Accelerator challenges in SuperKEKB

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Acknowledgments

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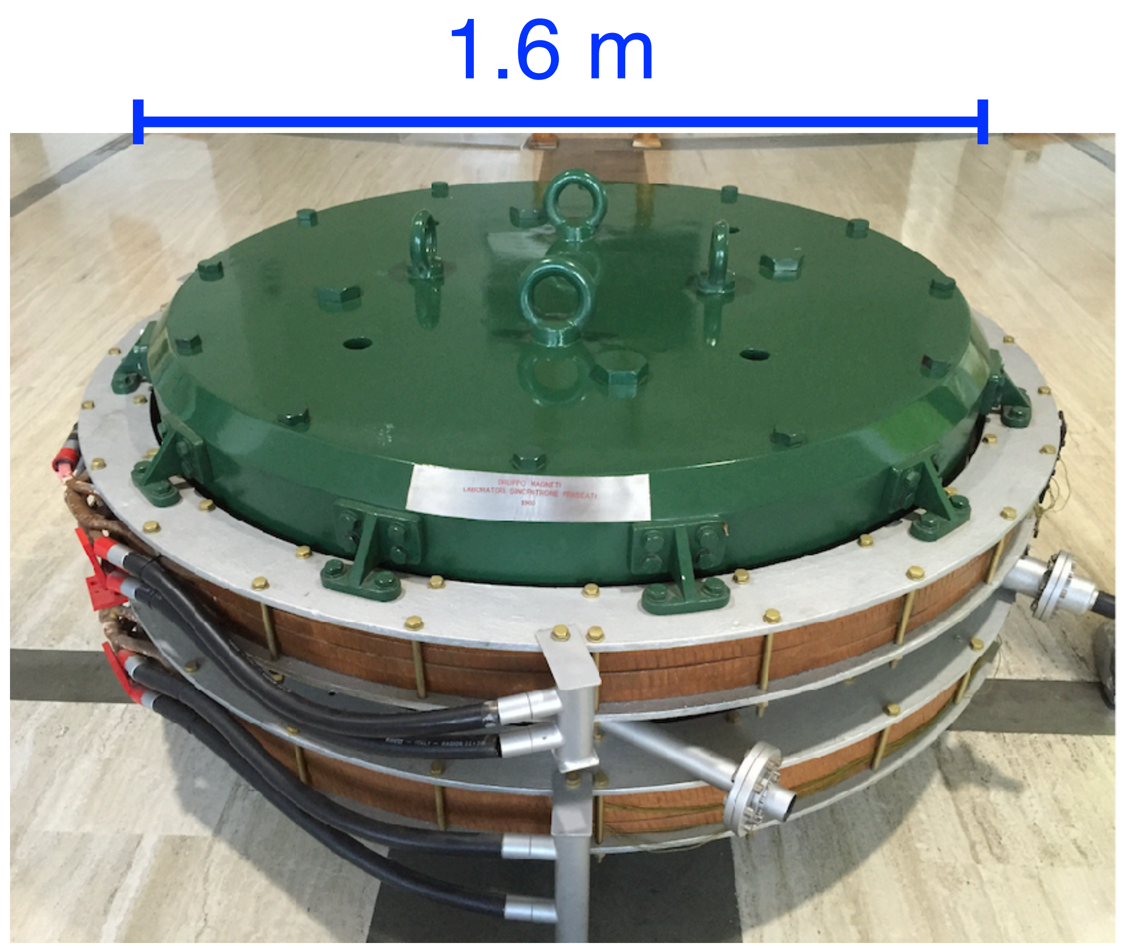
Outline

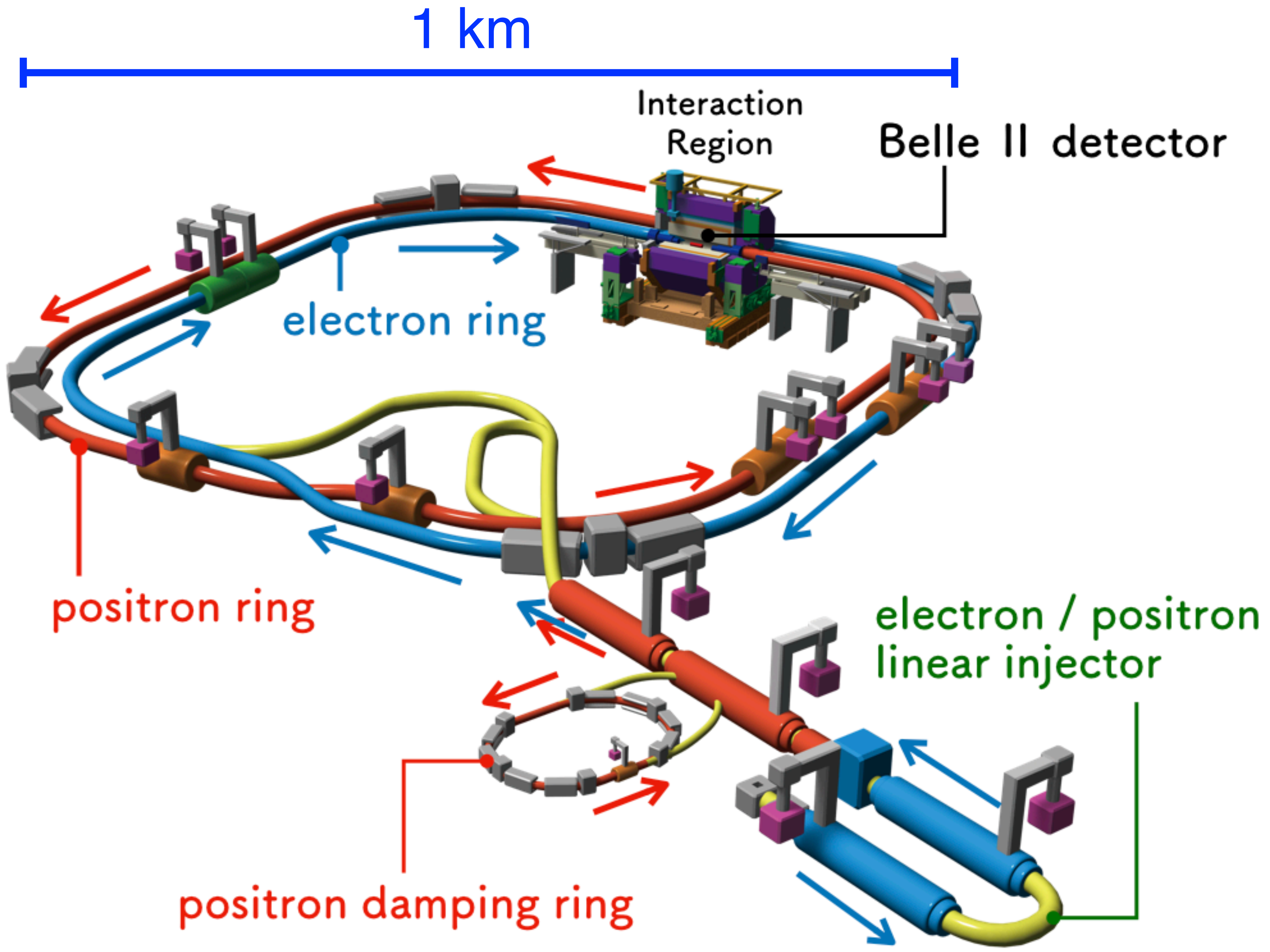
- Status of SuperKEKB
- Luminosity performance
- Accelerator challenges
- Luminosity perspective
- Summary

Very brief history of e+e- circular colliders [1,2]

- Pioneering colliders (L<10^{30} $cm^{-2}s^{-1}$)
  - AdA (Frascati, 1962), ACO (Orsay, 1966)
- First-generation colliders (L=10^{30}-10^{32} $cm^{-2}s^{-1}$)
  - Single ring: Adone (Frascati, 1969-1993), SPEAR (SLAC, 1972-1990), VEPP-2/2M (BINP, 1974-), PETRA (DESY, 1978-1986), VEPP-4M (BINP, 1979-), CESR (Cornell, 1979-2002), PEP (SLAC, 1980-1990), TRISTAN (KEK, 1986-1994), BEPC (IHEP, 1989-2005), LEP (CERN, 1989-1994), LEP2 (CERN, 1995-2000), CESR-c (Cornell, 2002-2008), VEPP-2000 (BINP, 2006-)
  - Double ring: DORIS (DESY, 1974-1993), DCI (Orsay, 1976-2003), DAΦNE (Frascati, 1997-).
- Second-generation double-ring colliders (L=10^{33}-10^{34} $cm^{-2}s^{-1}$)
  - PEP-II (SLAC, 1999-2008), KEKB (KEK, 1999-2010), BEPCII (IHEP, 2007-)
- Third-generation double-ring colliders (L=10^{35}-10^{36} $cm^{-2}s^{-1}$)
  - SuperKEKB (KEK, 2016-)
  - Design stage: STCF (USTC,BINP), CEPC (IHEP), FCCee (CERN)



AdA



SuperKEKB

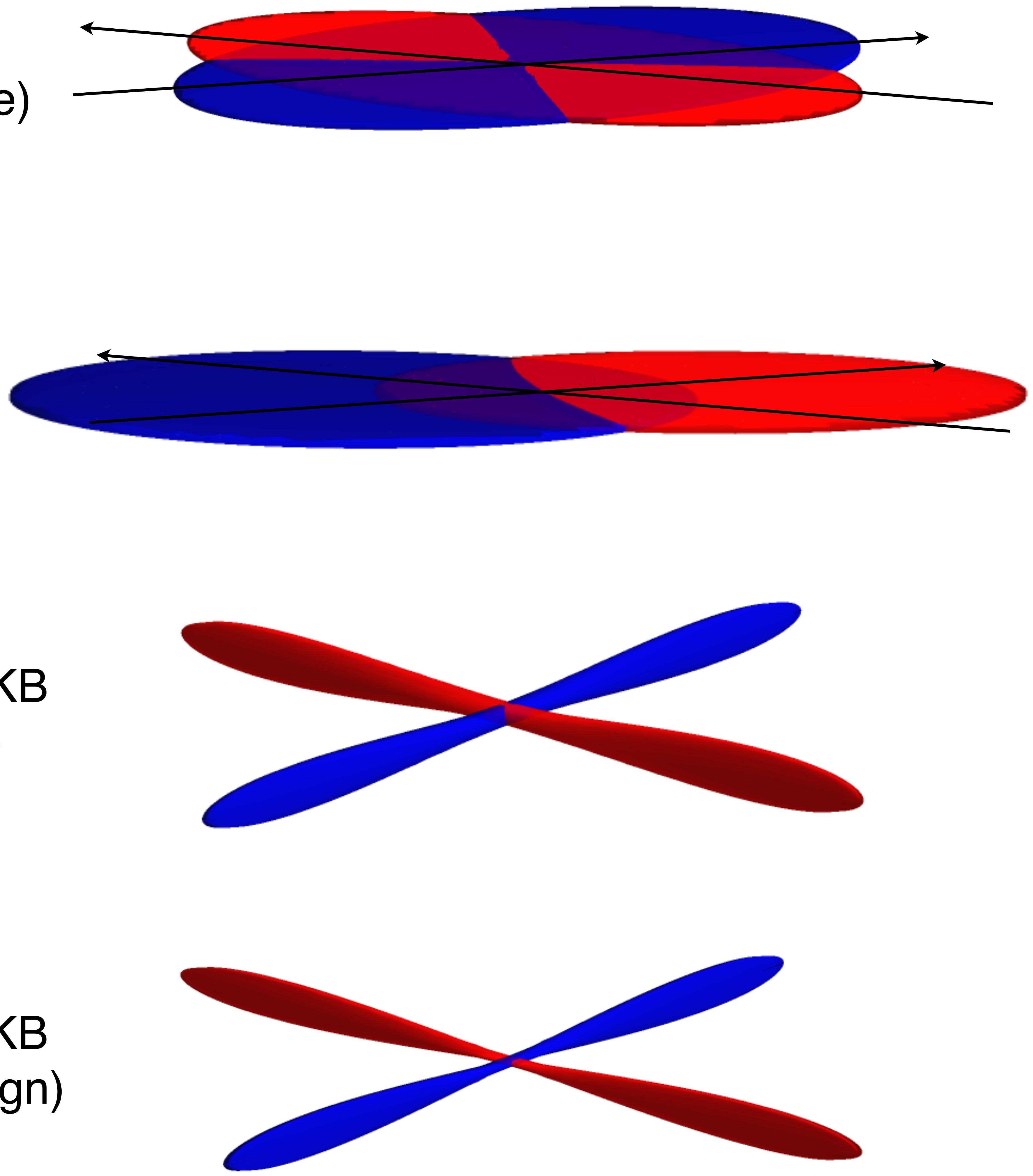
[1] K. Oide, RAST Vol. 7 (2014). [2] K. Ohmi, "Luminosity challenge in e+e- colliders".

Machine overview

- Collision scheme (KEKB → SuperKEKB [1])
  - Beam energy E (LER/HER): 3.5/8 ⇒ 4/7 GeV.
  - Vertical beam-beam parameter ξ_y: 0.09 ⇒ 0.09.
  - Crab waist: Optional (installed in 2020).
  - Luminosity L: 2.1 ⇒ 80 $\times 10^{34}$ cm^{-2}s^{-1}.

	KEKB (2009.06.17)		SKEKB (2021c)		SKEKB (Final design)	
	HER	LER	HER	LER	HER	LER
I_{bunch} (mA)	1.2	1.0	0.64	0.8	2.6	3.6
# bunch	1585		1272		2500	
ε_x (nm)	24	18	4.6	4.0	4.6	3.2
ε_y (pm)	150	150	40	40	12.9	8.64
β_x (mm)	1200	1200	60	80	25	32
β_y (mm)	5.9	5.9	1	1	0.3	0.27
σ_z (mm)	6	6	5	6	5	6
ν_x	44.511	45.506	45.533	44.525	45.53	44.53
ν_y	41.585	43.561	43.581	46.595	43.57	46.57
ν_s	0.0209	0.0246	0.0272	0.0233	0.028	0.0245
Crab waist	-		40%	80%	-	
Crossing angle (mrad)	0 (22)		83		83	

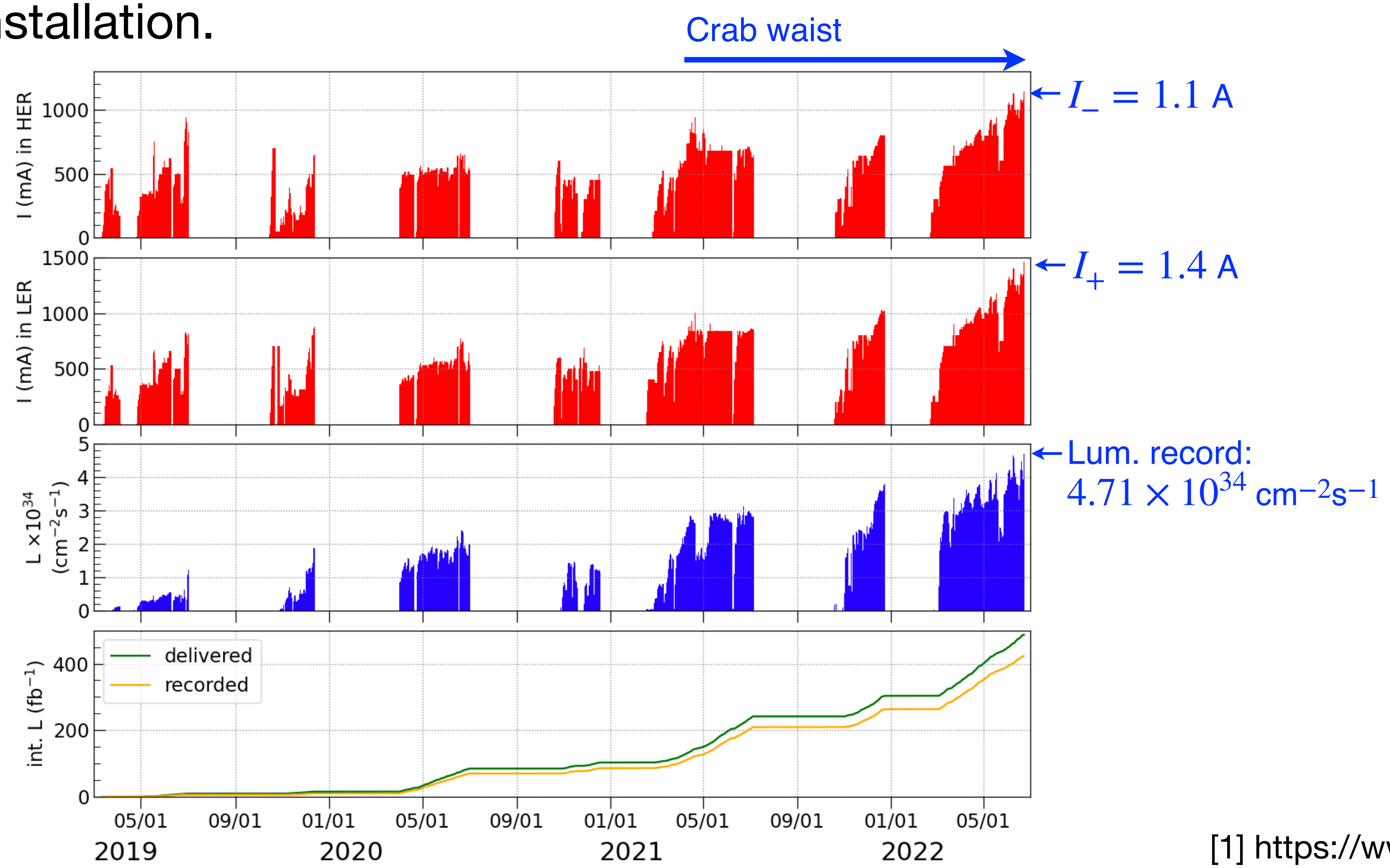
Schematic view of collision schemes

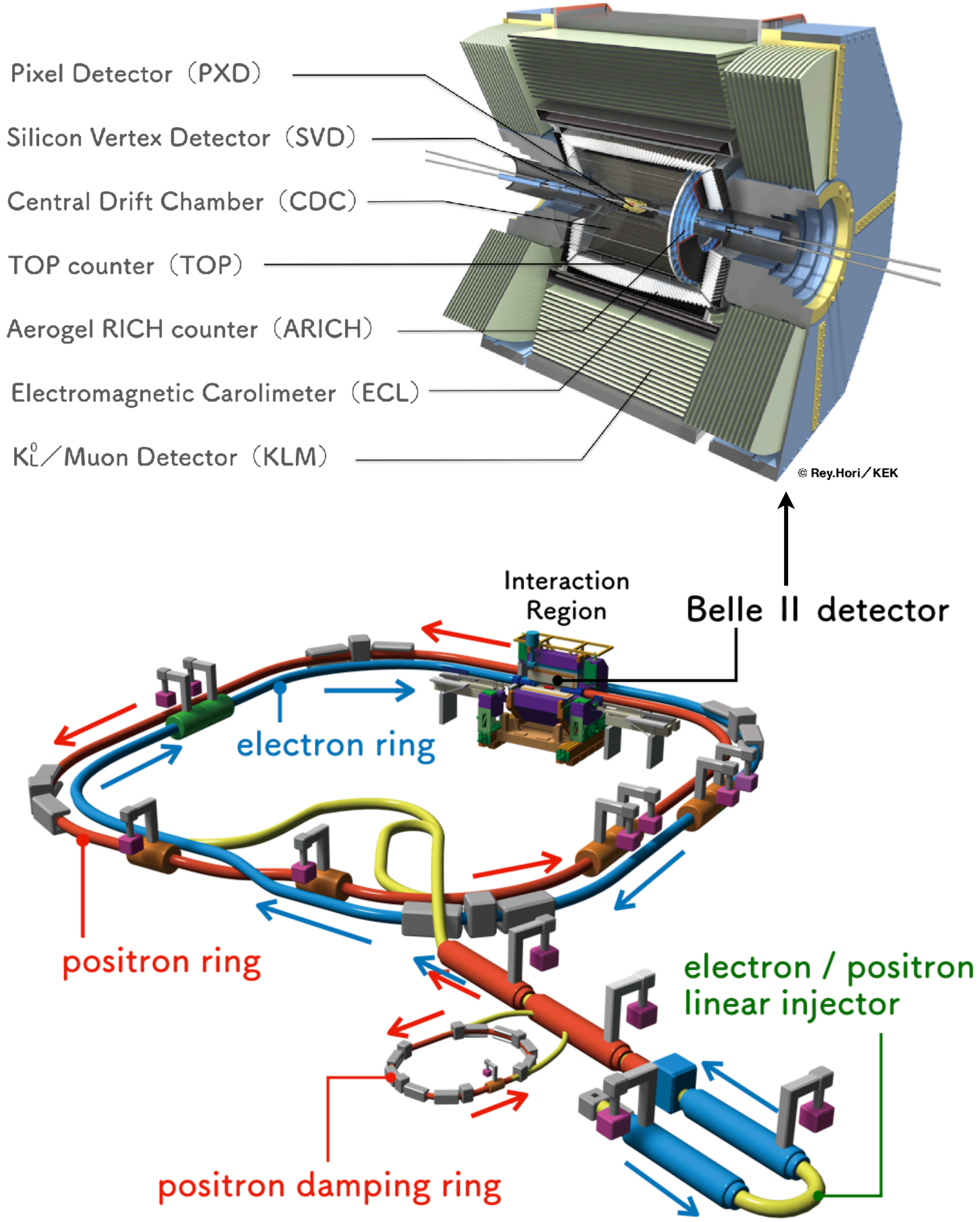


[1] Y. Ohnishi, et al., "Accelerator design at SuperKEKB".

Status of SuperKEKB [1]

- Construction: Jul. 2010 - Jan. 2016
- Phase-1: Feb. 2016 - Jun. 2016 w/o QCS mag. and Belle II.
- Phase-2: Feb. 2018 - Jul. 2018 w/ QCS and Belle II, w/o Vertex detector.
- Phase-3: March, 2019 - w/ Full Belle II.
- LS1: Jul. 2022 - Dec. 2023, Belle II upgrade and NLC installation.

