SuperKEKB and Belle II operations

Kodai Matsuoka (KEK, Nagoya Univ.)

Nov. 28, 2022

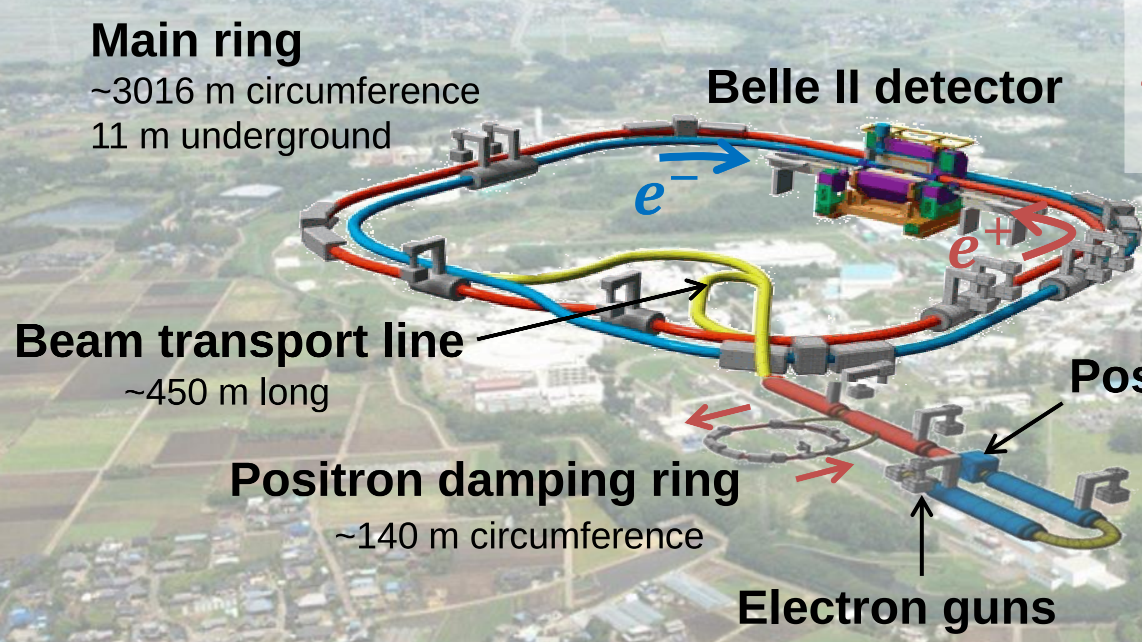
2022 Belle II physics week

Belle II @ SuperKEKB

B-“factory” accelerator in Tsukuba, Japan, upgraded from KEKB

- High luminosity (30 x KEKB = 6 x 10^{35} cm^{-2}s^{-1})
- Long stable operation of the machine and detector

7 GeV e^{-} (HER; High Energy Ring)
4 GeV e^{+} (LER; Low Energy Ring)
→ E_{CM} =10.58 GeV @ $\Upsilon(4S)$



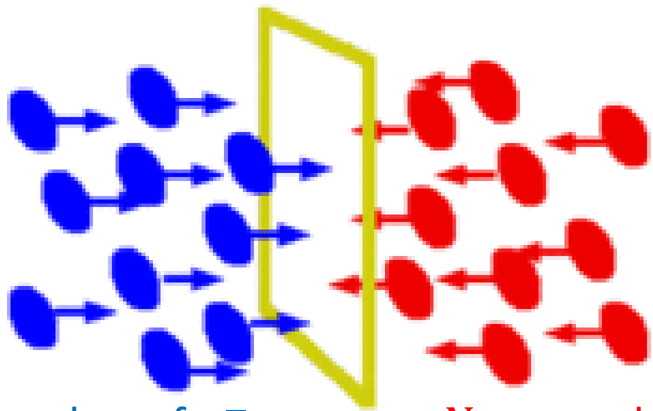
Goal: Accumulate 50 ab^{-1} in the coming ~10 years

How to get high luminosity

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mathcal{L} \cdot \sigma$$

$$\mathcal{L} = \frac{N_{e^+} \cdot N_{e^-}}{S} \cdot f$$

S: Area of the beam crossing



N_{e^-}: number of e^-

N_{e^+}: number of e^+

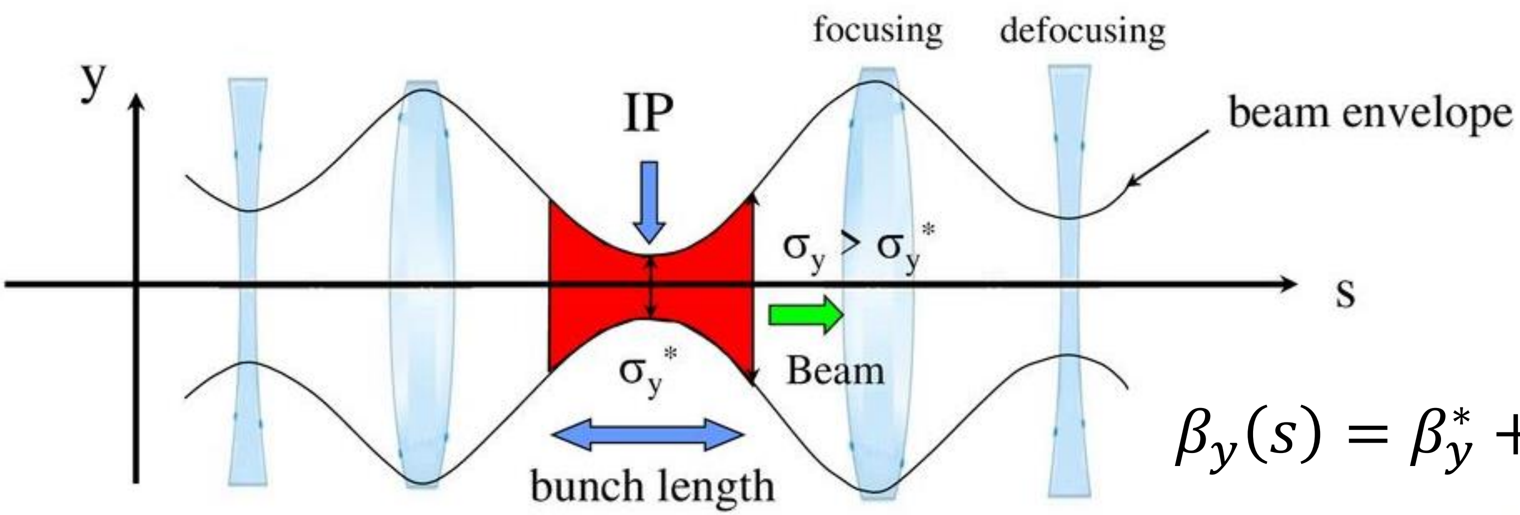
f: beam crossing rate

Put many particles in a small region

- Squeeze the beam size
- Increase the beam current

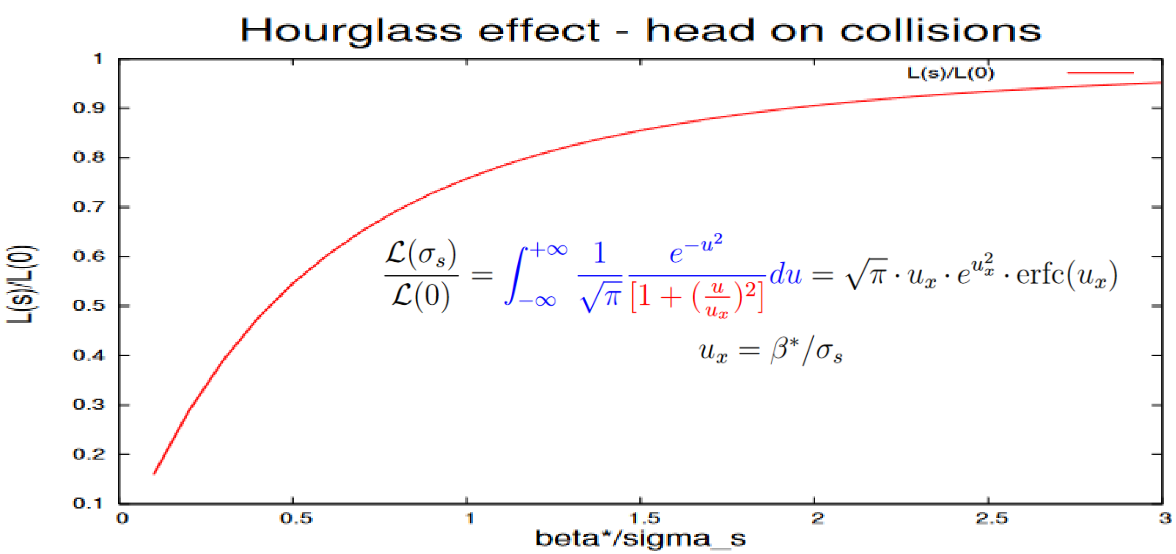
These are not trivial in fact as there are many limitations.

Hour-glass effect



Y. Ohnishi

$$\beta_y(s) = \beta_y^* + \frac{s^2}{\beta_y^*}$$



Luminosity increases by squeezing β_y^* but only down to $\sim\sigma_z$.

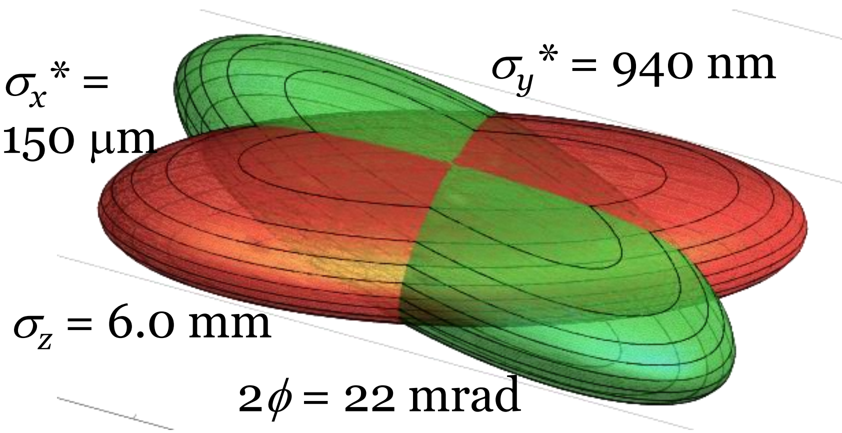
(One of the limitations on luminosity in KEKB, $\beta_y^* = 5.9$ mm, $\sigma_z \approx 7$ mm)

https://www.cockcroft.ac.uk/wp-content/uploads/2014/12/luminosity-werner.pdf

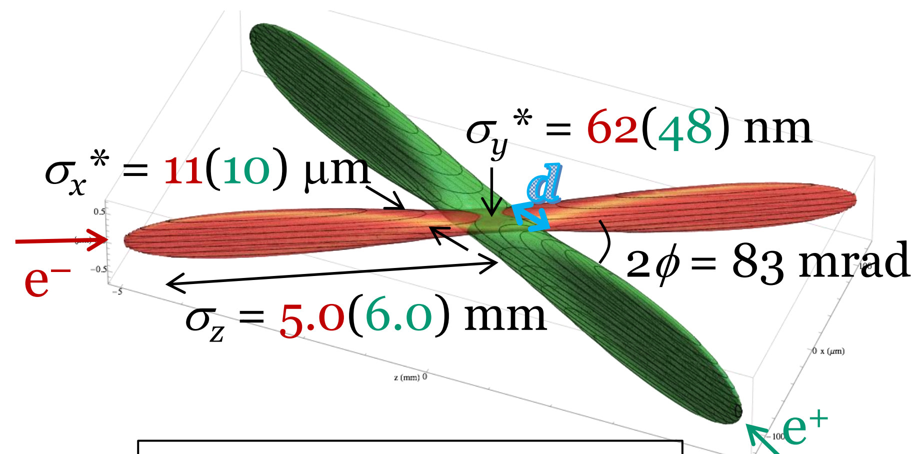
Nano-beam scheme (P. Raimondi)

- At a large crossing angle and small σ_x^*, the hour-glass effect can be avoided. → β_y^* can be squeezed.

KEKB ($\beta_y^* = 5.9$ mm)



SuperKEKB (Target $\beta_y^* = 0.3$ mm)



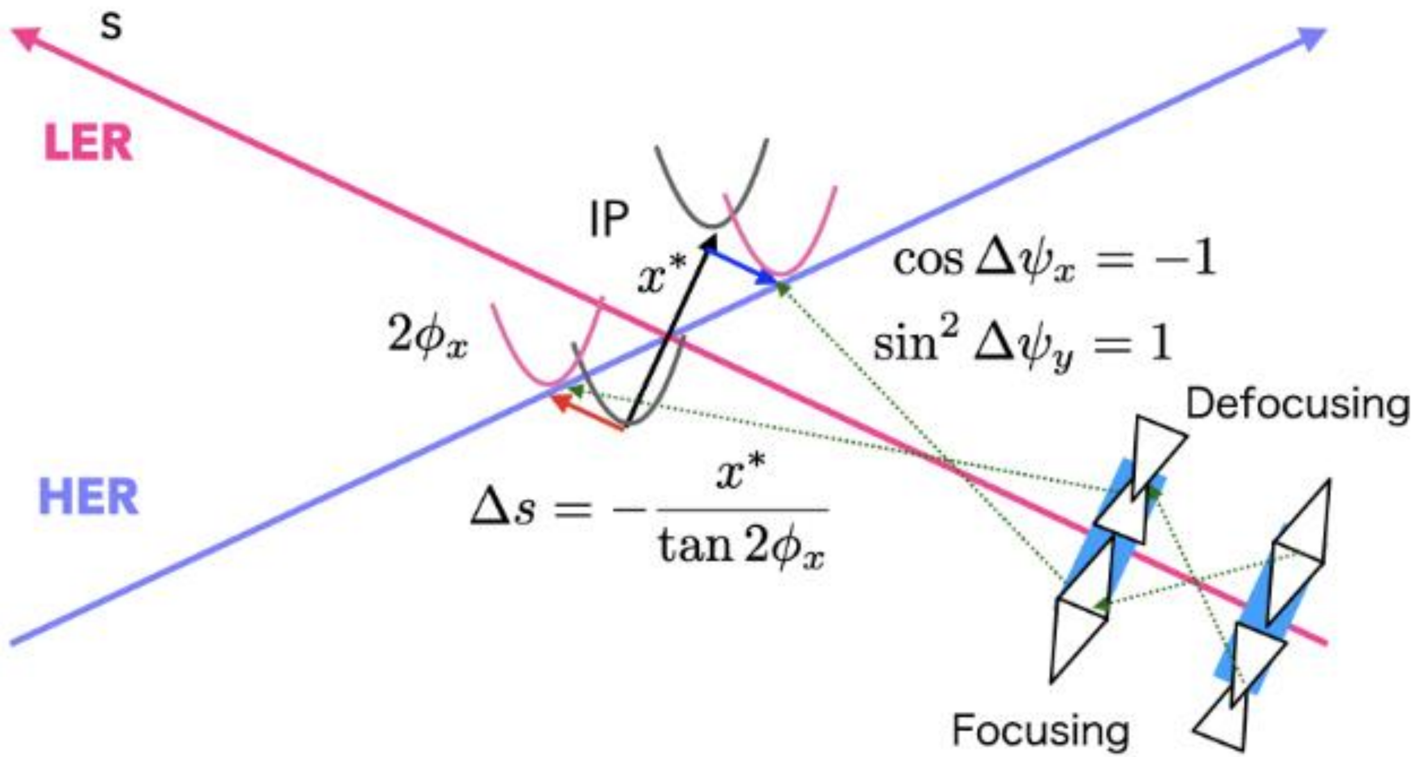
Interaction length

$$d = \frac{\sigma_x^*}{\sin\phi} = 0.24 \text{ mm}$$

Crab waist

(P. Raimondi)

- With a large crossing angle, off-centered particles do not intersect with the oncoming beam at their waist (minimum position of β function).
- Align the waist with the oncoming beam axis by using sextupole magnets.



Y. Ohnishi, PoS(ICHEP2020)695

Crab waist sextupoles (-I' transfer)

Luminosity

Major concerns in the past machine operation

- Beam instabilities
- Beam-beam blowup
- Injector power
- Sudden beam loss

$$\mathcal{L} \approx \frac{f n_b N_+ N_-}{2\pi\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}} \frac{1}{\tan\phi}$$

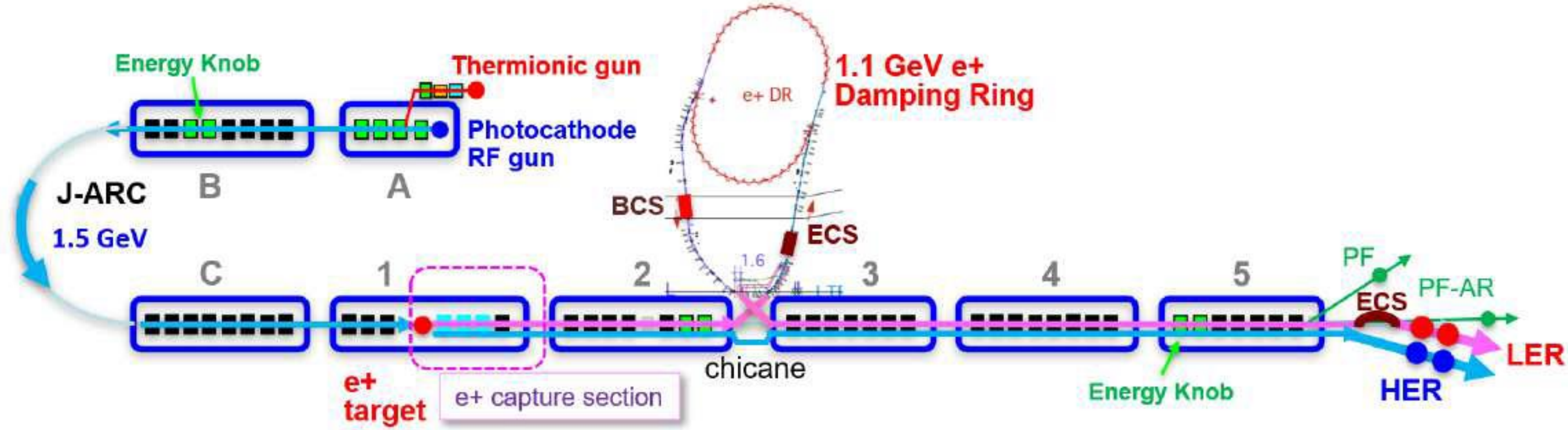
$$\left(\sigma_i^* = \sqrt{\beta_i^* \varepsilon_i}\right)$$

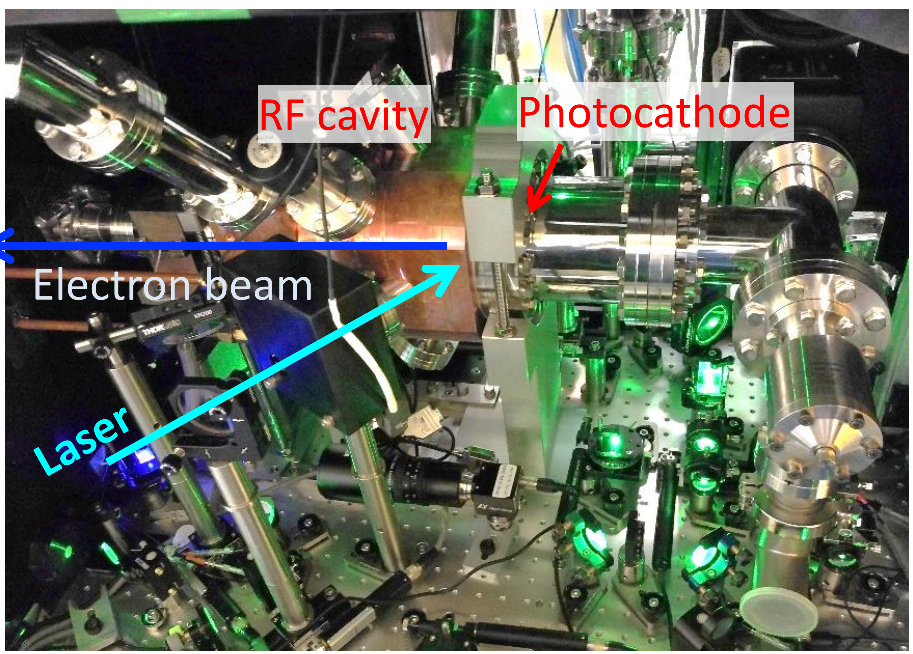
f: revolution frequency
n_b: number of bunches per beam
$N_\pm$: number of particles per bunch
$\sigma_{y\pm}^{*2}$: vertical beam size at IP
$\sigma_{z\pm}^2$: bunch length
ϕ: half crossing angle
β: beta function at IP
ε: emittance

Assumptions to derive this equation:

- 3D Gaussian distribution
- $\sigma_{x,y,z}$ is constant along the interaction length
- $\sigma_z \tan\phi \gg \sigma_x$
- Beam-beam effect is not taken into account.

