Beam dynamics issues

Demin Zhou

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SuperKEKB 2021c run summary meeting, Jan. 14, 2022

Outline

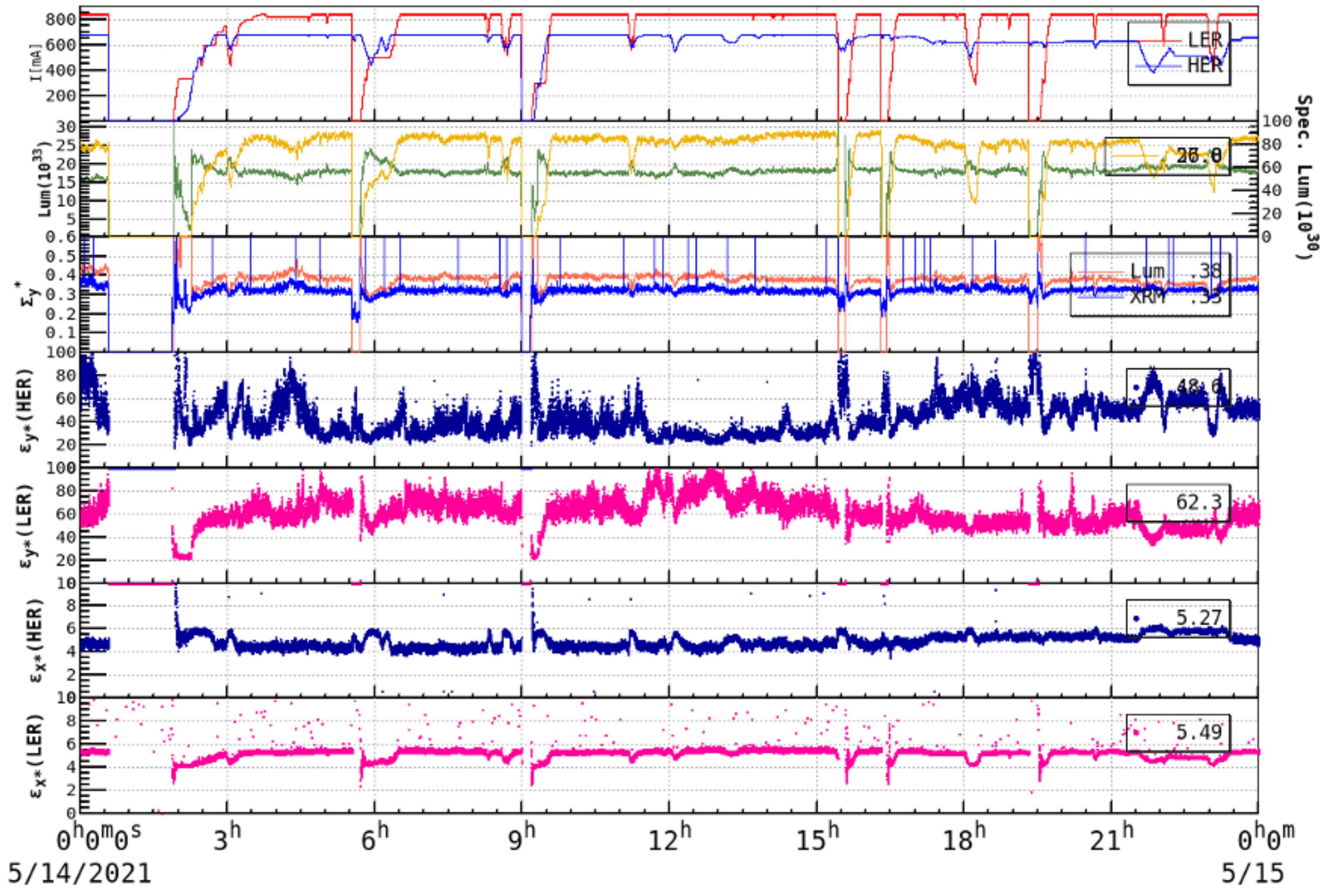
- Beam-beam
  - Overview of beam-beam simulations and comparisons with observations
  - Beam-beam study on Dec. 21-22, 2021
- Resonances and tune survey
- Impedance models for LER
  - Longitudinal impedance model and bunch lengthening simulation
  - Transverse impedance model and tune shift
- Discussion on vertical emittance blowup and reaching 1E35 luminosity

