SuperKEKB Status and plan

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  - Achievements
  - Challenges
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- LINAC Summary
- LS1
- Summary

Makoto Tobiyama, Mika Masuzawa
Accelerator Laboratory

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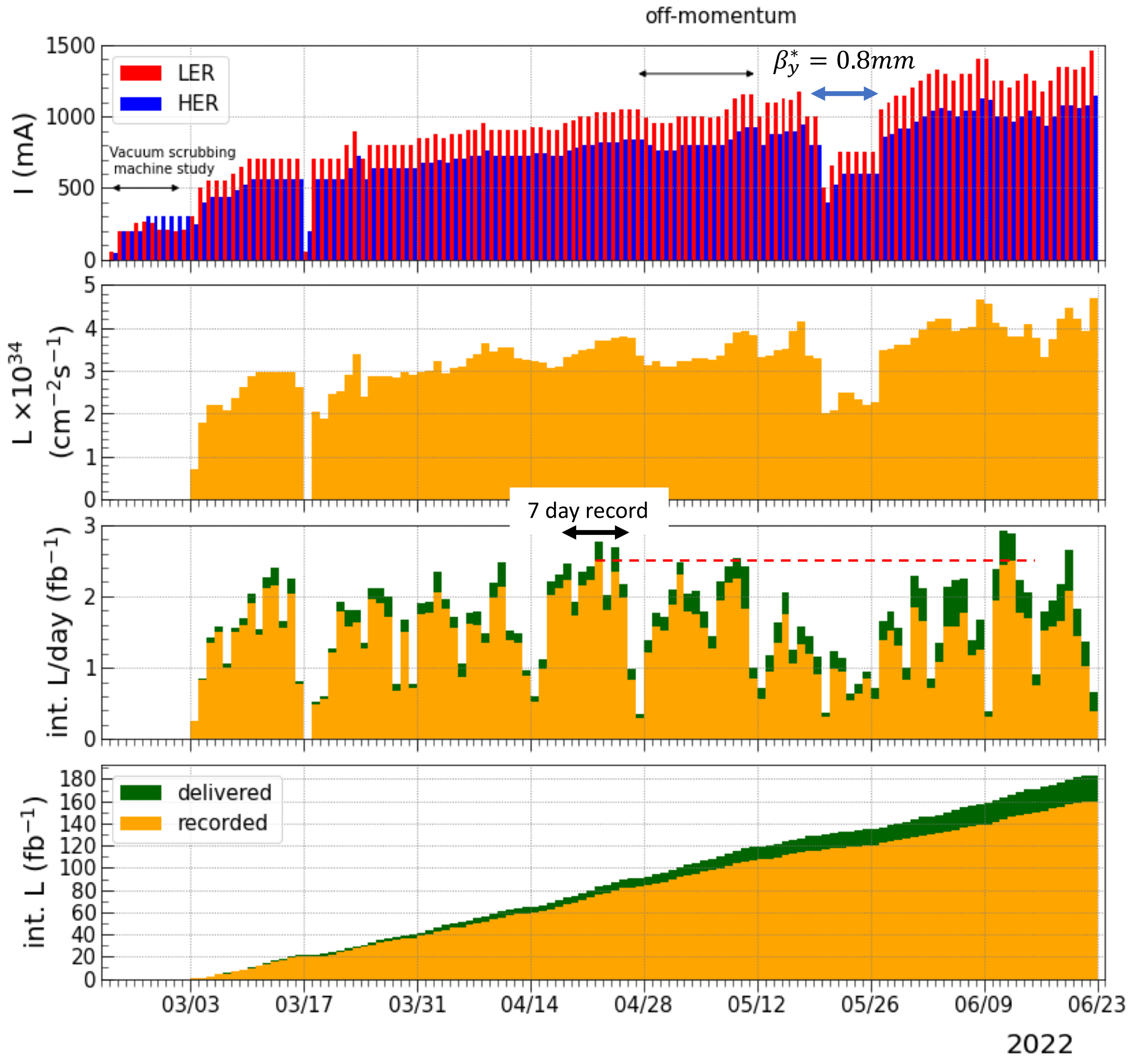
2022ab Run



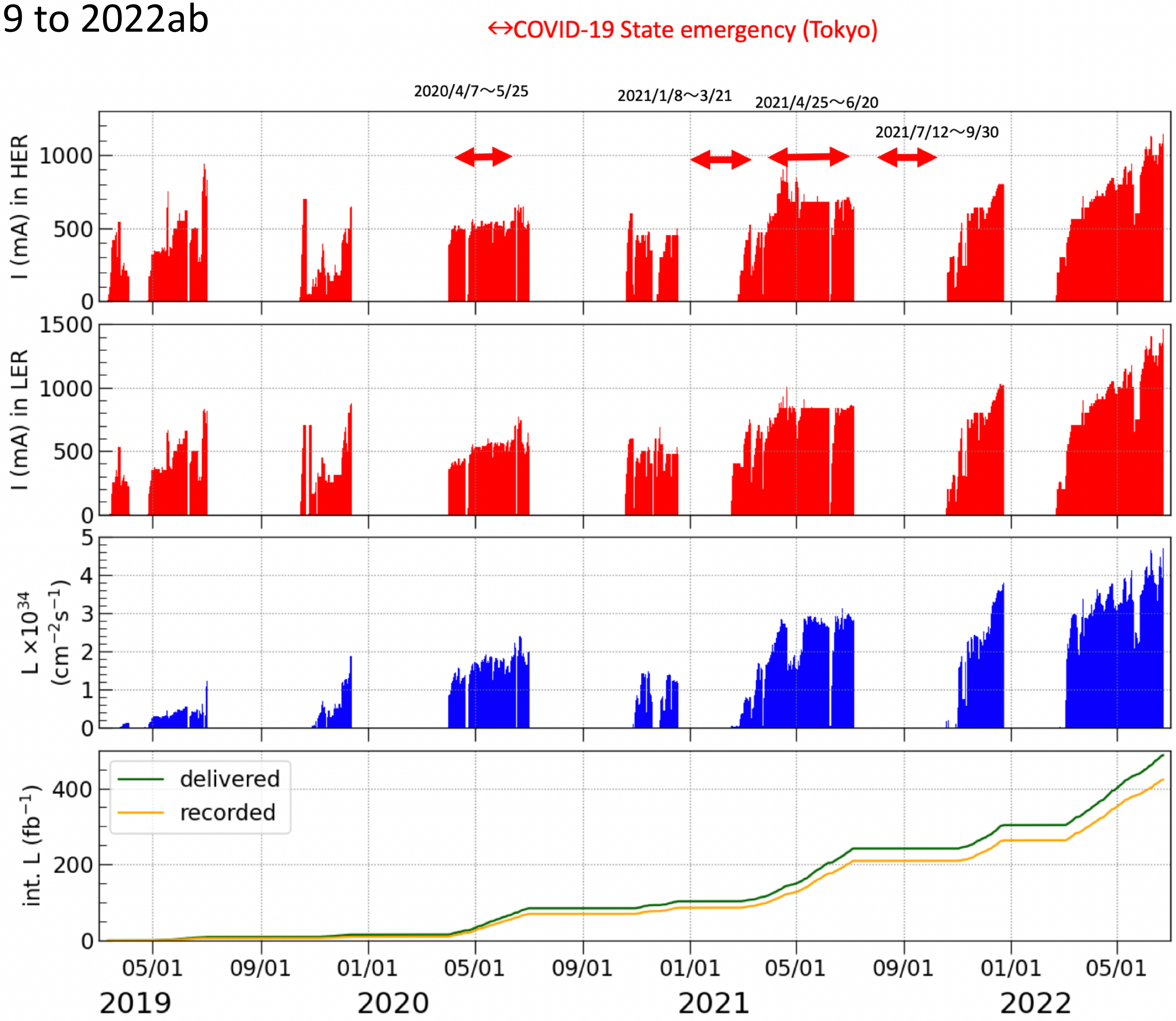
Achievements

- 1460mA in LER, 1143mA in HER
- \# of bunches was increased to 2346 (2 bucket spacing)
- Peak luminosity 4.65×10^{34} cm^2s^{-1} , 4.71×10^{34} cm^2s^{-1} (Belle HV off)
- Stable operation at higher beam currents
- 1.3A or more in LER seemed less stable but we managed to run the machine at 1.4 A at the end.
- Confirmed specific luminosity increase when $\beta_y^* = 0.8\ mm$

Integrated luminosity	Recorded	Date	Delivered	Date
Shift (pb^{-1})	958.1	April 24, swing, 2022	1035.9	April 22, swing, 2022
1 days (fb^{-1})	2.503	April 22, 2022	2.912	June 11, 2022
7 days (fb^{-1})	15.001	April 18 - April 24, 2022	16.599	April 18 - April 24, 2022

- Integrated luminosity ~160 fb^{-1}

From 2019 to 2022ab

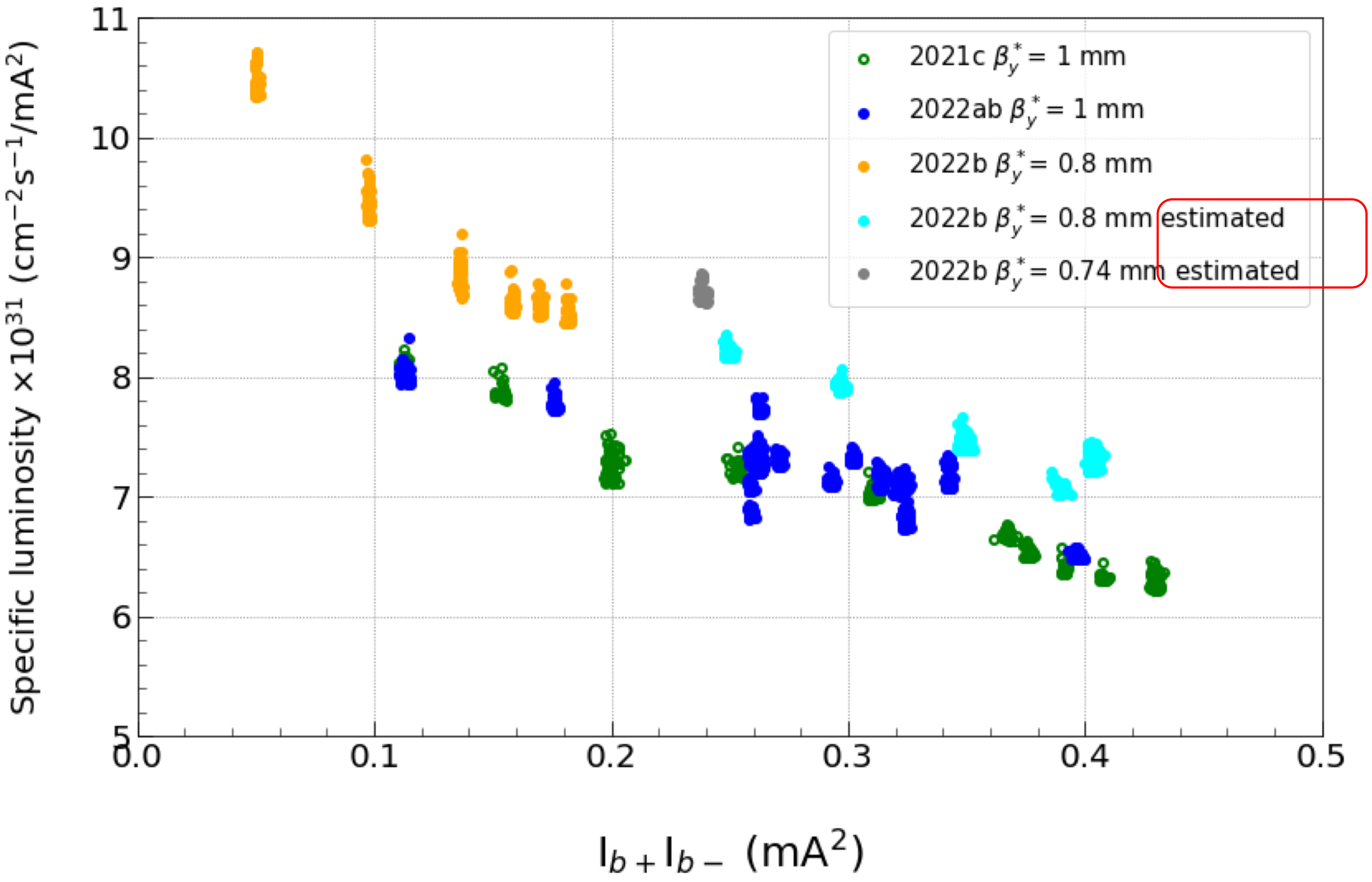


COVID-19
There were tough times
- No face-to-face meetings
- Minimum number of people in the control room required
- Travel restrictions

