Updates on beam-beam simulations and results of recent beam-beam machine study

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Acknowledgements

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6th meeting of beam-beam workgroup, Jan. 25, 2022, KEK

Outline

- Updates on beam-beam simulations for SuperKEKB
  - BBSS simulations of IP knobs (R3 and R4)
  - BBSS simulations of LER ν_x
- Beam-beam study on Dec. 21-22, 2021
- Summary

Updates on beam-beam simulations

- Simulations of IP knobs (R3 and R4) with longitudinal pseudo-Green function wakes
  - Beam parameters similar to observations on 2021.07.01.
  - Assumed principle of IP knobs:

$$\frac{\partial L(\vec{R})}{\partial R_i} = 0 \quad \Rightarrow \quad R_i = 0$$ **with R_i a parameter observed at IP.**

  - The scaling law of vertical beam sizes at IP follows [1]

$$\sigma_y^{*2} = \mu^2 \epsilon_y \left(\beta_y^* + \frac{\Delta s^2}{\beta_y^*} \right) + \left(\eta_y^* \sigma_\delta \right)^2 + \epsilon_x \frac{\left(R_2^* + R_4^* \Delta s \right)^2}{\beta_x^*} + \epsilon_x \beta_x^* \left(R_1^* + R_3^* \Delta s \right)^2$$

  - Δs is the deviation of vertical waist position.

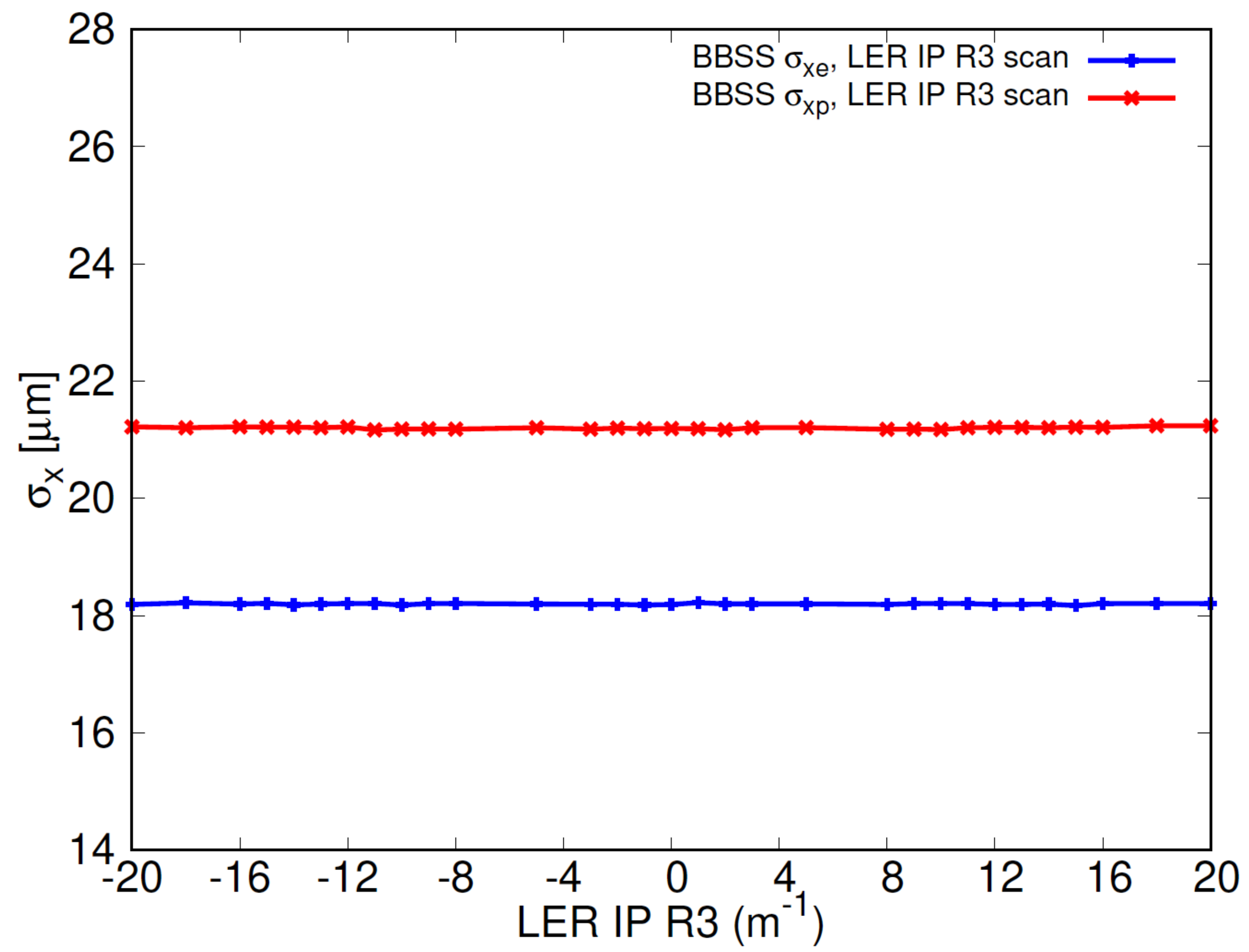
	2021.07.01		Comments
	HER	LER	
I_{bunch} (mA)	0.80	1.0	
# bunch	1174		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	23	23	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured tune of pilot bunch
ν_y	43.582	46.593	Measured tune of pilot bunch
ν_s	0.0272	0.0221	Calculated from lattice
Crab waist	40%	80%	Lattice design

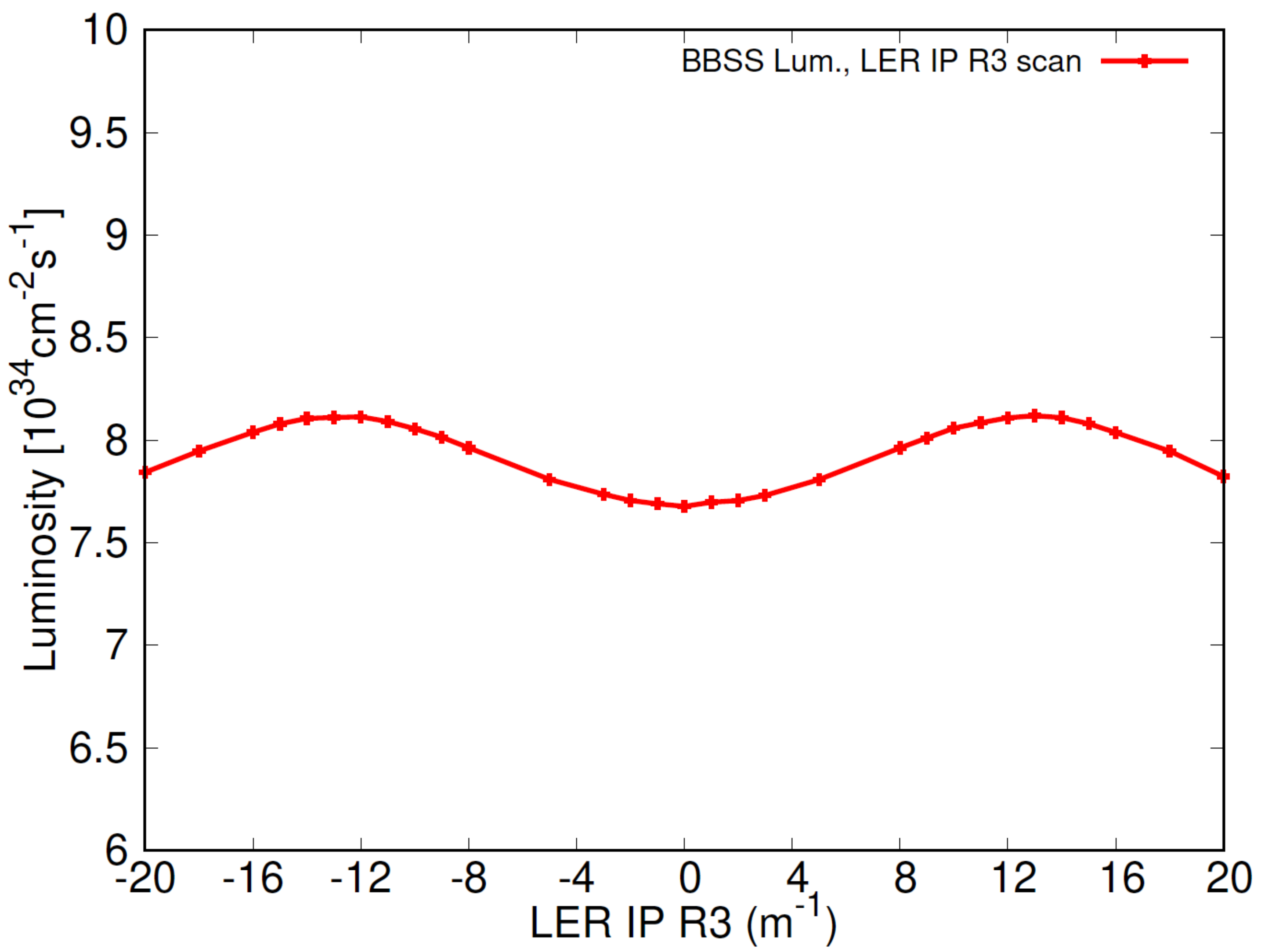
[1] Y. Ohnishi et al., The European Physical Journal Plus 136, 1023 (2021)

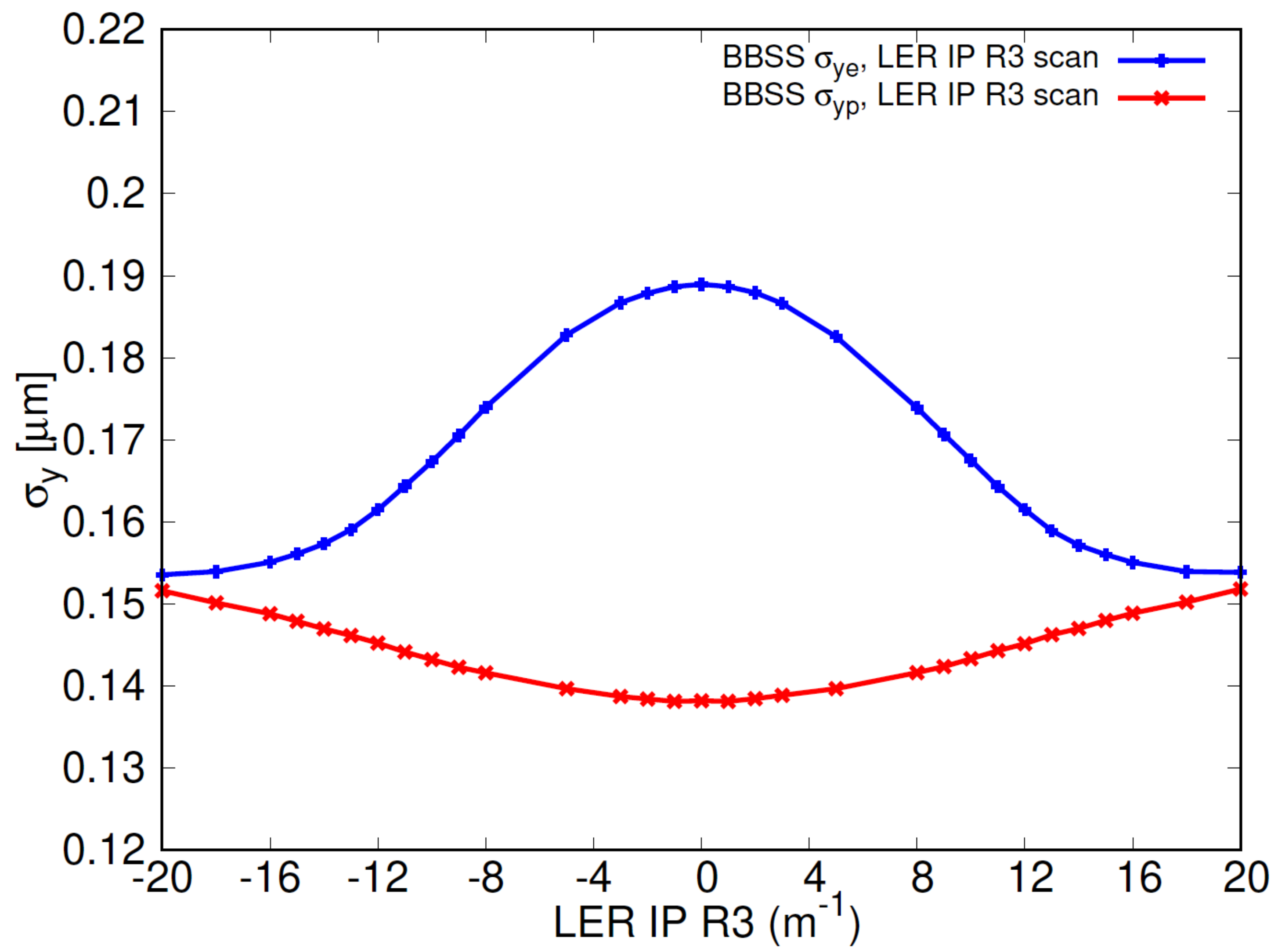
Updates on beam-beam simulations

- IP R3 scan
  - Simulations were done using simple one-turn matrix.
  - In this scan, nonzero LER IP R3 can increase luminosity (Double peaks in the luminosity scan). This is because HER σ_y^* shrinks due to weak beam-beam force.
  - HER σ_y^* blowup at LER IP R3=0 is mainly due to insufficient crab waist strength in HER (40%).
  - The sensitivity of LER σ_y^* against R3 is scaled by $\epsilon_x \beta_x^*$ with $\beta_x^* \ll 1$ m.

$$\sigma_y^{*2} = \mu^2 \epsilon_y \left(\beta_y^* + \frac{\Delta s^2}{\beta_y^*} \right) + \left(\eta_y^* \sigma_\delta \right)^2 + \epsilon_x \frac{\left(R_2^* + R_4^* \Delta s \right)^2}{\beta_x^*} + \epsilon_x \beta_x^* \left(R_1^* + R_3^* \Delta s \right)^2$$

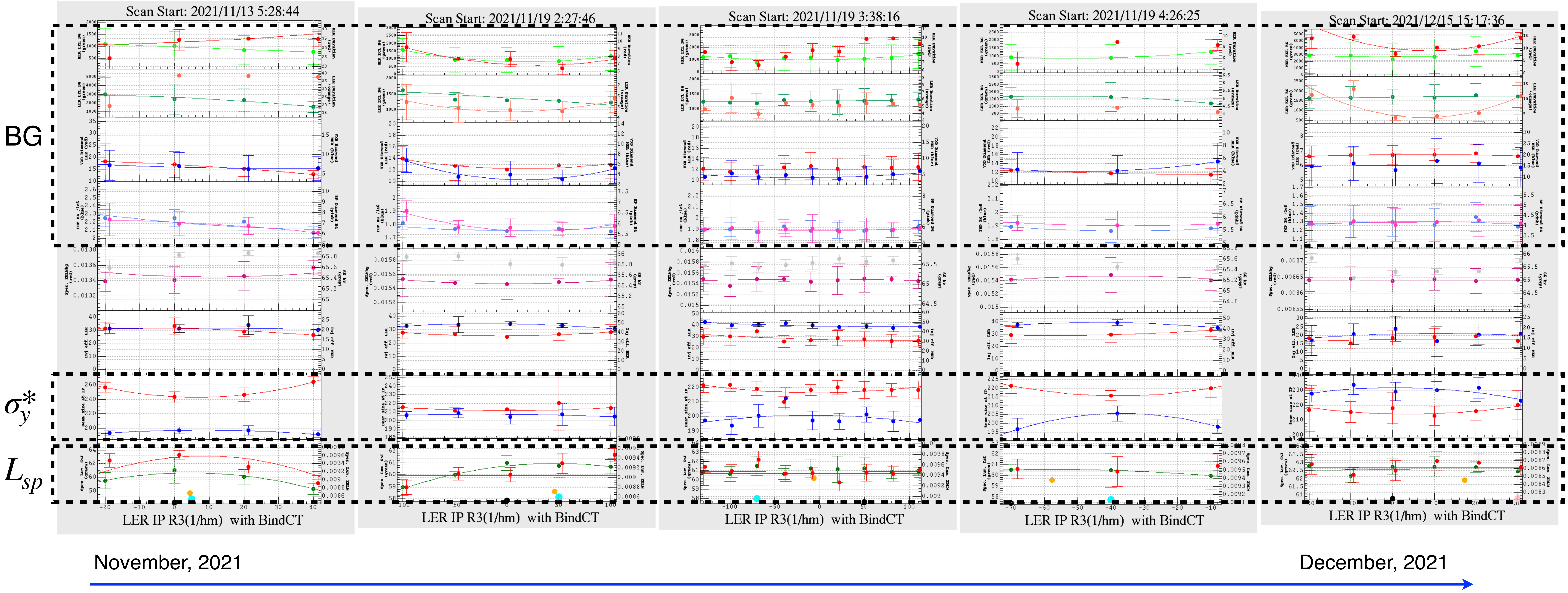






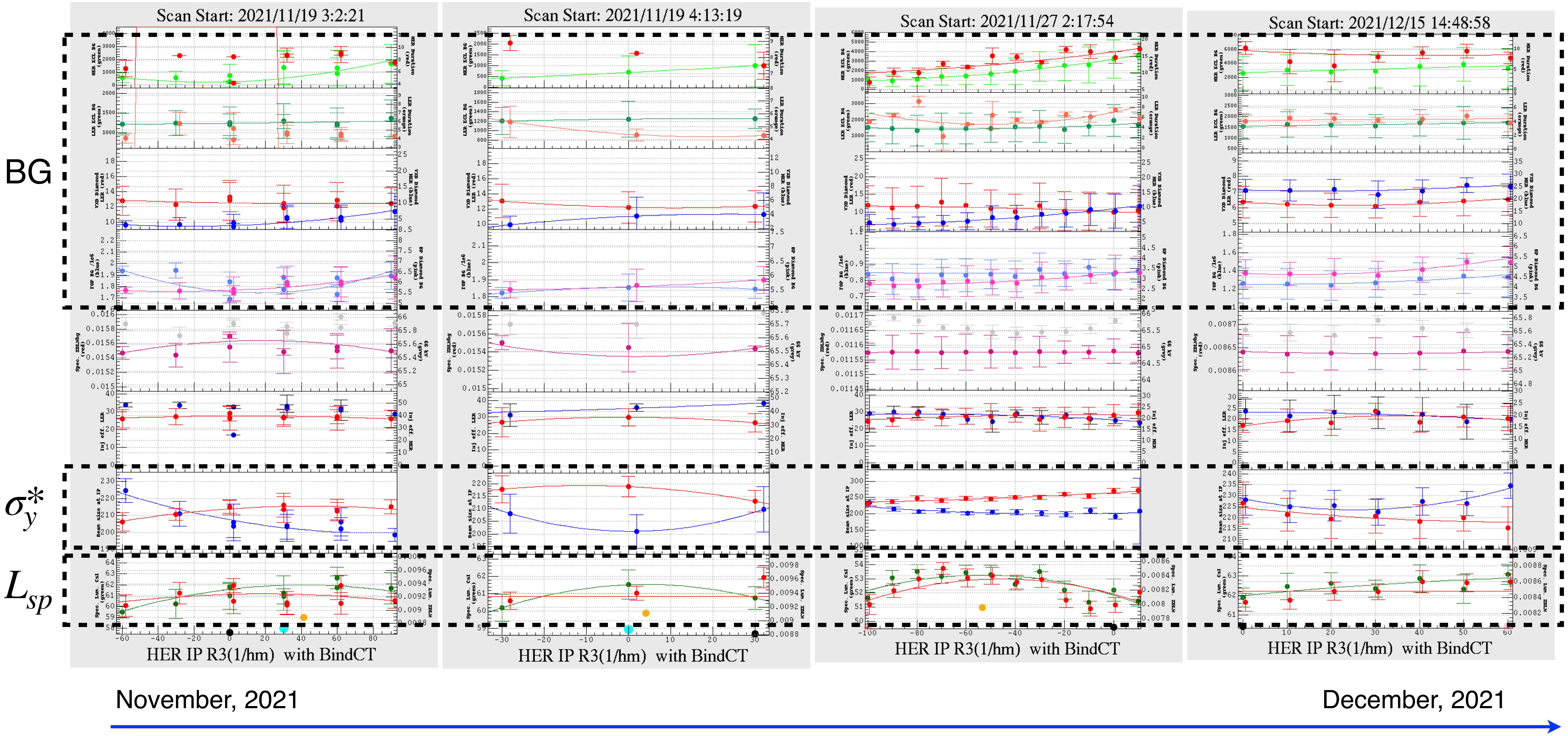
Updates on beam-beam simulations

- IP R3 scan
  - Knobs with beam showed luminosity is not sensitive to IP R3 in the range of (-1,1) m^{-1}.
  - Belle2 background was sensitive to IP R3 knobs.
  - Correlation of σ_y^* vs. R_3^*(LER) looked to be stable during 2021c run.



