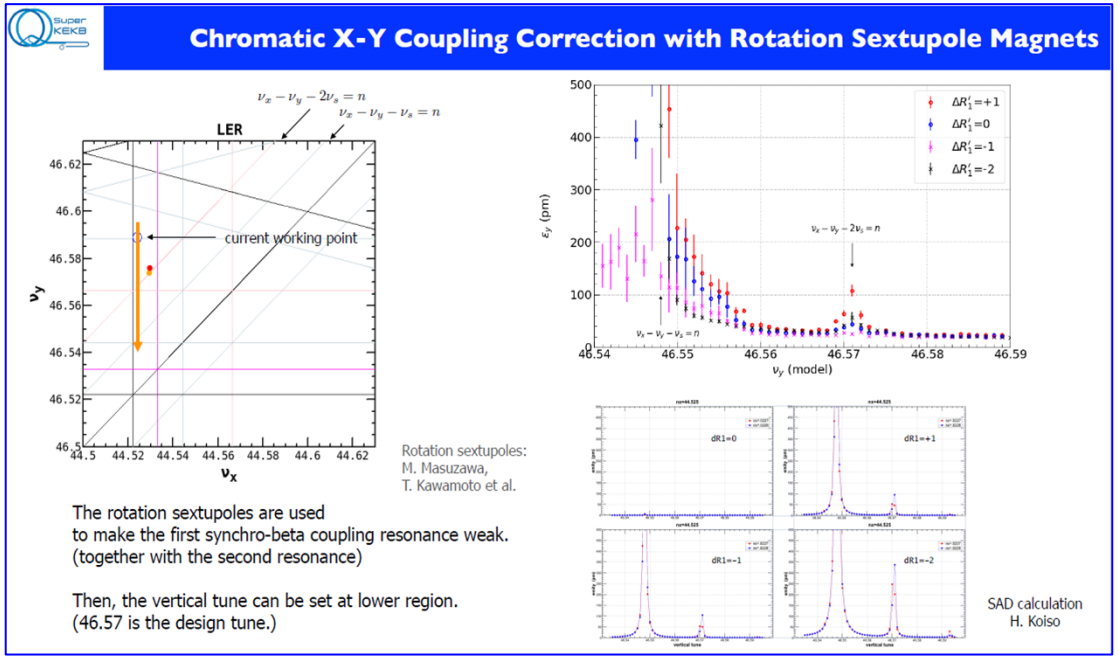


SuperKEKB 2021c run (2021/10/19～12/23)

■ Some results from beam studies -1

- Rotatable sextupole magnets

by Y. Ohnishi



Rotatable Sextupole magnet

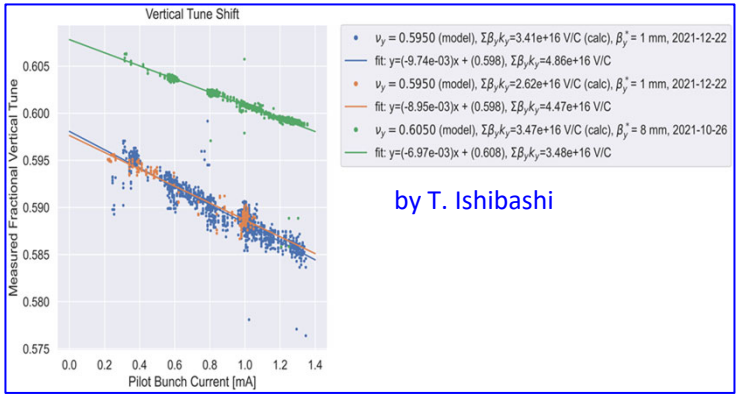
M. Masuzawa

- Succeeded to suppress emittance blow-up by tuning rotation angle.
- Succeeded to rotate sextupoles with beam, although single and low beam currents.
  - No need to optics correction each rotation.