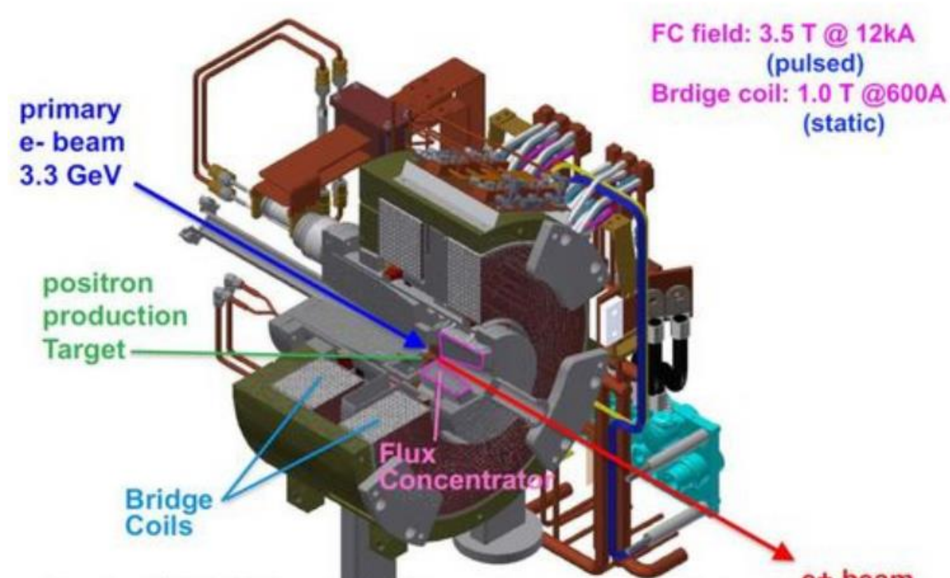
Upgrade (KEKB → SuperKEKB)





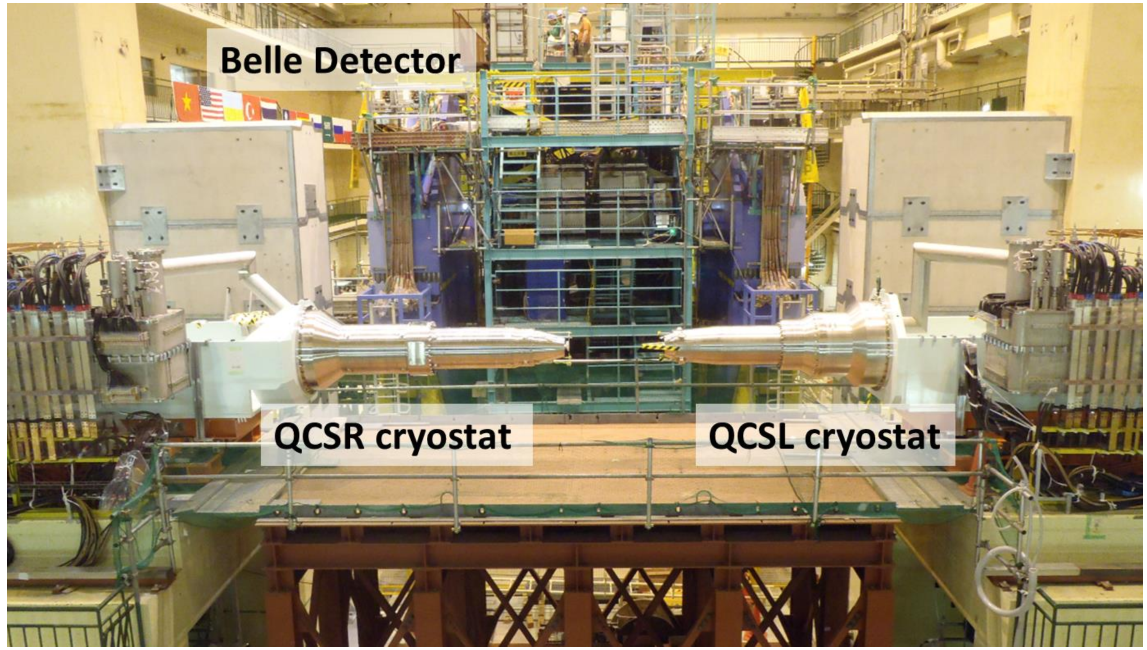
Low emittance RF electron gun

Flux Concentrator

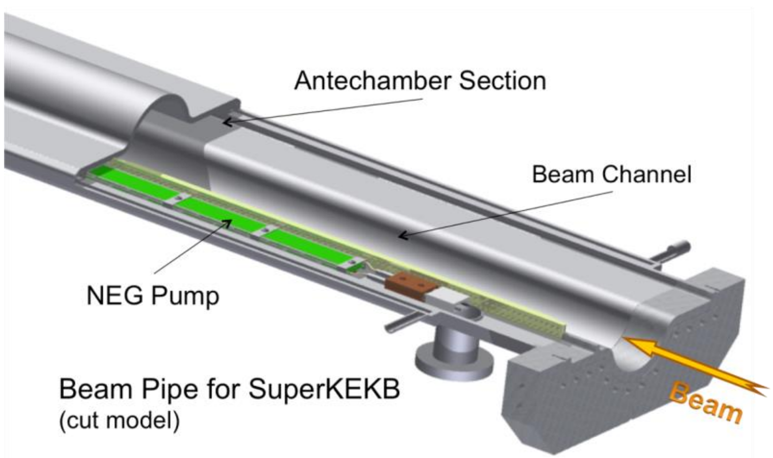


Posipol2016 “SuperKEKB positron source status” Kamitani

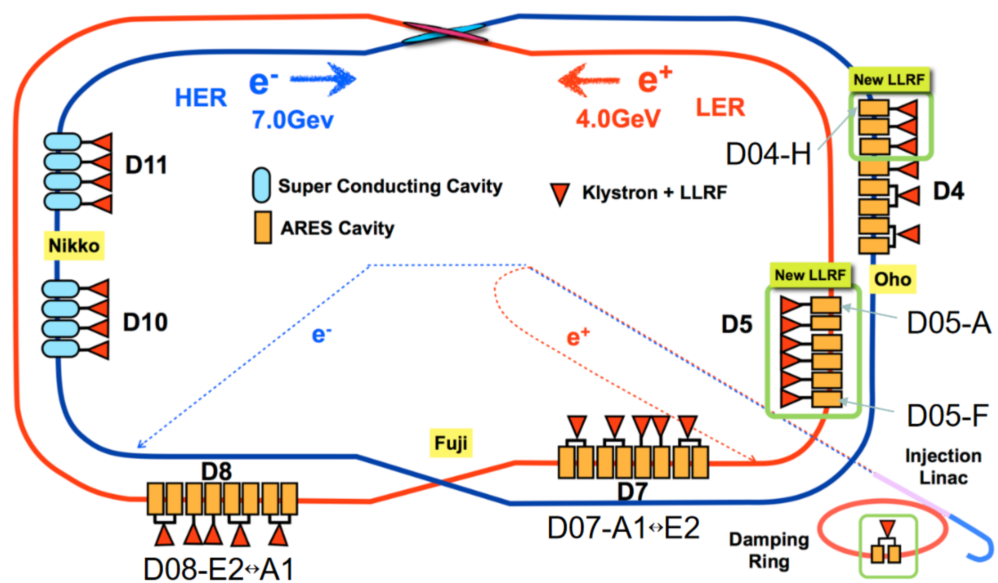
LER dipole magnets were replaced with longer ones (0.82 → 4.2 m) to reduce emittance.



New final-focus superconducting magnet system (QCS)



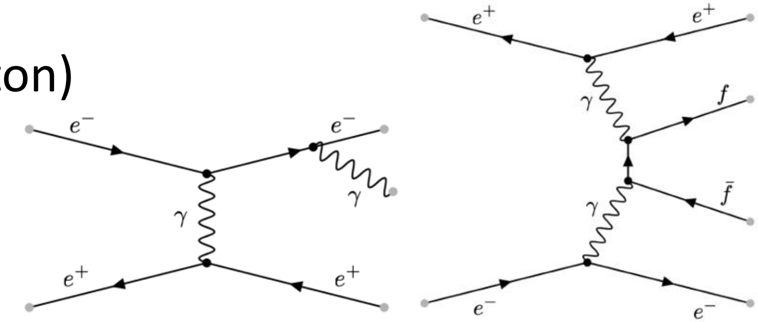
Antechamber with TiN coating for LER to suppress electron cloud instability

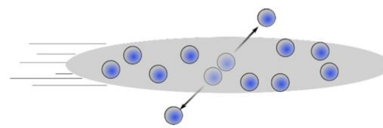


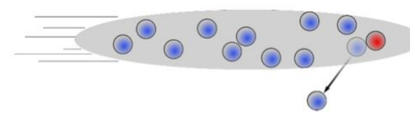
Enhanced RF stations

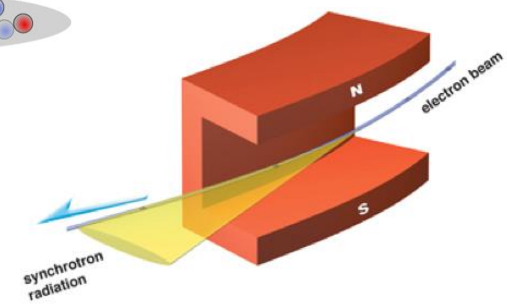
Beam background

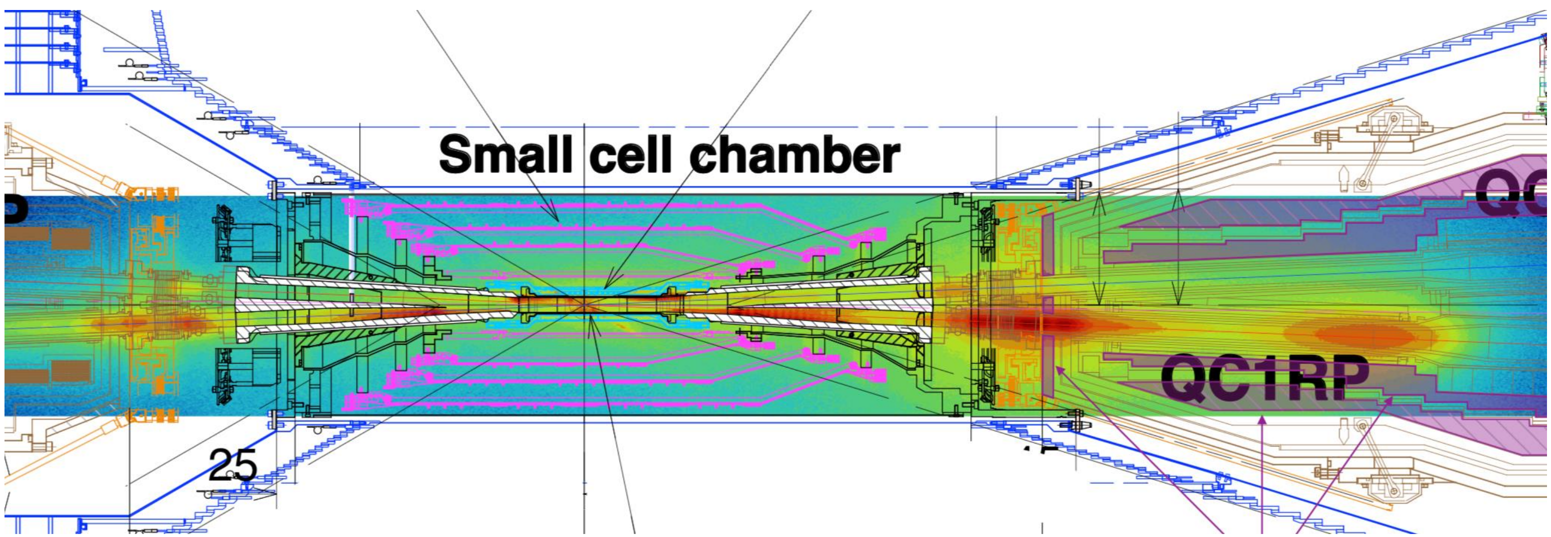
- Beam collision (radiative Bhabha, two-photon)
  - rate $\propto \mathcal{L}$
- Touschek scattering
  - rate $\propto I^2/(\sigma n_b E^3)$
- Beam-gas scattering
  - rate $\propto I \cdot (P_{\text{dynamic}} + P_{\text{base}}) \propto \sim I^2$
- Synchrotron radiation
  - Power $\propto IE^4/\rho^2$
- Beam injection





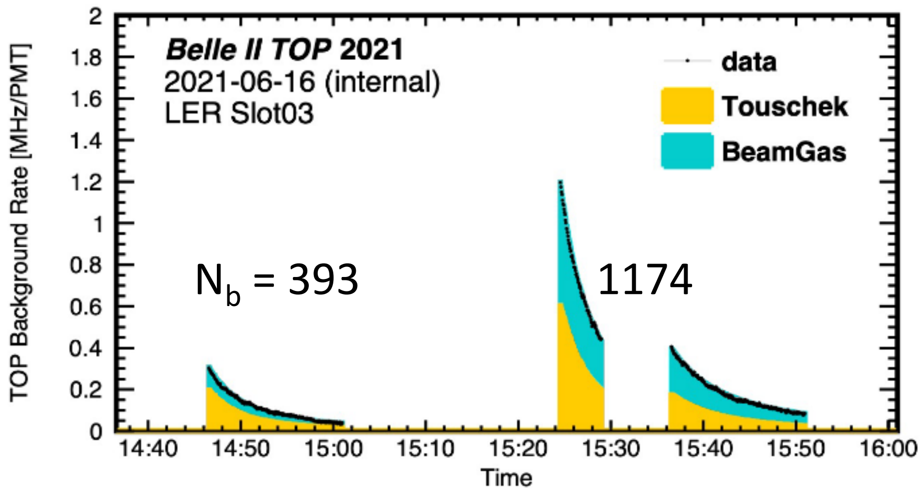


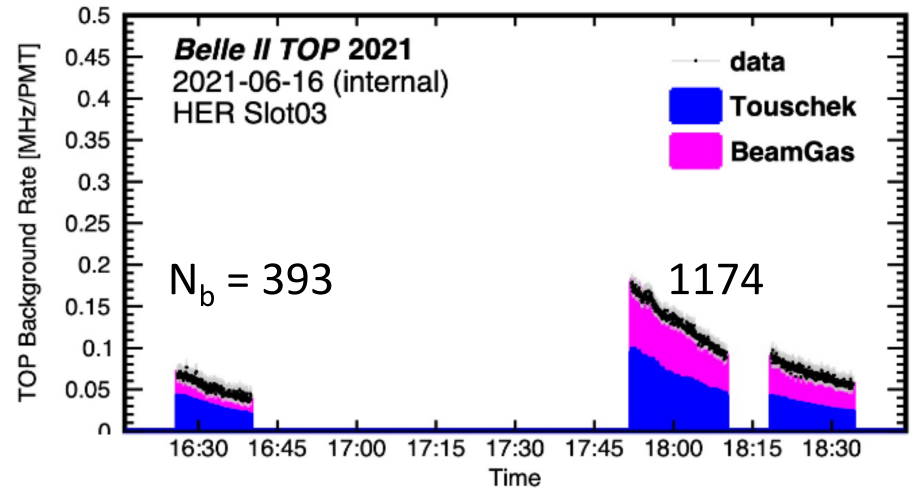




Beam background measurement

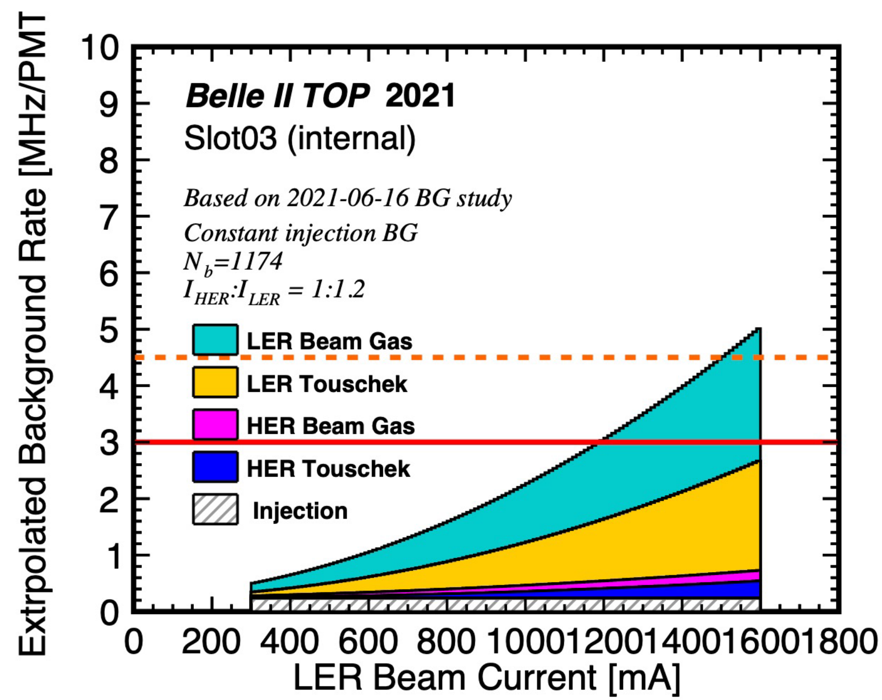
K. Kojima





$$\underbrace{T\frac{I^2}{\sigma_y n_b}}_{\text{Touschek}} + \underbrace{B_0 I + B_1 I^2}_{\text{Beam gas}} + \underbrace{C}_{\text{Pedestal}}$$

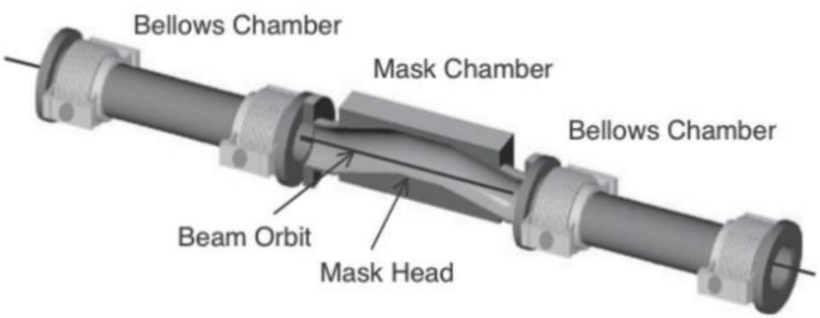
(Noise from FEE)



- LER Touschek and beam-gas are dominant so far.
- Luminosity background will be dominant in future.