Now we are facing new problems
- rising electricity
- delay/stop in supply-chain

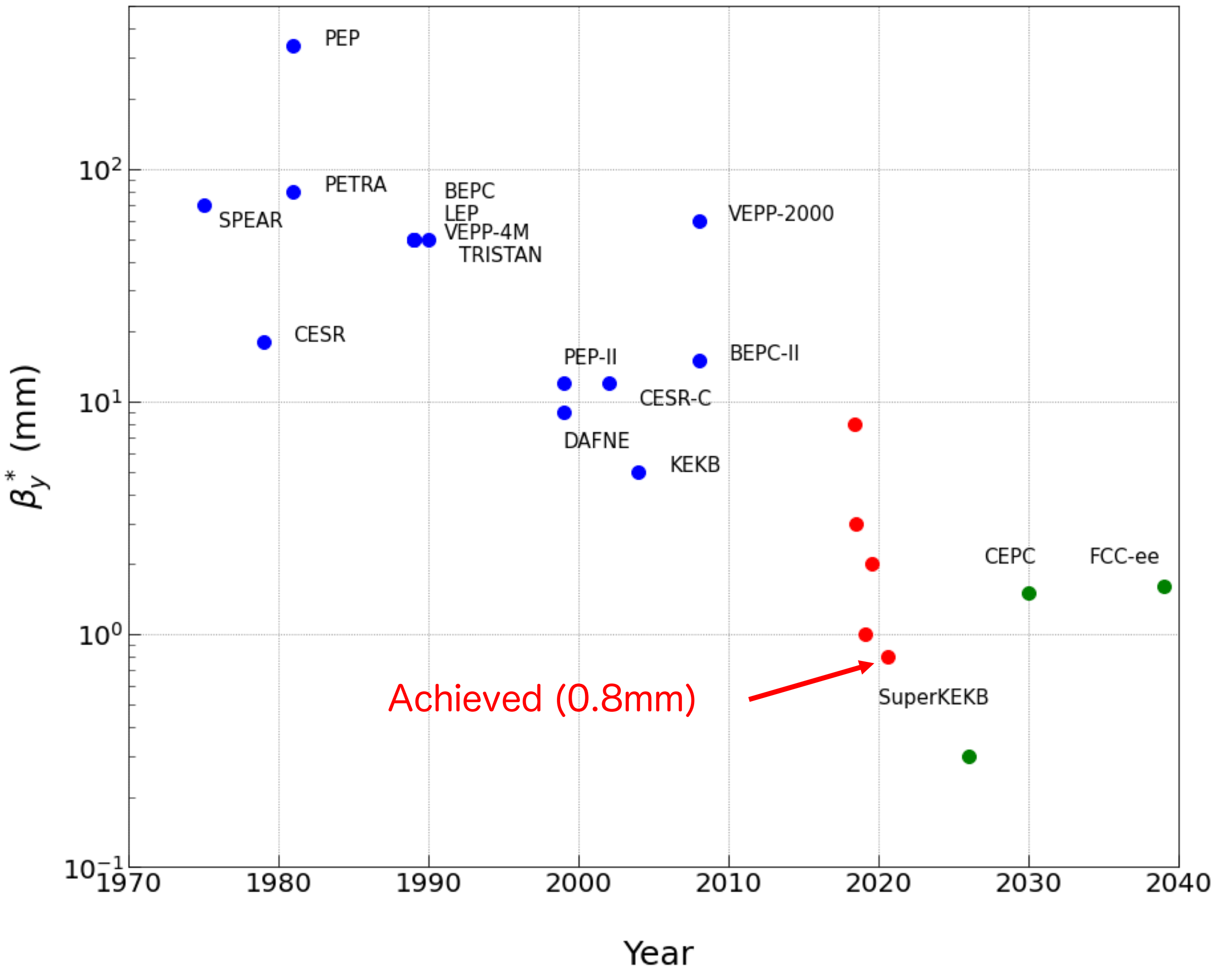
Integrated recorded luminosity ~428 fb^{-1}
Corresponds to ~ 40% of BELLE data

Specific luminosity



"estimated" explained later

Vertical beta function at the IP β_y^*



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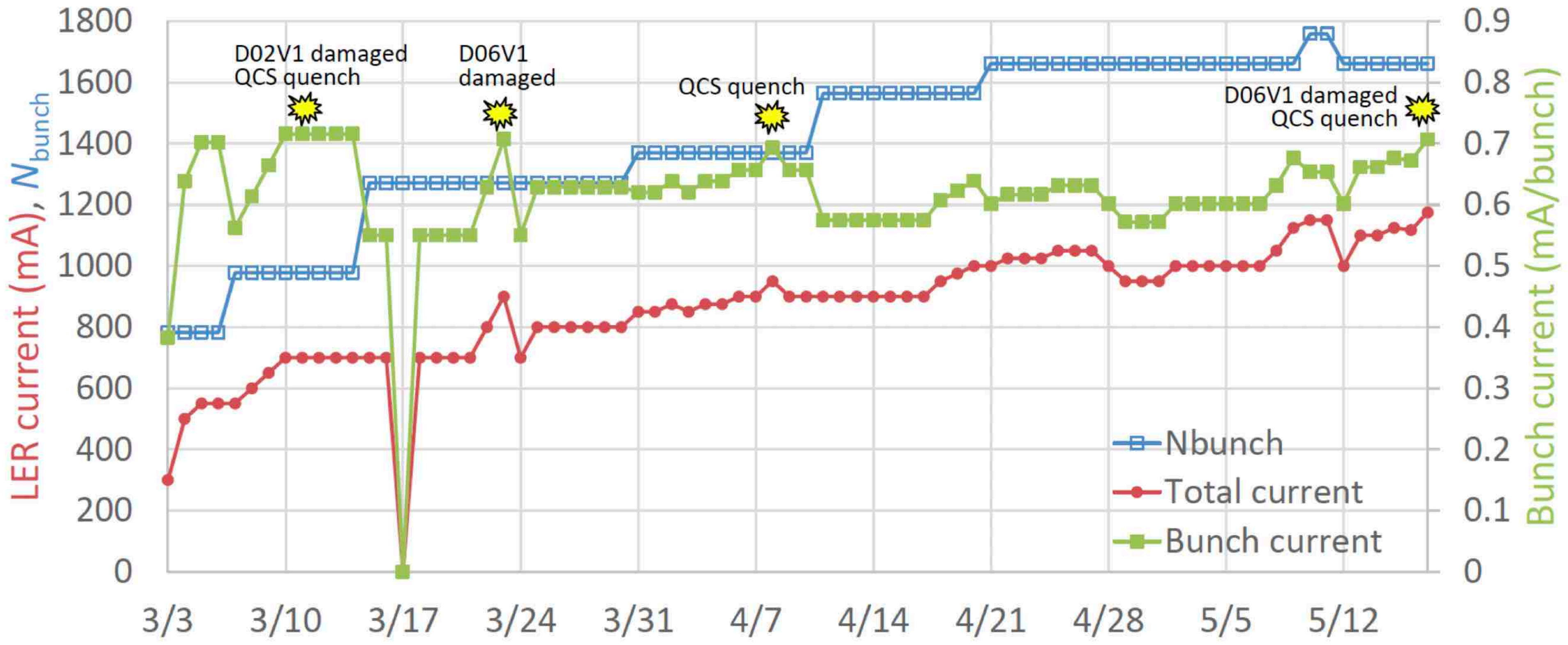
Challenges : Fast and large beam losses

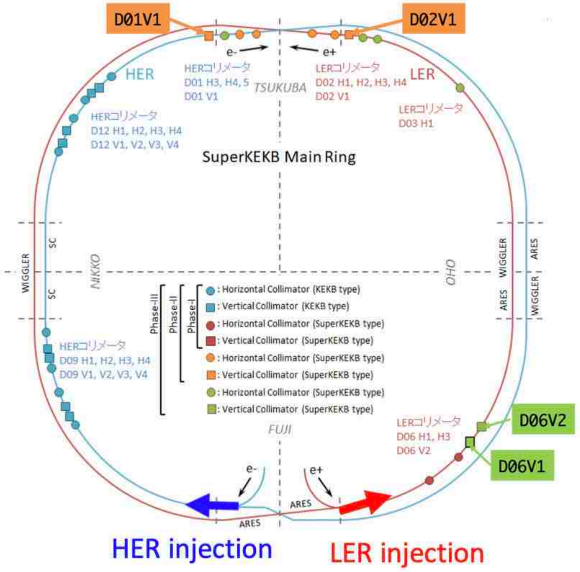
- Observations
  - Fast and large beam losses within 3 turns, particularly in LER are observed.
  - These losses cause collimator damage and QCS quench.
  - Empirical rule: Bunch current $I_b^{\pm}$ must not exceed 0.7mA “Matsuoka rule”.
    - We had to increase beam currents with $I_b^{\pm}$ lower than 0.7mA.

- Mechanism
  - Not really understood.
    - Some hypotheses, simulations → need to be verified.
    - A joint Belle2-SuperKEKB team has been organized (https://kds.kek.jp/event/41394/contributions/209334/attachments/154298/195935/16aA561-03.pdf)
    - Within the framework of ITF (H. Ikeda and H. Nakayama) ?

Y. Funakoshi, IPAC’22

Matsuoka rule, well categorized by Matsuoka-san

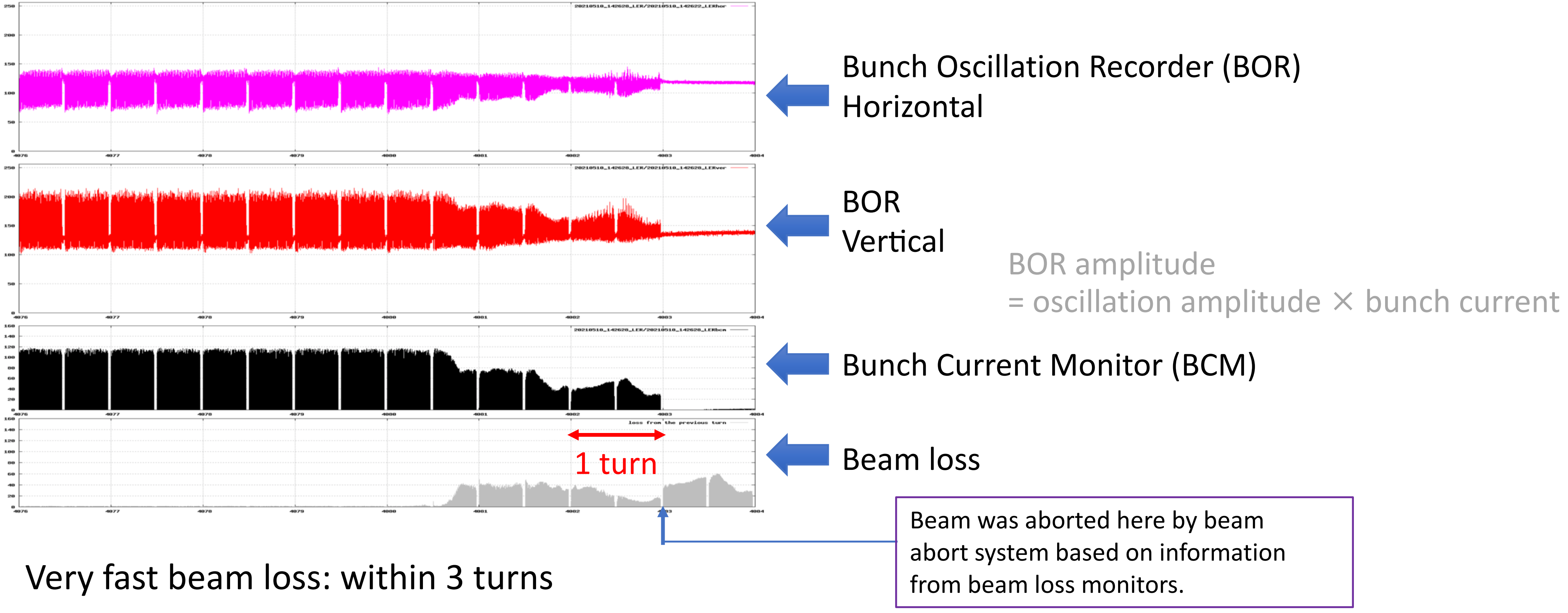




In the case of a small number of bunches (N_b= 793, I_t^+ =61mA, I_t^- = 31mA) we could exceed this limit.
Large beam loss in LER happened even within the limit (I_b^+~0.62mA) when the total beam current I_t^+~ 1325mA.