SuperKEKB 2021c run (2021/10/19～12/23)

Some results from beam studies -2

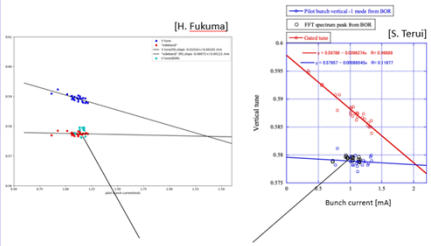
- Collimator and TMCI studies



by T. Ishibashi

How about the "ordinary" TMCI

- The mode 0 and -1 seems to be coupled 2.0-2.3 mA/bunch for $\Sigma\beta_y k_y$ = 4.86e16 V/C.
- The calculated threshold using the simple formula is about 1.44 mA/bunch.
  - When we adopt not 8 but 4π, it's ~2.26 mA/bunch.



When we observe the beam size blow-up, the sideband of -1 mode appears.

$$I_{th} = \frac{8\nu_s(E/e)}{T_0 \sum_i \beta_{y,i} k_{y,i}}$$

$\nu_s = 0.022, E/e = 4$ GV, $T_0 = 1$e-5 s

β_y^* [mm]	$\Sigma\beta_y k_y$ [V/C]	I_{th} [mA/bunch]
8	3.48e16	2.01
1	4.86e16	1.44
0.25	7.77e16	0.90

Summary

by T. Ishibashi

- The vertical tune shift in the β_y^* = 1 mm optics is larger that in β_y^* = 8 mm despite the vertical collimator setting is almost same in terms of $\Sigma\beta_y k_y$.
  - ➢ This is not caused by the damaged vertical collimators.
  - ➢ This may indicate that there are sensitive impedance sources to the β_y^*, which is tapered beam-pipes in QCS, for example.
  - ➢ If this is correct, the bunch current threshold may decrease with squeezing β_y^*.
  - ➢ If this is correct, there is a possibility that the Non-Linear Collimator (NLC) could not raise the threshold much as we expected.
    - NLC could help to raise the threshold around β_y^* = 1 mm, however it could not be when we squeeze it further.
- The bunch current threshold for the vertical beam size blow-up decreases in the situation of β_y^* = 1 mm, and this may be caused by the unexpected larger $\Sigma\beta_y k_y$.
- This vertical beam size blow-up may be driven by transverse localized wakes in the vertical collimators and the tapered beam-pipe in the QCS cryostats and a local linear and chromatic X-Y coupling around QCS.
  - ➢ Ohmi-san will talk about how we interpret this phenomenon in beam dynamics tomorrow.
- BxB FB or/and increasing vertical chromaticity can suppress this instability.
  - ➢ However, there are side-effects.
  - ➢ Even if we overcome this instability, we may encounter the next instability because the threshold of the ordinary TMCI is not very high. Then, this TMCI can be an ultimate limit of the bunch current.