Collimator

KEKB type

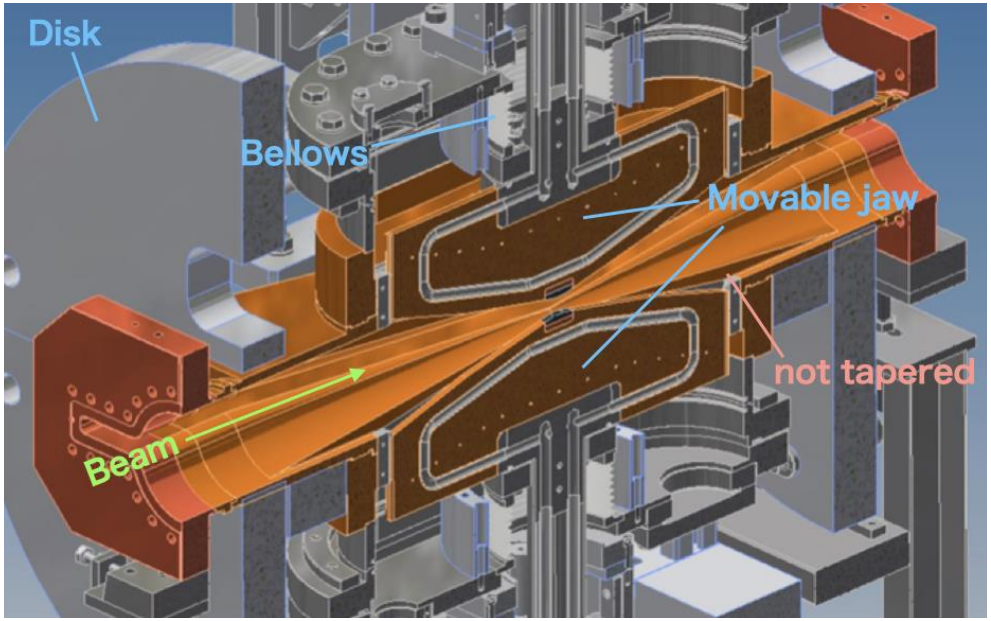


Y. Suetsugu et al., NIM A 513, 465 (2003)

KEKB type: Tapered chamber itself approaches the beam. The tip is made of Cu coated titanium.

SuperKEKB type

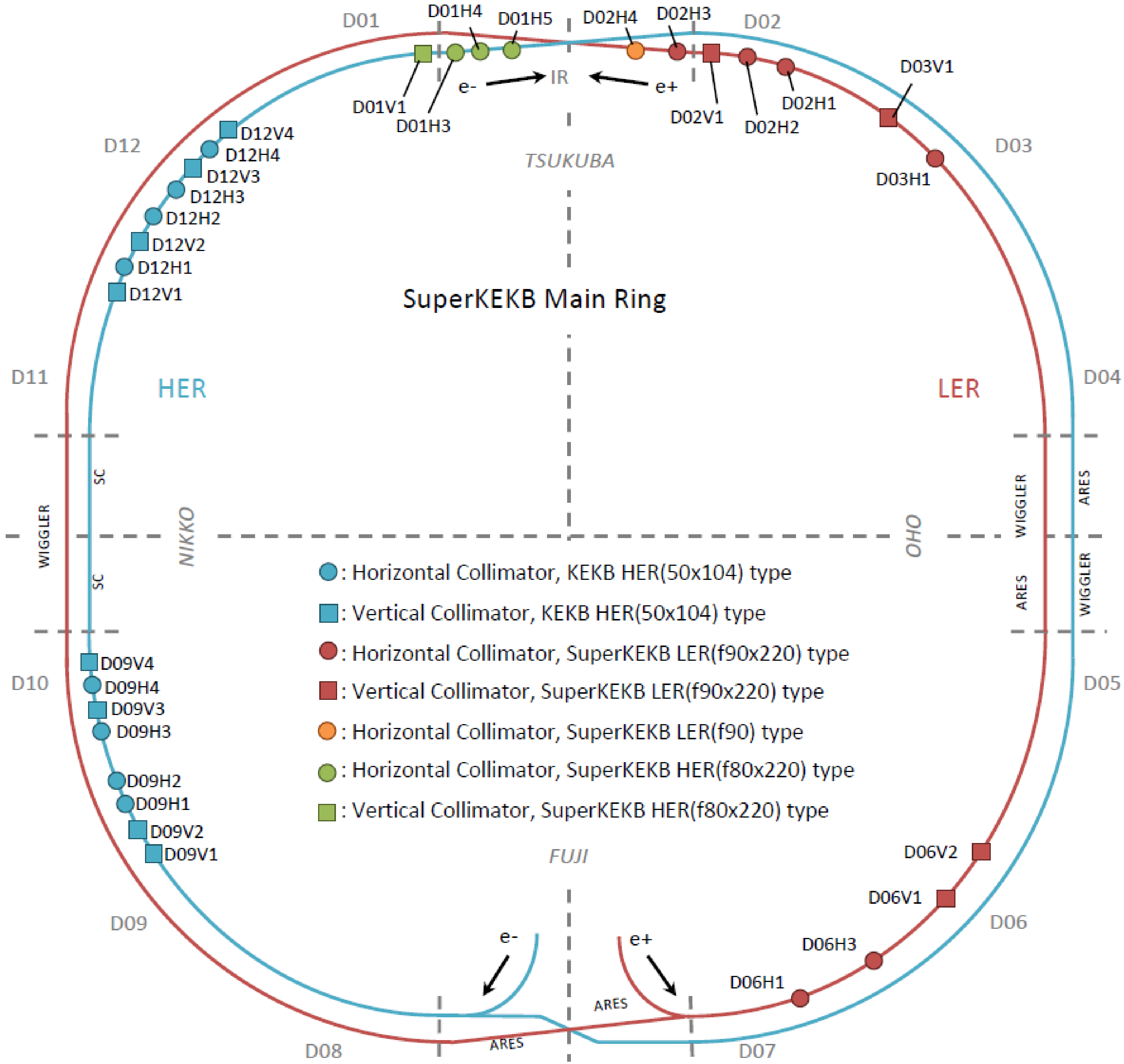
Vertical collimator



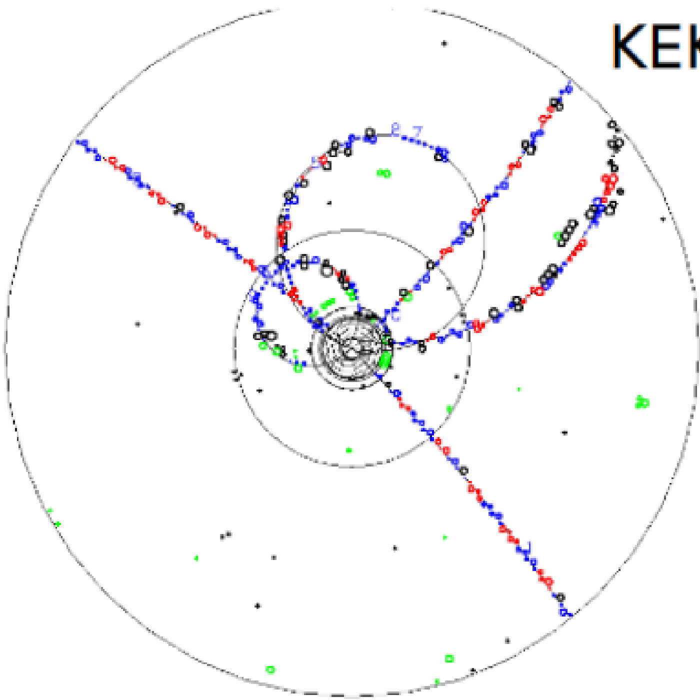
T. Ishibashi et al., PRAB 23, 053501 (2020)

Two movable jaws approach the beam individually.

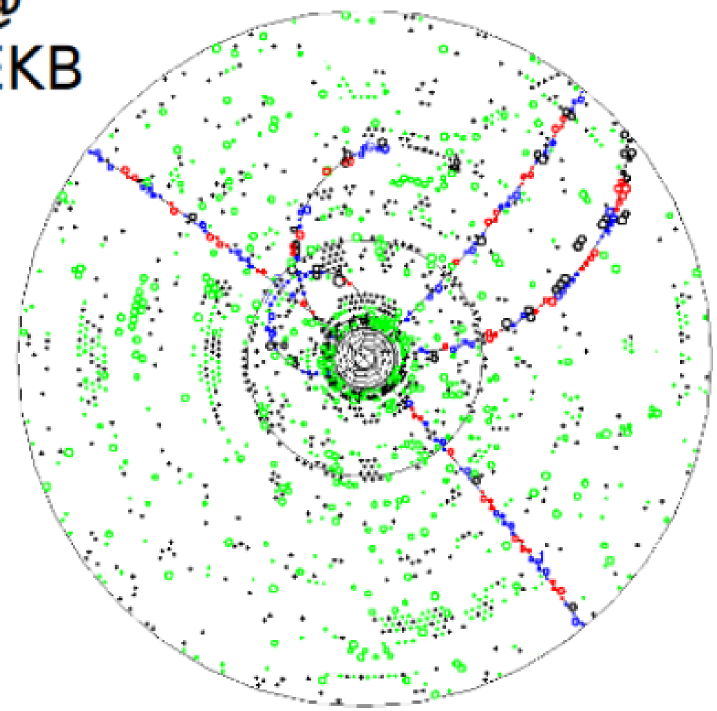
Horizontal collimators mainly stops stray particles from Touschek scattering and vertical collimators mainly stop those from beam-gas Coulomb scattering.
They are also important to protect machine components and Belle II detector.


SuperKEKB Main Ring
HER
LER
TSUKUBA
NIKKO
OHO
FUJI
IR
e-
e+
D01
D02
D03
D04
D05
D06
D07
D08
D09
D10
D11
D12
D01V1
D01H3
D01H4
D01H5
D02H4
D02H3
D02V1
D02H2
D02H1
D03V1
D03H1
D12V4
D12H4
D12V3
D12H3
D12H2
D12V2
D12H1
D12V1
D09V4
D09H4
D09V3
D09H3
D09H2
D09H1
D09V2
D09V1
D06V2
D06V1
D06H3
D06H1
WIGGLER
SC
ARES
: Horizontal Collimator, KEKB HER(50x104) type
: Vertical Collimator, KEKB HER(50x104) type
: Horizontal Collimator, SuperKEKB LER(f90x220) type
: Vertical Collimator, SuperKEKB LER(f90x220) type
: Horizontal Collimator, SuperKEKB LER(f90) type
: Horizontal Collimator, SuperKEKB HER(f80x220) type
: Vertical Collimator, SuperKEKB HER(f80x220) type

Belle @ KEKB

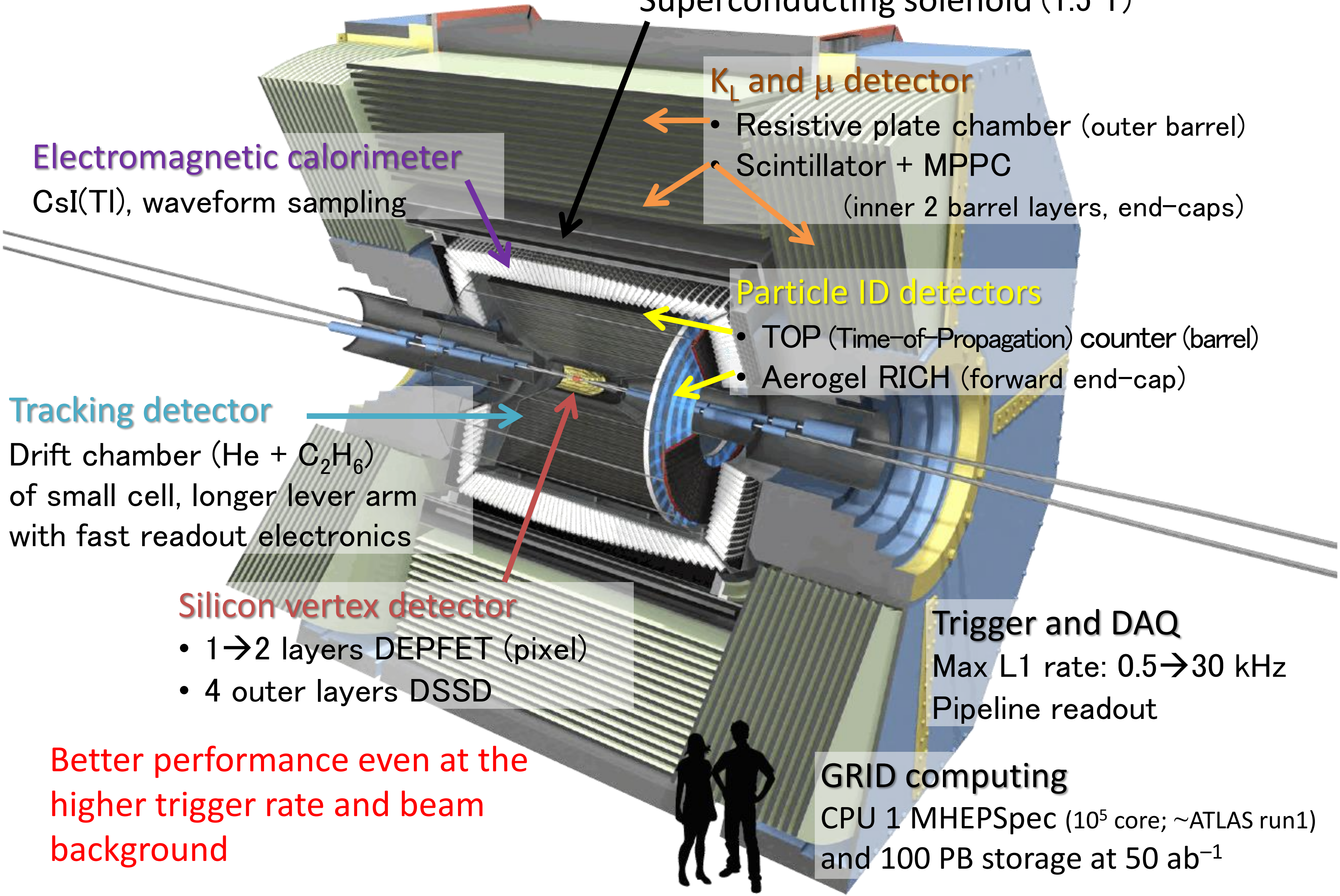


Belle @ SuperKEKB



The same event with simulated background at 8 x 10^{35} $cm^{-2}s^{-1}$

Belle II detector

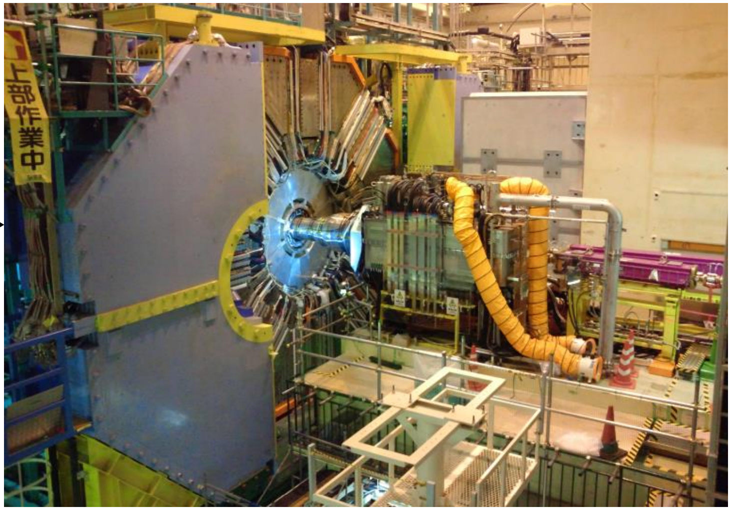


Better performance even at the higher trigger rate and beam background

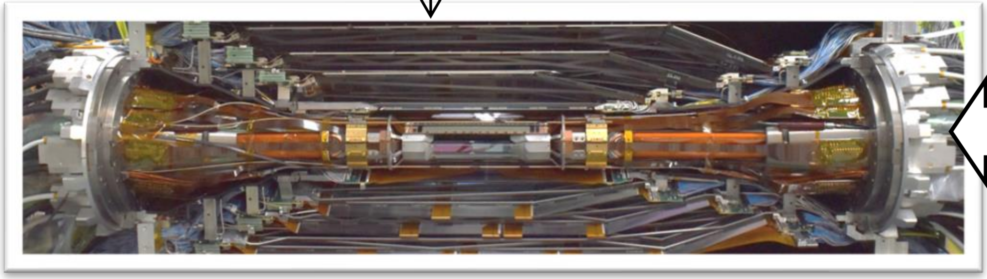
SuperKEKB/Belle II history

- 2010 KEKB run end
  SuperKEKB construction start
- 2016 SuperKEKB phase 1
  - Without QCS, no collisions
  - Without Belle II detector
  - Beam background measurement with BEAST II

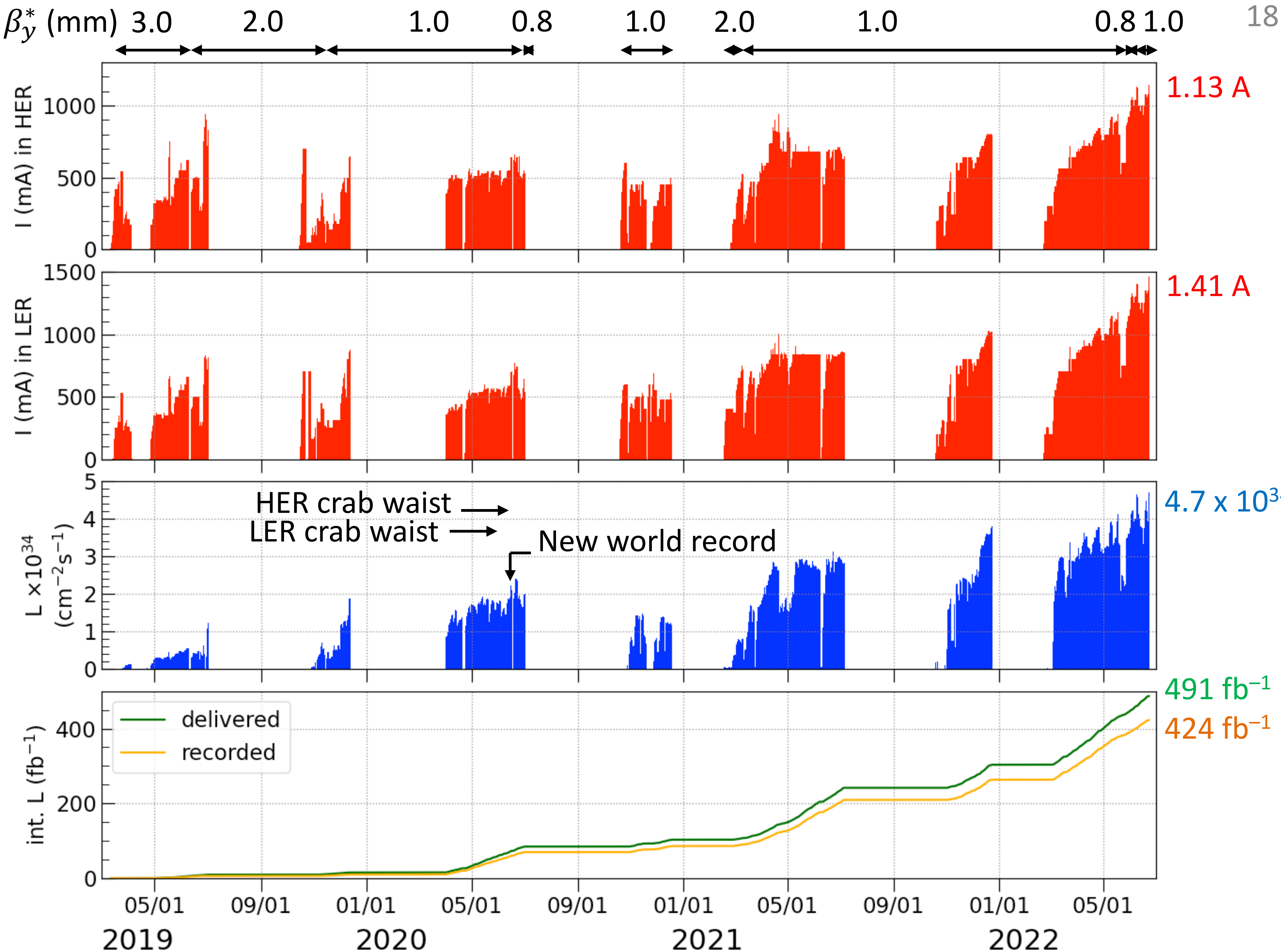
- 2018 Phase 2 (first collisions)
  - QCS, Belle II (except VXD) installed
  - BEAST II in the inner most