- Other talks covering beam dynamics issues:
  - Y. Ohnishi, “Operation Summary”
  - T. Ishibashi, “TMCI 関連”
  - H. Sugimoto, “Optics Issues”
  - H. Ikeda, “Bunch length、SRM測定について”
  - K. Ohmi, “Chromatic aberrations, nonlinear resonances and Head-tail instability”
  - Y. Funakoshi, “High Bunch Current Study + 今後の見通し”

Beam-beam: simulations vs observations

- May 14, 2021: Physics run
  - With single-beam ϵ_y of 22.5 pm, BBSS simulations predict luminosity of ~3.75e34 $cm^{-2}s^{-1}$ at bunch current product of about 0.4 mA^2 without obvious BBHTI. This is compared to the achieved luminosity of 3.0e34 $cm^{-2}s^{-1}$ in 2021ab run.
  - Slope of Lsp is affected by bunch lengthening (due to potential-well distortion) and nonlinear beam-beam effects.
  - Weak blowup in ϵ_x was observed in the control room, but not well-confirmed.

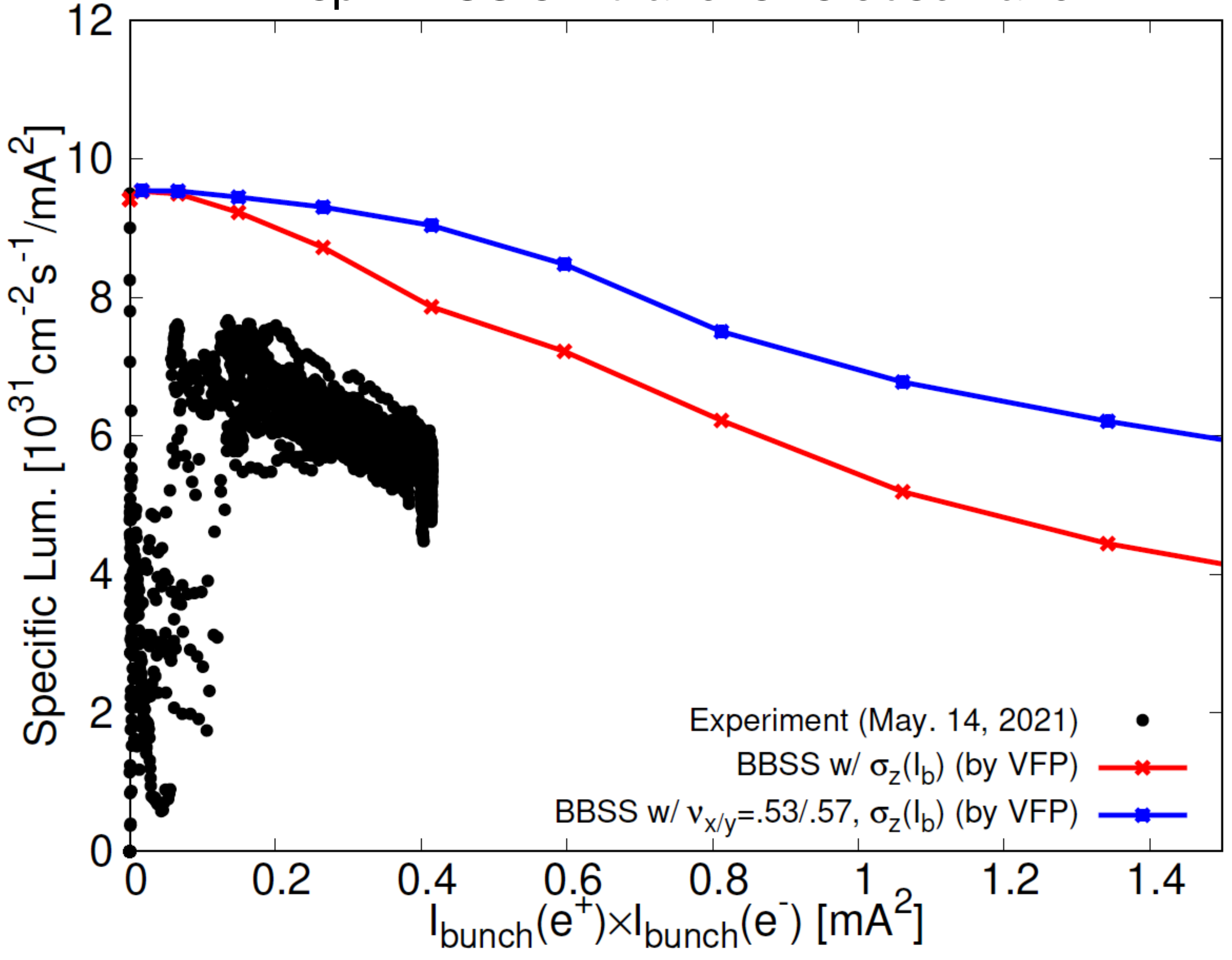
Luminosity history panel seen in SuperKEKB control room