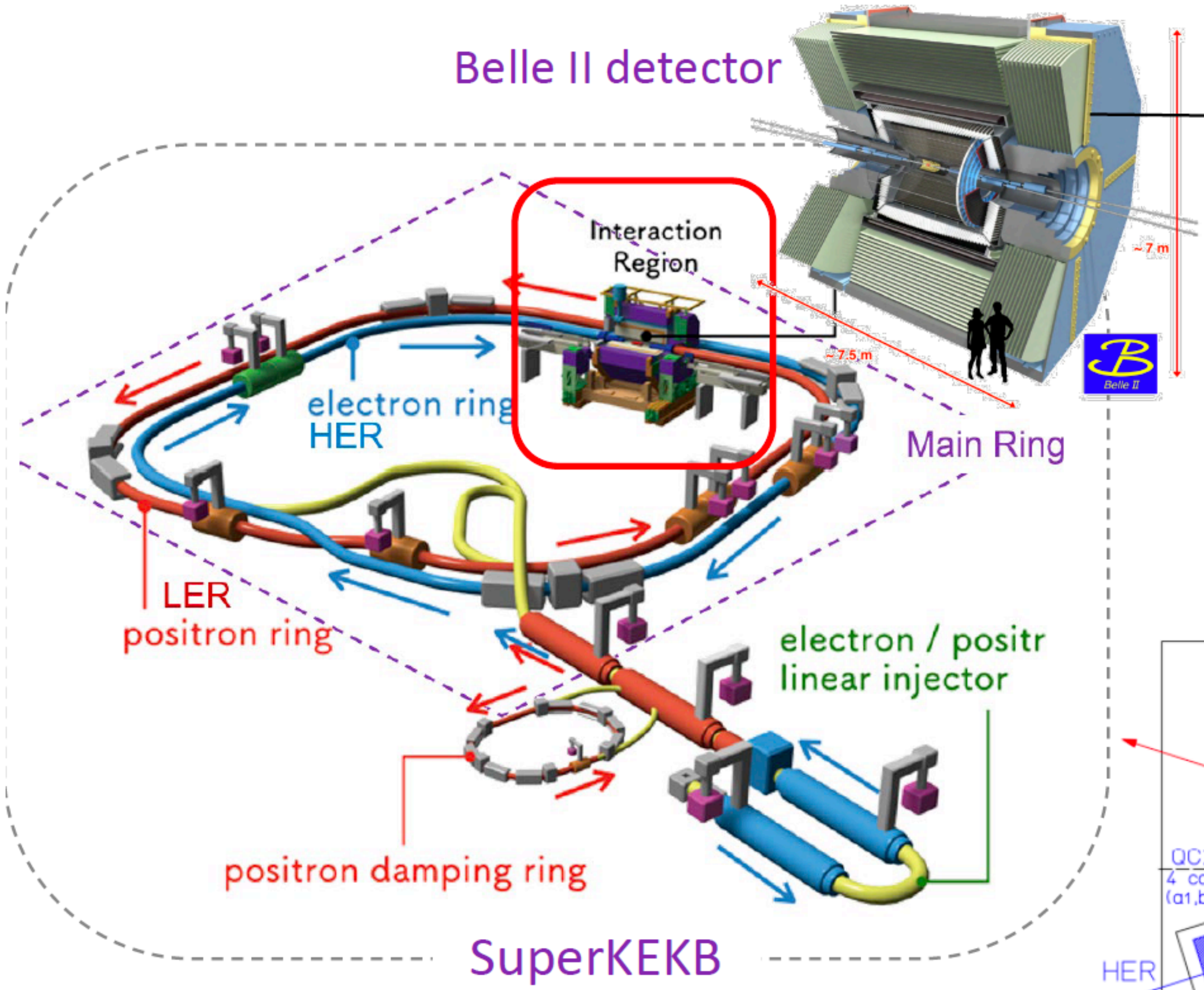




[1] https://www-superkekb.kek.jp/index.html

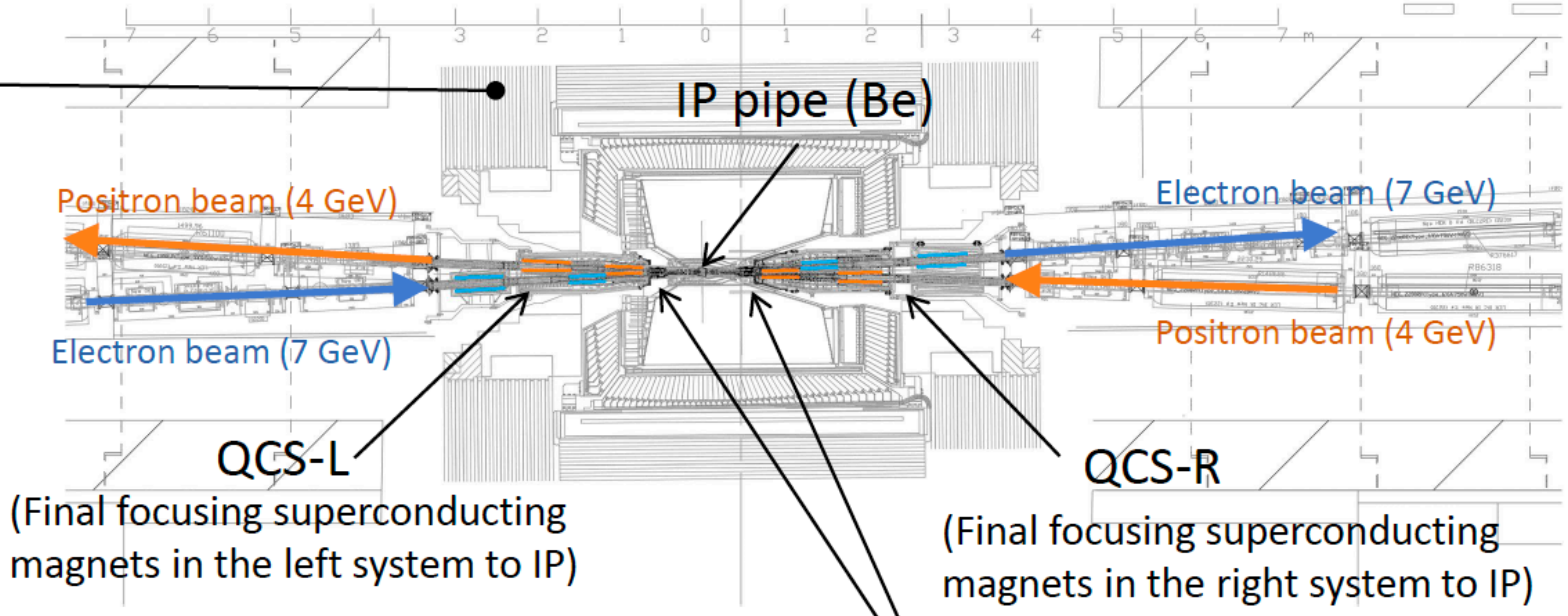
Accelerator challenges

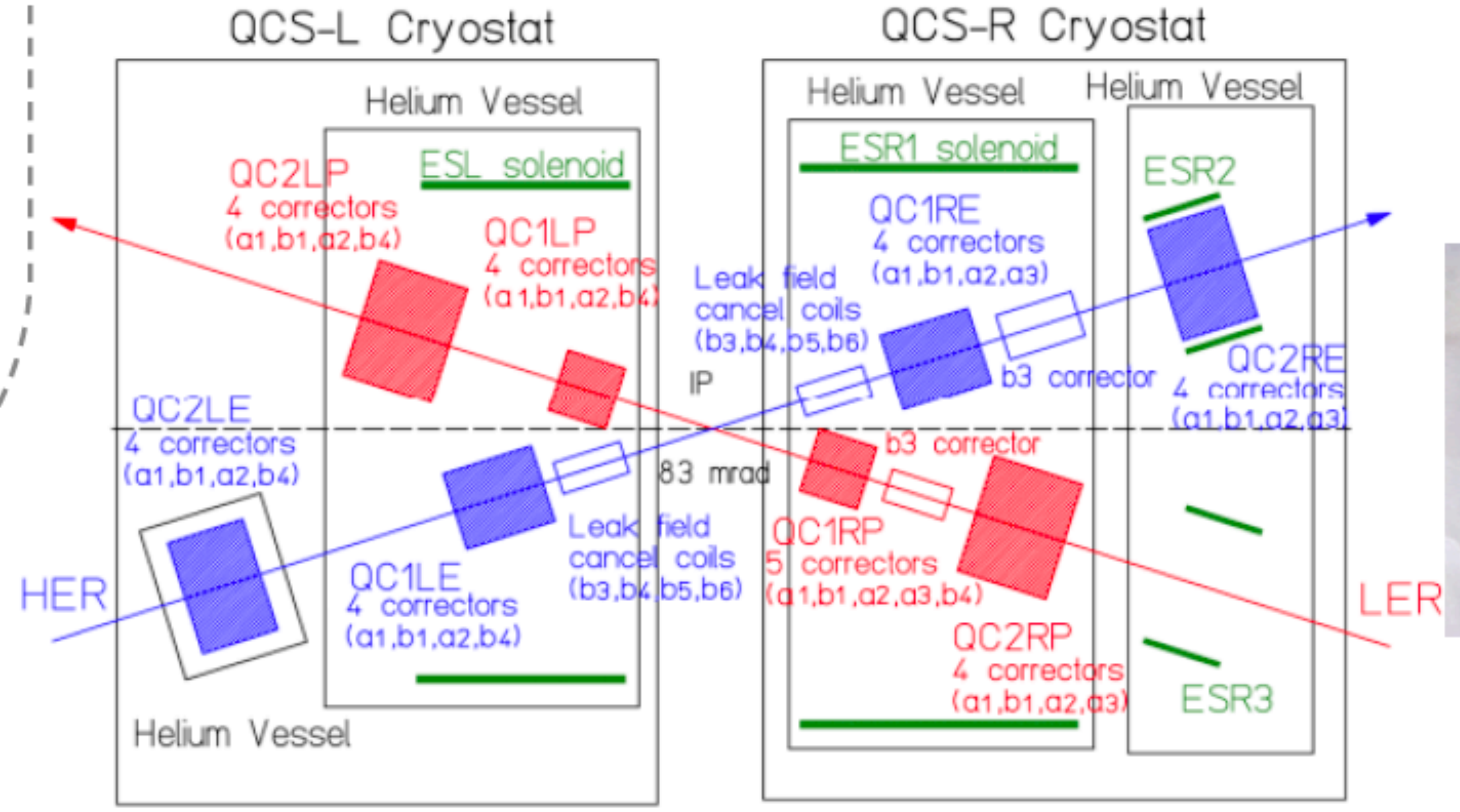
- Complicated interaction region (IR) [1]



IP pipe

SuperKEKB Interaction Region (IR)





QCS
Final focusing superconducting magnet system

RVC
Remote vacuum connection

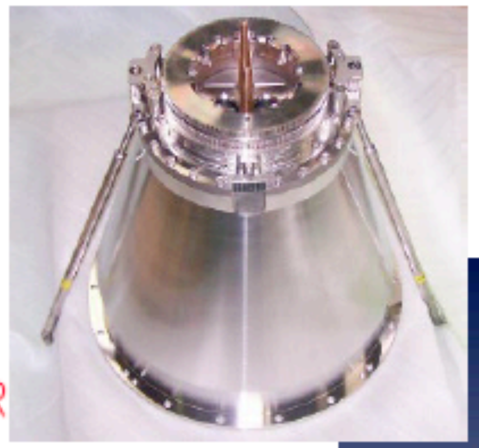
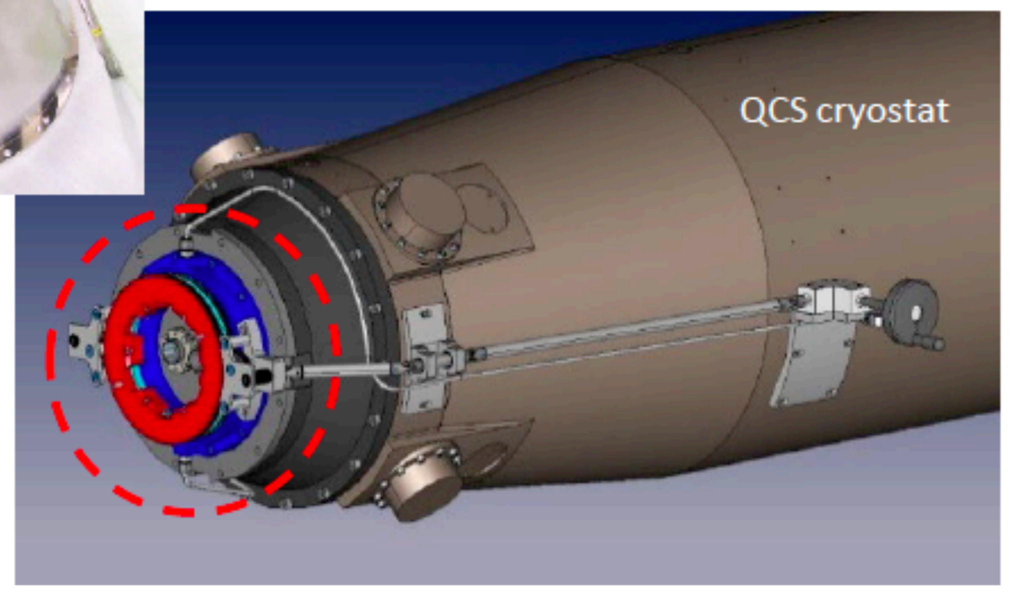


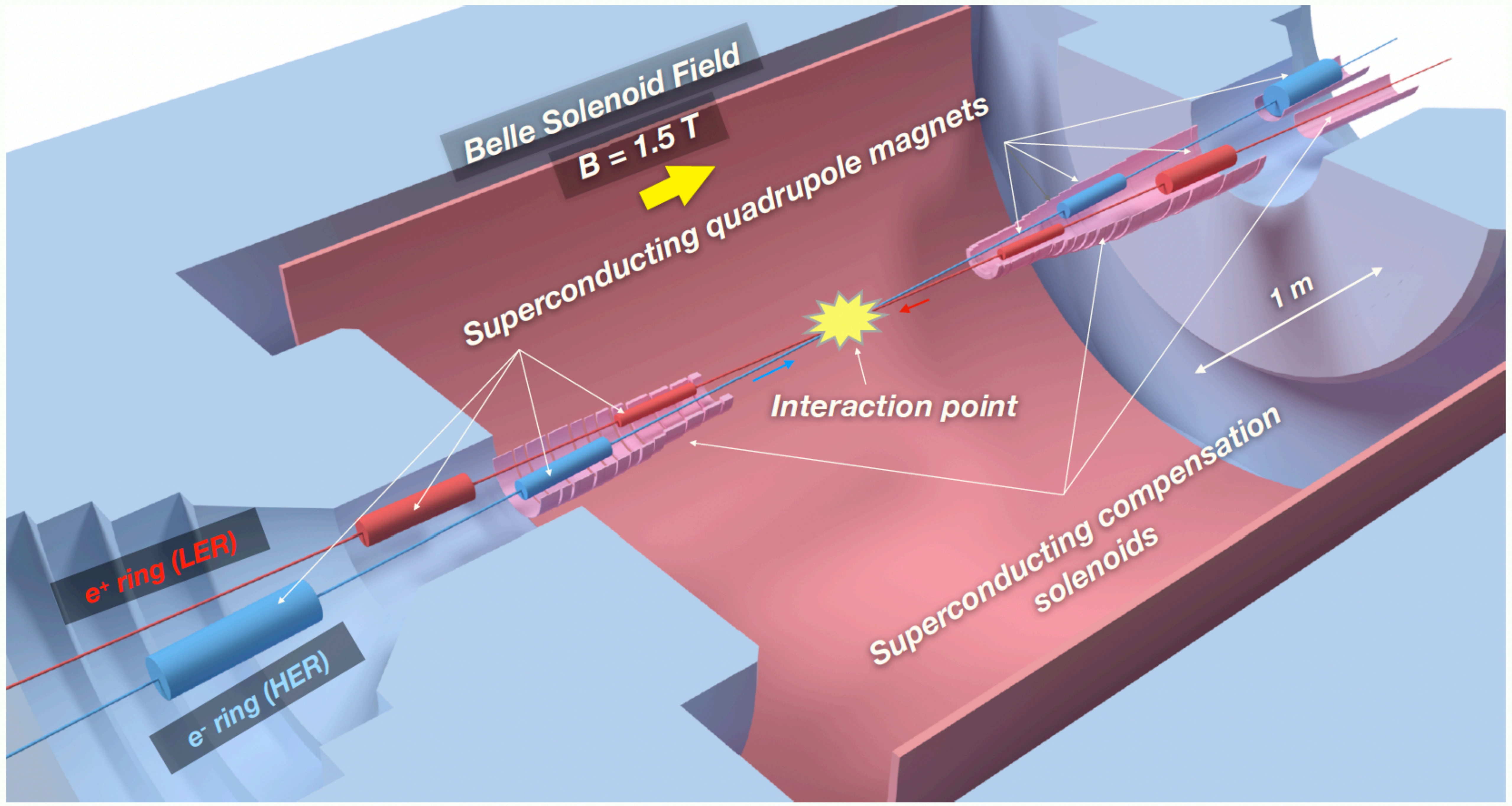
Photo by DESY



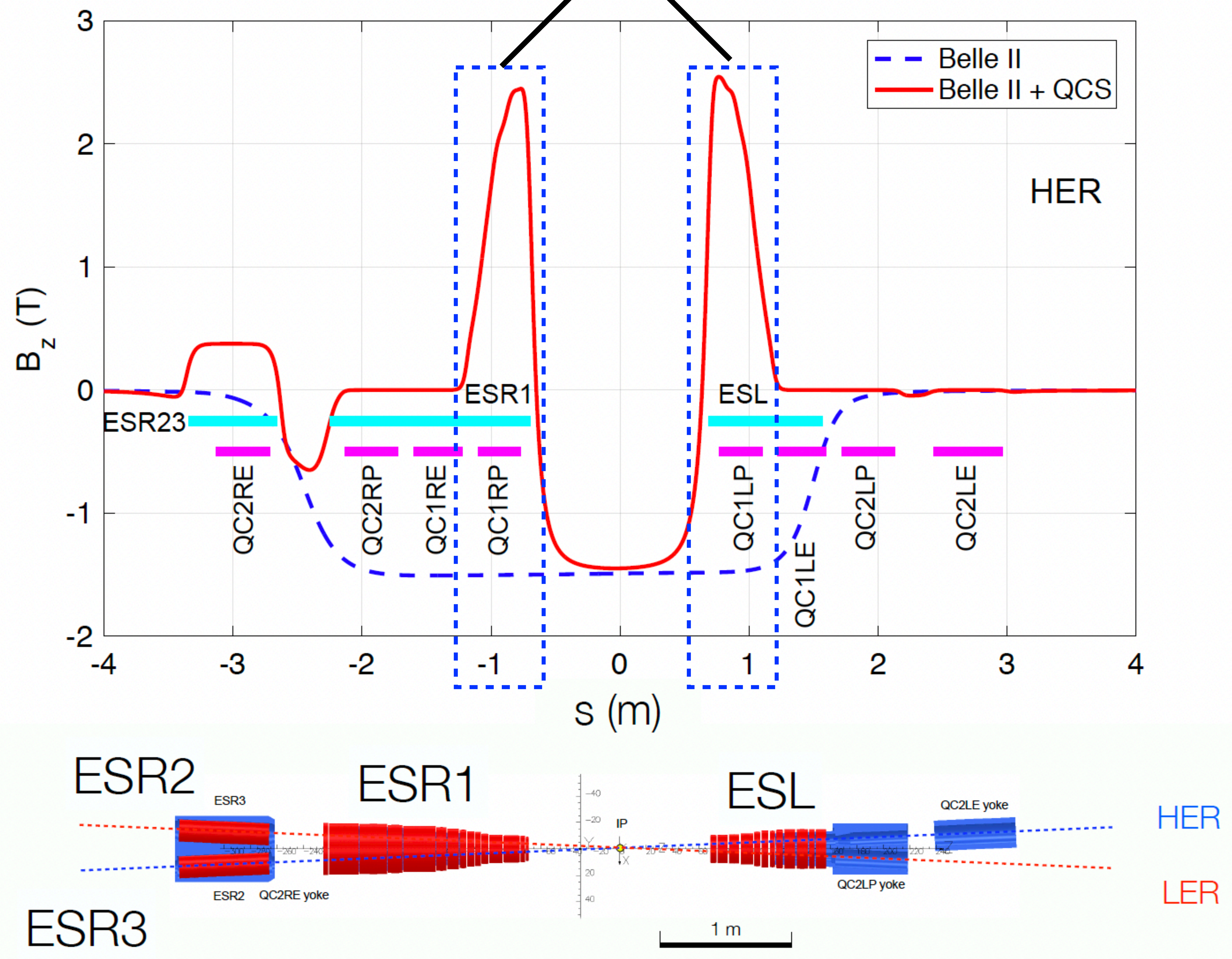
[1] K. Shibata, "Overview of SuperKEKB IR".

Accelerator challenges

- Complicated interaction region (IR) [1]
  - Large crossing angle (required by collision scheme) and limited spaces for hardwares increase the complexity of optics.



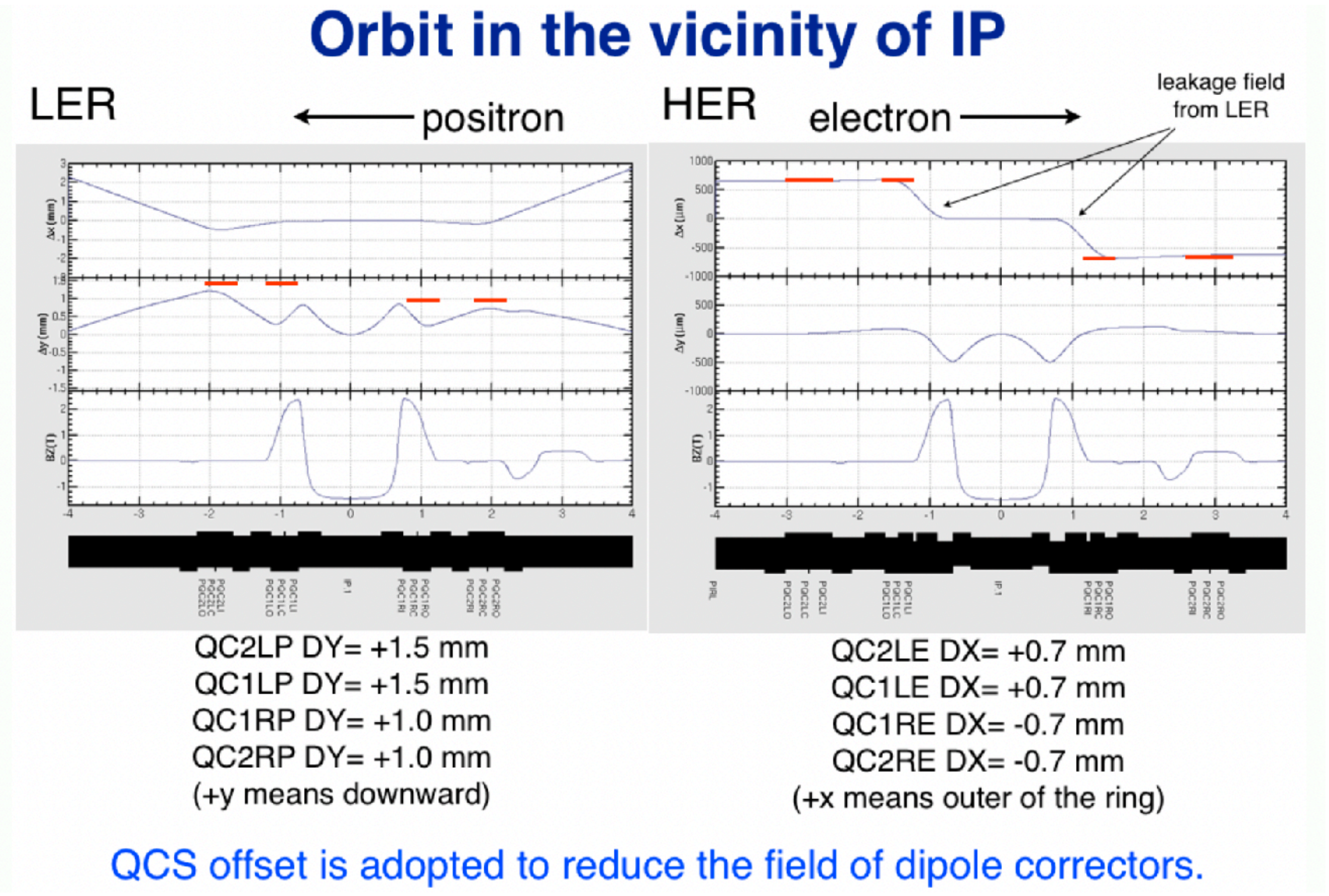
Overlap of solenoids and FF quads

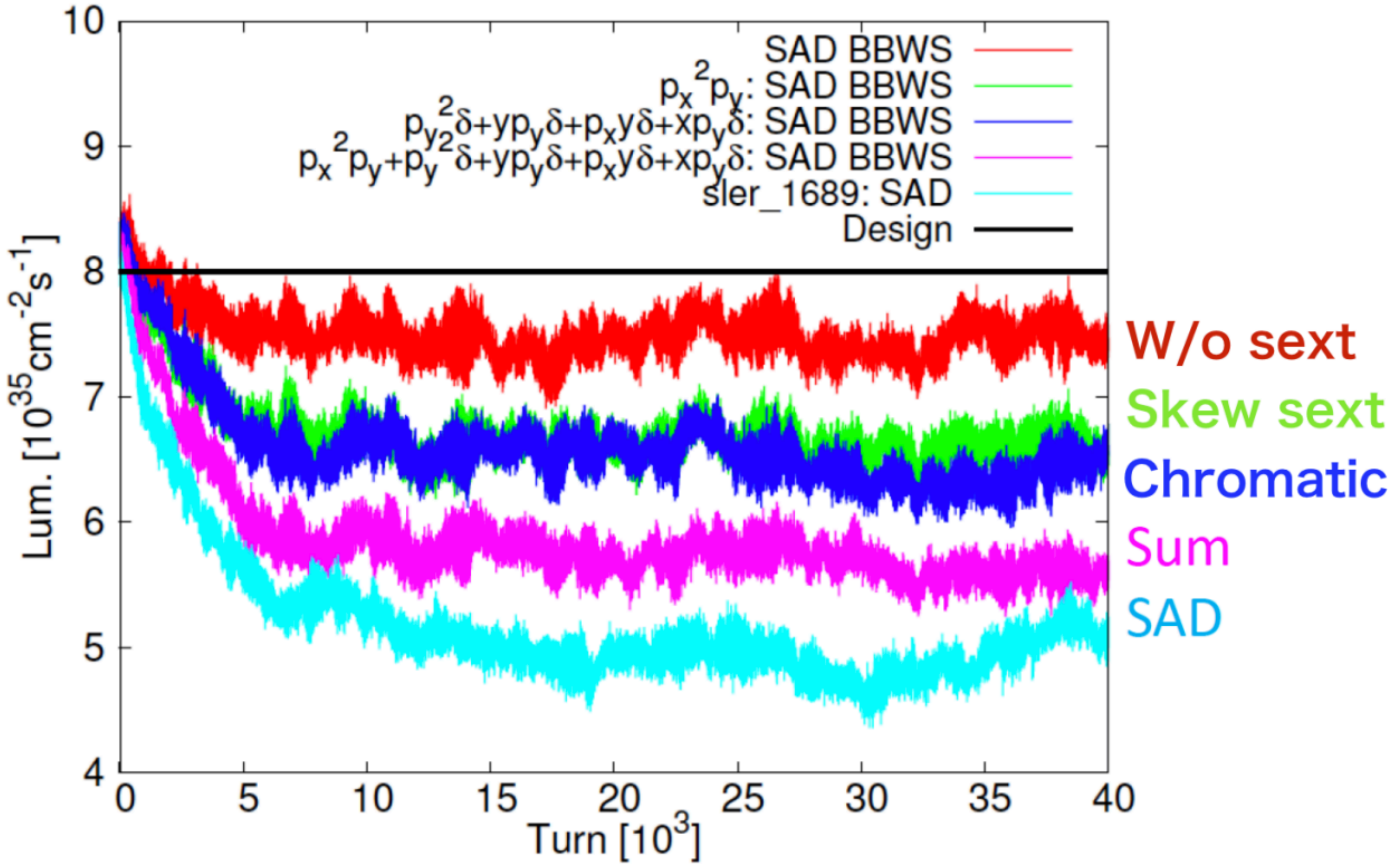


[1] Y. Arimoto, "Current QCS magnet system".

Accelerator challenges

- Complicated interaction region (IR): Side effects from beam physics viewpoint
  - Extremely small β_y^* → Nonlinear effects from kinematic term of IP drift and fringe fields of final focus (FF) quadrupoles [1] → Fundamental limit on dynamic aperture and lifetime [1,2,3] → Poor injection efficiency [4] and high detector background [5].
  - Overlap of solenoid and FF quadrupoles, offsets of FF quadrupoles, etc. → Vertical emittance growth (single-beam) due to local linear and chromatic couplings [6] → Vertical emittance growth (two-beam) from interplay of beam-beam and lattice nonlinearity [7,8] → Imperfect crab waist due to nontransparent IR [2].

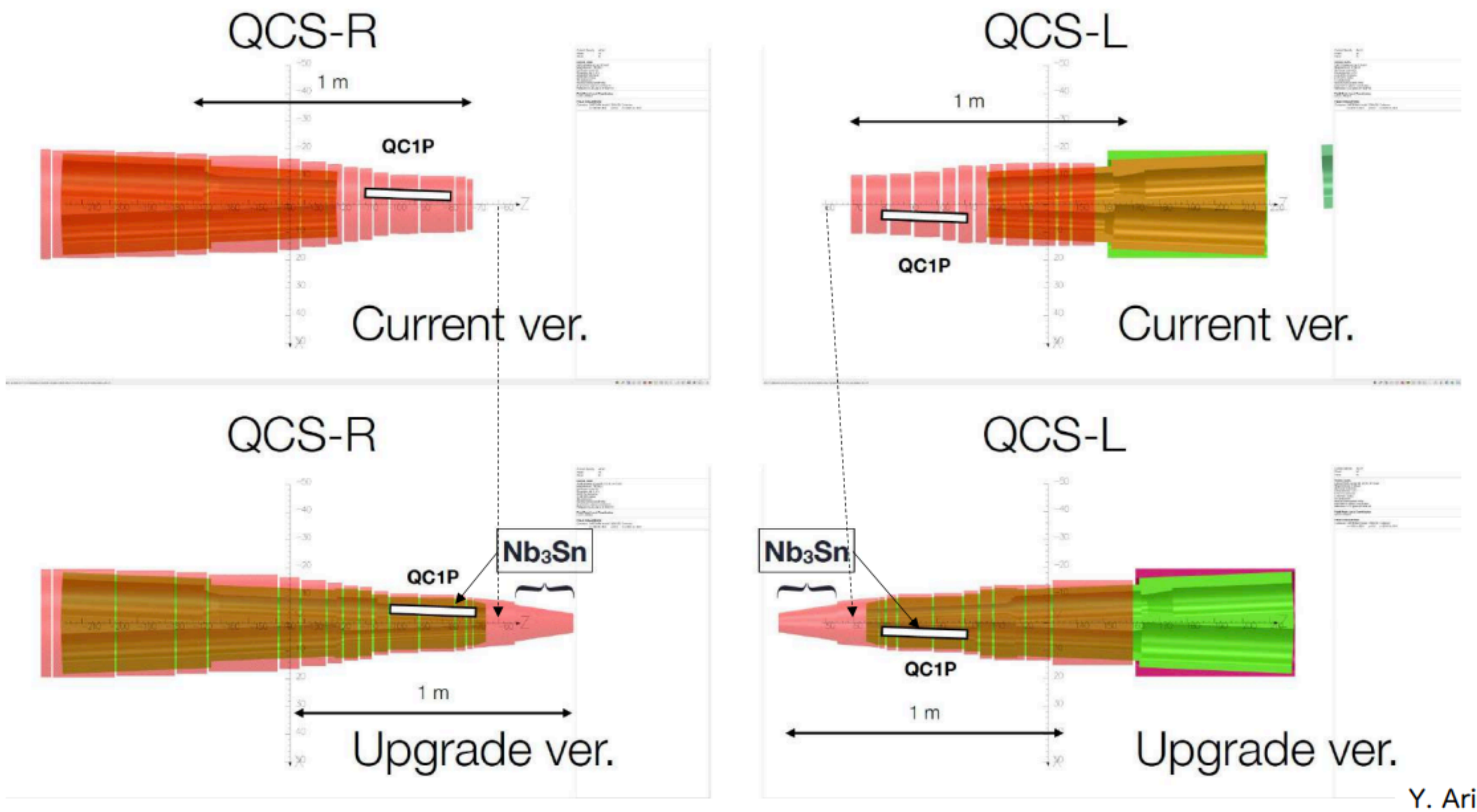




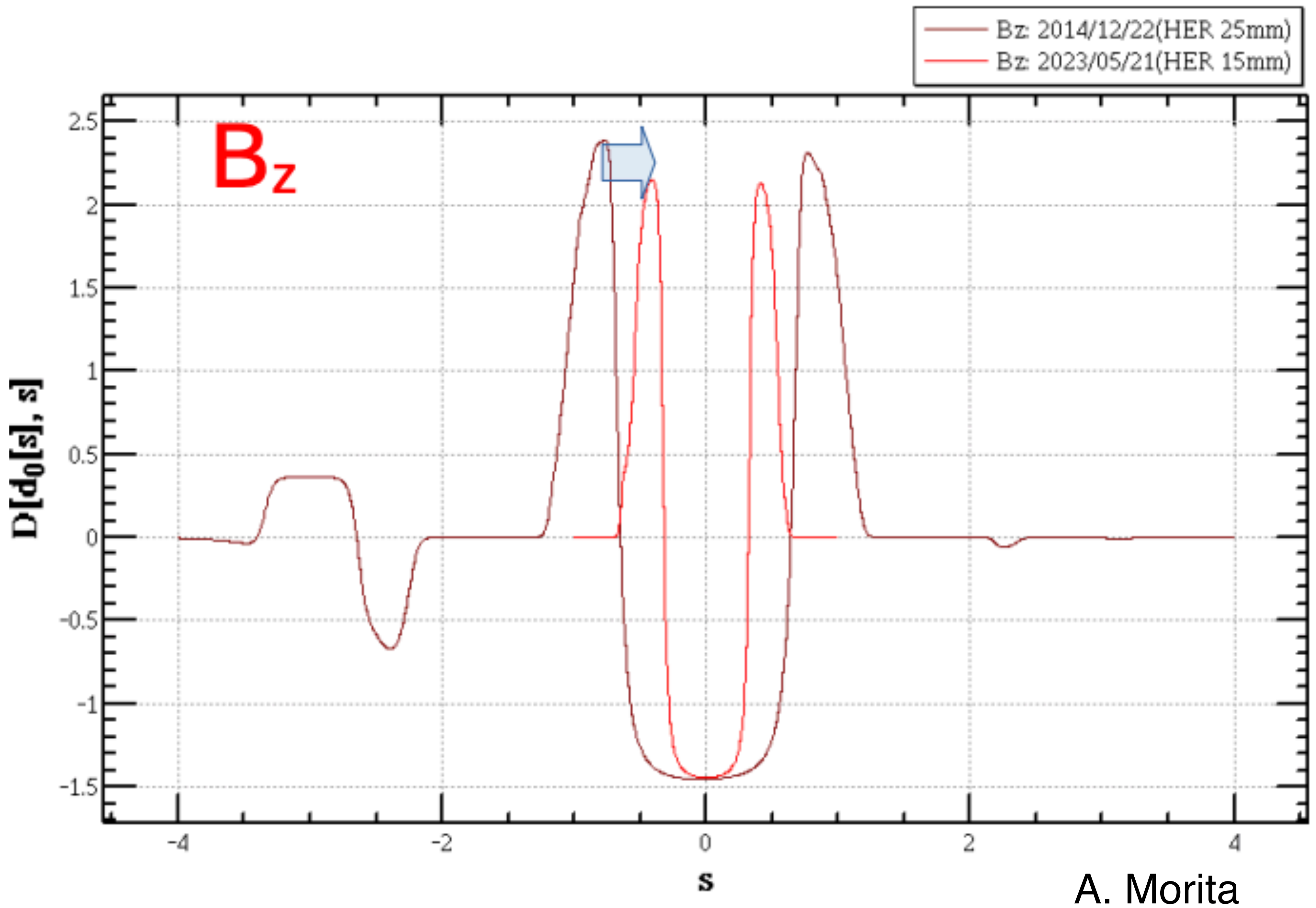
[1] K. Oide and H. Koiso, Phys. Rev. E 47, 2010 (1993). [2] SuperKEKB TDR. [3] Y. Suetsugu, et al., PRAB 26, 013201 (2023). [5] A. Natochii, et al., "Beam background expectations for Belle II at SuperKEKB".
[6] M. Masuzawa, IPAC'22. [7] D. Zhou et al., "Beam Dynamics Issues in the SuperKEKB". [8] K. Hirosawa et al., J. Phys.: Conf. Ser. 1067 062004 (2018).