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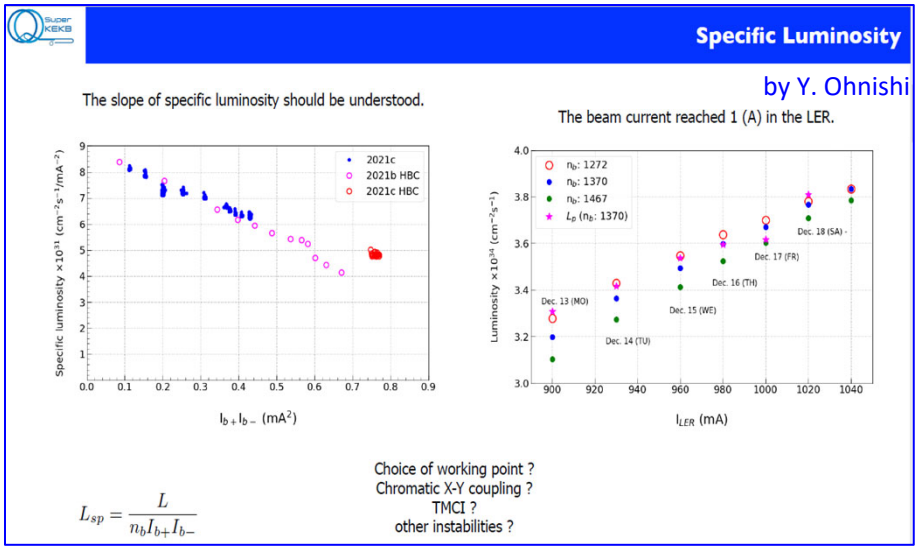
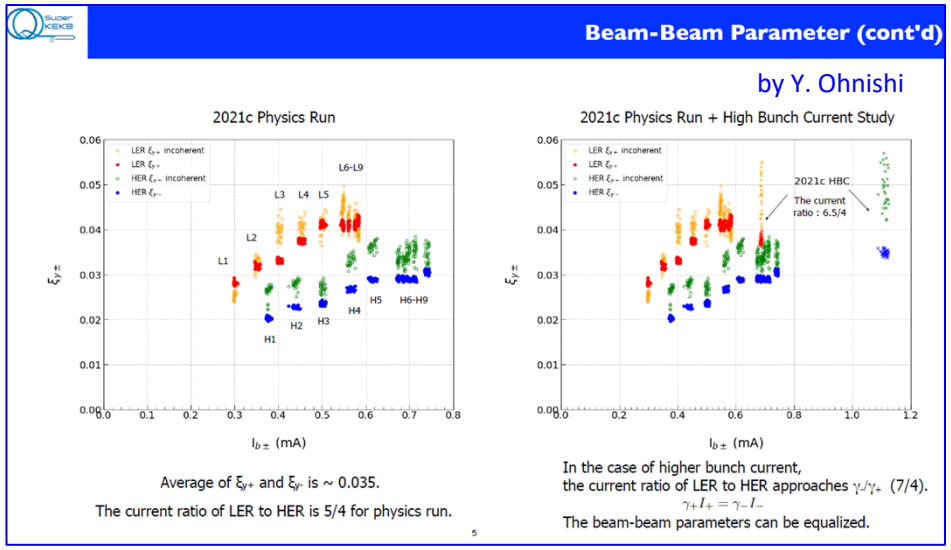
- Very interesting and informative results to the future were obtained, although still further investigation is required.
- Please check Ishibashi-san's report in the summary meeting (in English). https://kds.kek.jp/event/40680/

SuperKEKB 2021c run (2021/10/19～12/23)

- Some results from beam studies -3
  - High-bunch current (HBC) studies



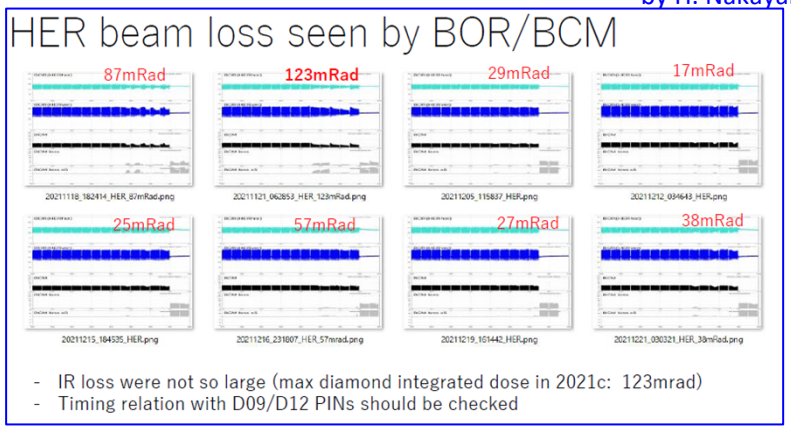


- The decrease in the specific luminosity with bunch-current products is still observed. The cause should be understood.
- The specific luminosity at high bunch current seems to be improved compared to that in 2021b.
- Increase in the beam-beam parameter seems to be still expected for higher bunch current.

SuperKEKB 2021c run (2021/10/19～12/23)

- **Major challenges -1**
  - Frequent accidental firing of LER injection kickers
    - The beam currents was kept low for safety. Deterioration of 30 years' old thyratron exchanged during summer shutdown could be a cause. They were replaced to those that had been used until 2021b. Long-term countermeasures are under consideration.
    - D06_H3 collimator head was damaged. It was replaced to new one this winter shutdown.
  - Increase in the vertical beam size at high bunch current
    - Single beam: Synchro-beta resonance? Head tail or strong head-tail instability (TMCI)?
    - Two beam: Beam-beam effect? Chromatic x-y coupling at IP?
    - The cause has not been understood yet. Detailed study is on going.
  - Bunch current limit of LER
    - Limiting factor seems not a simple TMCI due to high impedances of collimators. Other instabilities?
  - Rapid beam loss and abort
    - No severe beam loss at IP and damage of vertical-type collimators were happened in this run, though rapid beam losses were observed several times. High risks for increasing beam currents.
    - The large losses were more frequent for HER.
    - The cause has not been clarified. Damaged collimator head might be a reason, but it should be studied further.
    - New and rapid loss monitors at collimators are being prepared by Belle II.