- 2019 Phase 3 (physics runs)
  - VXD installed

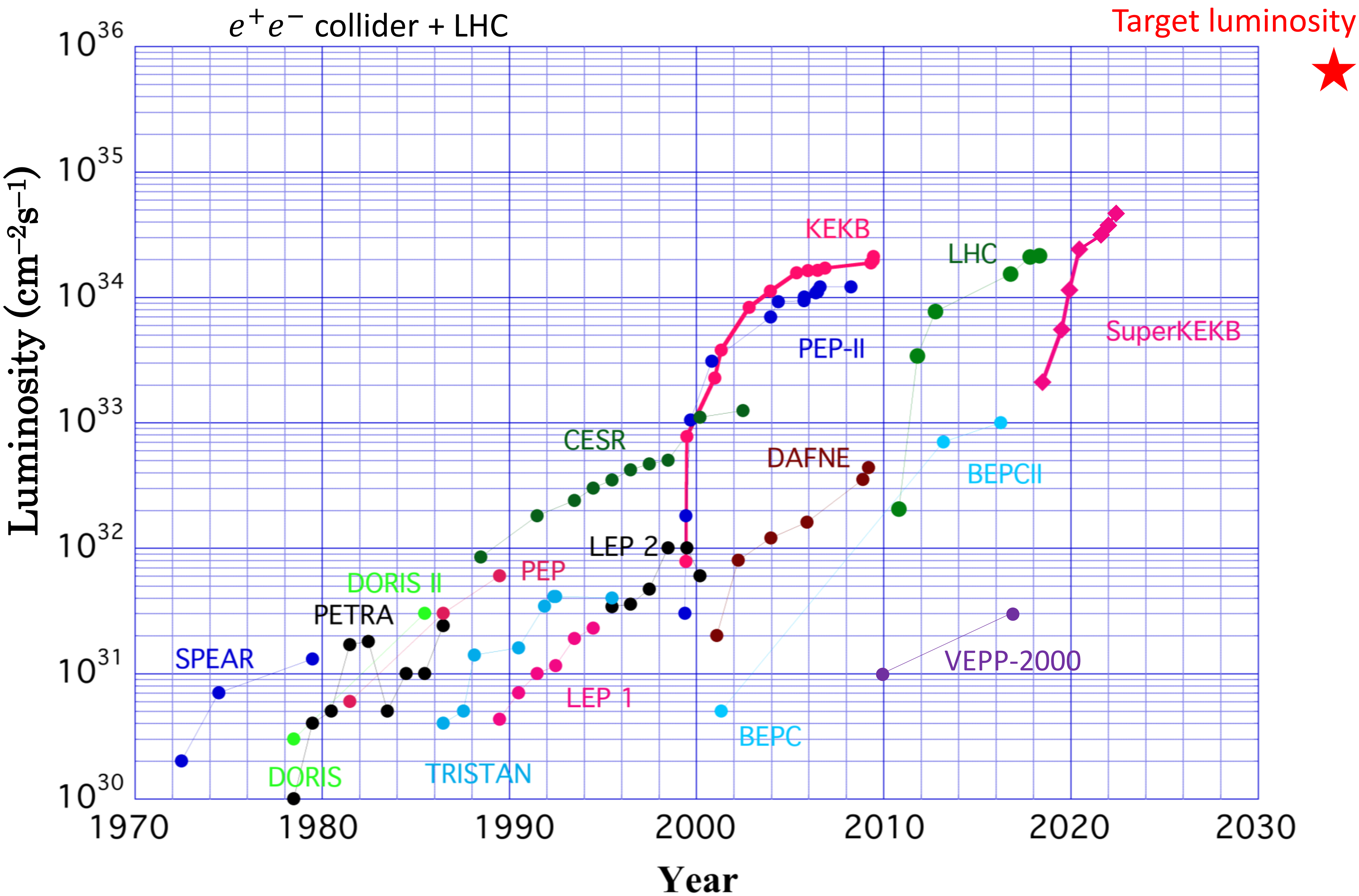


SuperKEKB operation

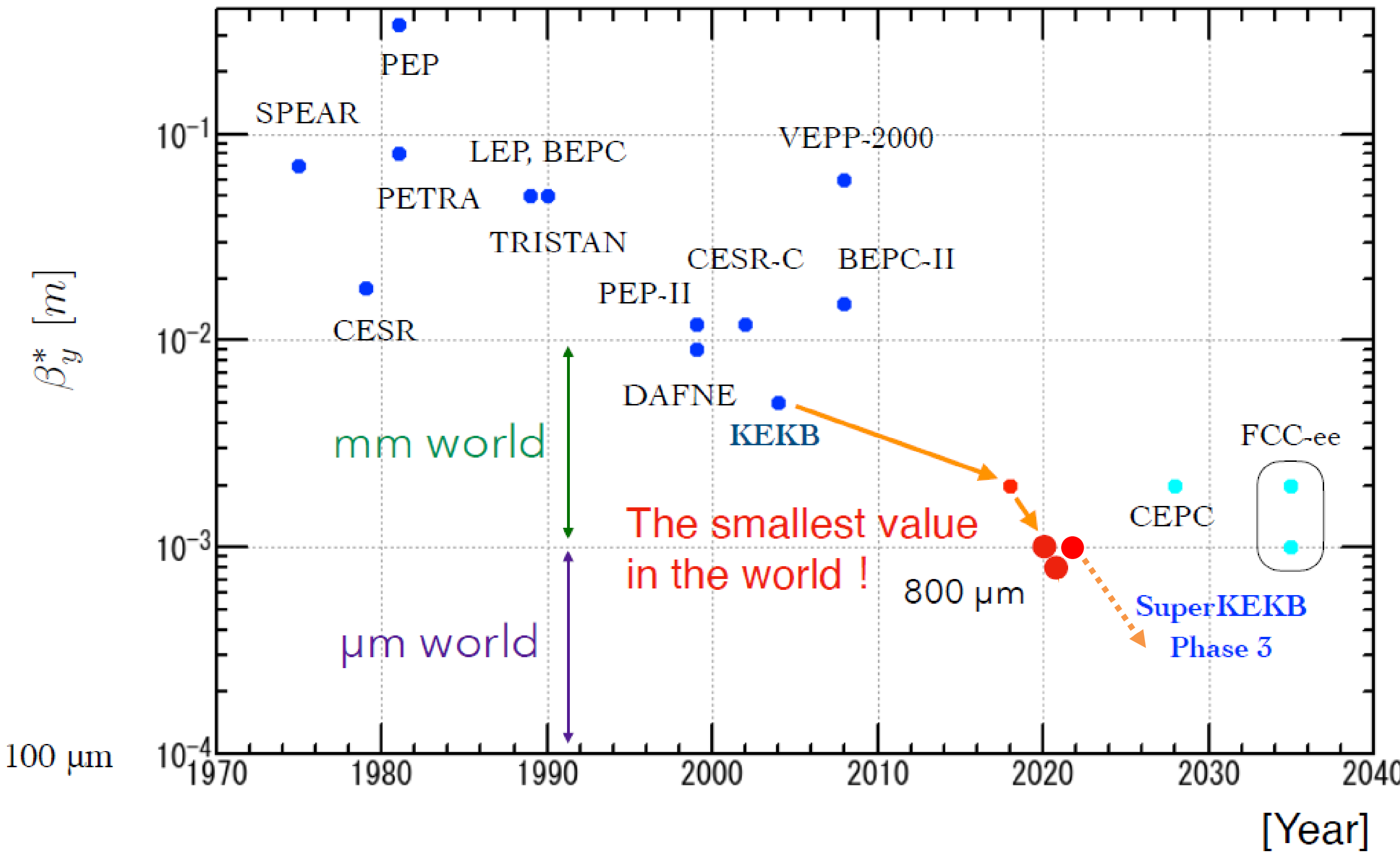


β_y^* (mm) 3.0 2.0 1.0 0.8 1.0 2.0 1.0 0.8 1.0
I (mA) in HER
1.13 A
I (mA) in LER
1.41 A
L ×10^{34} (cm^{-2}s^{-1})
HER crab waist
LER crab waist
New world record
4.7 x 10^{34}
int. L (fb^{-1})
delivered
recorded
491 fb^{-1}
424 fb^{-1}
05/01 09/01 01/01 05/01 09/01 01/01 05/01 09/01 01/01 05/01
2019 2020 2021 2022

Luminosity record



Nano-beam

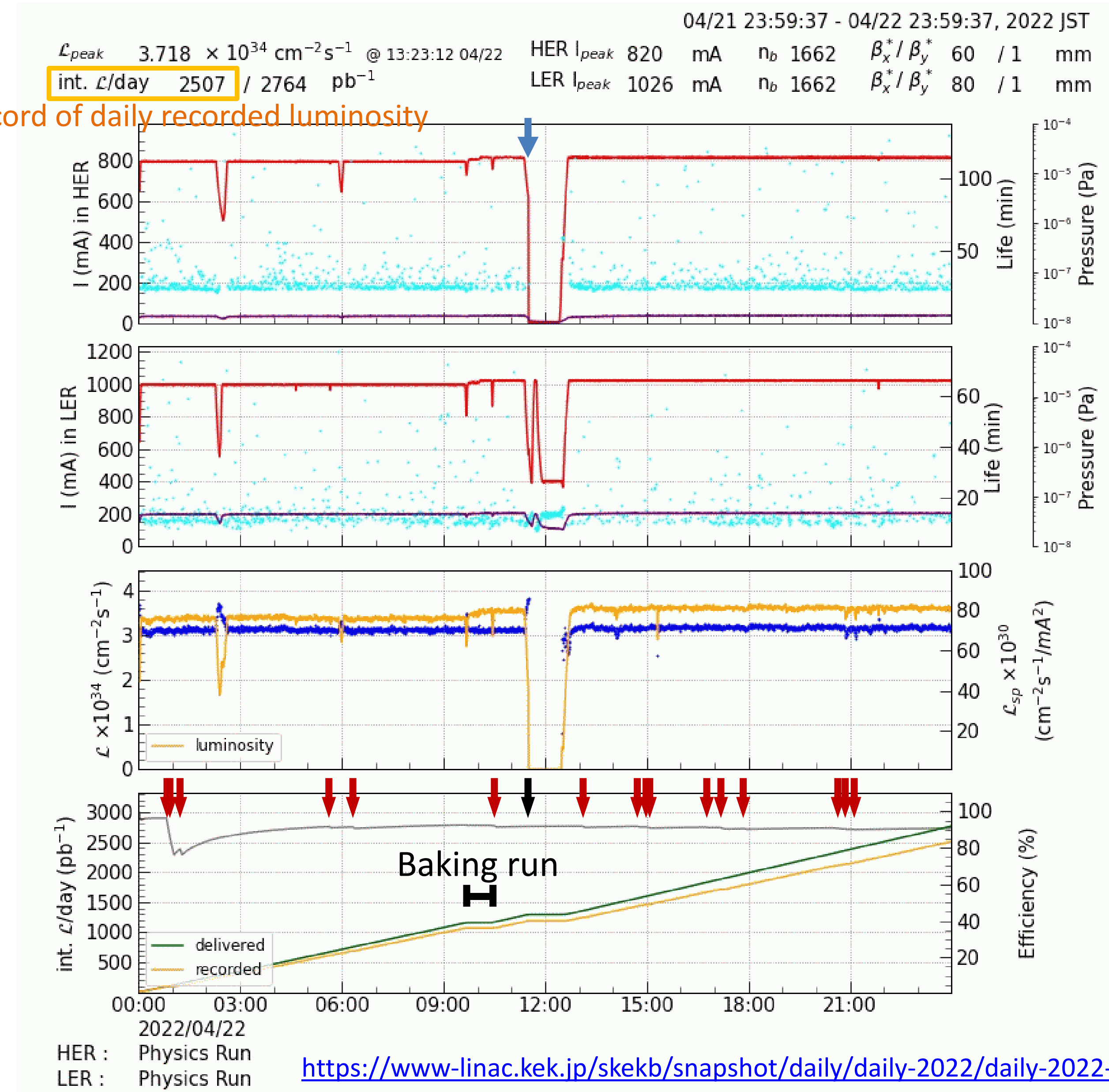


σ_y^* = 0.7 μm at SLC
"SLC - THE END GAME"
R. Assmann et al., EPAC2000

Y. Ohnishi, ICHEP2020

Vertical beam size at IP measured by XRM: 0.224/0.224 μm (LER/HER) at 4.65 x 10^{34} /cm^{-2}s^{-1}

Example of daily machine operation



https://www-linac.kek.jp/skekb/snapshot/daily/daily-2022/daily-2022-04.html

[Beam abort reason]

Severe beam loss

Minor beam loss

Beam loss at injection

Pressure burst

RF

Earthquake

[Run stop reason]

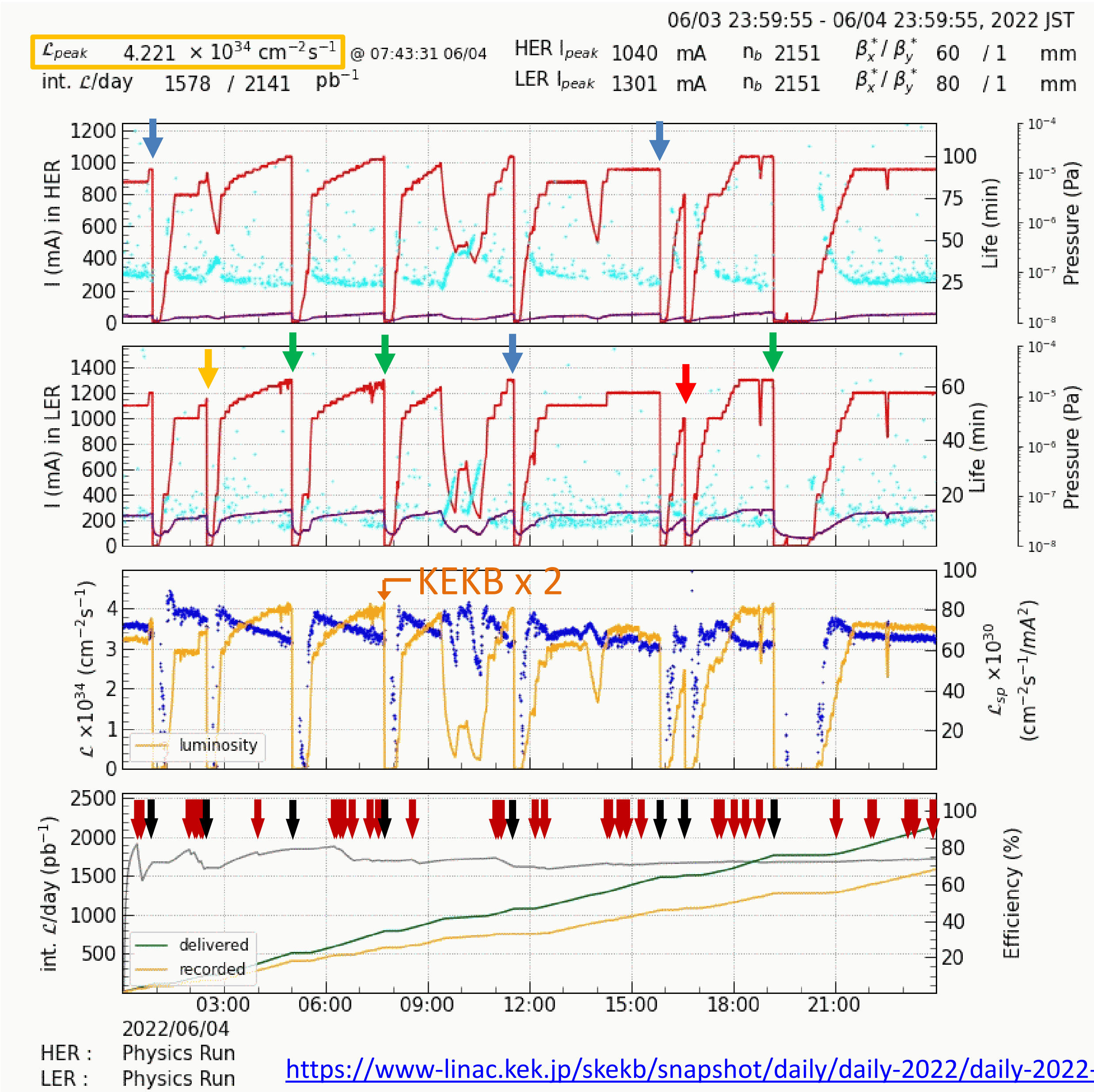
Beam abort

Subsystem error*

- CDC x 8
- TOP x 8

* Including repeating errors of the same cause

Example of daily machine operation



https://www-linac.kek.jp/skekb/snapshot/daily/daily-2022/daily-2022-06.html

[Beam abort reason]

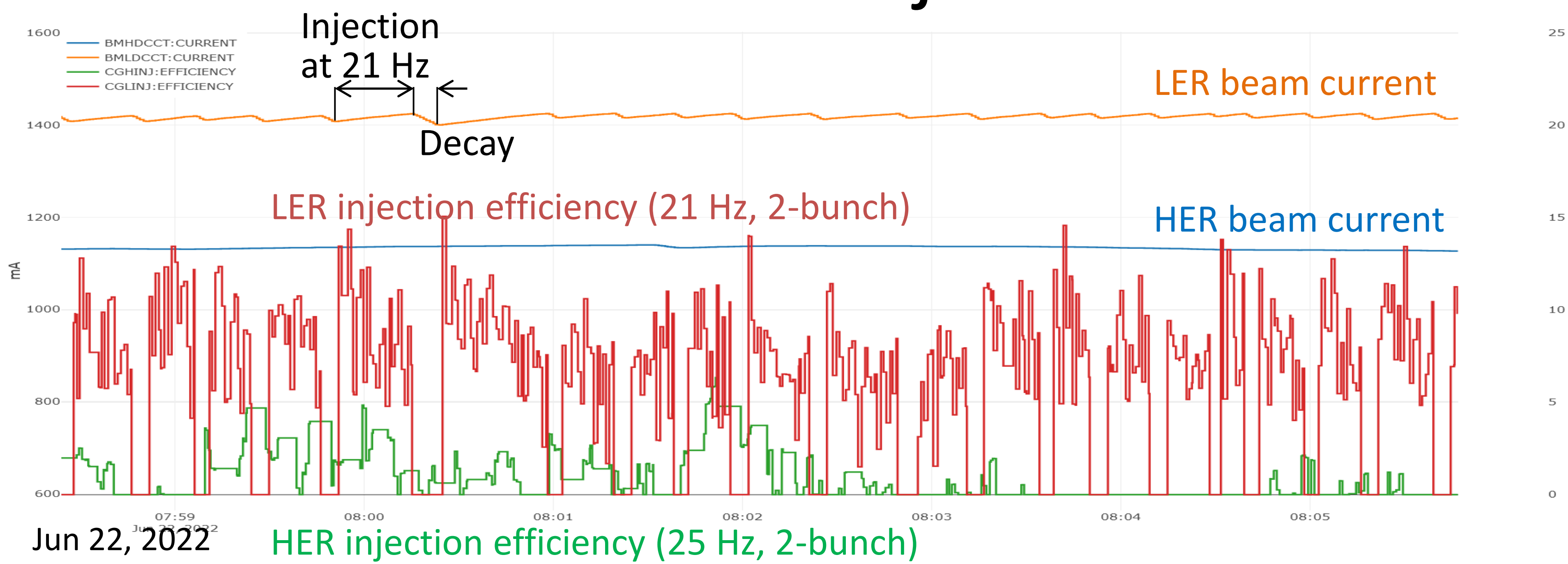
- Severe beam loss
- Minor beam loss
- Beam loss at injection
- Pressure burst
- RF
- Earthquake

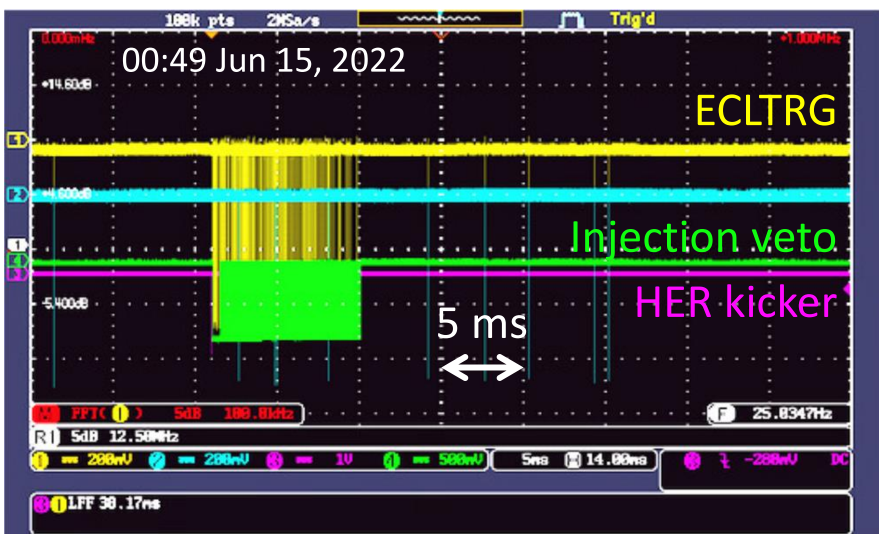
[Run stop reason]

