SuperKEKB status and outlook of reaching 1E35 peak luminosity

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on behalf of the SuperKEKB commissioning group

Acknowledgements

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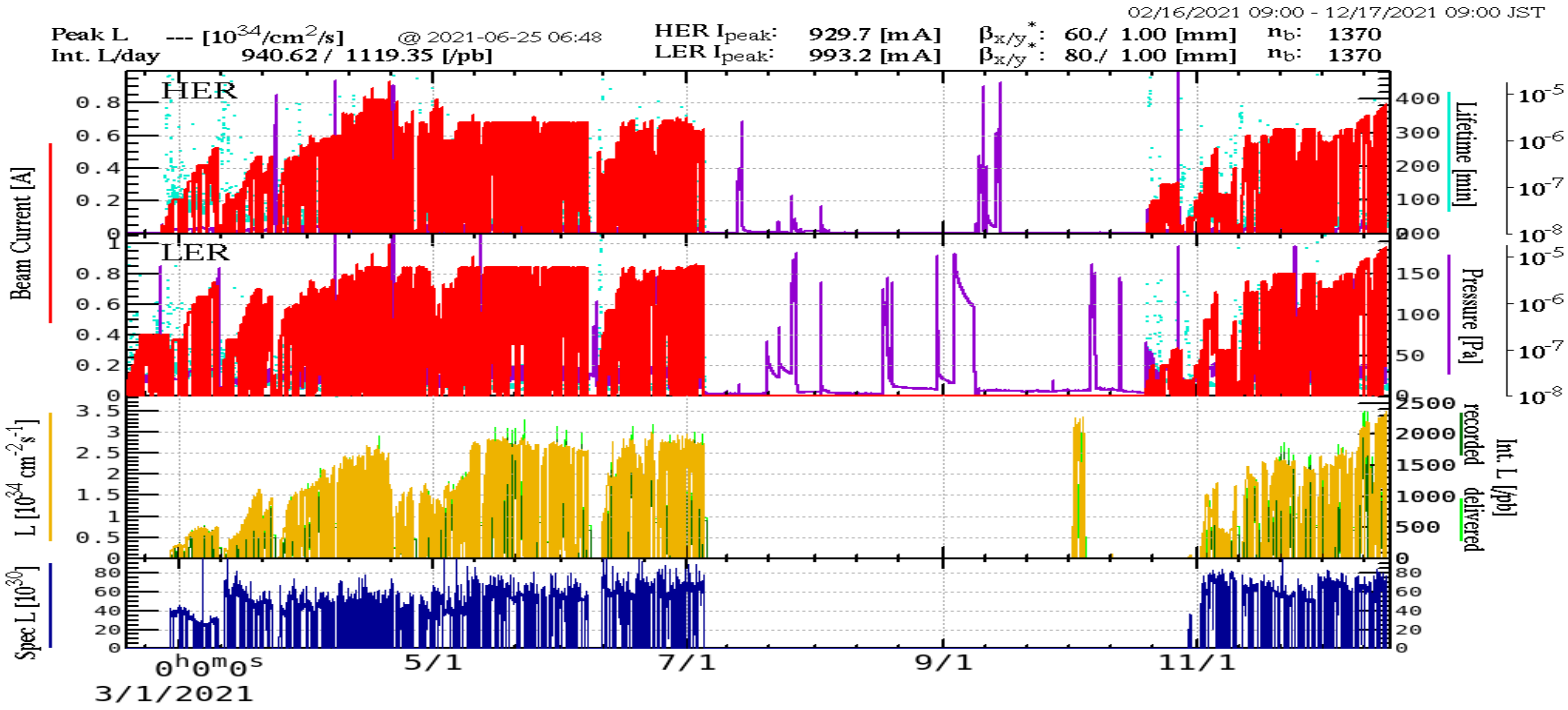
Belle II meeting in Italy, Dec. 16, 2021

Outline

- Status of SuperKEKB
- Near-term plan to 2024
- Scaling laws of luminosity
- Outlook of reaching 10E35 luminosity (personal viewpoint)

Status of SuperKEKB

- 2021a/b run: Feb.16 - Jul.5, 2021
  - Challenges: damaged collimators, unidentified sudden beam losses, injection troubles, etc.
- 2021c run: Oct.19 - Dec.23, 2021
  - Achievements: healthy collimators, less sudden beam losses, less injection troubles, etc.

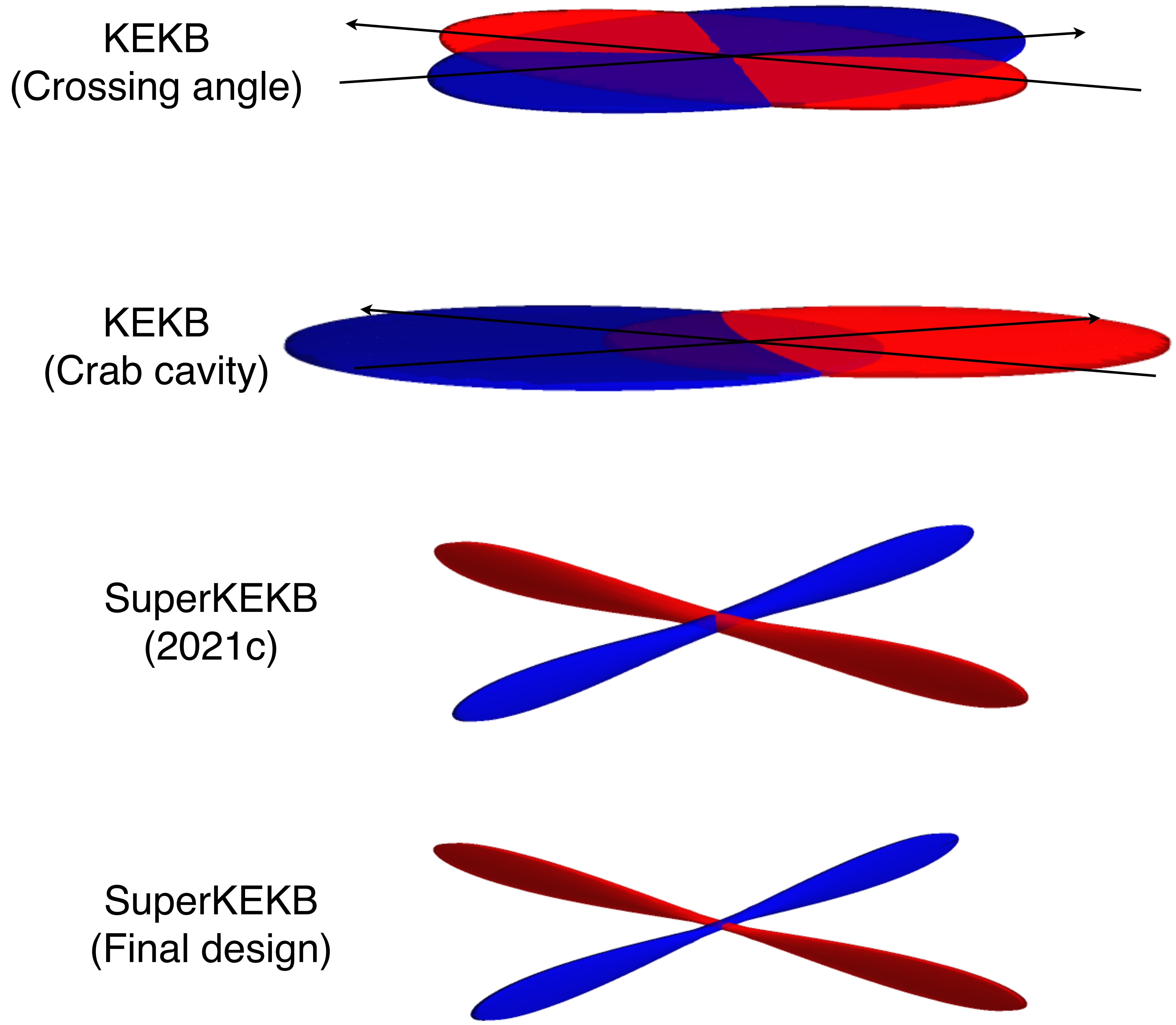


Status of SuperKEKB

- Collision scheme (KEKB → SuperKEKB)
  - SuperKEKB: A “green” collider

	KEKB (2009.06.17)		SKEKB (2021c)		SKEKB (Final design)	
	HER	LER	HER	LER	HER	LER
I_{beam} (A)	1.2	1.0	0.79	0.98	2.6	3.6
# bunch	1585		1370		2500	
ε_x (nm)	24	18	4.6	4.0	4.6	3.2
ε_y (pm)	150	150	~50	~50	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	46.589	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	
Luminosity (10^{34} cm^{-2}s^{-1})	2.1		3.56		80	