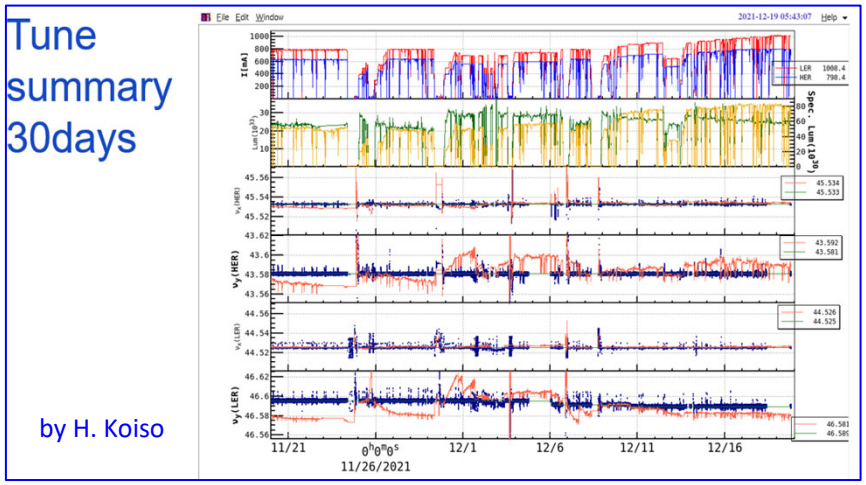
by H. Nakayama



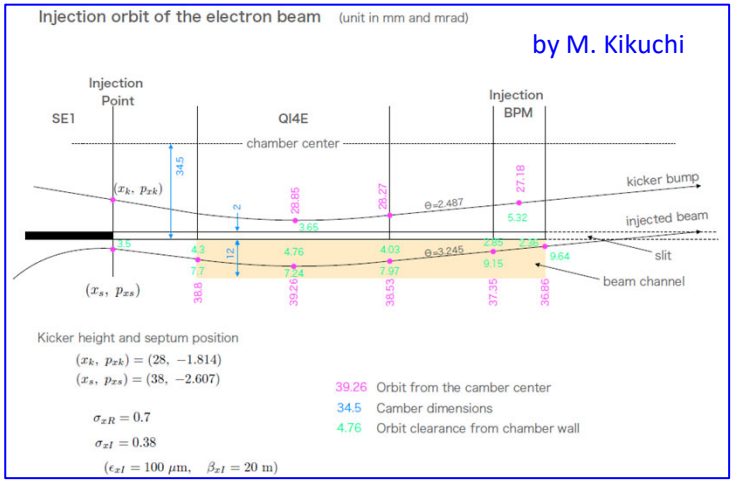
SuperKEKB 2021c run (2021/10/19～12/23)

- **Major challenges -2**
  - Long-term (~ weeks) drift of collision tuning knobs and betatron tunes
    - Drift of magnetic fields of QCS is said to be a cause. The measurement in a test bench is on going.
  - Injection efficiency
    - Efficiency has greatly improved in this run especially for HER, but further improvement is required considering future increase in beam current and operation at low β_y^*.
    - Beam clearance in the injection beam channel is very tight. Expansion of the apertures is under discussion.
    - Quality and stability of the injection beam. Emittance blowup in the beam transport line.