Challenges : Fast and large beam losses

An example



- 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.

Y. Funakoshi, IPAC'22

Challenges with Injection (more later)

- SuperKEKB injection scheme
  - 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 Beam Transport line (BT) is important.

K. Furukawa, IPAC'22

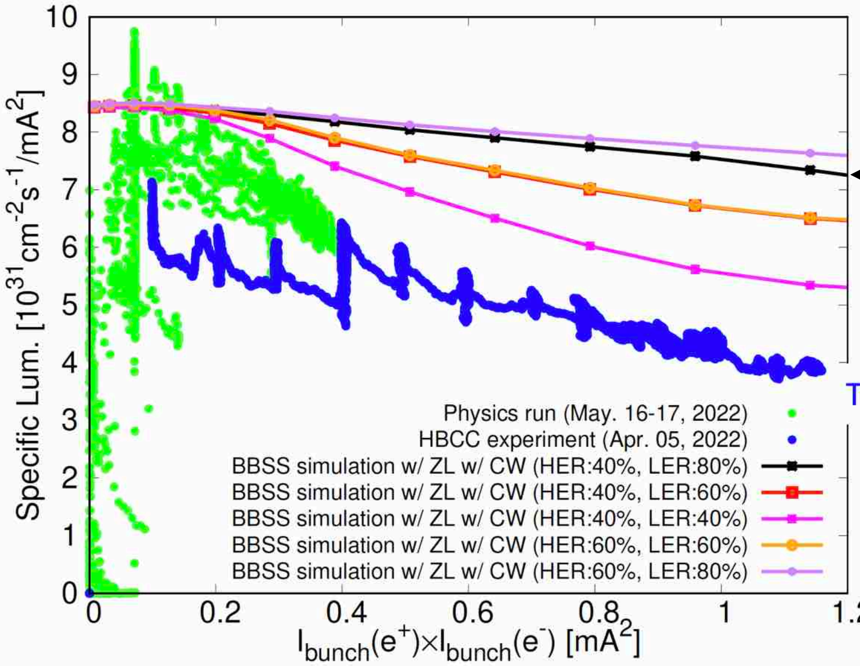
Challenges , beam-beam

- Luminosity is much lower than simulations with BBSS (Beam-Beam Strong-Strong)
- Possible Cause
  - Machine imperfections:
    - Non-zero linear and chromatic coupling and dispersions at IP, can be corrected by skew sextupole field.
    - Optics degradation at higher beam current due to orbit changes at QCS* and SLY*, etc . ← Will explain later
  - 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% (???)

D. Zhou, IPAC’22

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



HER 40%, LER 80% is here

Tried briefly

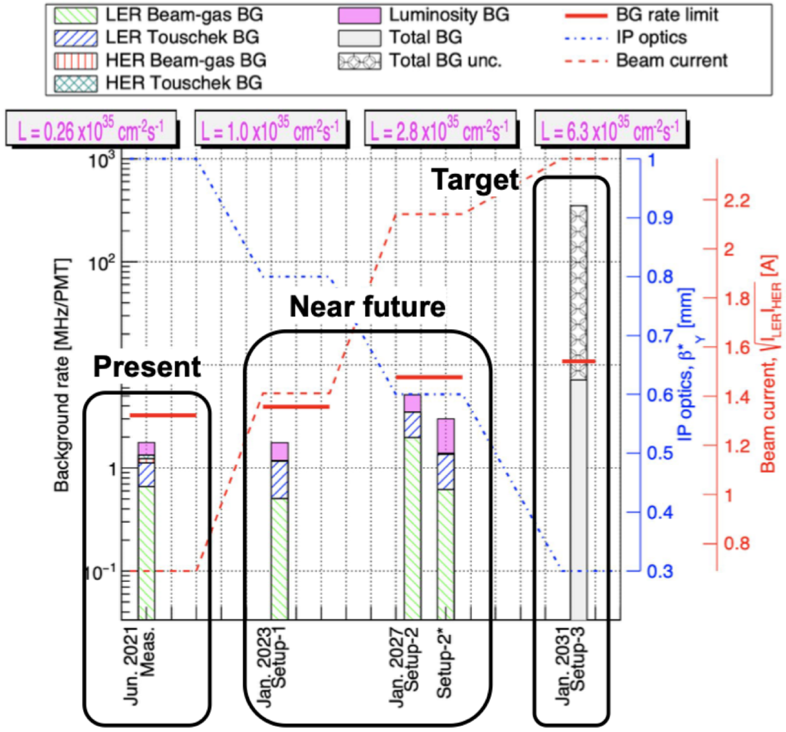
Y. Funakoshi, IPAC’22

Challenges , collimator issues

LER TMCI (Transverse Mode Coupling Instability)
The apertures of vertical collimators ↔TMCI
TMCI threshold will be lower than the design bunch current of 1.44mA when $\beta_y^* \leq 0.6$mm.
Non-linear collimator may help to increase the limit and to reduce the BELLE II BG.

Background status and evolution

- Current background rates in Belle II are well below limits, see Figure
  - There is margin for injection backgrounds and unexpected problems
- Backgrounds will remain high but acceptable until a luminosity of at least 2.8 x10^{35} $cm^{-2}s^{-1}$ is reached
- The total background at target luminosity is very uncertain due to
  - Future IR redesign *(under discussion)*
  - Unexpected IR beam pipe contribution to beam instabilities *(under investigation)*



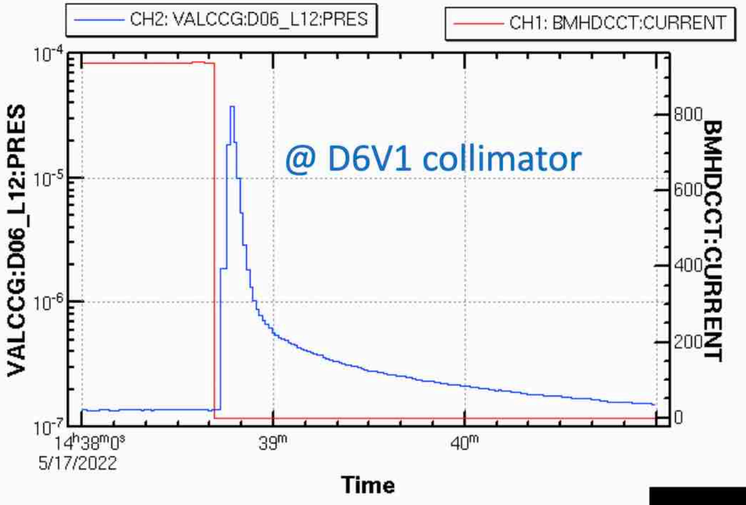
Measured and predicted beam background hit rates in the Belle II TOP detector, for various machine configurations. These PMTs are expected to be the detector components most vulnerable to beam backgrounds.

7
Andrii Natochii

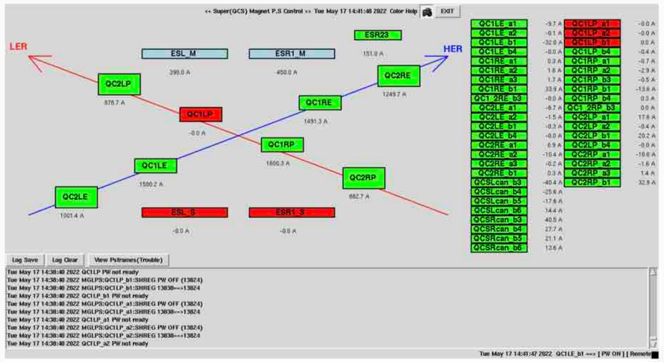
Challenges , collimator damages

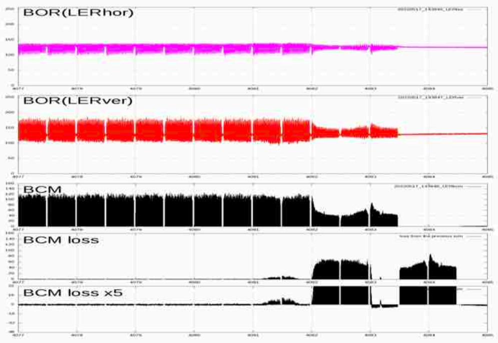
Collimator damage of D06V1, D02V1, and D09V1: Impedance increases ?

An example
May 17, 14:38:40 HER/LER abort



QCS quench





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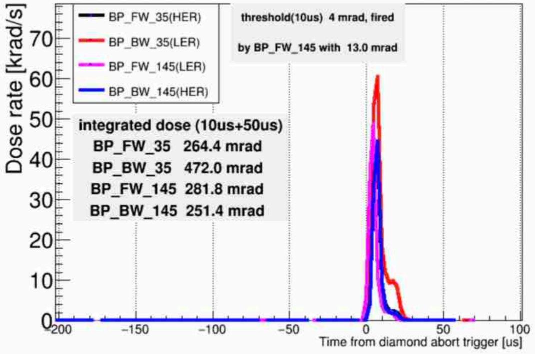
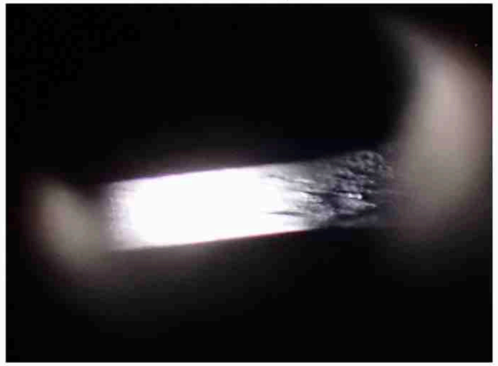


D06V1 bottom

beam

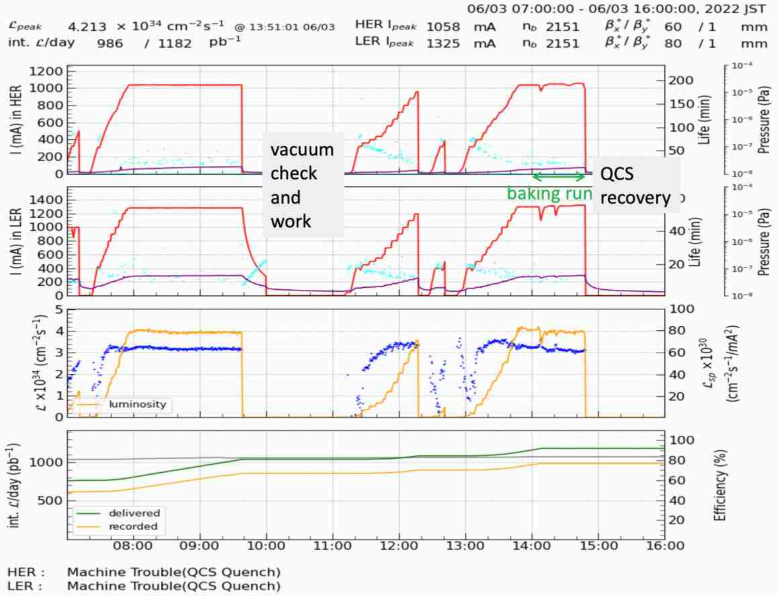
D06V1 top



beam

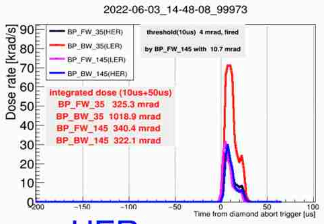
Challenges , collimator damages

6-03 14:48 QCS quench

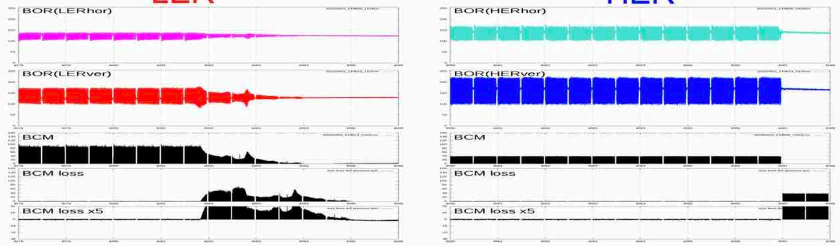


Abort 4-2 14:48:08

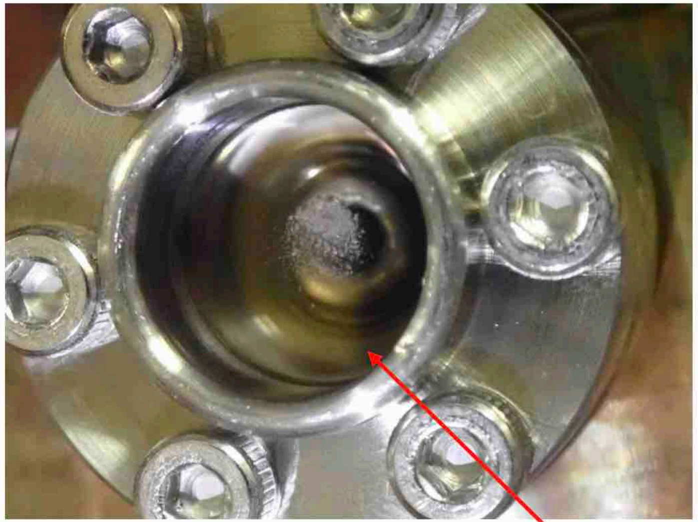
RING: both
Source: Belle2CLAWS+diamond
Currents: 989 + 1323 mA, 2151 bunch(noBelleHV)
Rads: 117 + 129 mRad/s
Pres. burst: ccg -25s(D02_L17)
(QLX1RP.2/BLX4RP.2/BLX2RP.2)