Schematic view of collision schemes



Status of SuperKEKB

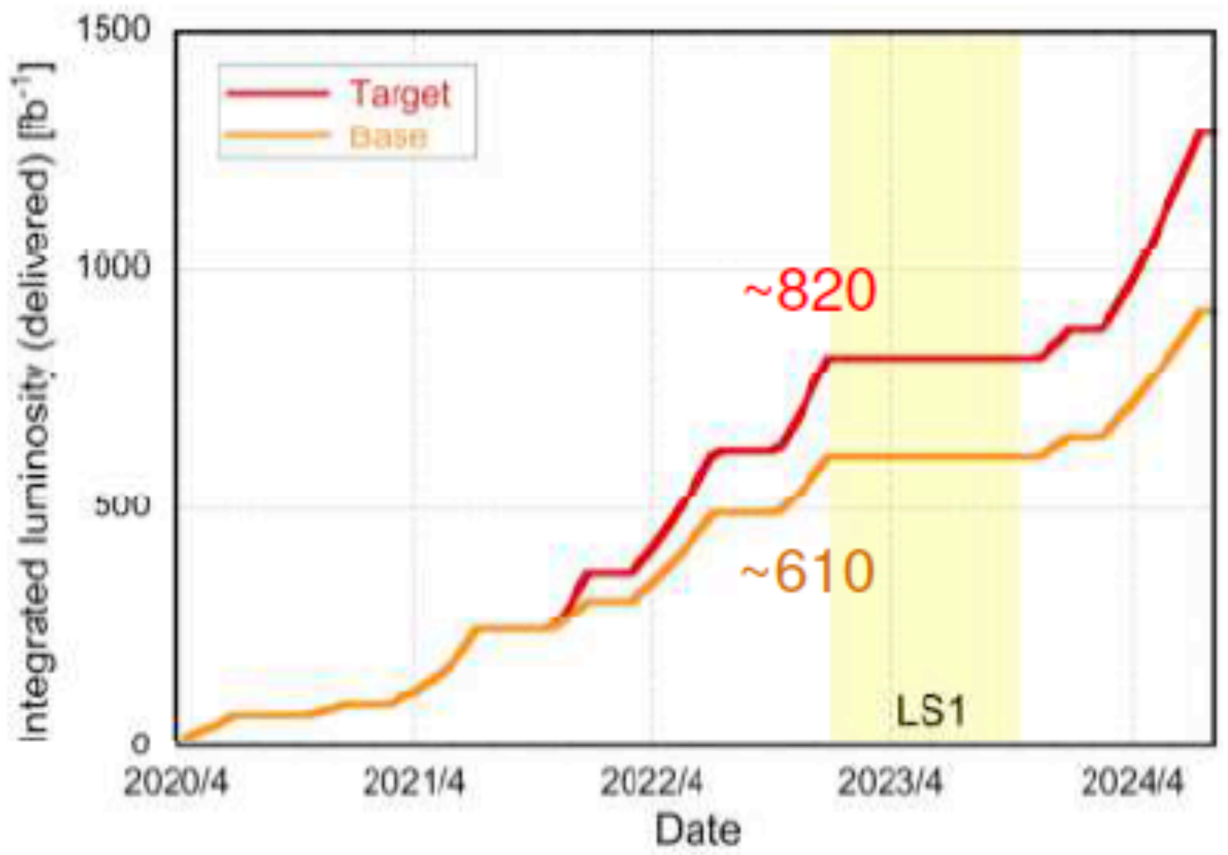
- Hardware work during summer shutdown of 2021 [1]

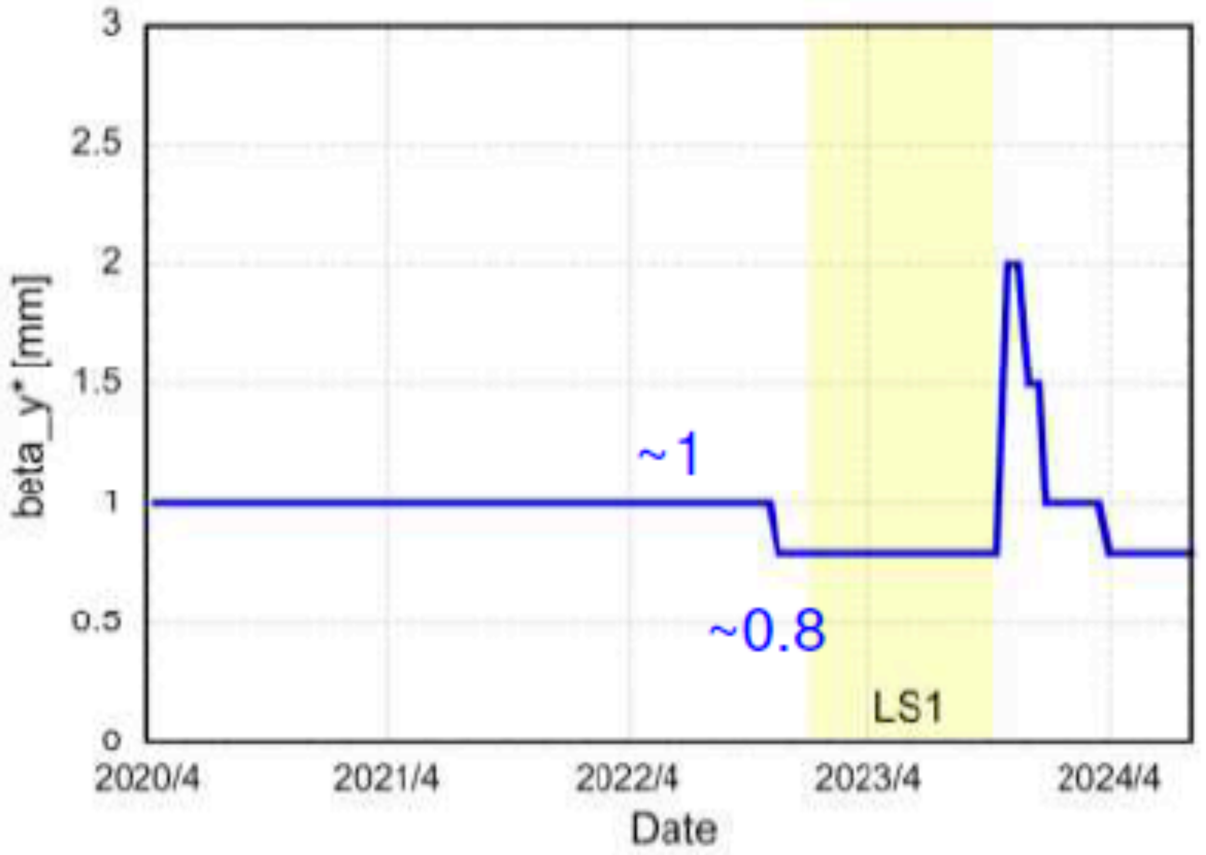
  - Regular maintenance (Water flow meters, Power supplies for RF and magnets, etc.
  - Collimators (see also next page)
    - Installation of new collimator heads with 3 mm Tantalum and graphite (at LER arc).
      - Robust against damages from beam.
    - Relocation of LER D02V1 collimators
    - Replacement of 2 collimator heads (HER).
    - Upgrade of driving device of 2 collimators (HER)
  - LER injection kicker
    - Exchange of all thyratrons to those with higher withstanding voltage to avoid unexpected-firing.
    - Rewiring of trigger cables to control each kicker timing separately.
  - Exchange of the mirror and its folder of SR beam size monitor for LER.
  - Installation of a HOM absorber at RF section (HER Nikko).
  - BT
    - Installation of beam profile monitors with OTR screen.
    - Installation of a beam shutter in LER injection line.
  - Installation of a strip-line kicker into RTL line at DR
  - Anti-aging measures
    - Replacement of HV (66 kV and 6.6 kV) power cables.
    - Repair of water leak from roof of some power stations.