- Beam abort
- Subsystem error*
  - CDC x 23
  - TOP x 14
  - PXD x 2

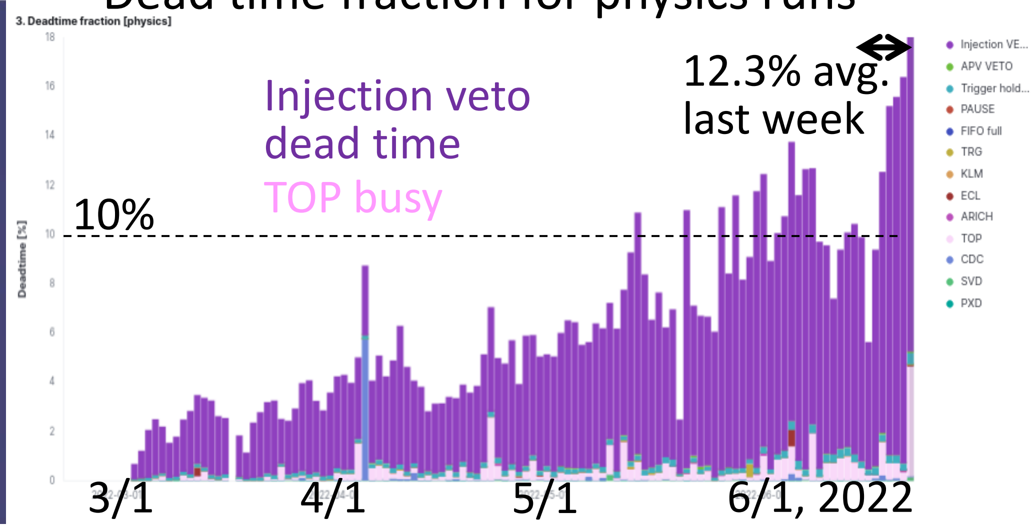
* Including repeating errors of the same cause

Continuous injection





Dead time fraction for physics runs

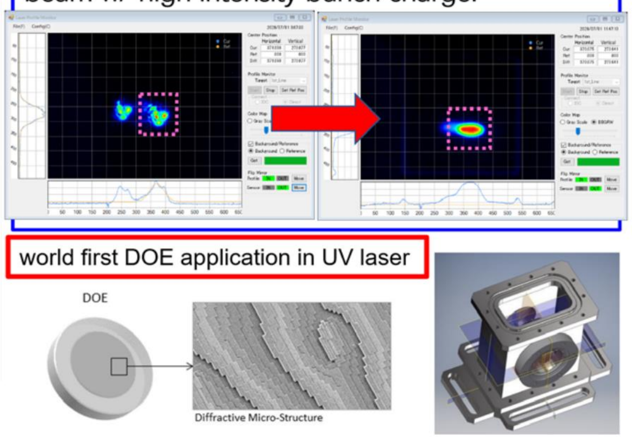


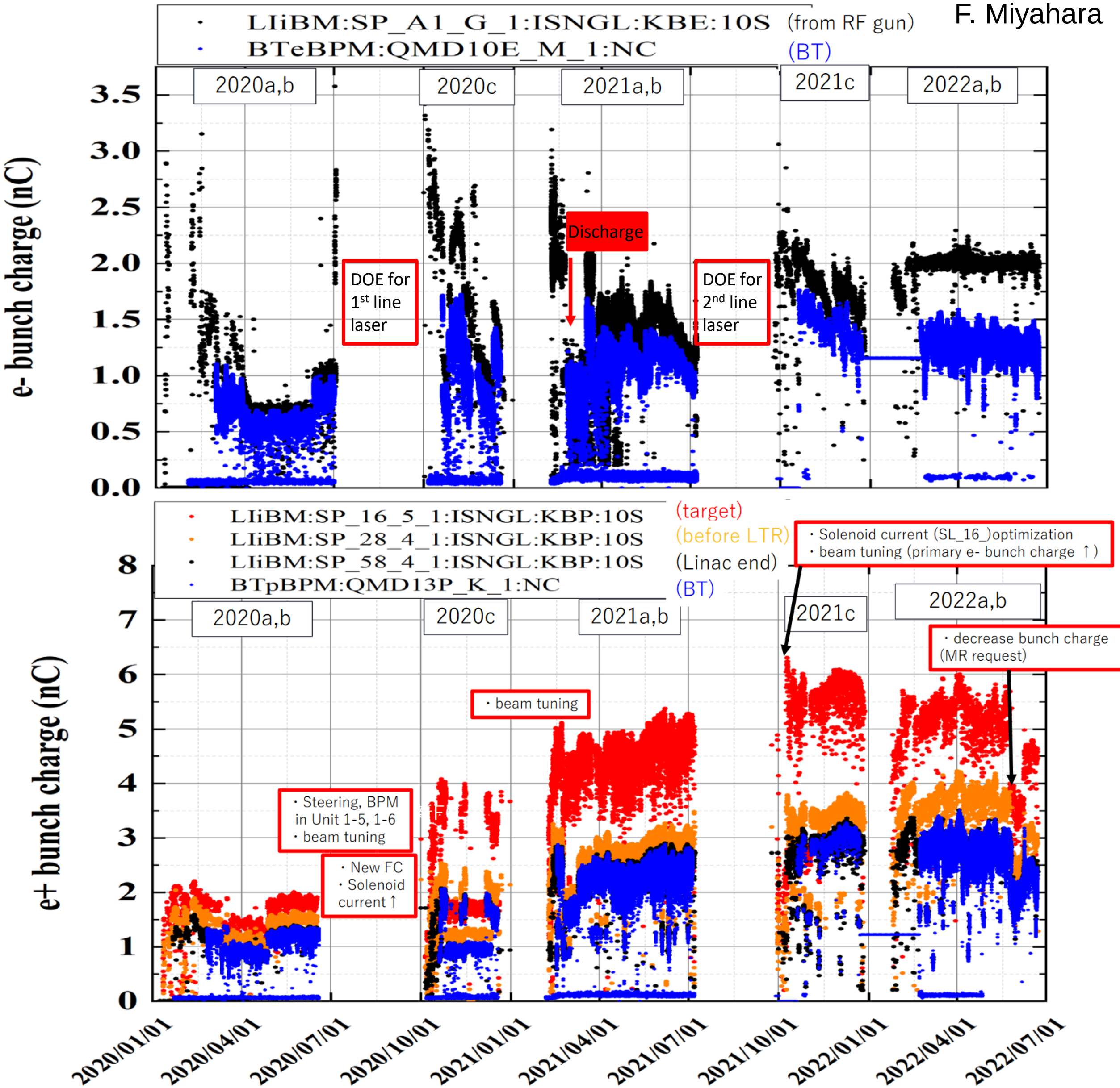
Major limiting factor for luminosity increase

Injector performance

F. Miyahara

DOE (diffractive optical element) in 1st laser line: Laser beam homogenizer for low emittance beam w/ high intensity bunch charge.





Target (design):
4 nC/bunch for e^- and e^+ each

Short beam lifetime

Y. Ohnishi, https://kds.kek.jp/event/44562/contributions/227034/attachments/161845/208670/Lifetime_Summary.pdf

2022-06-22_08:44:38.036_IPTiltwBCT with mod. sextupoles

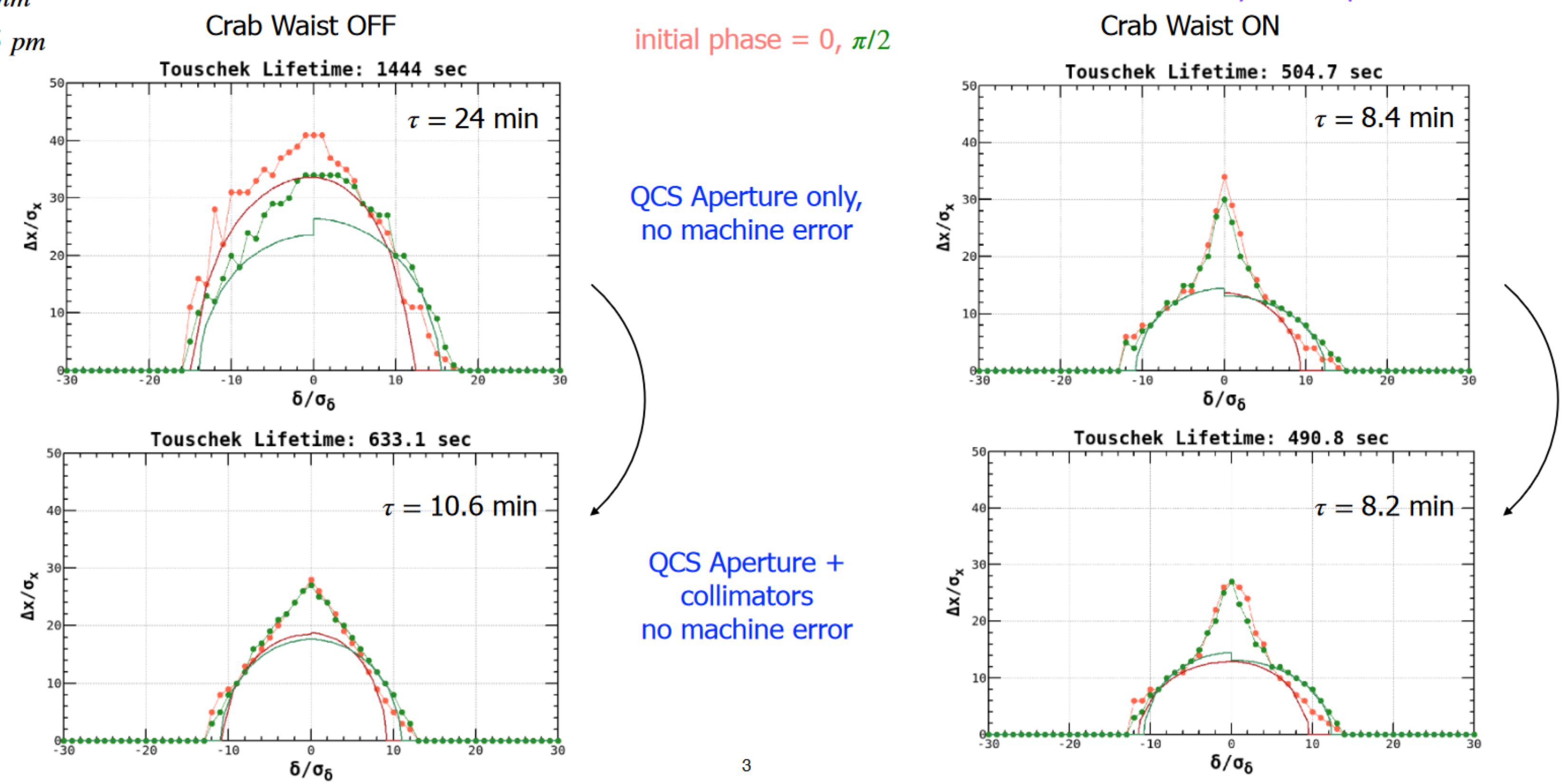
I_{b+} = 0.68 mA
(800 mA / n_b:1174)

$\varepsilon_x = 4\ nm$

$\varepsilon_y = 25\ pm$

The beam lifetime is evaluated by an ellipse inscribed in the dynamic aperture (stable region).

CW ON reduces the dynamic aperture。



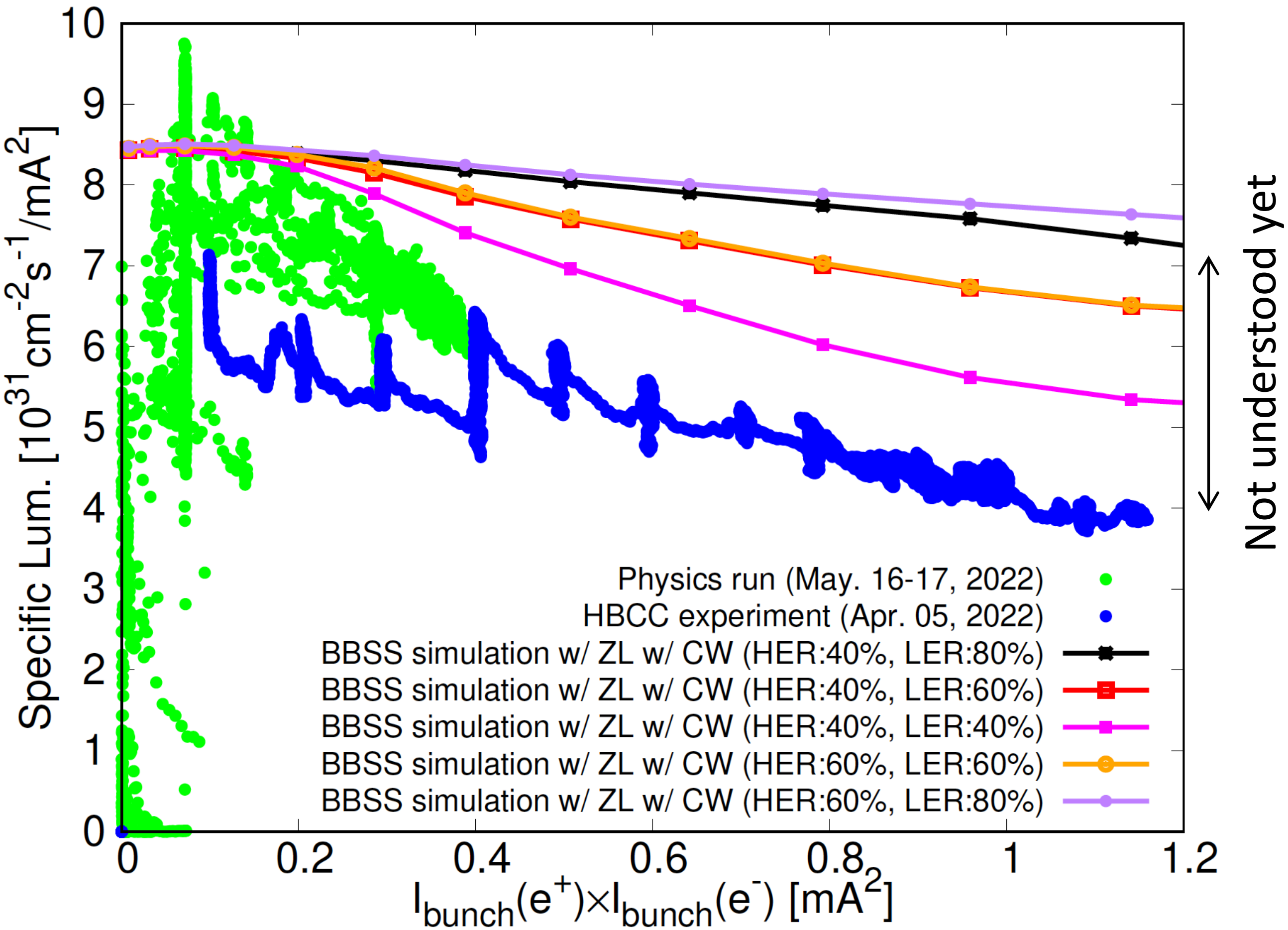
Crab Waist decreases horizontal dynamic aperture. It becomes more significant with momentum deviation. The reason is the interference between QCS nonlinear Maxwellian fringe and Crab Waist sextupoles.

Beam-beam performance

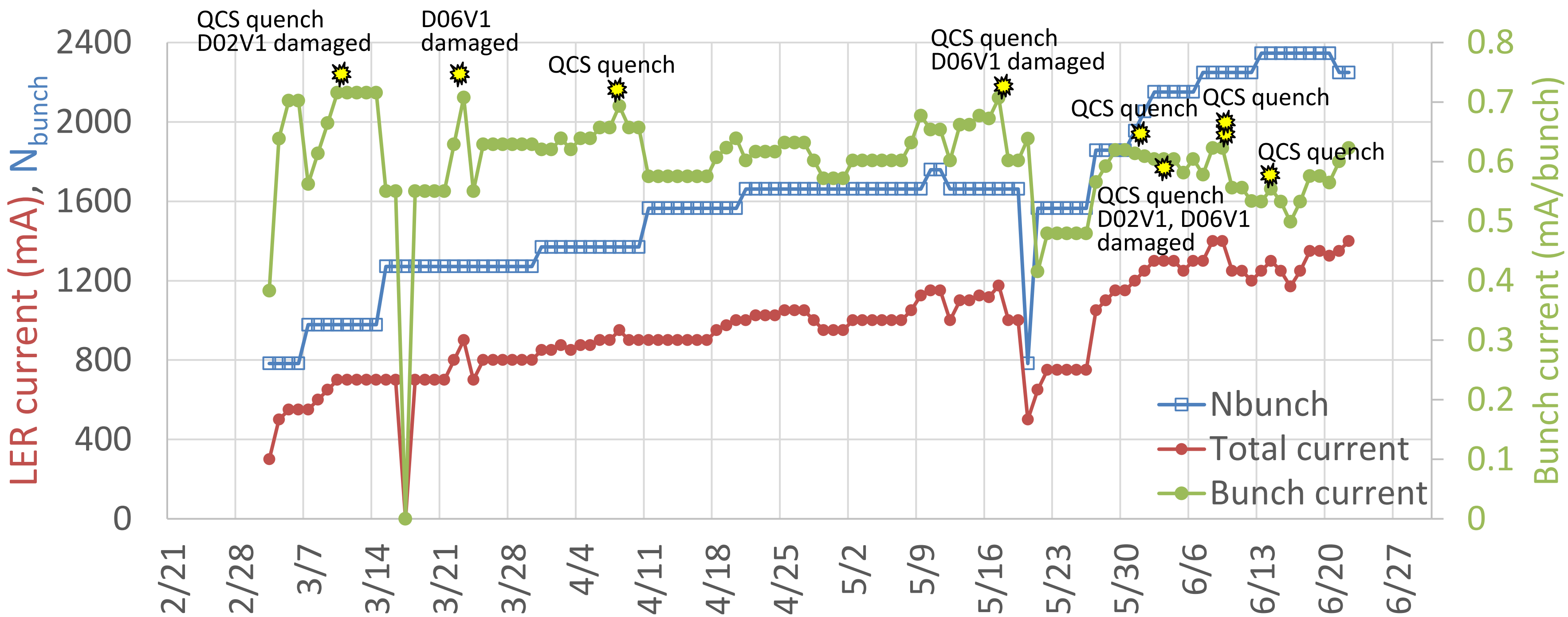
- Observed luminosity performance is much lower than simulations with BBSS (Beam-Beam Strong-Strong).

$$\mathcal{L}_{\mathrm{sp}} = \frac{\mathcal{L}}{I_{b+}I_{b-}n_b} \propto \frac{1}{\sigma^*_{x,\mathrm{eff}}\sigma^*_y}$$