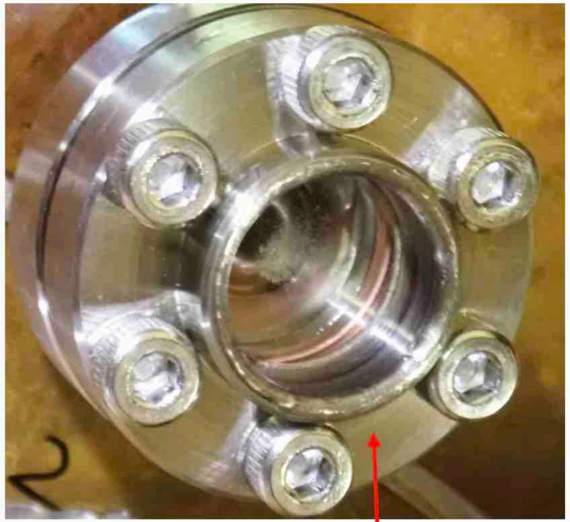


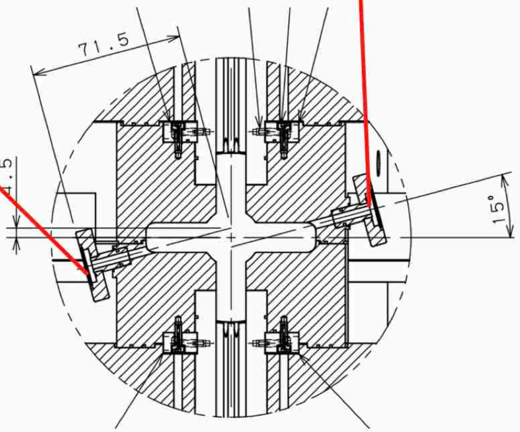
LER HER



D02V1 Ta deposition on the view port, collimator damage







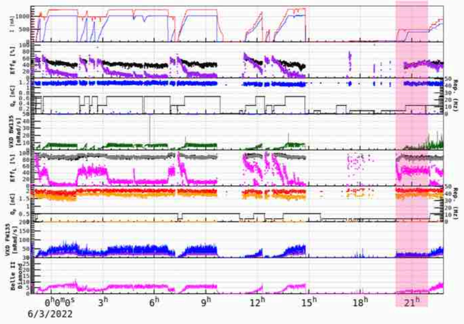
Collimator tuning needed to be done after
(K.Yoshihara et al)

Summary

D02V1TOP: 0.95 -> 1.15
D02V1BTM: -1.05 -> -1.25
D06V2: 2.8 -> 2.2

D09V1: -1.76 -> -1.80
D09V3: -1.57 -> 1.74
D09H2: -15 -> -16
D09H1: -10 -> -12

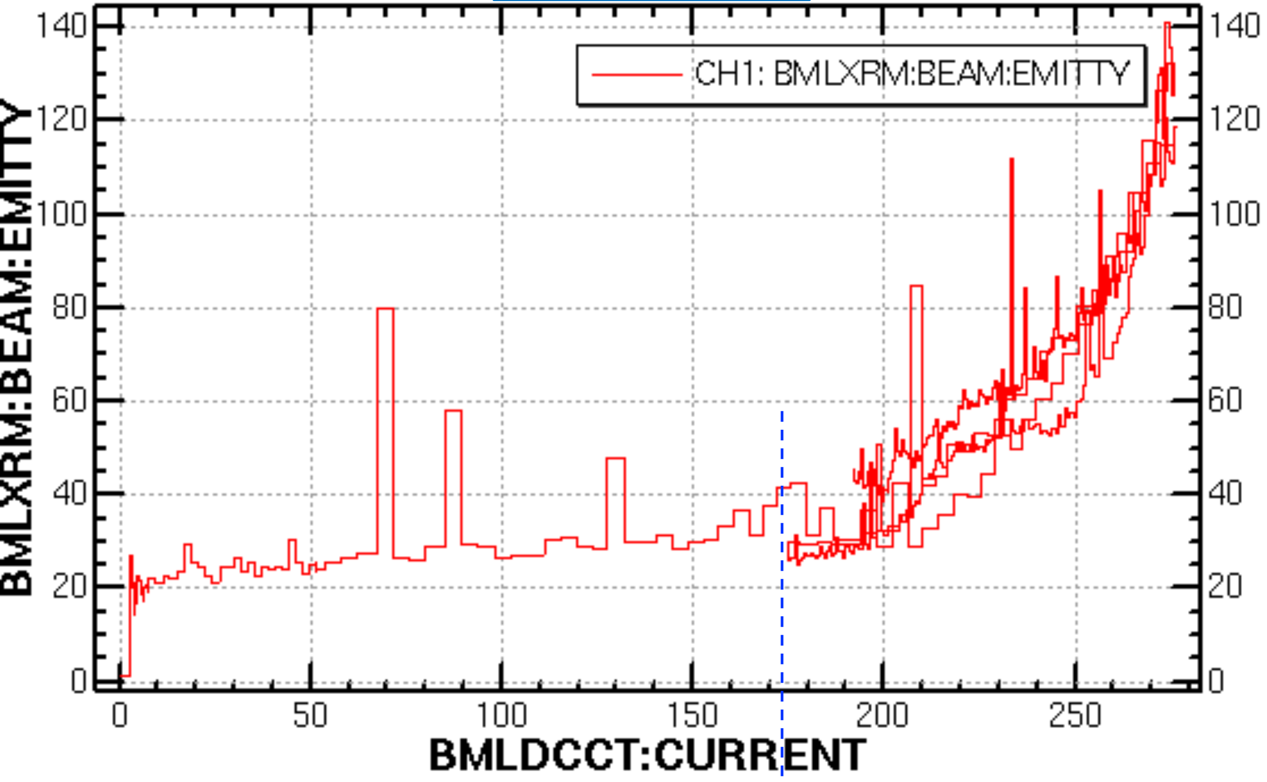
collimator tuning



LER vertical beam size blowup study, the effect of the damaged D06V1 collimator on June 21

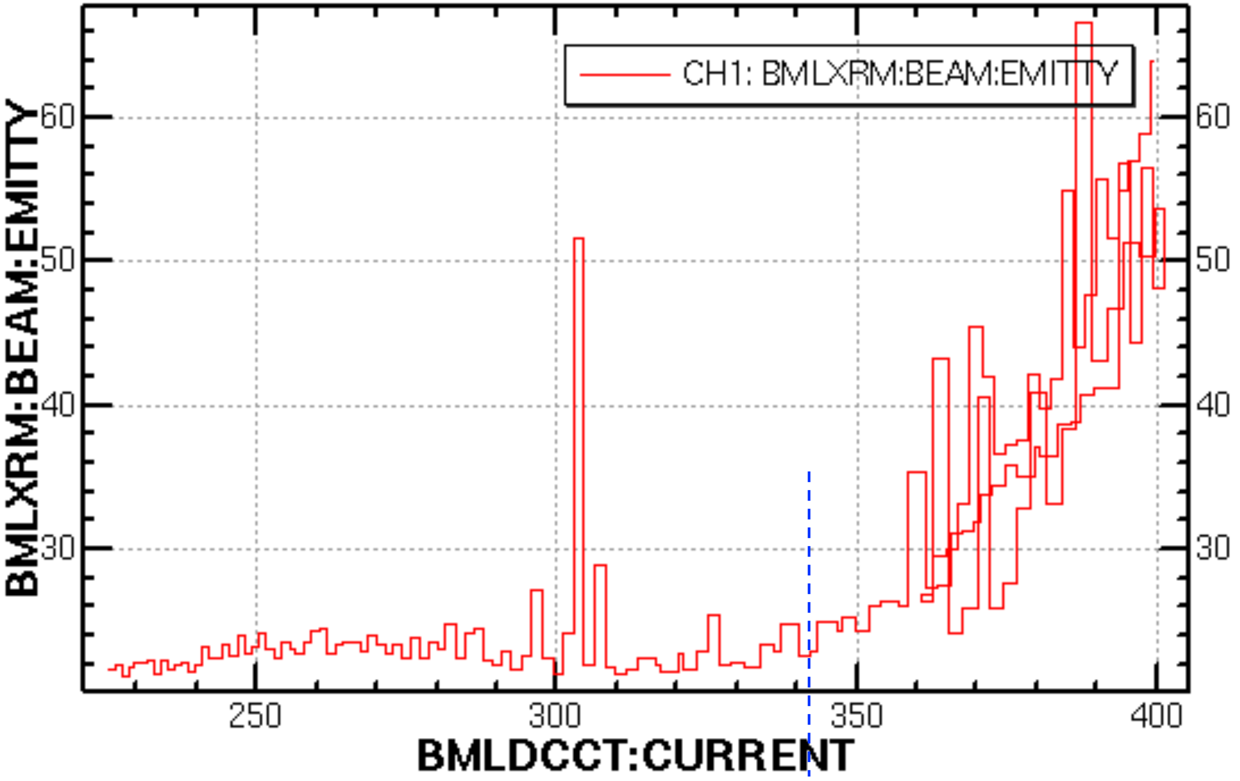
When D06V1 collimator bottom was opened, the emittance threshold increased,
Indication that the collimator damage resulted in an impedance increase…