Updates on beam-beam simulations

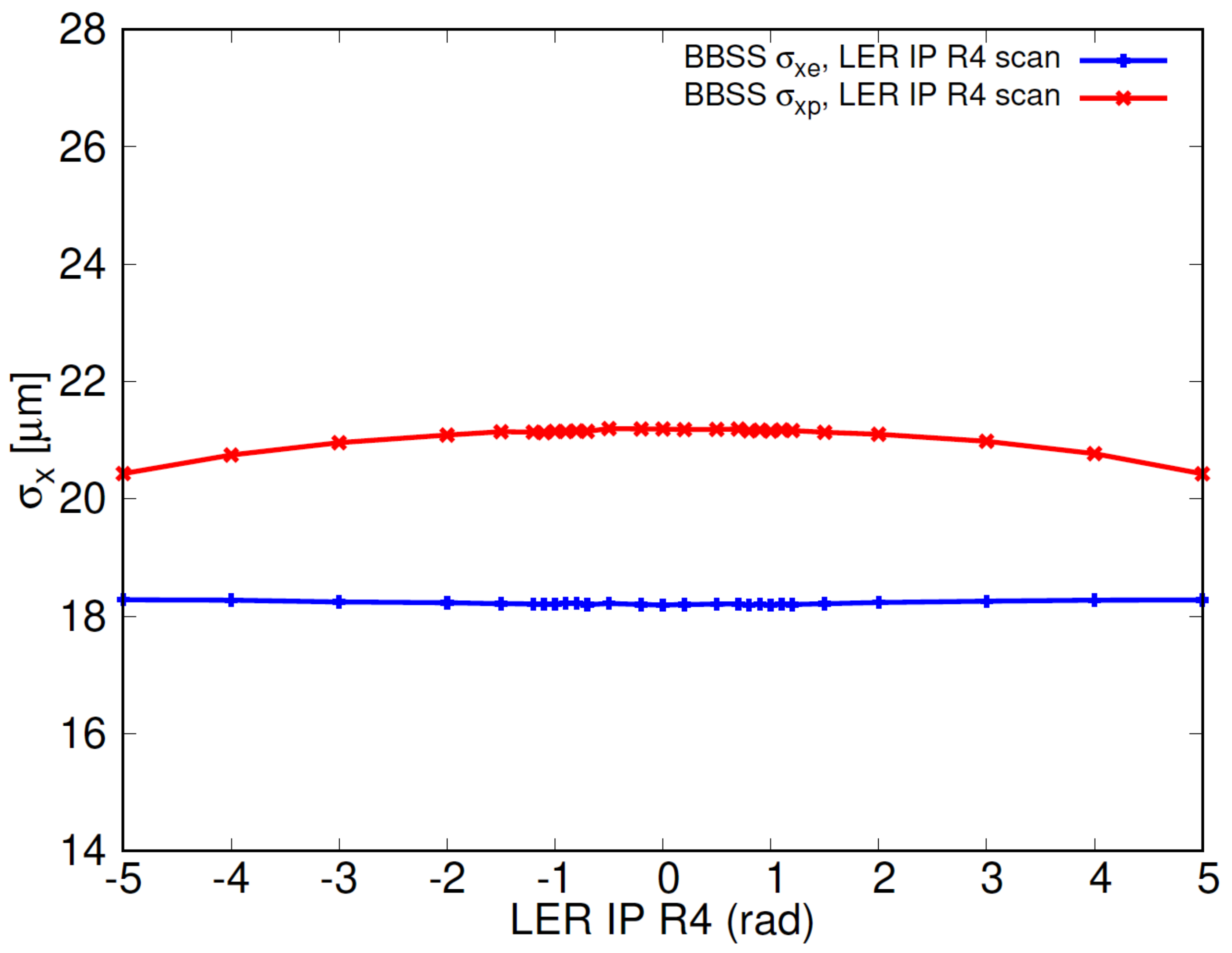
- IP R3 scan
  - Knobs with beam showed luminosity is not sensitive to IP R3 in the range of (-1,1) m^{-1}.
  - Belle2 background was sensitive to IP R3 knobs.
  - Correlation of σ_y^* vs. R_3^*(HER) looked to be complicated during 2021c run.

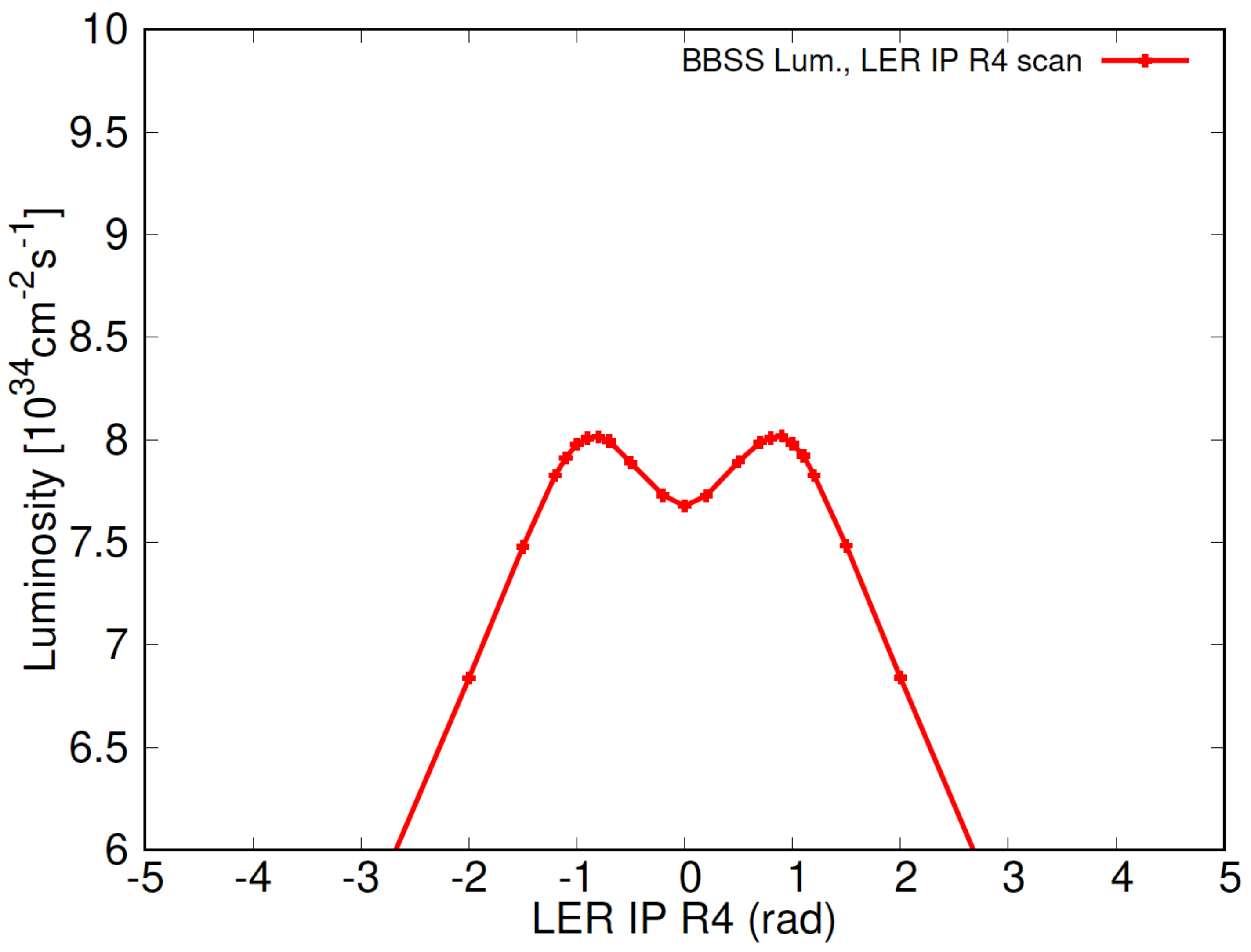


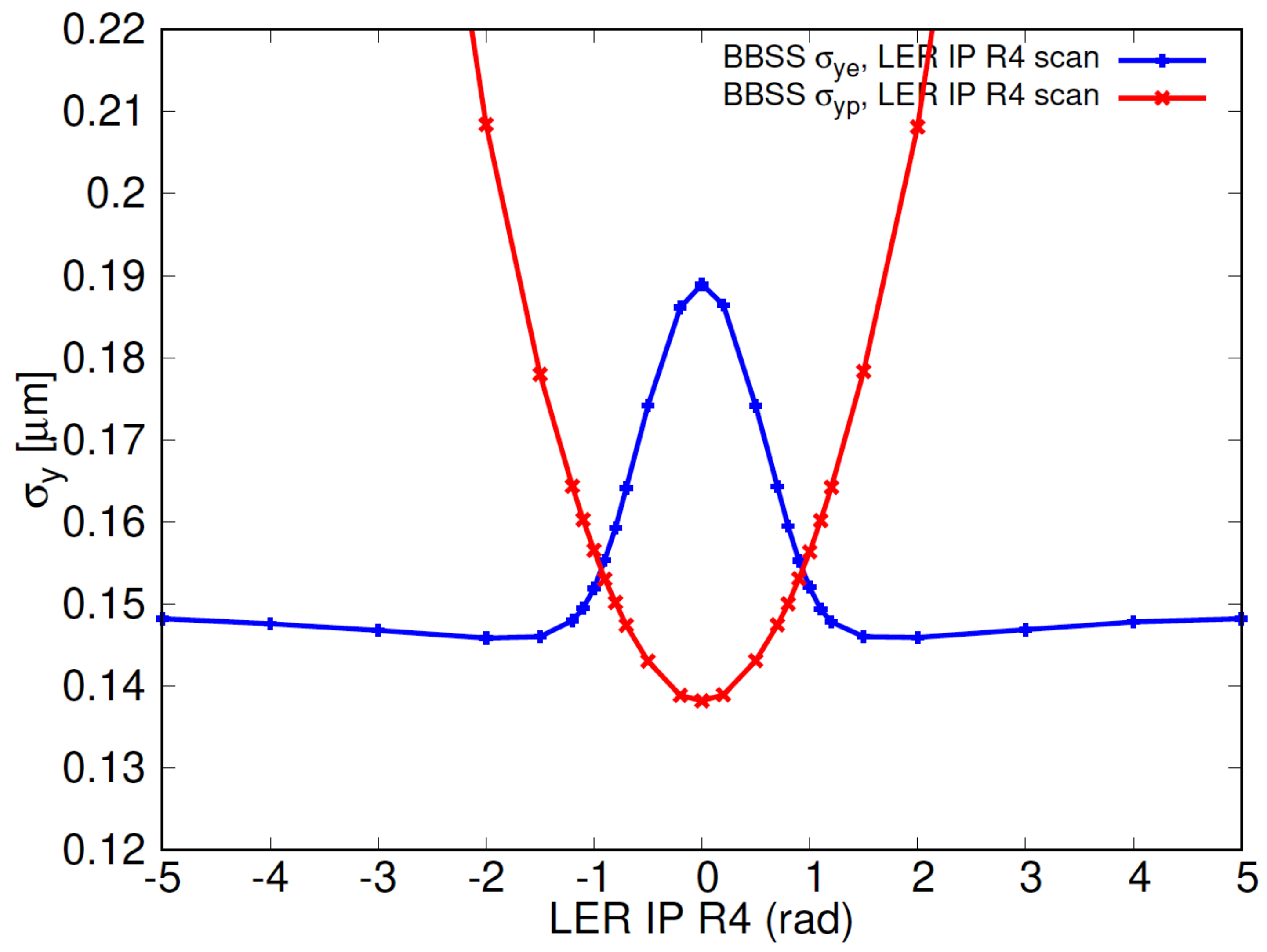
Updates on beam-beam simulations

- IP R4 scan
  - Simulations were done using simple one-turn matrix.
  - In this scan, nonzero LER IP R4 can increase luminosity (Double peaks in the luminosity scan). This is because HER σ_y^* shrinks due to weak beam-beam force.
  - HER σ_y^* blowup at LER IP R4=0 is mainly due to insufficient crab waist strength in HER (40%).
  - The sensitivity of LER σ_y^* against R4 is scaled by ϵ_x/β_x^* with $\beta_x^* \ll 1$ m.

$$\sigma_y^{*2} = \mu^2\epsilon_y\left(\beta_y^* + \frac{\Delta s^2}{\beta_y^*}\right) + \left(\eta_y^*\sigma_\delta\right)^2 + \epsilon_x\frac{\left(R_2^* + R_4^*\Delta s\right)^2}{\beta_x^*} + \epsilon_x\beta_x^*\left(R_1^* + R_3^*\Delta s\right)^2$$

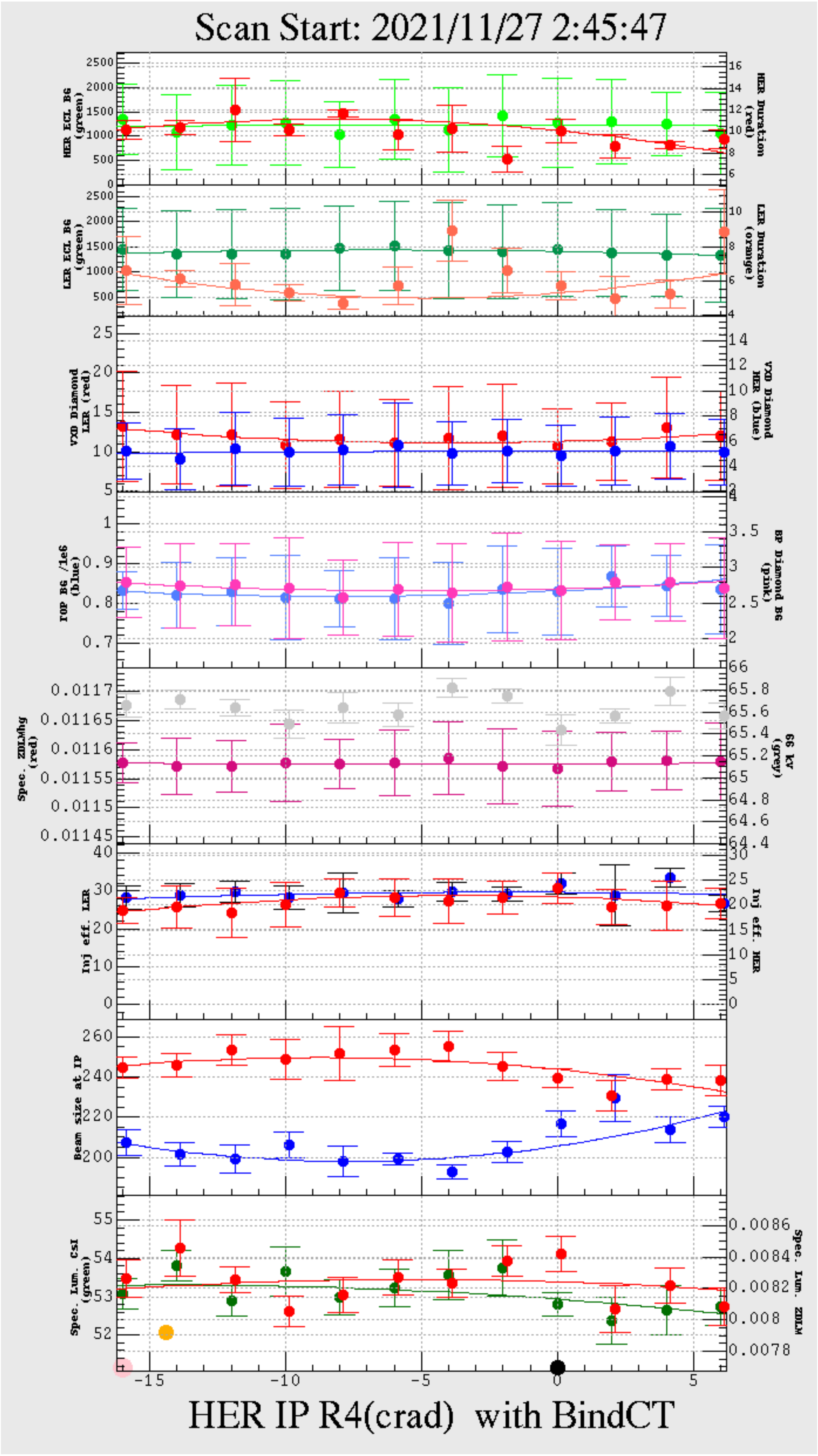






Updates on beam-beam simulations

- IP R4 scan
  - Only one IP R4 scan during 2021c run (from SKB log system)



Updates on beam-beam simulations

- BBSS simulations: Scan LER ν_x (with LER ν_y and HER $\nu_{x,y}$ are fixed, same as the parameter table of 2021.12.21)

	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	
# bunch	393		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	20	35	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured tune of pilot bunch
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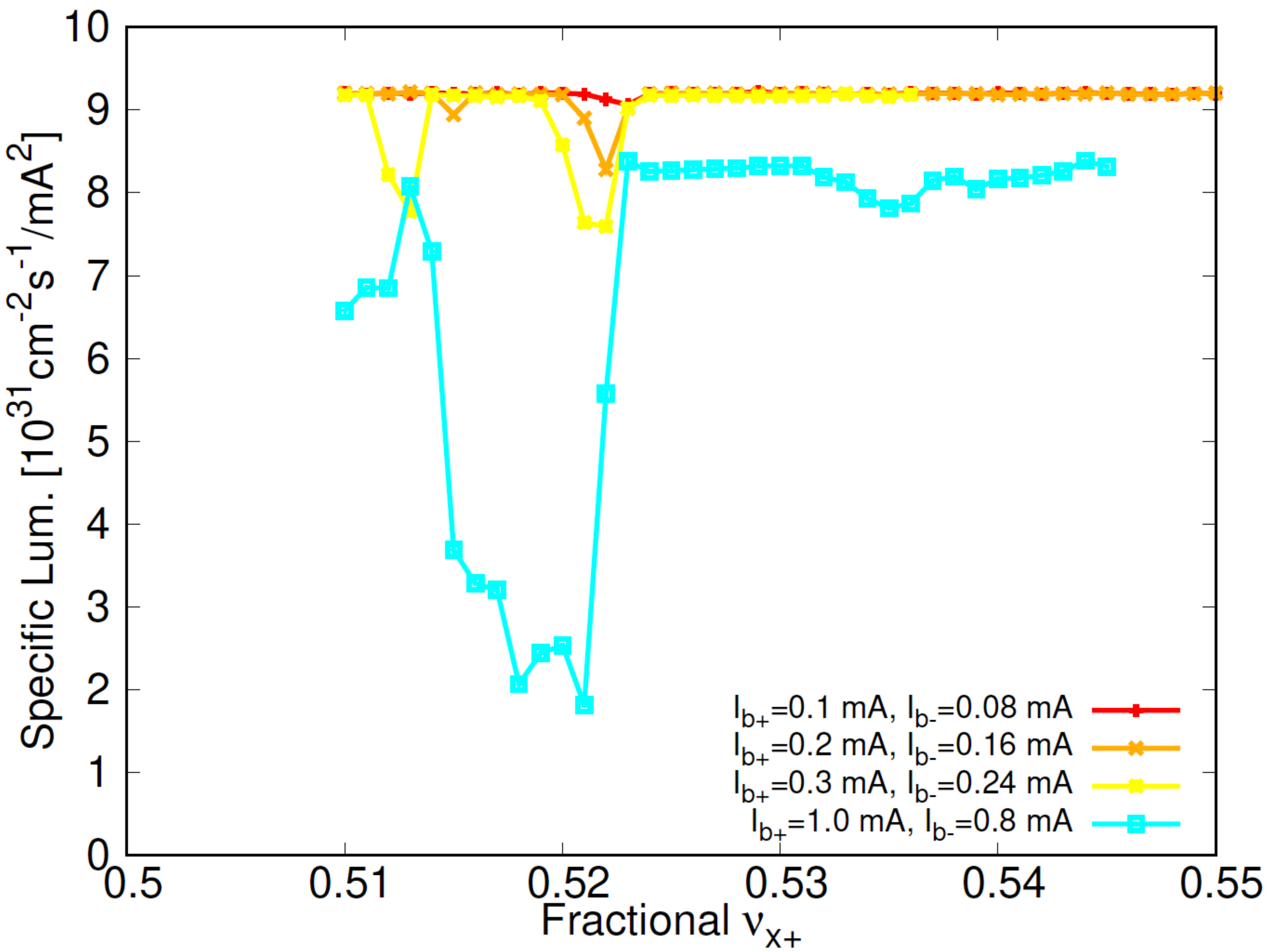
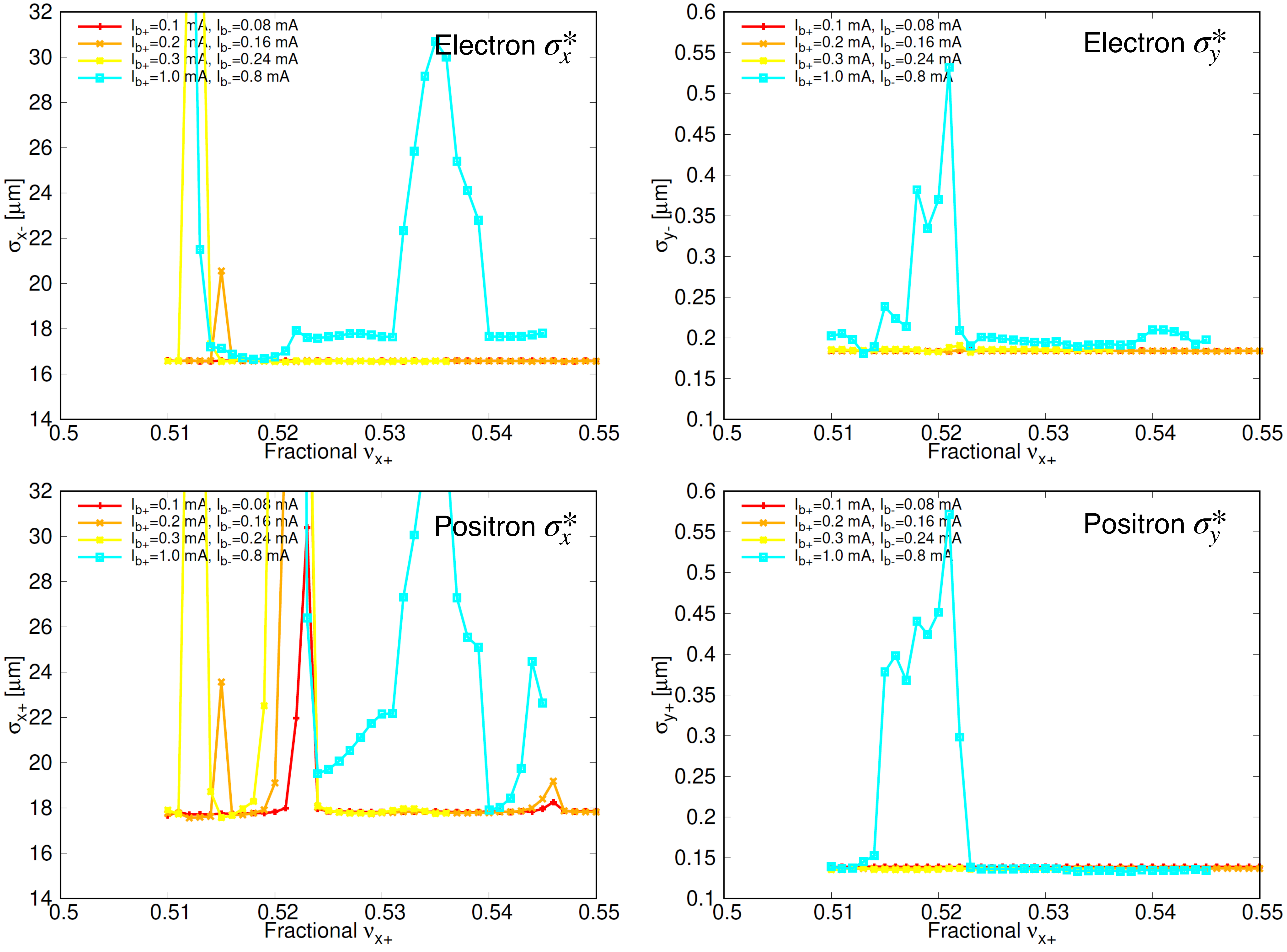