Operation parameter set

	2021.05.14		Comments
	HER	LER	
I_b (A)	0.68	0.84	
# bunch	1174		
ε_x (nm)	4.6	4.24	w/ IBS
ε_y (pm)	22.5	22.5	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	6	6	w/ bunch lengthening by impedance
σ_y (μm)	0.15	0.15	Observed from XRM
ν_x	45.52989	44.5247	Measured tune of pilot bunch
ν_y	43.59055	46.57279	Measured tune of pilot bunch
ν_s	0.02719	0.02212	Calculated from lattice
Crab waist	40%	80%	Lattice design

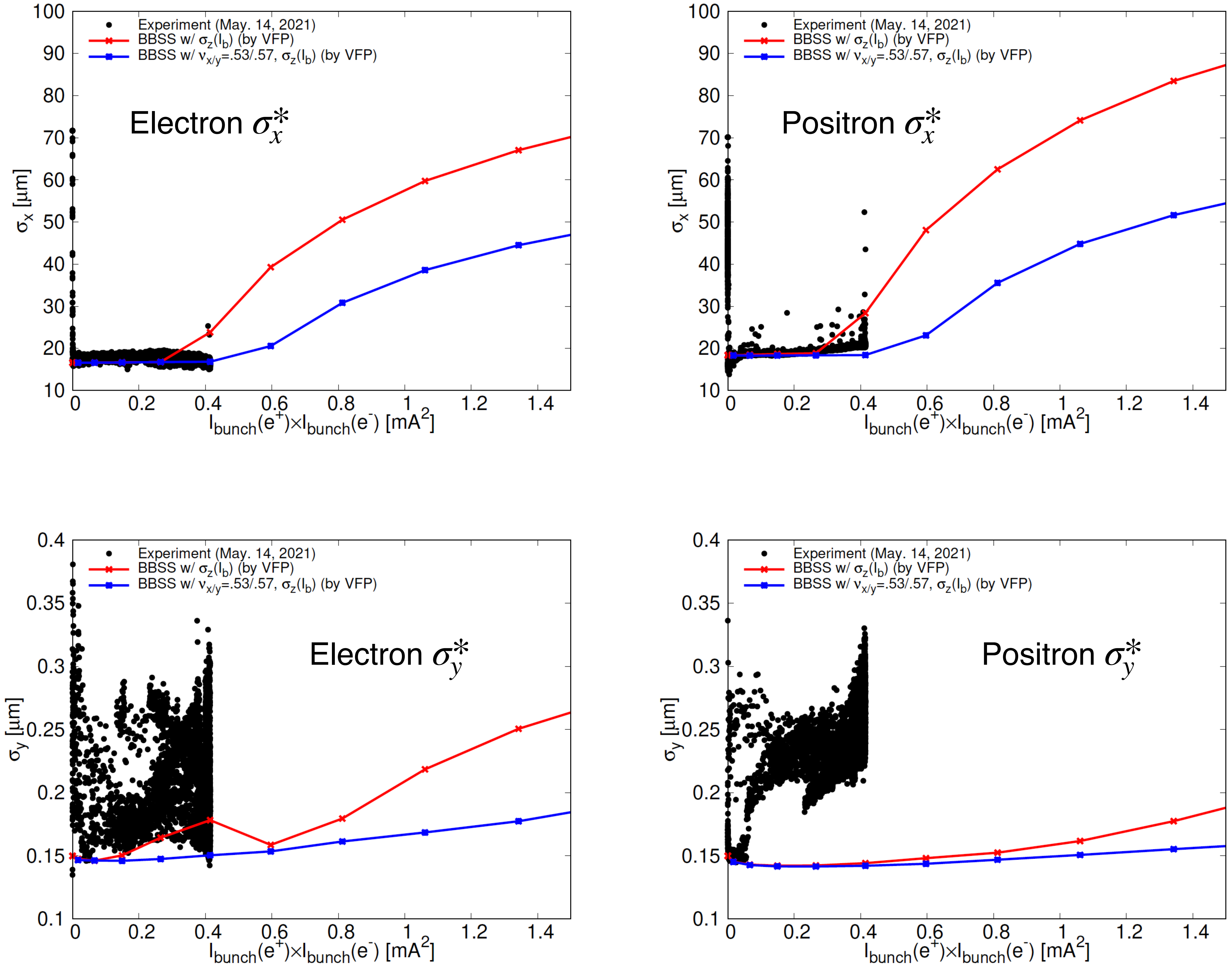
Lsp: BBSS simulations vs observation



[5] D. Zhou, Talk presented at the 1st ITF-BB subgroup meeting, KEK, Aug. 24, 2021, https://kds.kek.jp/event/39142/.