D. Zhou

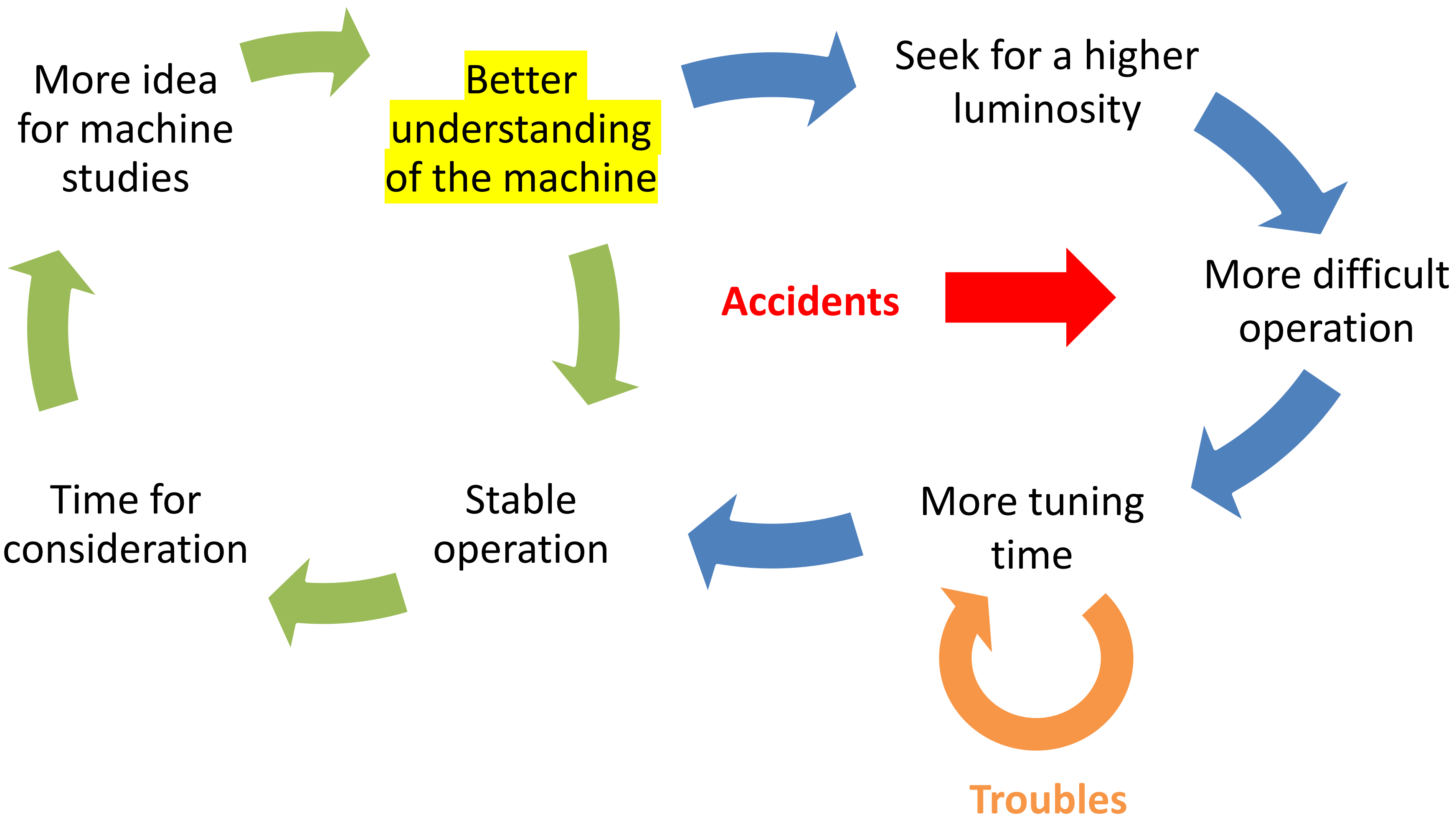


Beam loss accidents and bunch current

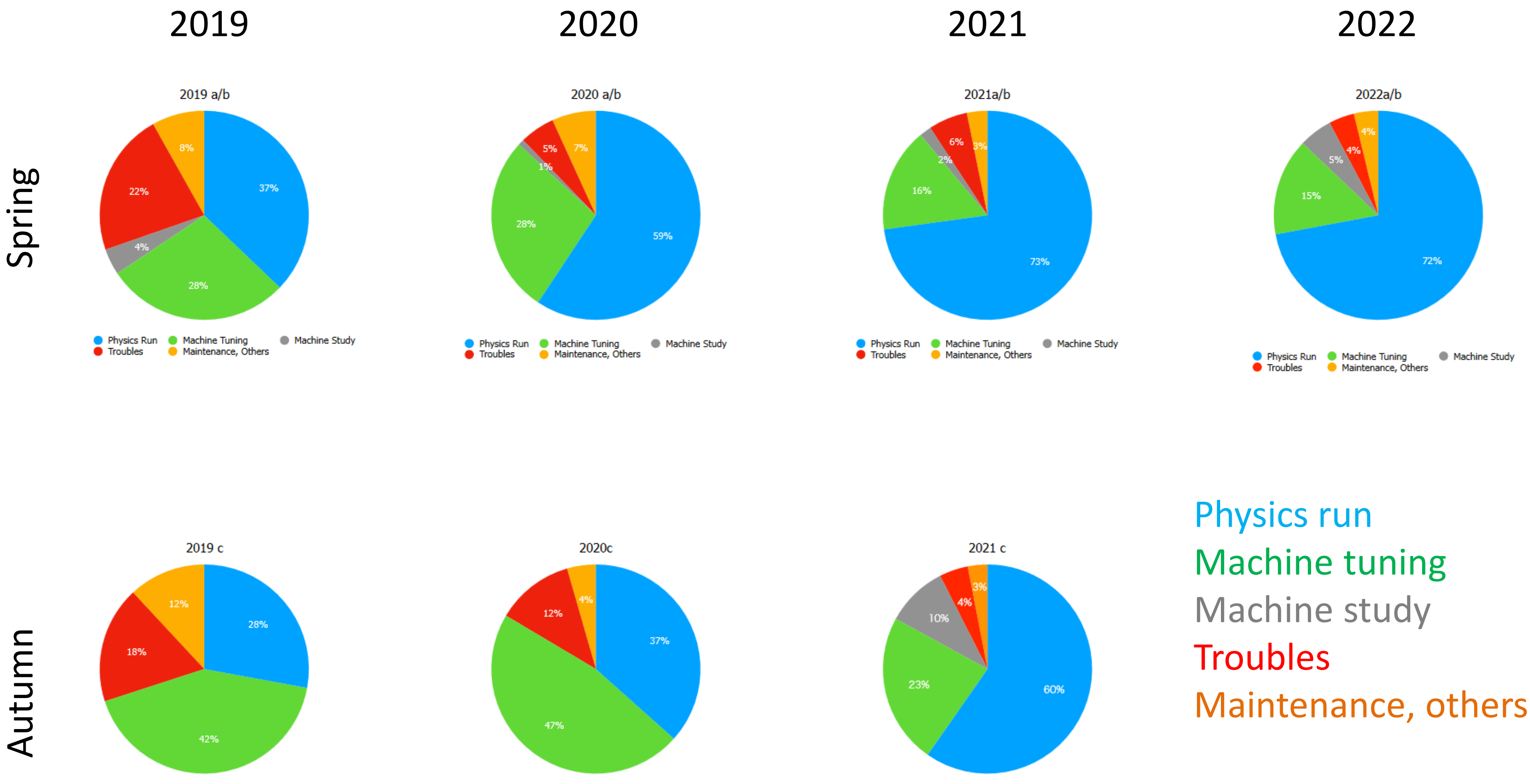


The first four accidents of LER beam loss in 2022 happened at $I_b \gtrsim 0.7$ mA/bunch within a day after increasing the beam current at each different N_{bunch}.
The threshold became somehow lower after the D06V1 damage on May 17.
It might be due to the D06V1 damage, different collimator configuration than usual to mitigate the beam background, or something else. Need investigation.

Rough picture of the machine progress



Breakdown of machine operation time

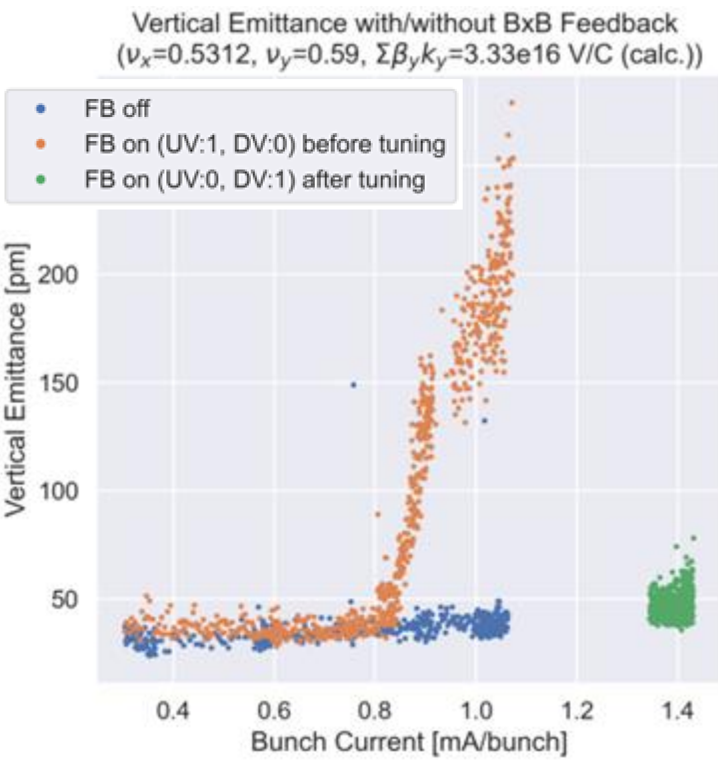


Y. Ohnishi

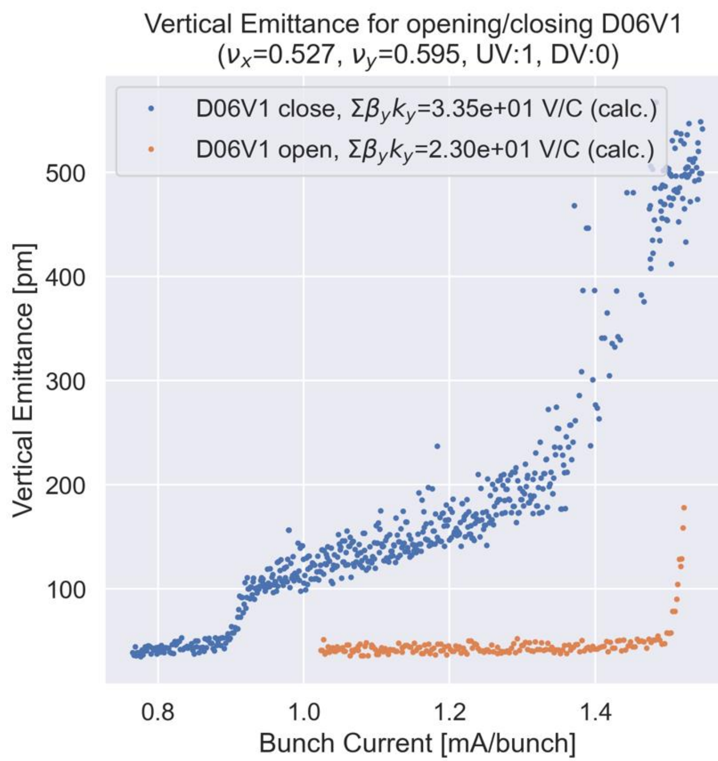
Getting better (less troubles, get practiced at machine tuning)

Recent major machine progress 1

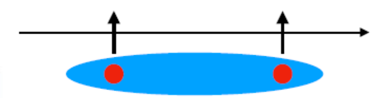
Effect of the bunch-by-bunch vertical feedback (Mar 1, 2022)



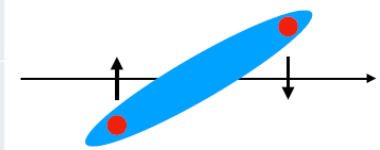
Effect of D06V1 collimator (Feb 28, 2022)



0 mode instability



–1 mode instability



Same eigen frequency at high I_b

⇩

Transverse mode coupling instability (TMCI)

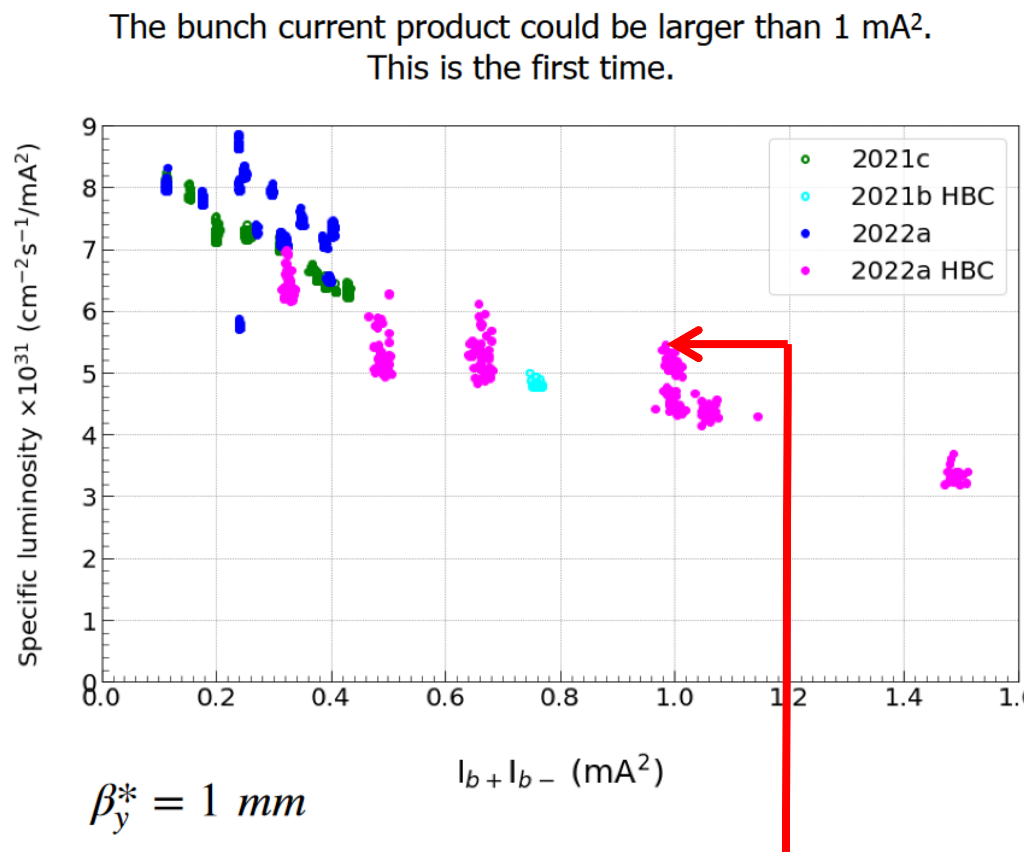
Ishibashi-san's report:
https://kds.kek.jp/event/41509/contributions/209154/attachments/153746/194916/20220324_TMCI.pptx

- TMCI threshold was found to be slightly higher than the design bunch current.
- The beam size blow-up due to –1 mode instability can be suppressed by tuning the feedback or opening the collimator.

Recent major machine progress 2

Machine study with $N_{bunch} = 31$ (low beam current) on Mar 28

- Reached $I_b I_b = 1.1\ mA^2$ without beam size blow-up
- Reached $I_b I_b = 1.5\ mA$ (design bunch current) for the first time.
  - Due to the low beam current, QCS BPM was not working properly, and iBump tuning was difficult. That could be the cause of the low specific luminosity at $I_{bunch} = 1.5\ mA$.



$L = 5.5 \times 10^{31}\ (cm^{-2}s^{-1}/mA^2) \times 1.0\ (mA^2) \times n_b$

$L = 10^{35}\ (cm^{-2}s^{-1})$ for 2.1 A / 1.6 A with 1859 bunches

Clear path to $1 \times 10^{35}\ /cm^2/s$

if the same L_{spec} is maintained at a higher beam current.

Ohnishi-san's report:
https://kds.kek.jp/event/41815/contributions/210134/attachments/154021/195440/BelleII_Monday_2022.04.04ACC.pdf

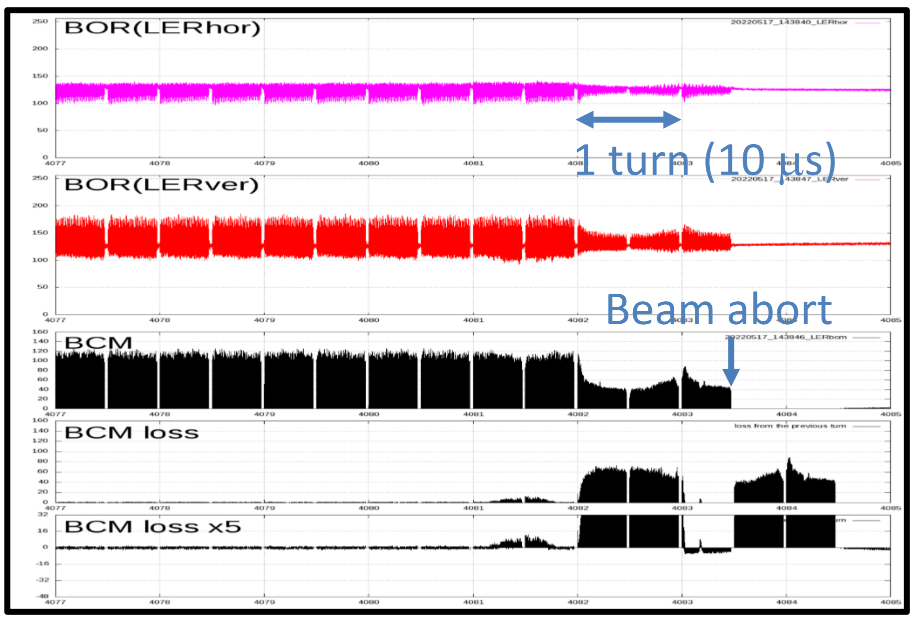
Belle II operation

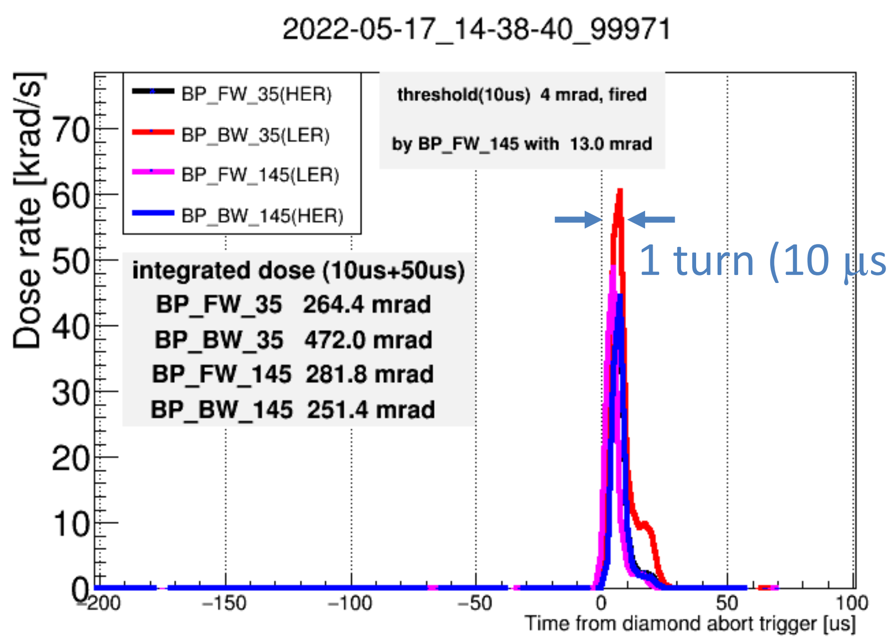
Basic strategy of Belle II operation

- First priority on the peak luminosity (machine tuning and study)
  - Except for safety issues
- Safe operation not to damage Belle II detector or machine components
- Physics data taking with a high efficiency
  - ➢ Mission of luminosity frontier experiments
  - Our first target: 90% of data taking efficiency
- Beam background control to suppress
  - Detector deterioration by integrated radiation dose
  - Detector performance degradation by high rate beam background
  - ➢ Required for precision experiments

