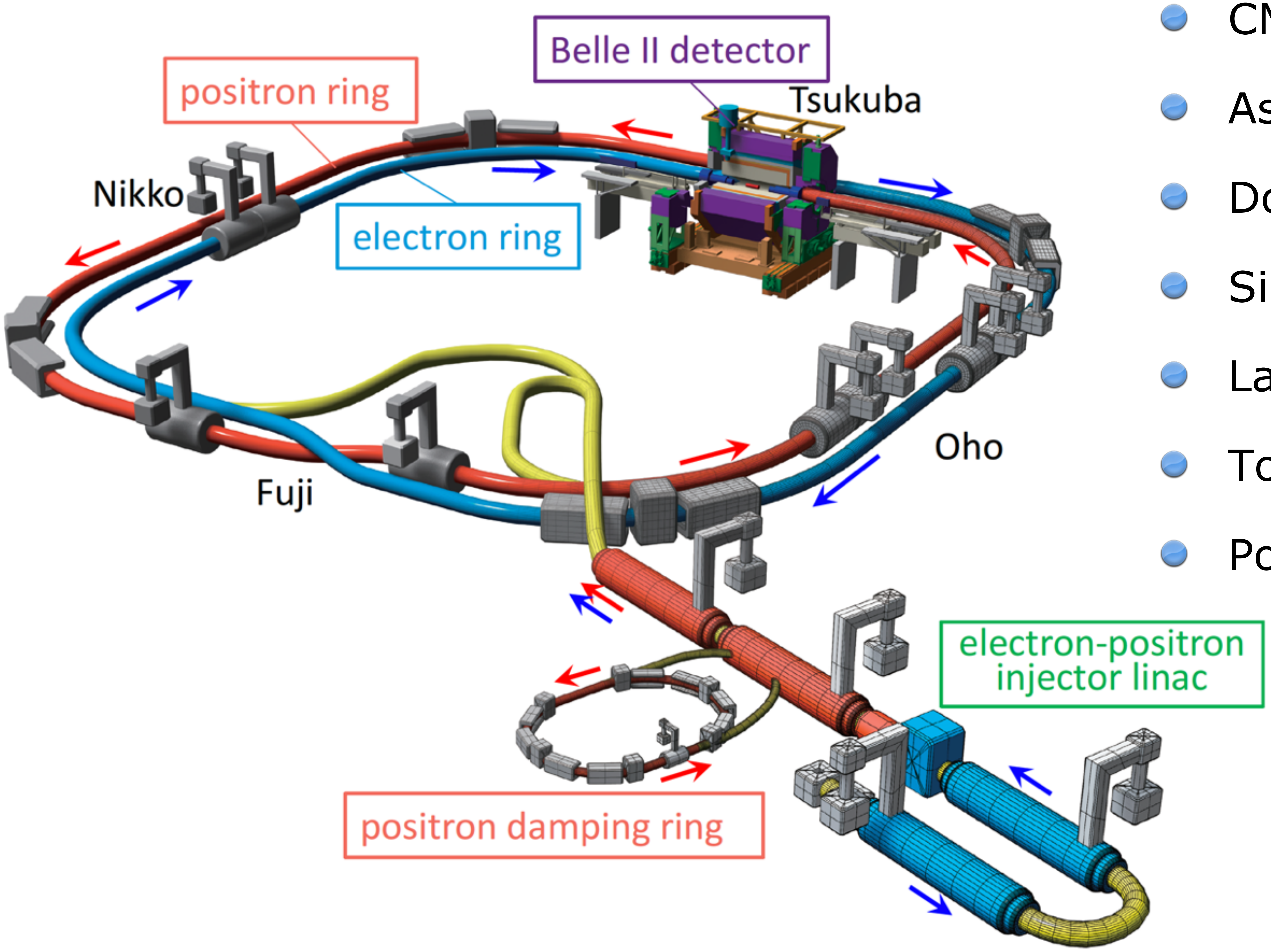
Status of SuperKEKB

Y. Ohnishi

SuperKEKB and Belle II



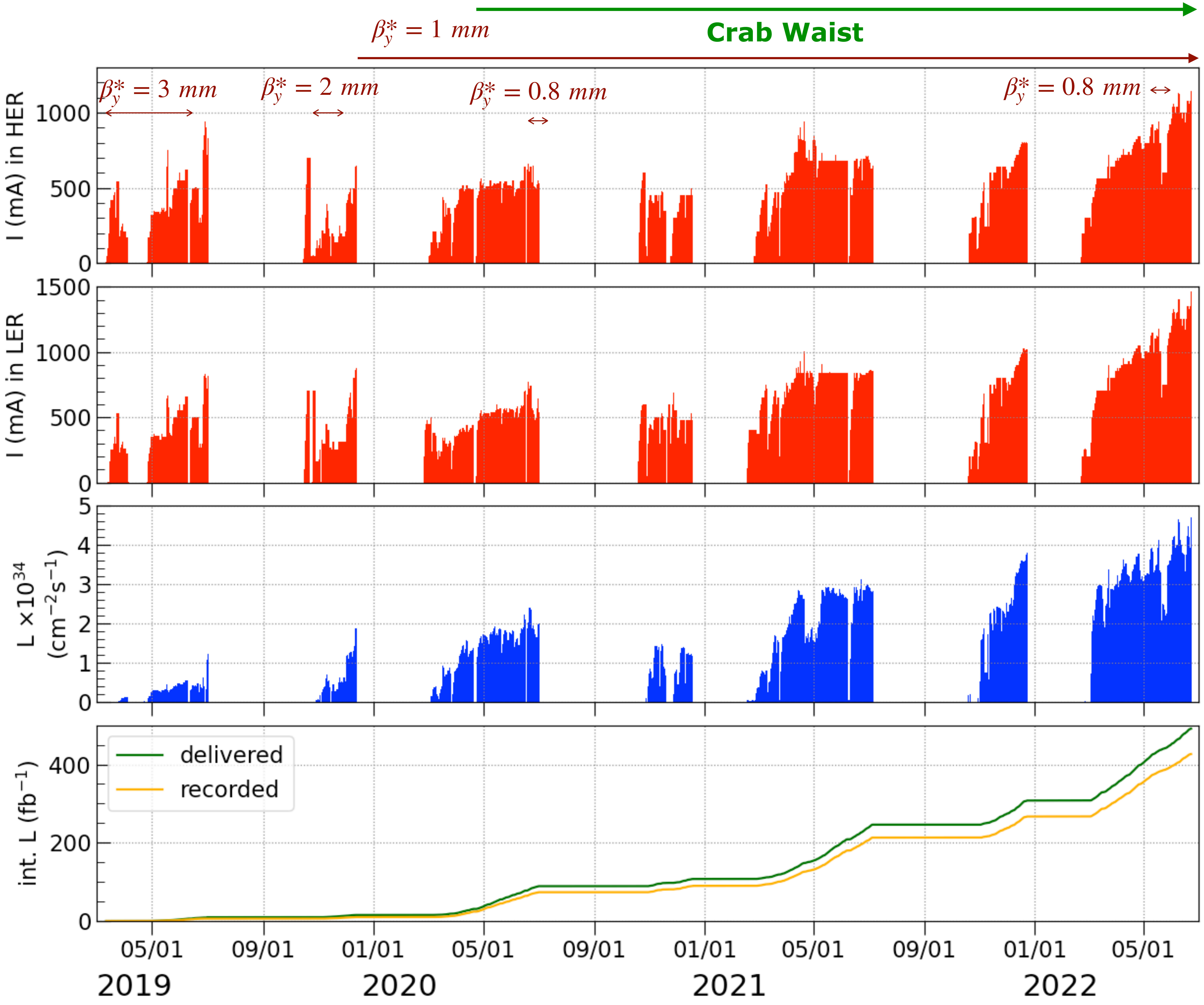
- CMS Energy: 10.58 GeV
- Asymmetric Energy
- Double Rings
- Single Interaction Point
- Large Crossing Angle at IP : 83 mrad
- Top-Up Injection
- Positron Damping Ring

- Beam Energy LER(e+): 4 GeV, HER(e-): 7GeV
- Circumference: 3 km
- Emittance LER: 4 nm, HER: 4.6 nm — Achievements:
- Beam current LER: 3.6 A, HER: 2.6 A — LER: 1.46 A, HER: 1.14 A
- Max. number of bunches: 2346
- Vertical beta at IP: 0.3 mm — 0.8 mm - 1.0 mm
- Target Luminosity: > 6×10^{35} $cm^{-2}s^{-1}$ — $4.65(4.71) \times 10^{34}$
- Nano-Beam Scheme + Crab-Waist Scheme — < 1/10 of Target

Still Far from Target Luminosity ...

Pirates of the Caribbean: Dead Man Tell No Tales (2017)

History of SuperKEKB



1145 mA

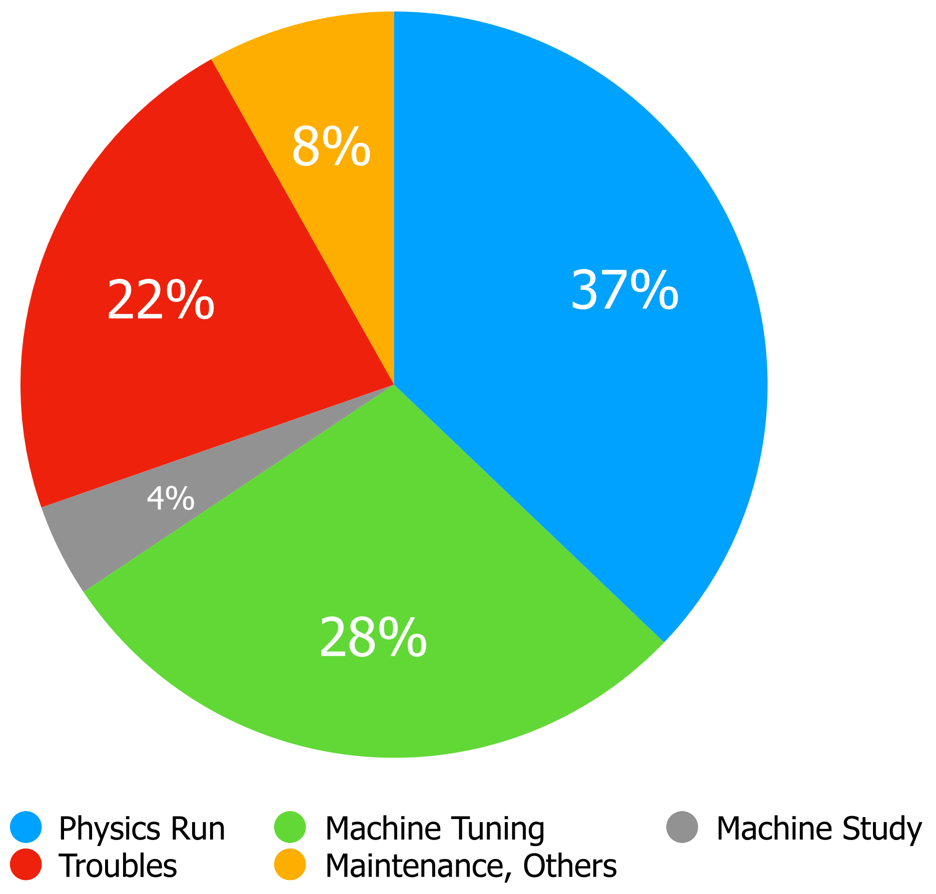
1460 mA

4.65 x 10^{34} $cm^{-2}s^{-1}$

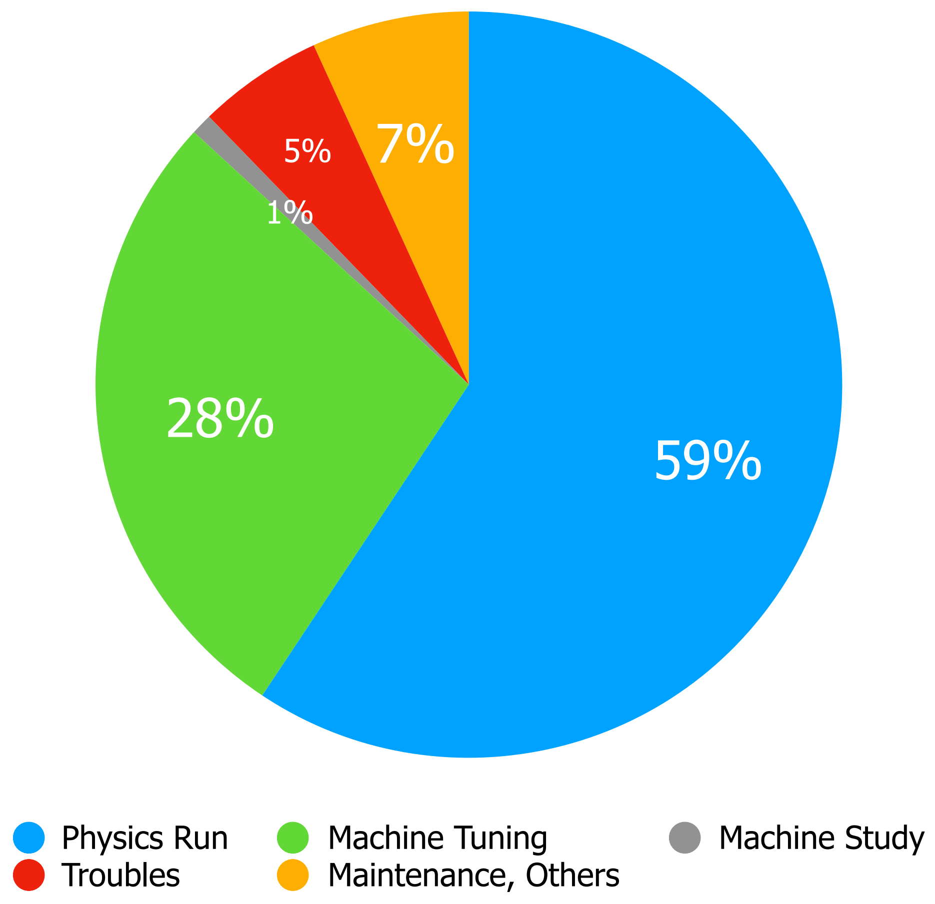
4.71 x 10^{34} $cm^{-2}s^{-1}$: Belle II HV off