Beam-beam: simulations vs observations

- May 14, 2021: Physics run
  - Simulations were done without using self-consistent model of longitudinal impedance (only bunch length was varied in those simulations). Consequently, BBHTI appears in BBSS simulations.
  - The observed blowup of σ_y^* of both electron and positron beams was complicated (see 24 hours' history of ϵ_y). BBSS simulations cannot reproduce the trends of σ_y^* blowup.
  - Simulations showed working point (.53,.57) is better: Higher BBHTI threshold and weaker beam-size blowup.

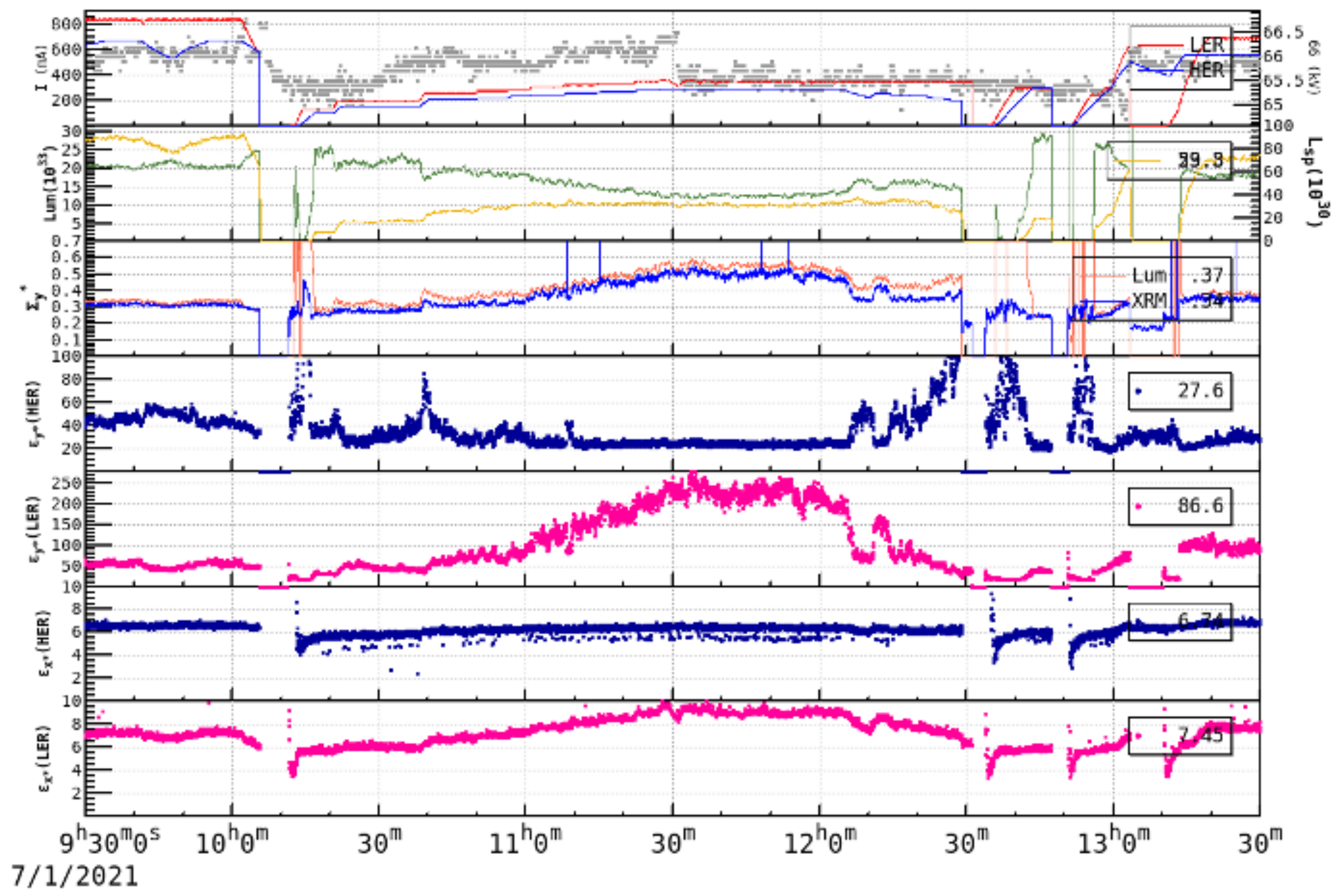


[5] D. Zhou, Talk presented at the 1st ITF-BB subgroup meeting, KEK, Aug. 24, 2021, https://kds.kek.jp/event/39142/.