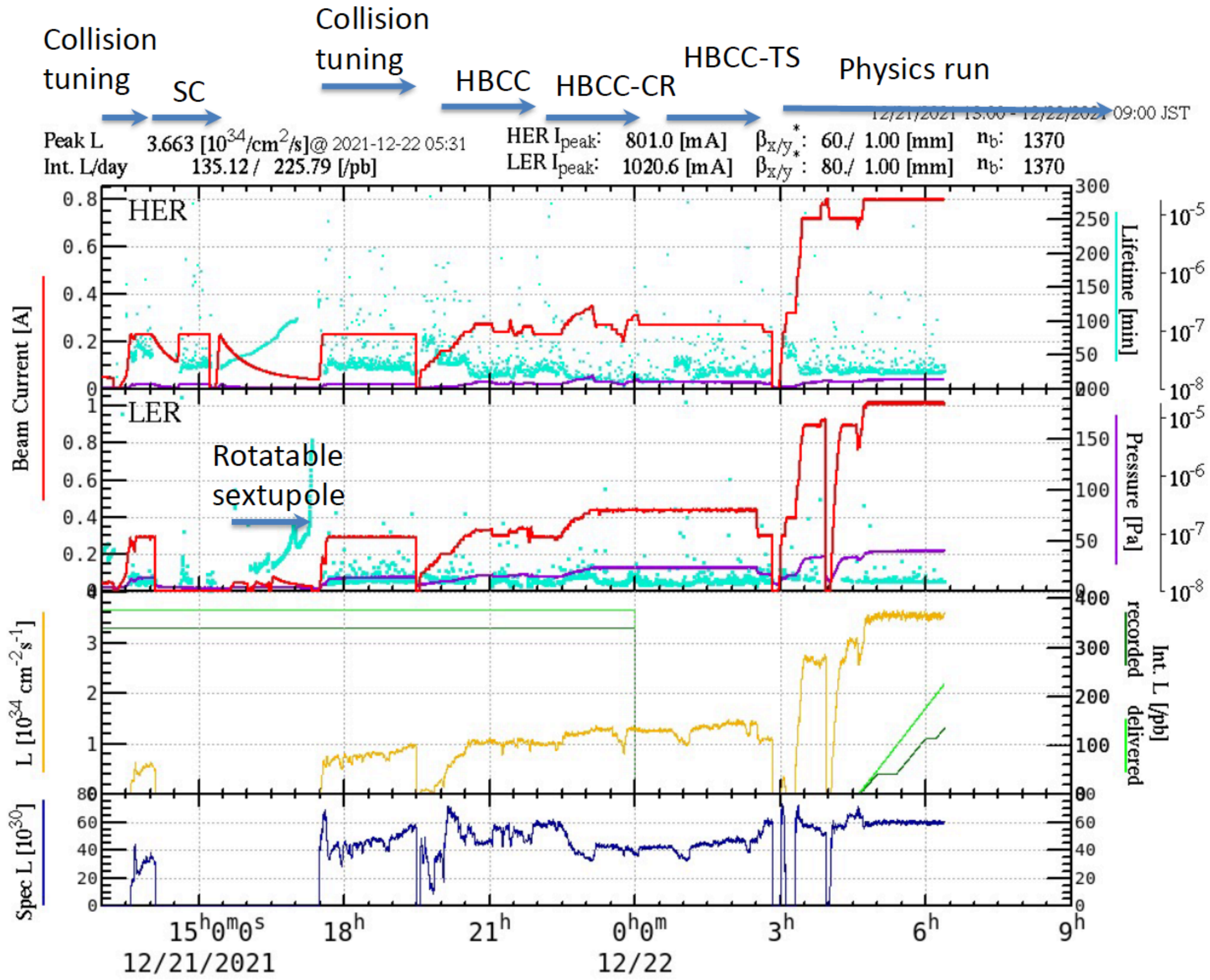
Updates on beam-beam simulations

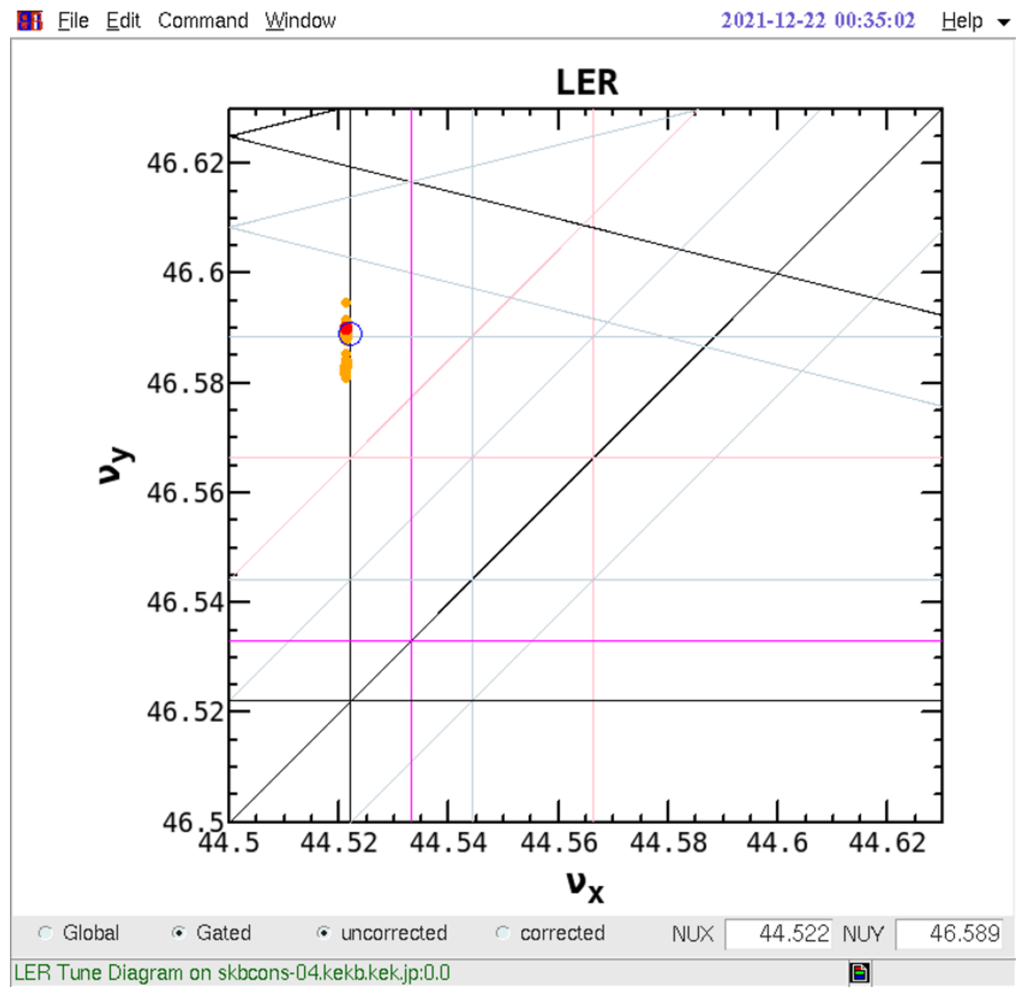
- BBSS simulations: Scan LER ν_x (with LER ν_y and HER $\nu_{x,y}$ are fixed, same as the parameter table
  - Responses of LER and HER beam sizes to LER ν_x are complicated



Beam-beam machine study

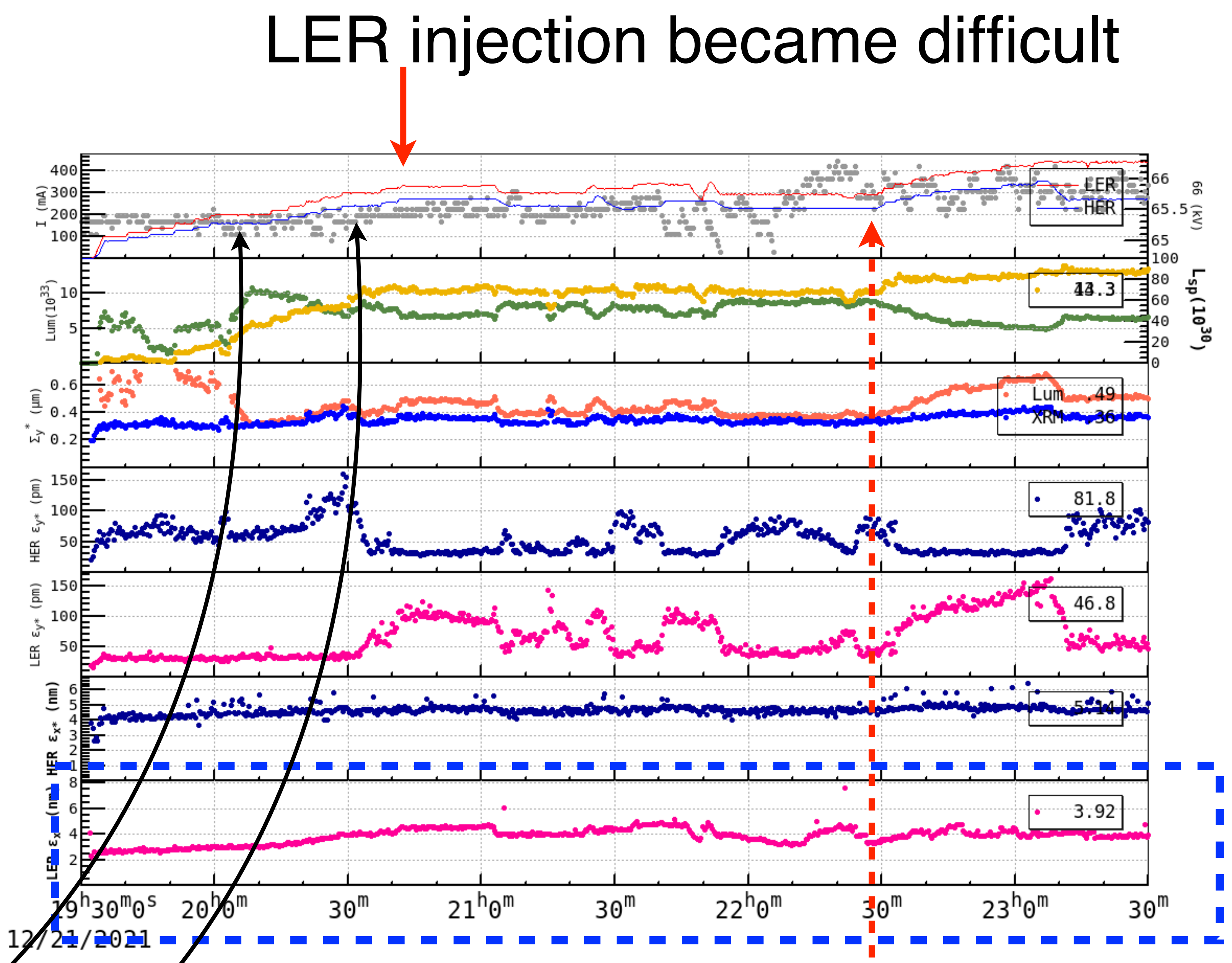
- Dec. 21-22, 2021: Beam-beam study overview
  - The beam-beam machine study was very successful with several important findings.
  - LER horizontal ϵ_x blowup was verified: It is driven by beam-beam and sensitive to LER ν_x. It is not simply coherent BBHTI. It can be a phenomenon of beam-beam driven synchro-betatron resonance with inclusion of longitudinal impedance effect.
  - Operating LER on top of and even left side of $\nu_x - \nu_{s0} = N/2$ (here ν_x is measured gated tune of pilot bunch, ν_{s0} is the nominal synchrotron tune): LER ϵ_x blowup can be relaxed and LER injection efficiency can be improved.
  - Optimization of working point (with chromatic coupling correction in LER) helped achieve a balanced collision and contributed to new luminosity record.