Accelerator challenges

- Complicated interaction region (IR): Strategy of future IR upgrade
  - Various upgrade plans have been evaluated.
  - Removing the solenoid-QCS overlap is the main direction under investigation. Benefits: 1) Reduce the local linear and chromatic coupling; 2) Improve Touschek lifetime; 3) Easy IR optics corrections and tunings.



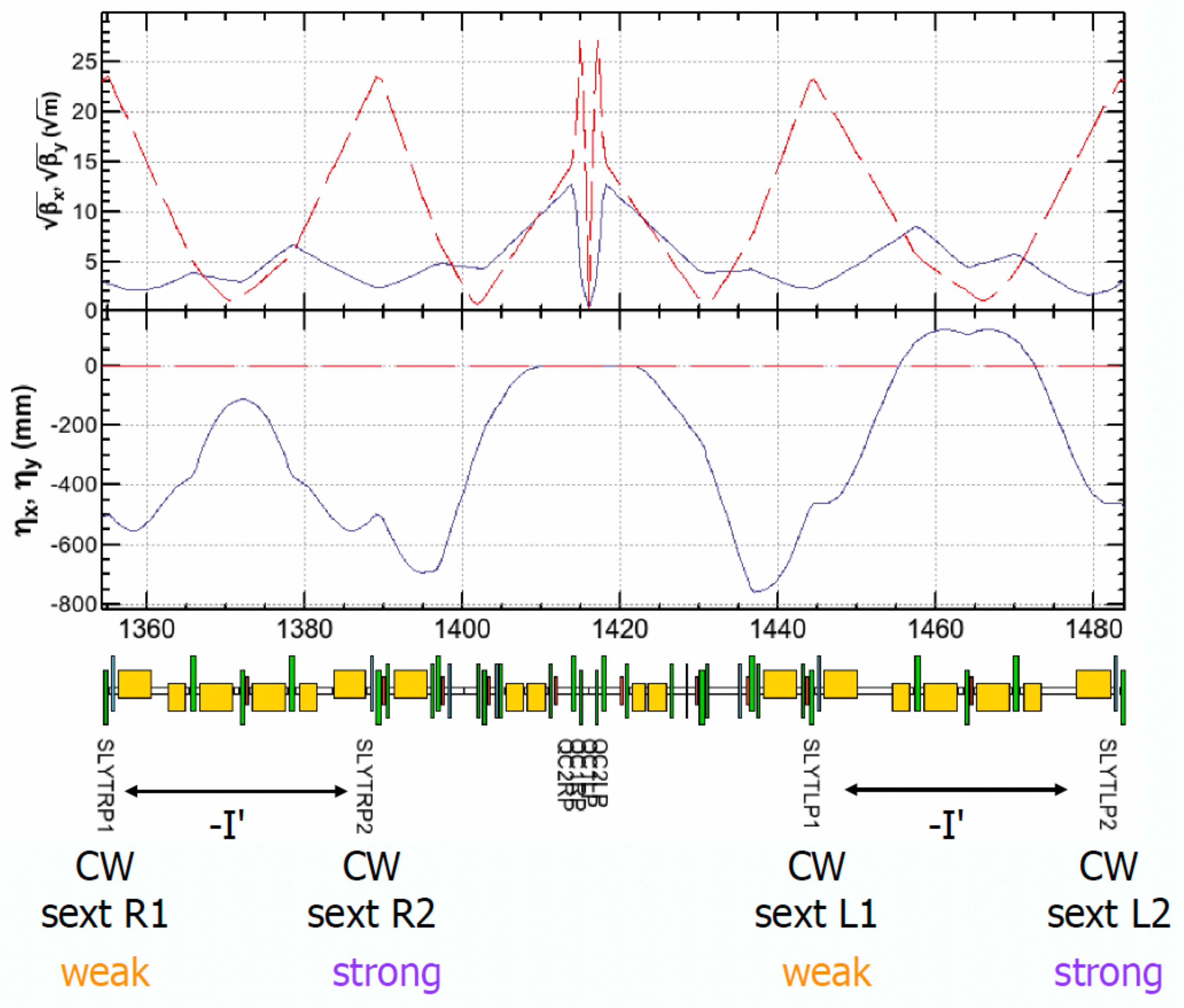
Y. Arimoto

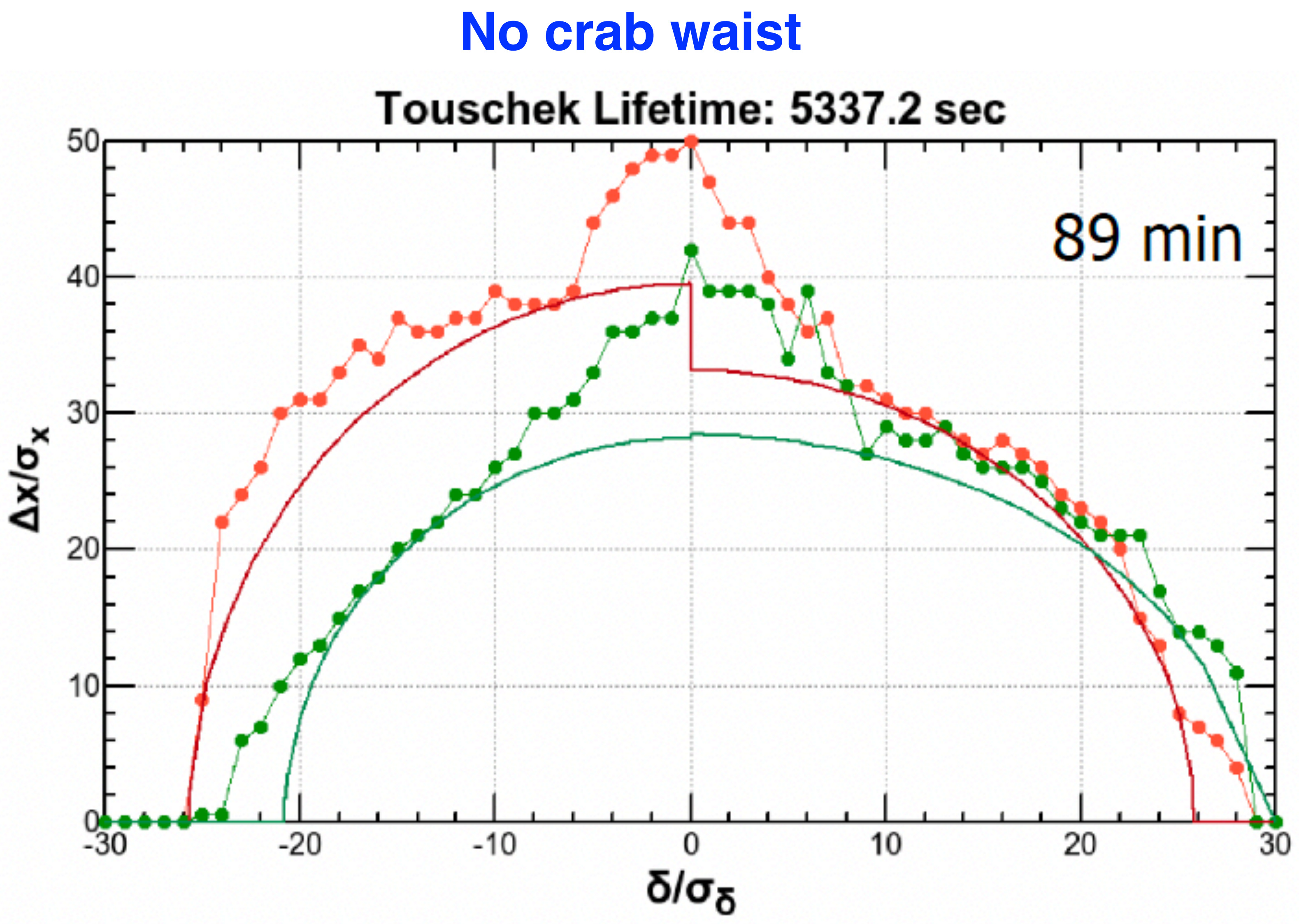


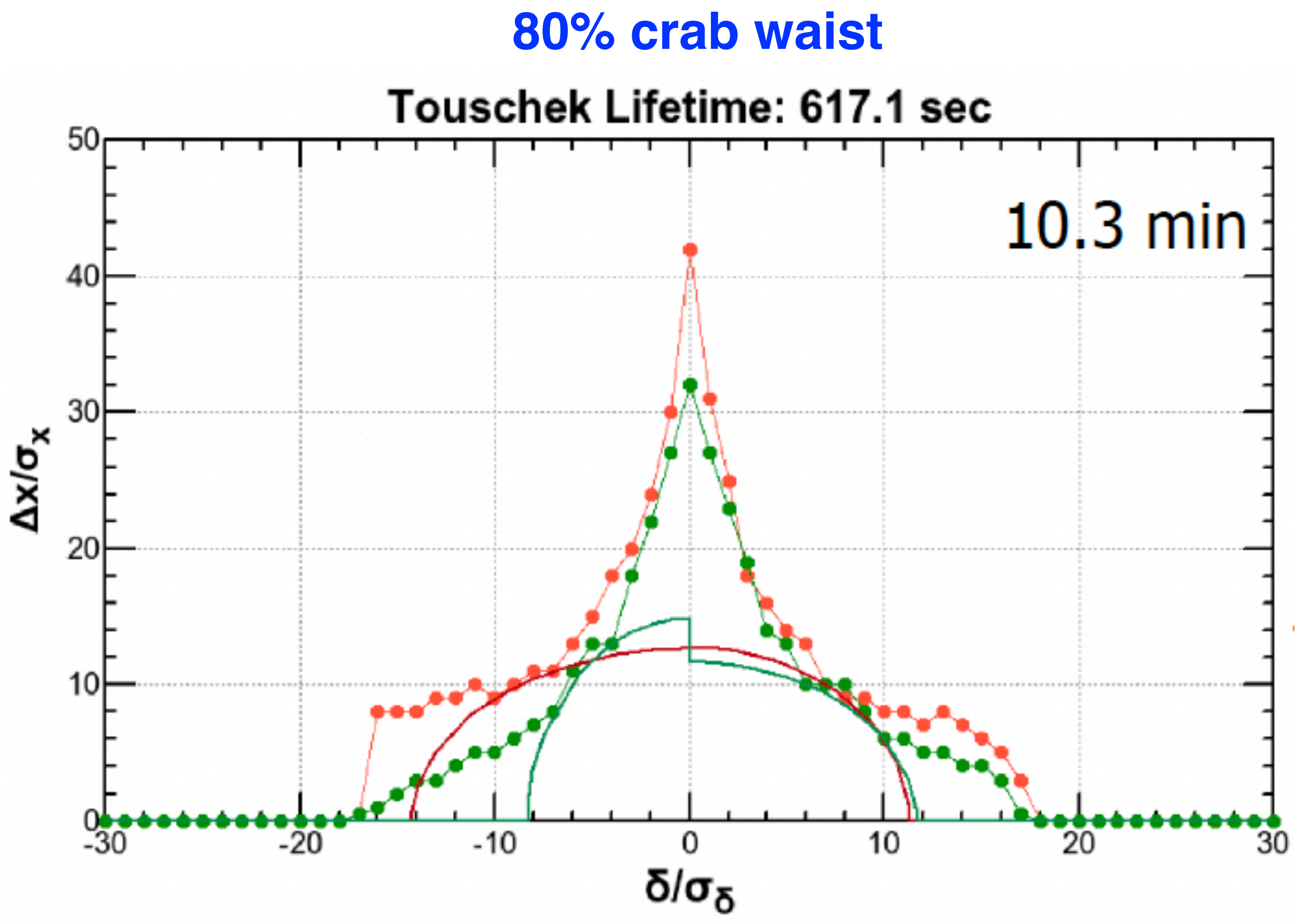
A. Morita

Accelerator challenges

- Implementation of crab waist at SuperKEKB
  - Crab waist [1] was optional in SuperKEKB final design, because it significantly reduces dynamic aperture and lifetime (from optics design with a realistic IR) [2].
  - Beam commissioning experienced severe emittance blowup and poor luminosity, forcing implementation of crab waist (Oide's scheme [3]).
  - Crab waist is efficient in suppressing beam-beam blowup, but cause significant loss of dynamic aperture and lifetime at SuperKEKB with β_y^*=1 mm [4].



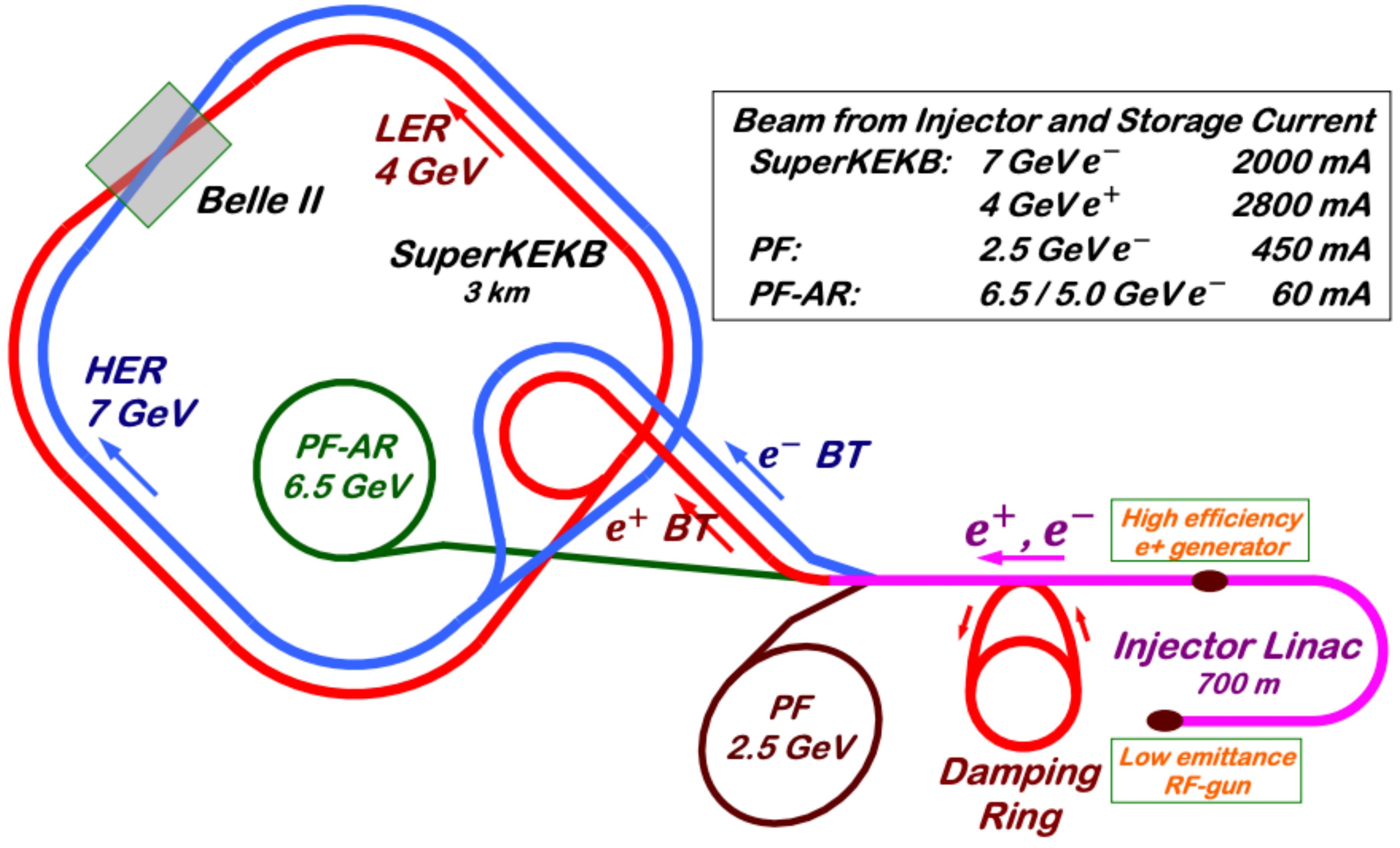


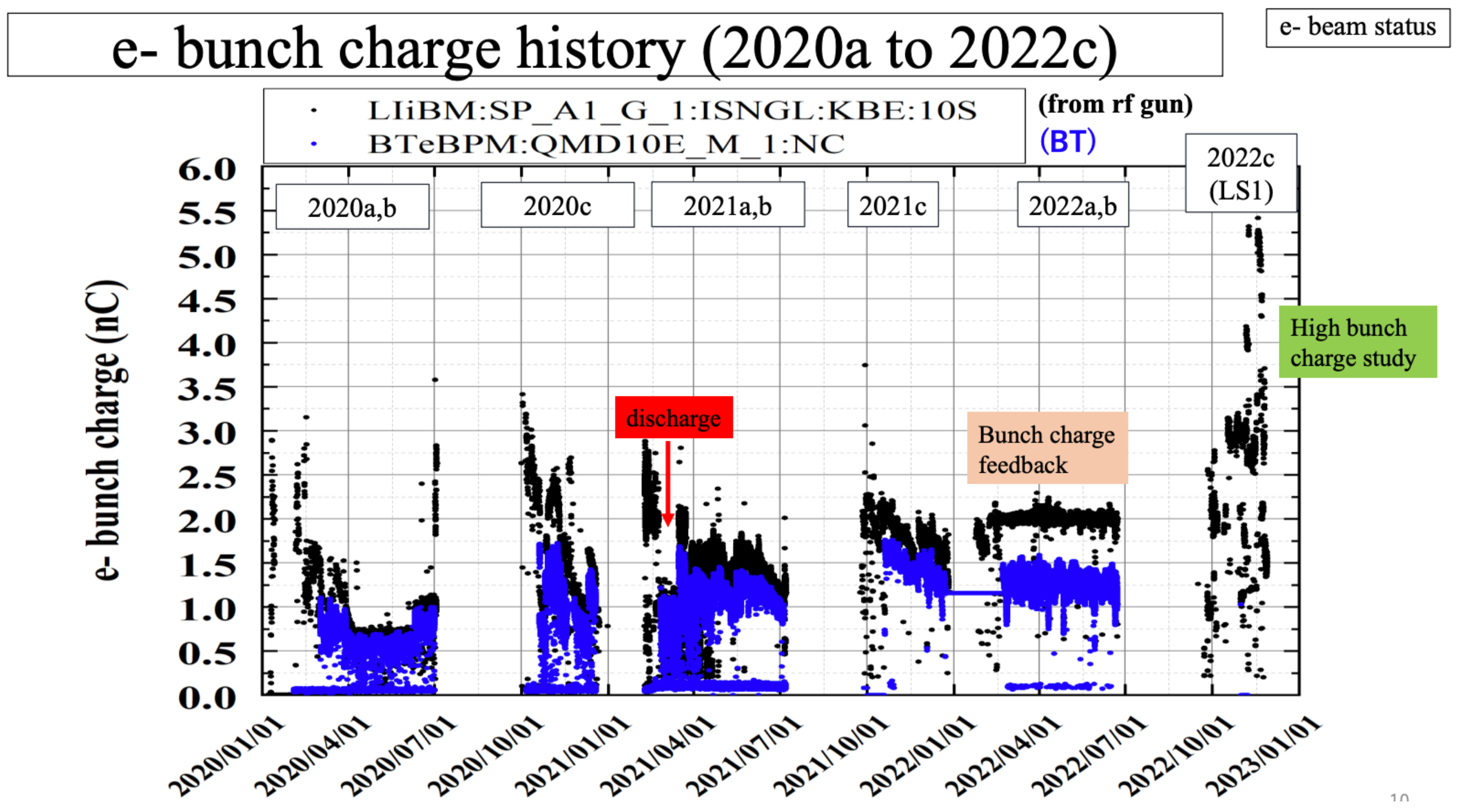


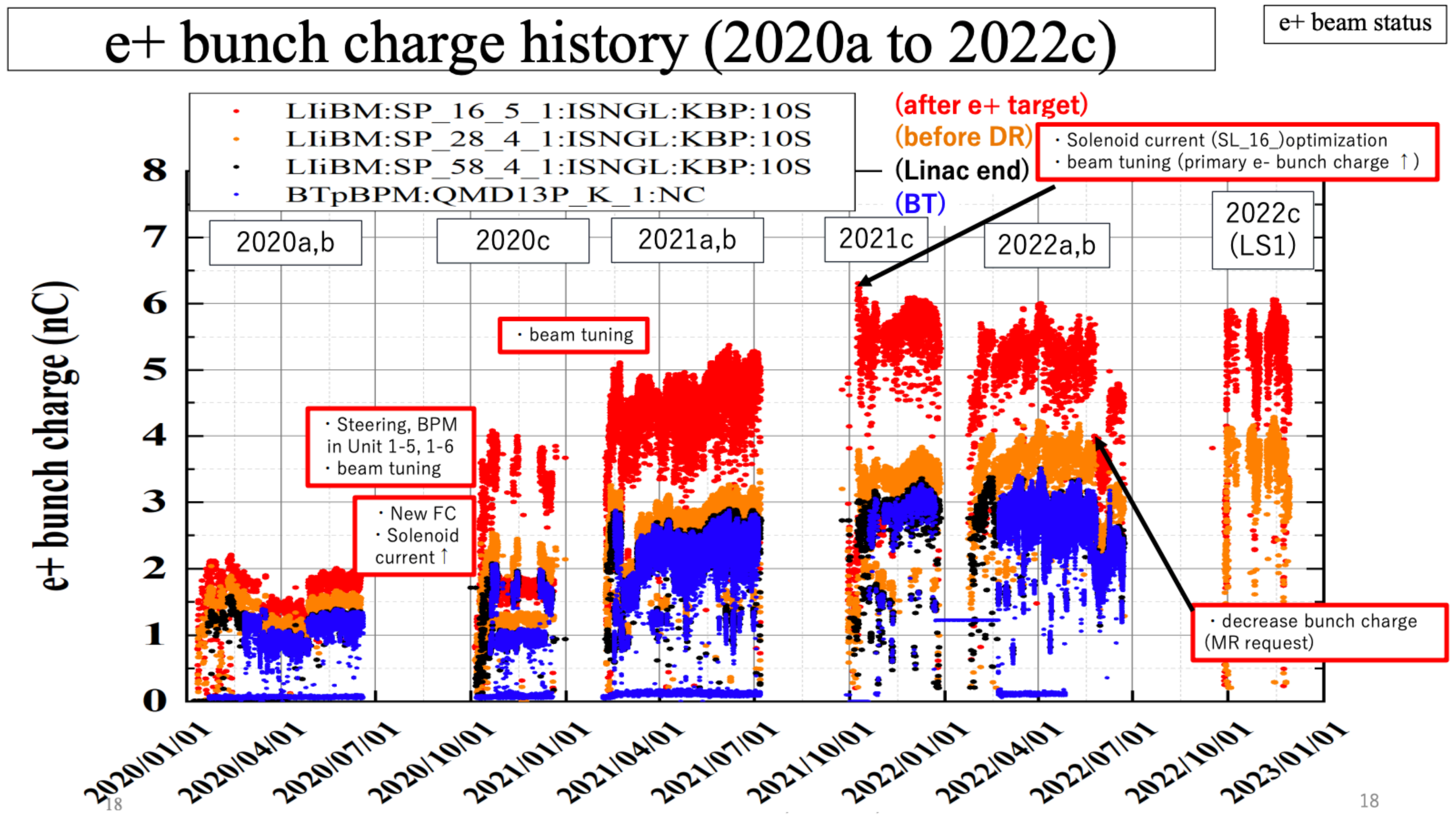
[1] M. Zobov et al., Phys. Rev. Lett. 104, 174801 (2010). [2] SuperKEKB TDR. [3] K. Oide et al., Phys. Rev. Accel. Beams 19, 111005 (2016). [4] Y. Ohnishi, "Dynamic Aperture for Crab Waist in LER".

Accelerator challenges

- Complicated linac and beam transport lines
  - The linac inject beams to SuperKEKB (LER and HER), PF, and PF-AR [1].
  - Short lifetime of the ring beams requires injections with high-charge and high injection rate.
  - Low emittance preservation is challenging in the presence of incoherent and coherent synchrotron radiation (ISR and CSR), RF-cavity wakefields, alignment errors, etc. [2,3]
  - Two-bunch injection has been achieved, but injection efficiency of the second bunch is poor [4].