Beam-beam: simulations vs observations

- Jul. 01, 2021: HBCC study
  - BBSS simulations with self-consistent model of longitudinal impedance did not show strong BBHTI. The slope of Lsp is mainly affected by bunch lengthening.
  - Bunch lengthening simulated by BBSS is weaker than VFP simulations. Impedance modeling in BBSS needs to be improved.
  - Weak blowup in ϵ_x was observed in the control room. It was confirmed in beam-beam machine study on Dec. 21, 2021

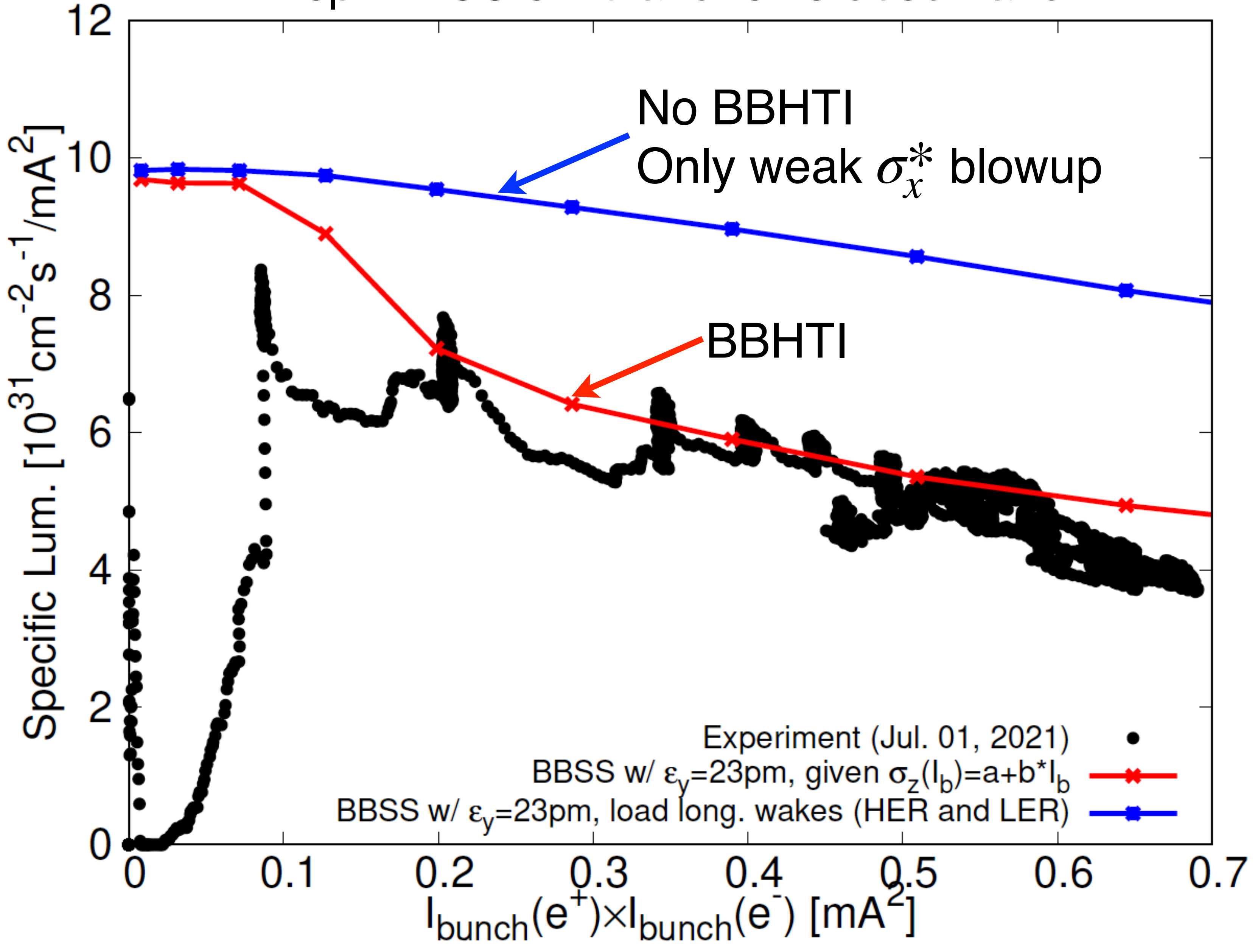
Luminosity history panel seen in SuperKEKB control room