424 fb^{-1} / 491 fb^{-1}

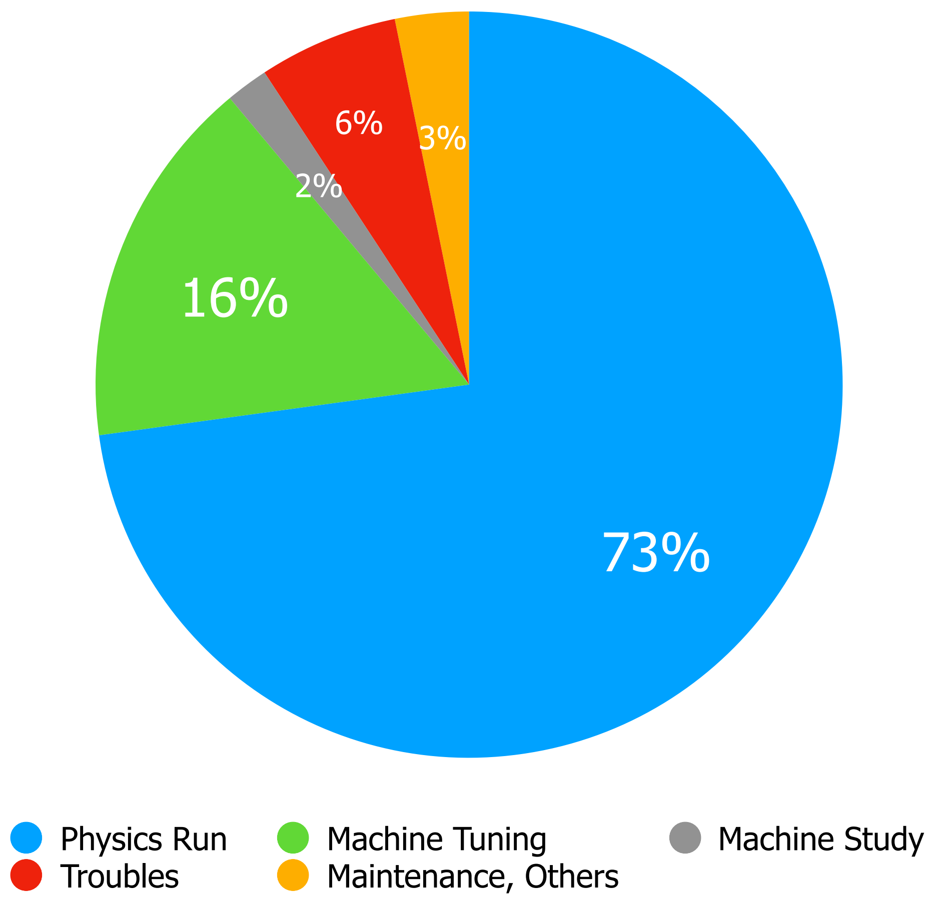
March - July, 2019



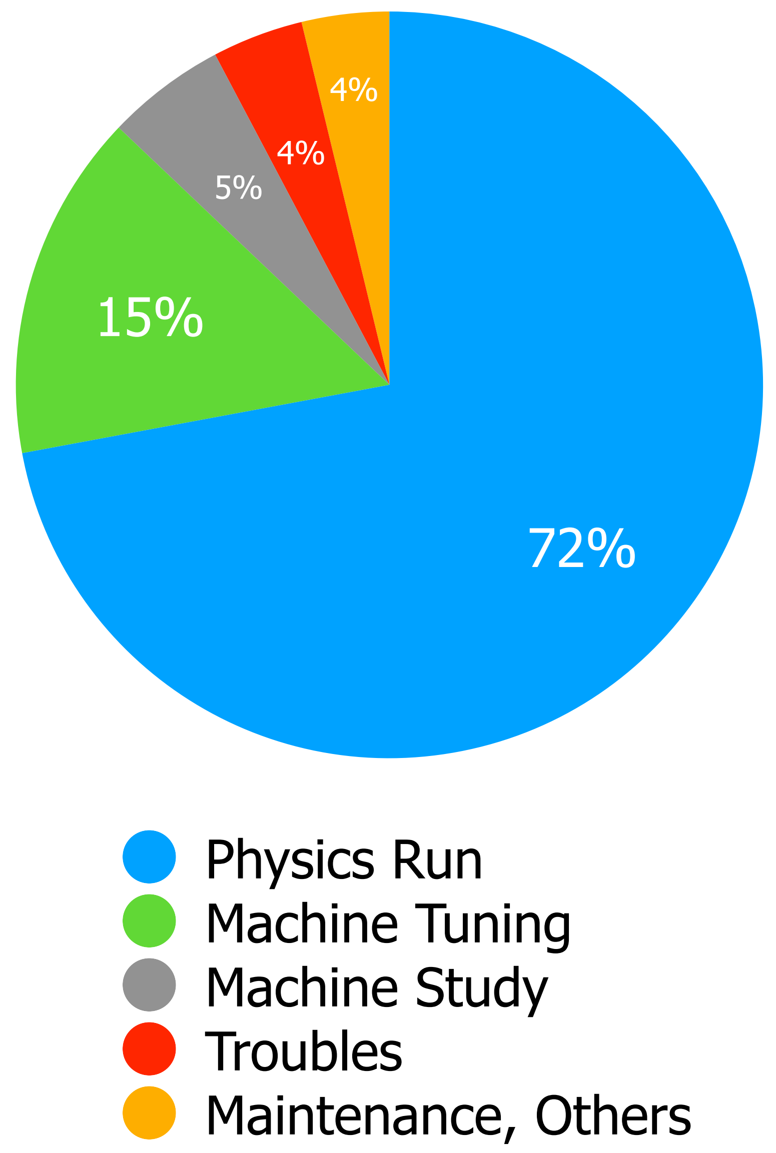
February - July, 2020



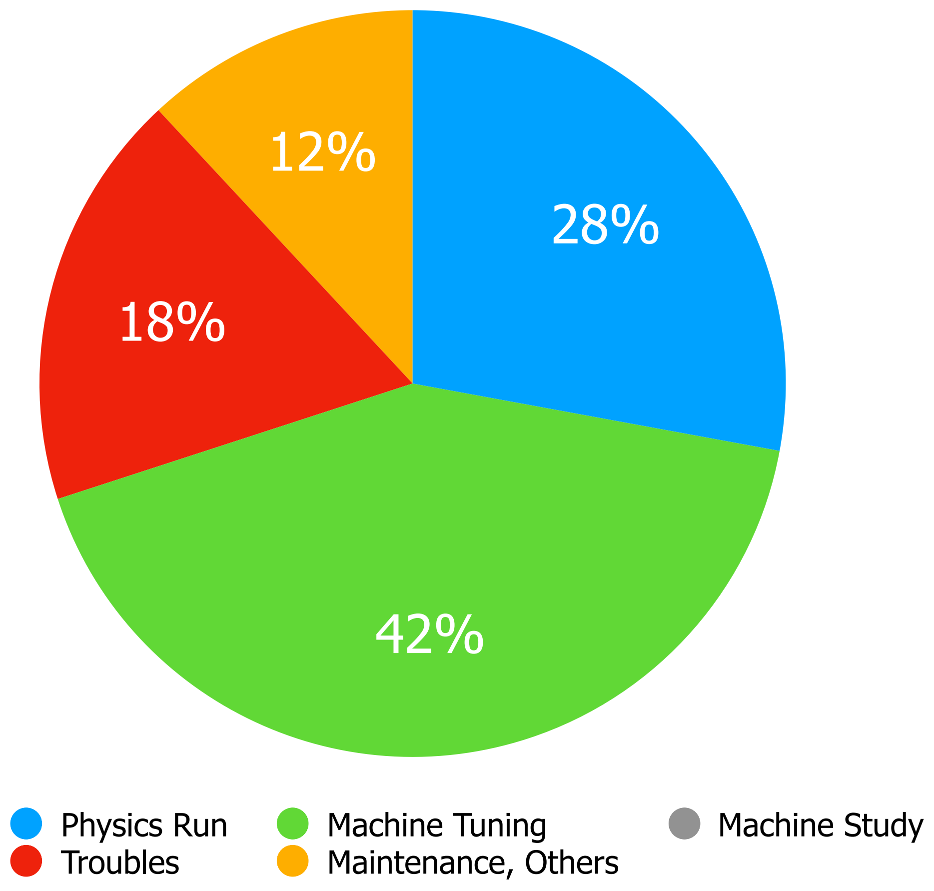
February - July, 2021



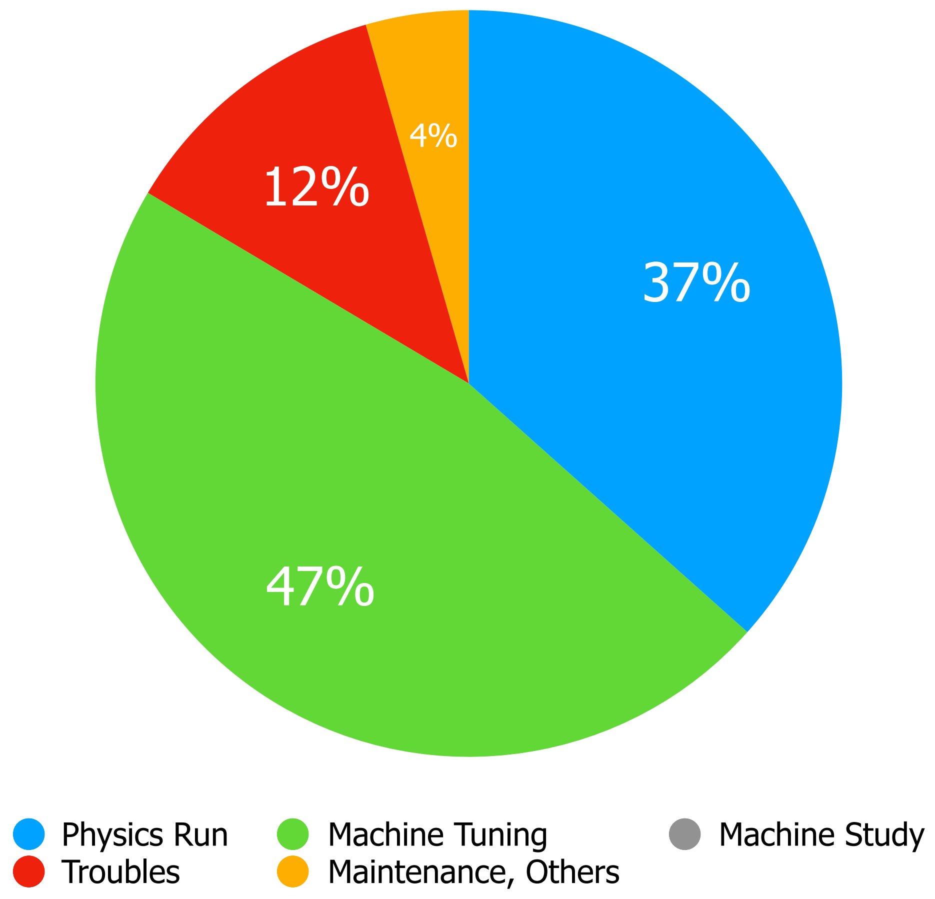
February - June, 2022



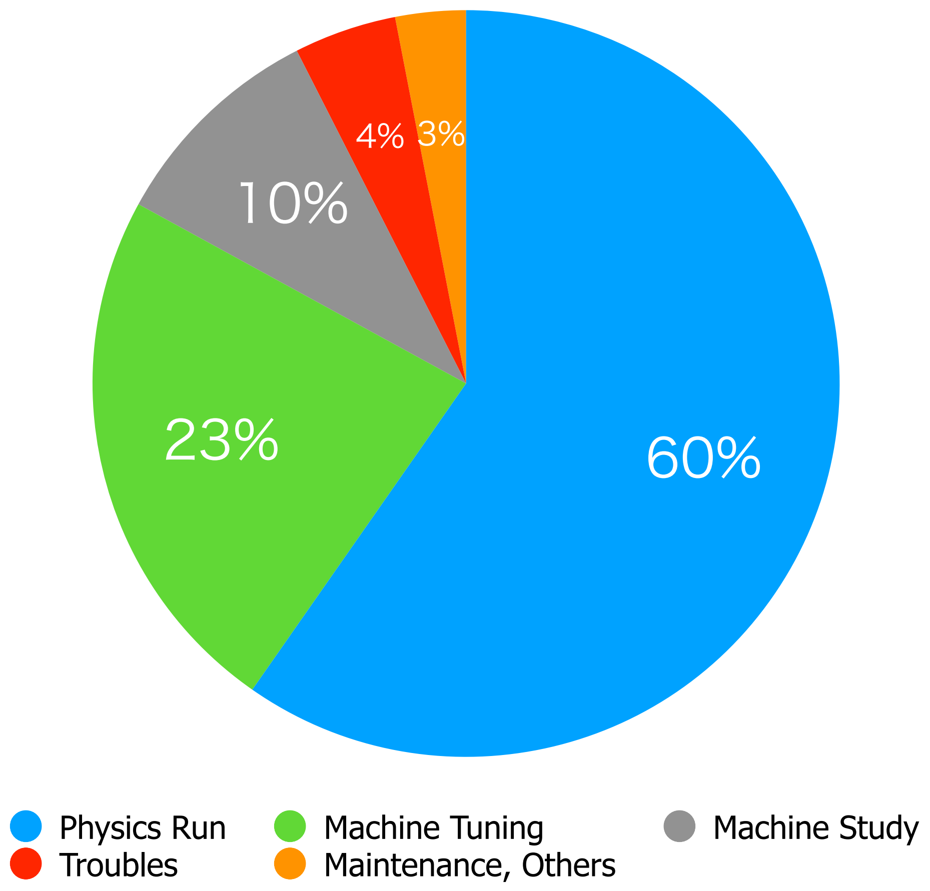
October - December, 2019



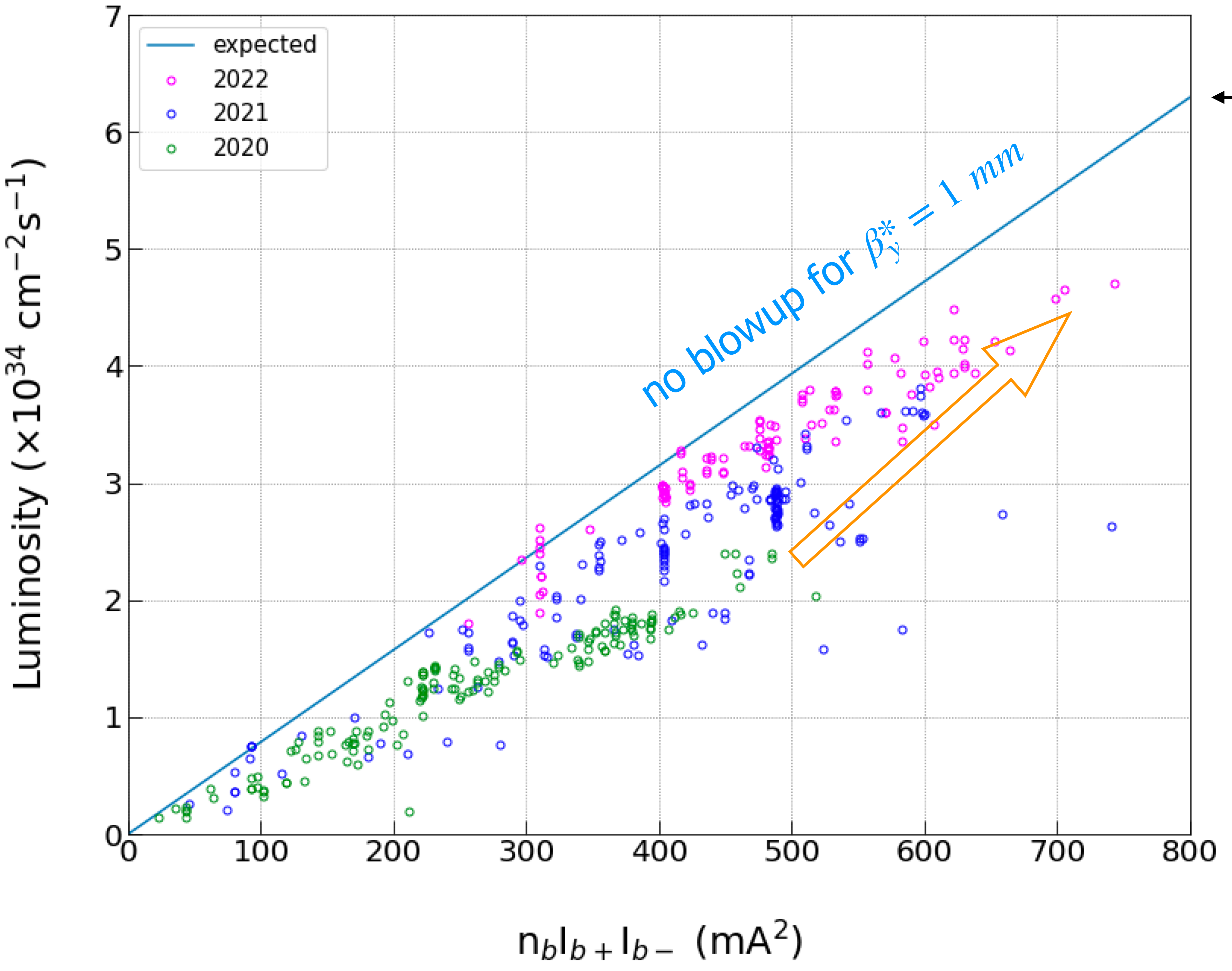
October - December, 2020



October - December, 2021



Operation Statistics 2019 -2022



$$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma_x^* \sigma_y^*} R_L$$

$$= \frac{n_b I_{b+} I_{b-}}{2\pi (e^2 f_0) \phi_x \Sigma_z \Sigma_y^*}$$

Expected Bunch Length: $\Sigma_z = 7.8\ mm$

$$\Sigma_z = \sqrt{(\sigma_{z+})^2 + (\sigma_{z-})^2}$$

$\beta_y^* = 1\ mm$

$\varepsilon_{y+} = 35\ pm$

$\varepsilon_{y-} = 25\ pm$

$$\Sigma_y^* = \sqrt{(\varepsilon_{y+} + \varepsilon_{y-})\beta_y^*}$$

Half Crossing-Angle: $\phi_x = 41.5\ mrad$