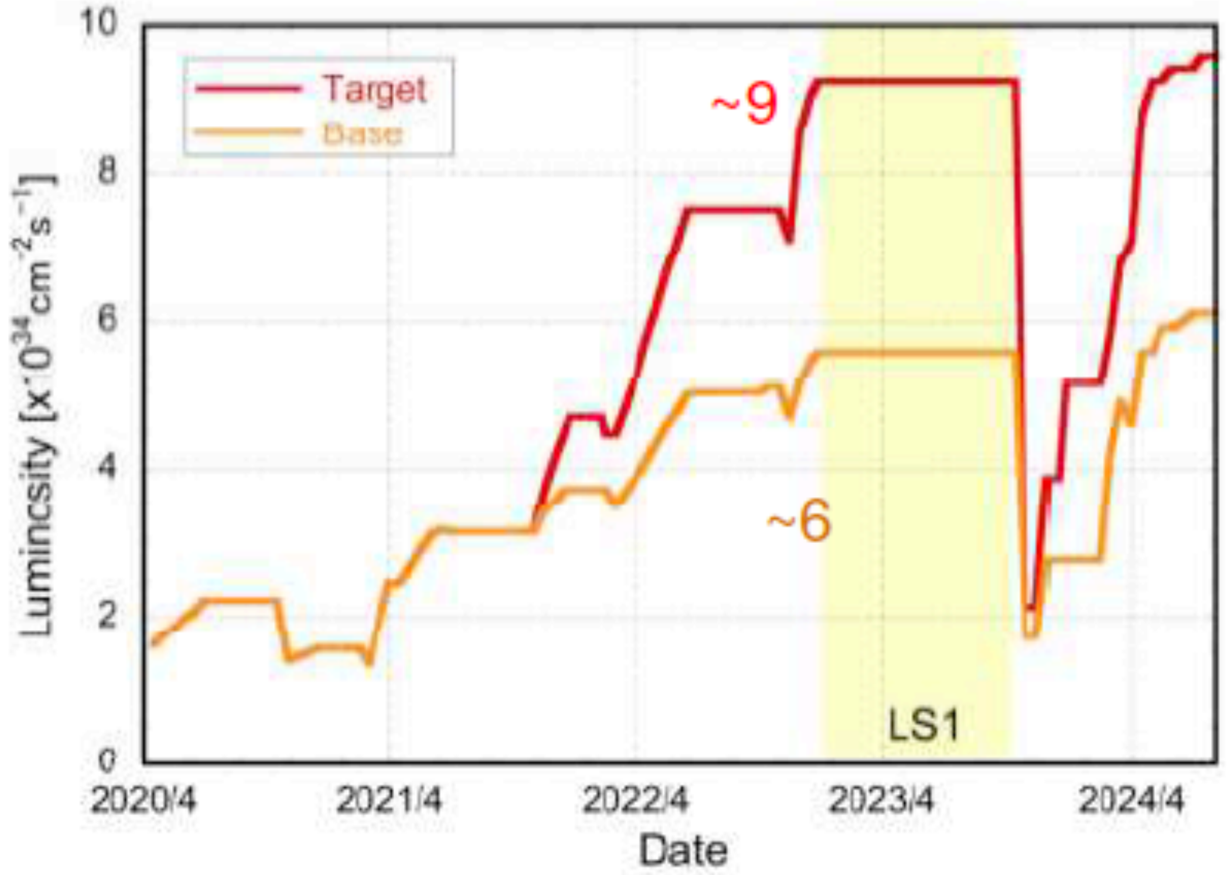
[1] Y. Suetsugu, “Status of SuperKEKB Ring”, Talk to BPAC, Nov. 09, 2021