BTM -5.1 mm → BTM -8 mm



393 bunches
V-tune : .5820 -> .5950
D6V1 TOP 4.2 mm

$I_b^+ \sim$ 0.5mA/bunch

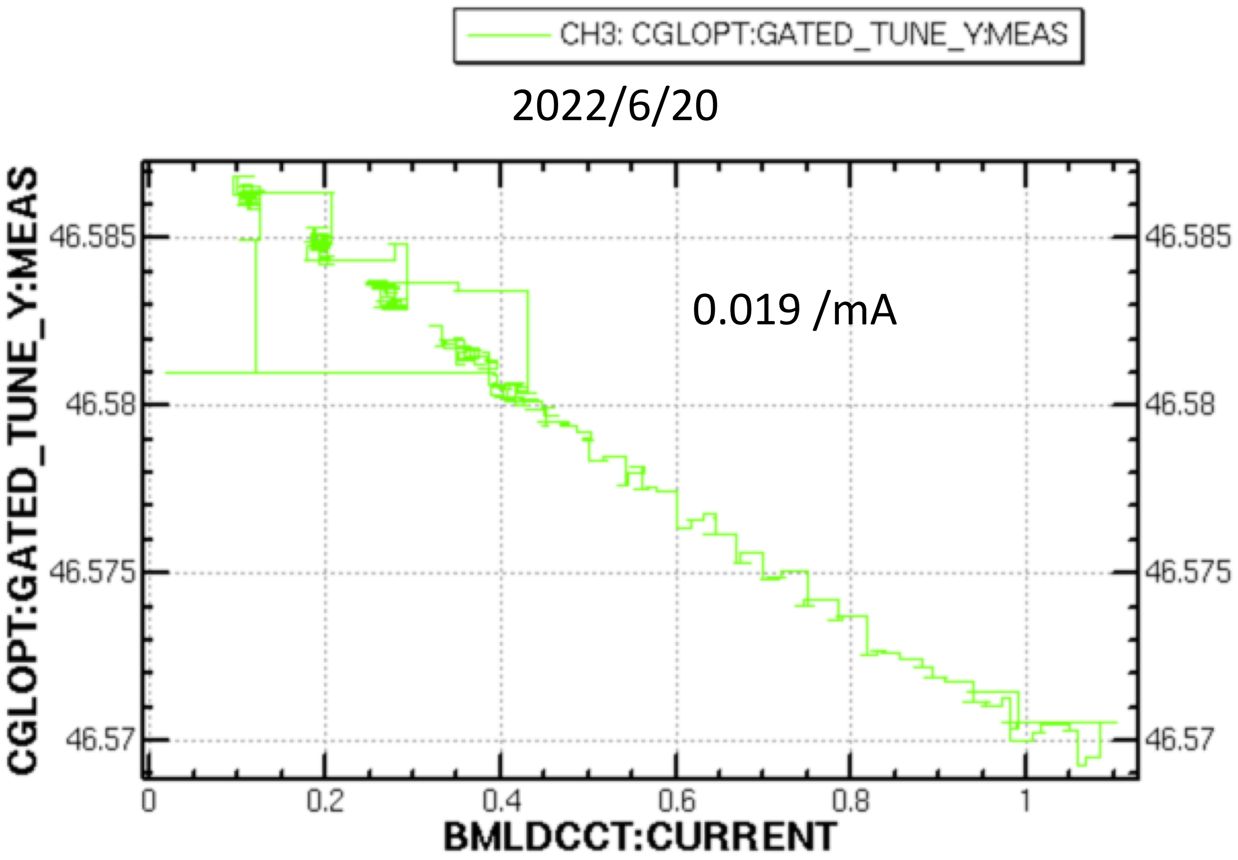


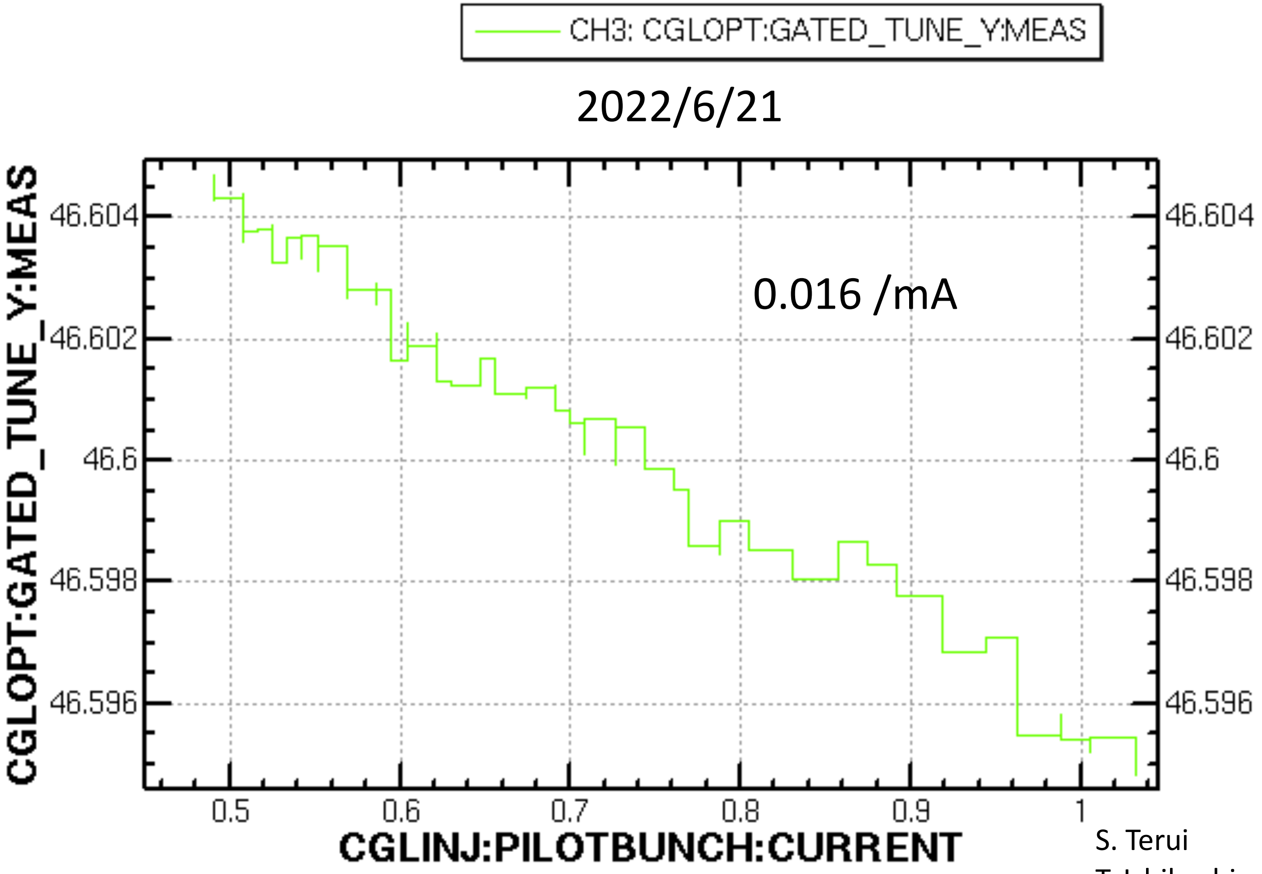
$I_b^+ \sim$ 0.87mA/bunch

Study by
S. Terui
T. Ishibashi
K. Yoshihara

LER vertical beam size blowup study, the effect of the damaged D06V1 collimator on June 21

When D06V1 collimator bottom was opened, tune shift became smaller,
Indication that the collimator damage resulted in a larger tune shift.

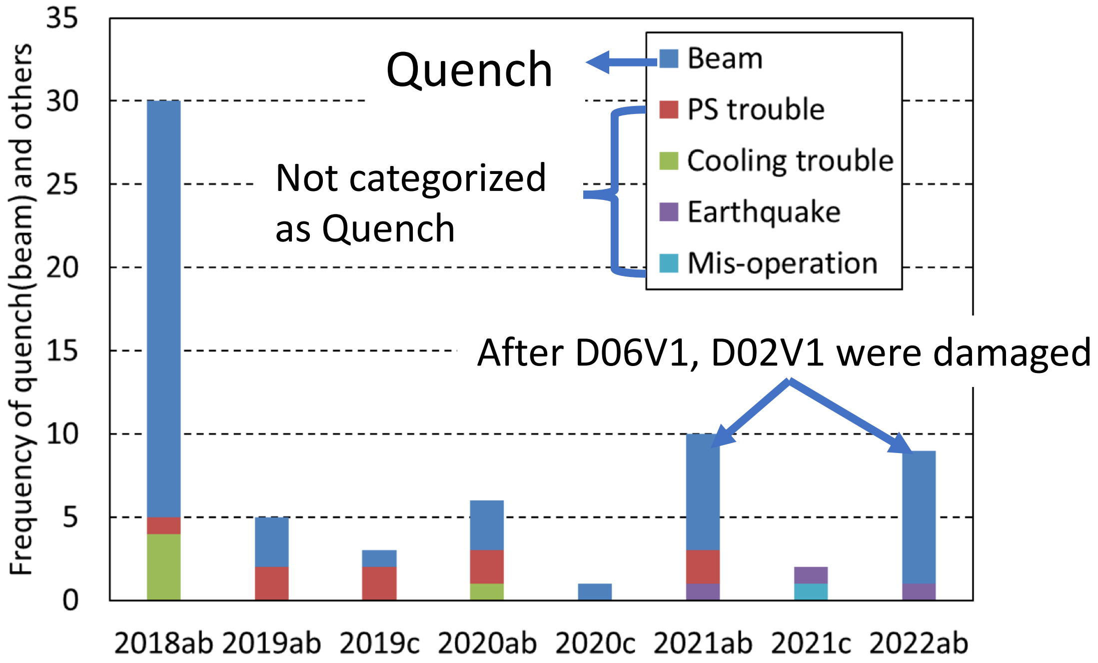


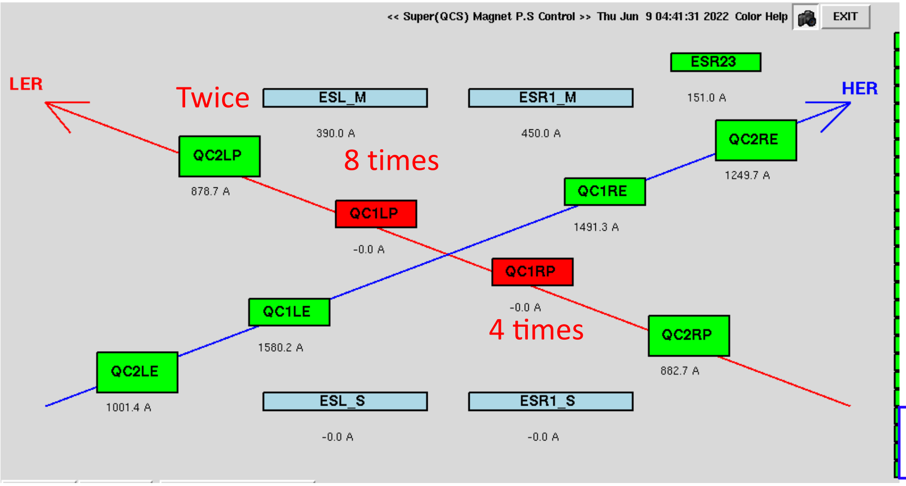


S. Terui
T. Ishibashi

2022ab QCS Quench Summary

Date	Where	Cause of Abort
2022.3.11 10：08	QC1LP（all coil) QC2LP	beam loss (CLAWS+Dia.)
2022.3.16 23：35	Not known	Earthquake
2022.4.8 11：55	QC1LP（coil 2)	beam loss (CLAWS+Dia.)
2022.5.17 14：38	QC1LP（coil1,2,4)	beam loss (CLAWS+Dia.)
2022.6.1 22：05	QC1RP（coil1,2) QC1LP（coil1,2)	beam loss (CLAWS+Dia.)
2022.6.3 14：48	QC1LP（all coil) QC2LP	beam loss (CLAWS+Dia.)
2022.6.9 00：37	QC1RP（coil1,2) QC1LP（coil1,2)	beam loss (CLAWS+Dia.)
2022.6.9 04：26	QC1RP（coil1,2,3) QC1LP（all coil)	beam loss (CLAWS+Dia.)
2022.6.14 14：34	QC1RP QC1LP（coil1,2,4)	beam loss (CLAWS+Dia.)