Improvements:
from 2020 to 2021: Manage of HER BxB FB Gain and Collimator Impedance
from 2021 to 2022: Chromatic X-Y Coupling Correction and LER BxB FB Optimization

Seven Major Issues

1. Sudden Beam Loss
2. Beam-Size Blowup due to Beam-Beam Interactions
3. Beam-Related Background
4. Injection Efficiency and Emittance Blowup in the Beam Transport Line
5. Difficulties to Keep Beam Orbit Stable (from Low Current to Hight Current)
6. Short Lifetime and Narrow Dynamic Aperture with β_y^* Squeezing
7. Beam-Size Blowup due to -1 Mode Instability in the LER (Almost Fixed)

Sudden Beam Loss (SBL)

Beam Becomes Unstable Suddenly at High Beam Current.
Beam Loss Leads to Severe Damage on Collimators or Final Focus Magnet (QCS) Quench.

LER Beam Current : 1.4 A
Number of Bunches : 2249
Luminosity : 4.58 x 10^{34} $cm^{-2}s^{-1}$

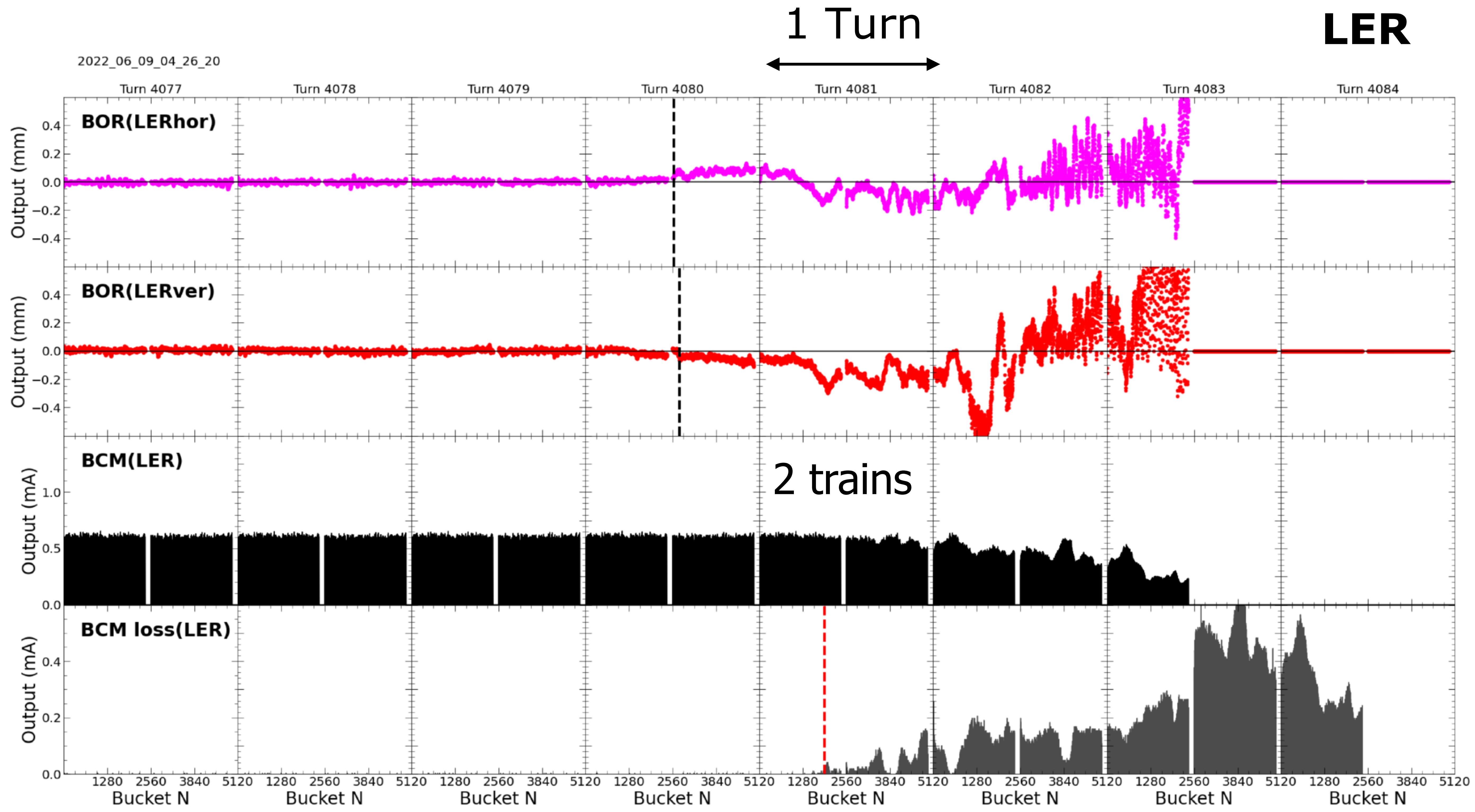
Beam Loss within a Few Turns
Without Large Oscillation Before the Loss.