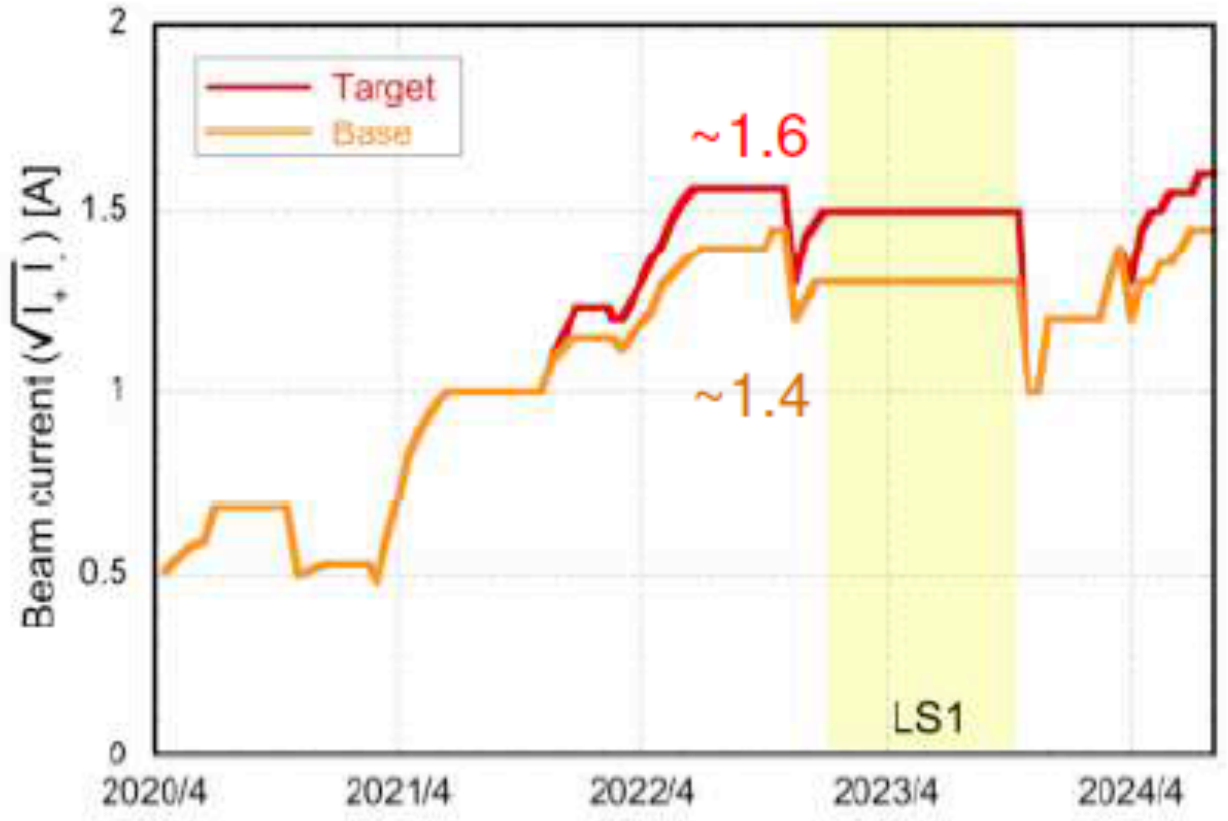
Near-term plan to 2024

- Near-term luminosity profile ~2024 (official) [1]
  - Luminosity profile



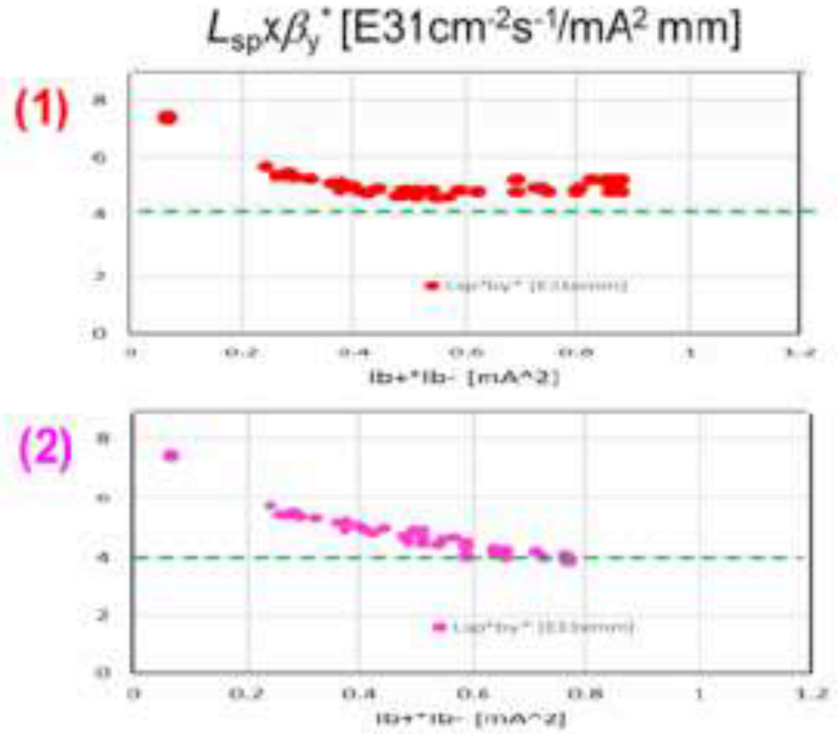


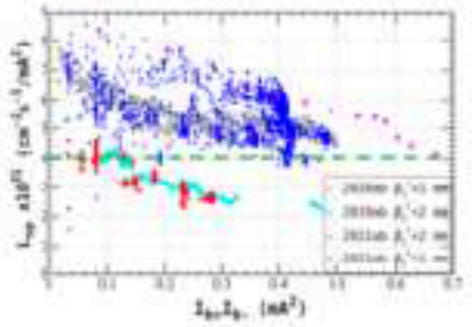




BPAC, 11/09/2021

	Target profile*	Base profile
Profile until 2022b	Same profile as previous one	Modified from 2021c
Operation efficiency	~2021c: 0.65, 2022a~: 0.4	2021c~: 0.4
Bunch current	≤ 0.95 mA	≤ 0.9 mA
Total current	≤ 1.6 A	≤ 1.5 A
Specific luminosity	Fig. (1)	Fig. (2)
Squeeze β_y^*	Squeeze to 0.8 mm at a proper timing after 2022c.	
After LS1	Need ~4 months' operation to fully recover the previous luminosity	





Y. Ohnishi

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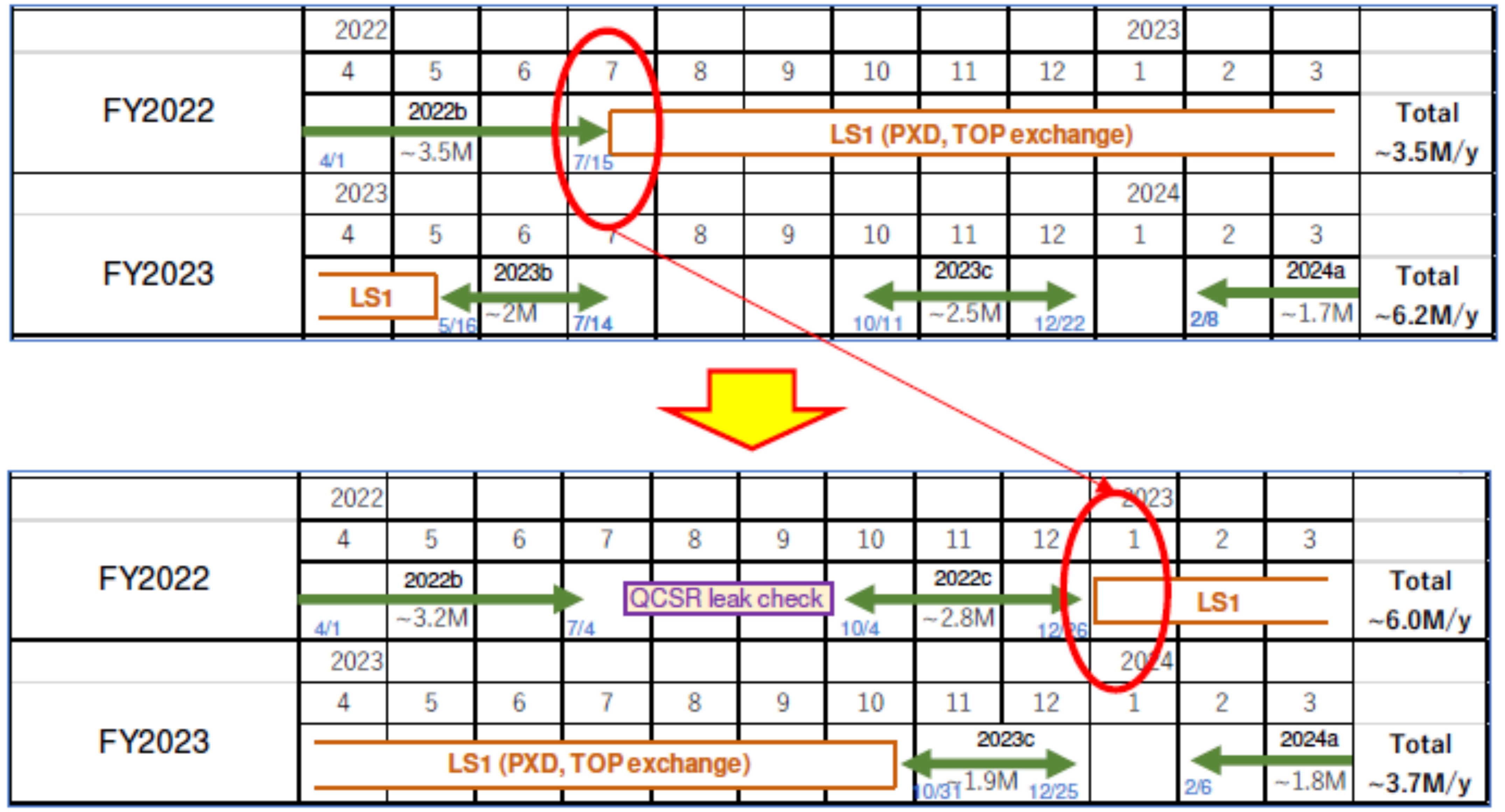
[1] Y. Suetsugu, "Status of SuperKEKB Ring", Talk to BPAC, Nov. 09, 2021

Near-term plan to 2024

- Near-term operation plan ~2024 [1]

- We decided to postpone the LS1 by a half year.
  - The LS1 will start from January, 2023.
  - A detailed leak check of QCSR cryostat vacuum tank is scheduled in summer shutdown 2022.



- Items to be considered
  - Influence of Covid-19
  - Fabrication of a new IP chamber
  - Integrated luminosity until LS1
  - QCSR leak
  - Availability of expertise especially in PXD.

- Requested budget is compatible with 6 months operation.

  - The schedule will be discussed again in May 2022, considering the situation at that time.

[1] Y. Suetsugu, "Status of SuperKEKB Ring", Talk to BPAC, Nov. 09, 2021

Scaling laws of luminosity

- Simple formula of luminosity for "nano-beam" scheme:

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

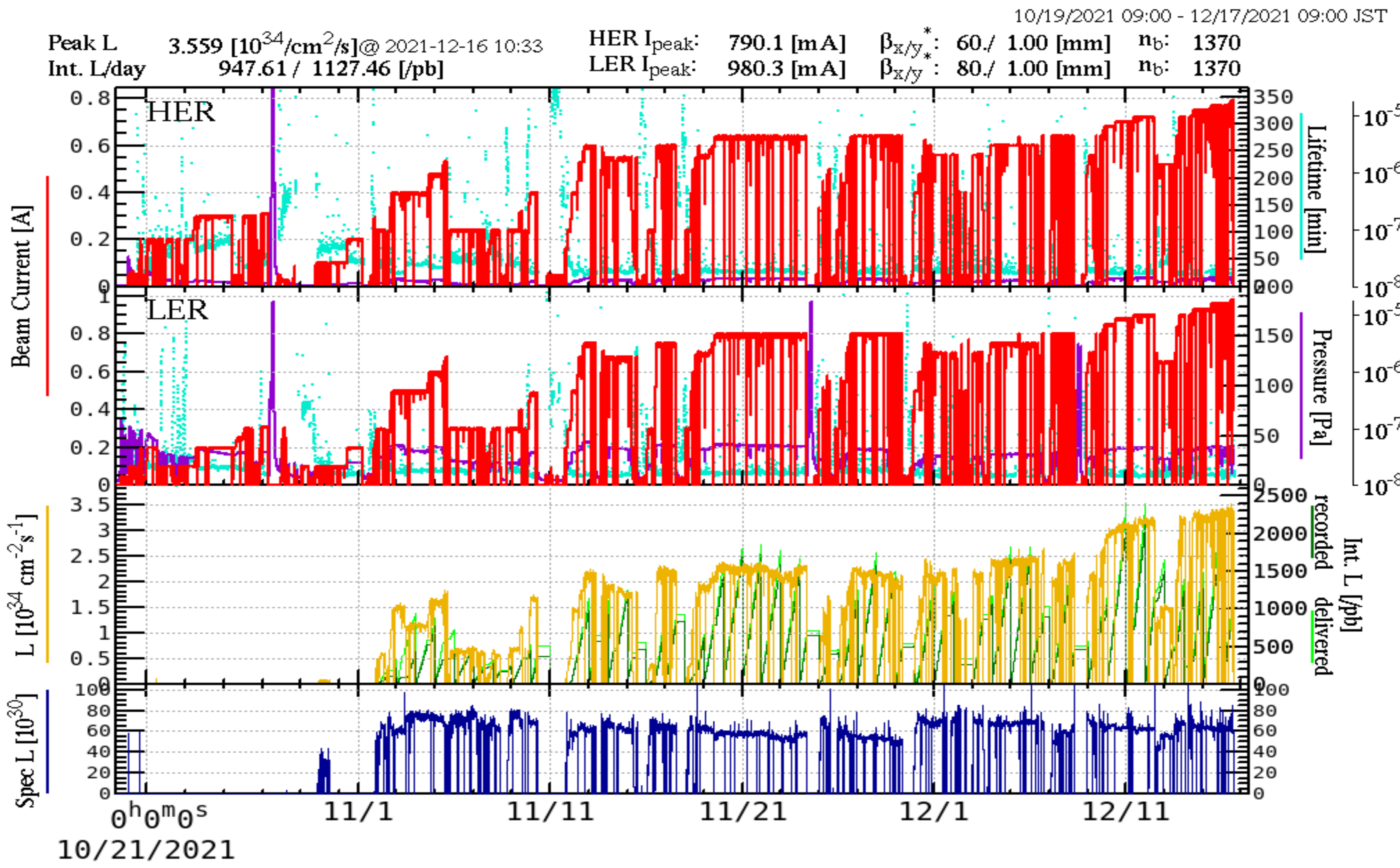
- In terms of total beam currents I_+ and I_-:

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

- Specific luminosity: Efficiency of extracting luminosity from given beam currents:

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

- "Easy" ways of achieving high luminosity:
  - Increasing number of colliding bunches
  - Increasing the total beam currents
- But challenges will arise from:
  - Tolerances of hardwares on high beam currents and number of bunches
  - Injection power of linac
  - Beam-size blowup due to collective effects (jargon of beam physics)



Scaling laws of luminosity

- Beam physics behind the luminosity at SuperKEKB

* Tolerance of hardwares
* Injection
* …

* Impedance effects (TMCI, PWD, HOM, etc.)
* Beam-beam blowup
* …

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

Note:
* $\sigma_{x\pm}^*$ do not appear in this luminosity formulae. But they play a role of “invisible hand” and have very important impact on beam dynamics, eventually affecting the luminosity.

* TMCI (Y-Z instability)
* Beam-beam blowup
* β_y^*, ϵ_y
* Optics correction
* Tunes $\nu_{x,y}$
* Machine imperfections
* …

* Impedance effects
* Beam-beam blowup
* …

* Coherent X-Z instability
* Beam-beam resonances (X-Y coupling)
* β_x^*
* Crab waist
* …

Scaling laws of luminosity

- The luminosity is discussed in accelerator side in different ways. One concept is the so-called "beam-beam parameter". For SuperKEKB, vertical beam-beam parameters ξ_{y+} and ξ_{y-} are most essential, and are calculated from luminosity by:

$$L = \frac{1}{2er_e}\frac{\gamma_+ I_+}{\beta^*_{y+}}\xi_{y+} = \frac{1}{2er_e}\frac{\gamma_- I_-}{\beta^*_{y-}}\xi_{y-}$$

- Another concept, so called "incoherent beam-beam tune shift" ξ^i_{y+} and ξ^i_{y-} (they measure the strengths of beam-beam forces), is used to discuss the beam-beam driven beam-size blowup.

- The incoherent beam-beam tune shifts are calculated from beam sizes and "beta functions":

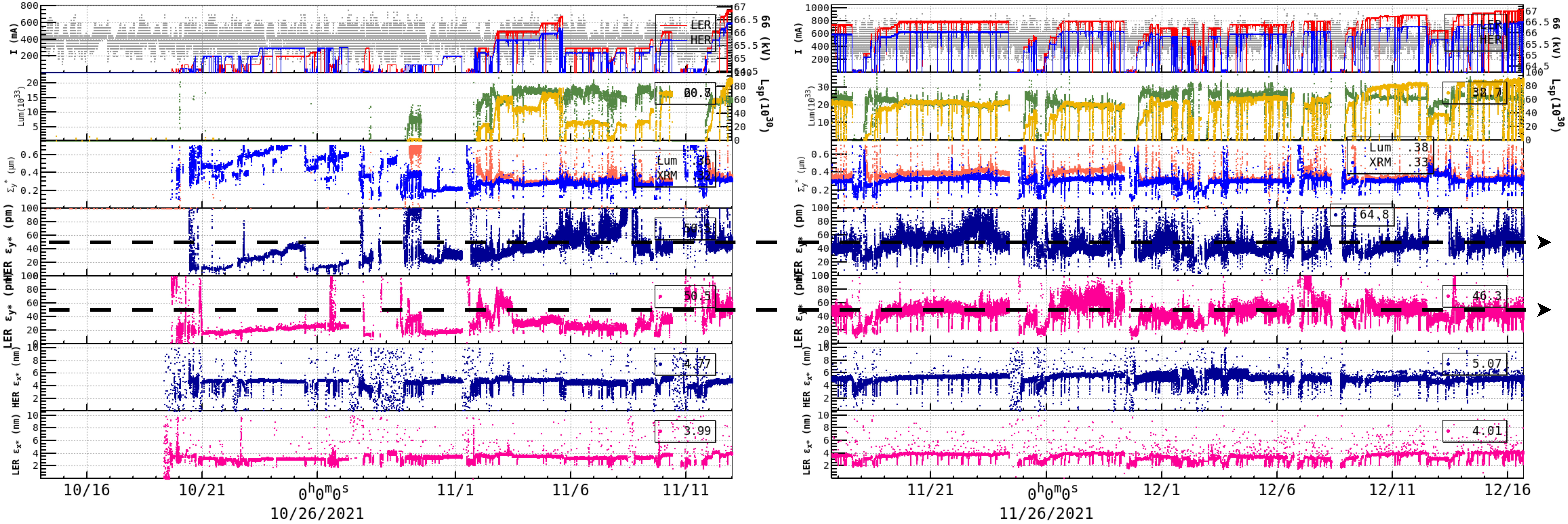
$$\xi^i_{y+} \approx \frac{r_e}{2\pi\gamma_+}\frac{N_-\beta^*_{y+}}{\sigma^*_{y-}\sqrt{\sigma^2_{z-}\tan^2\frac{\theta_c}{2} + \sigma^{*2}_{x-}}}$$

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

- For a "balanced" collision: $\sigma^*_{y+} = \sigma^*_{y-}$, $\sigma_{z+} = \sigma_{z-}$, there are $\xi_{y+} \approx \xi^i_{y+}$ and $\xi_{y-} \approx \xi^i_{y-}$. When the collision is out of balance, $\xi_{y+} \neq \xi^i_{y+}$ and $\xi_{y-} \neq \xi^i_{y-}$.
- To target high luminosity, a "balanced" collision is necessary. We assume it in the following discussions.