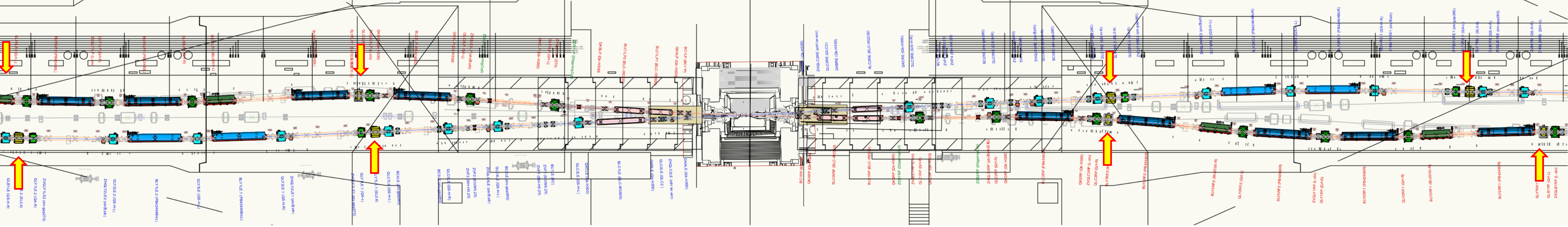


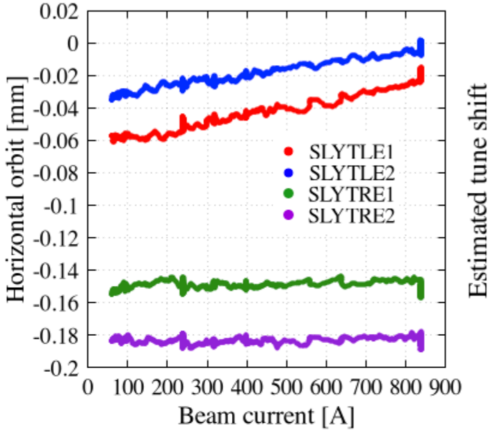
Wang Xudong

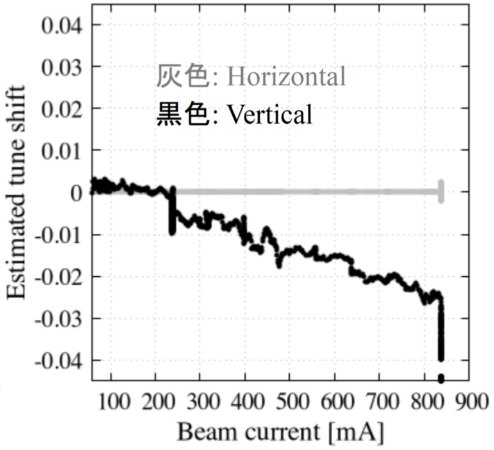
Challenges , Optics degradation at higher beam currents

Orbit control (to the level of μm) at sextupole magnets, especially at Local Chromaticity Correction (LCC) section is critical

SLY magnets







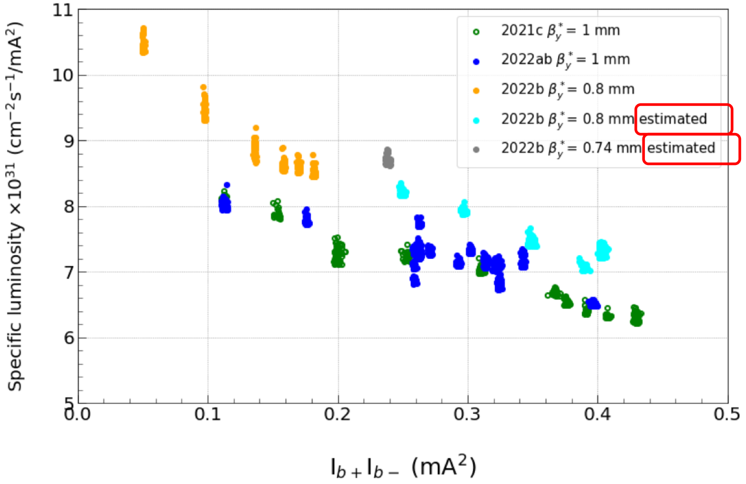
H. Sugimoto

An orbital change of 40 μm results in a vertical tune shift of about 0.025.

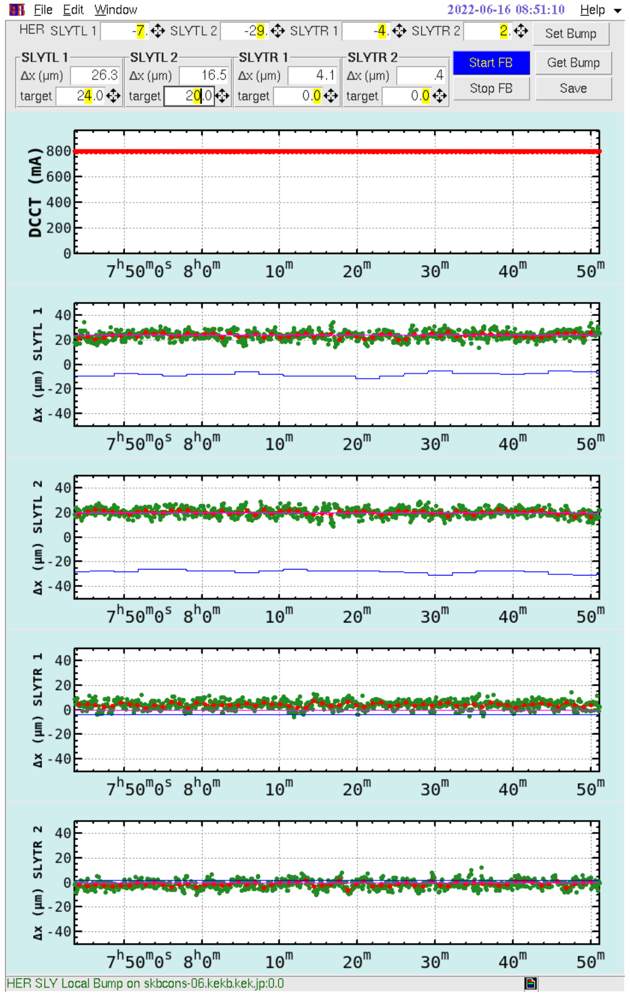
Tune Feed back keeps the tune at the target tune but the orbit at LCC sextupole mangnets is not controlled to the level of μm.

This results in a beta beat in the entire ring (optics degradation).

β_y^* was estimated to become smaller with these orbit change than when the optics were corrected at lower beam current (~50mA).



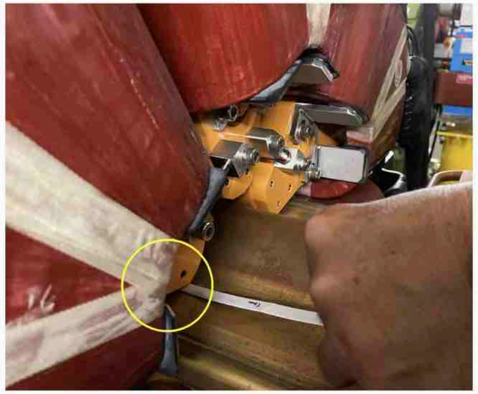
Challenges , Optics degradation at higher beam currents

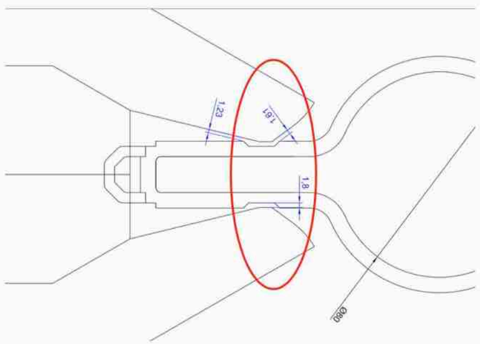


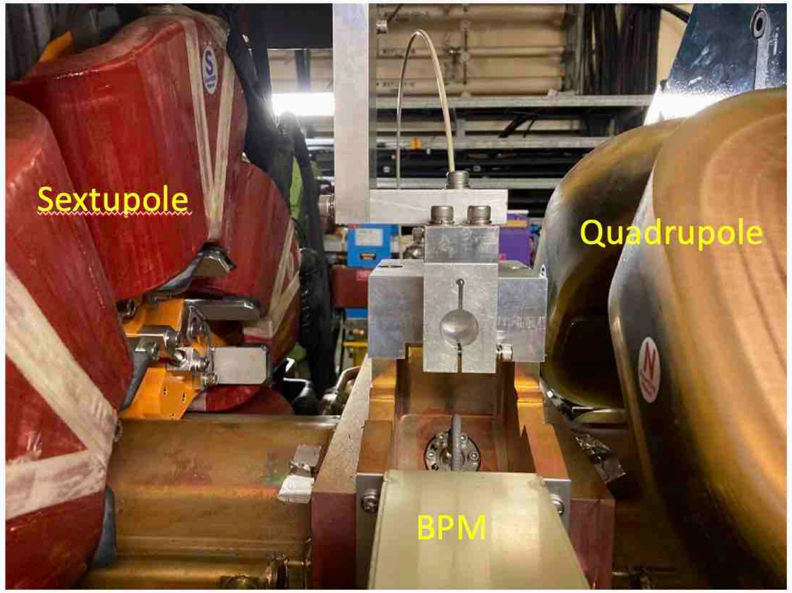
Changing the bump height (blue line) to keep the orbit constant

Orbit control feedback was introduced (Y. Ohnishi).

- But why orbit changes as a function of beam current?
- Duct move due to SR?
- Sextupole magnet moves with respect to the quad (BPM is attached to quad)
- What is moving wrt to what?
- Under investigation.



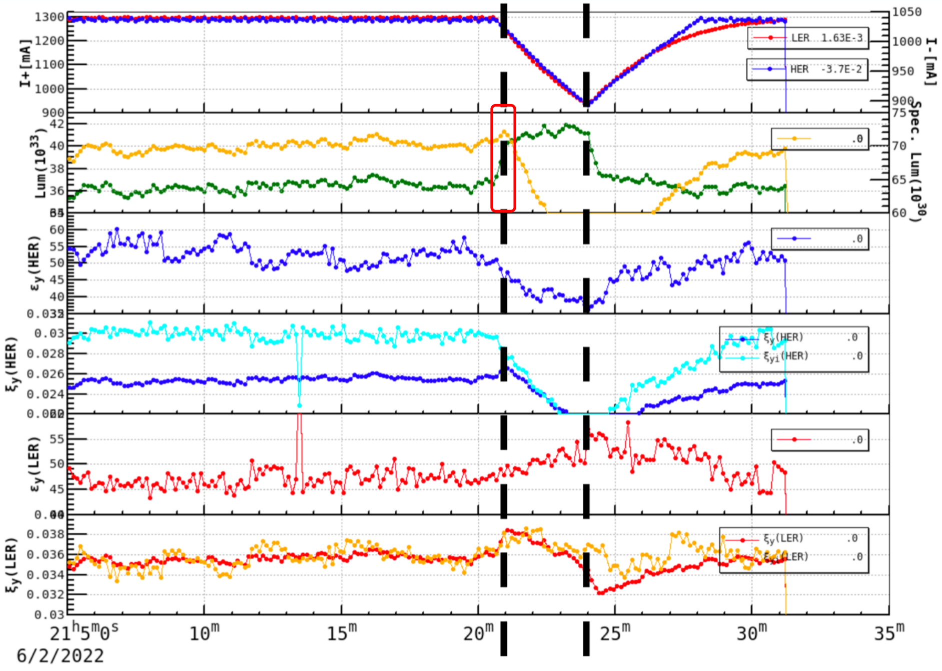


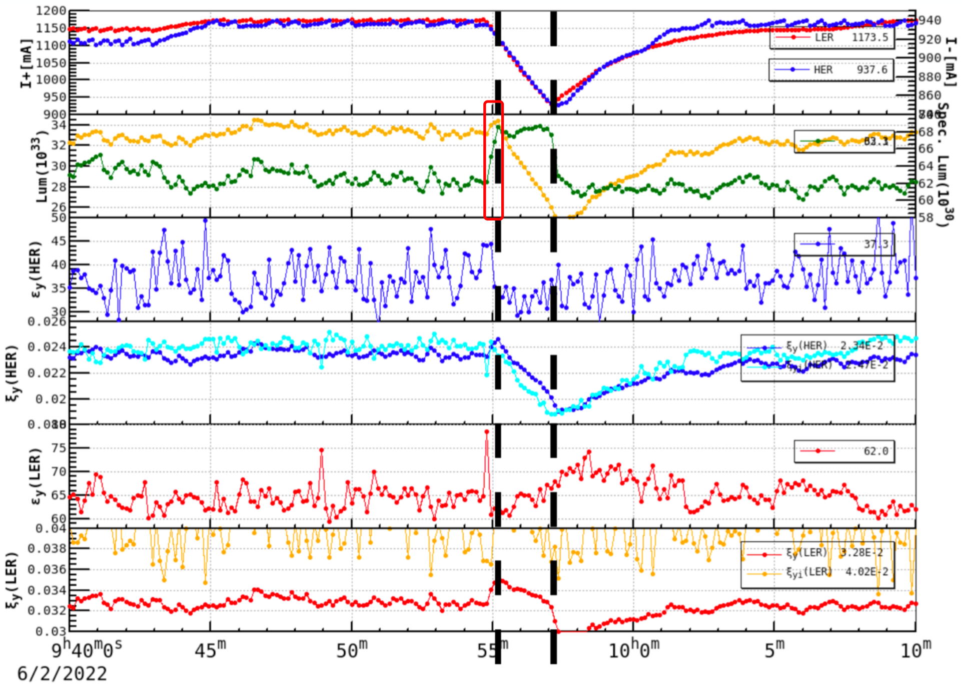


Beam oscillation excited by injection kickers at LER causes luminosity loss by ~10% (???)