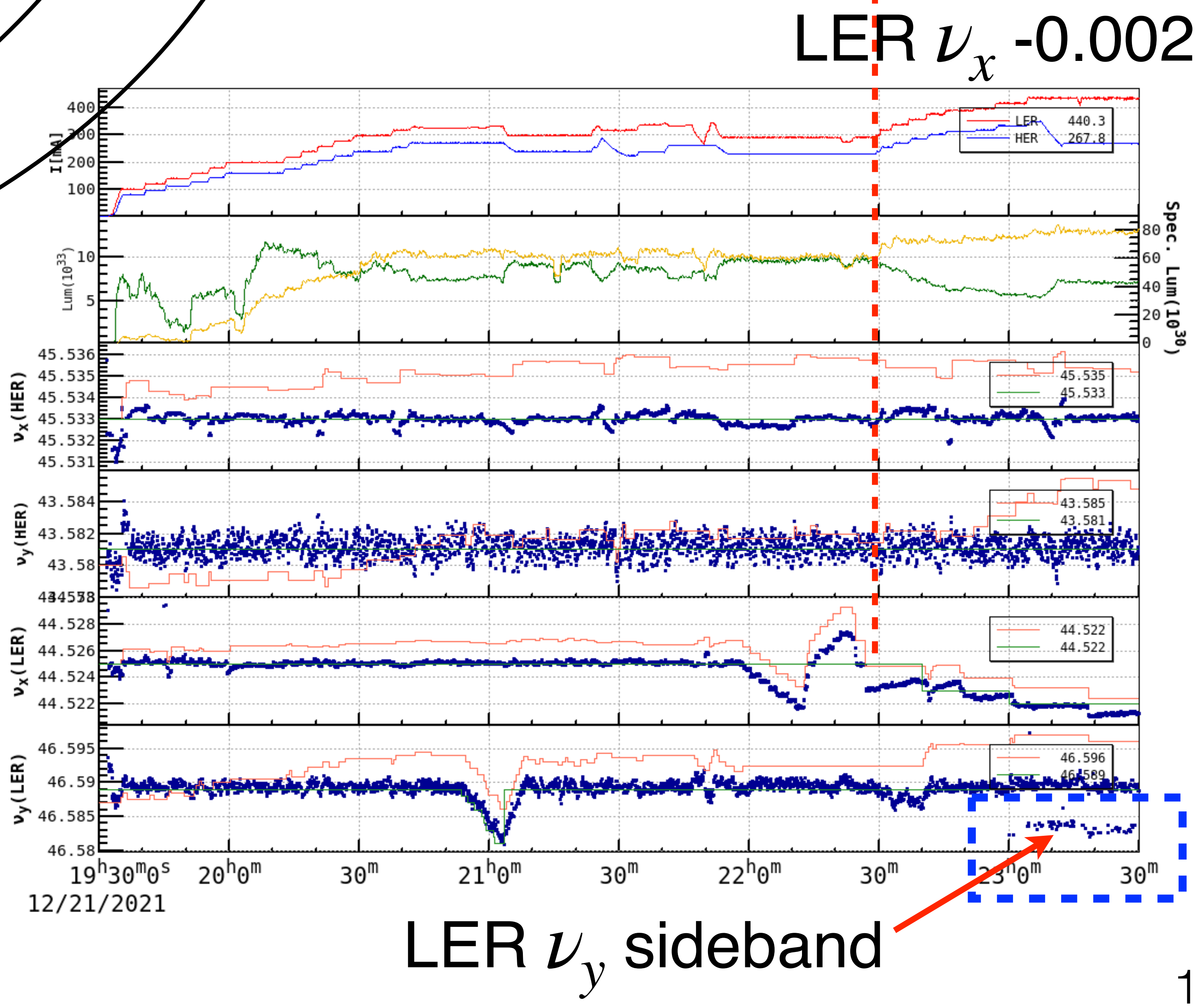


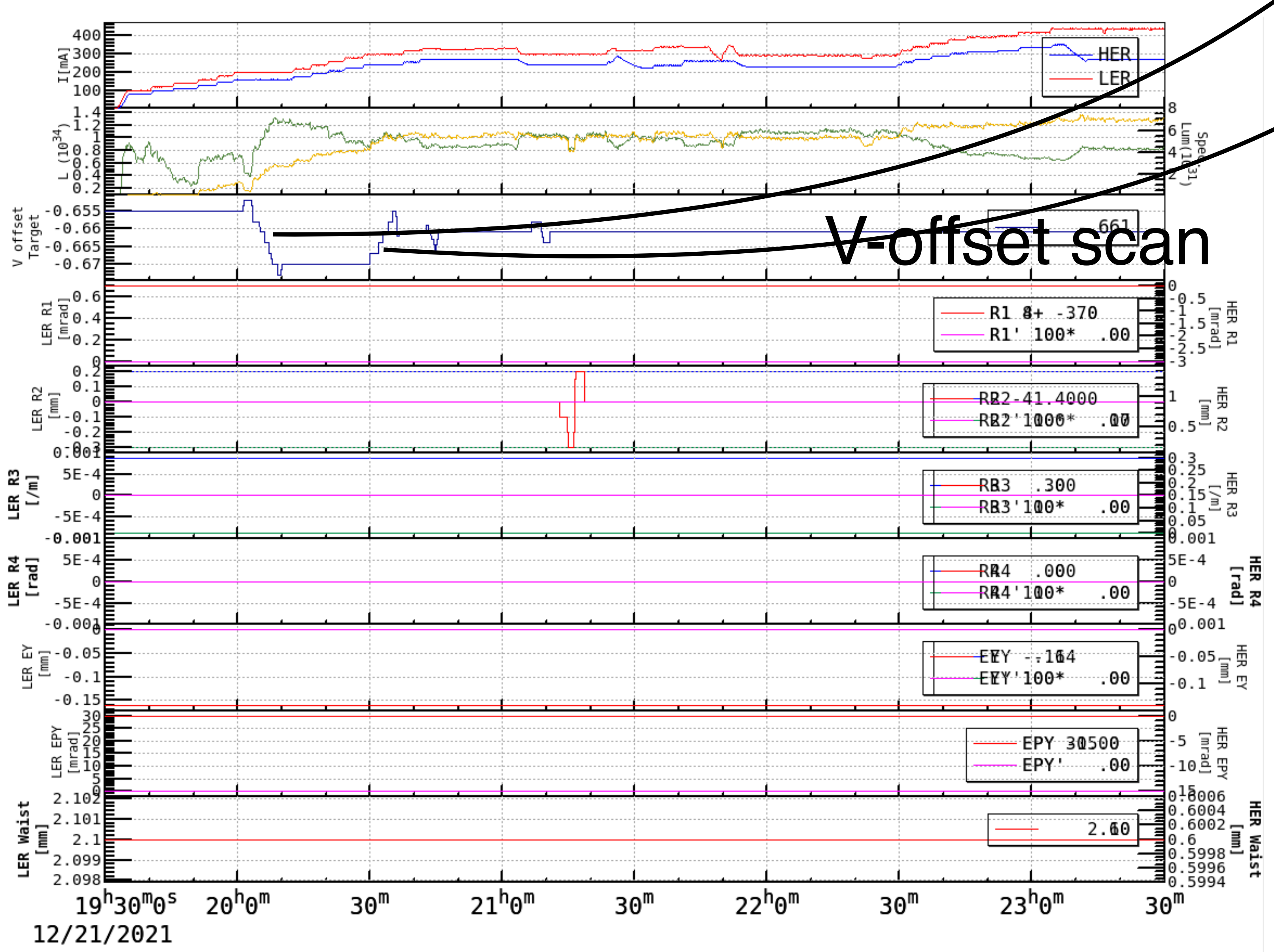


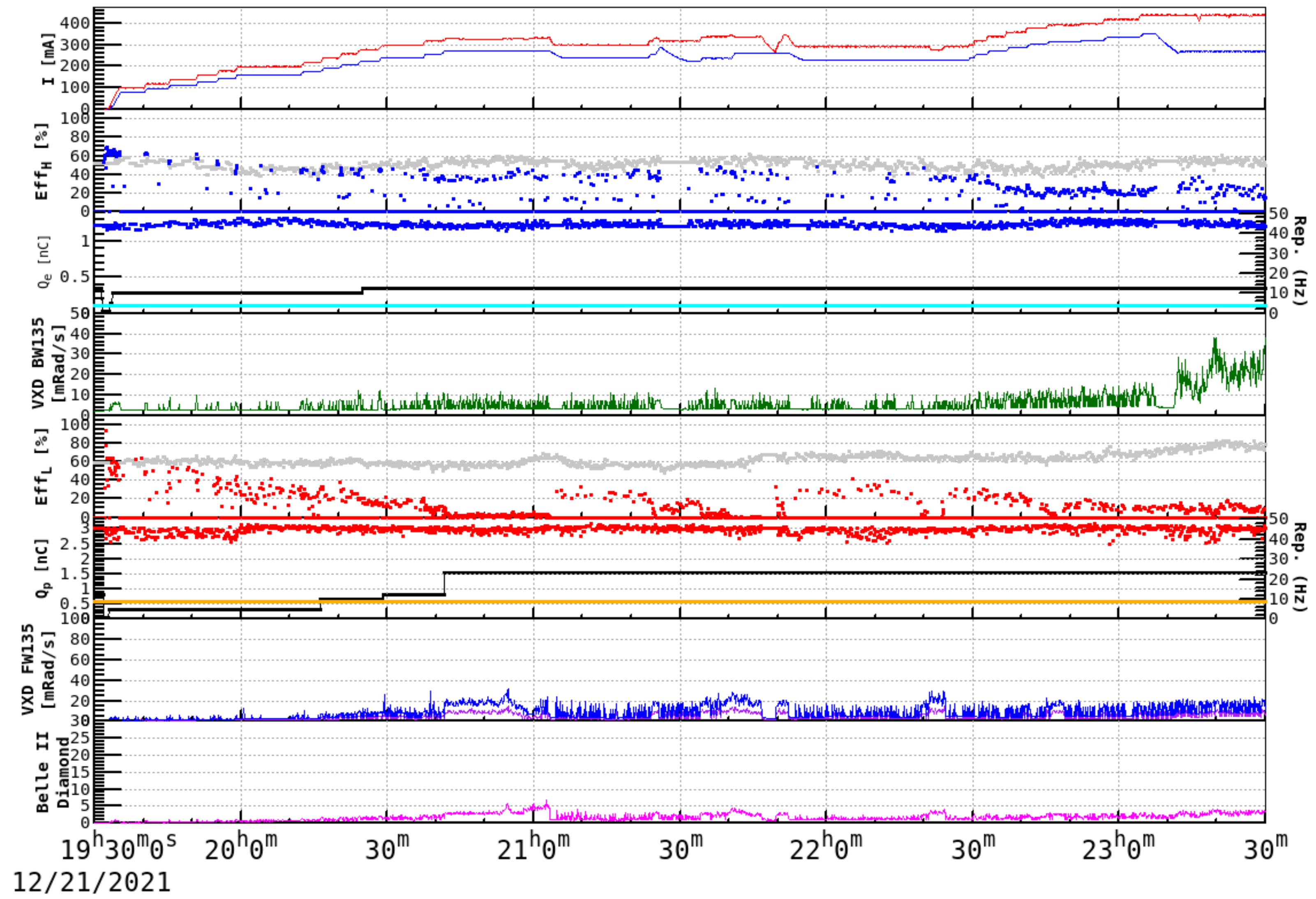
Beam-beam machine study

- Dec. 21-22, 2021: HBCC study
  - HBCC study was done after other machine studies: collision tunings were necessary, especially large change of HOFFSET and V-offset.
  - LER injection efficiency became very poor when I_{+}>340 mA (393 bunches in total). Setting LER ν_x by -0.002 improved LER injection. HBCC study finished at $I_{+}/I_{-} = 440/352$ mA with LER ν_x set by -0.003.
  - LER ϵ_x blowup was relaxed when reducing ν_x.
  - When I_{+}>400 mA ($I_{b+} \geq 1$ mA), strong ν_y sideband was observed. This was consistent with observations of TMCI machine study.