Horizontal Position

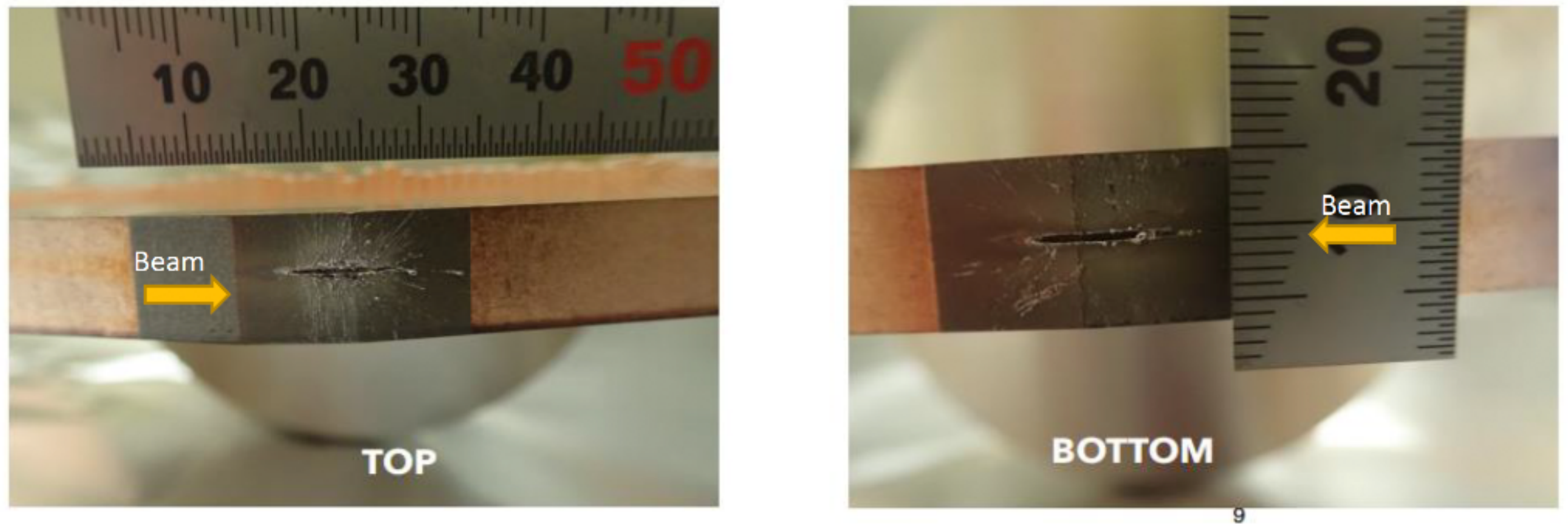
Vertical Position

Bunch Current

Amount of Beam Loss



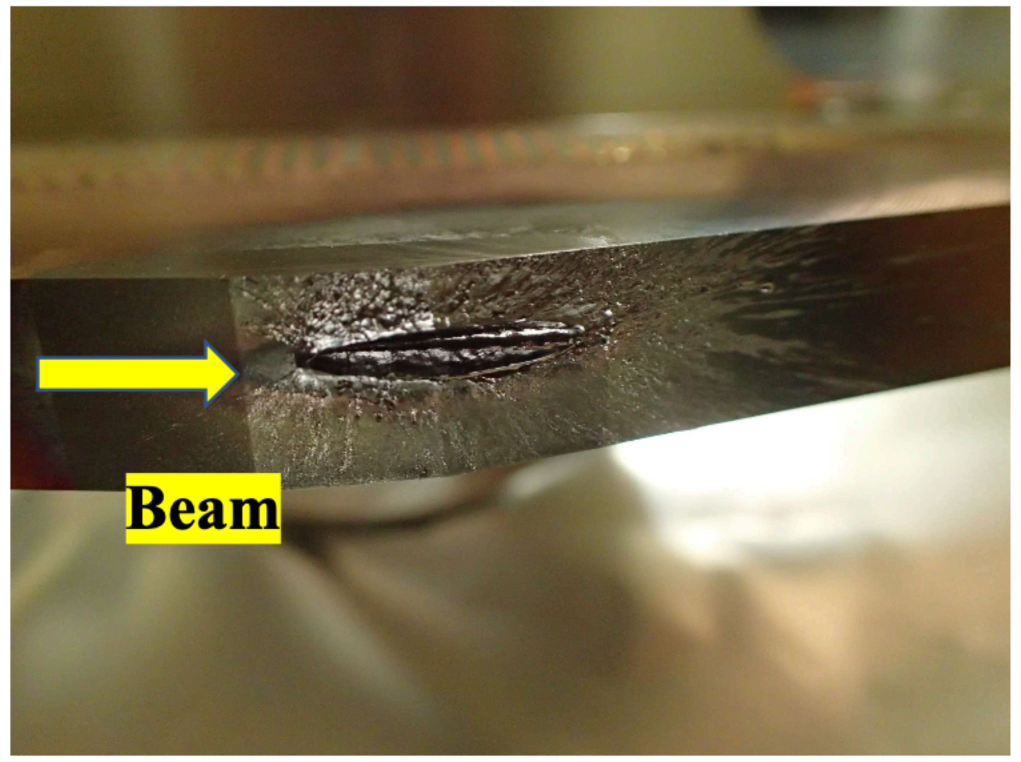
Damage of Collimator Head

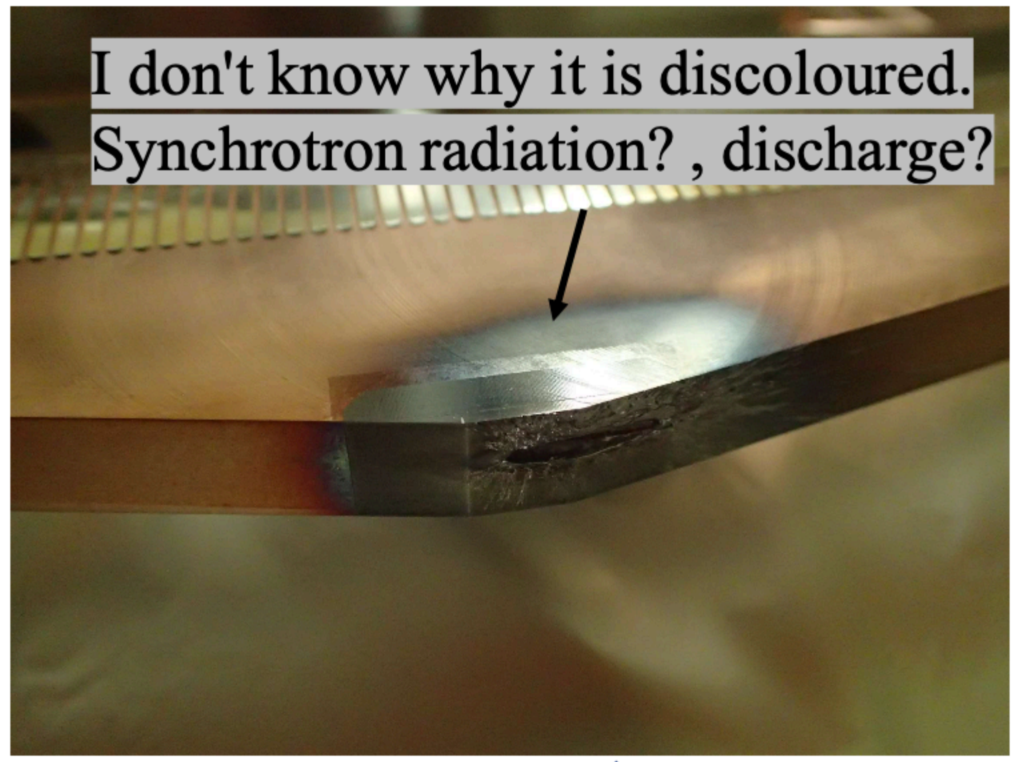


M. Aversano

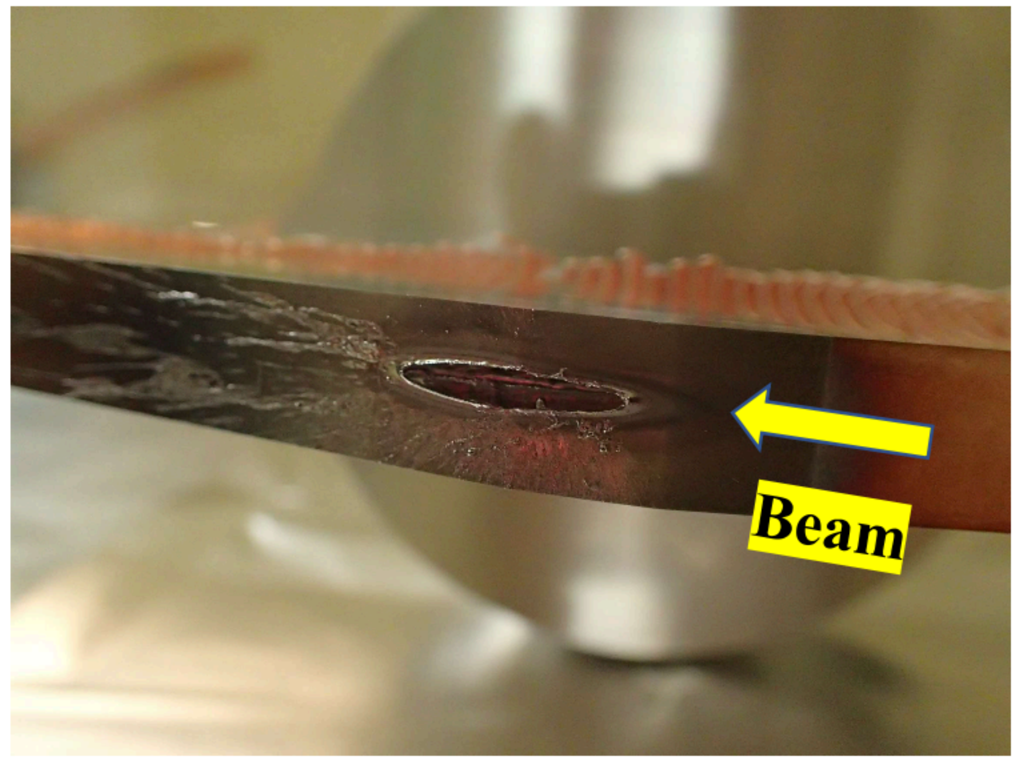
Vertical Collimator

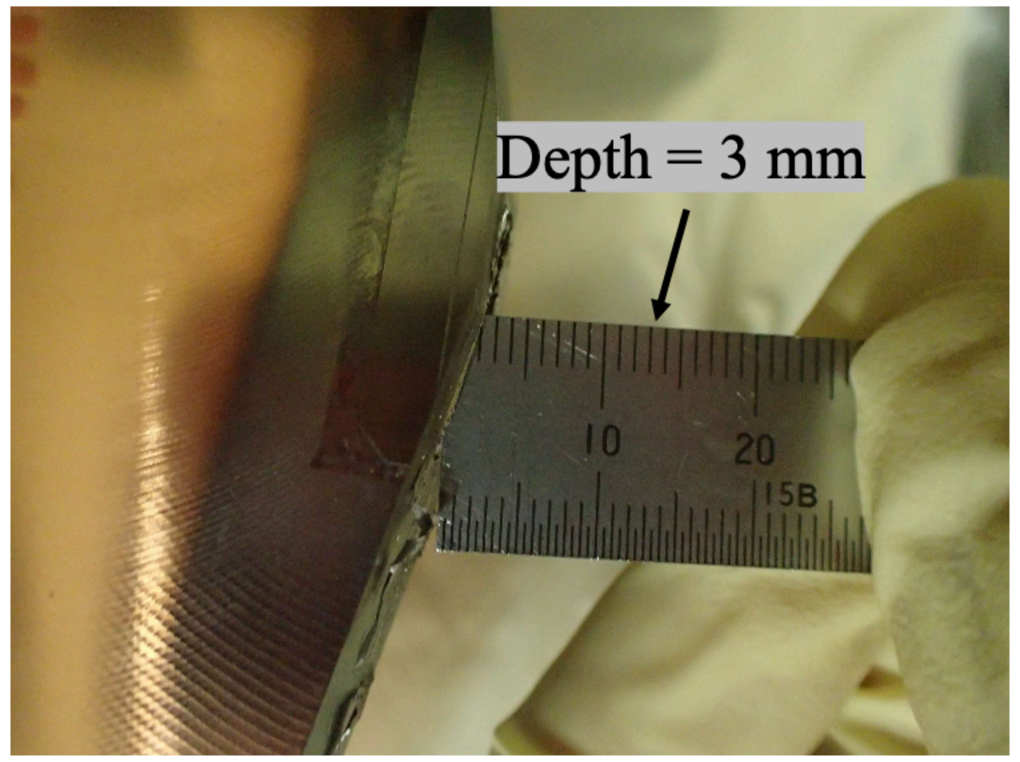
TOP side





BOTTOM side





I think the colours are similar.