Lsp-Injection correlation

- Careful analysis of KBlog data shows this phenomenon has always been there (since Phase-2)
  - Lsp degradation (by about 10%) due to injection has been clearly observed.
  - A sudden increase of Lsp causes a local peak luminosity. This is why we frequently saw the best luminosity just after injection.





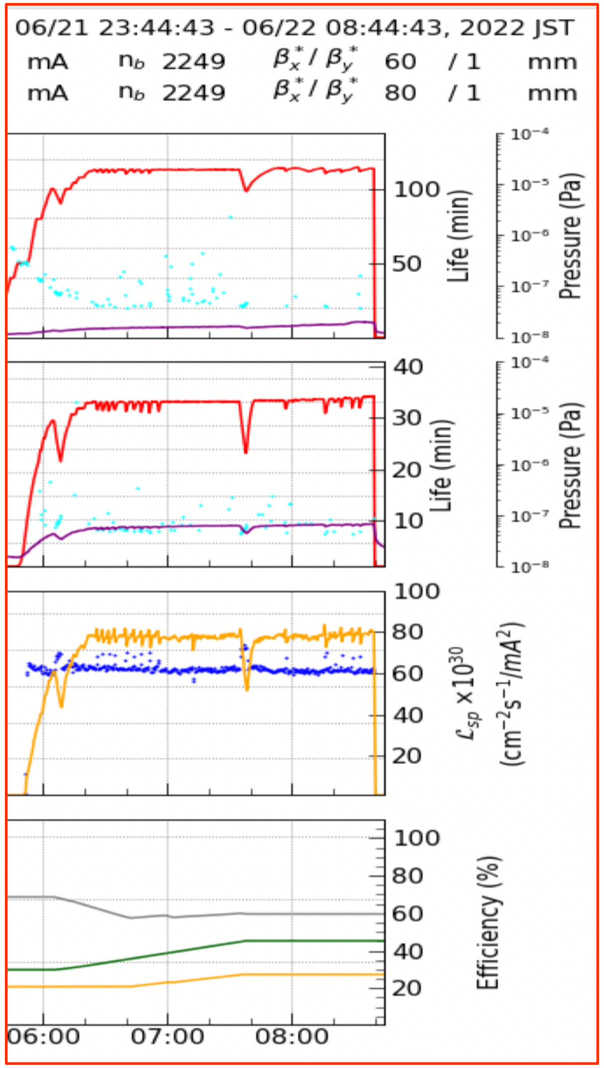
D. Zhou

Beam oscillation excited by injection kickers at LER causes luminosity loss by ~10% (???)

Lsp-Injection correlation

- Summary
  - An increase/decrease of Lsp around the stop/start of LER injection was found.
  - Lsp degradation correlated to injection is by the order of 10% at bunch product of ~0.3 mA^2.
  - It is a geometric luminosity loss/gain from orbit offset, not from beam-size blowup.
  - According to the KBlog data (tracked to 2020a run in this study), it has always been happening.
  - It is not correlated to the non-optimum balance of beam currents I_+/I_- around the stop/start of LER injection.
  - There is no clear evidence of correlation with iBump fast FB.
  - It is not directly correlated with beam-beam interaction, because BB causes emittance growth and then reduces Lsp. If beam-beam plays a role on Lsp, it should be seen in changes of vertical beam sizes.
  - It is confirmed by ZDLM and LumiBelle2 FFT analyses and (Thanks to S. Uehara).
- Hyperthesis
  - Leakage kicks from kickers cause residual orbit oscillation of the stored beams. The horizontal oscillation is coupled to the vertical by coupling. This coupling is amplified by IR (QCS magnets) and LCCs (SLY* magnets). => Most promising candidate.

Needs more investigation



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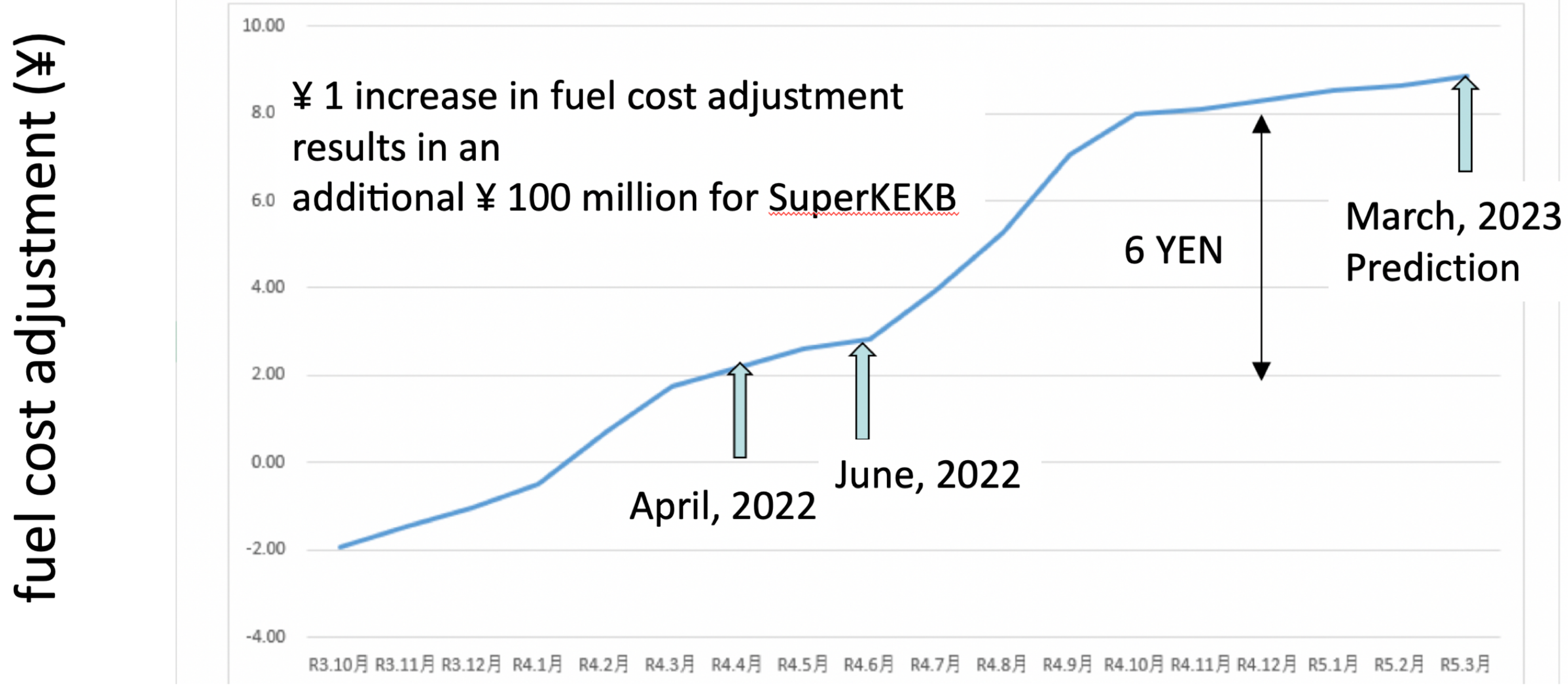
Other issues

Electricity rates

R4燃料調整費推計（KEK試算）　　（単位：円）

	R3.10月	R3.11月	R3.12月	R4.1月	R4.2月	R4.3月	R4.4月	R4.5月	R4.6月	R4.7月	R4.8月	R4.9月	R4.10月	R4.11月	R4.12月	R5.1月	R5.2月	R5.3月	R4年度平均
R4年予測値	-1.94	-1.46	-1.04	-0.51	0.71	1.75	2.17	2.61	2.83	3.96	5.29	7.05	7.99	8.08	8.32	8.53	8.62	8.86	6.19

※R4.7月までは実績。8月以降は推計



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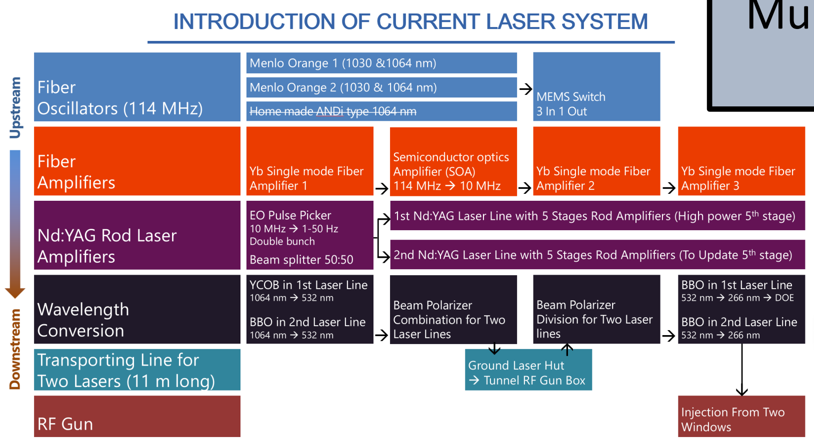
Injector Linac Operation Status presentation material for BPAC 2022

By courtesy of M. Satoh and N. Iida, 2022.06.21

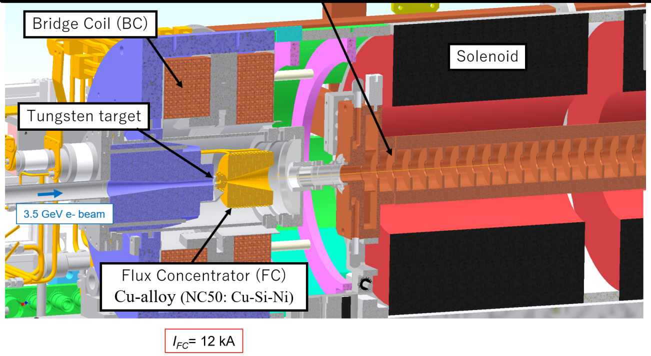
Injector linac operation

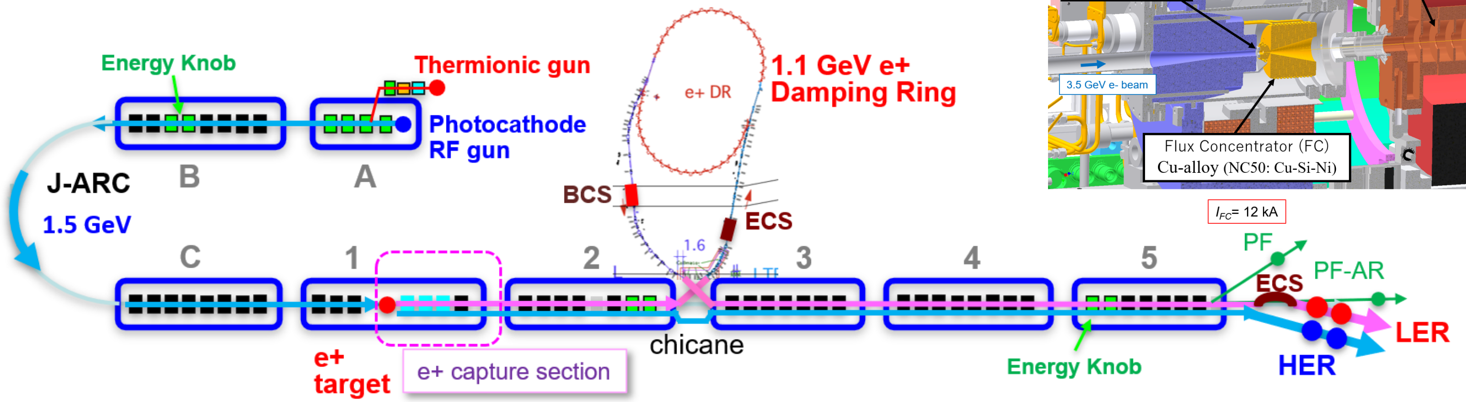
- Simultaneous top-up injection to 4 rings w/ two e- sources (thermionic, rf guns) , and 100 pulsed magnets have been successfully continued.
- Rf gun cavity, laser system, flux concentrator (FC), and other subsystems have been stably operated w/o any significant troubles through run 2022a,b.