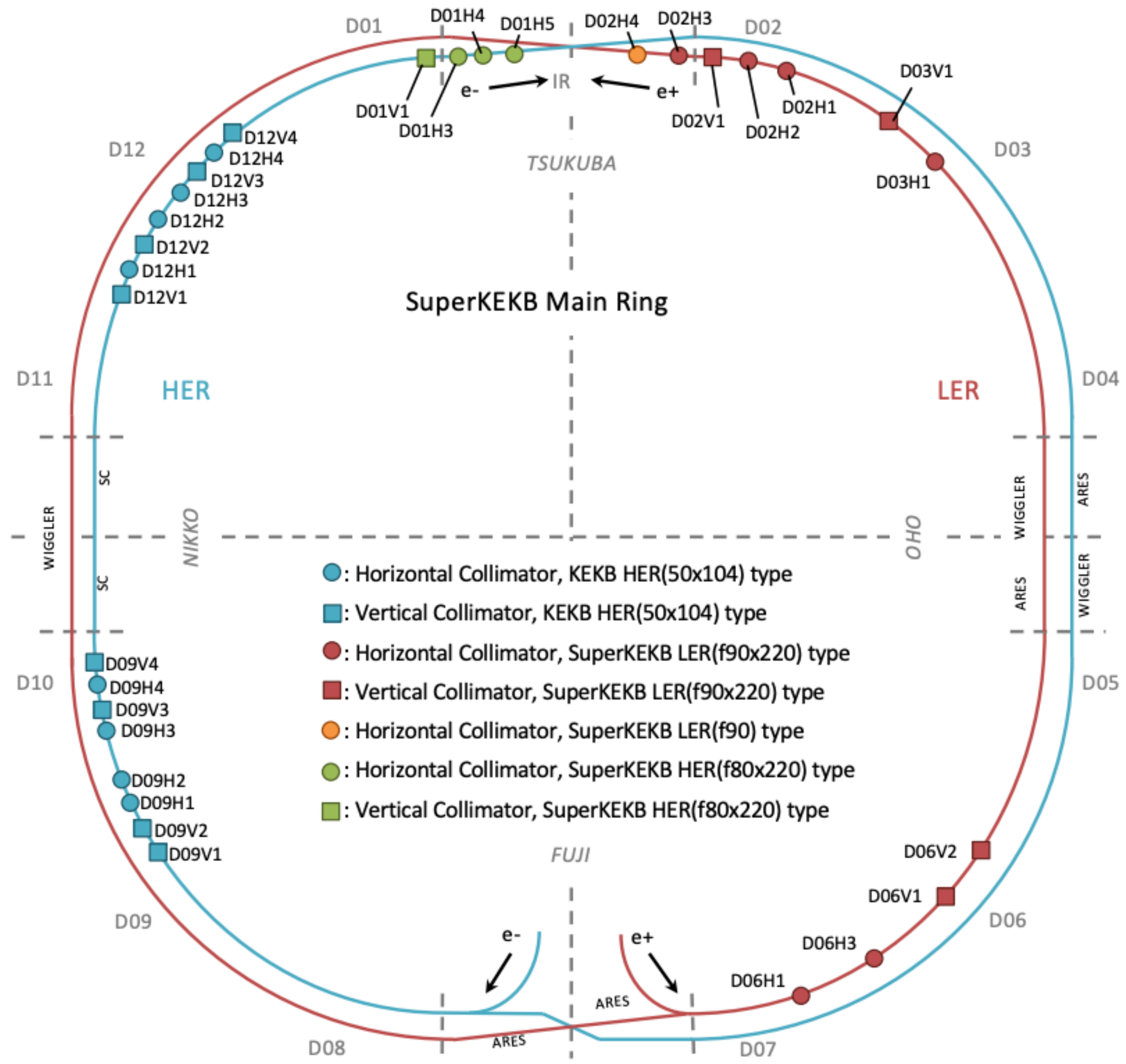


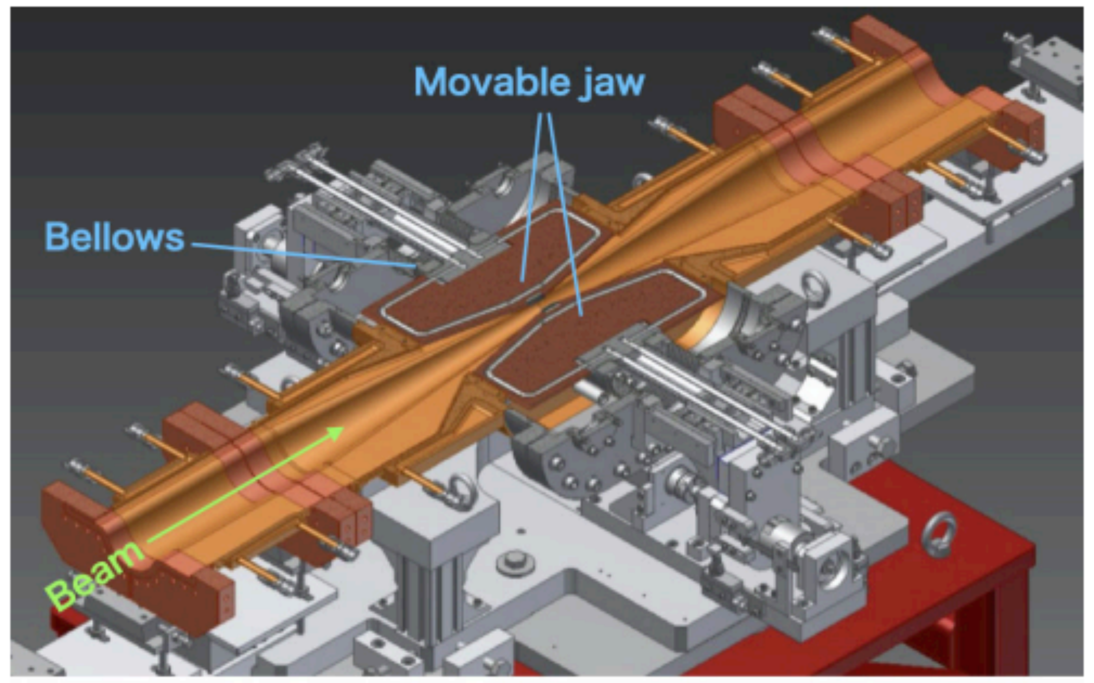


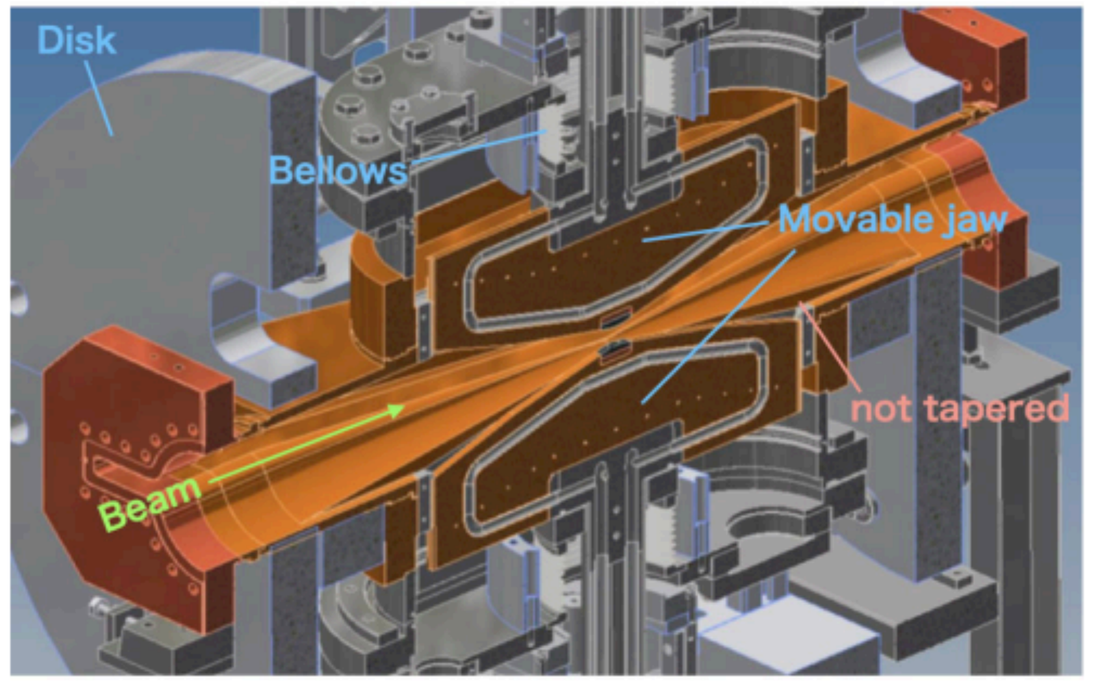
[1] K. Furukawa et al., J. Phys.: Conf. Ser. 2420 012021 (2023). [2] K. Furukawa et al., IPAC'22. [3] N. Iida, "Injection". [4] M. Satoh, "Injector".

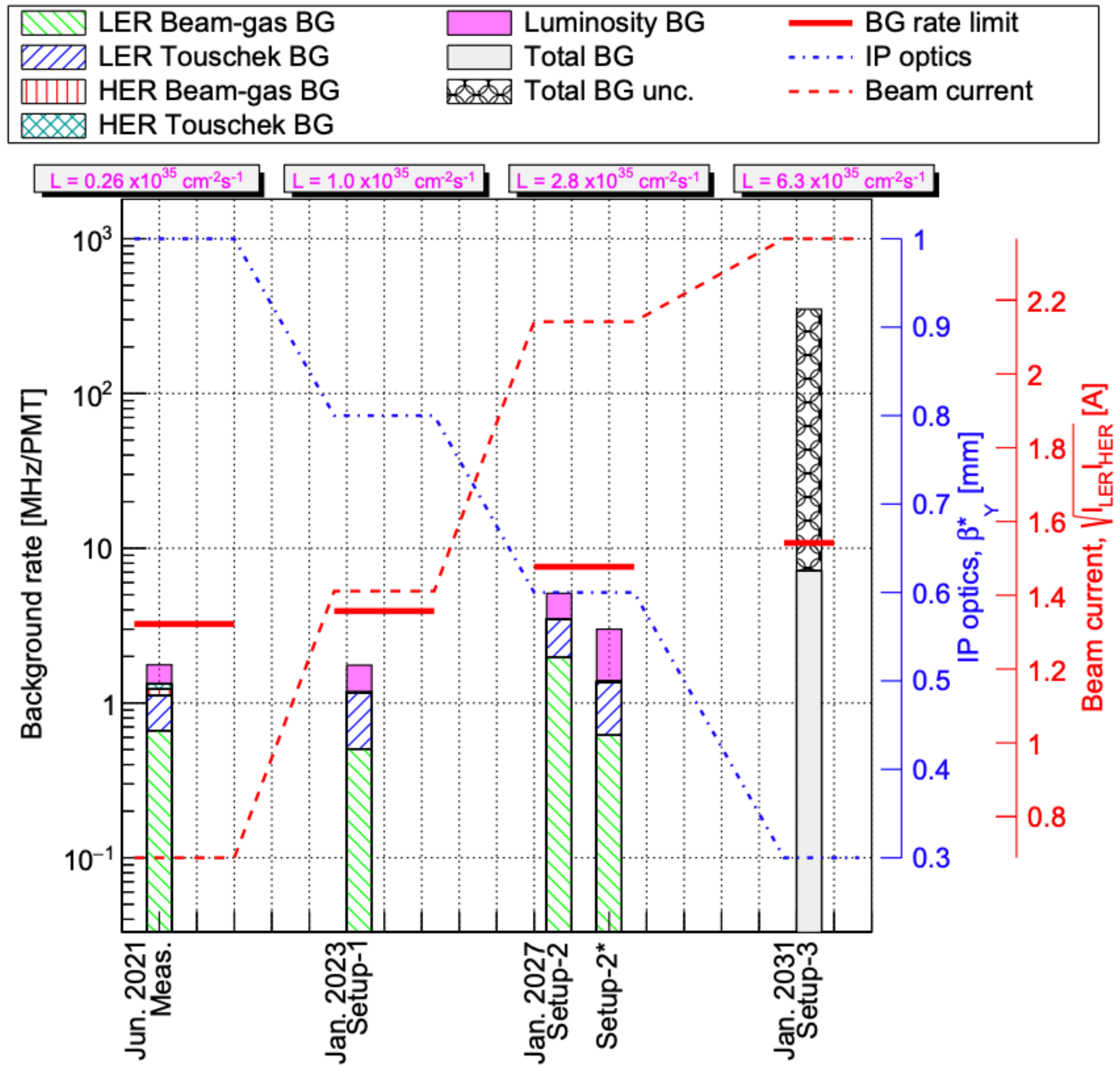
Accelerator challenges

- High detector background
  - The short lifetime and poor injection efficiency cause high background to Belle II [1,2], requiring tight configurations of collimation system [3]
  - Small-gap collimators contribute large impedance (especially after head damages) and caused trouble to vertical emittance blowup (Troubles in bunch-by-bunch feedback, interplay with beam-beam, etc.) [4].





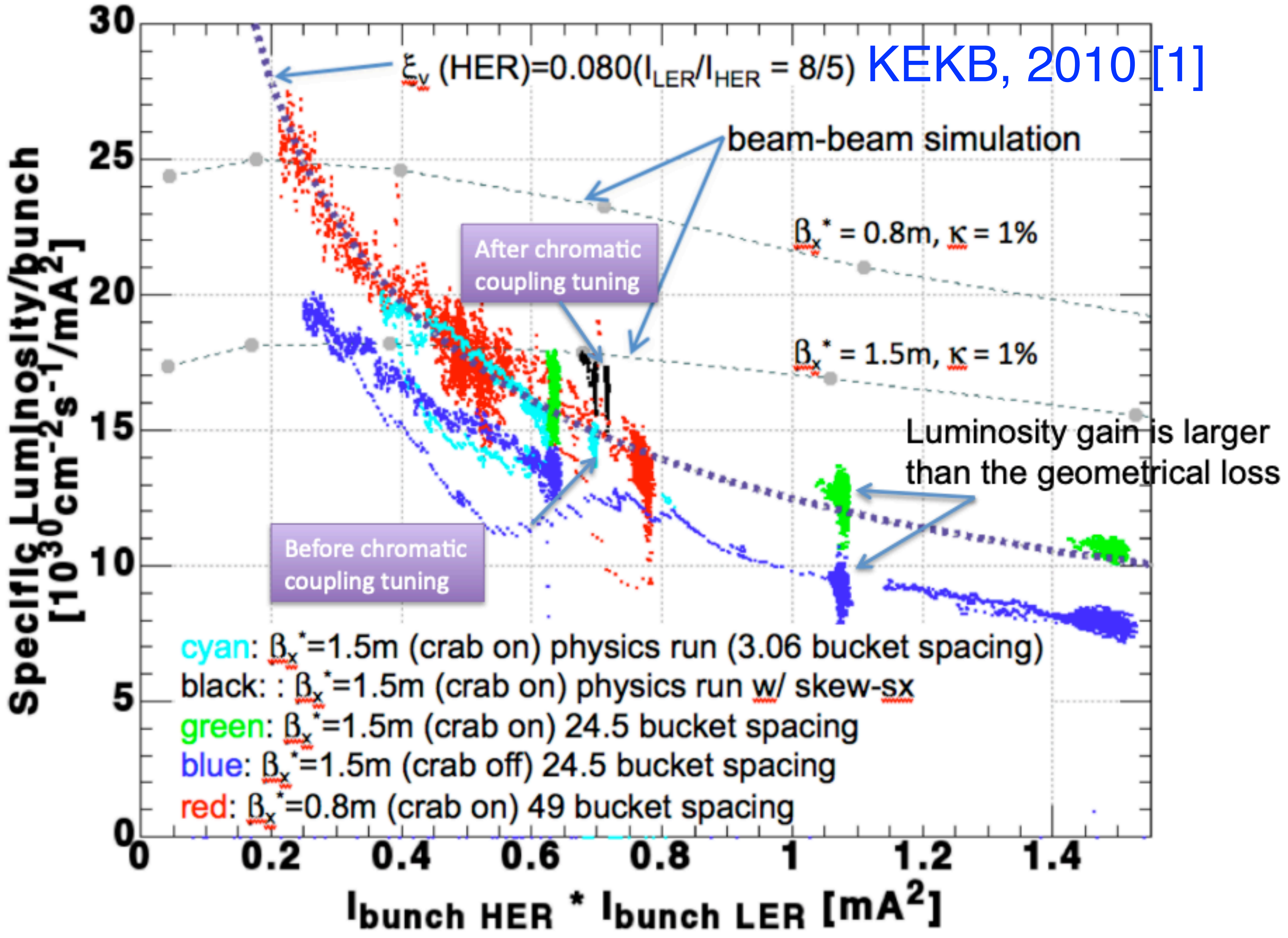




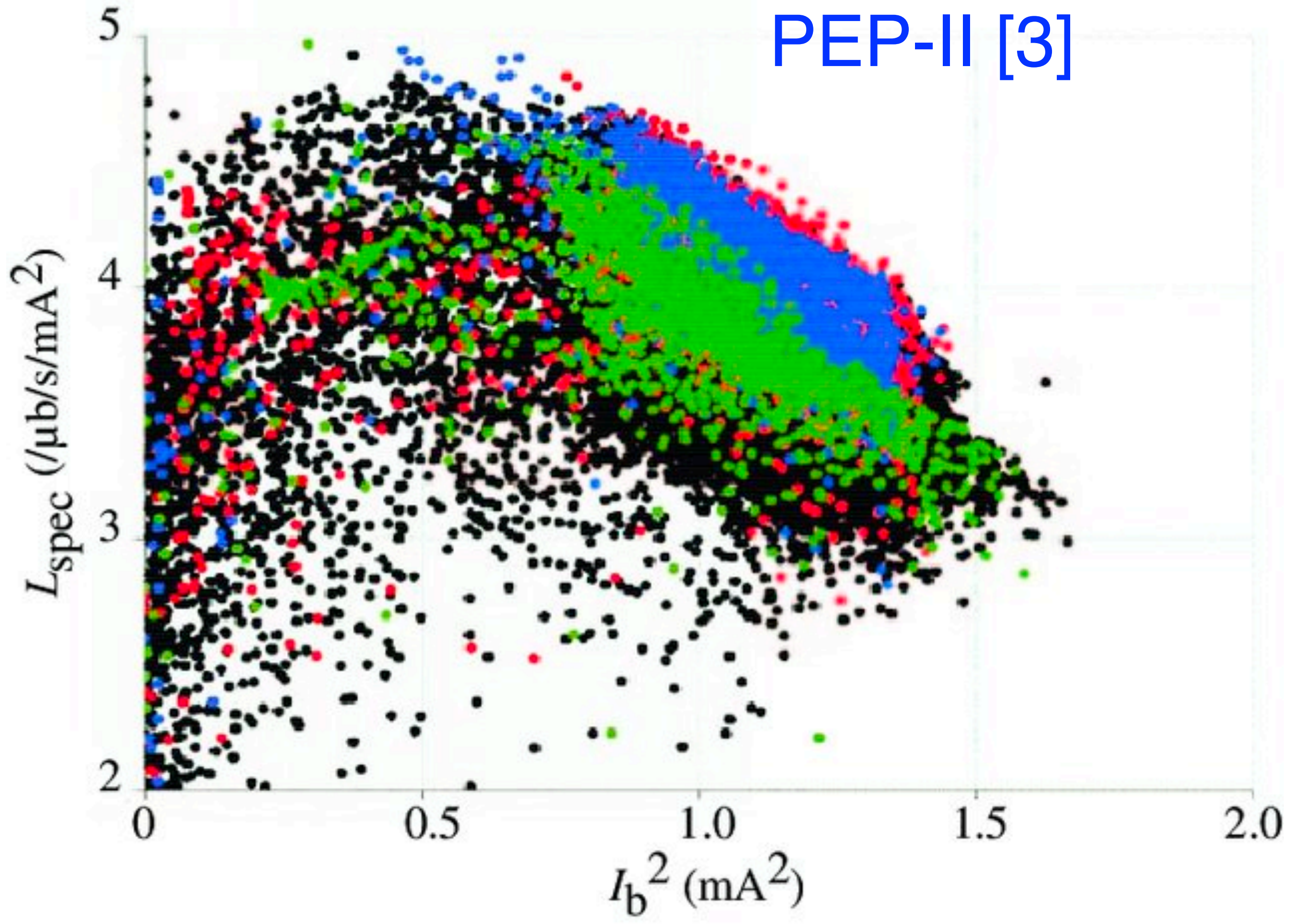
[1] A. Natochii, et al., "Beam background expectations for Belle II at SuperKEKB". [2] A. Natochii et al., PRAB 24, 081001 (2021).
[3] T. Ishibashi et al., PRAB 23, 053501 (2020). [4] T. Ishibashi et al., "Impedance modelling and single-bunch collective instability simulation in SuperKEKB main ring", To be published.

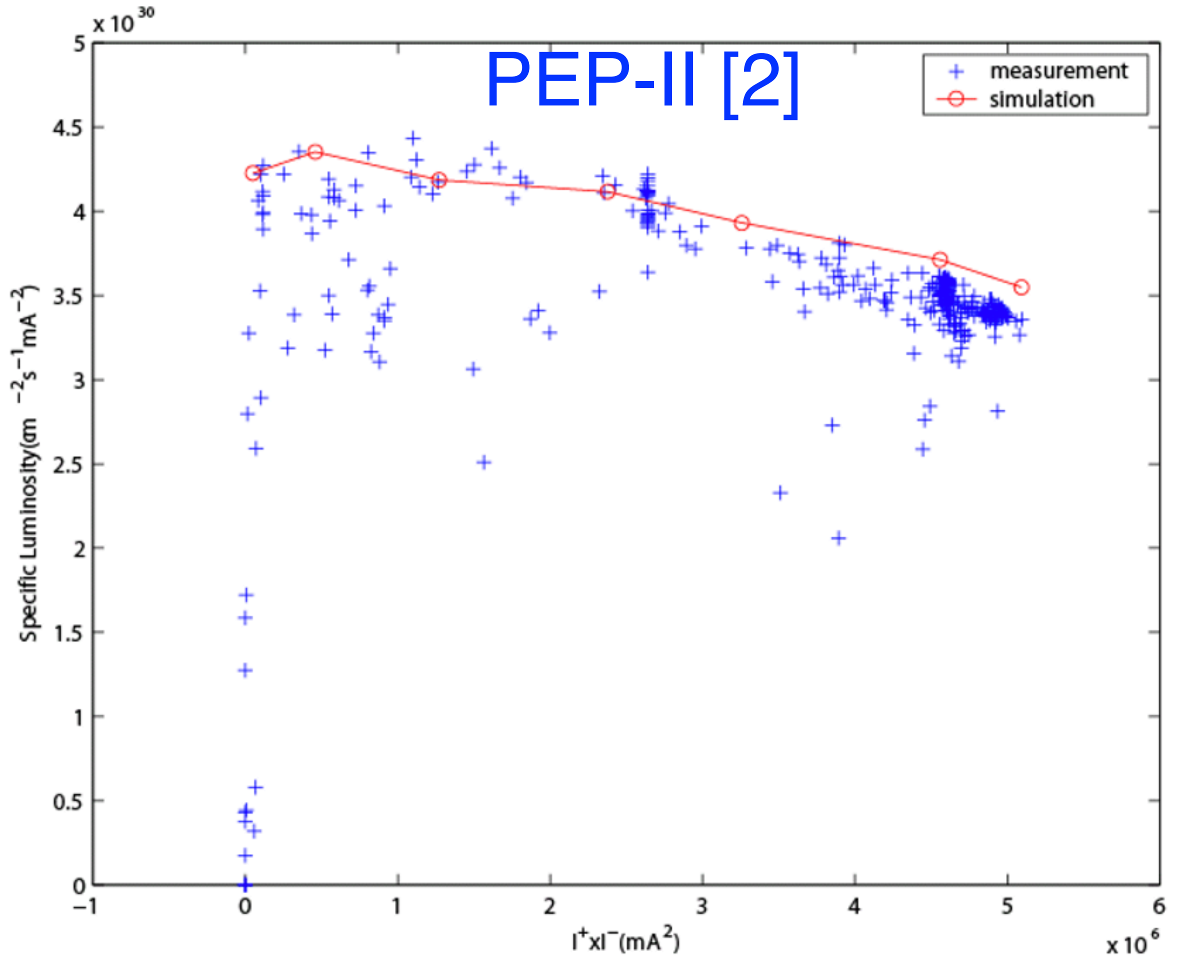
Accelerator physics challenges

- Severe beam-beam blowup
  - Interplay of multiple factors (beam-beam, impedances, IP linear aberrations, lattice nonlinearity, feedback, etc.) challenges the predictability of beam-beam simulations.
  - The ultimate goal is strong-strong beam-beam simulations with full lattices.