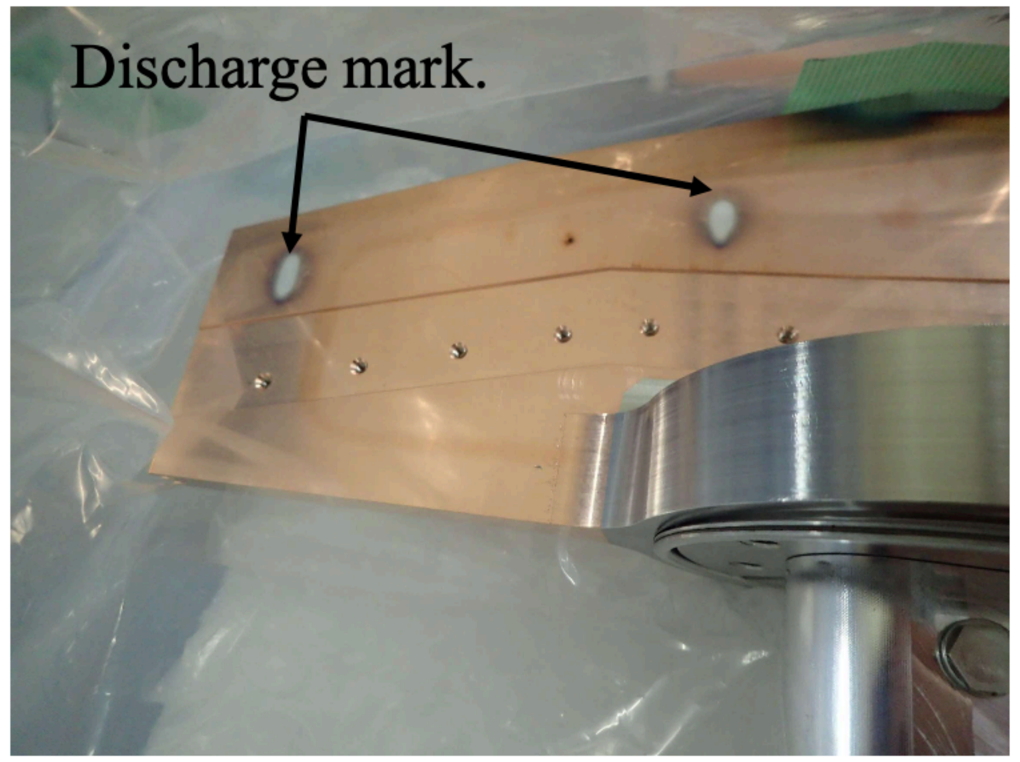
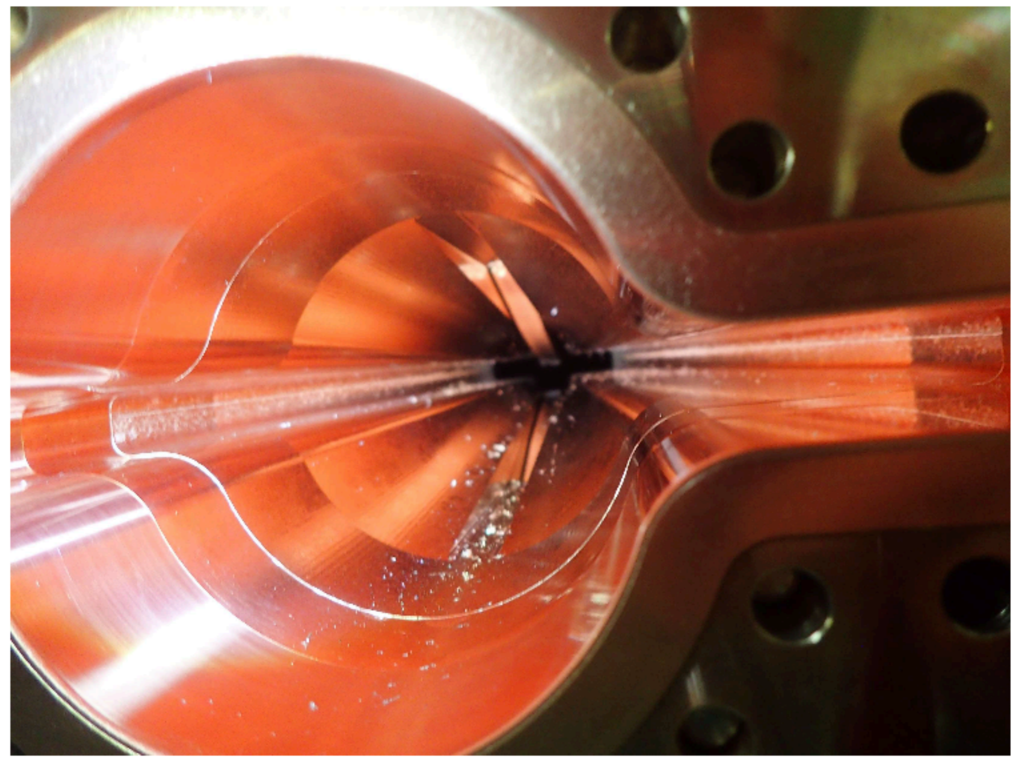
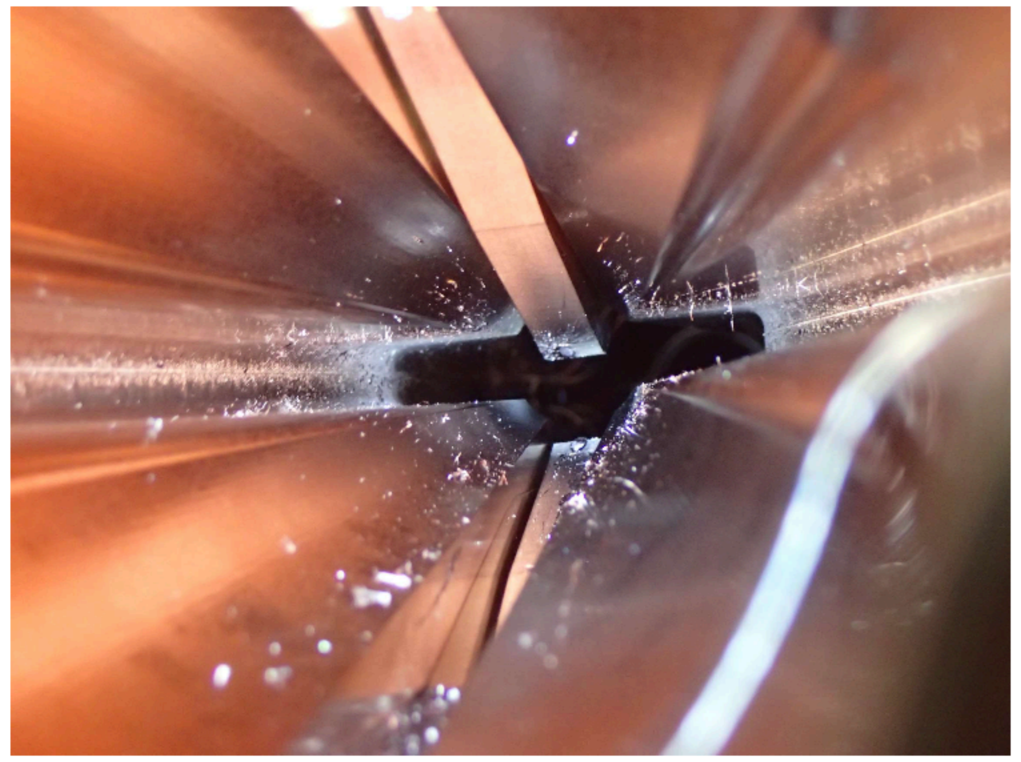


Photo from downstream.



Top

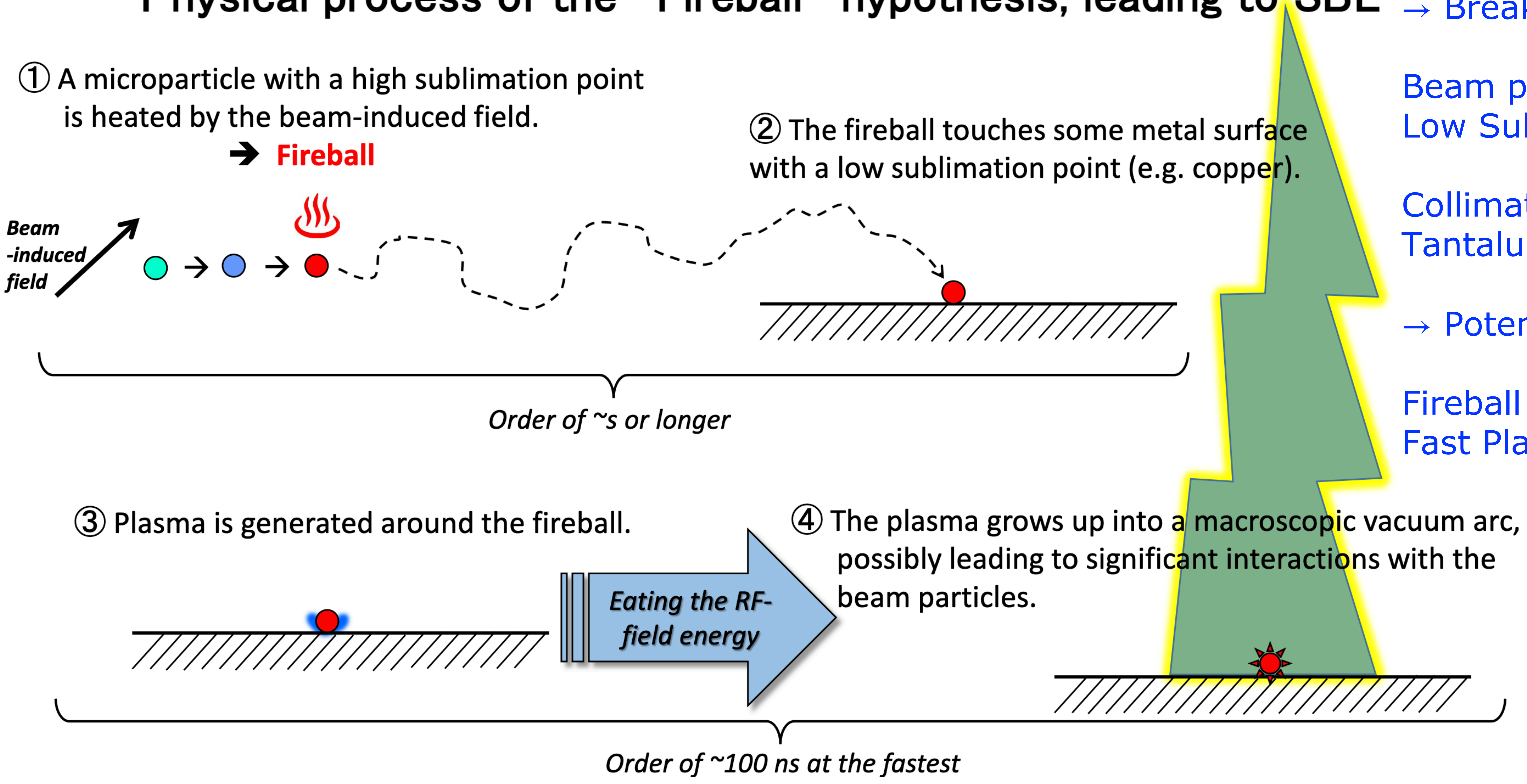


Bottom

Many Dusts

SBL and Fireball Hypothesis

Physical process of the “Fireball” hypothesis, leading to SBL



Fireball: Measured at RF Cavity
→ Breakdown Mechanism

Beam pipe: Copper;
Low Sublimation Point

Collimator Head: Tungsten or Tantalum; High Sublimation Point

→ Potential for Fireball

Fireball Hypothesis Explain SBL
Fast Plasma Evolution ~100 ns

Copper Coating of Collimator Head will be Effective if Different Sublimation Point is Problem.

T. Abe et al. "Direct observation of breakdown trigger seeds in a normal-conducting rf accelerating cavity", Phys. Rev. AB 21, 122002, 2018

Measure Against Seven Major Issues

1. Sudden Beam Loss

   ➡ Copper Coating of Collimator Head, Additional Monitors (Acoustic Sensors, Loss Monitors, Specific TBT BPM)

2. Beam-Size Blowup due to Beam-Beam Interactions

   ➡ Chromatic X-Y Coupling Correction, Reduction of Machine Error in IR

3. Beam-Related Background

   ➡ More IR Radiation Shields

4. Injection Efficiency and Emittance Blowup in the Beam Transport Line

   ➡ Wider Aperture at Injection Point, ~~Shielding Effect to Suppress Coherent Synchrotron Radiation (CSR)~~

5. Difficulties to Keep Beam Orbit Stable

   ➡ Beam Pipe Deformation due to SR Heating, BPMs Push Quadrupole Magnets. Isolation of BPM will Be Tested.

6. Short Lifetime and Narrow Dynamic Aperture with β_y^* Squeezing

   ➡ Sextupole and Octupole Optimization

7. Beam-Size Blowup due to -1 Mode Instability in LER → Reduce Impedance and BxB FB Optimization

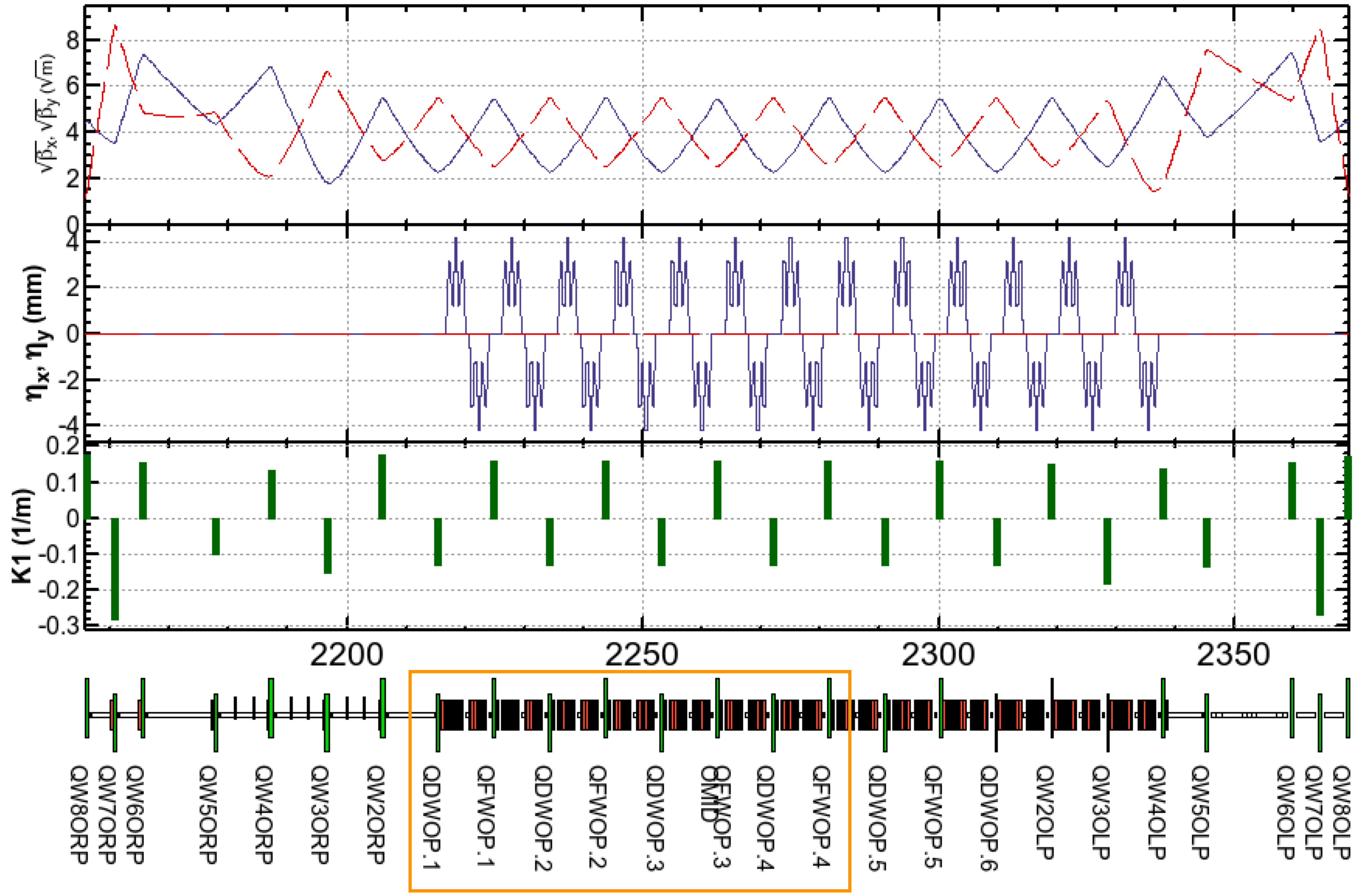
Reduction of Impedance: Nonlinear Collimator