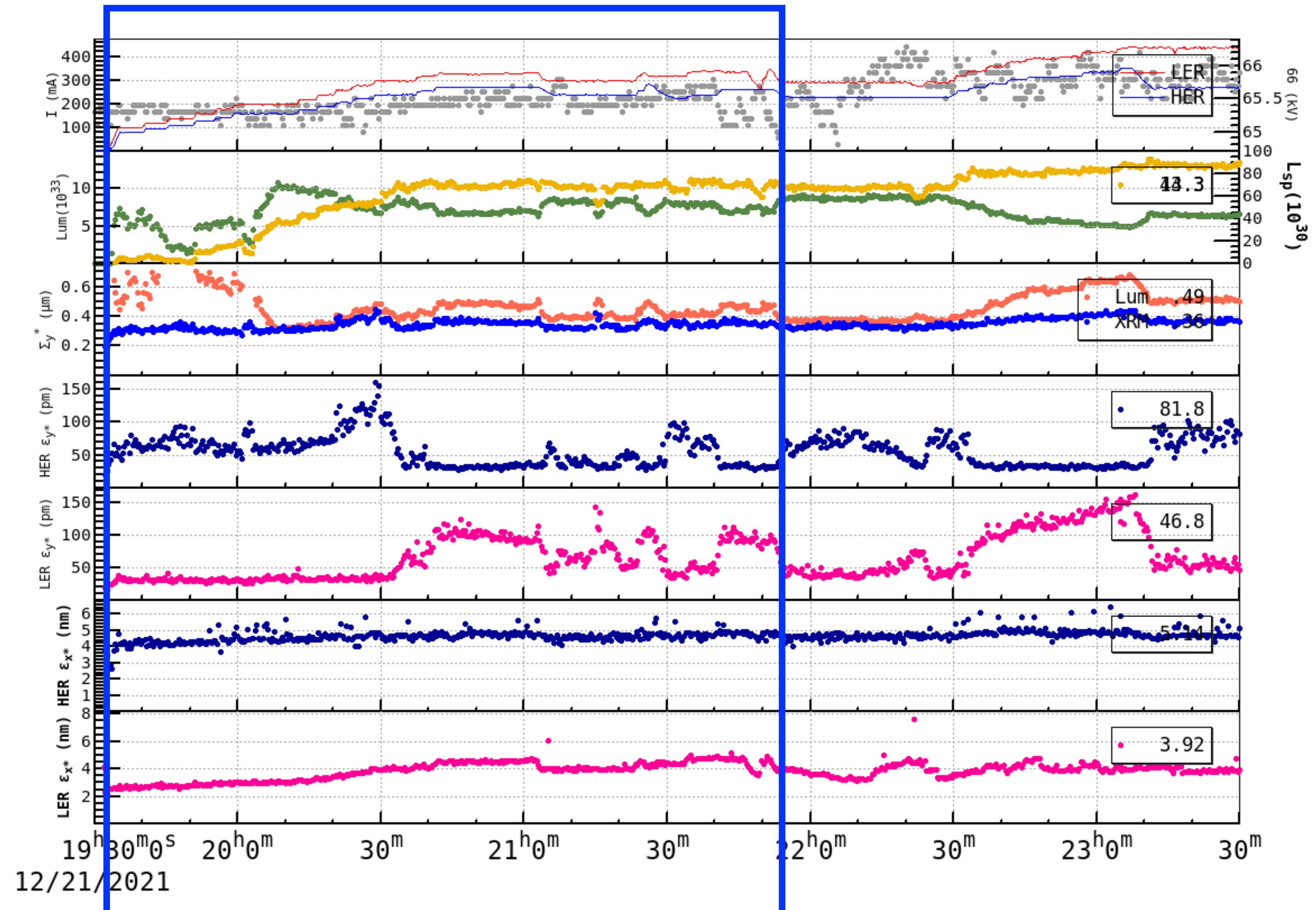


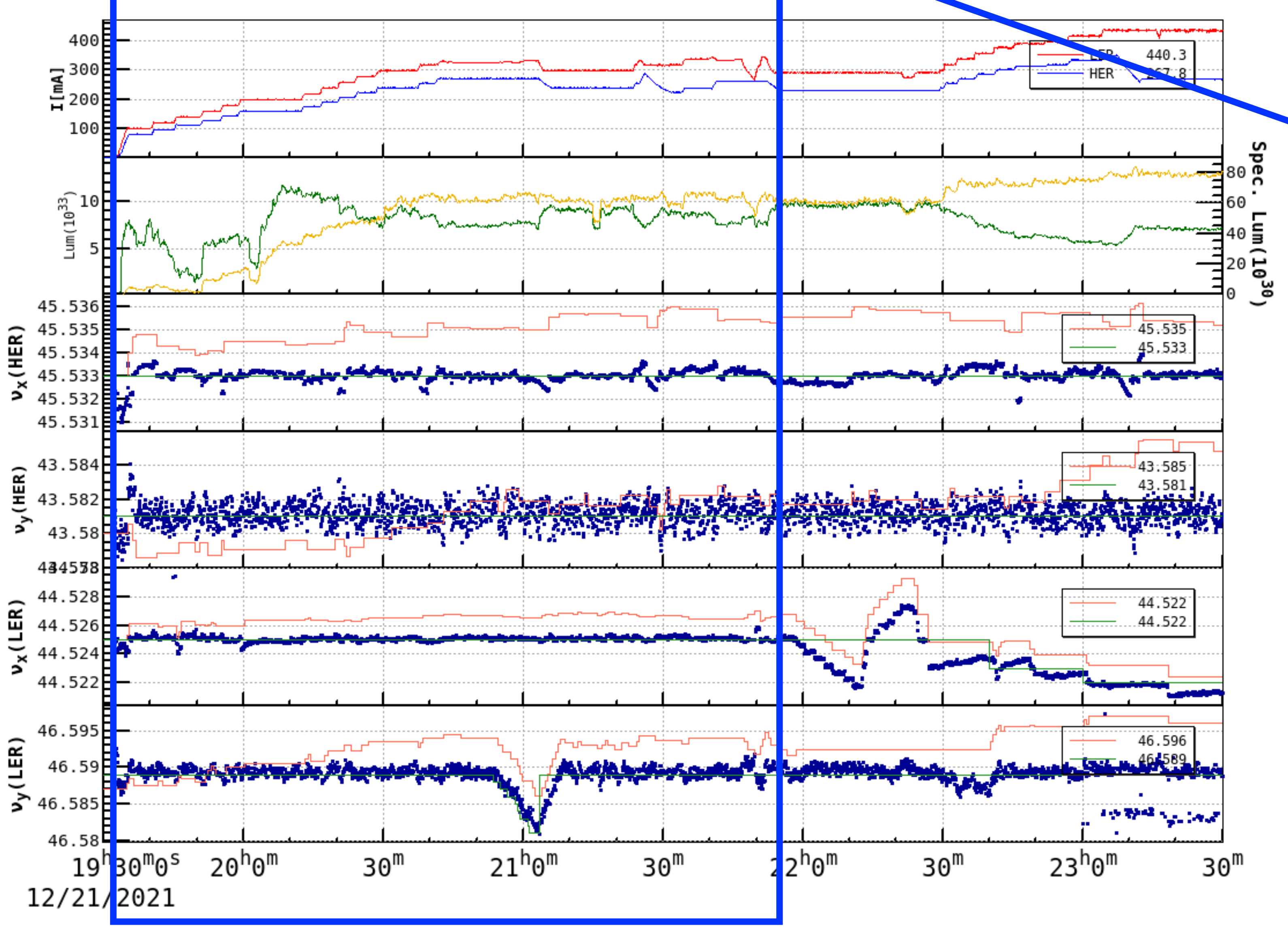




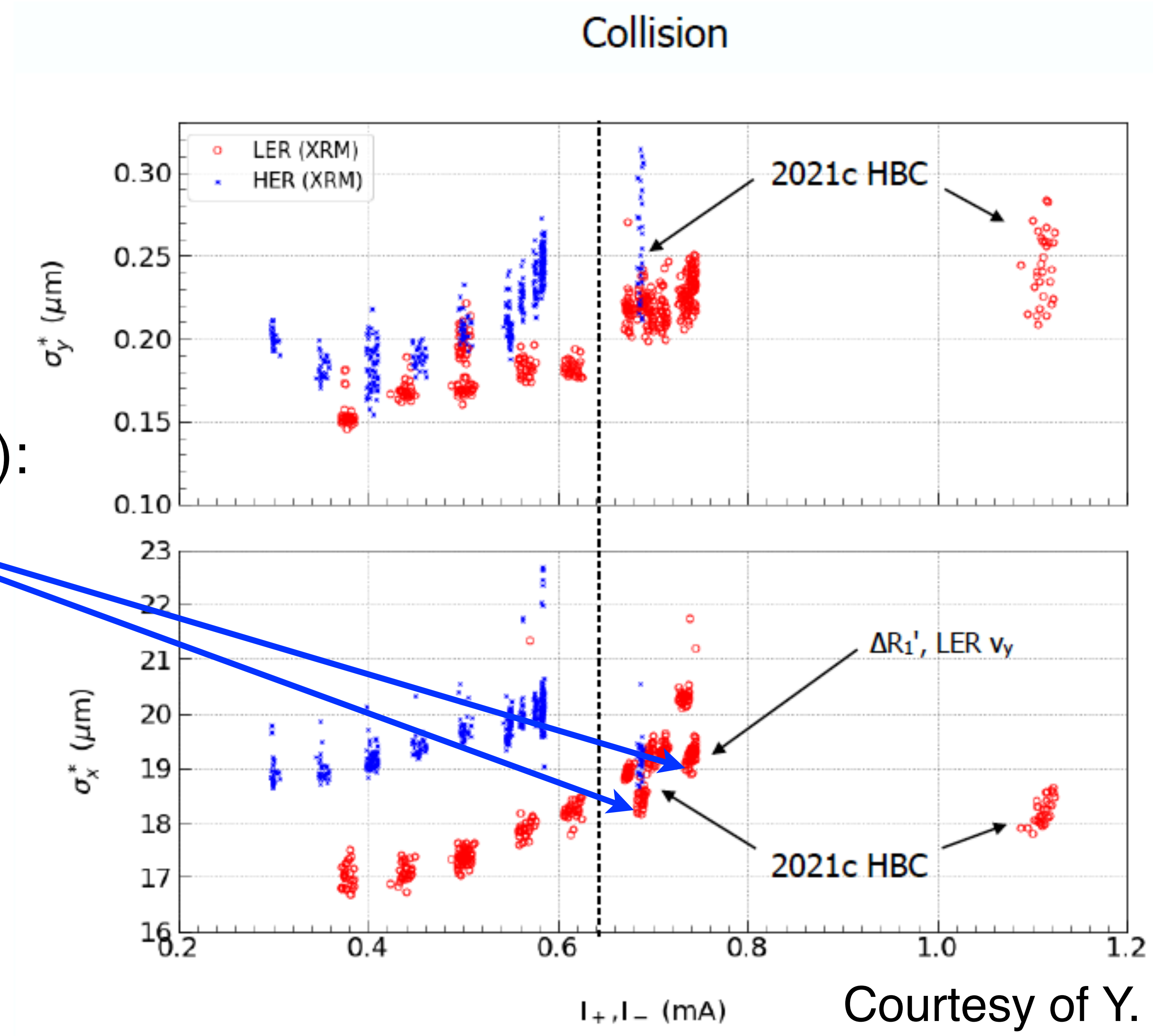


Beam-beam machine study



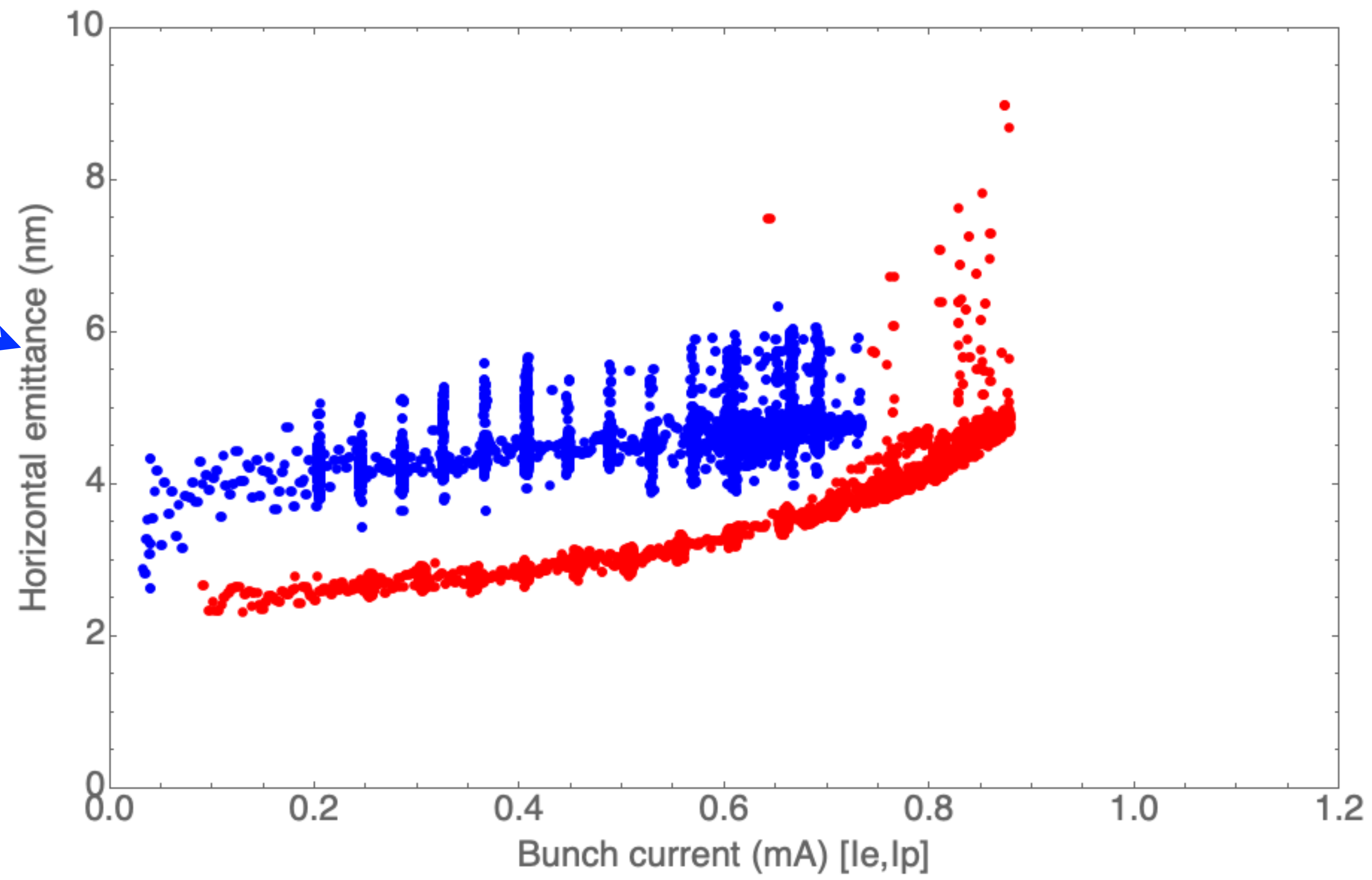


Physics run
(Dec. 22 and Dec. 23, 2021):
LER $\Delta\nu_x = -0.001$

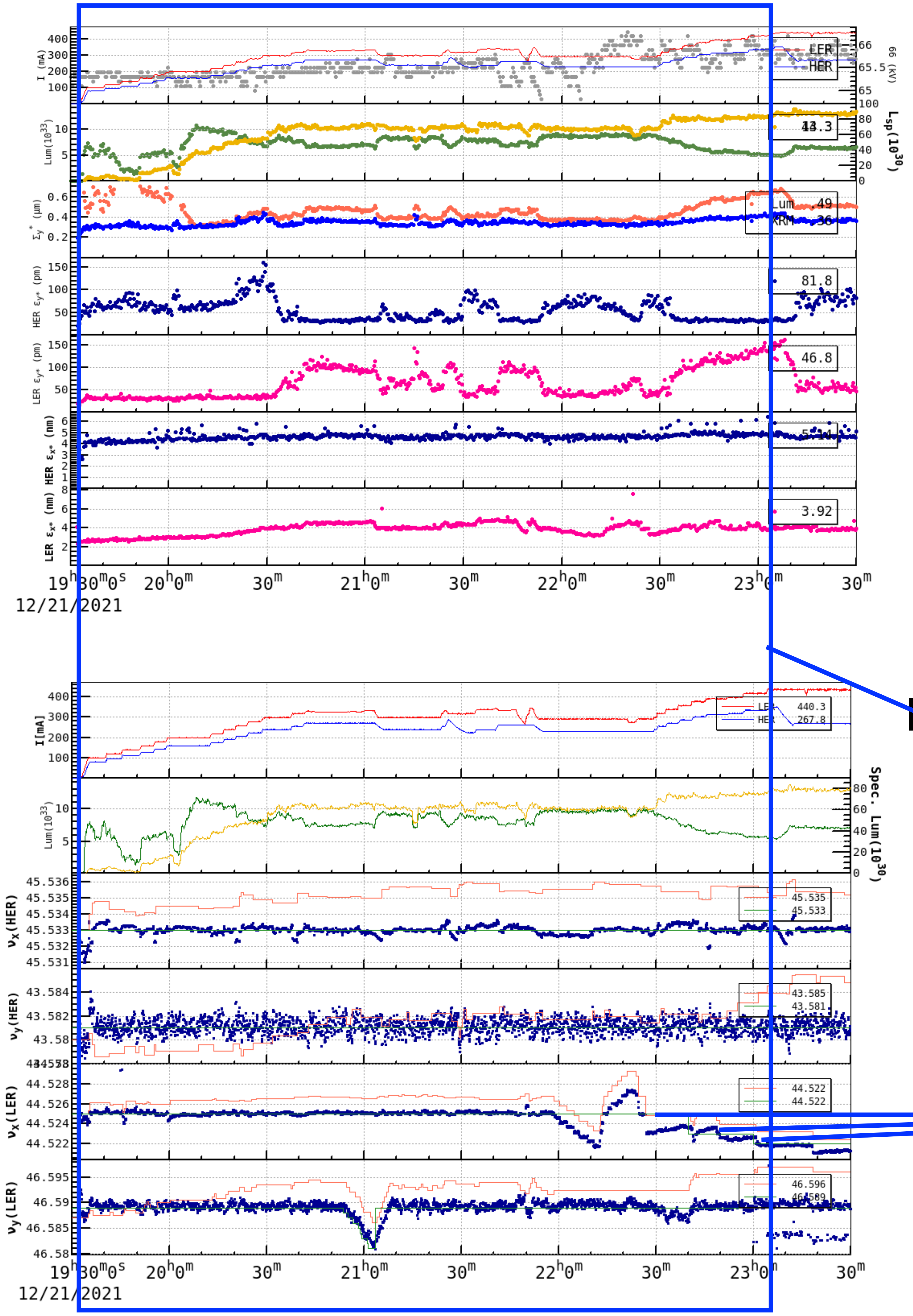


Courtesy of Y. Ohnishi

Data of 19:33 PM - 21:55 PM



Beam-beam machine study



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(Dec. 22 and Dec. 23, 2021):
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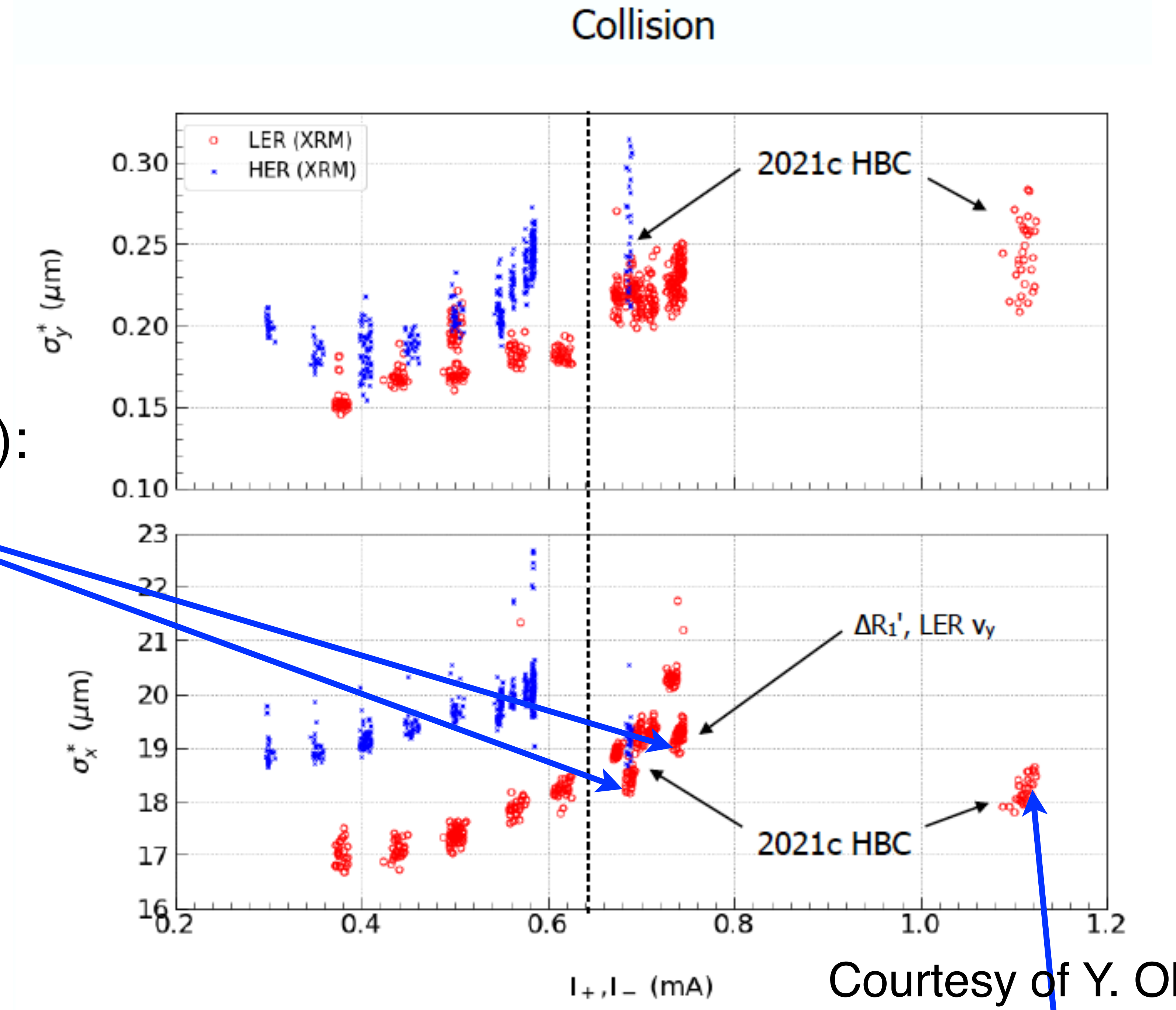
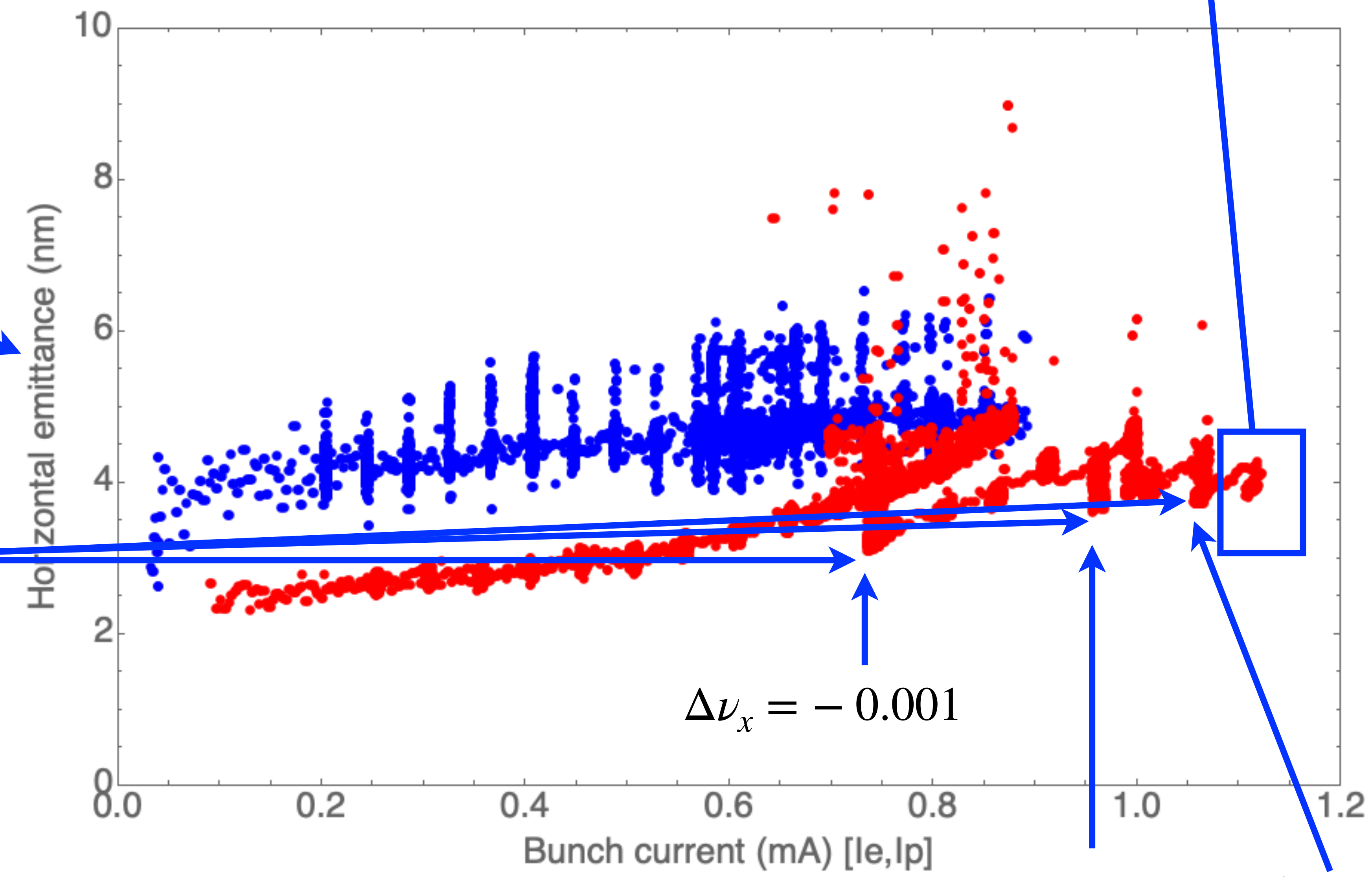


Courtesy of Y. Ohnishi

Data of 19:33 PM - 23:05 PM



$\Delta\nu_x = -0.001$

$\Delta\nu_x = -0.002$

$\Delta\nu_x = -0.003$

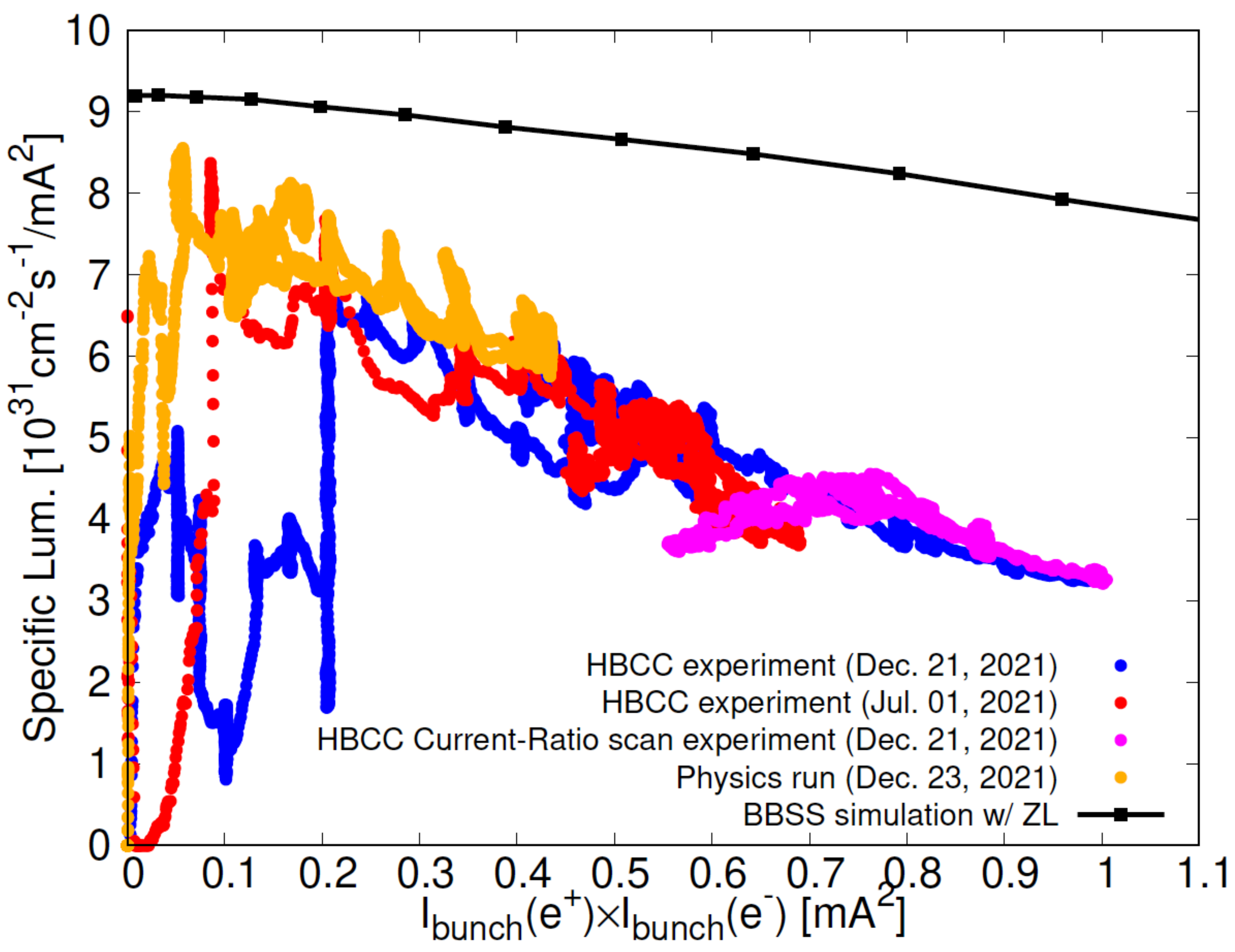
Beam-beam machine study

- Dec. 21-22, 2021: HBCC study
  - Compare HBCC study of Jul. 01 and Dec. 21: Specific luminosity is similar.
  - Current ratio scan showed better specific luminosity can be achieved.
  - With optimized working point and fine IP tuning knobs, slightly better luminosity performance can be achieved.
  - The discrepancy between simulated and observed luminosity became large when bunch currents increase.
  - Bunch lengthening is still an unclear factor. Efforts are ongoing to improve impedance model for simulations in order to reduce the discrepancy between simulations and measurements of bunch length and beam phase.

Operation parameter set for BBSS simulation

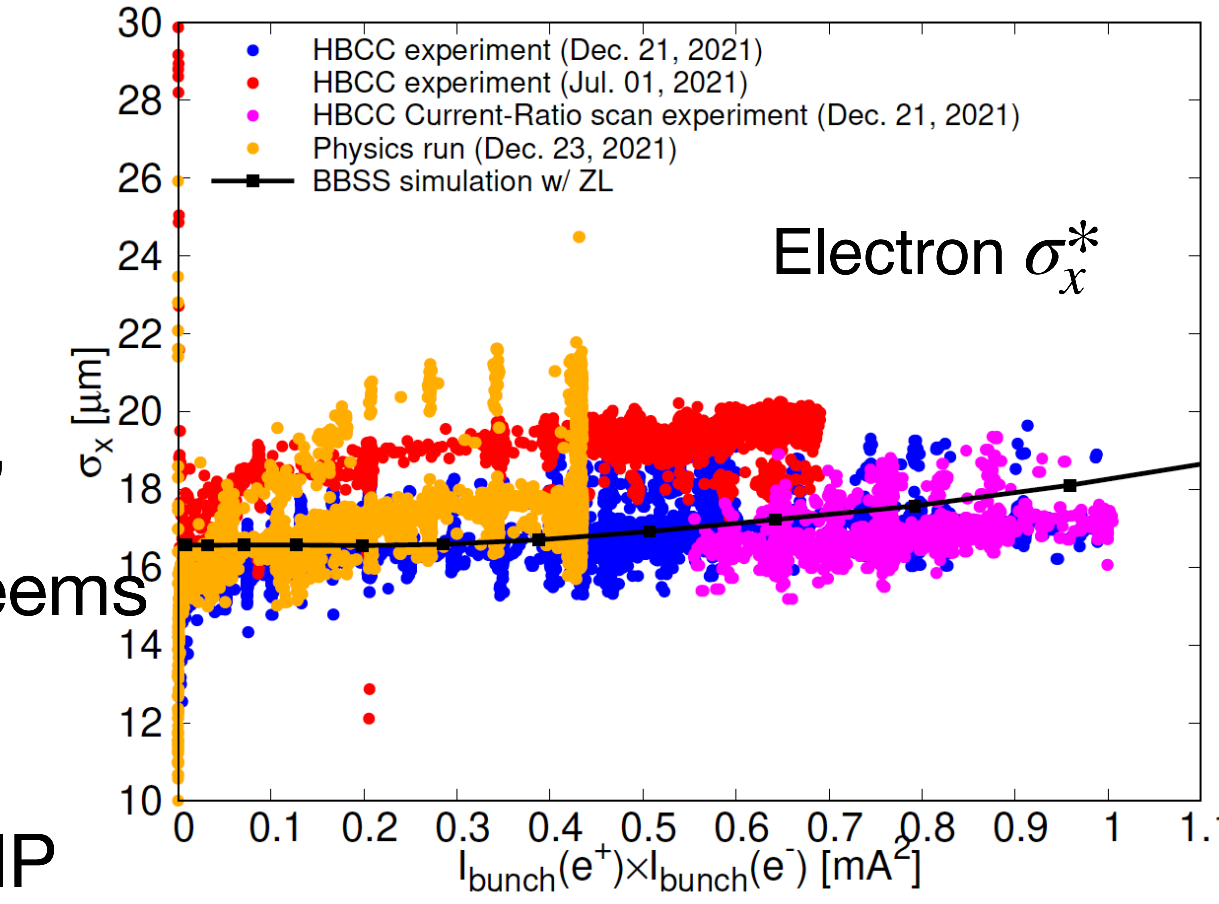
	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	
# bunch	393		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	20	35	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design