Long-term drift of tunes



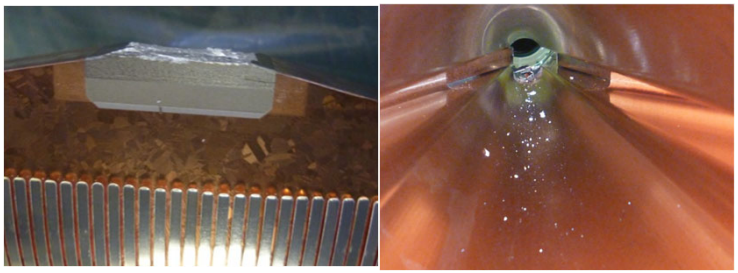
Small beam clearance at HER injection beam channel



Maintenance works during winter shutdown

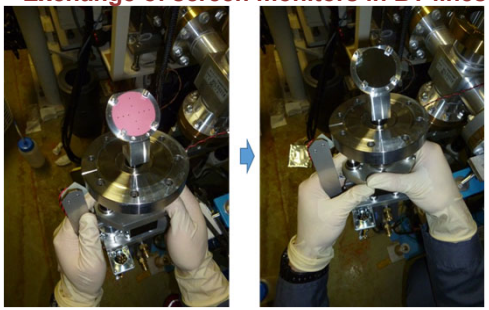
- Replacement of LER D06_H3 collimator heads.
  - The heads was found to be heavily damaged by steered abnormal beam due to accidental firing of injection kickers.

Damage of D06_H3 collimator heads



- Exchange of screen monitors in beam transport lines
  - Some alumina-fluorescence-type screen monitors were exchanged to OTR (Optical Transition Radiation)-type ones for improving the sensitivity.

Exchange of screen monitors in BT lines



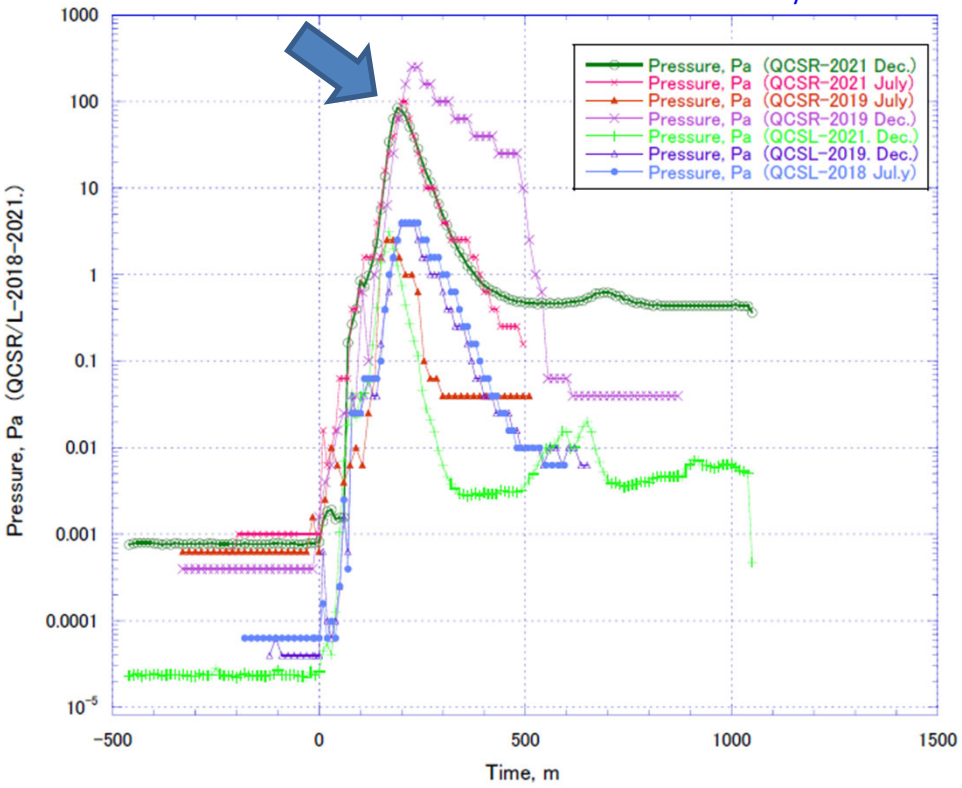
- Replacement of primary transformer of DR bending magnet power supply
  - The problem was found in the last summer shutdown and the rental trance had been used since then.
- Other usual maintenance, including periodic inspection of refrigerator system.
- Measures against aging facilities
  - Replacement of pure water pumps for vacuum chamber lines at Tsukuba.
    - We had no spears up to now since 2021a run.
  - Repairment of untreated water pumps for RF dummy loads lines at Fuji.
    - It was failed during 2021c run.
  - Roof waterproofing work at Fuji power-supply building.