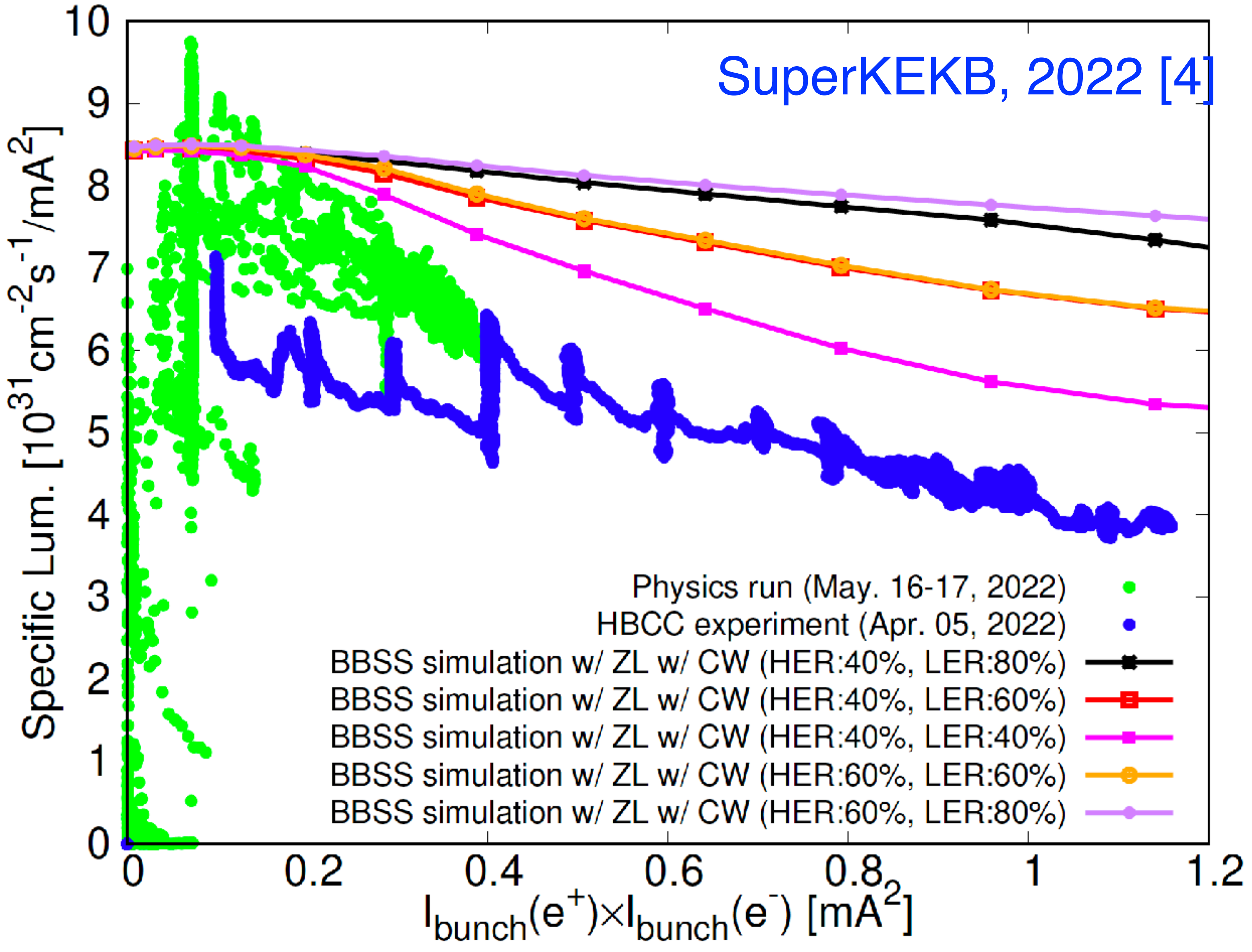


Specific Luminosity October 10, 2005
(I^+=2940mA, I^-=1733mA, n_b=1732)





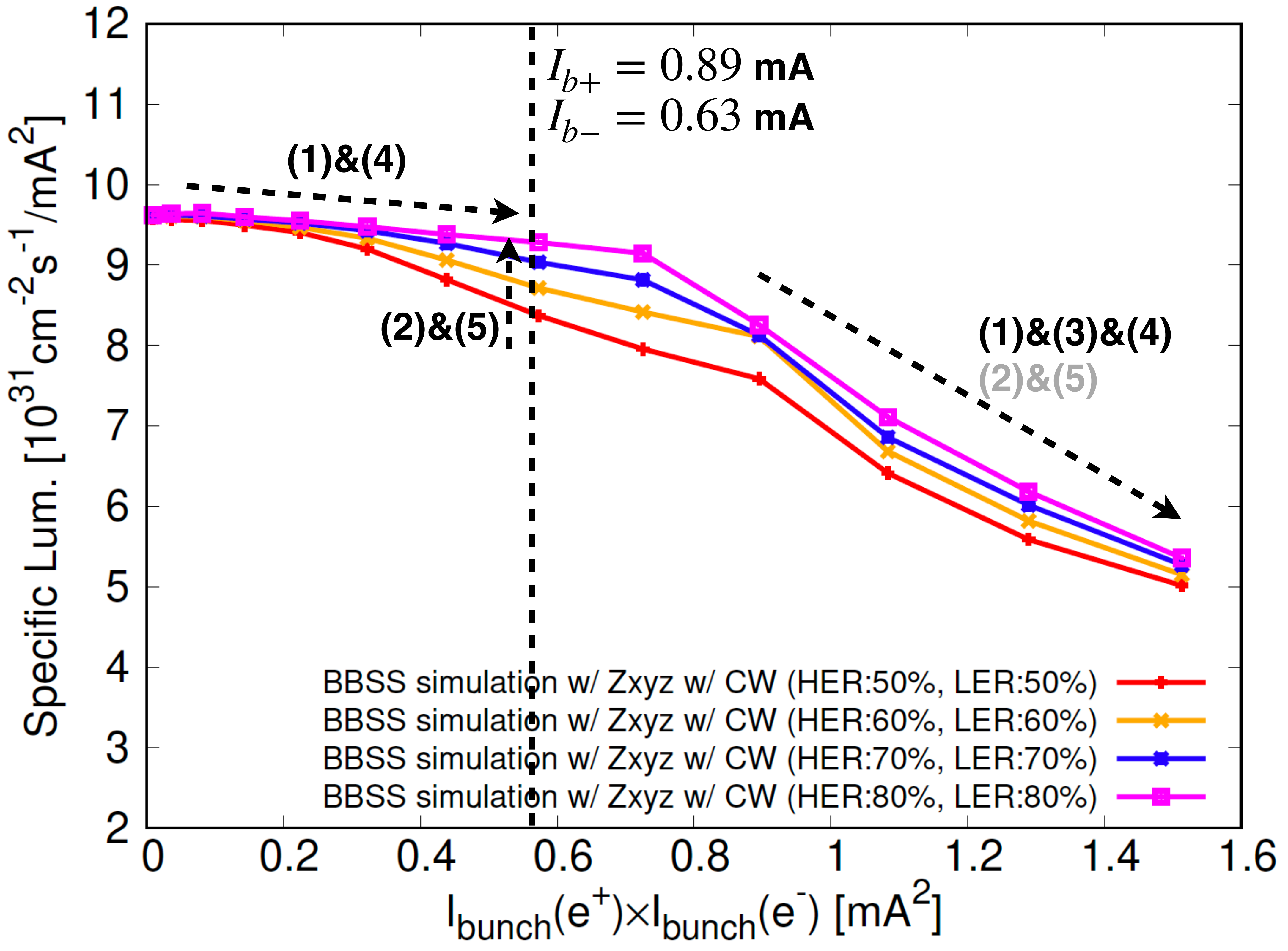
Data taken in the history buffer for a 24 hours period.
The simulation used an approximately fixed current ratio.



[1] Y. Funakoshi, KEKB MAC 2010; [2] Y. Cai, KEKB MAC 2006; [3] U. Wienands, PAC07.
[4] D. Zhou et al., PRAB 26, 071001 (2023).

Accelerator physics challenges

- Beam-beam simulations for post-LS1 operation (1E35 luminosity). Factors affecting luminosity:
  - (1) Bunch lengthening and synchrotron tune spread caused by longitudinal impedance → Unavoidable
  - (2) Beam-beam-driven fifth-order betatron resonances $\nu_x \pm 4\nu_y + \alpha = N$ → Cured by crab waist
  - (3) Vertical TMCI-like instability driven by the interplay of beam-beam and vertical impedance [1]
  - (4) Dynamic beta and dynamic emittance caused by linear transverse beam-beam force ($\beta_y^* \searrow$, $\epsilon_y \nearrow$)
  - (5) Crab waist (CW) suppresses the fifth-order beam-beam resonances

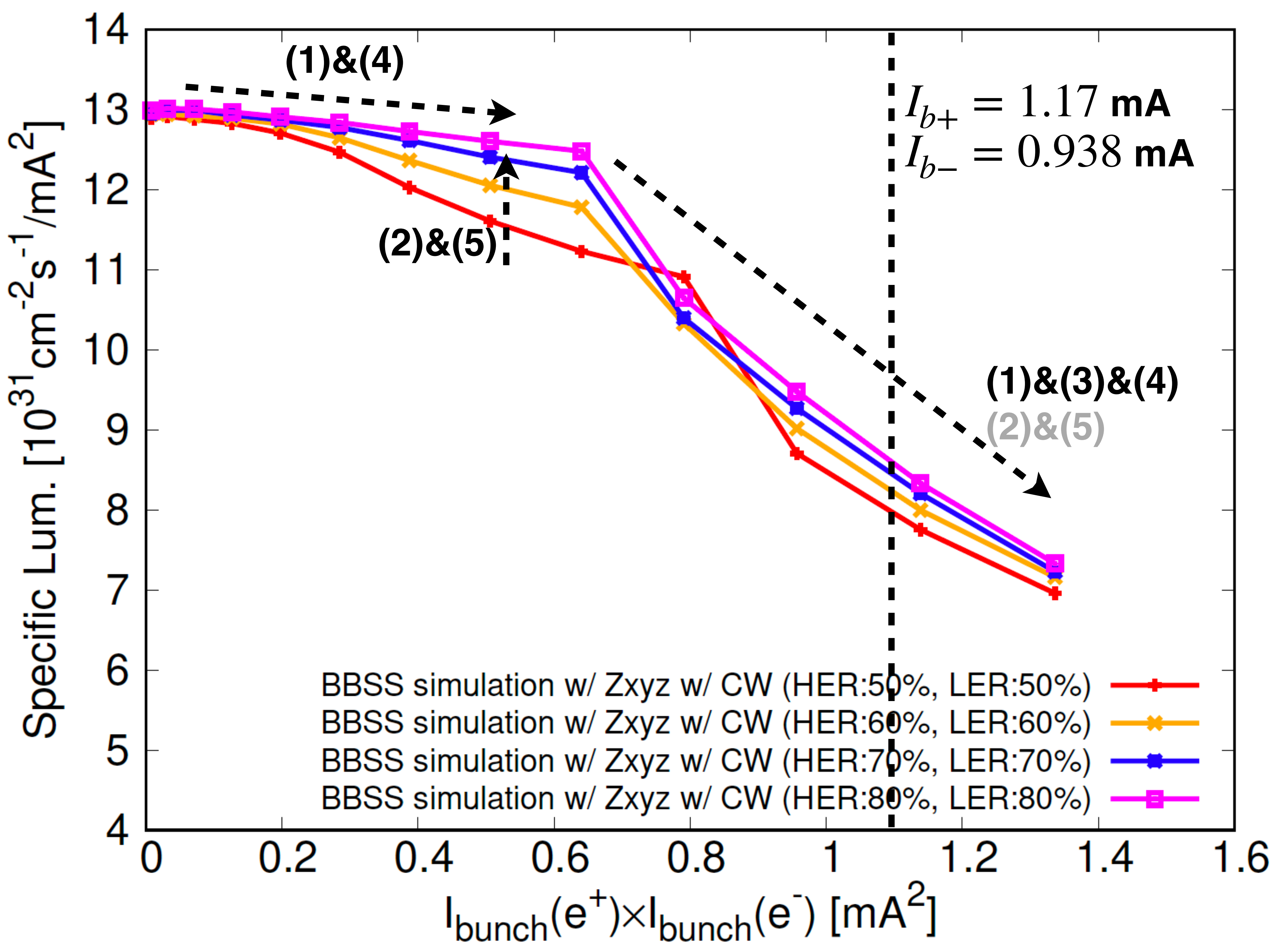


	post-LS1 1E35		Comments
	HER	LER	
I_{bunch} (mA)	0.63	0.89	
# bunch	2345		2022a operation value
ε_x (nm)	4.6	4.0	w/o IBS
ε_y (pm)	30	30	Single-beam emittance
β_x (mm)	60	60	Lattice design value
β_y (mm)	0.8	0.8	Lattice design value
σ_{z0} (mm)	5.1	4.6	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	2022a operation value
ν_y	43.574	46.589	2022a operation value
ν_s	0.0272	0.0222	Calculated from lattice
$\tau_{x,y}$ (ms)	58.0	53.1	Transverse damping time (w/ NLC)
τ_z (ms)	29.0	26.6	Longitudinal damping time
Crab waist	80%	80%	Lattice design

[1] Y. Zhang et al., PRAB 26, 064401 (2023)

Accelerator physics challenges

- Beam-beam simulations for post-LS1 operation (2.4E35 luminosity). Factors affecting luminosity:
  - (1) Bunch lengthening and synchrotron tune spread caused by longitudinal impedance → Unavoidable
  - (2) Beam-beam-driven fifth-order betatron resonances $\nu_x \pm 4\nu_y + \alpha = N$ → Cured by crab waist
  - (3) Vertical TMCI-like instability driven by the interplay of beam-beam and vertical impedance [1]
  - (4) Dynamic beta and dynamic emittance caused by linear transverse beam-beam force ($\beta_y^* \searrow$, $\epsilon_y \nearrow$)
  - (5) Crab waist (CW) suppresses the fifth-order beam-beam resonances



	post-LS1 2.4E35		Comments
	HER	LER	
I_{bunch} (mA)	0.938	1.17	
# bunch	2345		2022a operation value
ε_x (nm)	4.6	4.0	w/o IBS
ε_y (pm)	21	21	Single-beam emittance
β_x (mm)	60	60	Lattice design value
β_y (mm)	0.6	0.6	Lattice design value
σ_{z0} (mm)	5.1	4.6	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	2022a operation value
ν_y	43.574	46.589	2022a operation value
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τ_z (ms)	29.0	26.6	Longitudinal damping time
Crab waist	80%	80%	Lattice design

[1] Y. Zhang et al., PRAB 26, 064401 (2023)

Accelerator physics challenges

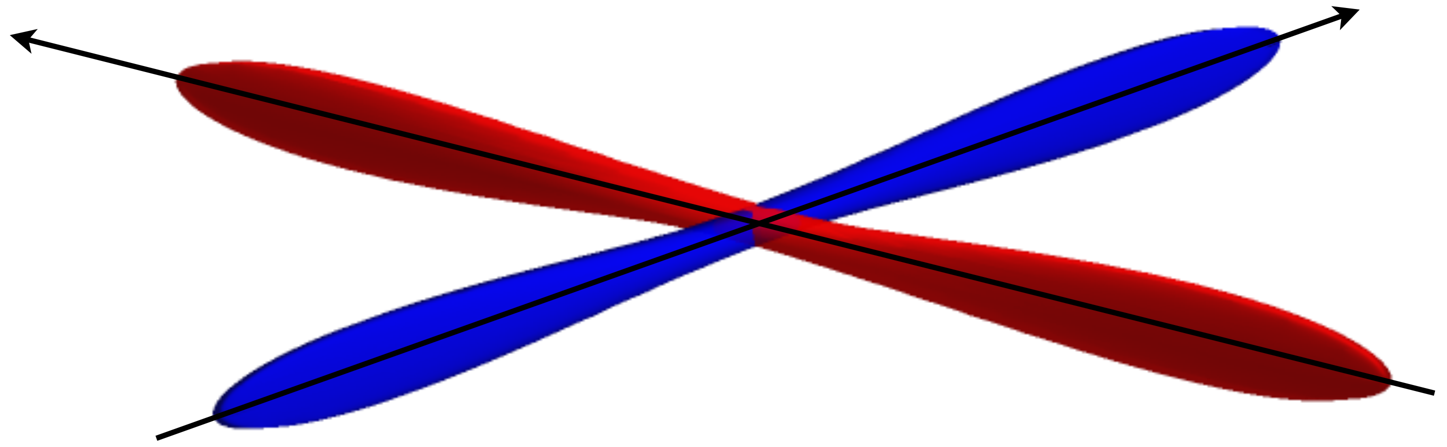
- On beam-beam:
  - Mechanisms of pure beam-beam effects
    - Horizontal: (coherent two-beam) X-Z instability [Ohmi 2017 (PRL), Kuroo 2018 (PRAB)] and (single-beam) synchro-beta resonances [Zhou 2023 (PRAB)]
    - Vertical: Nonlinear X-Y resonances [Ohmi 2004 (PRST-AB), Ohmi 2007 (PRST-AB), Zobov 2010 (PRL)]
  - On mechanisms of interplay between beam-beam and impedances
    - Horizontal: modified X-Z instability [Lin 2022 (PRAB)] (key issue: potential distortion and synchrotron tune spread due to impedance)
    - Vertical: TMCI-like head-tail instability [Zhang 2023 (PRAB), Zhou 2023 (PRAB)] (key issues: spread of synchrotron and vertical betatron tunes due to impedance)
  - On interplay of beam-beam and other problems (Zhou 2023 (PRAB))
    - BxB feedback: “-1 mode instability” [Ohmi 2022 (eeFACT), Ishibashi 2023 (JINST)]
    - Linear IP X-Y couplings [Ohmi 2018 (eeFACT)]
    - Chromatic IP X-Y couplings [Zhou 2009 (PRST-AB)]
    - Higher-order IP X-Y couplings [Zhou 2015 (ICFA Newsletter)]
    - Non-perfect crab waist [To be investigated]

Accelerator challenges in commissioning

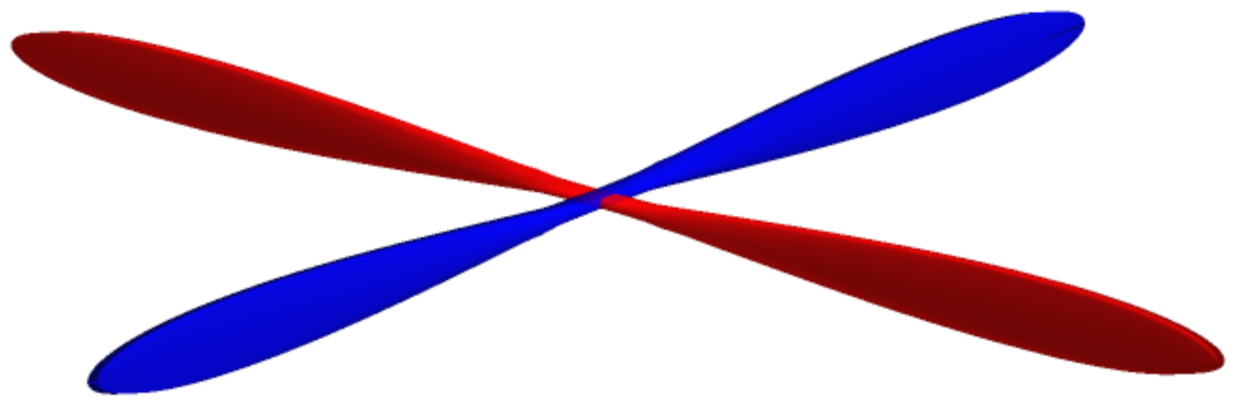
- From the luminosity viewpoint, we list some important issues [1]:
  - Issue 1: Limits on bunch currents
  - Issue 2: Multi-bunch effects
  - Issue 3: Optics distortion at high beam currents
  - Issue 4: Impedance effects
  - Issue 5: Lsp injection correlation

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^{2}+\sigma_{z-}^{2}}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

#5 (L); #1,2,3,4,5 ($N_b N_+ N_-$); #2,5 (Δ^2); #1,2,3,4,5 ($\sigma_{y+}^{*2}+\sigma_{y-}^{*2}$); #4 ($\sigma_{z+}^{2}+\sigma_{z-}^{2}$); BB, CW, … ($\frac{\theta_c}{2}$)



SuperKEKB (2021c)



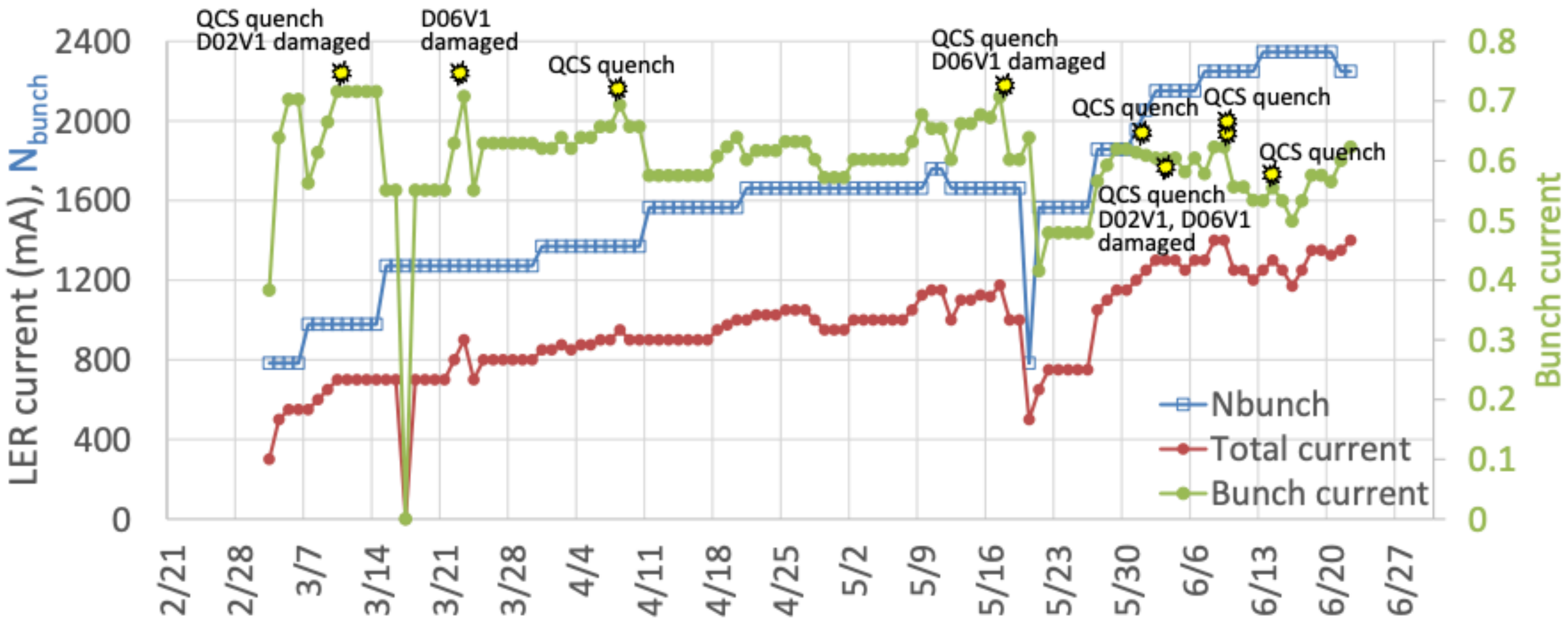
SuperKEKB (Final design)

[1] D. Zhou et al., PRAB 26, 071001 (2023).

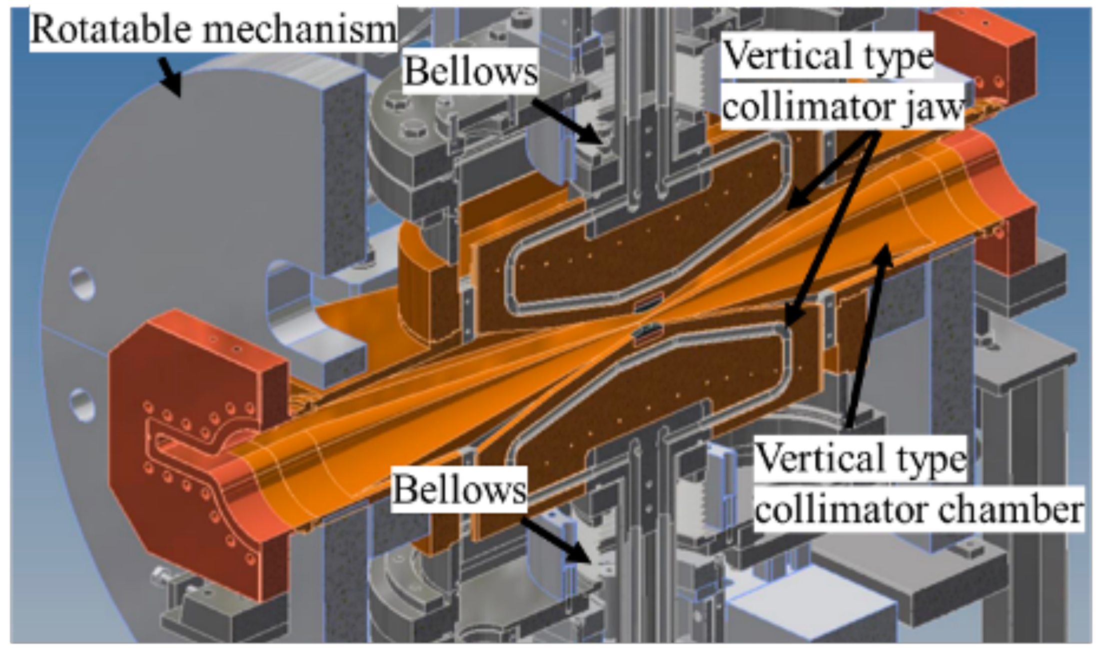
Issue-1: Limit on bunch currents by Sudden Beam Losses (SBLs)

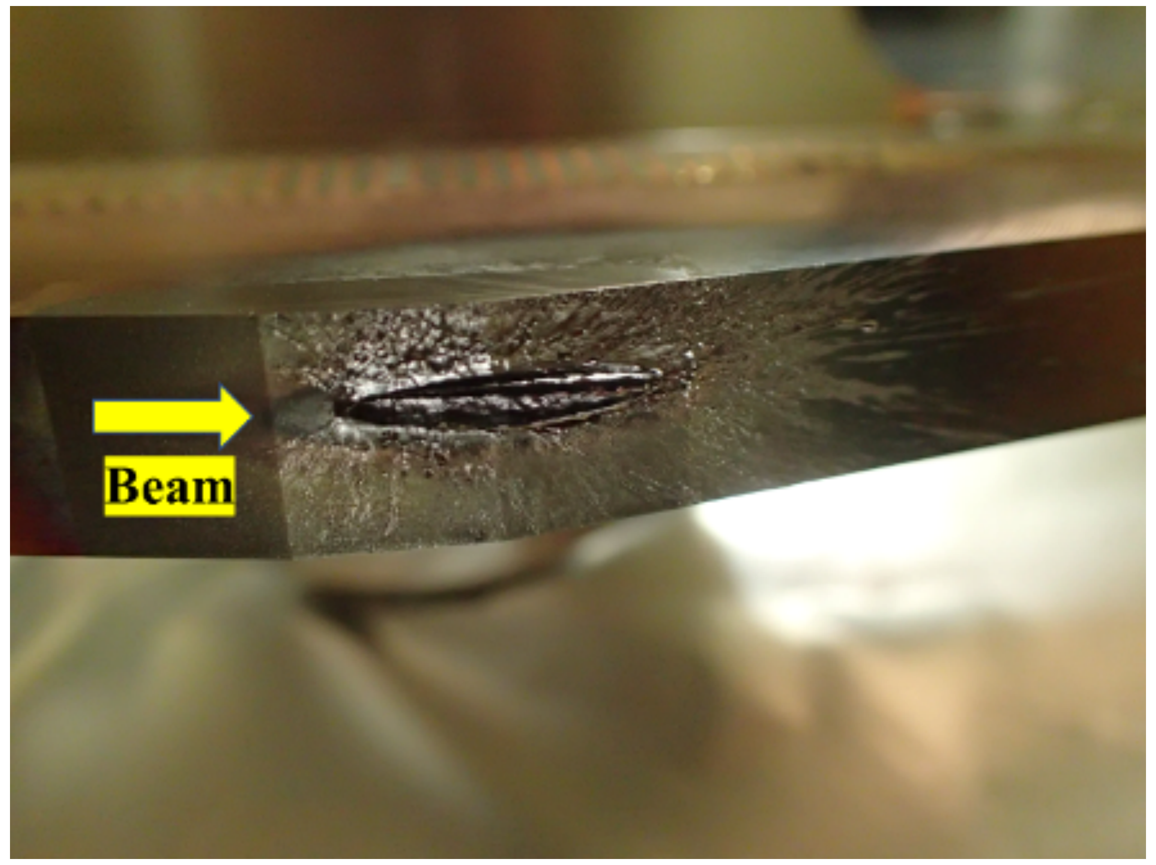
- Severe machine failures occurred at high beam currents when $I_{b+} > 0.7$ mA/bunch
- Bunch current $I_{b+} \lesssim 0.7$ mA (keeping $I_{b-}/I_{b+} = 0.8$) was respected in 2022ab run [1]

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2+\sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$