Nonlinear Collimator (D05V1) to Reduce Impedance (vertical)

about 60 % improvement

OHO section

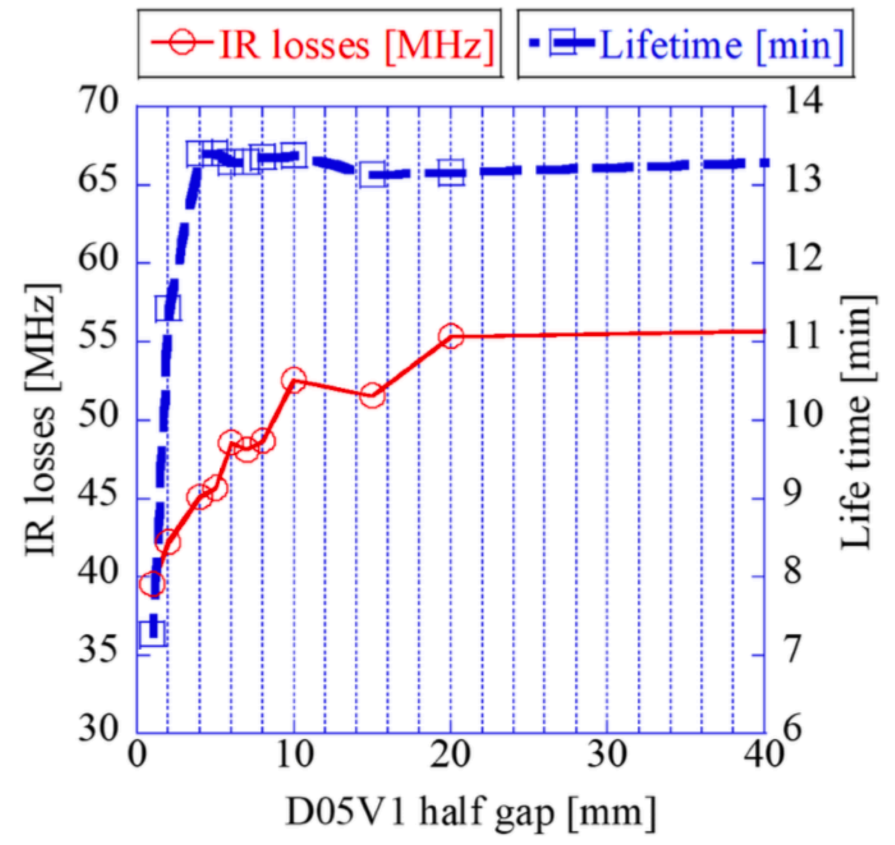
before LS1



positron ⟶

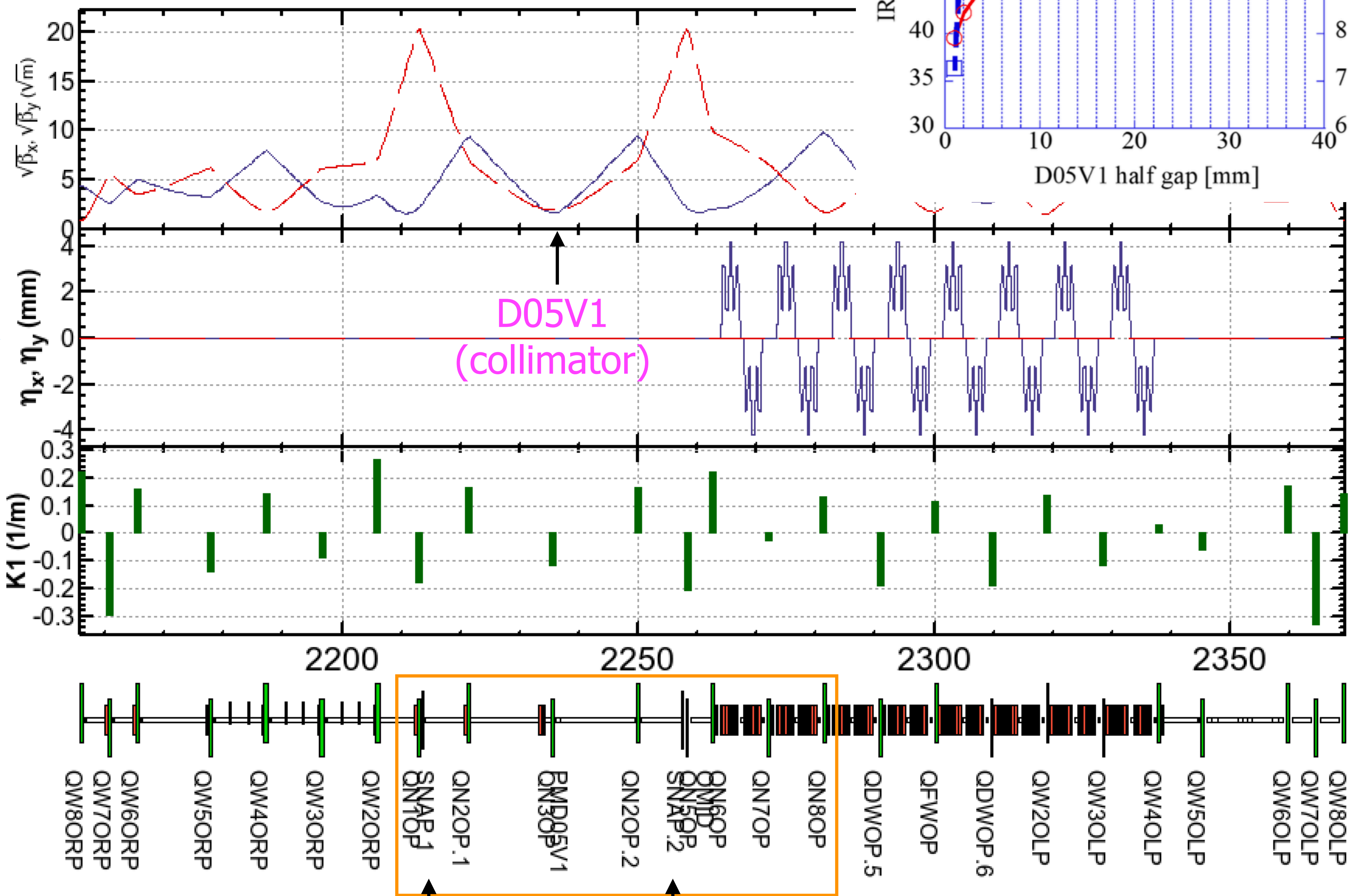
```
Damping time (msec):
X :  45.67757    Y :  45.68328    Z :  22.84954
```

Drop Beam Halo with Larger Aperture.



$$\Delta p_y = \frac{K_2}{2} \Delta y^2$$

after LS1



skew sextupole pair (SNAP)

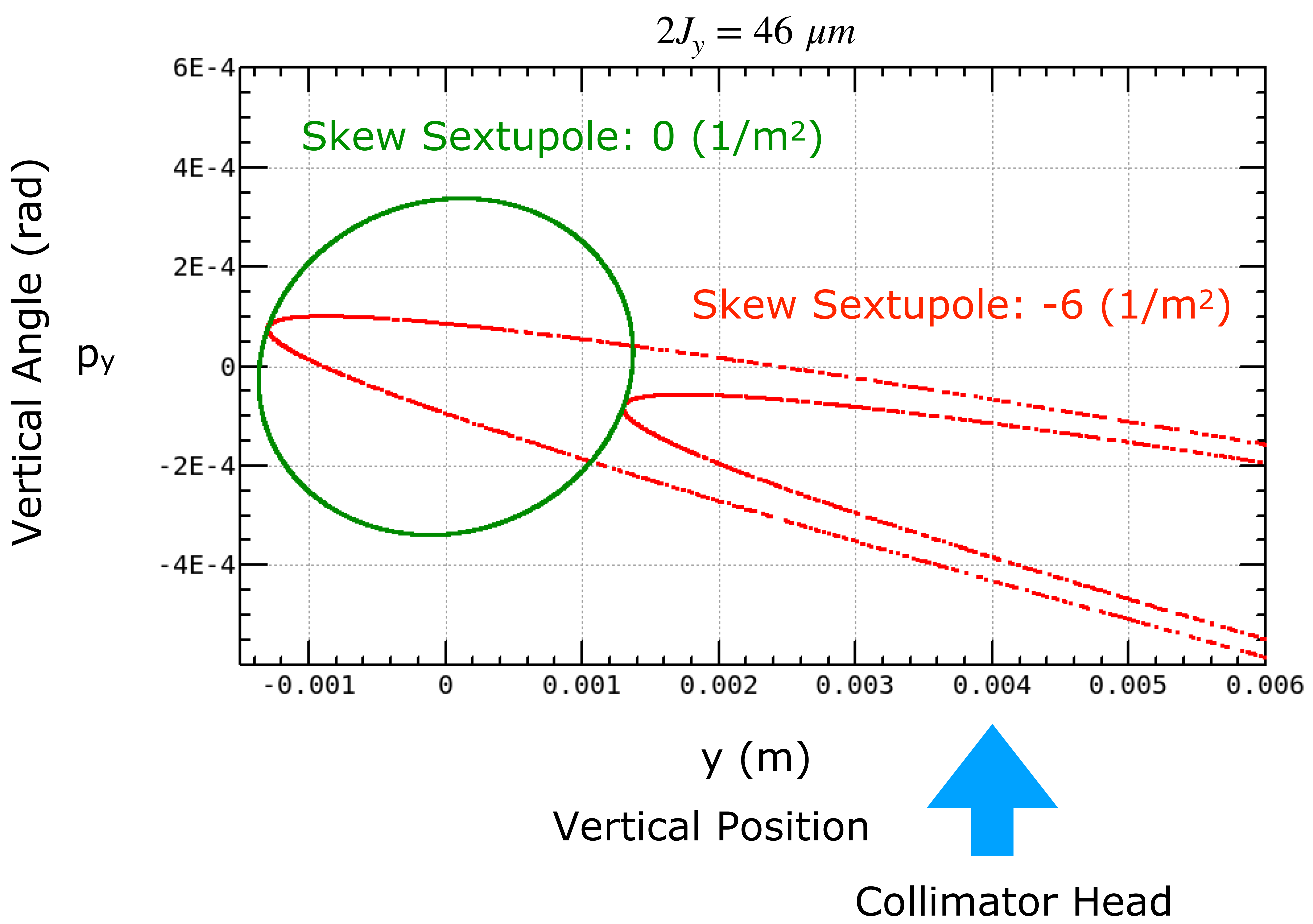
$\Delta\psi_y = 2\pi$ to QC1RP

positron ⟶

M = -I'

```
Damping time (msec):
X :  52.99557    Y :  53.00312    Z :  26.50934
```

Beam Halo Can Be Scraped by Large Collimator Aperture.