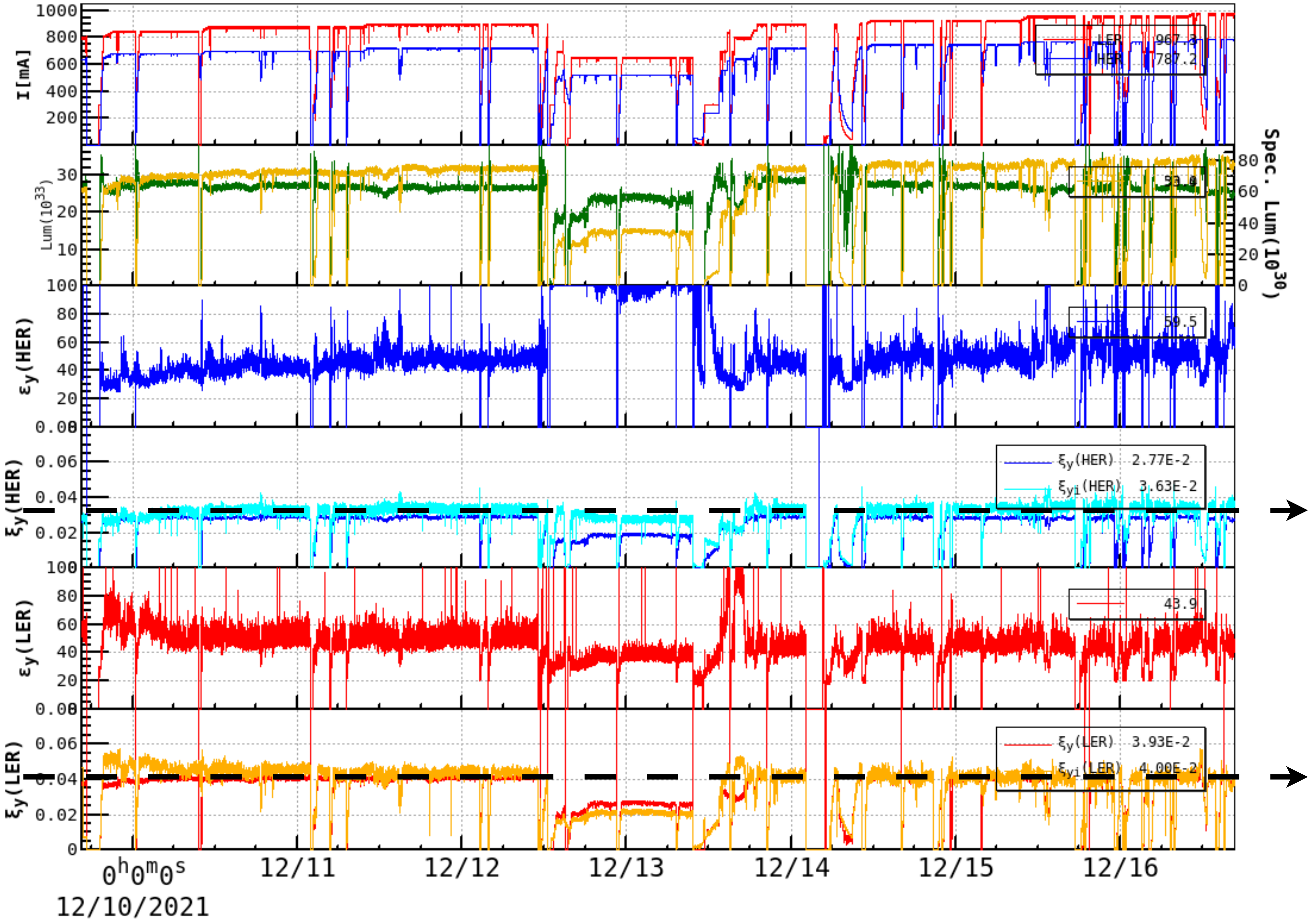
Scaling laws of luminosity

- “Balanced” collision was fairly achieved in 2021c run.
  - Recent optimum machine condition: Collision at $I_{+/-}$=800/640 → 980/790 mA with balanced vertical emittances of $\epsilon_{y+/-} \approx$ 50/50 pm (Single-beam emittances $\epsilon_{y+/-} \approx$ 20/20 pm).
  - Keeping “balanced” collision is one of the challenges while the machine condition changes day by day.



Scaling laws of luminosity

- Beam-beam parameter (tune shift)
  - Under balanced collision ($\sigma^*_{y+} \approx \sigma^*_{y-}$), the two methods for beam-beam parameter (tune shift) are almost equivalent.
  - The currently achieved beam-beam parameters are $\xi_{y+} \approx 0.04$ and $\xi_{y-} \approx 0.03$ (w/ crab waist), which are much lower than the design values of ~0.09 (w/o crab waist). This is the most important challenge at SuperKEKB.



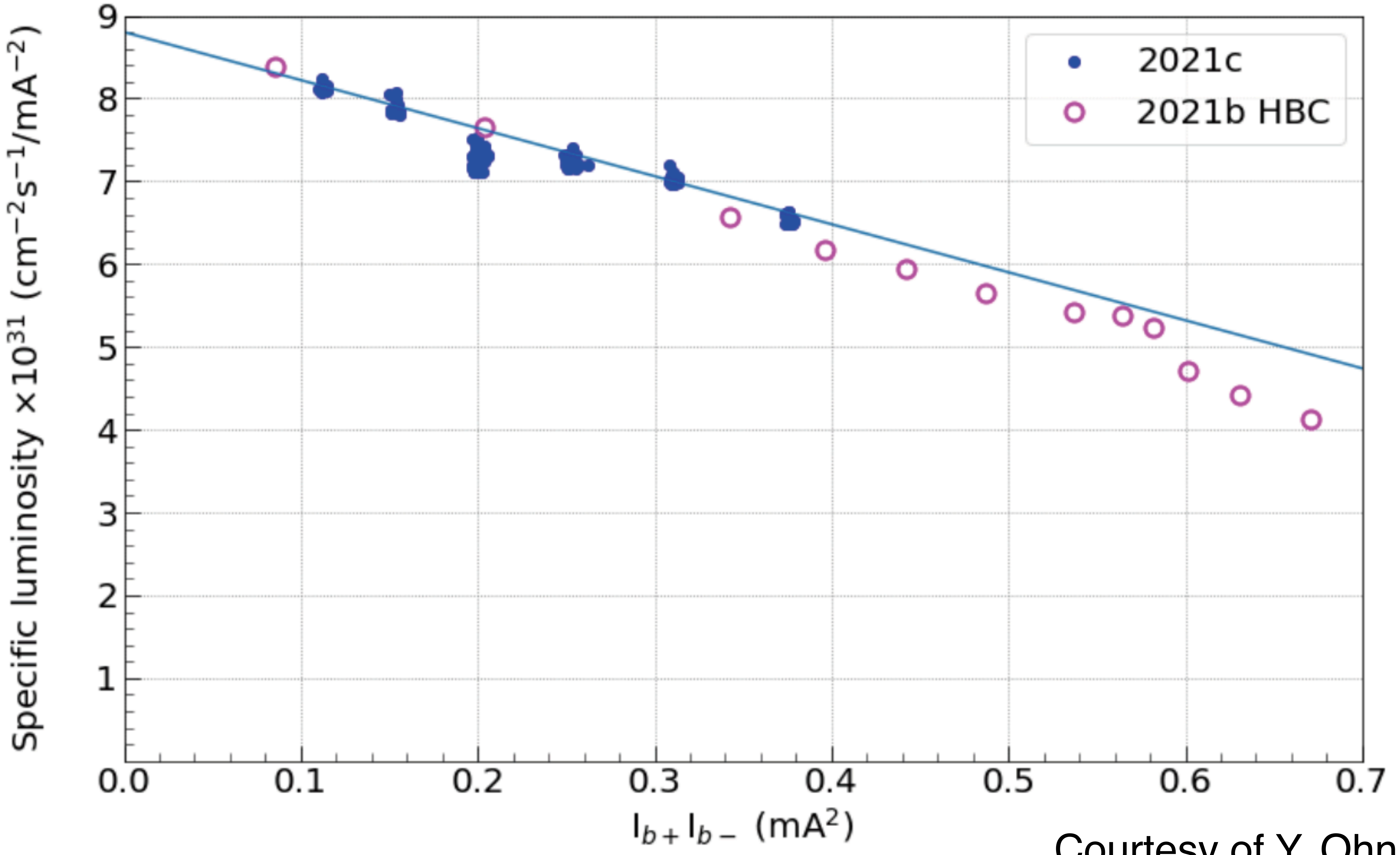
$$L = \frac{1}{2er_e}\frac{\gamma_+ I_+}{\beta^*_{y+}}\xi_{y+} = \frac{1}{2er_e}\frac{\gamma_- I_-}{\beta^*_{y-}}\xi_{y-}$$

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

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

Scaling laws of luminosity

- Specific luminosity
  - Specific luminosity L_{sp} is "the last piece of the puzzle" for discussion of reaching 1E35 luminosity at SuperKEKB.
  - The best scenario is: L_{sp} is a constant. It means there are no beam-size blowup.
  - But in the realistic machine, L_{sp} drops when bunch currents increase due to "collective effects".