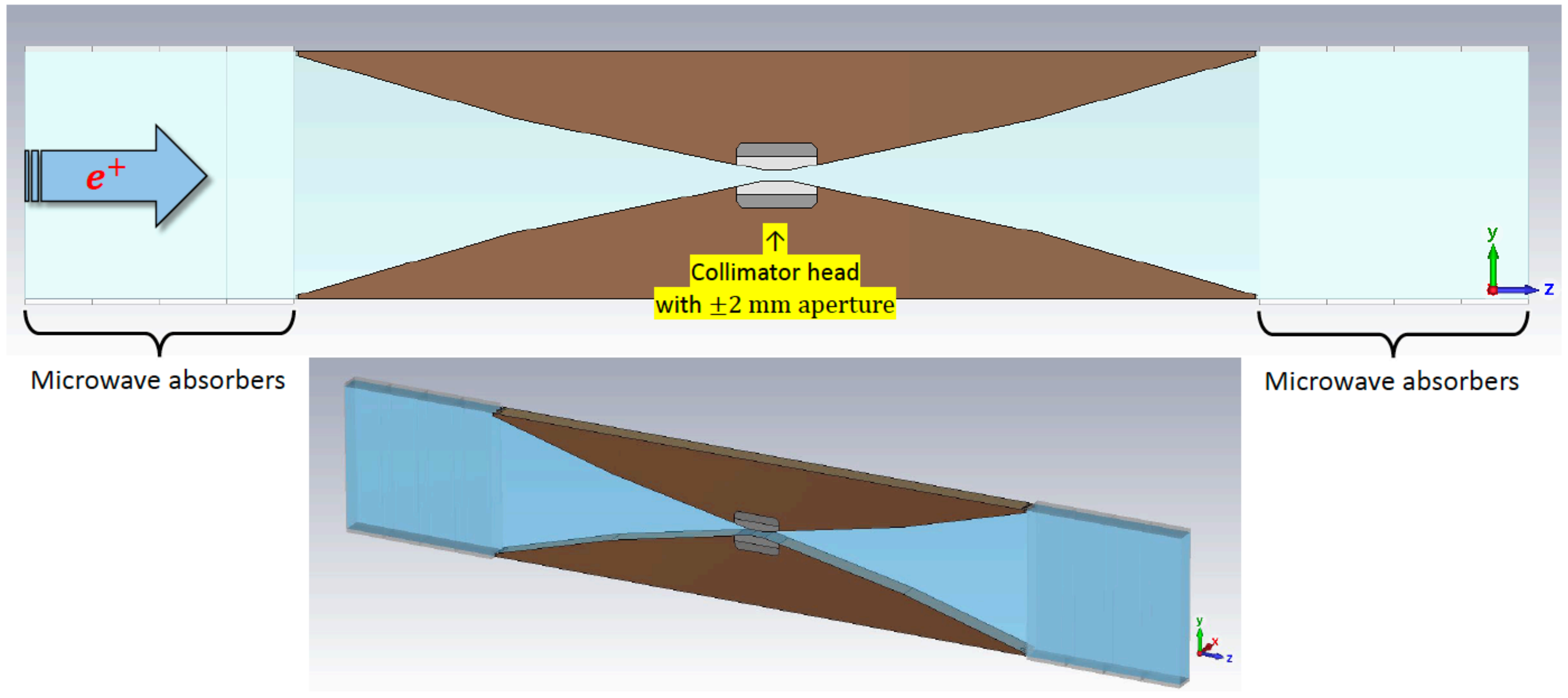
Courtesy of K. Matsuoka

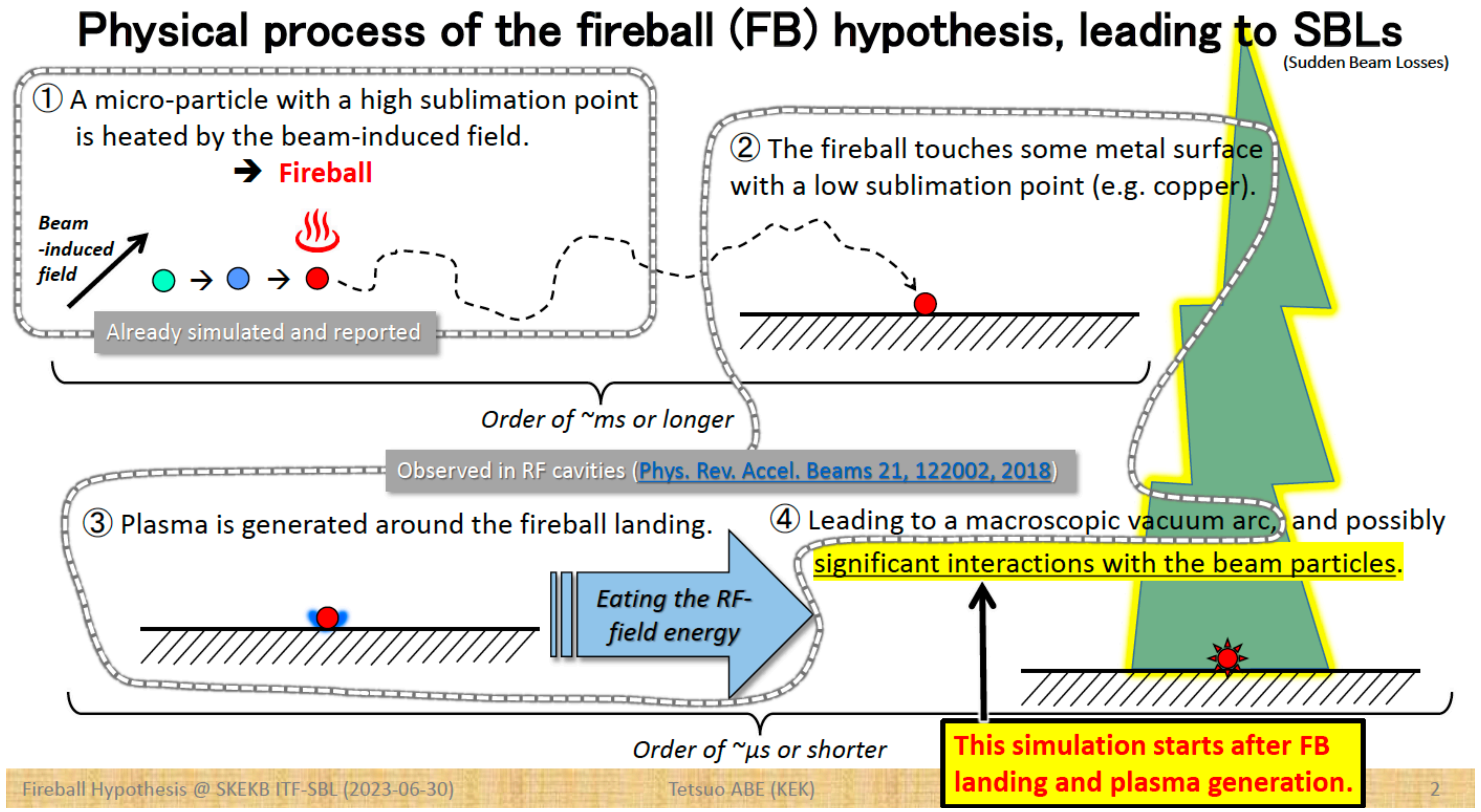




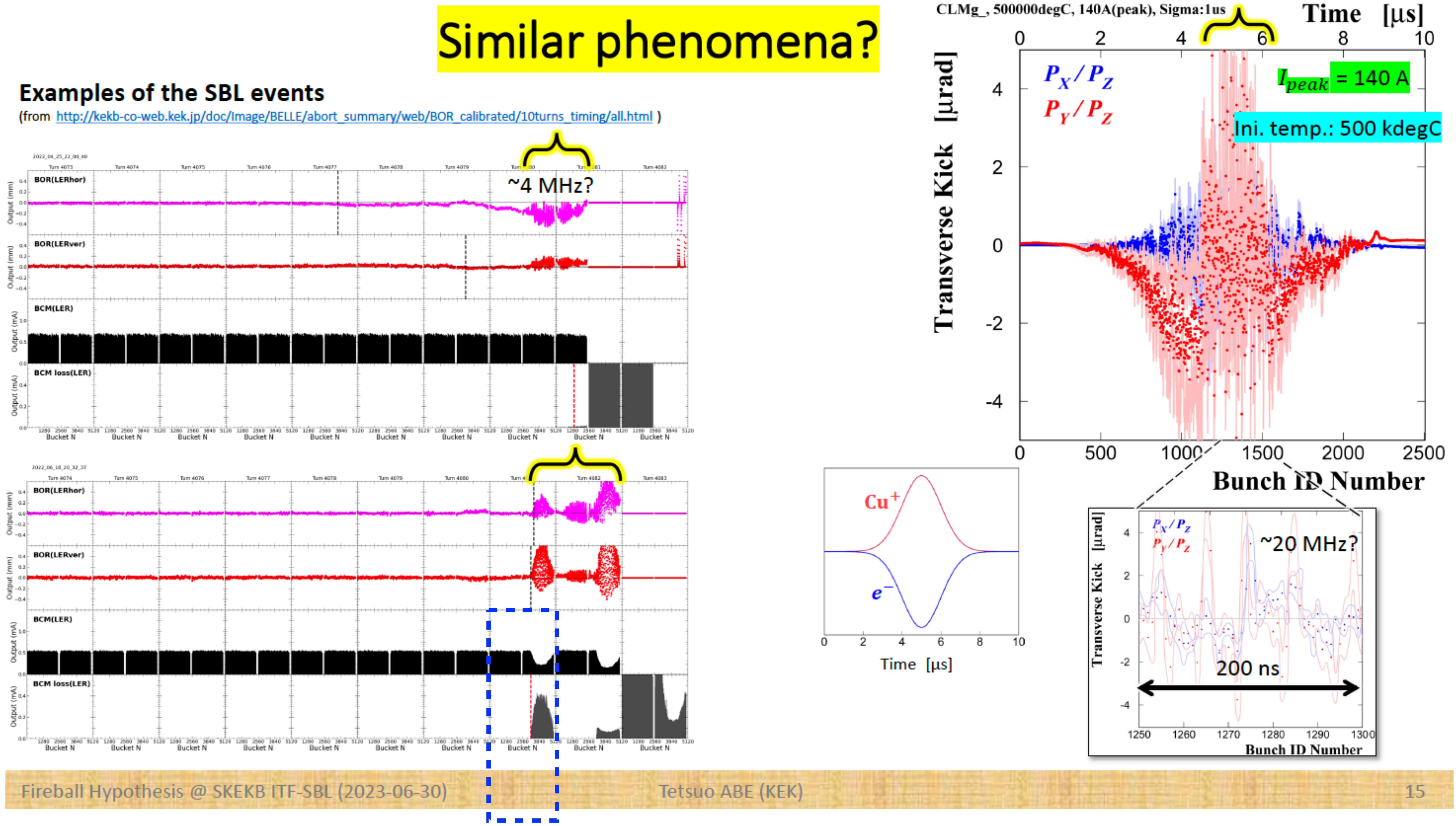
[1] K. Matsuoka, "Belle II Report", SuperKEKB 2022ab summary meeting, https://kds.kek.jp/event/42954/.

Issue-1: Limit on bunch currents by Sudden Beam Losses (SBLs)





"Fireball" hypothesis for SBLs
Proposed by T. Abe



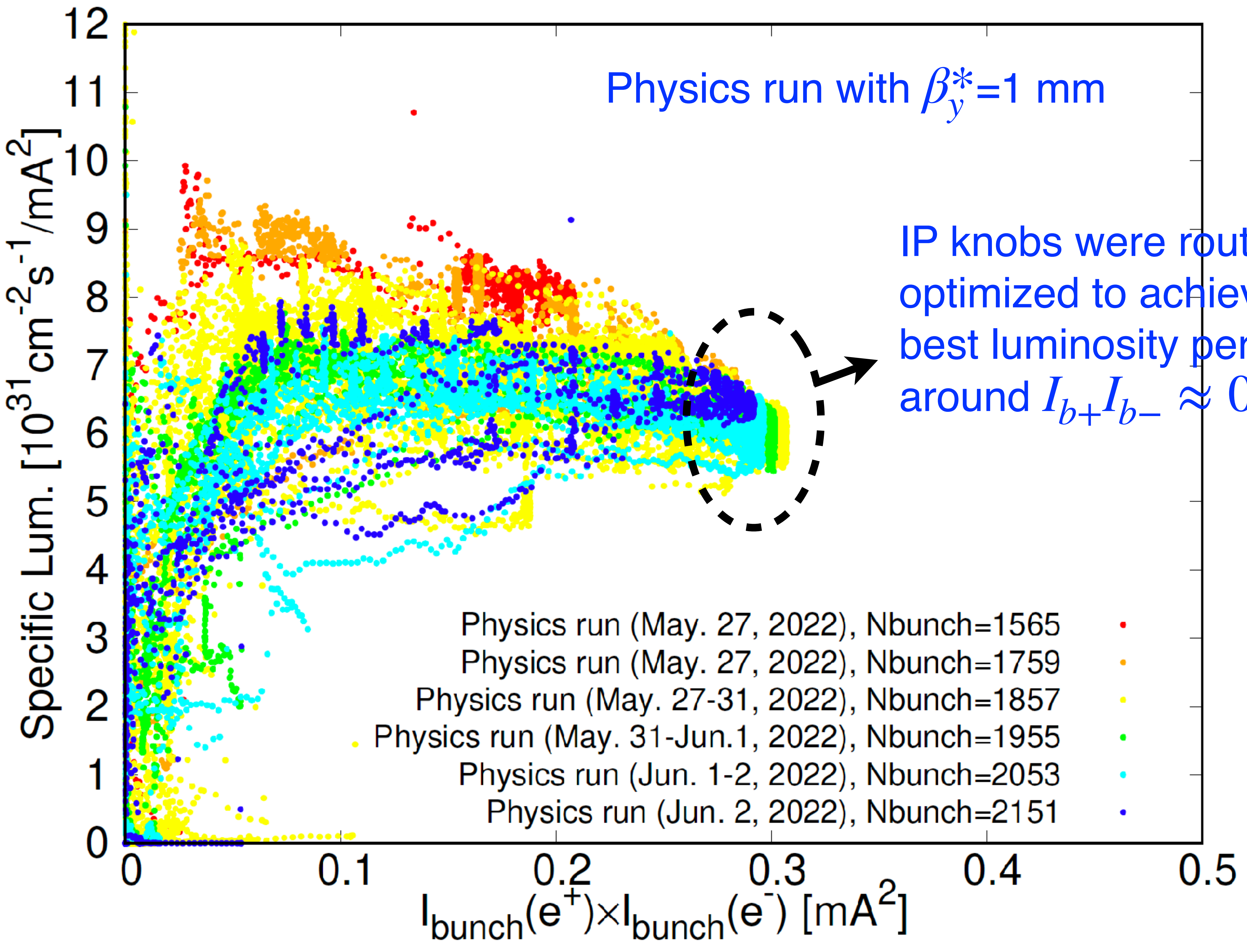
Huge beam loss in a single turn
Causing QCS quench, collimator damage, and huge Belle II background

[1] Y. Abe, "The 1st results of beam simulation for the fireball SBL hypothesis", https://kds.kek.jp/event/46940/

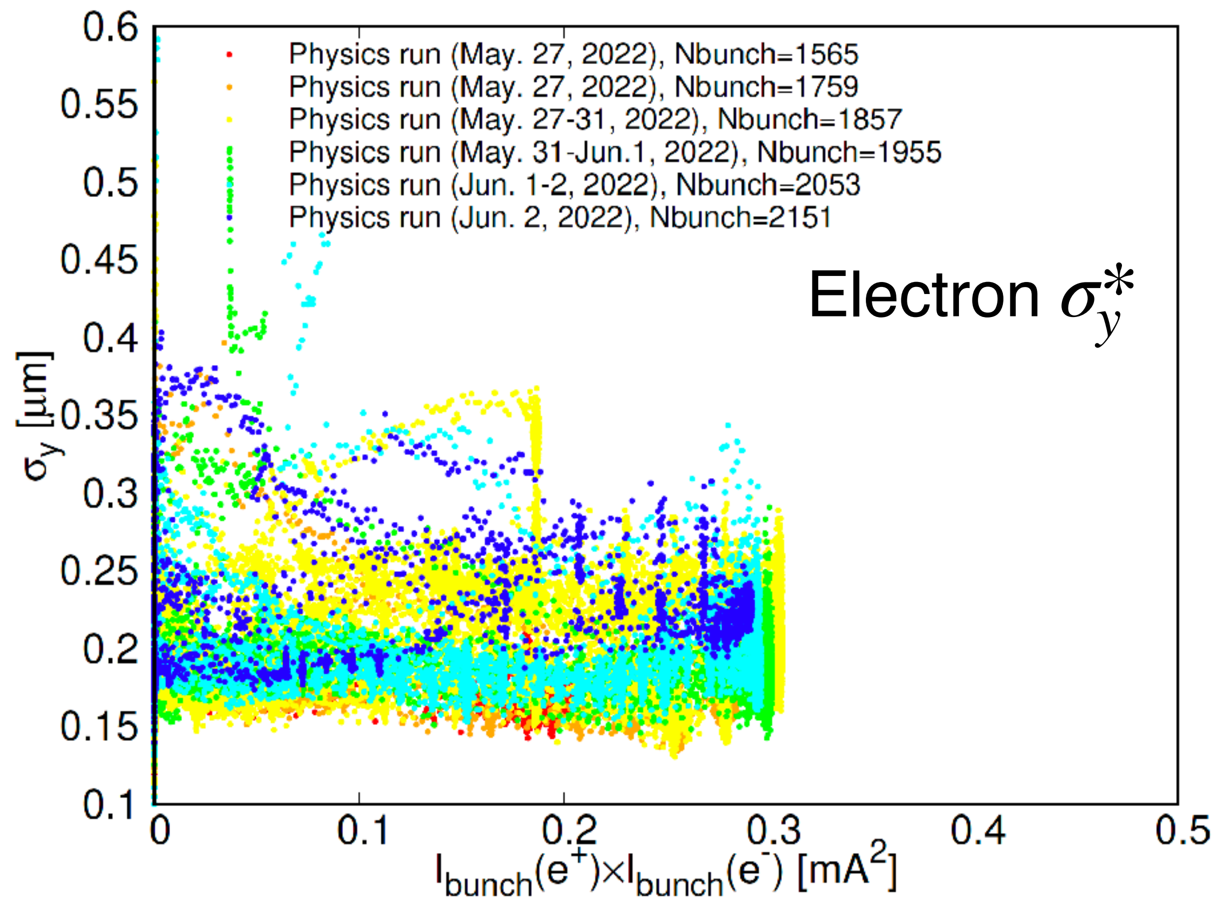
Issue-2: Multi-bunch effects

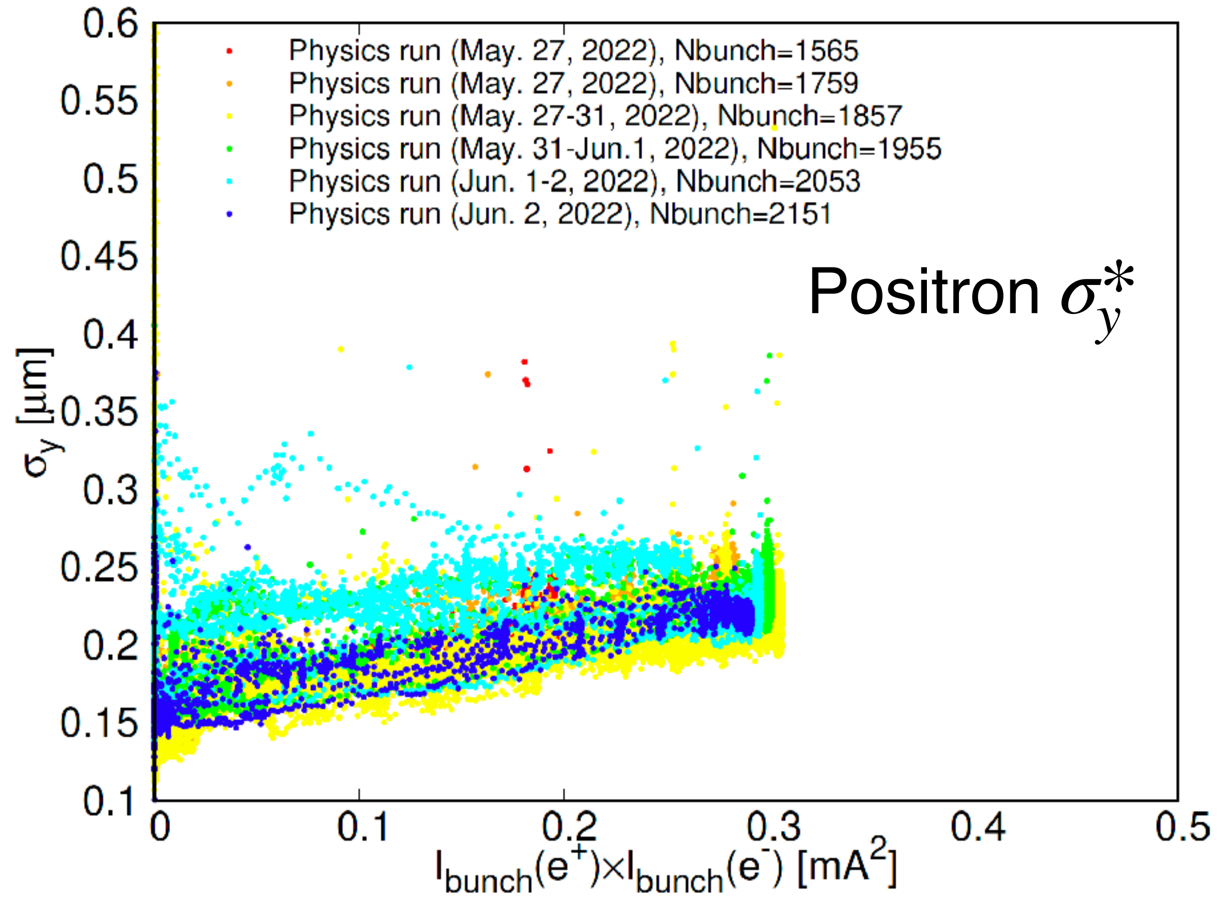
$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^{2}+\sigma_{z-}^{2}}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

- No clear evidence of Lsp degradation due to multi-bunch effects
  - Coupled-bunch instabilities were suppressed by the BxB FB system (M. Tobiyama).
  - Flat BxB luminosity was observed (S. Uehara).
  - Electron-cloud instability for e+ beam was not observed (Y. Suetsugu et al.).



IP knobs were routinely optimized to achieve the best luminosity performance around $I_{b+}I_{b-} \approx 0.3$ mA^2.



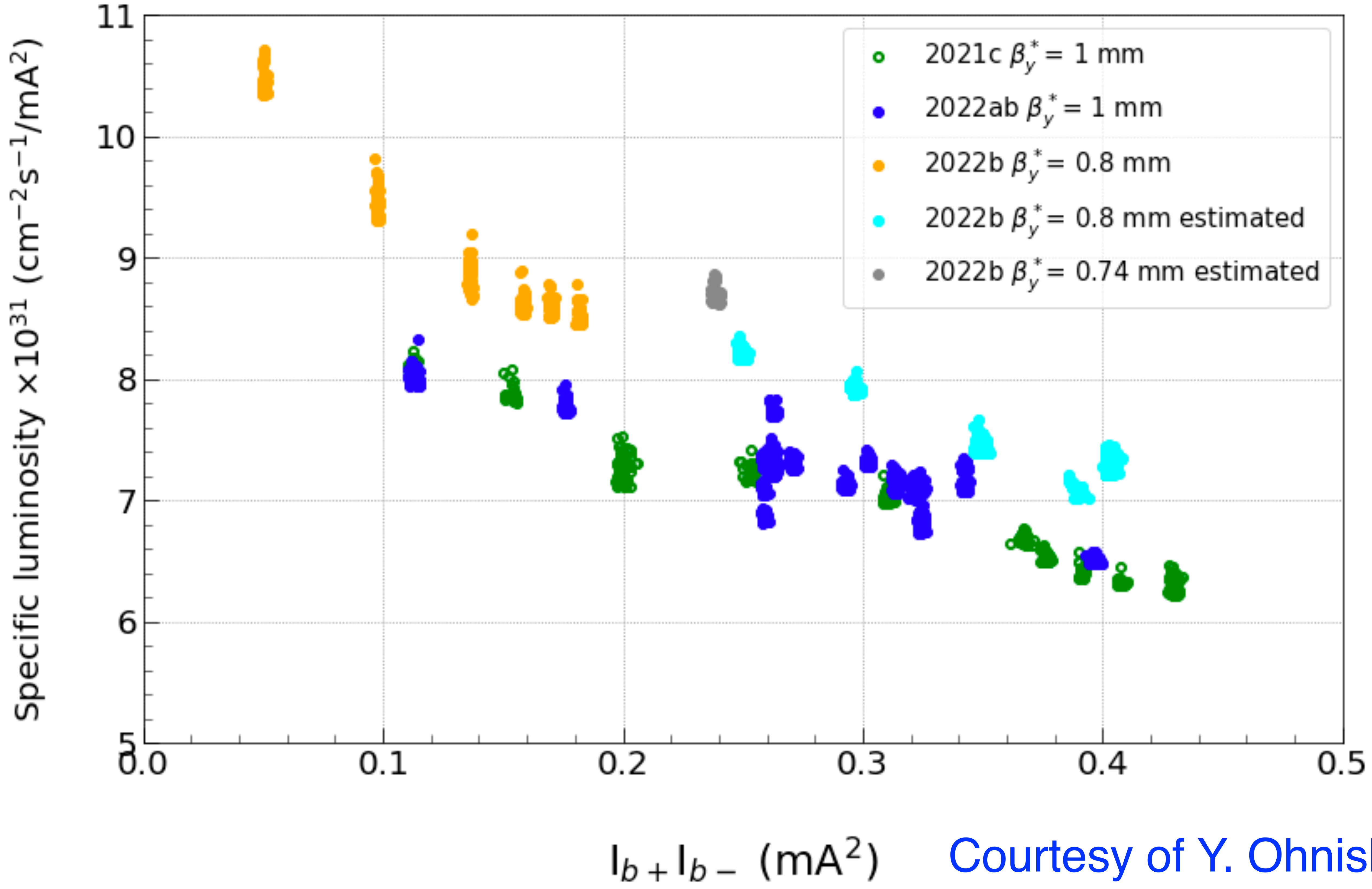


Issue-3: Optics distortion at high beam currents

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2+\sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

- Current-dependent optics distortion
  - Beta-beat and global coupling become worse at high currents.
  - An unexpected β_y^* squeeze explains the Lsp gain.

$$\xi_{y+}^i \approx \frac{r_e}{2\pi\gamma_+}\frac{N_-\beta_{y+}^*}{\sigma_{y-}^*\sqrt{\sigma_{z-}^2\tan^2\frac{\theta_c}{2}+\sigma_{x-}^{*2}}}$$



Courtesy of Y. Ohnishi

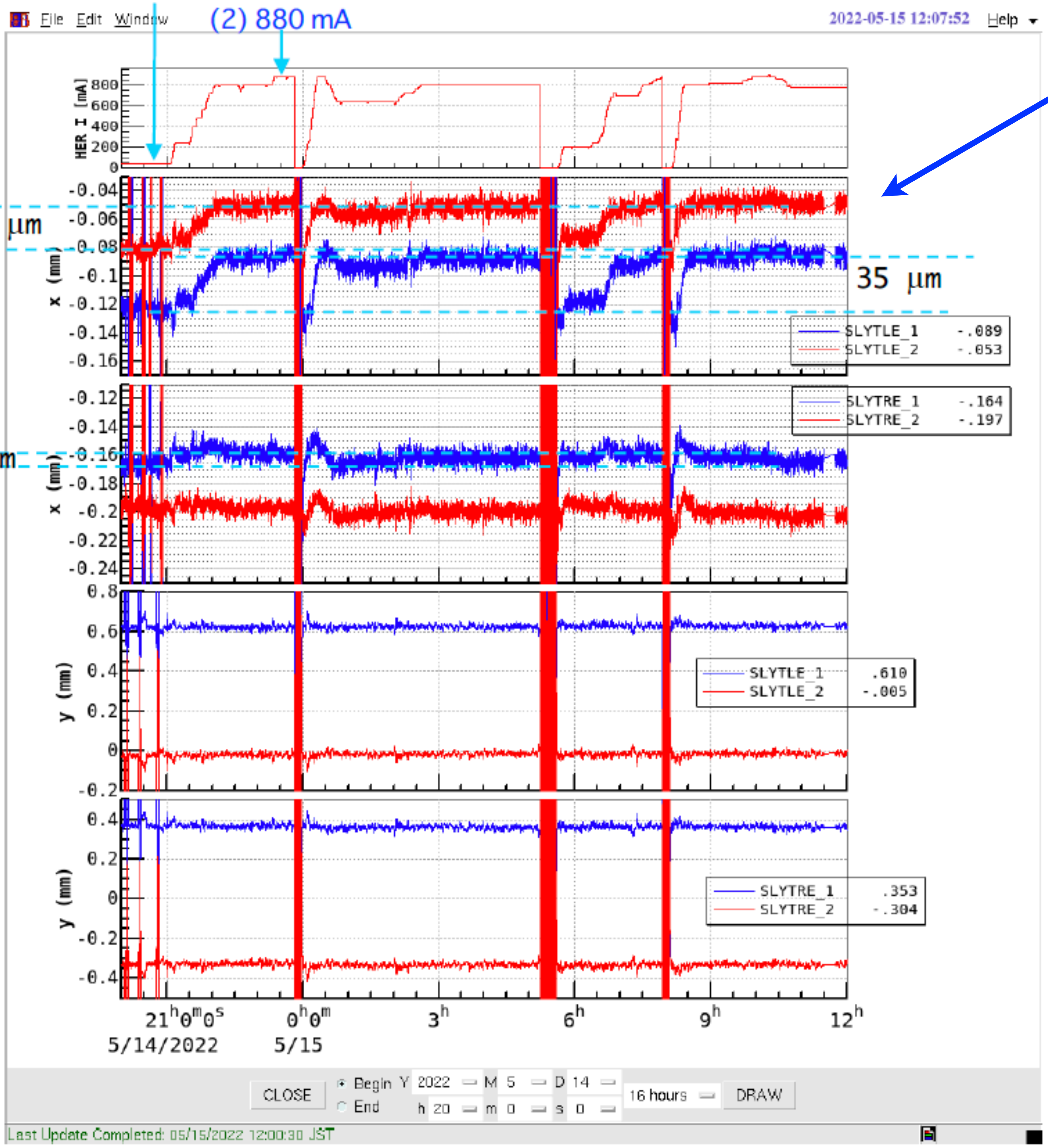
Issue-3: Optics distortion at high beam currents

$$\xi^i_{y+} \approx \frac{r_e}{2\pi\gamma_+} \frac{N_- \beta^*_{y+}}{\sigma^*_{y-}\sqrt{\sigma_{z-}^2 \tan^2\frac{\theta_c}{2} + \sigma^{*2}_{x-}}}$$