Water pumps at Fuji

Water leak of MR power supply building

Leakage of vacuum insulation tank of QCSR

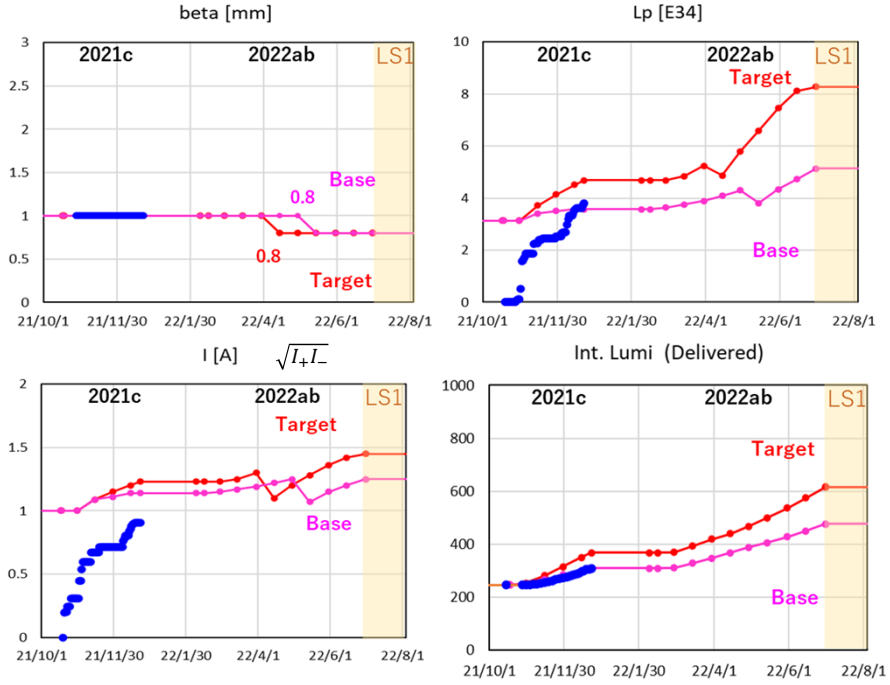
by N. Ohuchi



- QCS refrigerator stopped on 12/24, 2021.
- The increase of vacuum pressure (peak value) in the insulation tank was almost the same to that after 2021b.
- There seems no increase in the leak rate.