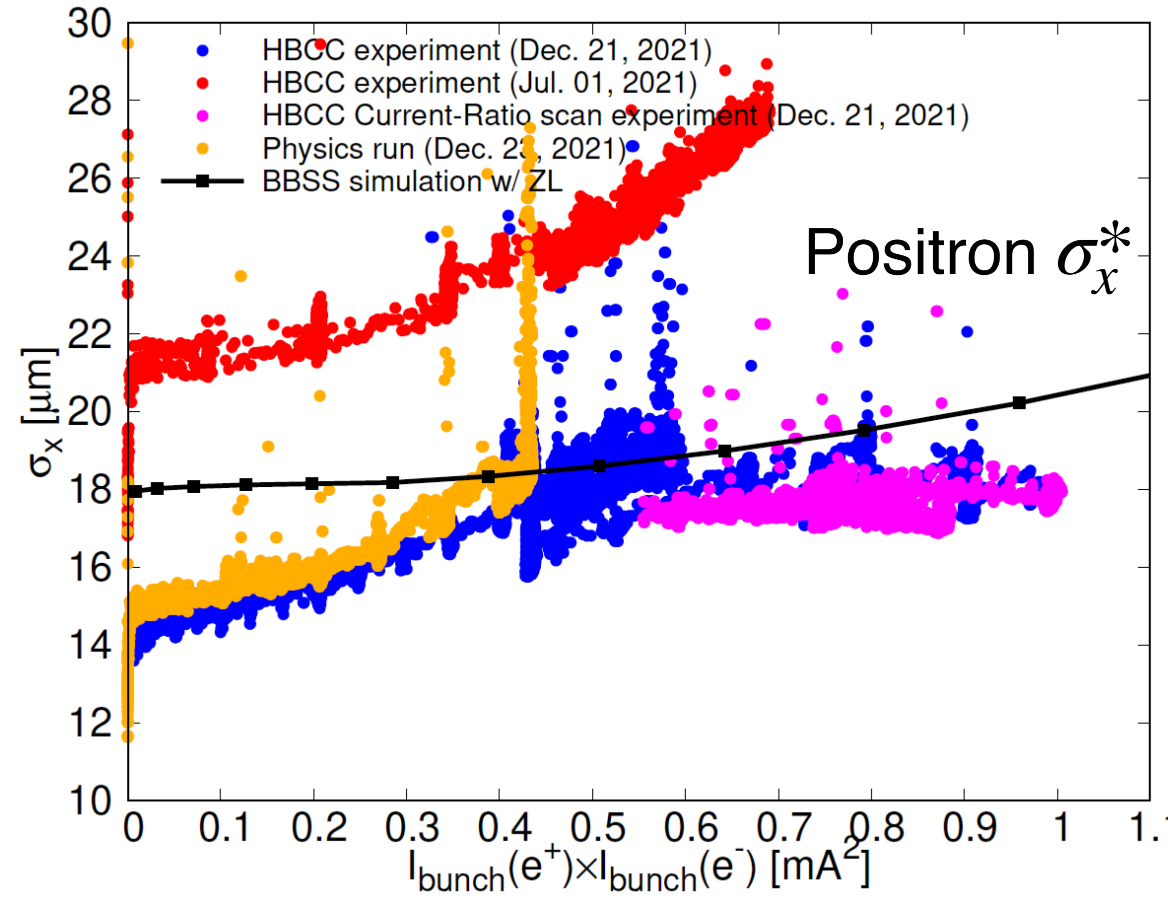
Lsp: BBSS simulations vs observation



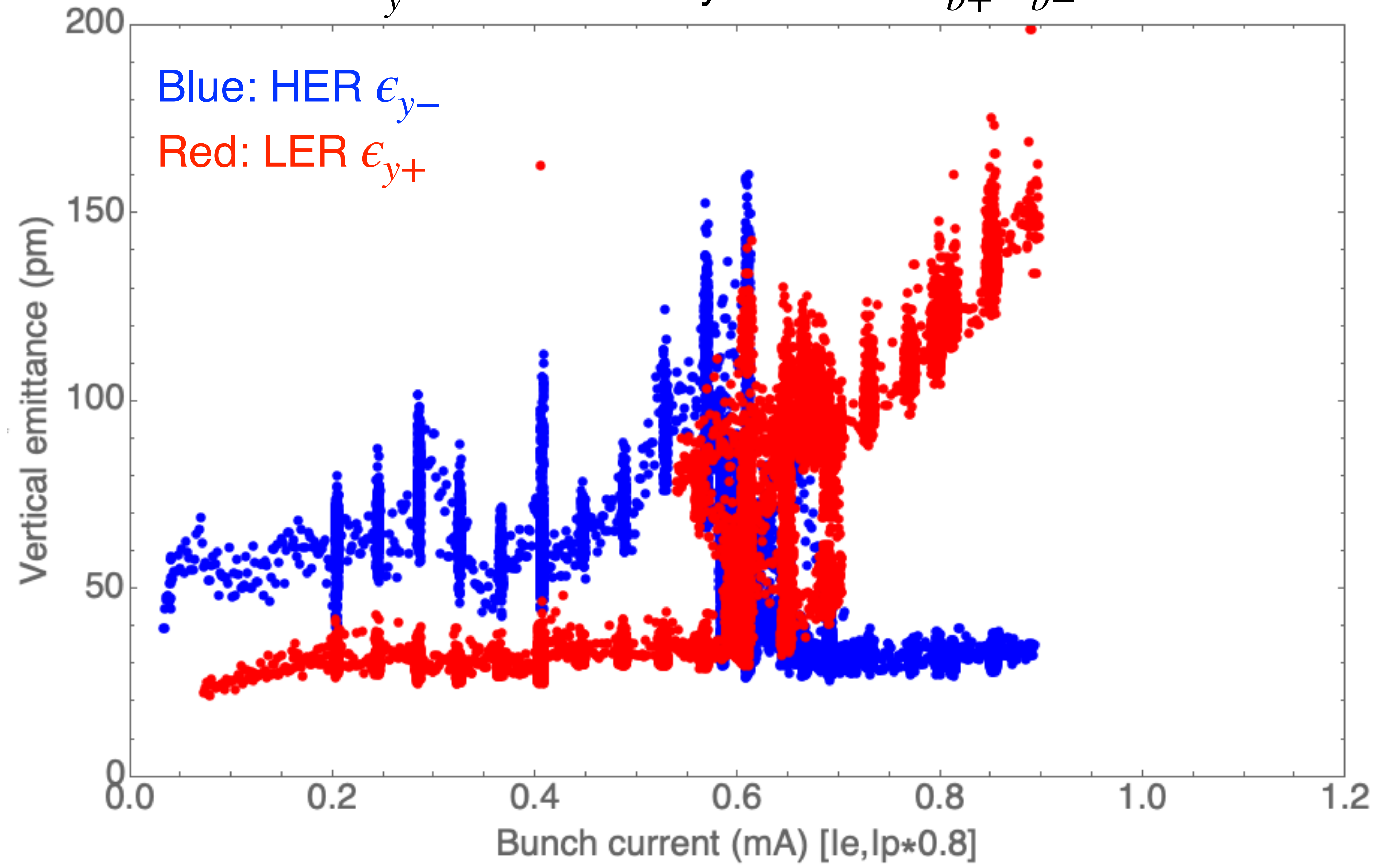
Beam-beam machine study

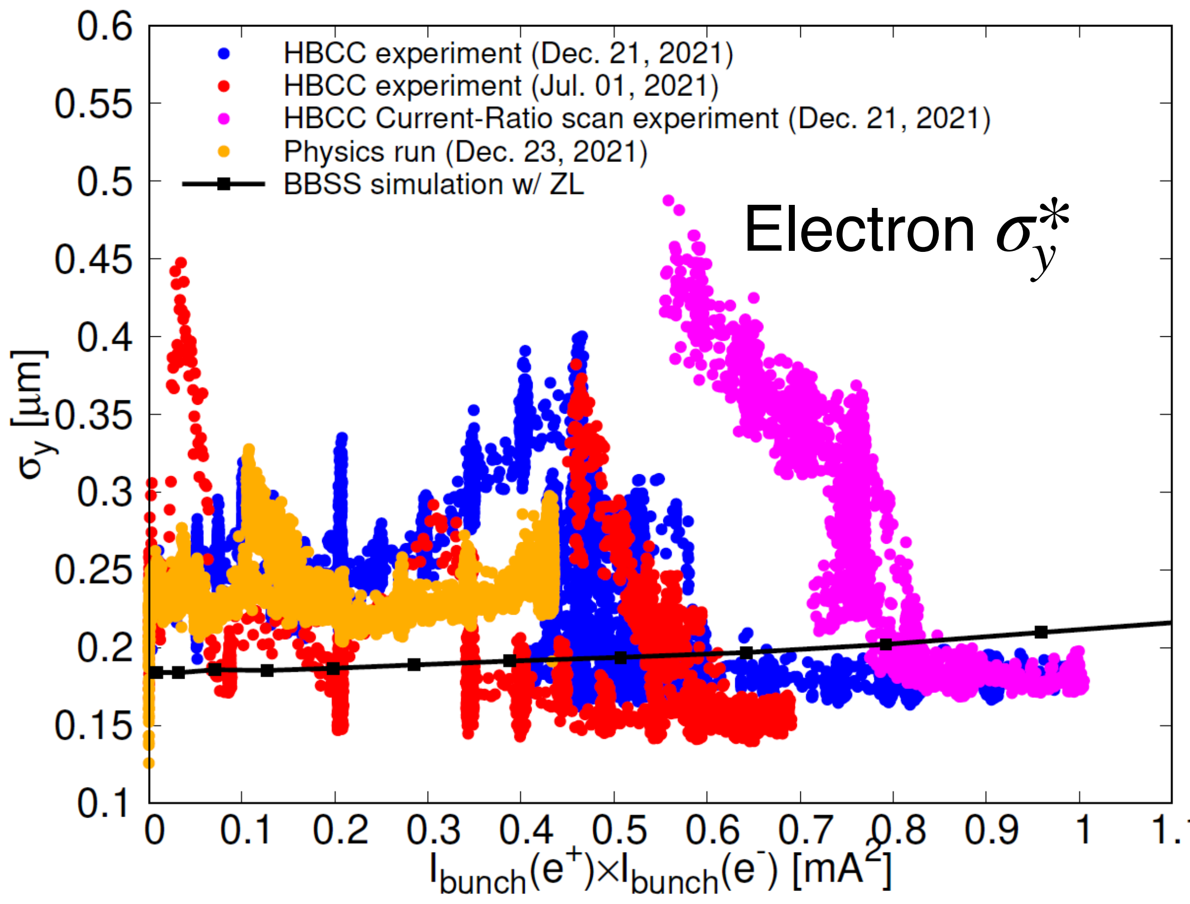
- Dec. 21-22, 2021: HBCC study
  - LER σ_x^* blowup was partially mitigated by reducing LER ν_x.
  - It was hard to achieve balanced collision ($\sigma_{y+}^* \approx \sigma_{y-}^*$) when $I_{b+}I_{b-} > 0.45$ mA².
  - When bunch current ratio is fixed with I_{b+}/I_{b-}=1.25, a "flip-flop" phenomenon appeared: At lower bunch currents, HER beam seems to be weaker; At higher bunch currents, LER beam is weaker (blowup due to head-tail instability? See Ohmi-san's talk). But balanced collision could be achieved by tune optimization and IP knob tunings at low bunch currents.