Sudden beam loss of unknown cause

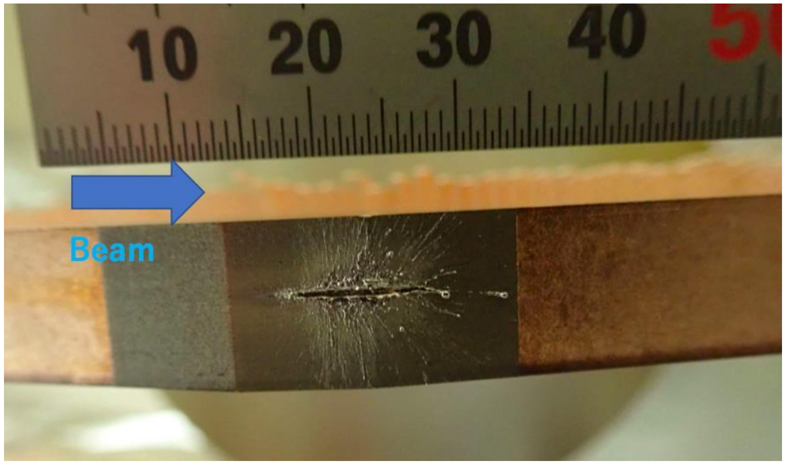
- Detector damage
  - PXD: a few % sensors became inoperable
  - SVD: 10 pin holes (June 2019)
  - Diamond: one control unit was damaged and replaced (May 10, 2021)
- Collimator damage
  - Beam background increase
- QCS quench



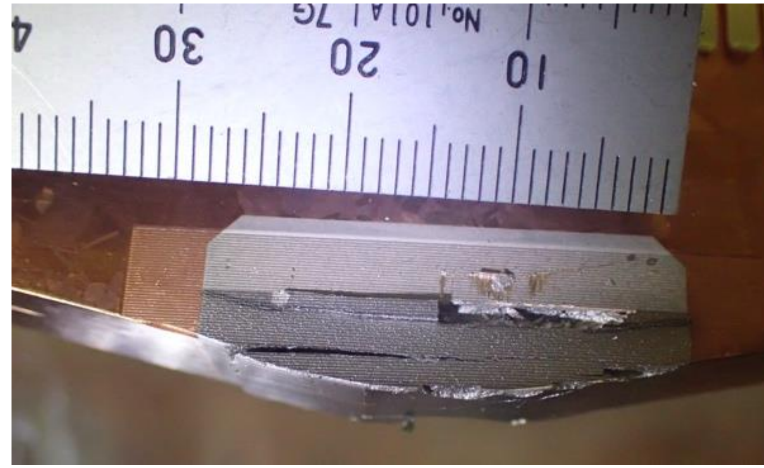


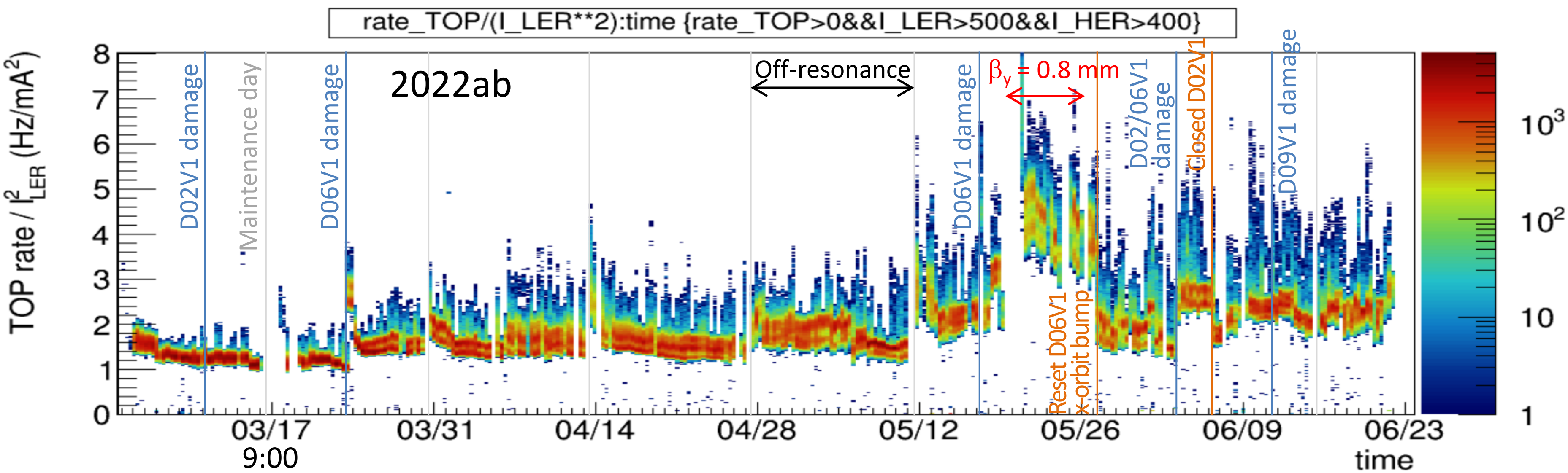
Collimator damage

Damaged jaw of D02V1 (LER) due to sudden beam loss



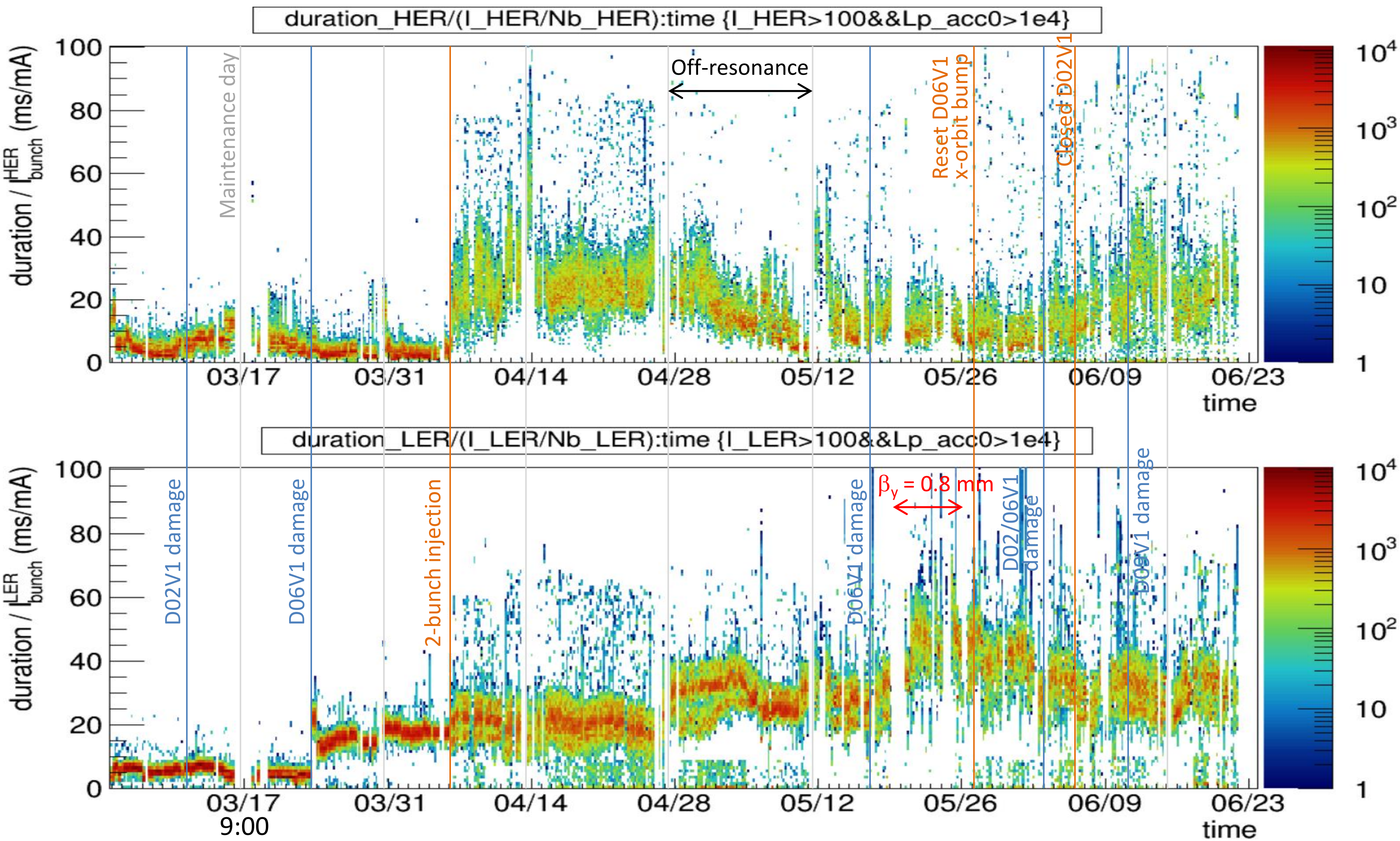
Damaged jaw of D06H3 (LER) due to (accidental firing of injection kickers)





Damaged collimators increase the beam background and they have to be opened to mitigate it.

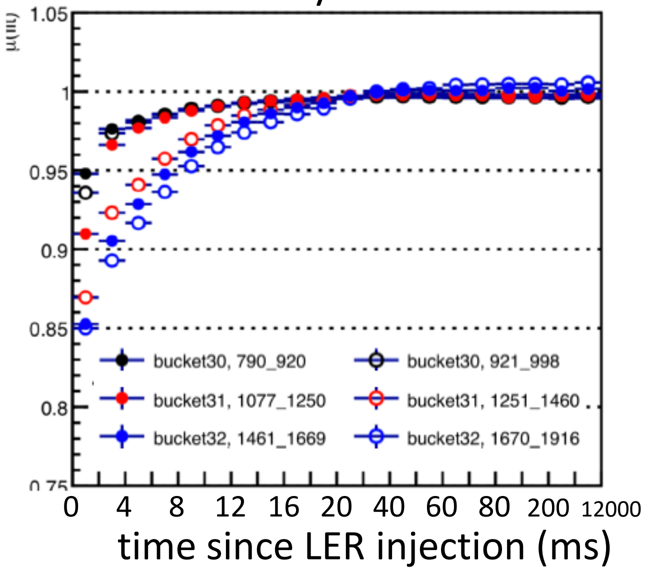
Injection background duration

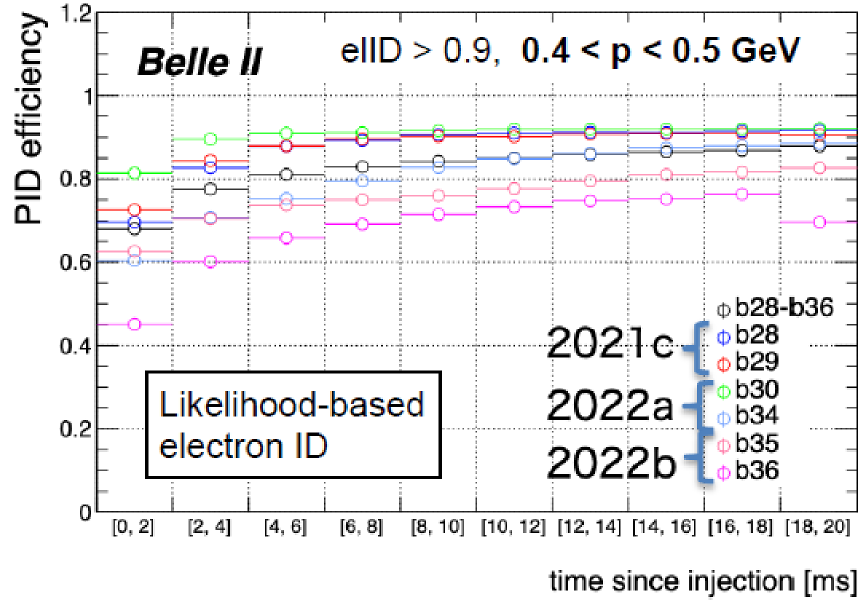


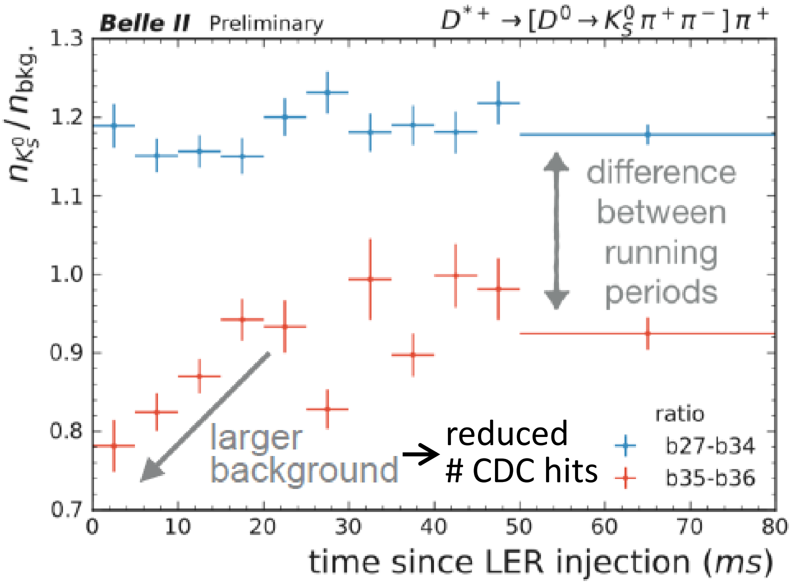
D06V1 damage and 2-bunch injection of bad quality significantly increased the injection background.

Effect of injection background

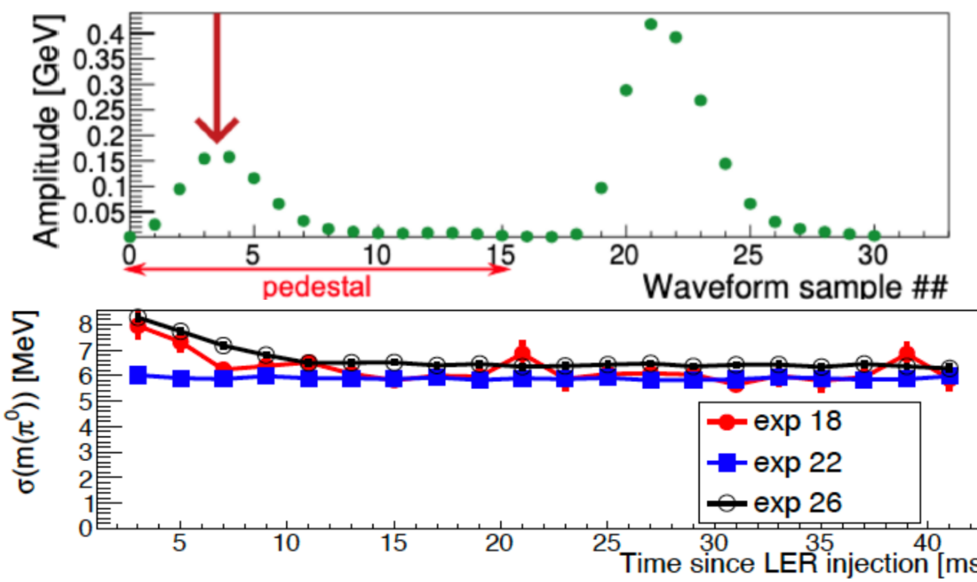
CDC dE/dx mean







ECL waveform data



Urgent issues in Belle II operation

Beam current increase

Sudden beam loss

Beam abort enhancement

greater risk ⇒ Collimator/detector damage ⇐ smaller risk

Beam background increase

Stop-gap collimator tuning

More aborts at injection

Balance with stable machine operation

⇒ **Obstacle in machine operation (low luminosity)**

Obstacle in Belle II operation (low data taking efficiency, detector performance degradation)

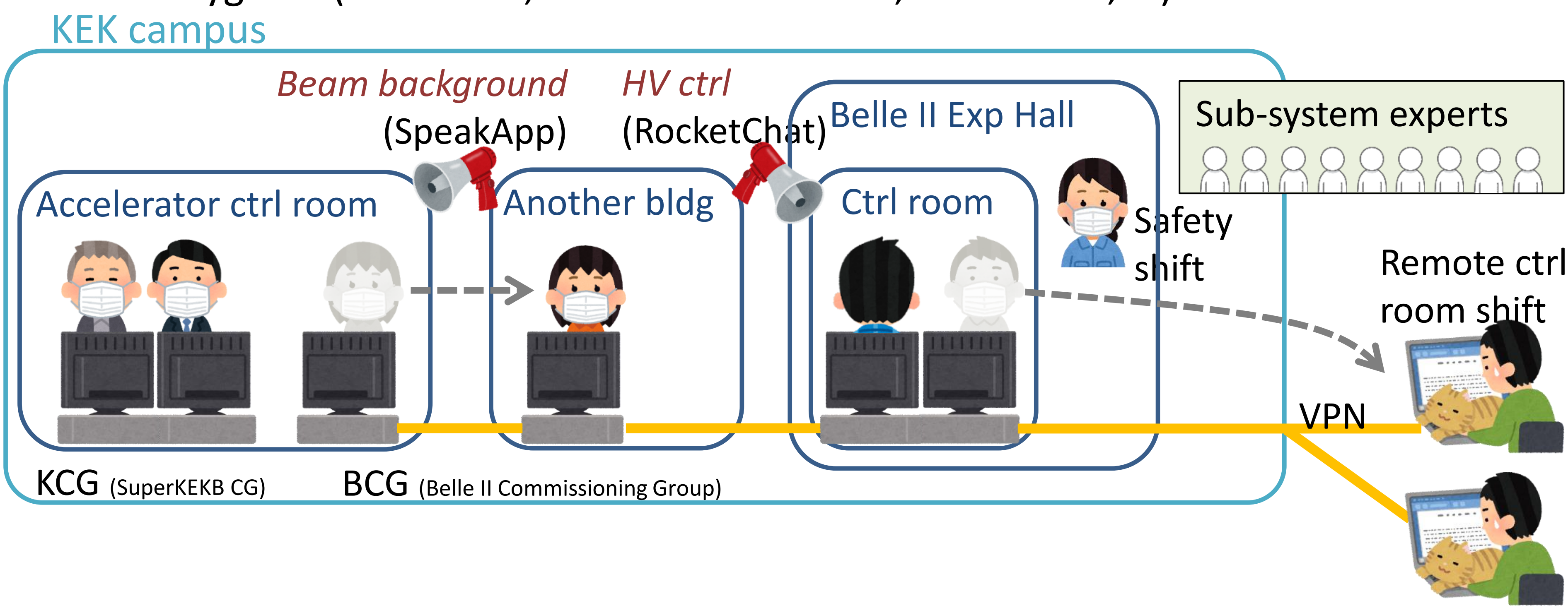
【Multiple measures】

- Investigation and resolution of the cause of sudden beam loss
- Faster beam abort and detector interlock
- Robust and redundant collimator
- Better strategy of collimator tuning with damaged collimators
- Mitigation of beam background with additional shield and non-linear collimator; More tolerance for beam background (DAQ system, detector, analysis)

Operation shifts under COVID-19

- SuperKEKB/Belle II was operated under Covid-19 pandemic since 2020 while minimizing risk of infection:
  - Minimize person-to-person contact and avoid 3C
    - Remote control room shifts and expert shifts
    - Travel restrictions (~40 Belle II colleagues on-site)
    - Online meetings
  - Hygiene (face mask, alcohol disinfection, ventilation, …)

Closed space
Crowded places
Close−contact settings



Scheme for operation/data quality control

Run start

Online

Run stop

Offline

<u>CR shifter's tasks</u>

- Operation control
- Monitoring of data quality and some detector status
- First troubleshooting
  - If not fixed, call experts
- Data quality flag in Run Registry
- Log writing

Any urgent issues which could affect physics data taking and quality are supposed to be immediately identified by CR shifters. Experts should provide just enough necessary information for that to CR shifters.