2022a and b run plan

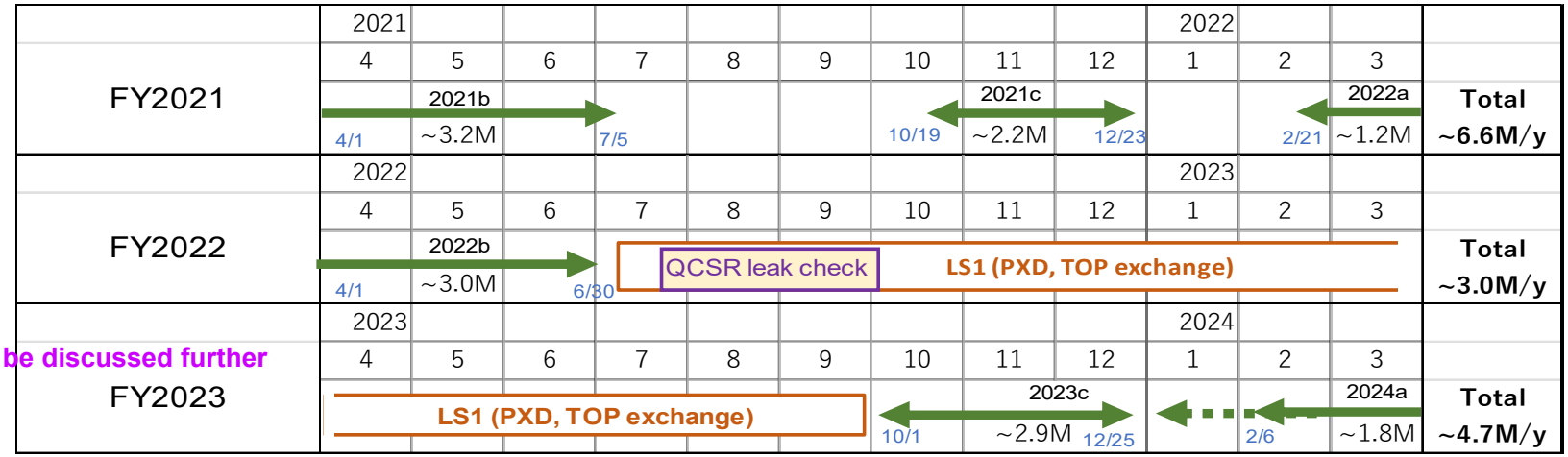
- 2022a run will start from 2/21, as scheduled.
  - The electricity charge is rising abnormally, as you know.
  - The budget is already short, but KEK will make up for it.
- In 2022a and b runs, we will continue physics run aiming higher luminosity and stable data taking, in parallel with necessary beam studies for improving luminosities, for investigating various challenges, and for finding effective upgrade plans in the future (LS1 and LS2).
  - Luminosity ~5E34 $cm^{-2}s^{-1}$ (Base)
  - Integrated luminosity ~490 fb^{-1} (Base)
    - Assumed Operation efficiency ~0.4
  - Beam currents ~1.4 A (Base)
  - β_y^* squeezing down to 0.8 mm, and 0.6 mm if possible.
  - Try new sextupole magnet setting to improve dynamic aperture.
  - Practical use of rotatable sextupole magnets during collision.
  - Try new tune and/or chromaticity values.
  - Change crab-waist ratio and beam current ratio.
  - Note: For some studies, we will perform them in proper timing during physics run, and need some period (~one week?) to see the effect of the settings on the luminosity.



FY2022 operation plan

- **Budget**
  - Good news: the total budget increased from the last year.
  - Good news: the facility maintenance cost was secured in the initial budget.
    - Measures against aging facilities and upgrades of Linac, MR and Belle II are possible.
    - It is expected that approximately 4 billion yen will be required in the same way in the future although whether it is approved or not is judged every year.
  - Bad news: six months operation requirement reduced to 4.8 months.
  - Bad news: the situation will be more severe due to the increase in the electricity unit price.
- **Operation plan**
  - The ratio of electric unit price around the last May to this March will be ~1.5 (operating month).
  - If the unit price is kept to that in March and does not increase after that, we will be able to operate for ~3 months in FY2022.
  - If the unit price continue to increase after March, we will be able to operate only for ~ 2 months in FY2022.
  - Therefore, no matter when we start LS1, there is a high possibility that we will not be able to operate 2022c run.

Operation Plan



High current scenario with increasing number of bunches (possible scenario)

物理ランで実績のあるバンチ電流

	Physics Run Dec. 23, 2021		HC1		HC2		Unit
Ring	LER	HER	LER	HER	LER	HER	
Beam Current	1015	797	1159	910	1783	1365	mA
Number of bunches	1370		1565		2346		
Bunch current	0.741	0.582	←	←	←	←	mA
Bunch current product	0.431		←		←		mA^2
Lifetime	600	1500	←	←	←	←	sec
Necessary injection charge (100 % eff.)	17.0	5.35	19.4	6.10	29.9	9.16	nC
β_x^* / β_y^*	80 / 1.0	60 / 1.0	←	←	←	←	mm
Specific luminosity	6.45×10^{31}		←		←		$cm^{-2}s^{-1}/mA^2$
Luminosity	3.81×10^{34}		4.35×10^{34}		6.52×10^{34}		$cm^{-2}s^{-1}$
β_y^* squeeze 0.8 mm scaling	4.76×10^{34}		5.44×10^{34}		8.15×10^{34}		$cm^{-2}s^{-1}$