Machine Parameters

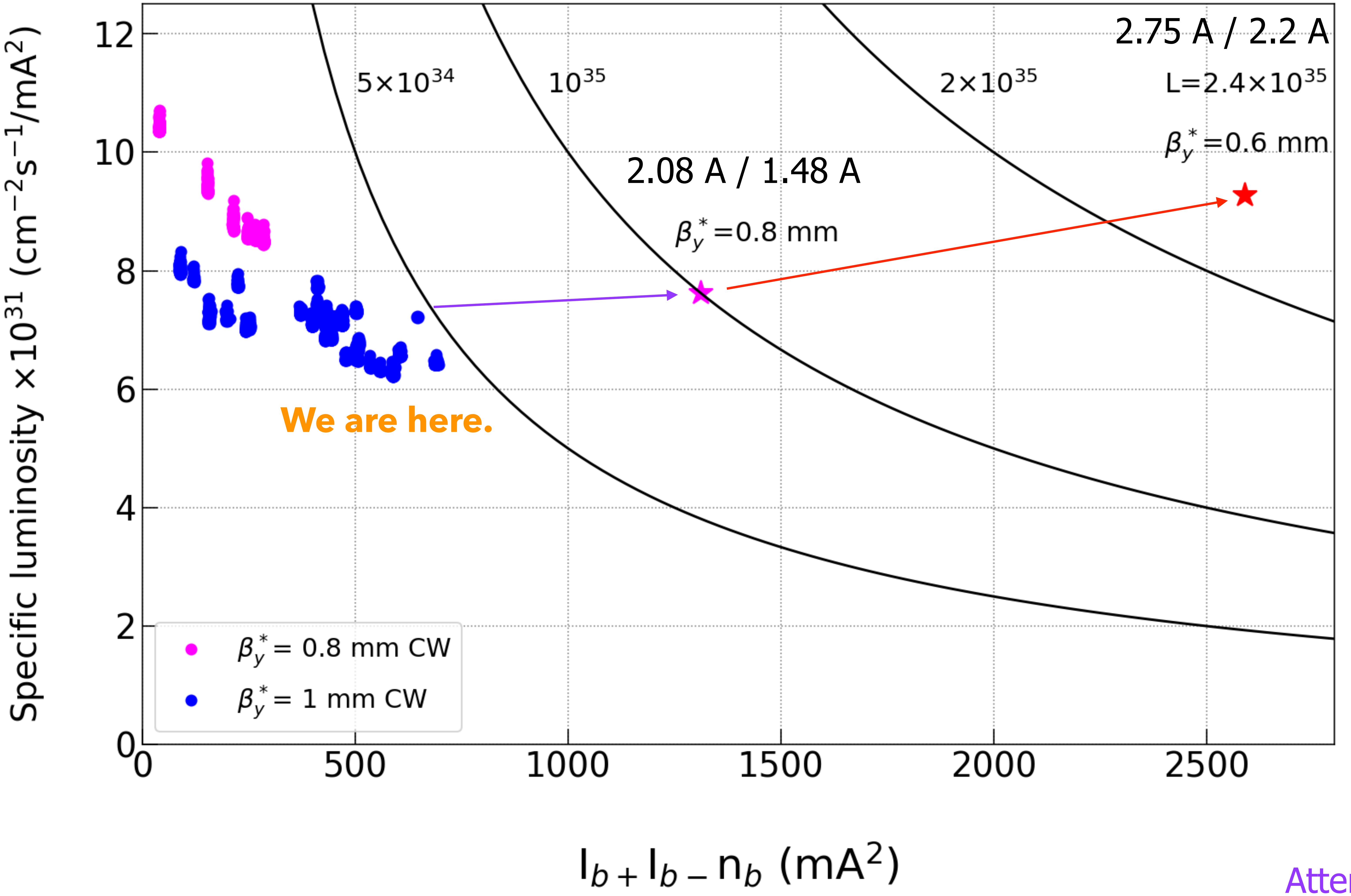
	June 8, 2022		Target at Post-LS1 (1)		Target at Post-LS1 (2)		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	1321	1099	2080	1480	2750	2200	mA
Number of Bunches	2249		2346		2346		
Bunch Current	0.587	0.489	0.89	0.63	1.17	0.94	mA
Horizontal Size σ_x^*	17.9	16.6	17.9	16.6	17.9	16.6	μm
Vertical Cap Sigma Σ_y^*	0.303		0.217		0.178		μm
Vertical Size σ_y^*	0.215		0.154		0.126		μm
Betatron Tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	
β_x^* / β_y^*	80 / 1.0	60 / 1.0	80 / 0.8	60 / 0.8	80 / 0.6	60 / 0.6	mm
σ_z	4.6	5.1	6.5	6.4	6.5	6.4	mm
Piwinski Angle	10.7	12.7	10.7	12.7	10.7	12.7	
Crab Waist Ratio	80	40	80	80	80	80	%
Beam-Beam ξ_y	0.0407	0.0279	0.0444	0.0356	0.0604	0.0431	
Specific Luminosity	7.21×10^{31}		7.62×10^{31}		9.31×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	4.65×10^{34}		1×10^{35}		2.4×10^{35}		$cm^{-2}s^{-1}$

10^{35} and 2.4×10^{35} are tentative and considered by Y. Funakoshi.

Strategy toward 2.4 x 10^{35} $cm^{-2}s^{-1}$

Number of Bunches Reaches Design.
Increase Bunch Current
Without Beam-Beam Blowup

The First Milestone after LS1: 10^{35} $cm^{-2}s^{-1}$.



$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b}$$

Luminosity Frontier

10^{34} $cm^{-2}s^{-1}$ ← KEKB

10^{35} $cm^{-2}s^{-1}$ ← SuperKEKB

Attempt to Improve Luminosity
Toward a New Luminosity Unit.

Have to Overcome These Challenges ...

葉問 Ip Man 4: The Finale (2019)

International Task Force (ITF) for SuperKEKB

Find Realistic Path to 10^{35} $cm^{-2}s^{-1}$ after LS1
Find Ideas to 6×10^{35} $cm^{-2}s^{-1}$ after LS2 with Major Modifications

ITF 2023 Activities from January 2023 for 1 year
Chairperson: Y. Ohnishi

A) KEK, B) CERN, C) Sapienza University of Rome, D) IHEP

B-Factory Promotion Office

N. Saito[A]
T. Koseki[A]

Accelerator Review Committee

F. Zimmermann[B]

75 Researchers joined
(39 Researchers from Foreign Institutes about 52 %)

FCC-ee, CEPC, EIC, Super-Tau-Charm

Collective Effects (Beam-Beam, Impedance)

G. Mitsuka[A]
M. Migliorati[C], N. Wang[D],
D. Zhou[A], T. Ishibashi[A]

Beam Tuning

Y. Ohnishi[A]
H. Sugimoto[A], R. Thomas[B]

IR Upgrade

D. Zhou[A]
X. Wang[A]

Sudden Beam Loss

H. Ikeda[A]
H. Nakayama[A]

Beam Injection

N. Iida[A]
T. Yoshimoto[A]

Organized under the B-Factory Promotion Office at KEK.

Need LS2 Upgrade to Achieve More than 2.4 x 10^{35} $cm^{-2}s^{-1}$ Luminosity

Upgrade in LS2

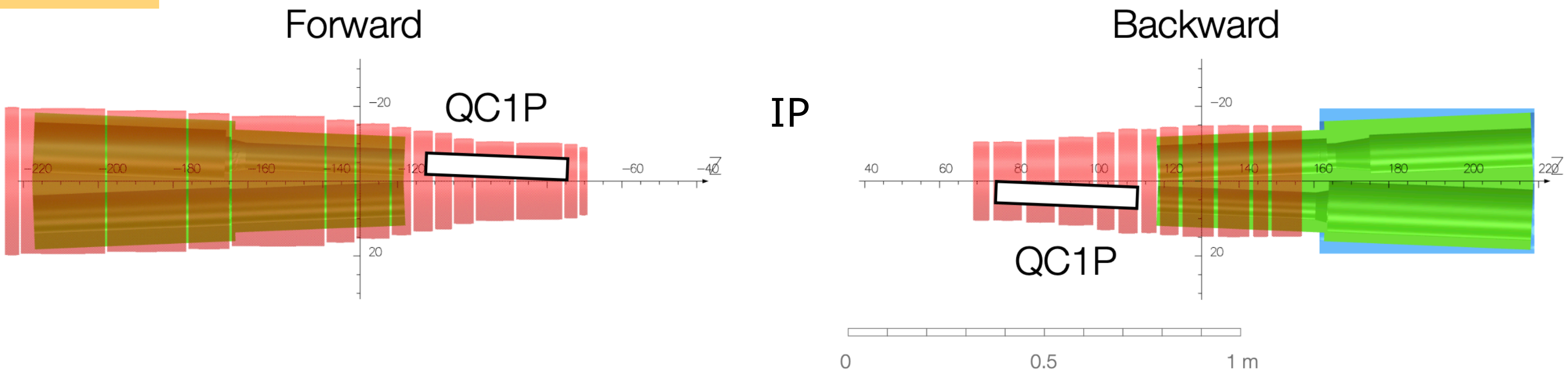
LS2 : The 2nd Long Shutdown

Possible Senario

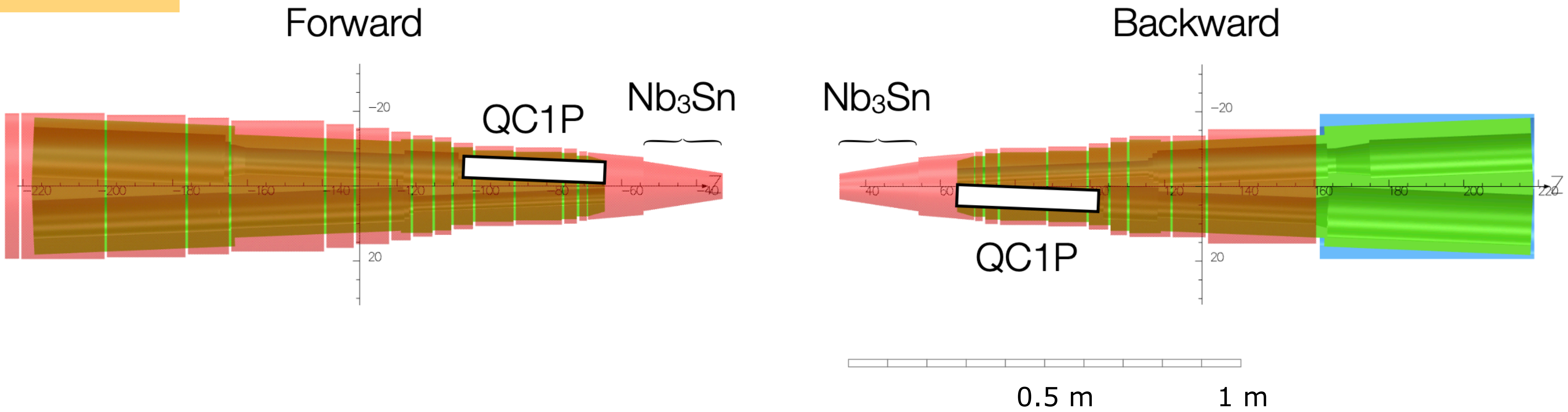
K. Aoki, Y. Arimoto, H. Koiso, N. Ohuchi, M. Tobiyama, M. Masuzawa

- IR Upgrade
  - QC1P (Final Focus Magnet) Relocation
    - Closer to the IP by 100 mm (from L*= 935 mm to 835 mm)
    - → Improve Dynamic Aperture and Touschek Lifetime
  - Separation of Solenoid Field and QC1P
    - → X-Y Couplings and Chromatic X-Y Couplings at IP
    - → Vertical Dispersion Induced by IR
  - Magnets with Nb_3Sn

Current Version



Updated Version



1. Increase QC1P Aperture (Vertical) from 13 mm to 20. 7mm
→ Large Physical Aperture

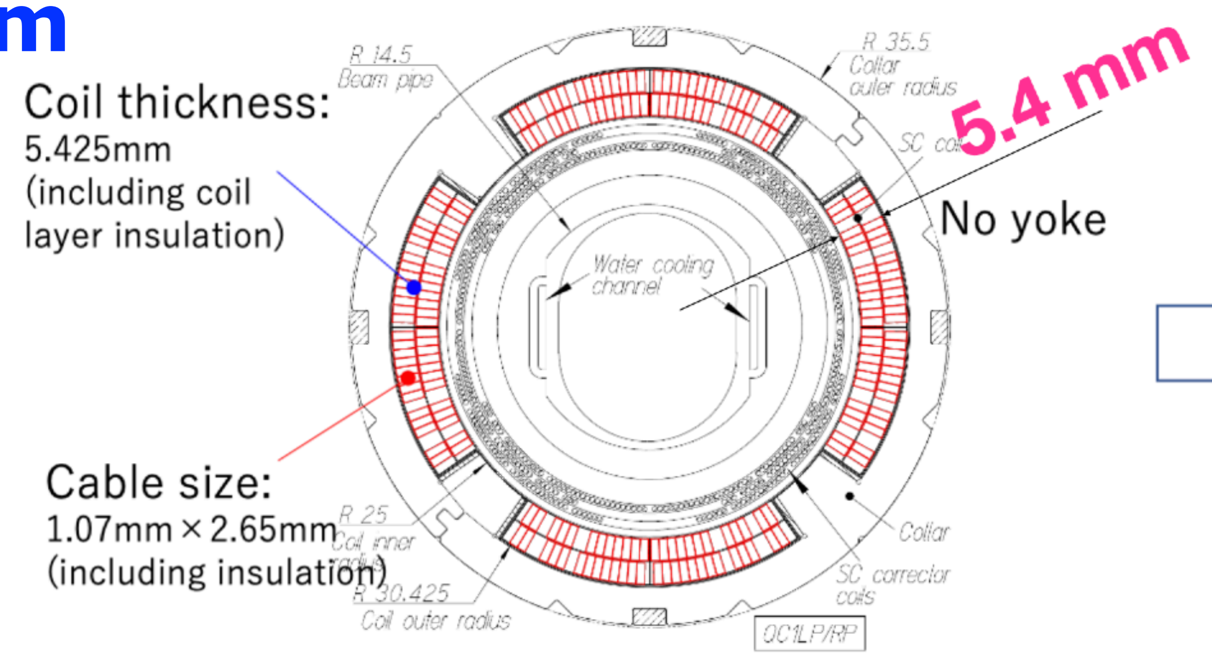
2. Fabricate New Anti-Solenoid Coil and Move It Closer to IP
→ Less X-Y Coupling

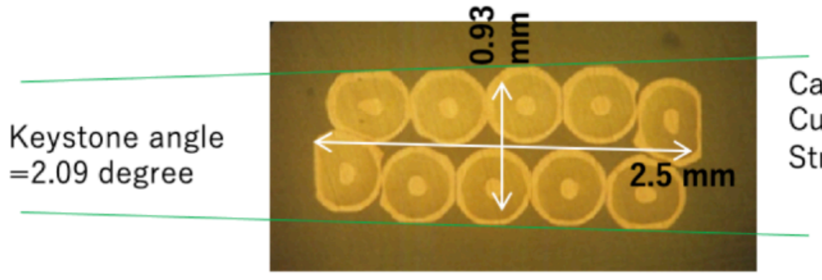
3. Cover QC1P by Magnetic Material
→ Reduce Magnetic Coupling