- Current-dependent orbit offsets at SLY* magnets

(1) Optics Correction 50mA

(2) 880 mA

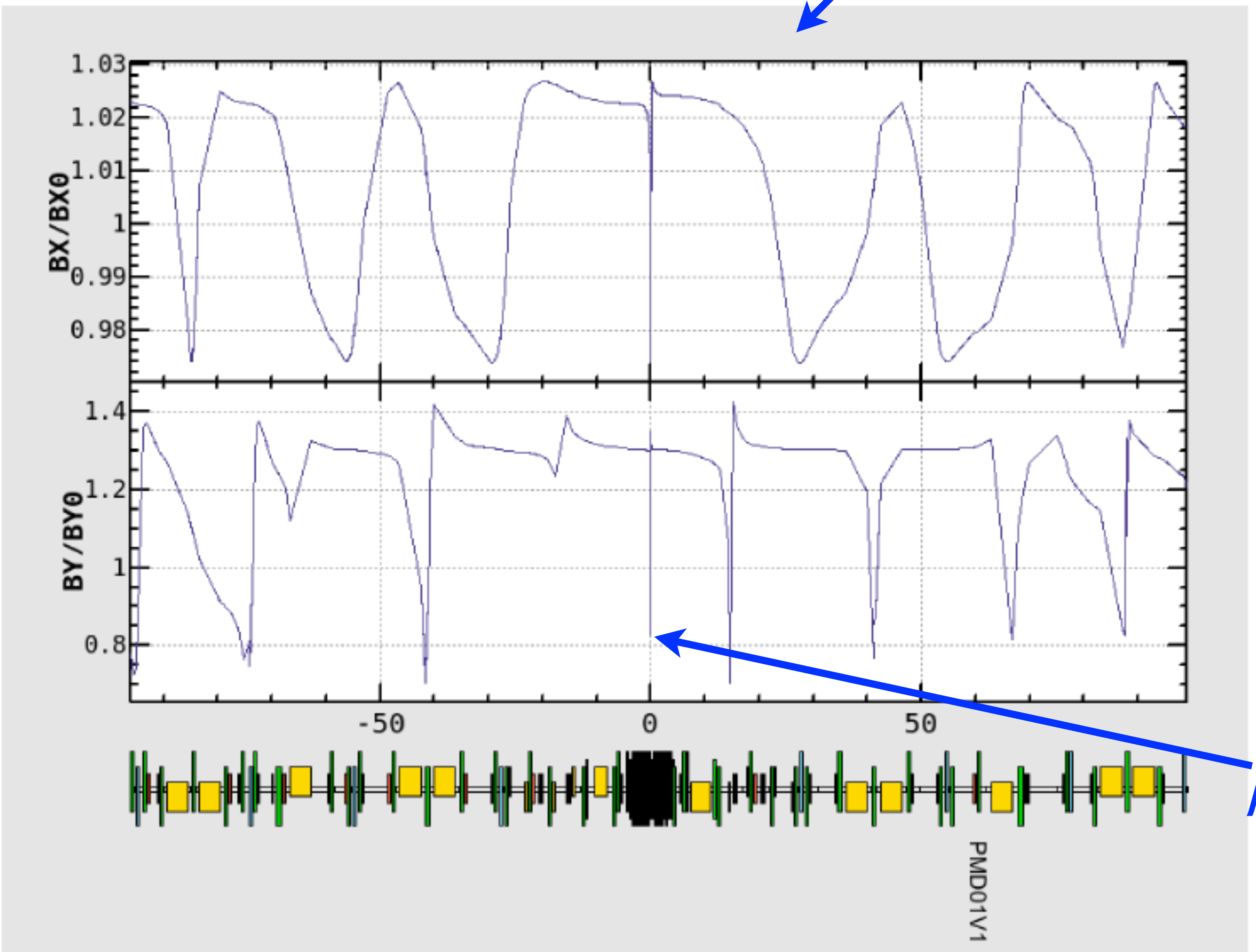


Observed offsets with beam

The following horizontal offsets of SLY* magnets are used to estimate the beta beats:

SLYTRE1	-8 µm
SLYTRE2	0
SLYTLE1	-35 µm
SLYTLE2	-33 µm

Resulting beta-beat (SAD simulation)



β^*_y squeezed

Courtesy of H. Koiso

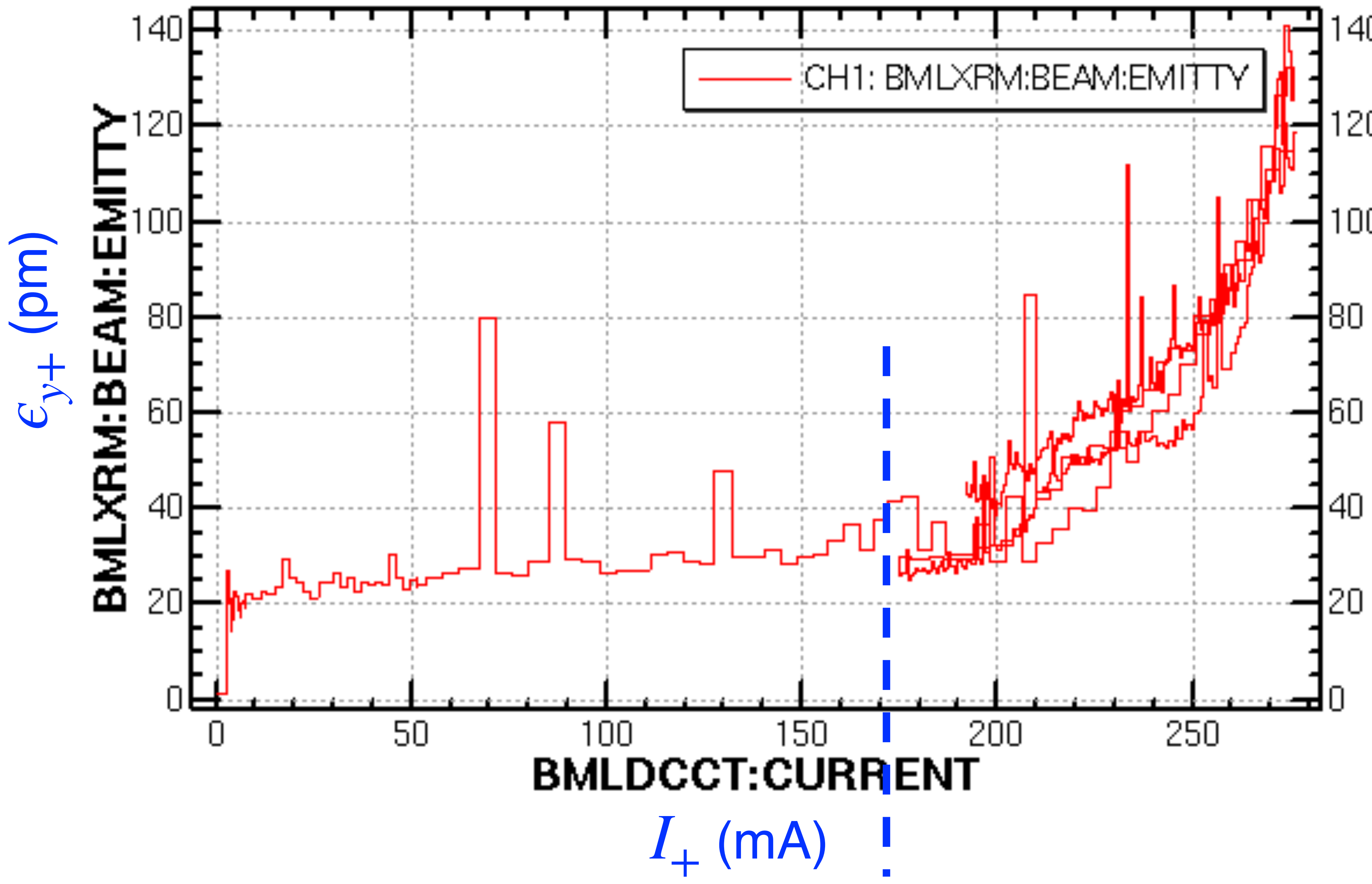
Issue-4: Impedance effects (LER)

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

- Current-dependent single-beam blowup in LER
  - This problem was partially solved by fine-tuning the FB system in Mar. 2022. After new damage to collimators (D06V1 and D02V1), the LER beam blowup problem re-appeared.
  - On Jun. 21, 2022, tunings were done to improve the blowup threshold (from 0.5 mA/bunch to ~0.87 mA/bunch). This contributed to achieving the luminosity record 4.71×10^{34} cm^{-2}s^{-1} on Jun. 22, 2022.

Machine conditions:
Single-beam, 393 bunches

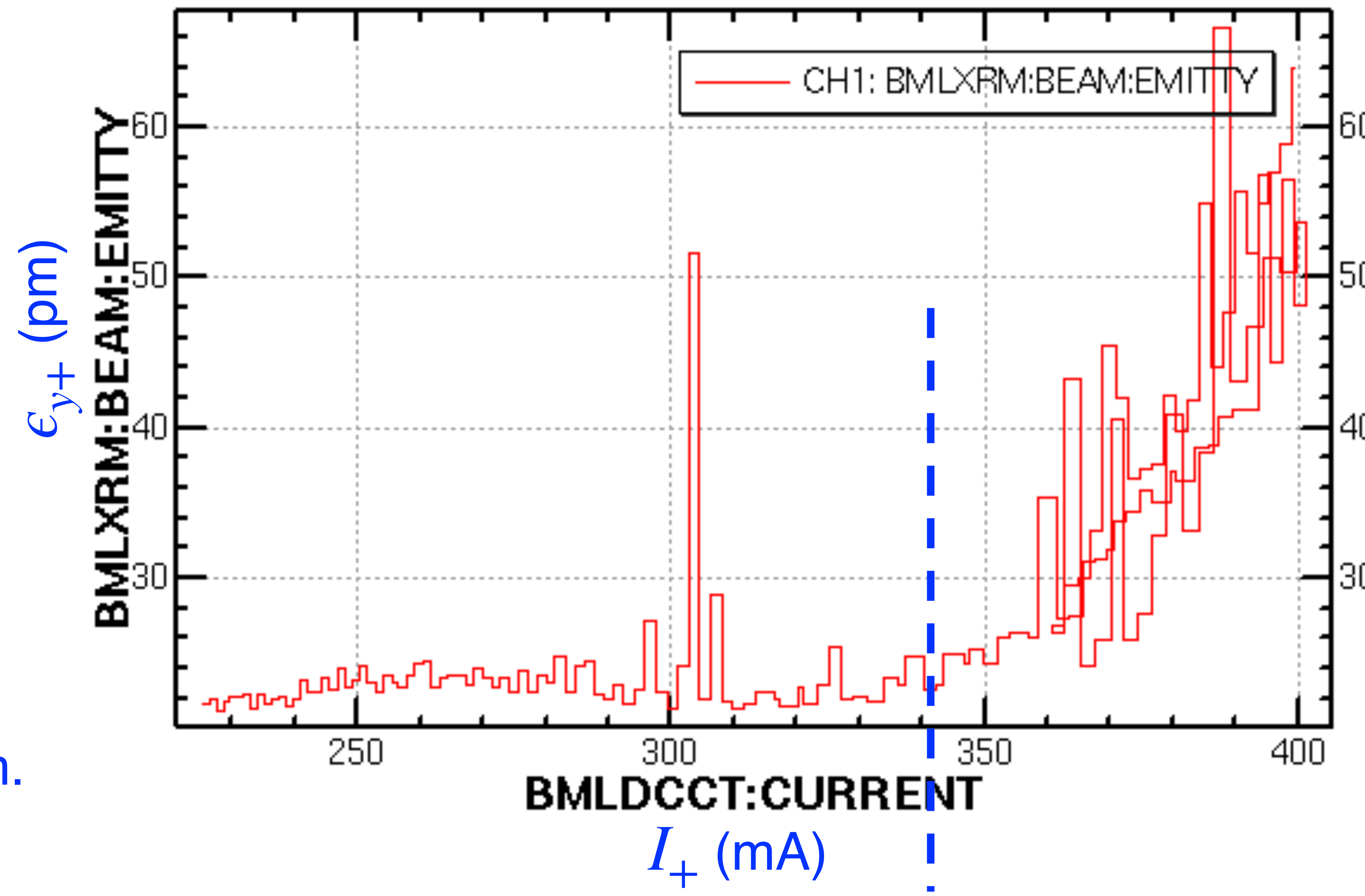
KCG shift report on LER vertical blowup study
By S. Terui, T. Ishibashi, K. Yoshihara, M. Nishiwaki
Jun. 21, 2022



Threshold <0.5mA/bunch

LER vertical tune: ν_y .582 → .595;

D06V1 gap:
TOP 4.2 mm,
BTM -5.1 → -8.0 mm.



After tunings ~0.87mA/bunch

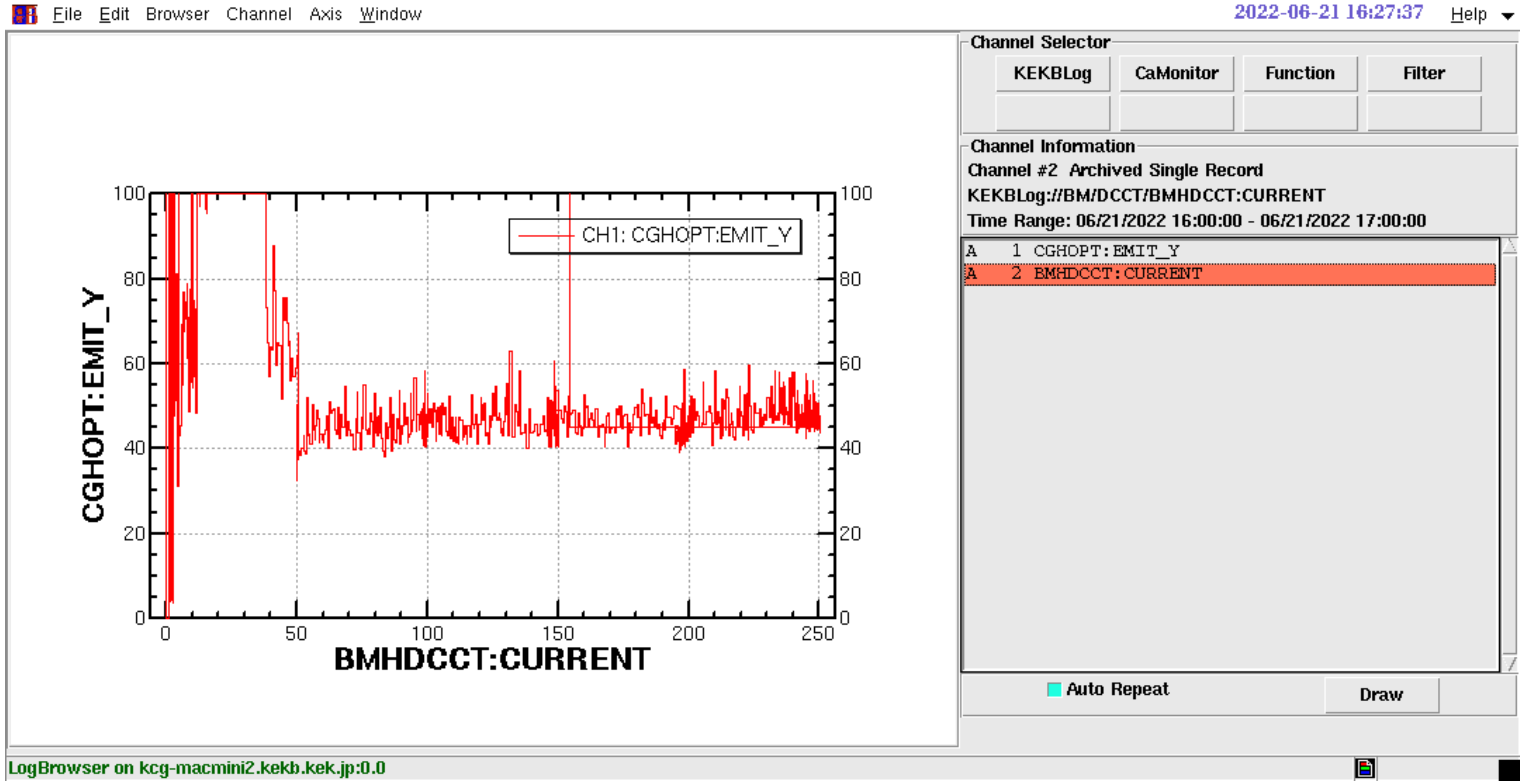
Issue-4: Impedance effects (HER)

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^{2}+\sigma_{z-}^{2}}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

- Current-dependent single-beam vertical emittance in HER
  - No clear evidence of single-beam blowup (up to 0.64 mA/bunch) in HER

Machine conditions:
Single-beam, 393 bunches

KCG shift report on high bunch-current collision study
By D. Zhou, R. Ueki, M. Nishiwaki
Jun. 21, 2022



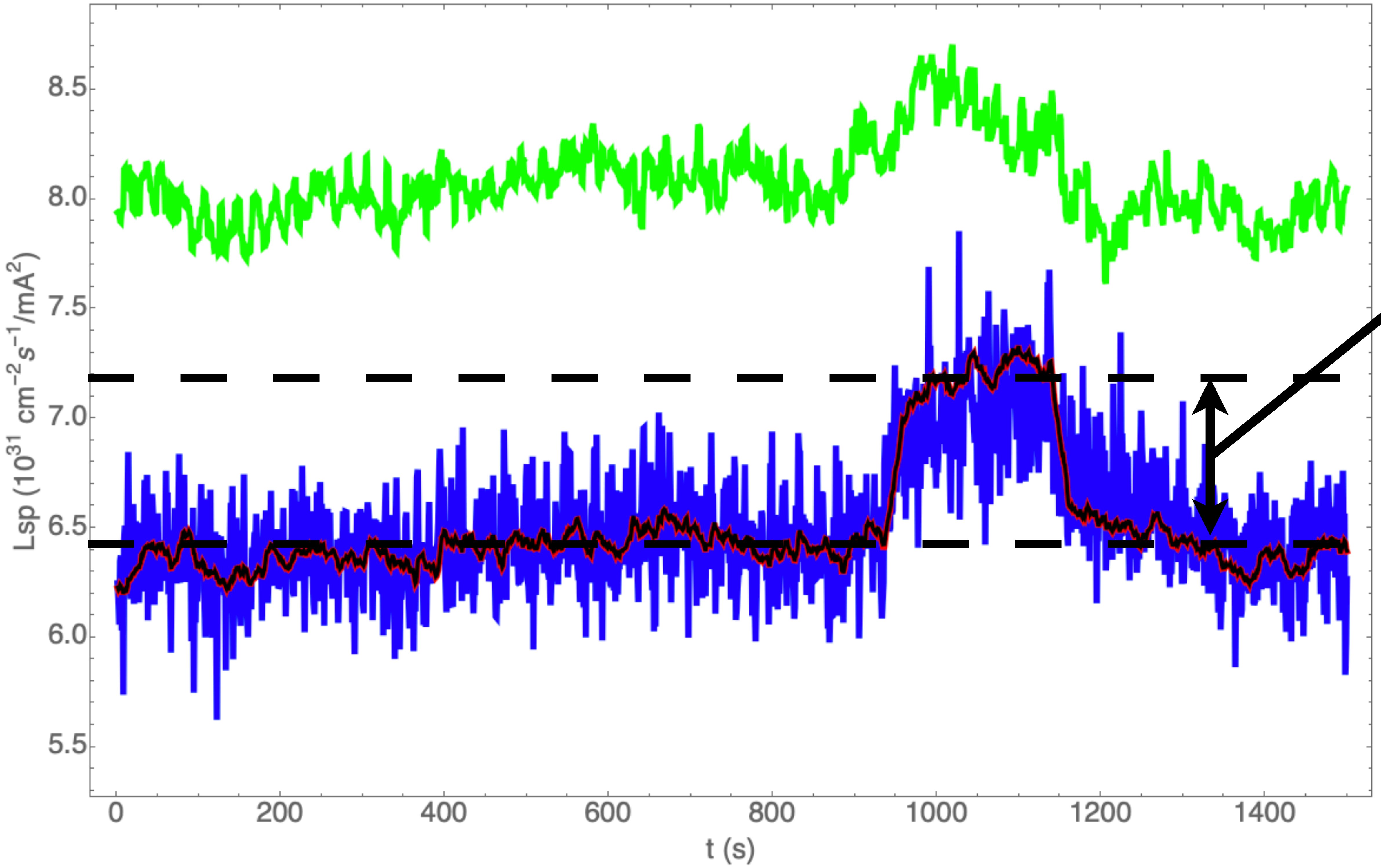
Issue-5: Lsp-Injection correlation

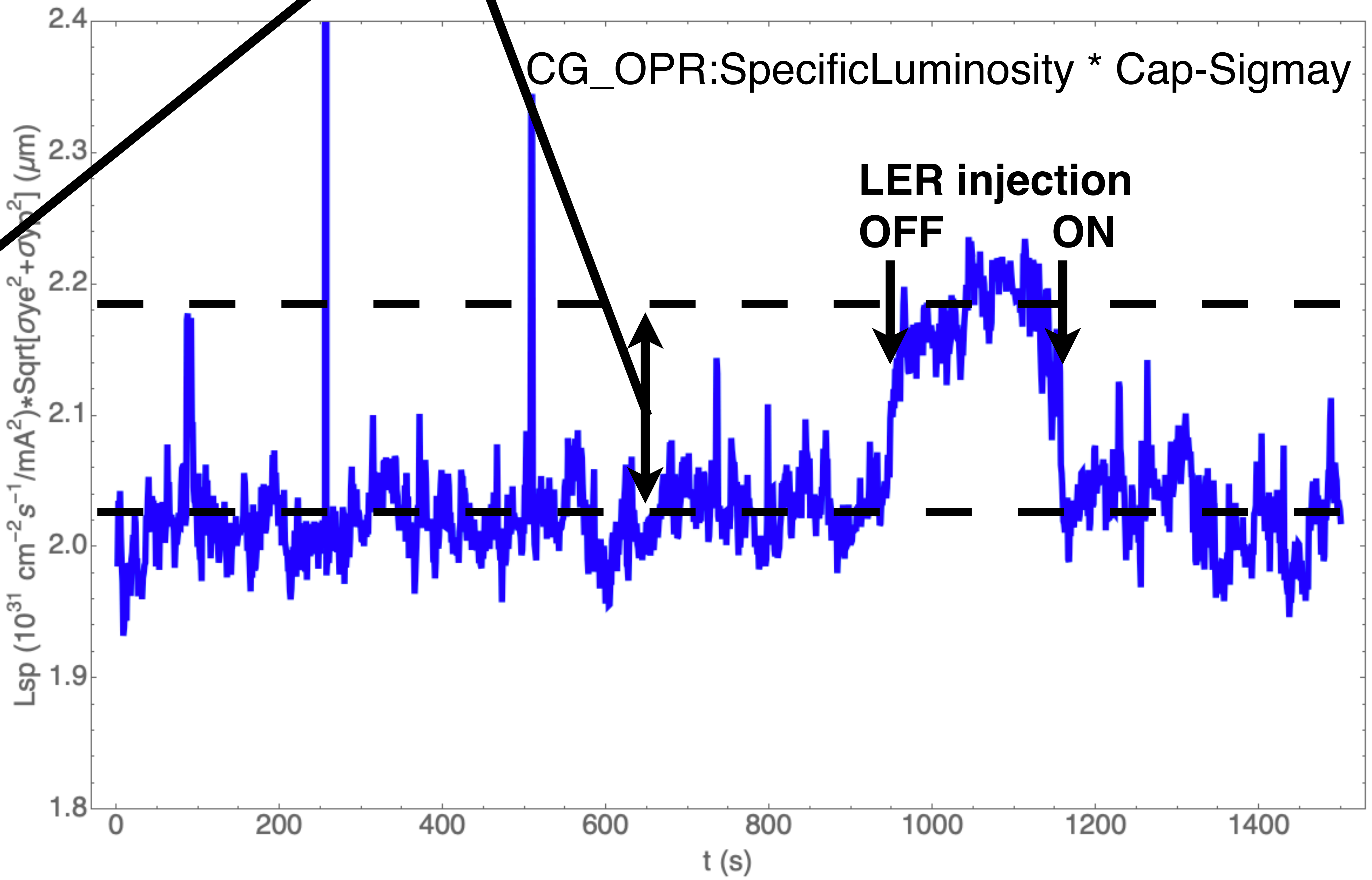
$$L_{sp} \approx \frac{1}{2\pi e^2 f \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}} \sqrt{\sigma_{z+}^{2} + \sigma_{z-}^{2}} \tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

- The phenomenon: 2022-06-02 21:05 PM
  - All luminosity PVs gave a similar jump response to injection stop/start.
  - $L_{sp} \cdot \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}$ still shows jump-response. It means there is a geometric loss of luminosity.