High bunch current and beta squeezing scenario with increasing number of bunches

マシン・スタディにおける最高バンチ電流

	High Bunch Current Dec. 22, 2021		Aggressive HC1		Aggressive HC2		Unit
Ring	LER	HER	LER	HER	LER	HER	
Beam Current	435	269	1737	1072	2604	1607	mA
Number of bunches	393		1565		2346		
Bunch current	1.11	0.685	←	←	←	←	mA
Bunch current product	0.76		←		←		mA^2
β_x^* / β_y^*	80 / 1.0	60 / 1.0	←	←	←	←	mm
Specific luminosity	4.99×10^{31}		←		←		$cm^{-2}s^{-1}/mA^2$
Luminosity	1.49×10^{34}		5.94×10^{34}		8.89×10^{34}		$cm^{-2}s^{-1}$
β_y^* squeeze 0.8 mm scaling	1.86×10^{34}		7.43×10^{34}		1.11×10^{35}		$cm^{-2}s^{-1}$

International Task force for SuperKEKB upgrade

Members

- ARC members prepared a list of possible candidates in June, 2021
- Initial members have been identified. More members who have required expertise and strong interest are welcome.
- Should work in close collaboration with KEKB commissioning team.

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
Kazuro Furukawa	SKEKB	Yutaka Ushiroda	Belle II
Kyo Shibata	SKEKB	Toru Iijima	Belle II
Yusuke Suetsugu	SKEKB	Kodai Matsuoka	Belle II

International Task Force

Charges

- Consider effective ideas to realize luminosity of ~6×10^{35} cm^{-2} s^{-1} as a result of an intermediate upgrade around 2026, which could include modifications of IR, final focus systems, injectors, but without changing the boundary to the Belle II detectors.
- Find a realistic way before long shutdown 1 (LS1) scheduled to start Jul/2022 in order to achieve luminosity of the order of 10^{35} cm^{-2} s^{-1} without large modification of accelerator components.
- Consider longer-term alternative idea to achieve ~6×10^{35} cm^{-2} s^{-1} or more, even by largely modifying the IR and the Belle II detector

Four working groups (sub-groups) organized and their indico sites created

- Optics (contact person: Akio Morita)
- Beam-beam (contact person: Demin Zhou)
- TMCI (contact person: Mauro Migliorati)
- Linac (contact person: Masanori Satoh)

https://kds.kek.jp/category/2242/

Examples of activities on the International Task Force

- Share the lattice file of SuperKEKB, examined the result with independent codes.
  - Successfully reproduced the result with LEGO (Y. Cai)
  - Try to find better dynamic aperture
  - Tried new sextupole sets found using LEGO.
- Beam-beam simulation, Impedance calculation by international collaborators.
- Deep discussions on the simulation results. Proposed many machine study items. Discussion on the results.

Mid-term review is scheduled by the KEKB Accelerator Review on 25th, Feb.

Summary

2021c runs

- New peak luminosity record and new daily integrated luminosity. Achieved base plan of the luminosity profile (despite the difficulties coming from LER injection kicker accidental fires).
- Energy scan (10.657, 10.706, 10.751, 10.810 GeV)
- Established the procedure to increase beam current safely. Performed physics run over 1A of LER.
- Improved HER injection efficiency.
- Initial trial of correction of chromatic R1' using rotatable sextupoles. Good response have been achieved.
- A new mystery on the TMCI related ? vertical beam size blowup.
  - Planned continuous study on the transverse impedance around QCS
- (Frequent) Accidental fire of LER injection kicker.
  - Counter measure: Double kicker system and robust beam collimator (made of carbon)

2022a/b run

- We will continue physics run aiming higher luminosity and stable data taking, in parallel with necessary beam studies for improving luminosities, for investigating various challenges, and for finding effective upgrade plans in the future (LS1 and LS2).
  - Evaluation of transverse impedance, especially around QCS.
  - Correction of chromatic couplings (R1' and R2') using rotatable sextupoles.
  - Betatron tune search.
  - Beam injection improvements, stability.
  - BT emittance blowup.
  - Squeezing of beta_y* (0.8 mm at first). Check the beam background.
  - Higher bunch / total beam current. etc..

International Task Force

- Very actively working with devoted international cooperation.
- Mid-term review is scheduled on 25/Feb.