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

Courtesy of Y. Ohnishi

Outlook of reaching 1E35 luminosity

- Scenario-1: Constant beam-beam parameter
  - When the machine hits a “beam-beam limit”, the beam-beam parameter will saturate and cannot increase furthers. This is an empirical observation based on experiences from colliders.
  - Let us tentatively accept $\xi_{y+} \approx 0.04$ and $\xi_{y-} \approx 0.03$ which are taken from the current SuperKEKB observation. Then we can simply find the necessary beam currents to achieve 1E35 luminosity. The results are summarized in the table.
  - Note that we achieved 3.5E34 luminosity wit β_y^*=1 mm today (Dec.16, 2021).

βy (mm)	3.5E+34		6E+34		1E+35	
	HER	LER	HER	LER	HER	LER
1	0.77	1.01	1.32	1.73	2.20	2.88
0.8	0.61	0.81	1.05	1.38	1.76	2.31
0.6	0.46	0.61	0.79	1.04	1.32	1.73
0.4	0.31	0.4	0.53	0.69	0.88	1.15
0.3	0.23	0.3	0.40	0.52	0.66	0.87

$$L = \frac{1}{2er_e}\frac{\gamma_+ I_+}{\beta^*_{y+}}\xi_{y+} = \frac{1}{2er_e}\frac{\gamma_- I_-}{\beta^*_{y-}}\xi_{y-}$$

Outlook of reaching 1E35 luminosity

- Scenario-2: Given specific luminosity slope
  - From the observed specific luminosity slope (see page.13), we can estimate the total luminosity with given beam currents.
  - We can assume $L_{sp}[10^{31}$ cm^{-2}s^{-1}/mA$^2] = 8.8 - 5.8 I_{b+} I_{b-}$[mA^2]. Note that this scaling law is only valid for for β_y^*=1 mm.
  - Also I assume bunch current ratio of $I_{b-}/I_{b+} = 0.8$ which is currently used at SuperEKKB. The possible bunch current products and number of bunches are listed in the table and resulting luminosity [scaled by 1E35].
  - Squeezing β_y^* is effective to increase L_{sp}, but has many other side effects (not discussed here).

$I_{b+}I_{b-}$ [mA^2]	0.5	0.7	1
1270	0.41	0.49	0.53
1370	0.44	0.53	0.57
1565	0.51	0.61	0.65
2000	0.65	0.78	0.83
2500	0.81	0.97	1.04

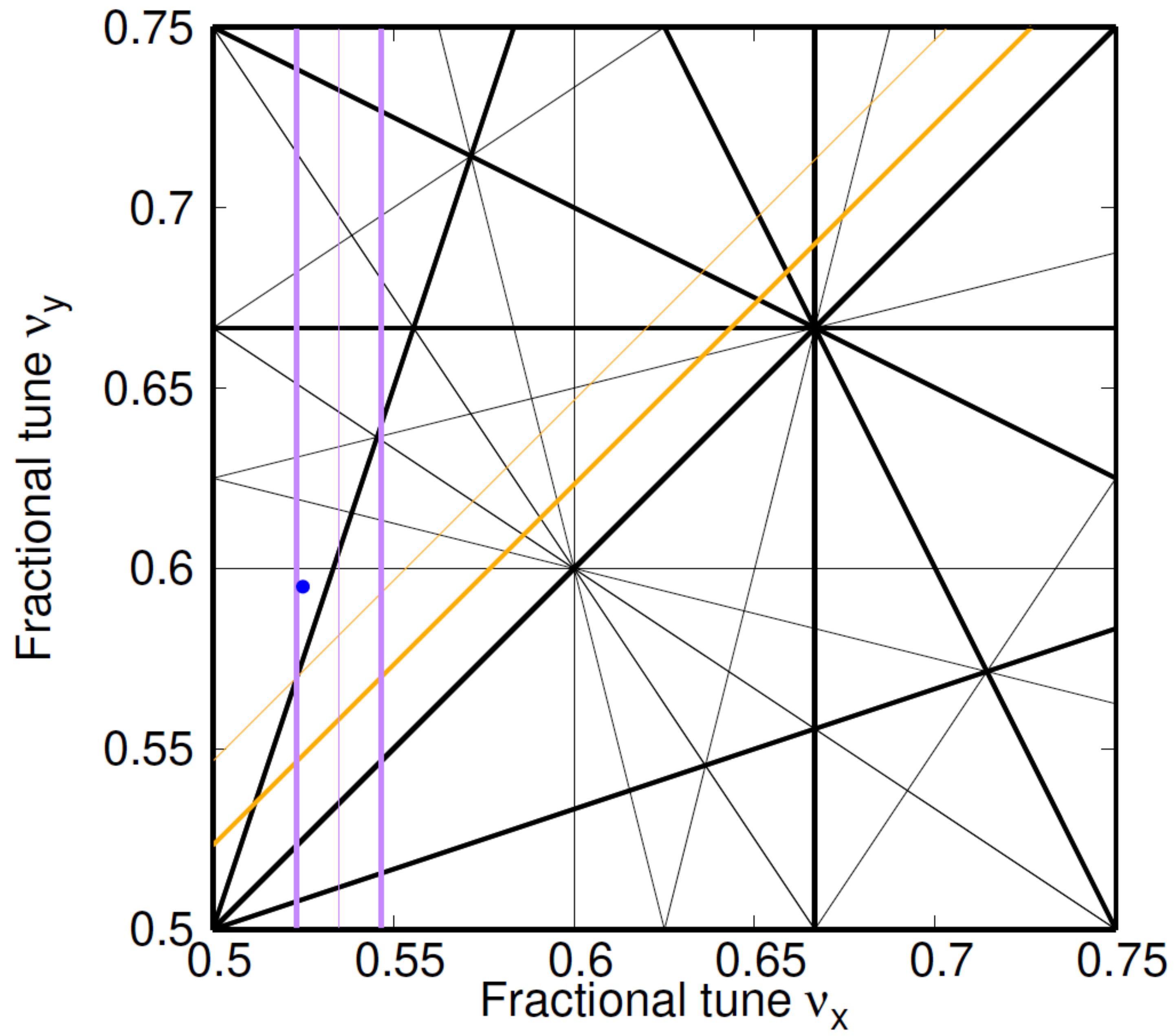
$$L_{sp} = \frac{L}{N_b N_+ N_- (ef)^2} \approx \frac{1}{2\pi e^2 f \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}} \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2} \tan\frac{\theta_c}{2}}$$