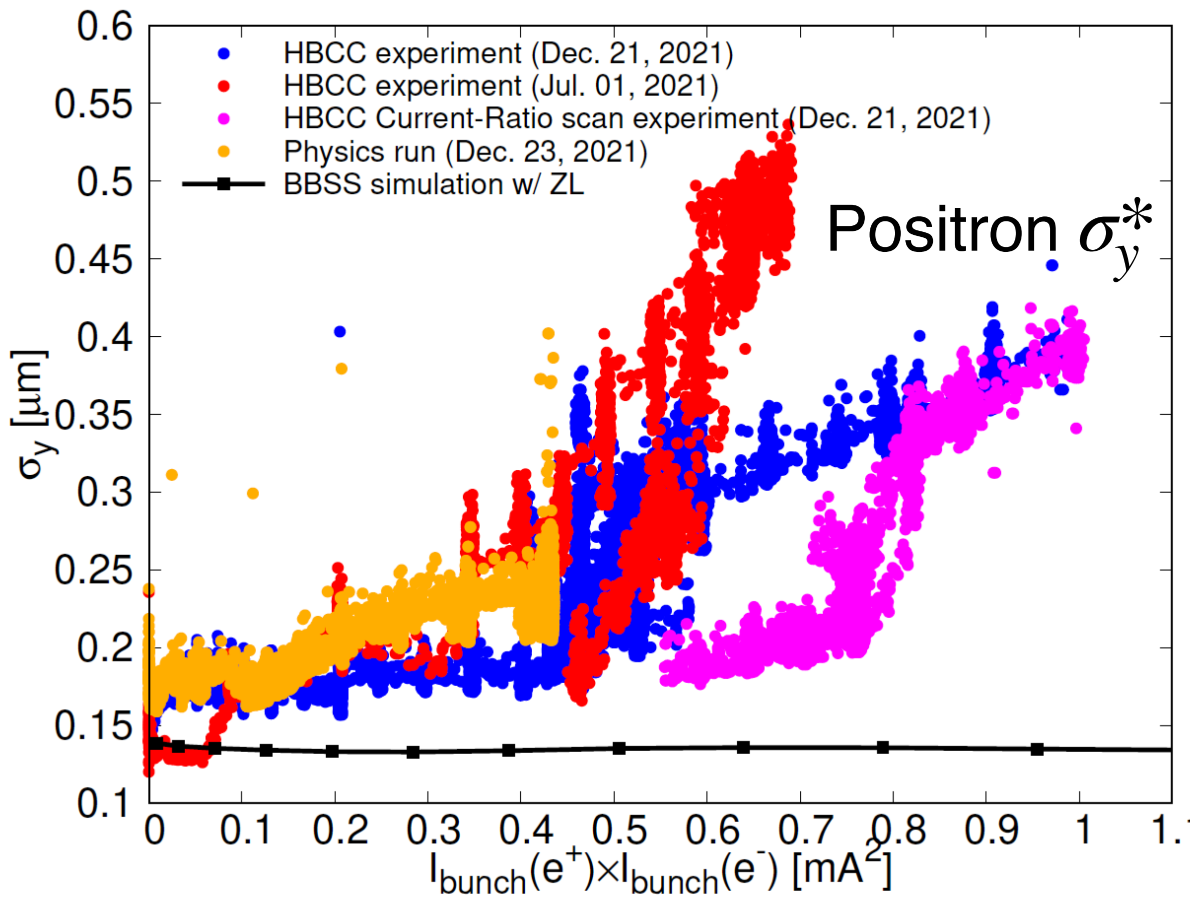




Vertical ϵ_y for HBCC study with fixed I_{b+}/I_{b-}=1.25

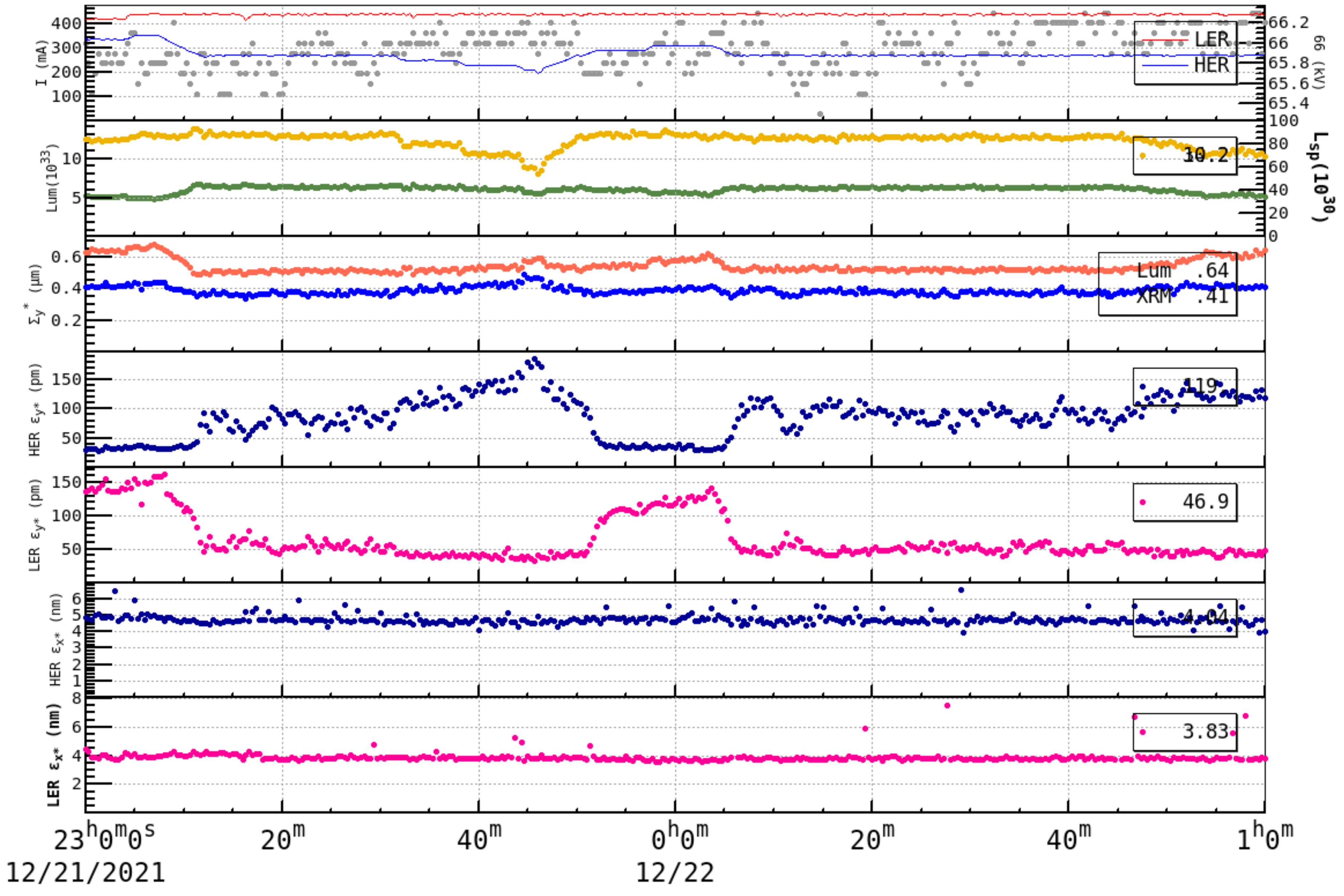


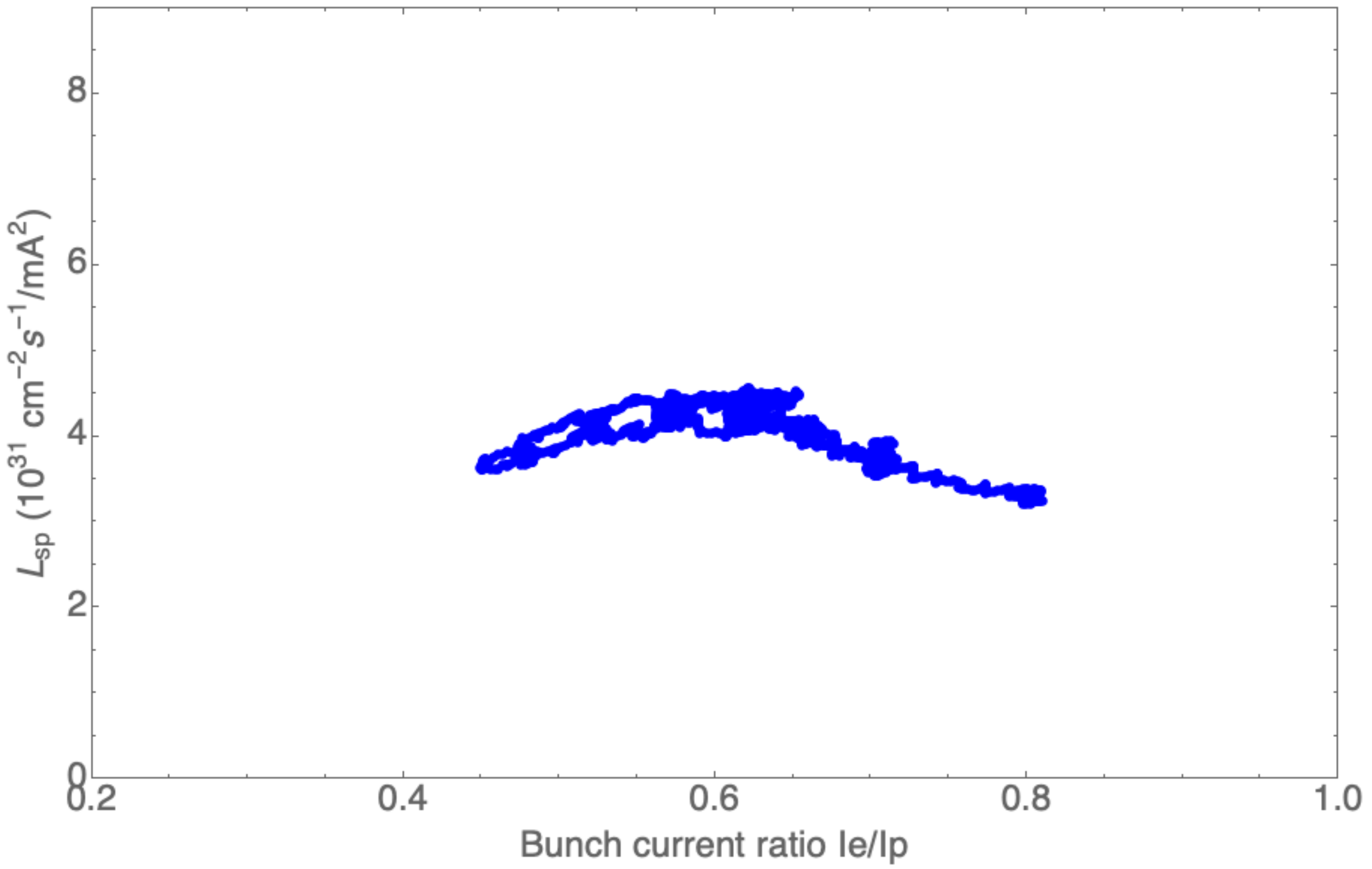


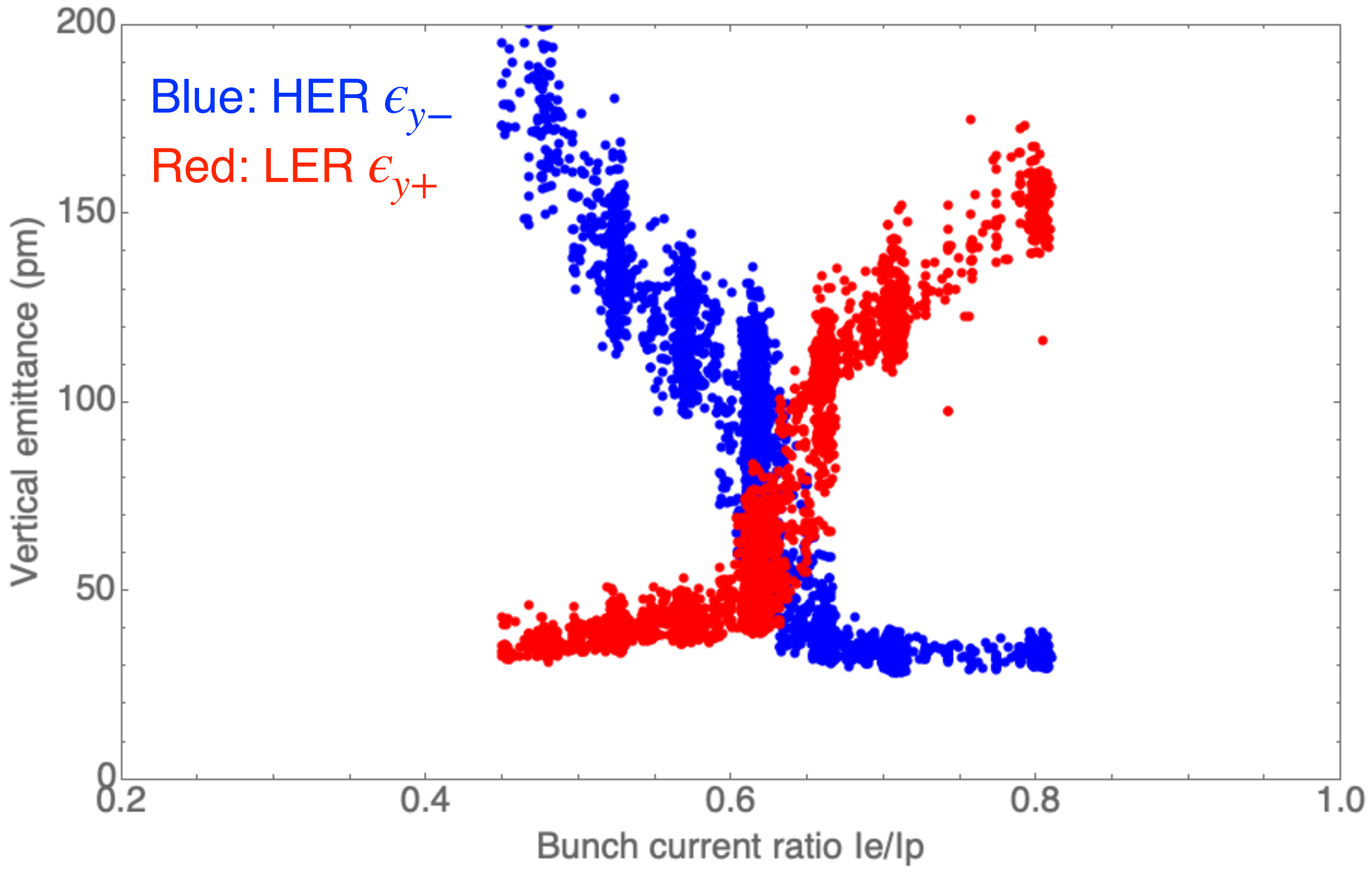


Beam-beam machine study

- Dec. 21-22, 2021: HBCC current-ratio study
  - When the LER beam current is fixed at 440 mA (393 bunches), the optimum current ratio ("optimum" means maximum Lsp with $\sigma^*_{y+} \approx \sigma^*_{y-}$) was found at $I_{b+}/I_{b-} \approx 1.7$, close to the energy transparency condition $I_{b+}/I_{b-} = \gamma_-/\gamma_+$.

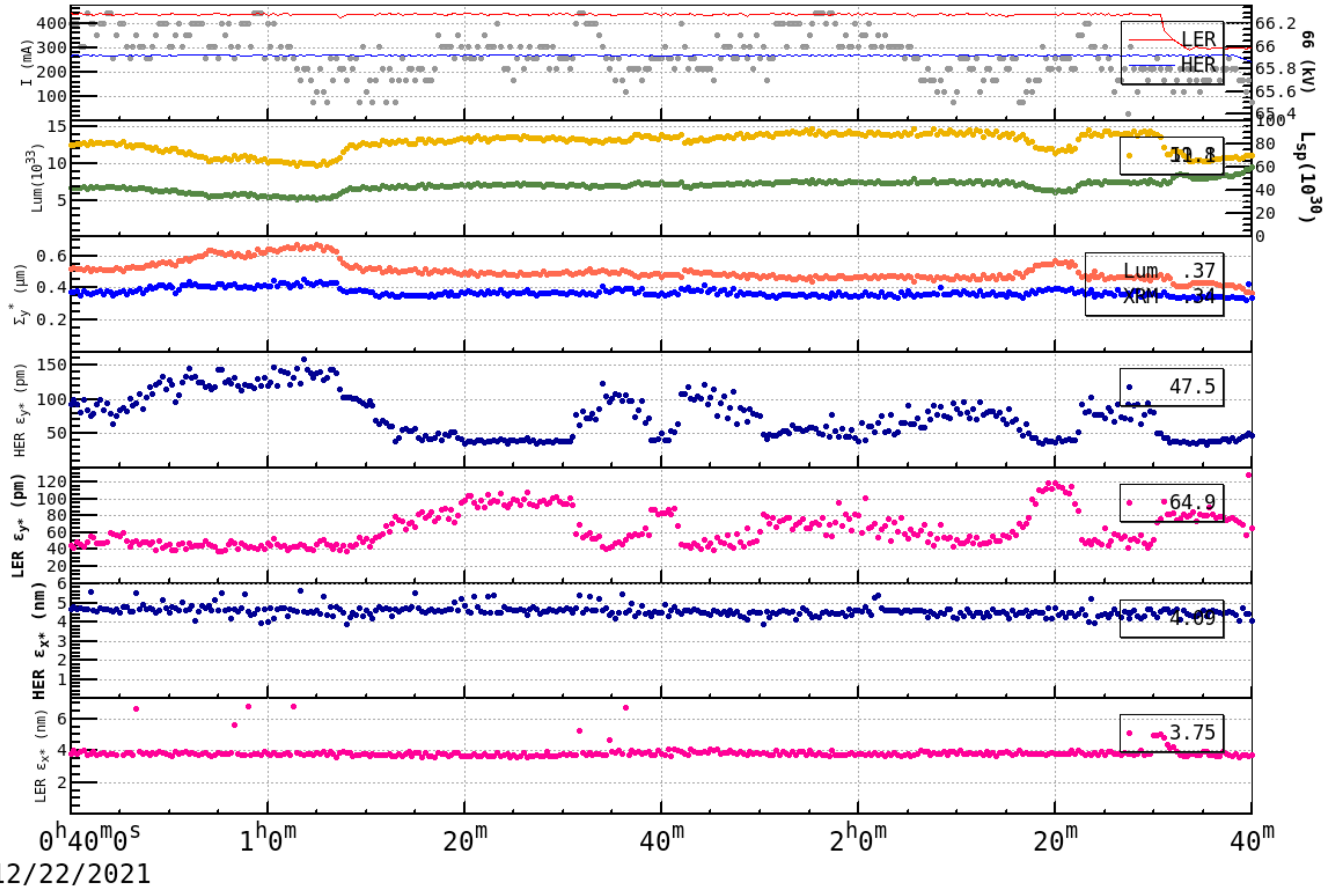


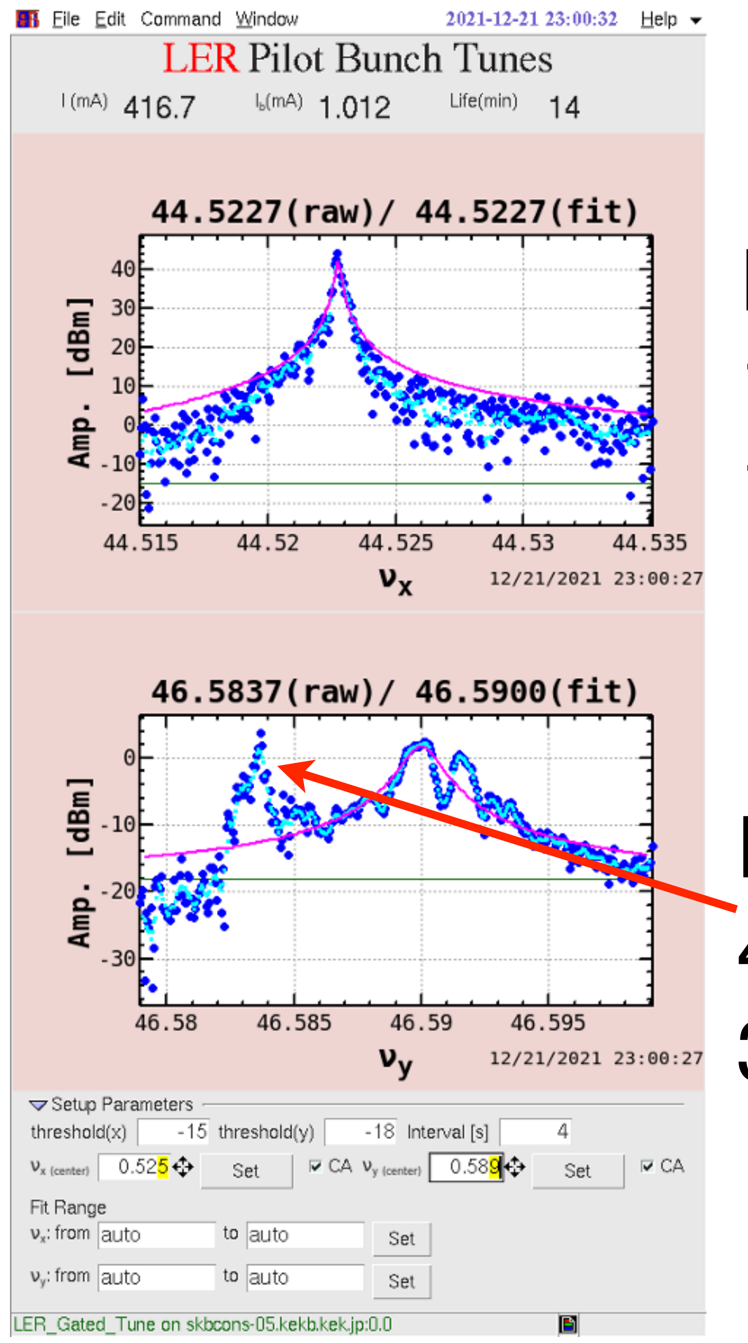




Beam-beam machine study

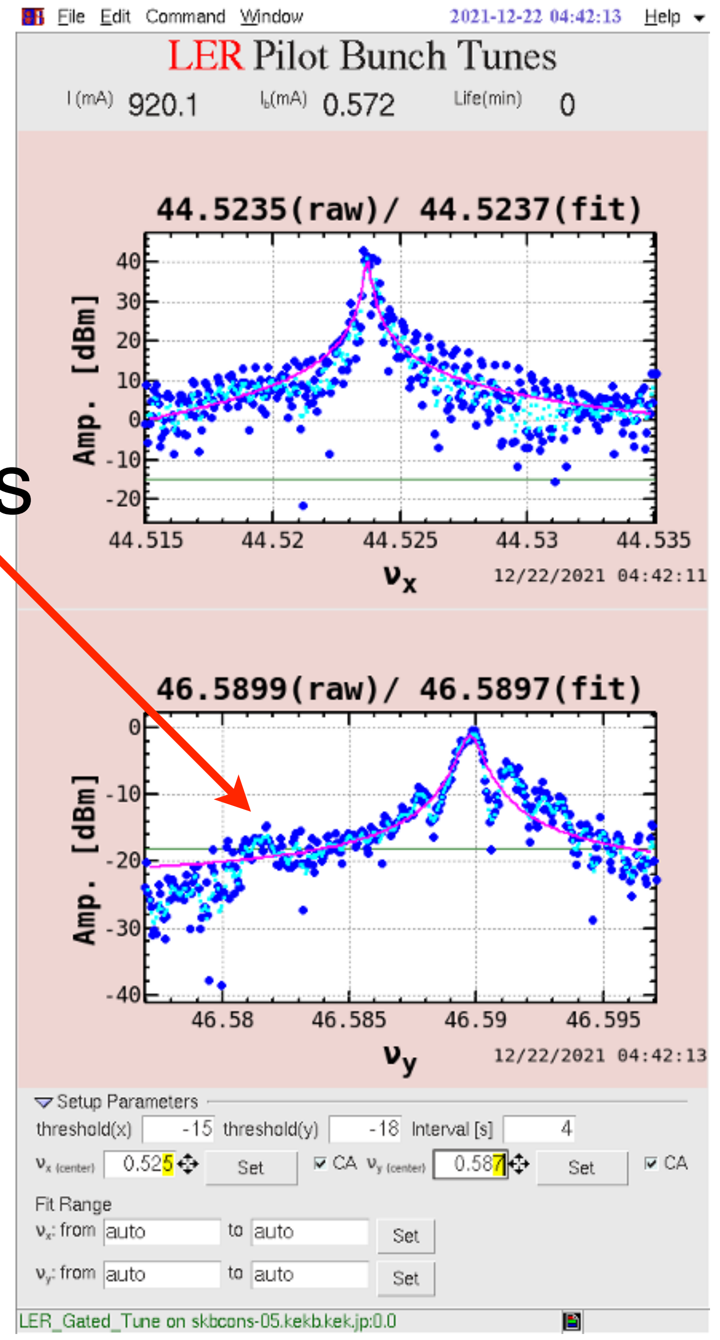
- Dec. 21-22, 2021: HBCC tune-survey study
  - Tune survey was done with fixed beam current I_+/I_-=440/352 mA (393 bunches).
  - With I_{b+}>1 mA, sideband of LER ν_y (-1 mode) was always seen.
  - Changing HER ν_y from 43.582 to upper side cause HER vertical blowup and luminosity loss, down side is better. HER ν_y was set at 43.572.
  - Changing LER ν_y toward 46.57 did not show improvement in luminosity (even worse with LER vertical blowup).