Blue: B2_nsm:get:ECL_LUM_MON:lum_acc_corrected
Red: B2_nsm:get:ECL_LUM_MON:lum_acc_20
Green: B2_nsm:get:MONZDLMINT:ZDLM_INTVAL:value
Black: CG_OPR:SpecificLuminosity

Lsp degradation by ~10%, independent to vertical emittances

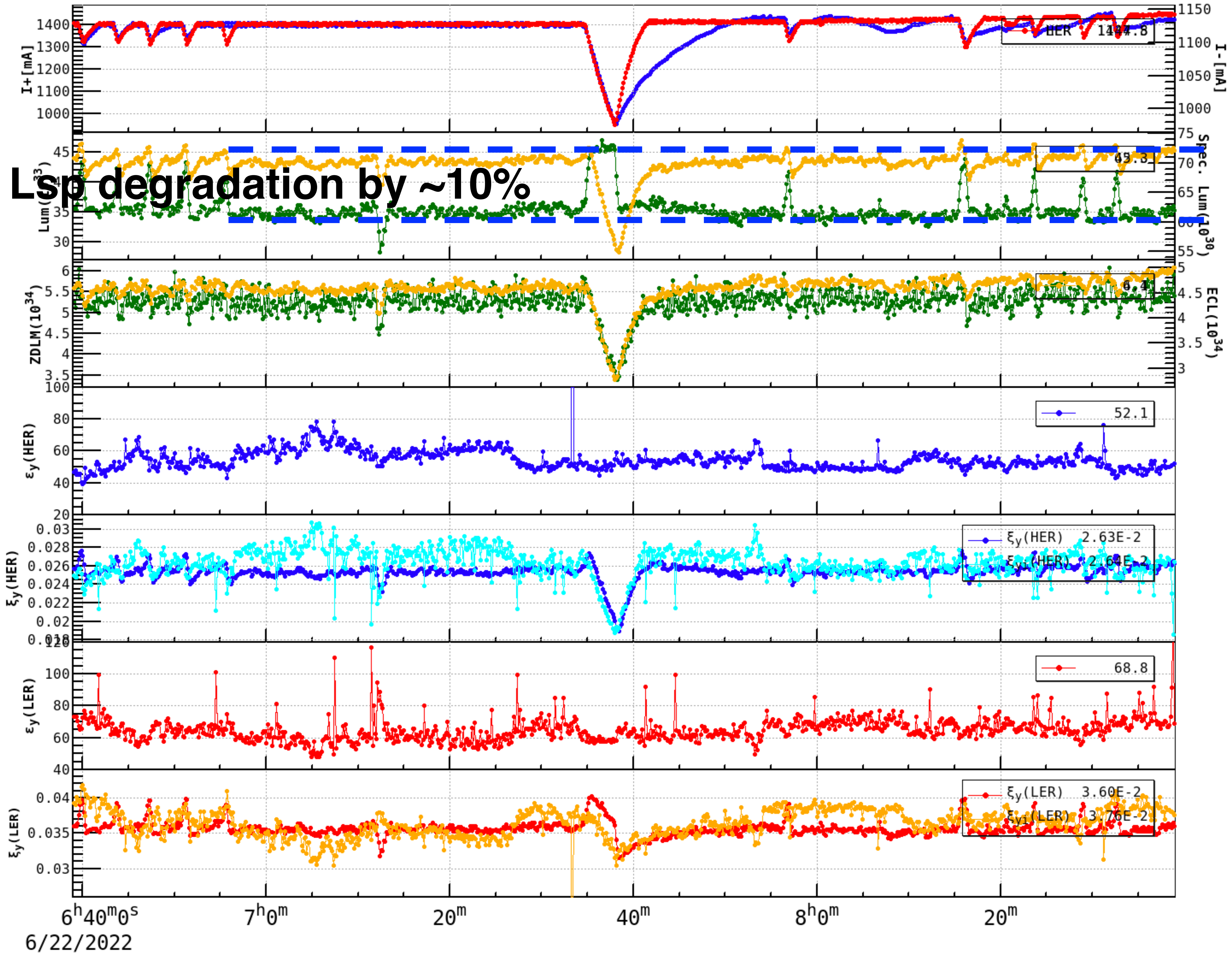


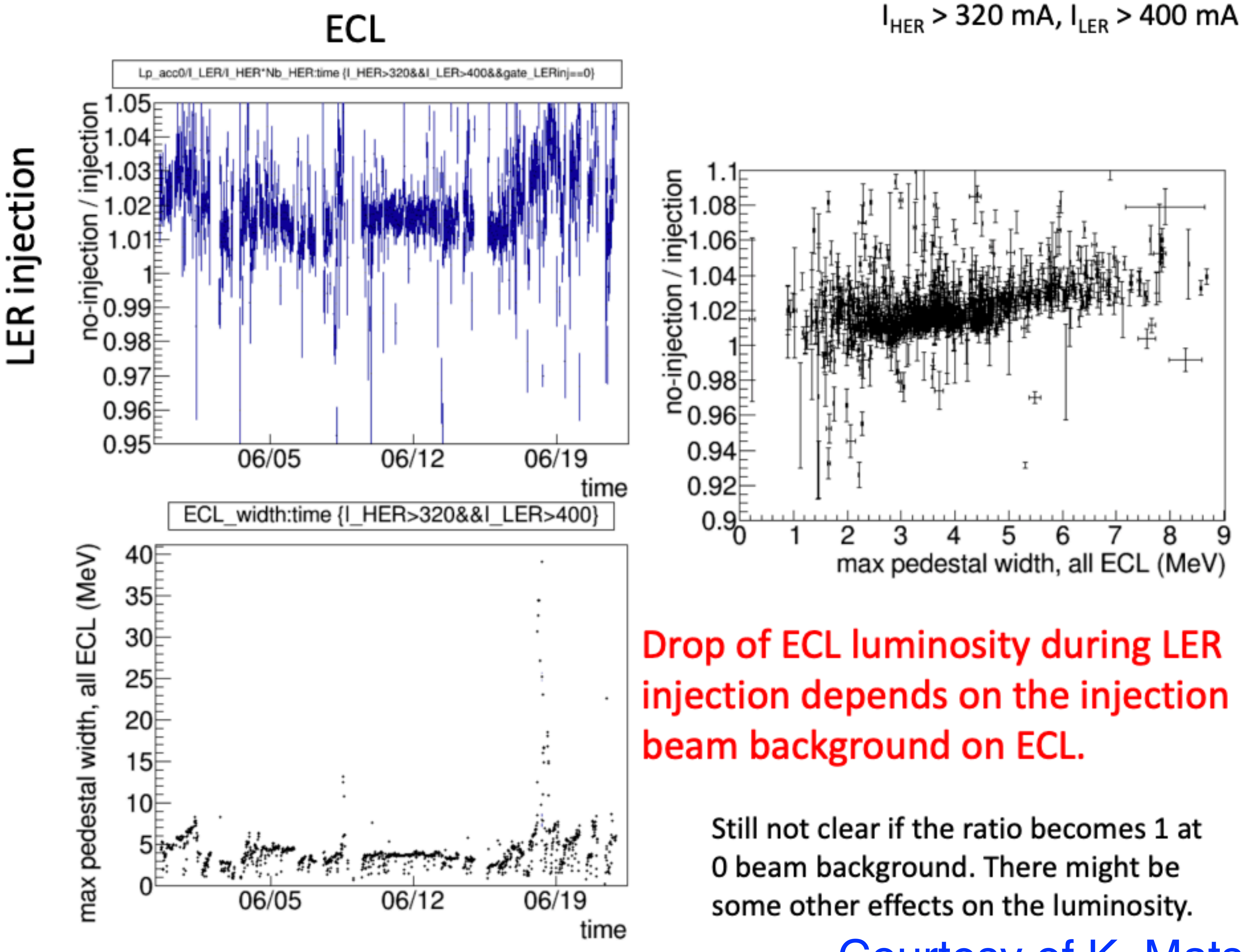


Issue-5: Lsp-Injection correlation

$$L_{sp} \approx \frac{1}{2\pi e^2 f \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}} \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2} \tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

- Injection background affected ECL luminosity [1]
- Data of Jun. 2022: Injection background contributed to ~5% luminosity "loss"





Drop of ECL luminosity during LER injection depends on the injection beam background on ECL.

Still not clear if the ratio becomes 1 at 0 beam background. There might be some other effects on the luminosity.

Courtesy of K. Matsuoka

[1] K. Matsuoka, Oct. 14, 2022, https://kds.kek.jp/event/44070/.

Luminosity perspective

- Achieving 10^{35} cm^{-2}s^{-1}: SBLs, "-1 mode instability", etc. → Non-Linear Collimator (NLC)
- Achieving 6×10^{35} cm^{-2}s^{-1}: DA (Dynamic aperture), lifetime, perfect CW, etc. → IR model (better understanding of the current IR) and upgrade ("Clean IR")

$$L = \frac{1}{2er_e} \frac{\gamma_{\pm} I_{\pm}}{\beta^*_{y\pm}} \xi^L_{y\pm}$$

Total beam currents:
We achieved 1.4 A in LER (Jun. 2022)
If we can achieve 3.6 A, we will gain by 2.5
Obstacles:
1) Sudden beam losses (SBLs)
2) Short lifetime (challenging injection power)

IR optics:
We achieved $\beta_y^* = 1$ mm
If we can achieve $\beta_y^* = 0.3$ mm, we will gain by 3.3
Obstacles:
1) DA and lifetime resulted from IR nonlinearity (+BB+CW)
2) Optics tuning at high currents

Beam-beam limit:
We achieved 0.04 in Jun. 2022
We expect the upper limit is ~0.1 (including the hourglass effect), then we will gain by 2.5
Obstacles:
1) Vertical blowup by "-1 mode instability" (NLC is the hoped solution)
2) Vertical blowup by BB (+Lattice nonlinearity+Impedance)
3) Imperfect crab waist (to be verified)

Summary

- A brief introduction to SuperKEKB is given.
- Many challenges are recognized from machine design and beam commissioning
  - Complicated IR
  - Crab waist
  - Injector and injection
  - Detector background
  - Beam-beam
  - High-current operation
- The SuperKEKB is demonstrating the crab waist scheme for future e+e- circular colliders.
- We invite full international collaboration on beam physics in SuperKEKB.

Backup

Luminosity performance

- “Nano-beam” + crab waist in SuperKEKB
  - Simple scaling laws are used to discuss challenges in achieving high luminosity with crab waist scheme [1].

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

$$L_{sp} \approx \frac{1}{2\pi e^2 f\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\tan\frac{\theta_c}{2}}$$

$$L = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta_{y\pm}^*}\xi_{y\pm}^L$$

$\xi_{y\pm}^L$ → Beam-beam parameter [2]

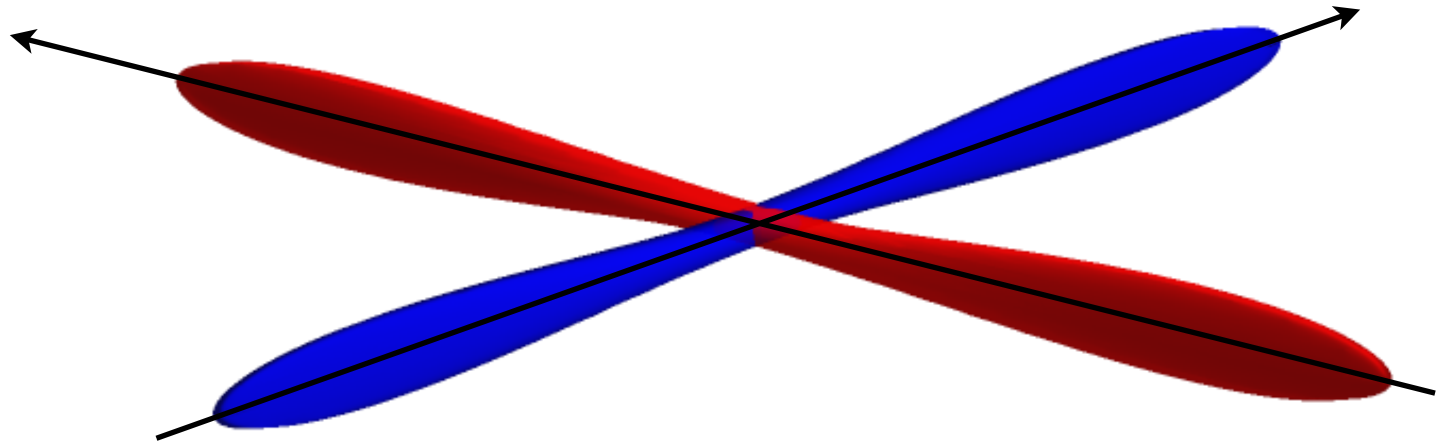
$$\xi_{y+}^i \approx \frac{r_e}{2\pi\gamma_+}\frac{N_- \beta_{y+}^*}{\sigma_{y-}^*\sqrt{\sigma_{z-}^2\tan^2\frac{\theta_c}{2} + \sigma_{x-}^{*2}}}$$

Beam-beam tune shift [3] ← ξ_{y+}^i

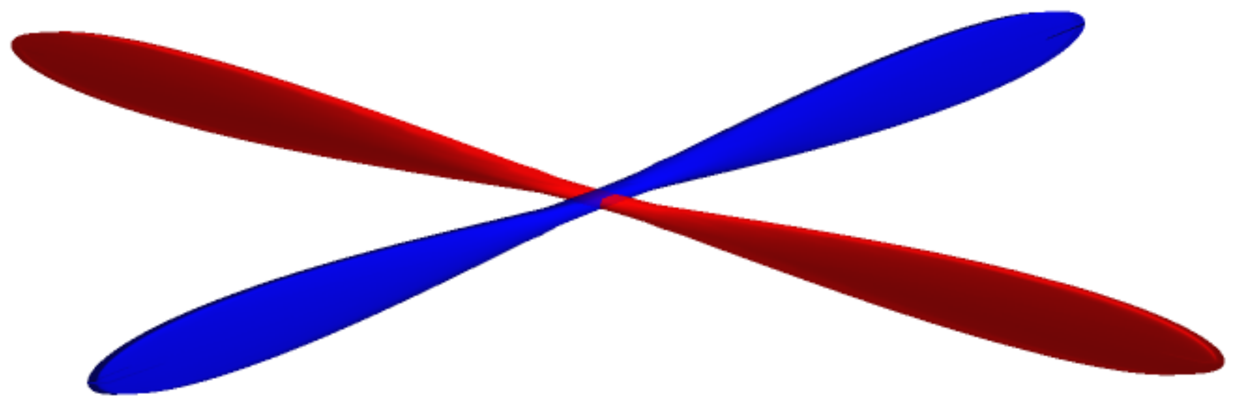
Piwinski angle: $\Phi_P = \frac{\sigma_z}{\sigma_x^*}\tan\frac{\theta_c}{2} \gg 1$

Hourglass condition: $\frac{\beta_y^*}{\sigma_x^*}\tan\frac{\theta_c}{2} \gtrsim 1$

Schematic view of collision schemes



SuperKEKB (2021c)



SuperKEKB (Final design)

[1] D. Zhou et al., PRAB 26, 071001 (2023). [2] K. Ohmi et al., PRST-AB 7, 104401 (2004). [3] D. Zhou, https://arxiv.org/pdf/2212.12706.

Luminosity performance

- Overview of beam-beam parameters with crab waist [1, 2]
  - The achieved beam-beam parameters during the physics run of SuperKEKB (i.e., the high voltage of Belle II was on.) in 2022 were 0.0407/0.0279 in LER/HER ($\gamma_+ I_{b+} \neq \gamma_- I_{b-}$, β_y^*=1 mm).
  - In 2022, 0.0565/0.0434 were achieved in LER/HER during HBCC machine studies (β_y^*=1 mm).

Table 1. Comparison of KEKB and SuperKEKB machine parameters.

	KEKB Achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 22nd		SuperKEKB Design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.363	1.118	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.606	0.497	1.440	1.040
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξ_y	$0.129^{a)}$	$0.090^{a)}$	$0.0236^{b)}$	$0.0219^{b)}$	$0.0398^{b)}$	$0.0278^{b)}$	$0.0881^{c)}$	$0.0807^{c)}$
	$0.10^{b)}$	$0.060^{b)}$			$0.0565^{d)}$	$0.0434^{d)}$	$0.069^{b)}$	$0.061^{b)}$
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	2.11		1.57		4.71		80	
$\int \mathcal{L}dt$ [ab^{-1}]	1.04		0.03		0.424		50	

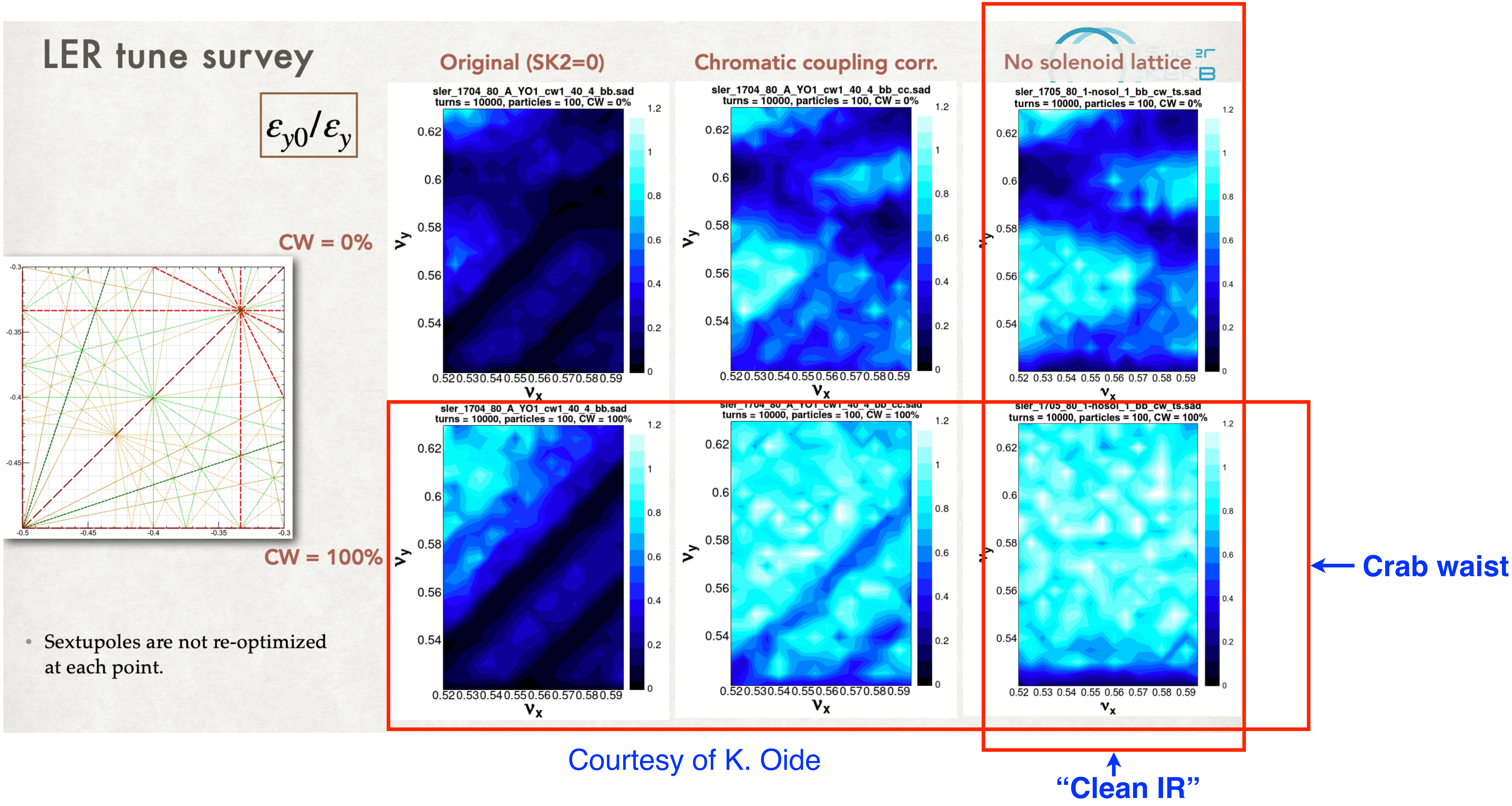
a)
$$\mathcal{L} = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta^*_{y\pm}}\xi^{ih}_{y\pm}\frac{R_\mathcal{L}}{R^\pm_{\xi y}}$$

b,d)
$$L = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta^*_{y\pm}}\xi^L_{y\pm}$$

c)
$$\xi^{ih}_{y+} = \frac{1}{4\pi p_0 c}\int_{-\infty}^{\infty} ds\beta_{y+}(s)\frac{\partial F_{y+}}{\partial y'}$$

[1] Y. Funakoshi, IPAC'22. [2] D. Zhou, ICFA Beam Dynamics Newsletter #85, 2023.

Beam-beam perspective on achieving target luminosity



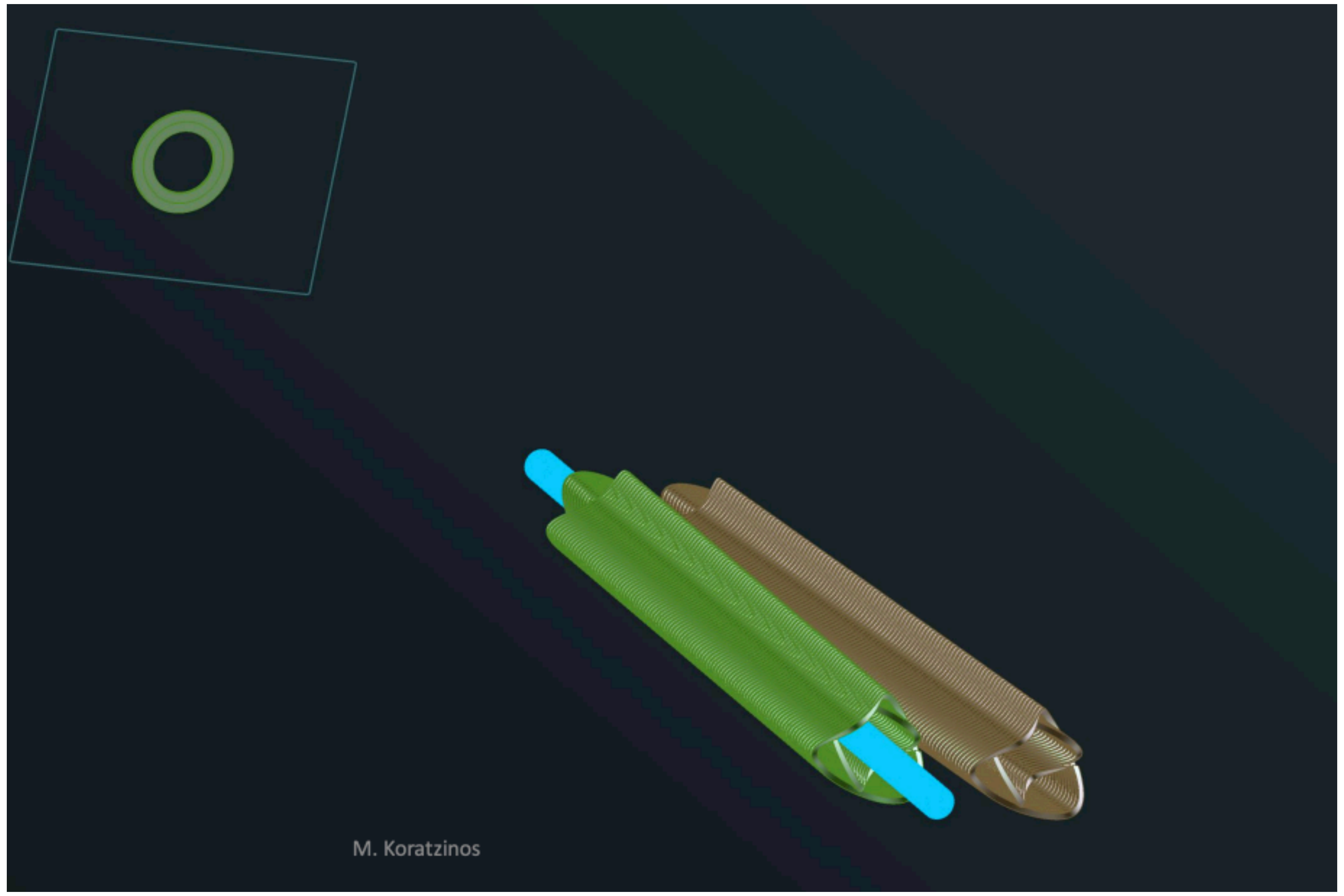
Courtesy of K. Oide

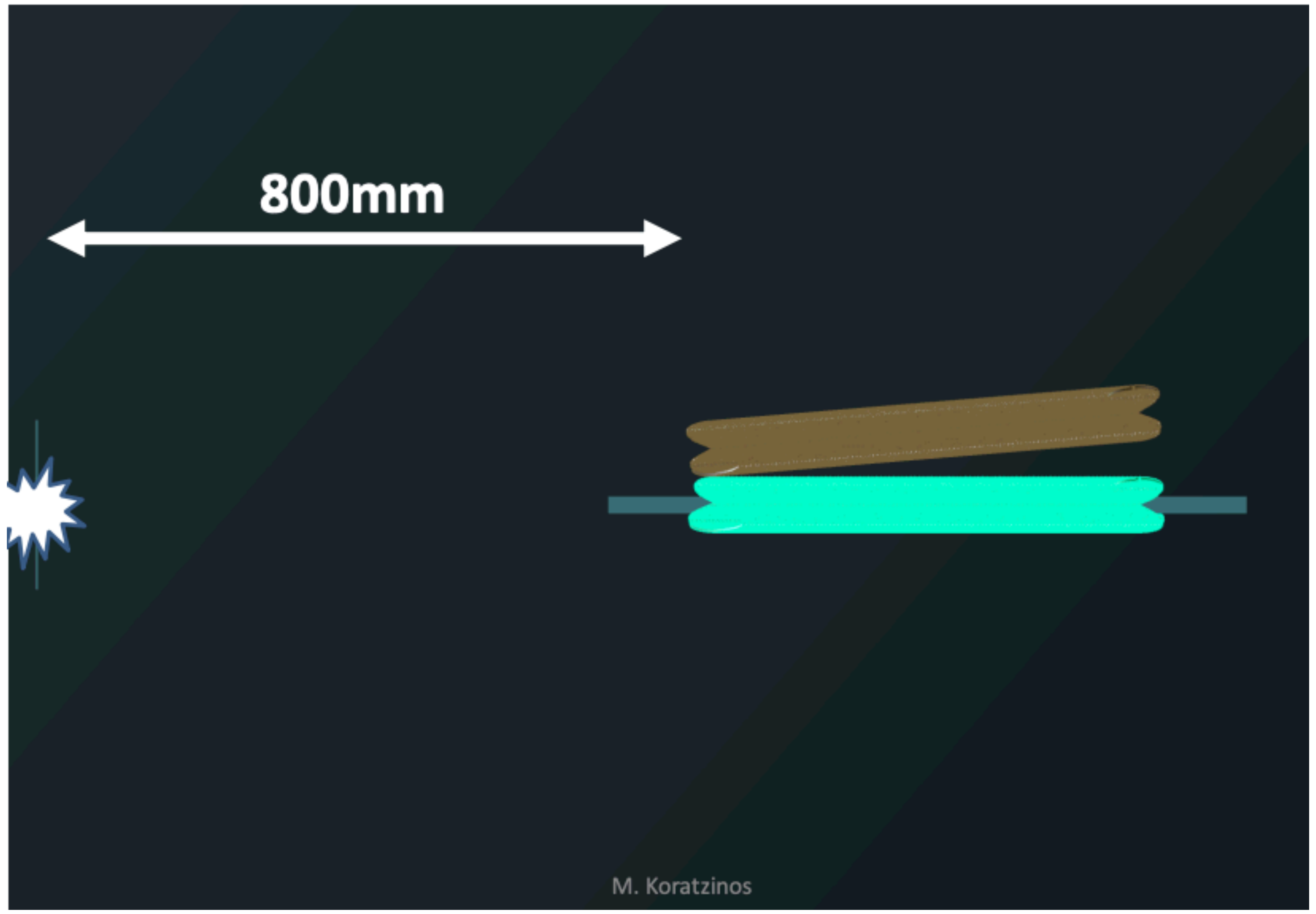
[1] K. Oide, https://kds.kek.jp/event/44644/.

"Clean IR": A transparent IR with minimal amplitude-dependent and chromatic nonlinearities

Beam-beam perspective on achieving target luminosity

- How to achieve a “clean IR”
  - IR remodeling (the mainstream upgrade plan (see M. Masuzawa’s talk) under investigation)
  - Using CCT (Canted Cosine Theta) magnets: M. Koratzinos did the first exercise (considering constraints from the technology and infrastructure of SuperKEKB) and showed encouraging results. Using the CCT magnets, a compact and cleaner IR is conceivable (Idea: “The current distribution of any canted layer generates a pure harmonic field as well as a solenoid that can be canceled with a similar but oppositely canted layer.” [2]).





Courtesy of M. Koratzinos

  - From the beam-beam perspective, we invite full international collaboration on IR upgrades to achieve the target luminosity of SuperKEKB.

[1] M. Koratzinos, https://kds.kek.jp/event/44644/. [2] S. Caspi et al., “Canted-Cosine-Theta magnet (CCT)-A concept for high field accelerator magnets” , IEEE Trans. Appl. Supercond. 24, 1. (2014).