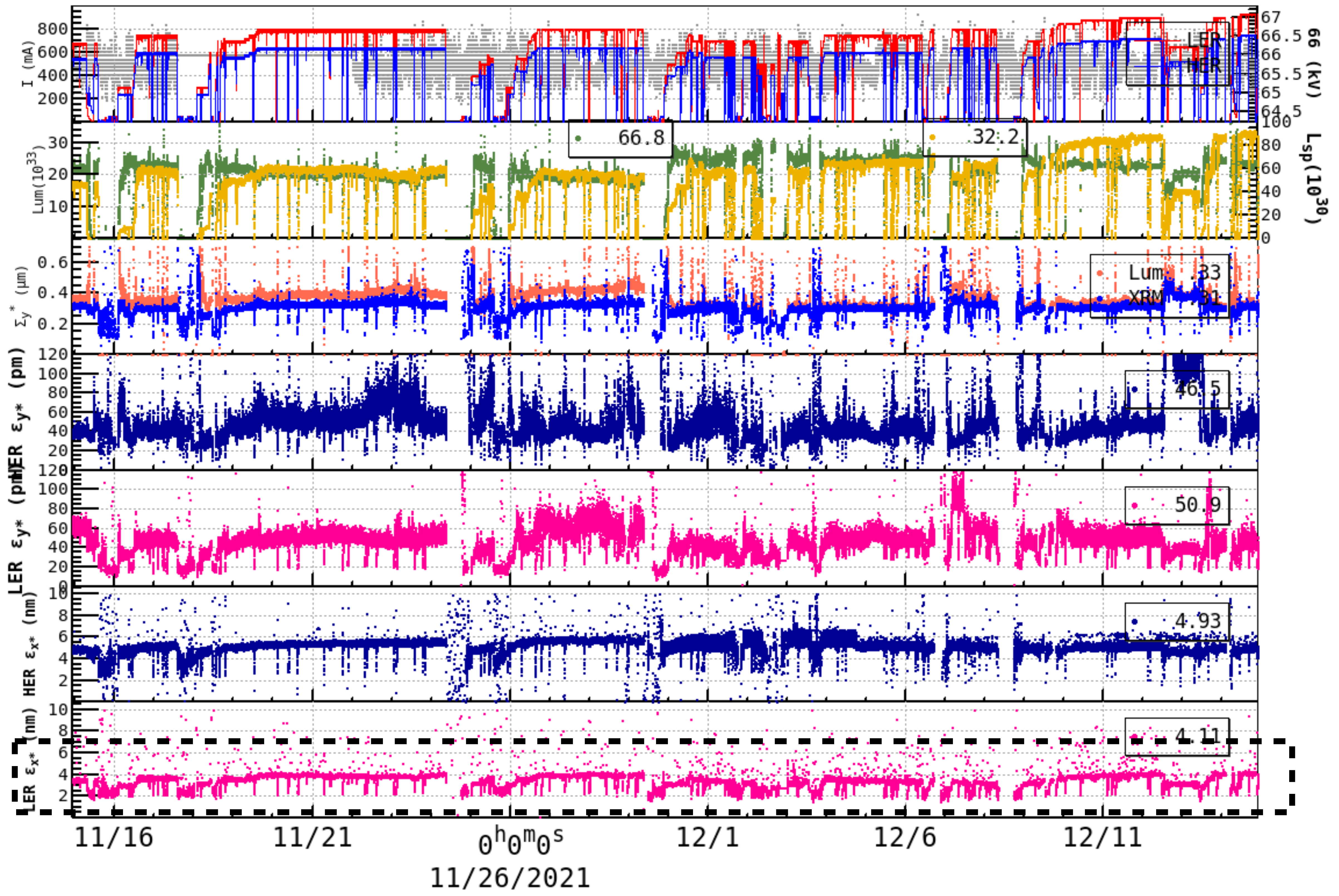
Outlook of reaching 10E35 luminosity

- Topic not covered in this talk
  - Belle II background
  - Beam lifetime
  - Injection
  - Hardware issues at high-current operation

Discussion on candidates for vertical emittance blowup

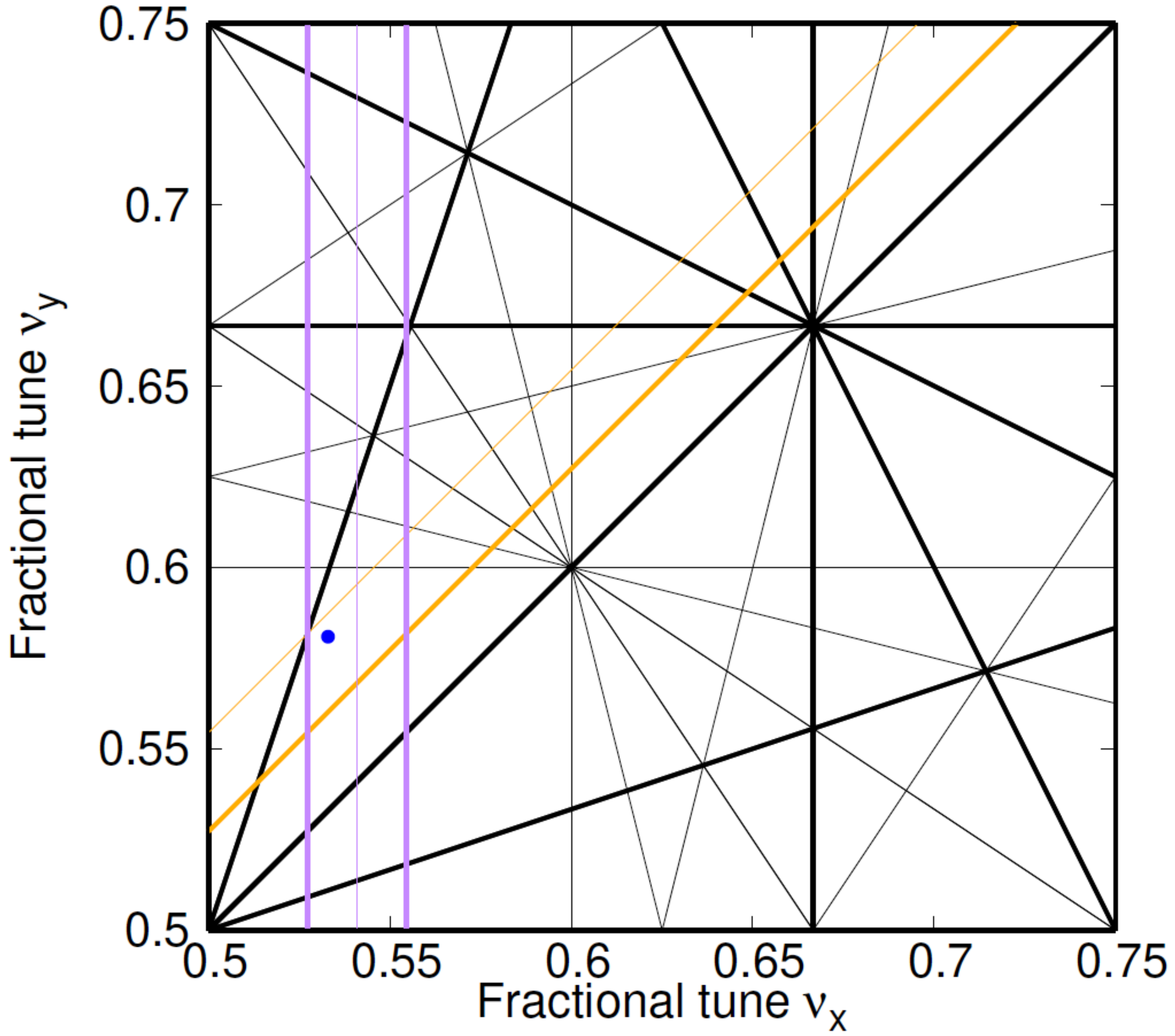
- LER
  - Beam-beam driven synchro-betatron resonance (here I mean single-beam effect, not BBHTI or X-Z instability which means coherent blowup of both beams. Potential-well distortion cause ν_s spread and increase width of $2\nu_x - k\nu_s = N$ resonances.)?.
  - TMCI: Interplay of beam-beam, impedance and lattice nonlinearity.
  - Imperfect CW (imperfect phase-advance between SLY* magnets, non-perfect CW for off-momentum particles)
  - Others?





Discussion on candidates for vertical emittance blowup

- HER
  - Chromatic coupling ($\nu_x - \nu_y + \nu_s = N$ and $\nu_x - \nu_y + 2\nu_s = N$)
  - $3\nu_x - \nu_y =$ N? Can it be excluded according to Ohmi-san's study?
  - Insufficient CW (now 40%, limited by SLY* strengths).
  - Imperfect CW (imperfect phase-advance between SLY* magnets, non-perfect CW for off-momentum particles)
  - Others?



How to understand this HER vertical blowup?