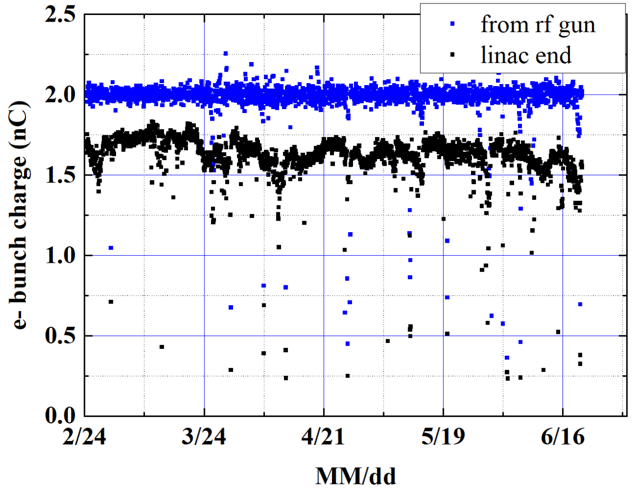
Multi-stage laser system for e- rf gun



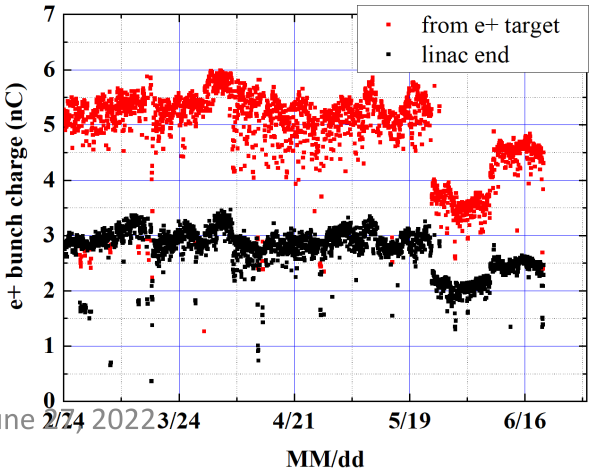
e+ target (W), capture section







- e- bunch charge from rf gun (blue dot) have been kept around 2 nC w/ bunch charge feedback system.



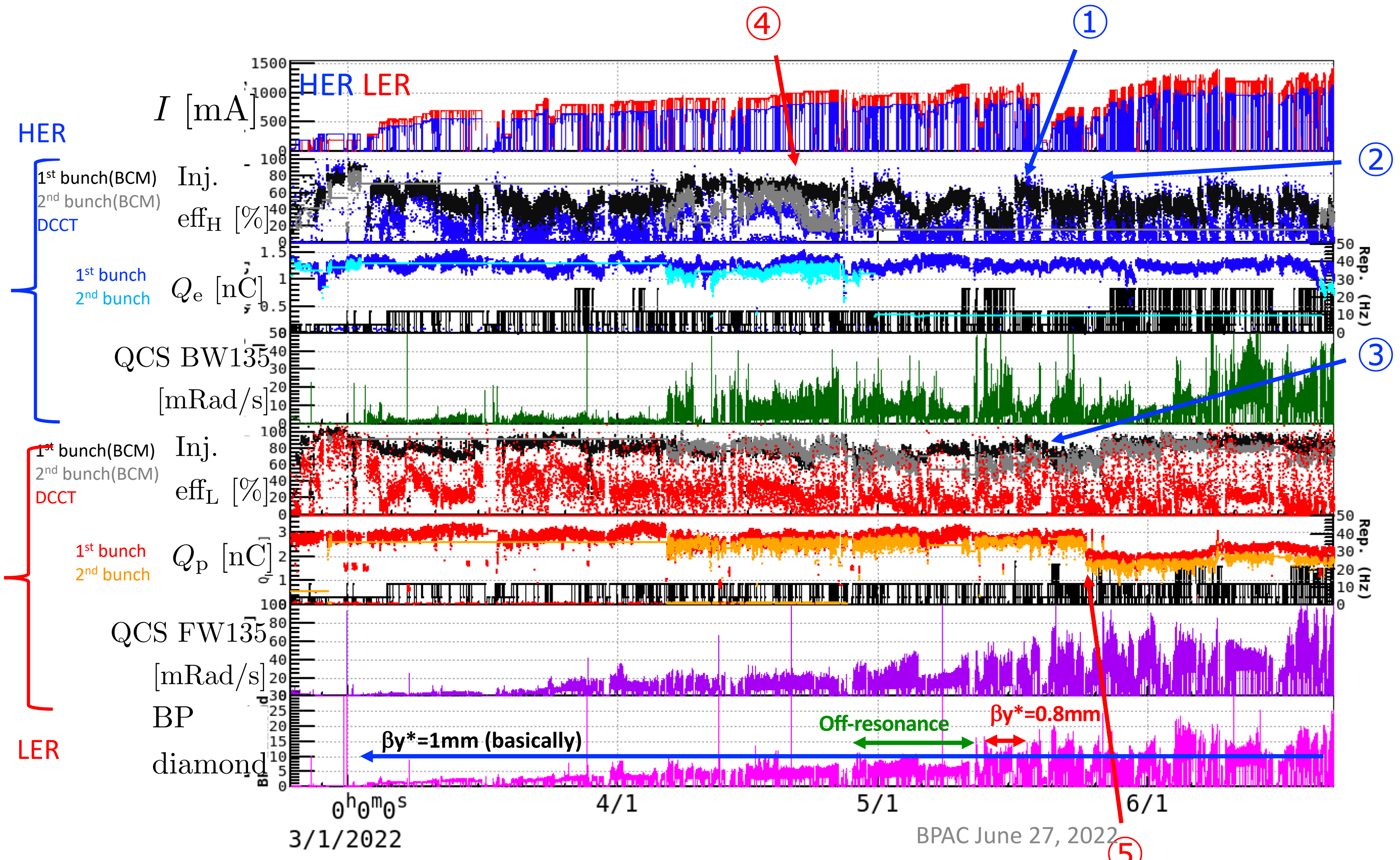
- e+ bunch charge at linac end (black dot) can reach around 3.5 nC (final goal is 4 nC).
- Sometimes, bunch charge is intentionally reduced by adjusting FC timing by the request from SuperKEKB MR.

Injections in 2022ab

- e- beam needs a tuning every few days.
- e+ beam is rather stable thanks to the DR.

The injection efficiency depends on;

- the quality of injection beam
- injection parameters such as septum angle
- status of the stored beams and collimators in the SuperKEKB ring



Improvements

① The injection was improved by the current-dependent correction of the horizontal orbit at SLYTE * in HER. Now the orbit feedback systems are working well.

② The septa have been operating at 25Hz.

③ The fast strip line kicker has been used to correct the horizontal orbit for the 2nd bunch

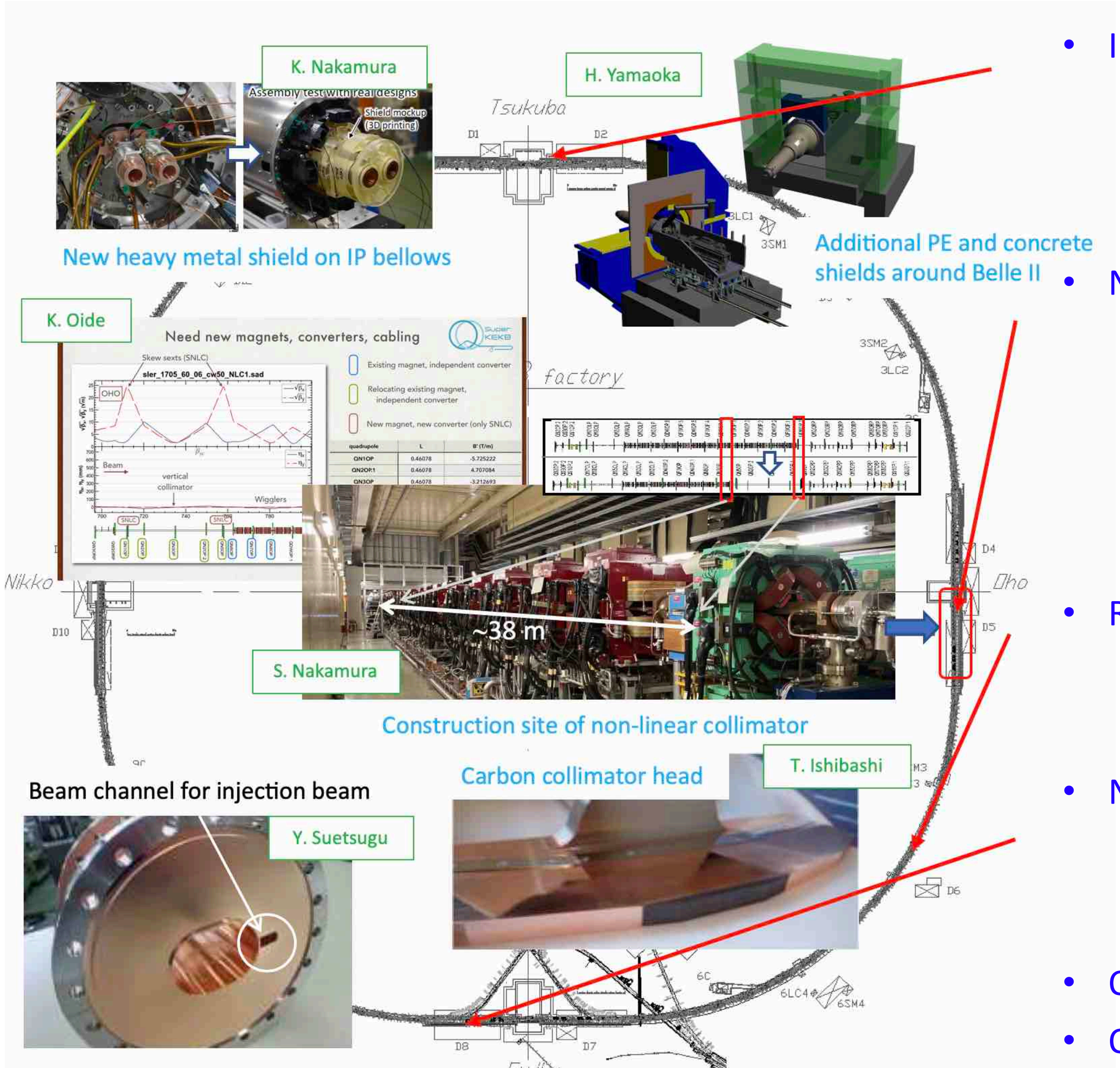
To be improved

④ Since the injection efficiency of the 2nd e- bunch decreased due to the drift of the vertical orbit and the worse emittances of the 2nd bunch, the two-bunch injection was temporarily given up.

⑤ e+ bunch charge has been reduced to avoid the CLAWS aborts. See the lower right figure in the previous page.

- MR
  - Achievements
  - Challenges
  - Other issues
- LINAC Summary
- LS1
- Summary

LS1



Beam pipe at
HER injection point

- 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 at smaller β_y^*
    - Removal of 50 wiggler magnets, emittance, circumference
    - 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
- QCS leak test
- Others

Y. Funakoshi, IPAC'22

LS1 schedule (~March, 2023)

		7			8			9			10			11			12			1			2			3		
		Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
IR	Shield removal																											
	BELLE II work																											
	QCS moving back																											
	Magnet removal																											
	QCS leak test																											
	QCS cap replace																											
	IR survey																											
OHO	Shield removal																											
	NonLC work																											
	ARES work																											
Fuji	ARES work																											

International Task Force (ITF)

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.

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

4 working groups
Optics, Beam-beam, TMCI, LINAC
+New group “beam loss”
The next one will be held in mid/late July
Hybrid (zoom + face-to-face)

- MR
  - Achievements
  - Challenges
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Summary

We achieved

- LER beam current: 1460 mA
- HER beam current: 1143 mA
- Number of bunches: 2346 bunches (2-bucket spacing, design) with a stable operation over 1 A in LER
- Peak luminosity: 4.65 x 10^{34} $cm^{-2}s^{-1}$ / 4.707 x 10^{34} $cm^{-2}s^{-1}$ with Belle II HV OFF

Challenges

- Understanding various beam loss mechanism
- Collimator damages
- Optics degradation due to orbit change at higher beam current
- Injection: stability of e- beams, 2-bunch injection

LS1 started

- Beam circulation in 2023 after various upgrade/modification work.