Operation parameter set

	2021.07.01		Comments
	HER	LER	
I_b (A)	Ie	1.255*Ie	
# bunch	393		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	18	18	Single beam (Estimated from XRM data)
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (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

Lsp: BBSS simulations vs observation

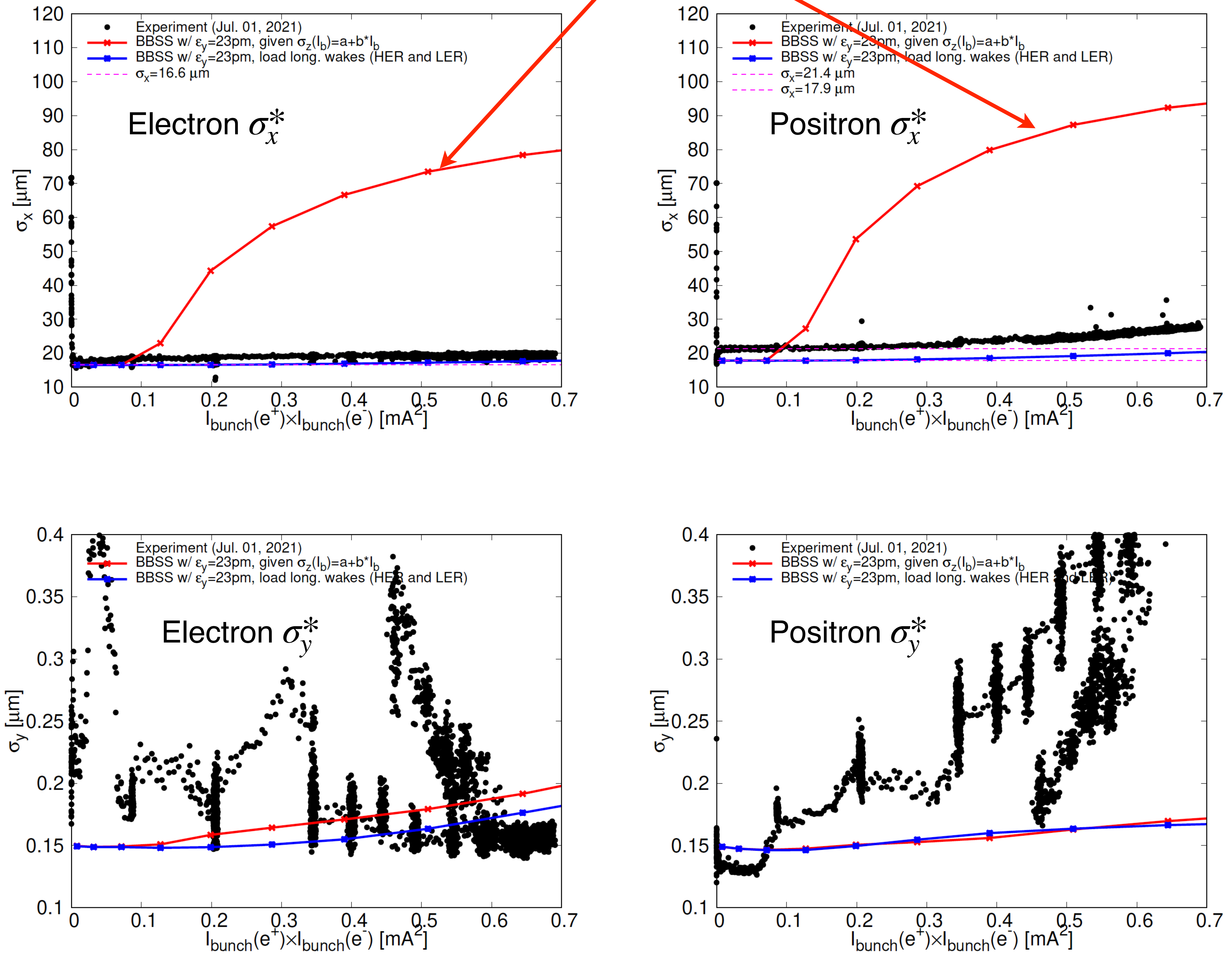


[1] D. Zhou, Talk presented at the 2nd ITF-BB subgroup meeting, KEK, Sep. 28, 2021, https://kds.kek.jp/event/39428/.