<u>Subsystem expert's tasks</u>

- Configuration optimization
- Monitoring of detector status
- Recovery from errors
- Data quality flag in Run Registry
- Check of detector performance and stability in detail

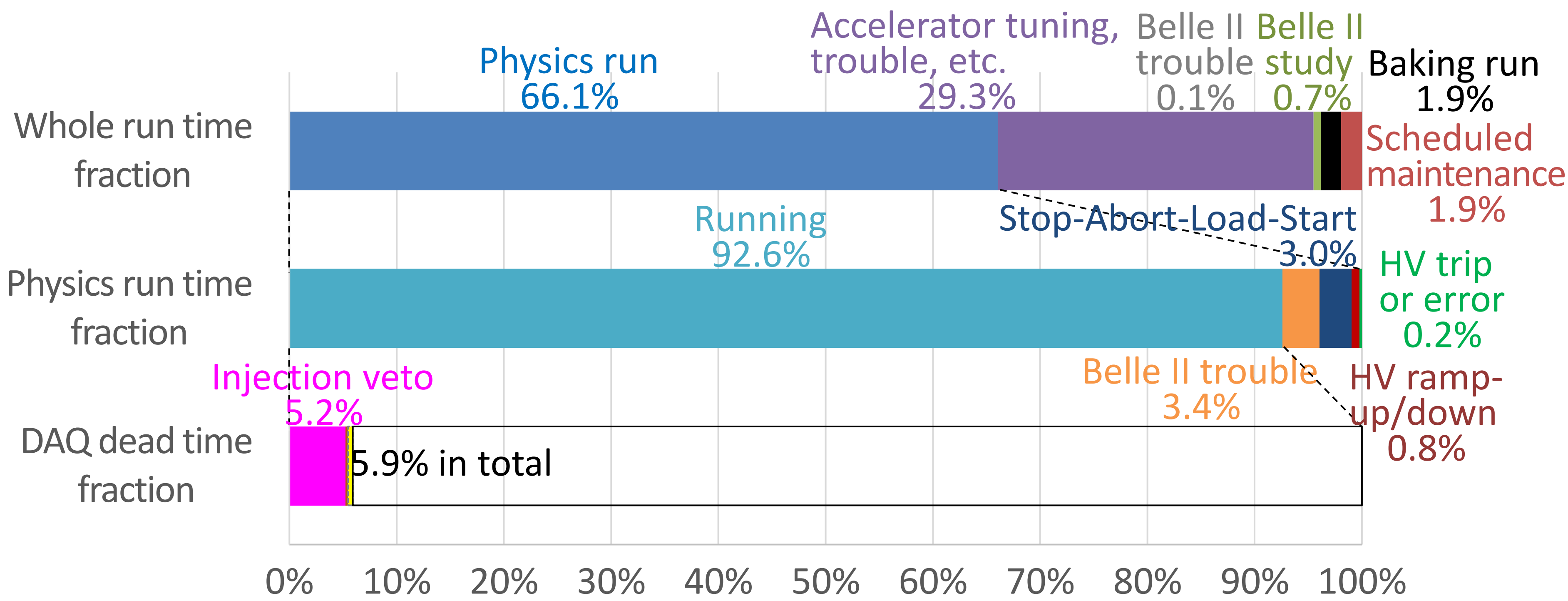
<u>Physics performance group's tasks</u>

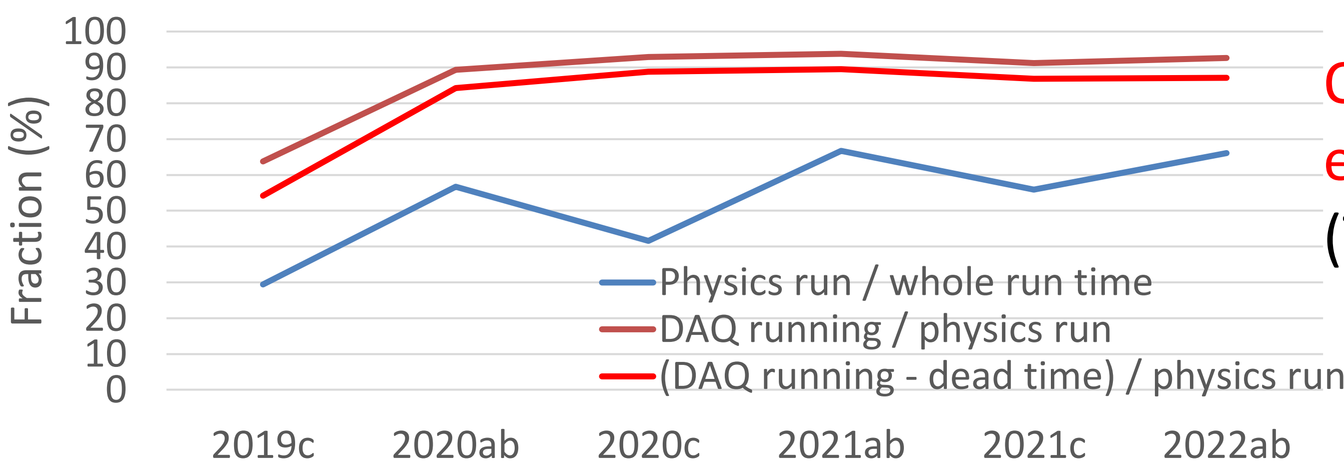
- Check of physics performance

Need prompt feedback to operation

Feb 21 - Jun 22, 2022

Data taking efficiency in 2022ab



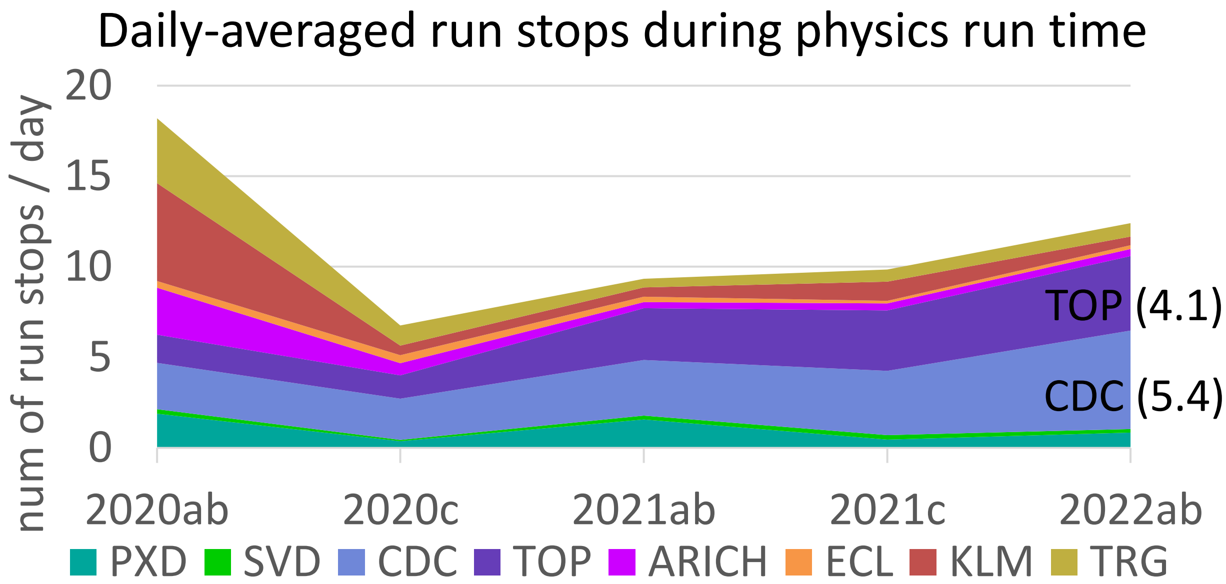


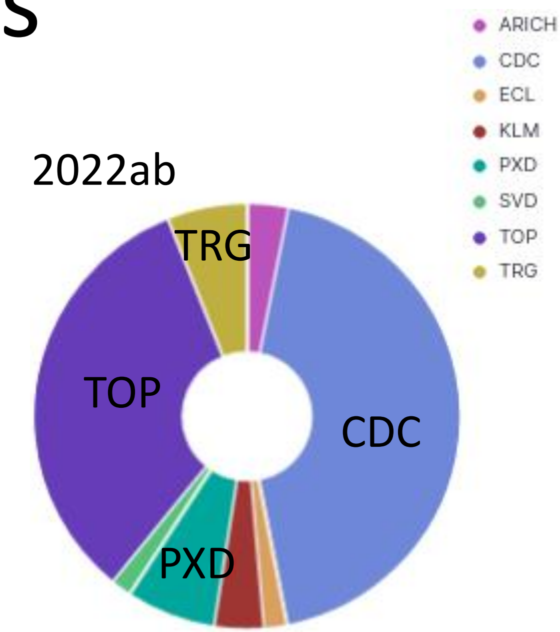
Overall data taking efficiency = 87.1%

(Target 90%)

Getting worse with the beam background.

Run stop reasons





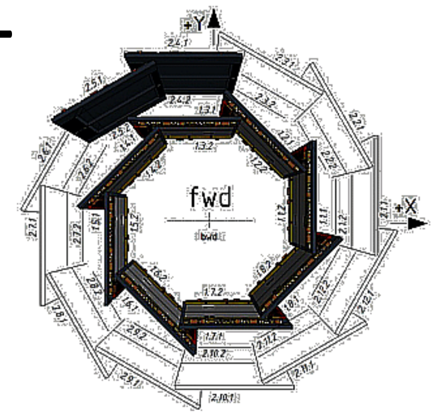
Feb 21 – Jun 22, 2022

FPGA Single Event Upsets on CDC and TOP front-end electronics is the major concern.

- Reduce recovery time
  - Reduction of time for HLT LOAD (~70 sec), which dominates time for Stop-Abort-Load-Start (~2 min)
- Reduce run-stopping errors
  - TOP firmware update to retire PS (Processing System) → It will eliminate almost all TOP-related run stops.
  - CDC software (and firmware) update to withstand corrupted data
    → Run stops will be reduced by ~30% (and more). Need more human resource to work on them.
- Reduce beam background
  - Additional neutron shield and shield at the QCS bellows
  - Non-linear collimator

Work in LS1

Major upgrades in LS1

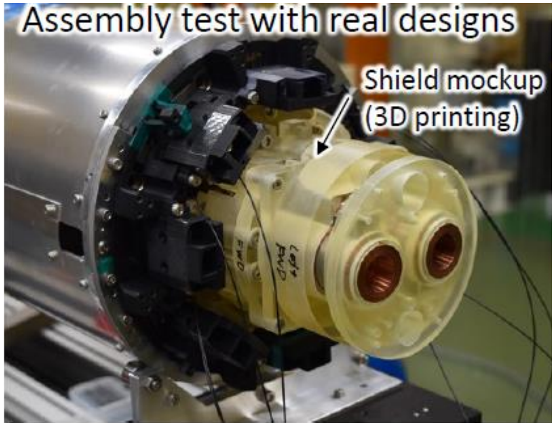


Belle II detector upgrade

- Exchange of PXD (pixel detector) with the full 2nd layer
- TOP conventional MCP-PMT replacement (TBD)
- Migration to new back-end readout (COPPER → PCIe40)

Beam background mitigation

- Additional shield on the QCS(*) bellows
- Additional shield for neutron background
- Installation of a non-linear collimator

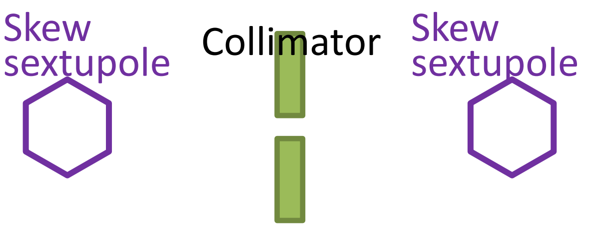


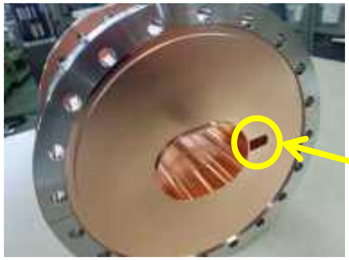
Protection of machine and Belle II

- Collimator heads of more robust material
- Faster beam abort system

Improvement of beam injection

- Enlarged beam pipe at the HER injection
- Pulse-by-pulse beam control for Linac





Beam channel for injection

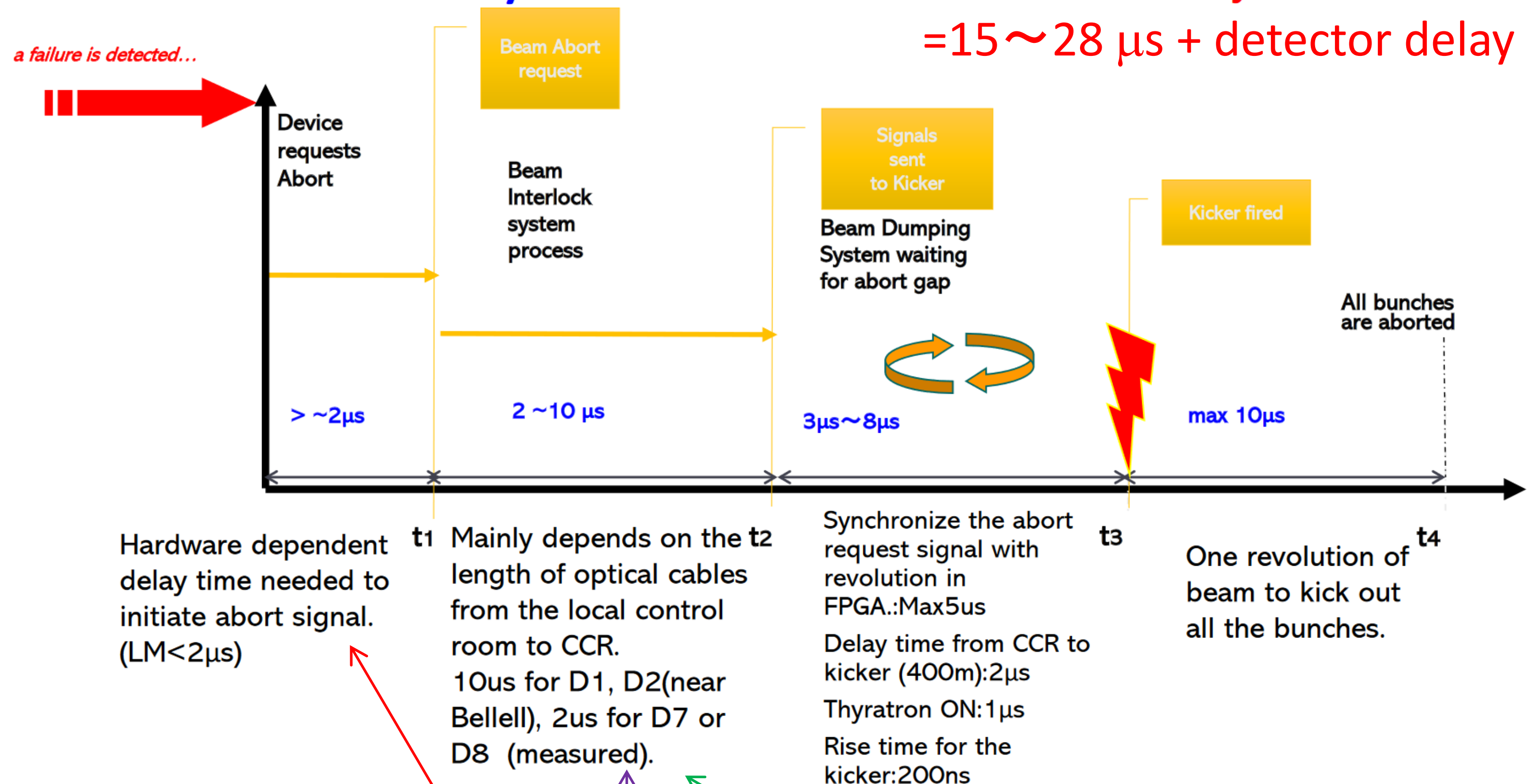
Beam kick by skew sextupole:

$$\Delta p_y = \frac{SK_2}{2}(y^2 - x^2),\ \Delta p_x = SK_2 xy$$

Reduction of beam abort delay

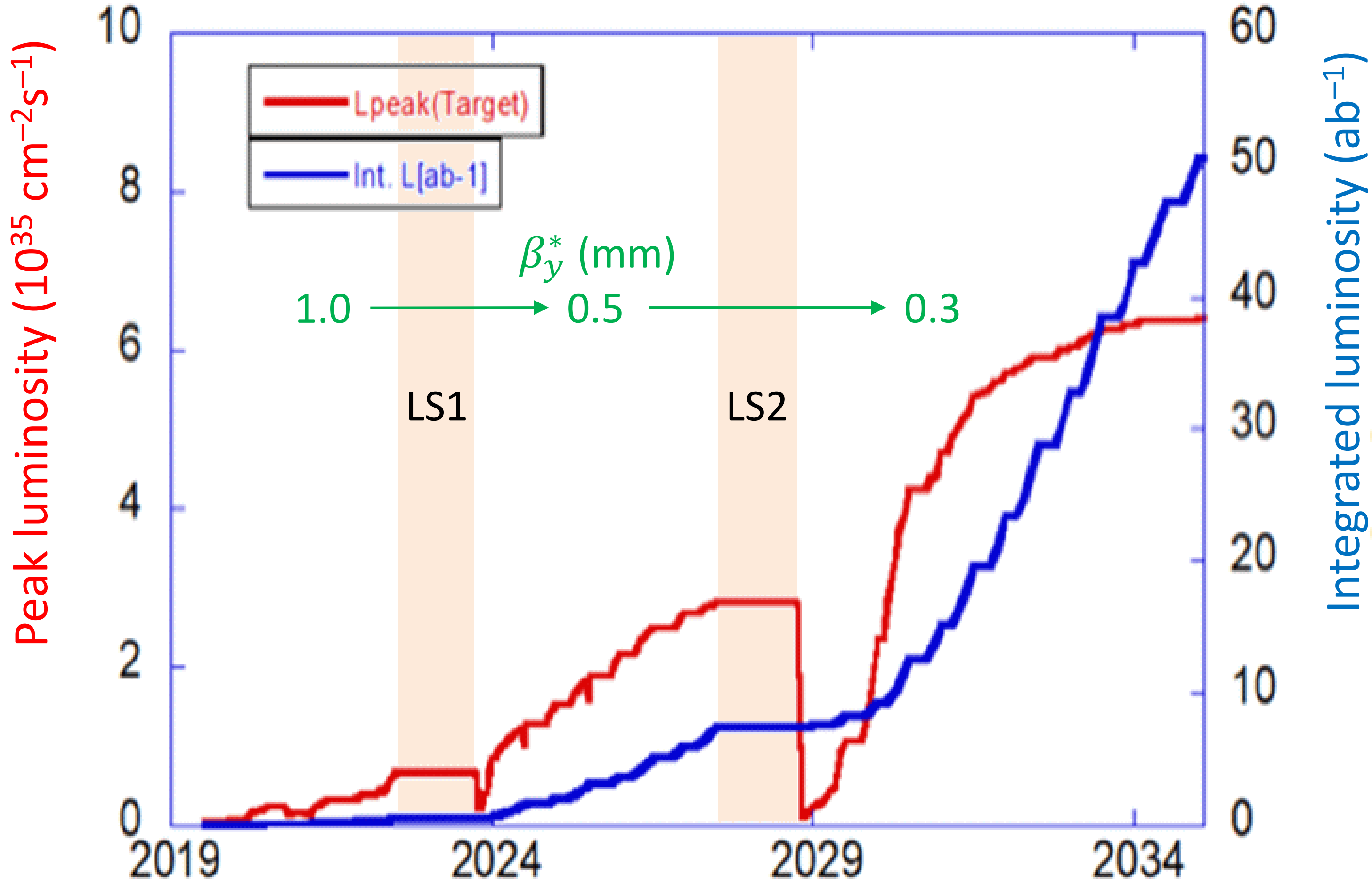
Beam Abort Delays

Minimum Abort Delay
=15～28 μs + detector delay



- …
- May 28, 2021, introduced CLAWS abort → faster by 3-24 μs (~10 μs avg.) than diamond
- Jun 9, 2022, introduced fiber loss monitor abort near D06V2 → minus several μs in some cases
- During LS1, CLAWS abort at D06 or D05 (NLC) being planned → minus 1-2 μs
- During LS1, direct abort signal to the abort kicker from D06 or D05 under consideration → minus 1.9 μs (D06) or 0.5 μs (D05; TBC)

Projection toward 50 ab^{-1}



Need to understand the machine and find solutions (many challenges ahead)

Summary

- We have faced with difficult challenges in terms of the performance and operation of this cutting-edge accelerator.
- Nevertheless, we have fixed issues one-by-one and built up understanding of the machine.
  - I am sure we can achieve 1×10^{35} $cm^{-2}s^{-1}$ soon after LS1.
- Increasing beam background is a big challenge in Belle II operation.
- Your contribution is essential:
  - Please join us in the operation of both Belle II and SuperKEKB.
  - Physics outcome is the driving force of this project.