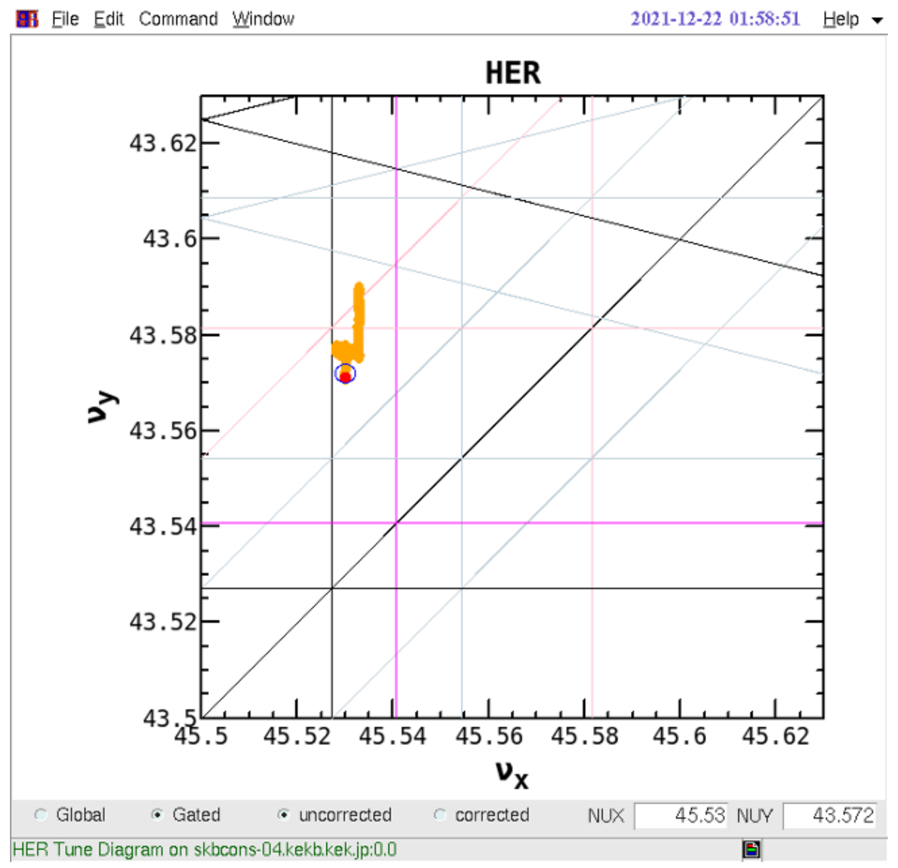


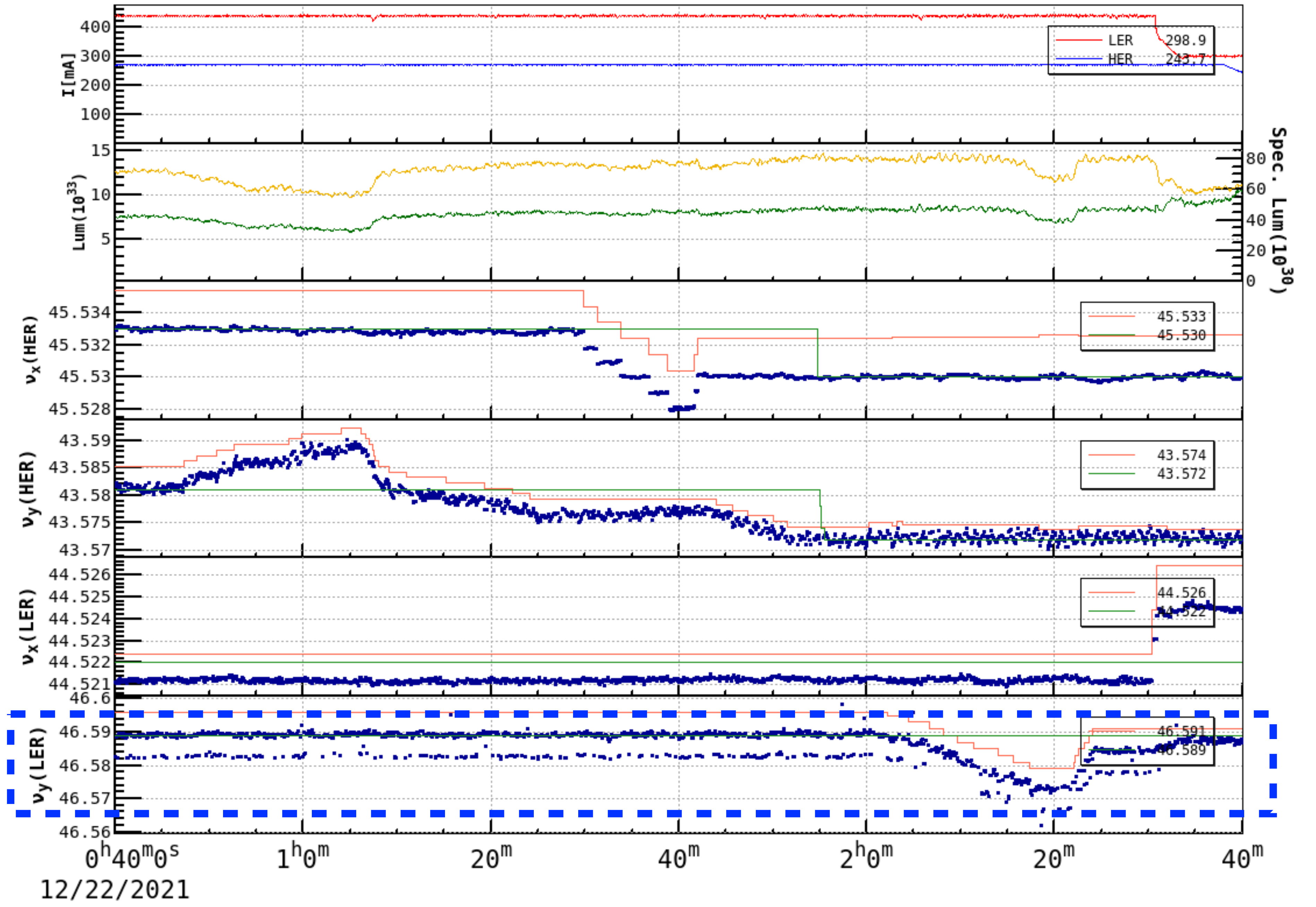


Physics run
1020 mA
1370 bunches

HBCC
440 mA
393 bunches



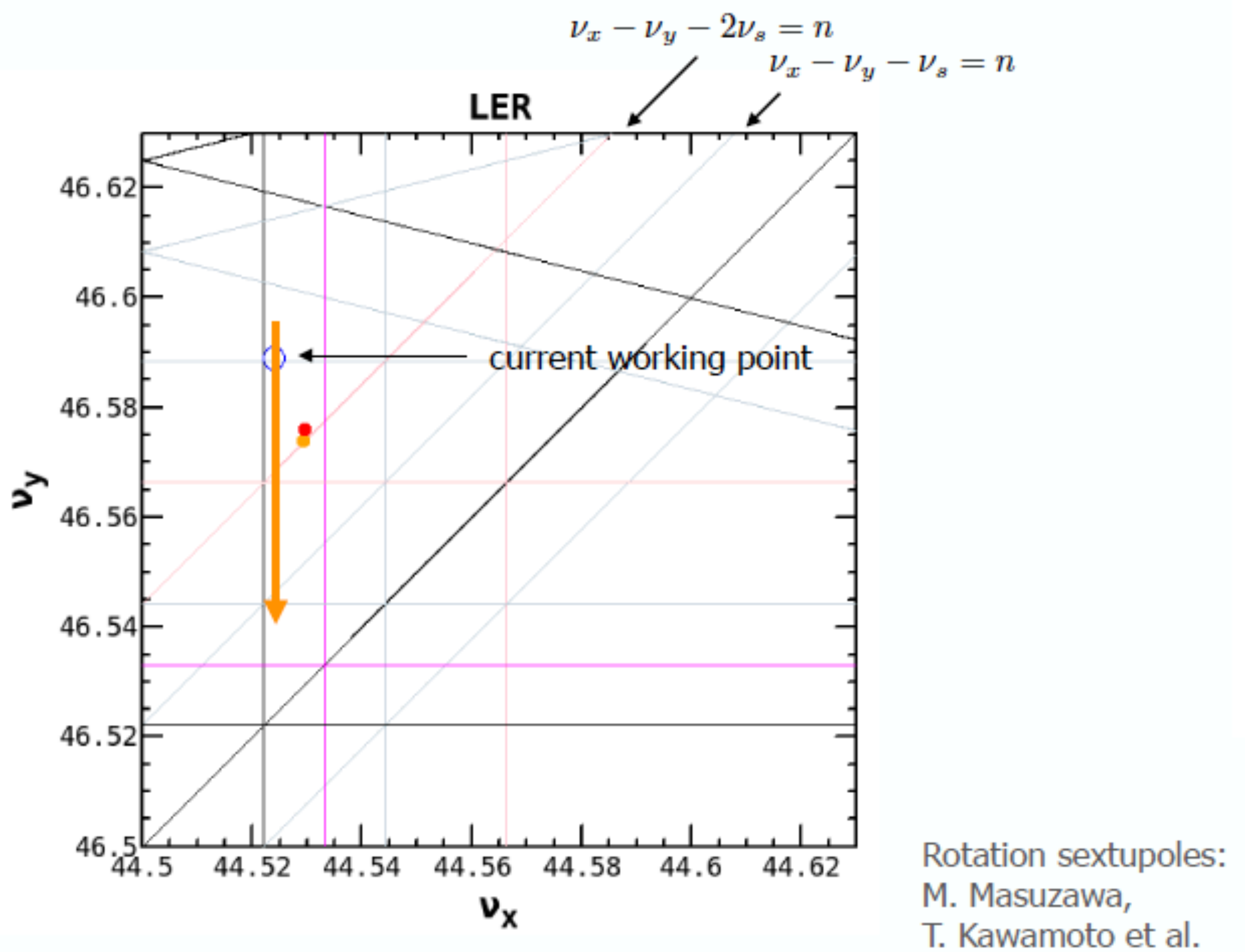




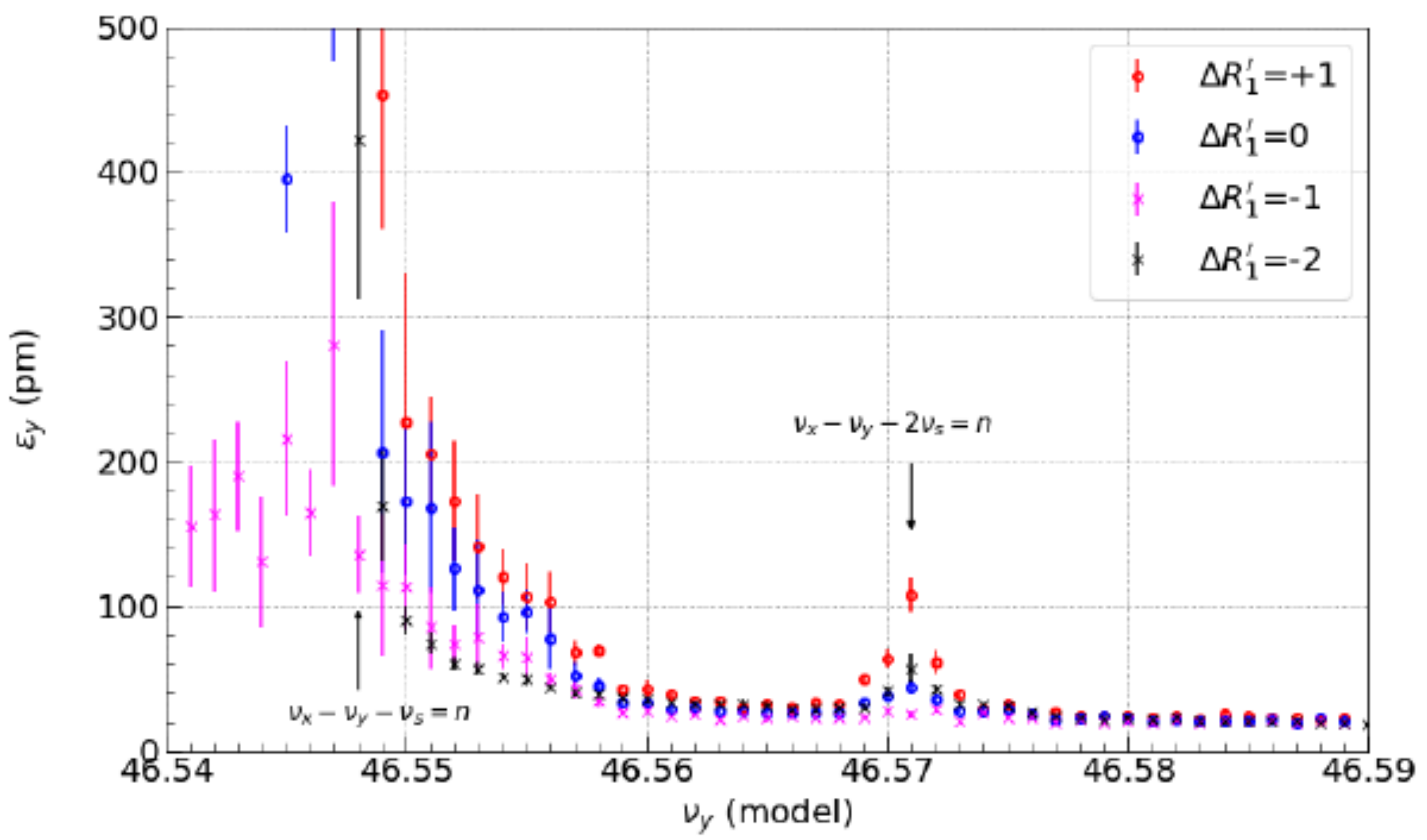
Tune survey for rotation sextupole study on Dec. 20-21, 2021

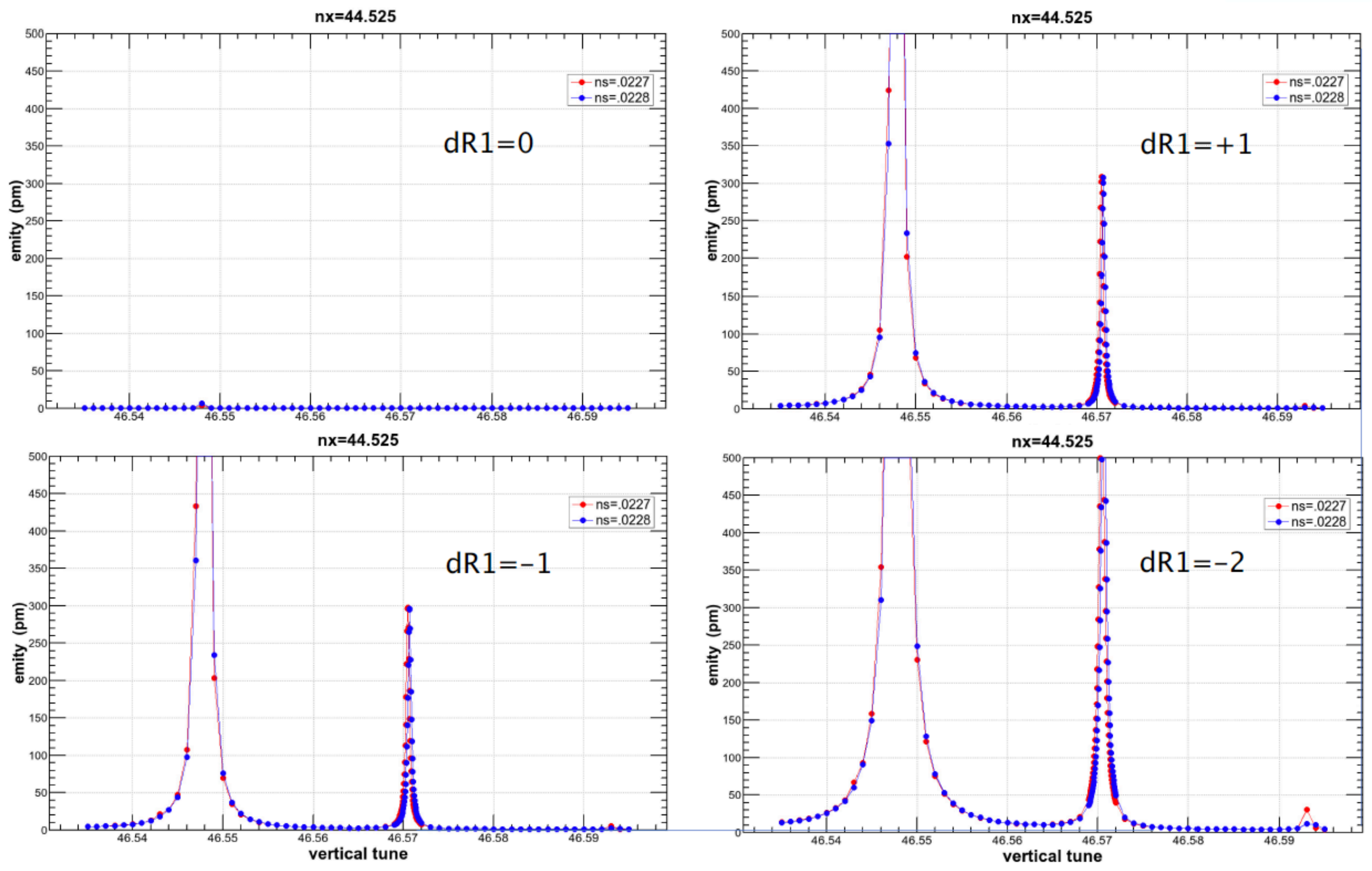
- Rotation sextupole study by M. Masuzawa, Y. Ohnishi, et al.
  - Tune survey showed chromatic resonances $\nu_x - \nu_y + k\nu_s = \text{N}$ were suppressed by rotation sextupole tuning

Chromatic X-Y Coupling Correction with Rotation Sextupole Magnets



Rotation sextupoles:
M. Masuzawa,
T. Kawamoto et al.





The rotation sextupoles are used
to make the first synchro-beta coupling resonance weak.
(together with the second resonance)

Then, the vertical tune can be set at lower region.
(46.57 is the design tune.)

Courtesy of Y. Ohnishi

SAD calculation
H. Koiso

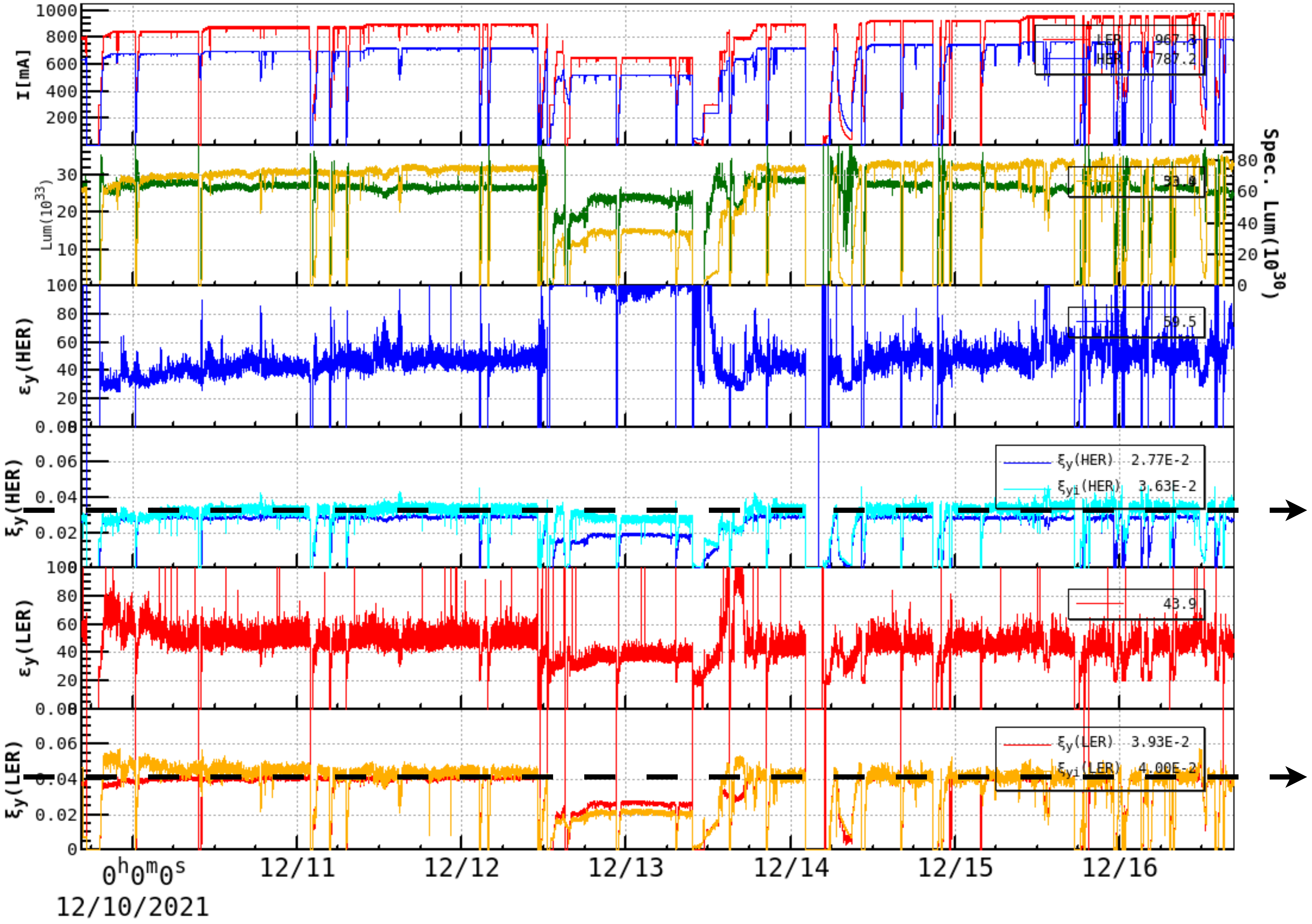
Summary

- Beam-beam simulations
  - LER R3 and R4 scans showed "double-peak" correlation of luminosity, which is associated with HER σ_y^* blowup at 40% crab waist strength.
  - ν_x scans showed complicated correlation of beam sizes with LER ν_x. It is associated with the asymmetries of the LER and HER beams (beam energies, tunes, emittances, beta functions, etc.).
- Beam-beam machine study
  - Luminosity performance is much lower than prediction of beam-beam simulations. The discrepancy became larger as bunch currents increase.
  - Horizontal emittance blowup driven by beam-beam was verified, and is sensitive to ν_x. LER horizontal blowup was correlated with LER injection efficiency. So far, machine study did not show clear evidence of vertical blowup and luminosity loss caused by horizontal blowup.
  - Optimization of working point was useful in: 1) alleviation of LER horizontal blowup; 2) better balance of vertical beam sizes with collision.

Backup

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.



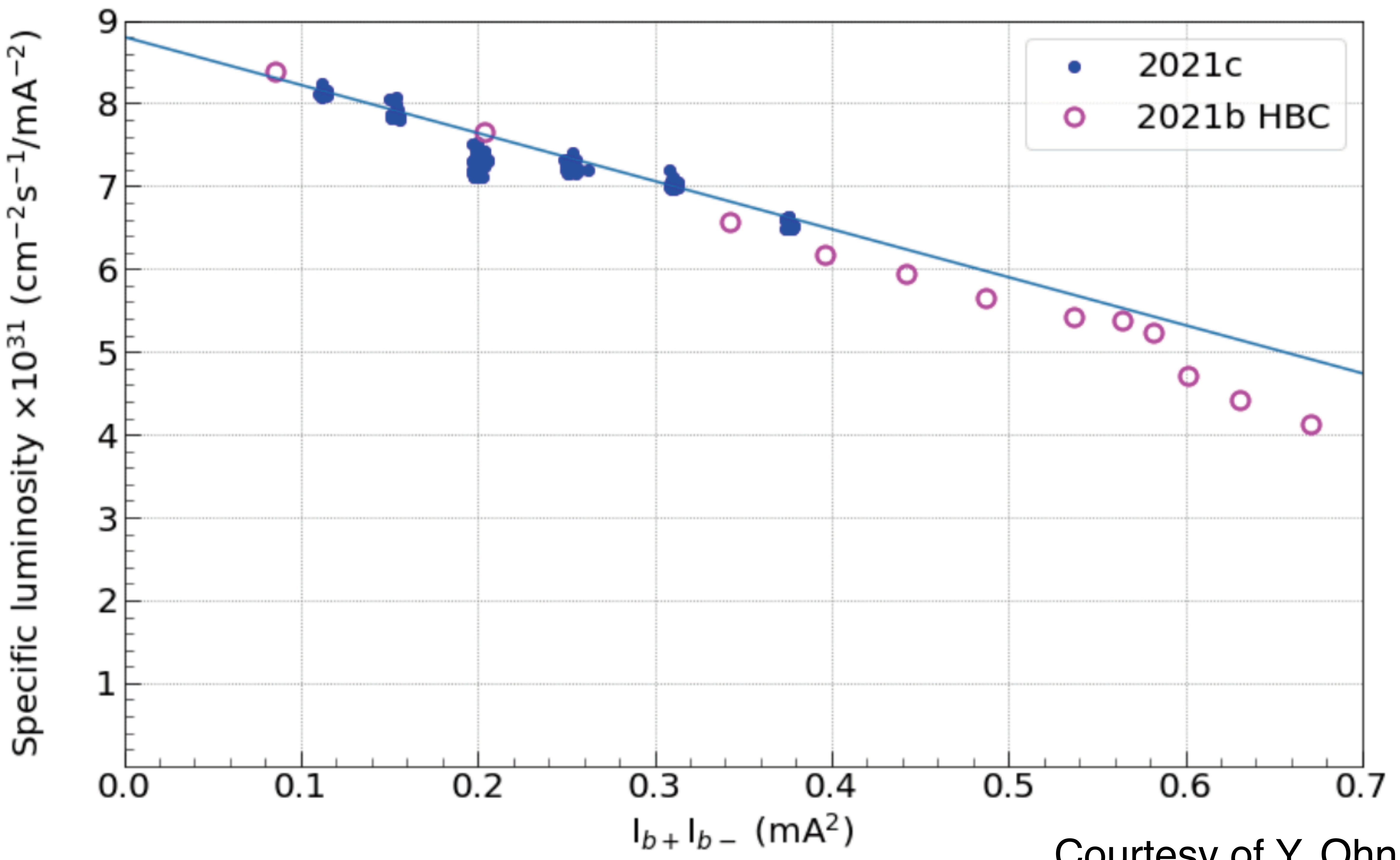
$$L = \frac{1}{2er_e}\frac{\gamma_+ I_+}{\beta^*_{y+}}\xi_{y+} = \frac{1}{2er_e}\frac{\gamma_- I_-}{\beta^*_{y-}}\xi_{y-}$$

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

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

Scaling laws of luminosity

- Specific luminosity
  - Observed specific luminosity L_{sp} can be used 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 3.815E34 luminosity wit β_y^*=1 mm (Dec. 23, 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 $L_{sp}[10^{31}\ \text{cm}^{-2}\text{s}^{-1}/\text{mA}^2] = 8.8 - 5.8 I_{b+} I_{b-}[\text{mA}^2]$. 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).

Bunch number	$I_{b+}I_{b-}$ [mA²]		
	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

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