4. Move QC1P Closer to IP (100 mm)
→ Larger Dynamic Aperture (Longer Touschek Lifetime)

NbTi

Present QC1P magnet configuration

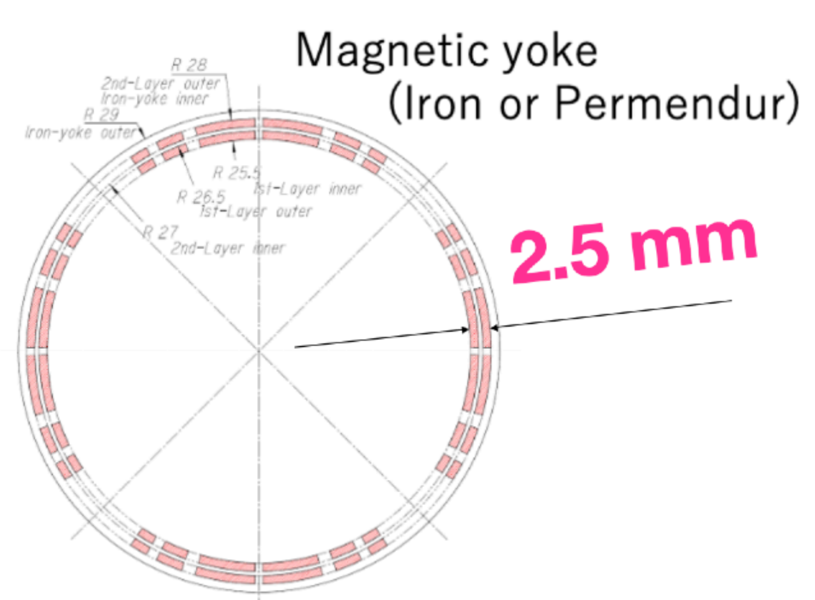




NbTi Rutherford cable

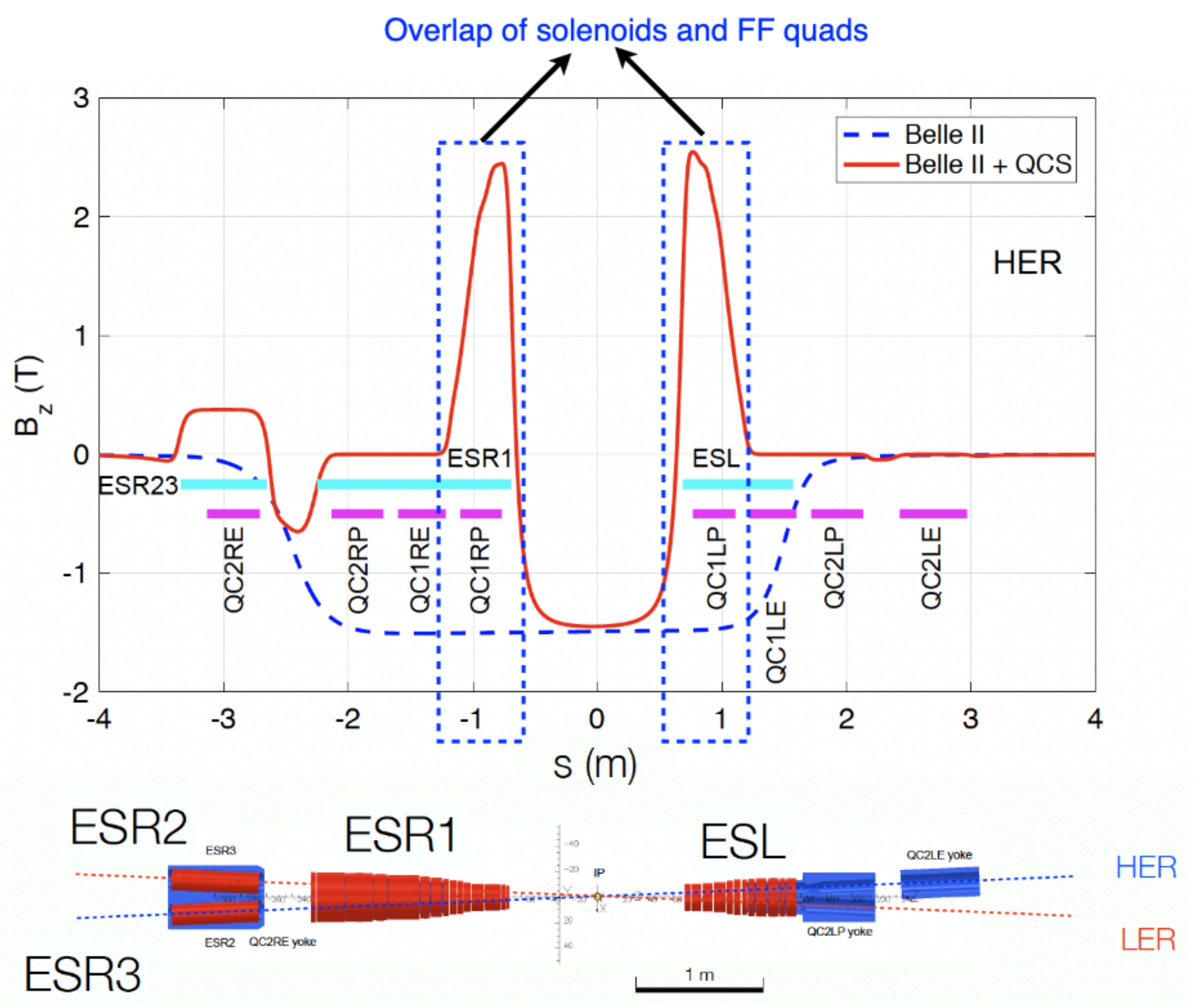
Cable size=2.5mm × 0.93mm
Cu/S ratio=1
Strand:
Diameter=0.498mm
Number=10
Filament dia.=7.7 μm
Filament num.=2113

Nb3Sn

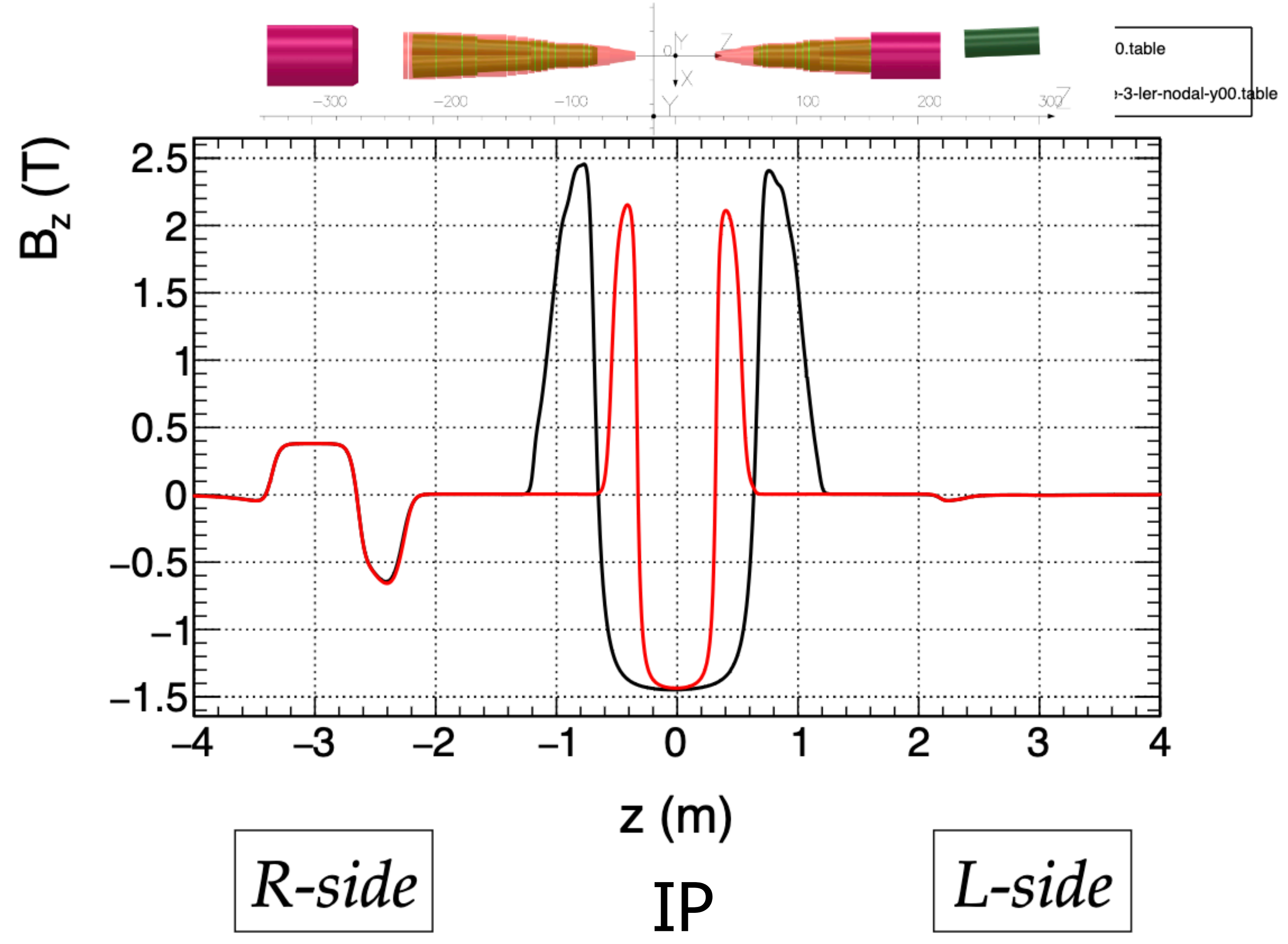


Coil thickness:
2.65mm(present QC1P)→1.0mm
Cable:
Nb_3Sn wire (**round** or rectangular)
Cu/S=1
Cable size=ϕ 0.9mm
Cable insulation thickness=0.05mm

Current Design



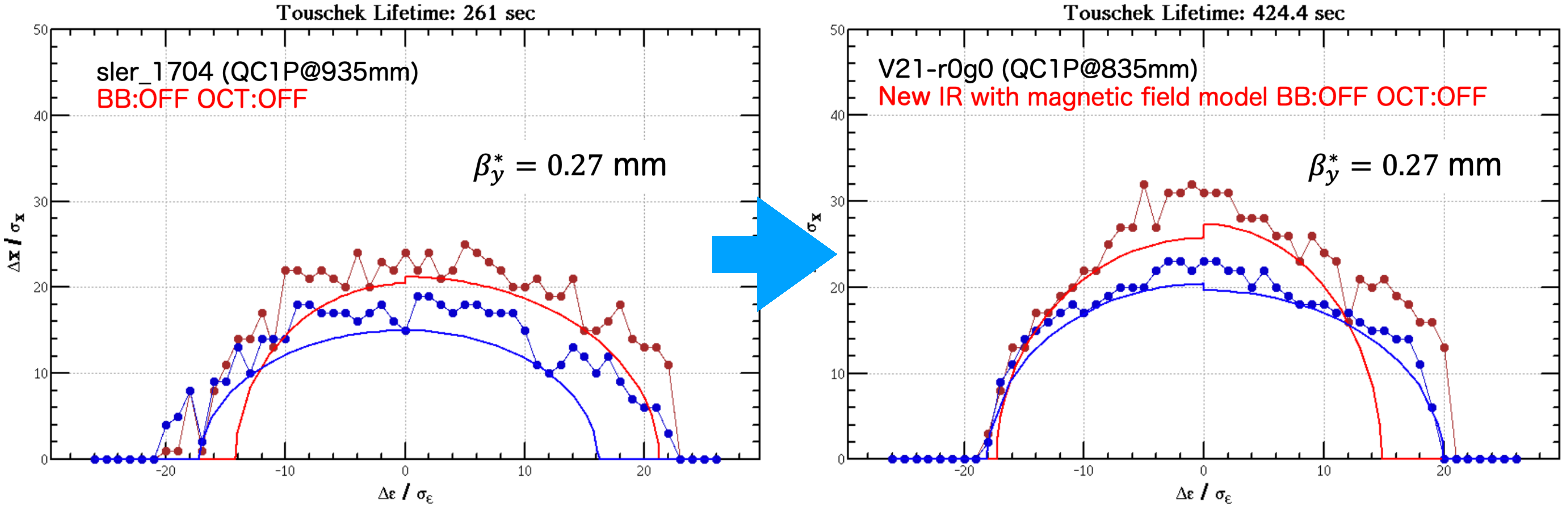
Modification of anti-solenoid



Dynamic Aperture and Touschek Lifetime

$$\beta_y^* = 270\ \mu m$$

Transverse Acceptance



Momentum Acceptance

Momentum Acceptance

Summary

- Luminosity Achievement in 2022: 4.7×10^{34} $cm^{-2}s^{-1}$
- Difficulties to Increase Beam Current.
  - Sudden Beam Loss
- β_y^* Squeezing < 1 mm
  - Short Lifetime and Narrow Dynamic Aperture
- January 2024: Resume Machine Operation after Long Shutdown (LS1)
  - First Target: More than 10^{35} $cm^{-2}s^{-1}$.
- LS2: Further Upgrade Program (2030s ?)
- Experiences from SuperKEKB Help in the Design and R&D of the Future Colliders
  - FCC-ee, CEPC, Super Tau-Charm Factories