Beam-beam: simulations vs observations

- Jul. 01, 2021: HBCC study
  - With self-consistent model of longitudinal impedance, only weak σ_x^* blowup is visible in simulations. σ_x^* blowup in LER beam is stronger than that in HER beam, somehow consistent with experimental observations.
  - The observed blowup of σ_y^* of both electron and positron beams was complicated. BBSS simulations cannot reproduce the trends of σ_y^* blowup.
  - To predict the experiments, other sources (Transverse wakes, collision offset noise, IP aberrations, etc.) are to be included in beam-beam simulations.

BBHTI appears with non-self-consistent model of longitudinal impedance



[1] D. Zhou, Talk presented at the 2nd ITF-BB subgroup meeting, KEK, Sep. 28, 2021, https://kds.kek.jp/event/39428/.

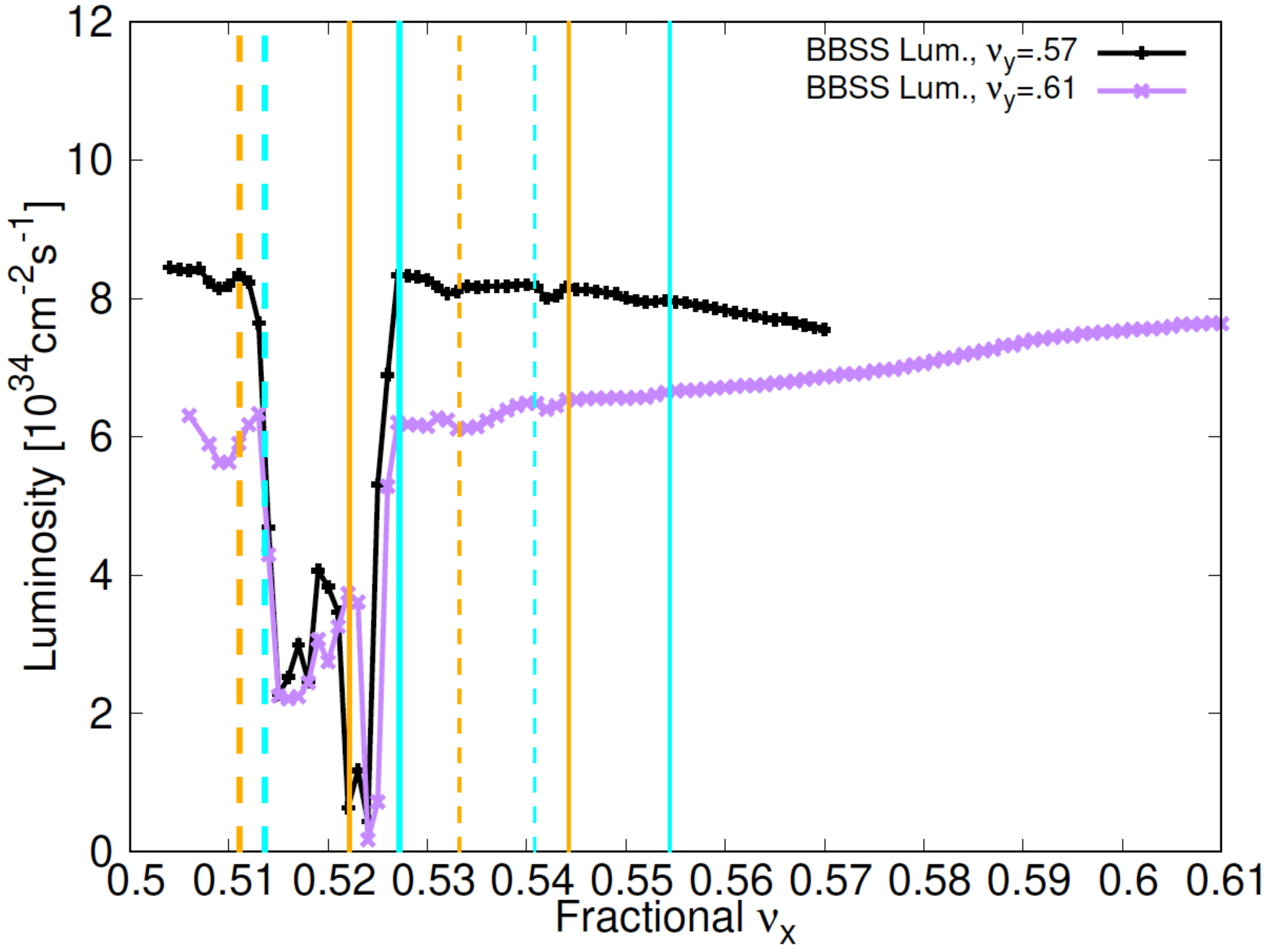
Beam-beam: simulations vs observations

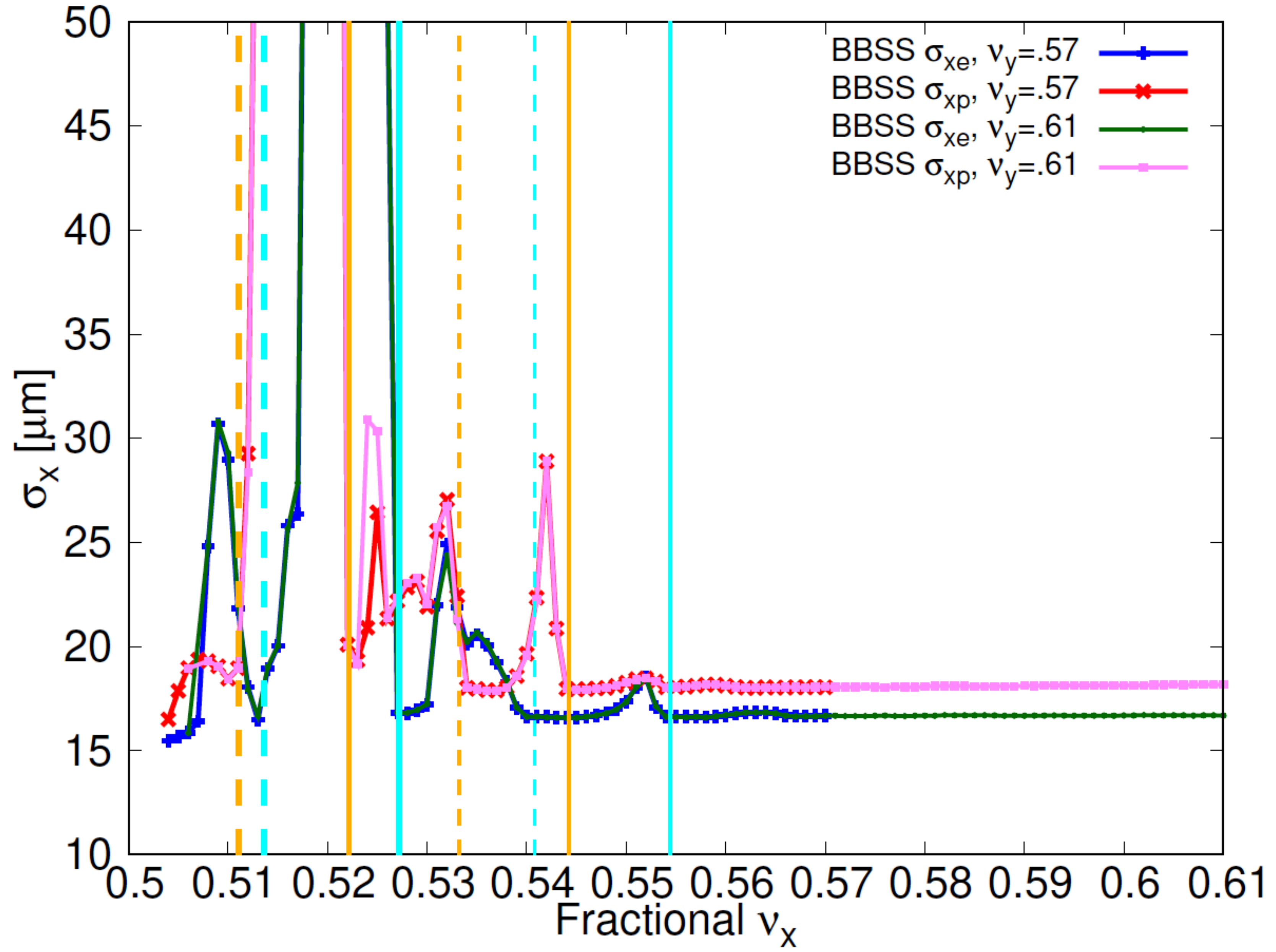
- Jul. 01, 2021: HBCC study
  - Horizontal tune scan using BBSS showed ν_x dependence of σ_x^* blowup.
  - ν_x dependent σ_x^* blowup driven by beam-beam was confirmed in the beam-beam machine study on Dec. 21, 2021.

Parameter set for simulations

	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

Synchro-betatron resonances: $\nu_x - k\nu_s/2 = N/2$
Odd k: Dashed lines; Even k: Solid lines
Orange lines: LER; Cyan lines: HER

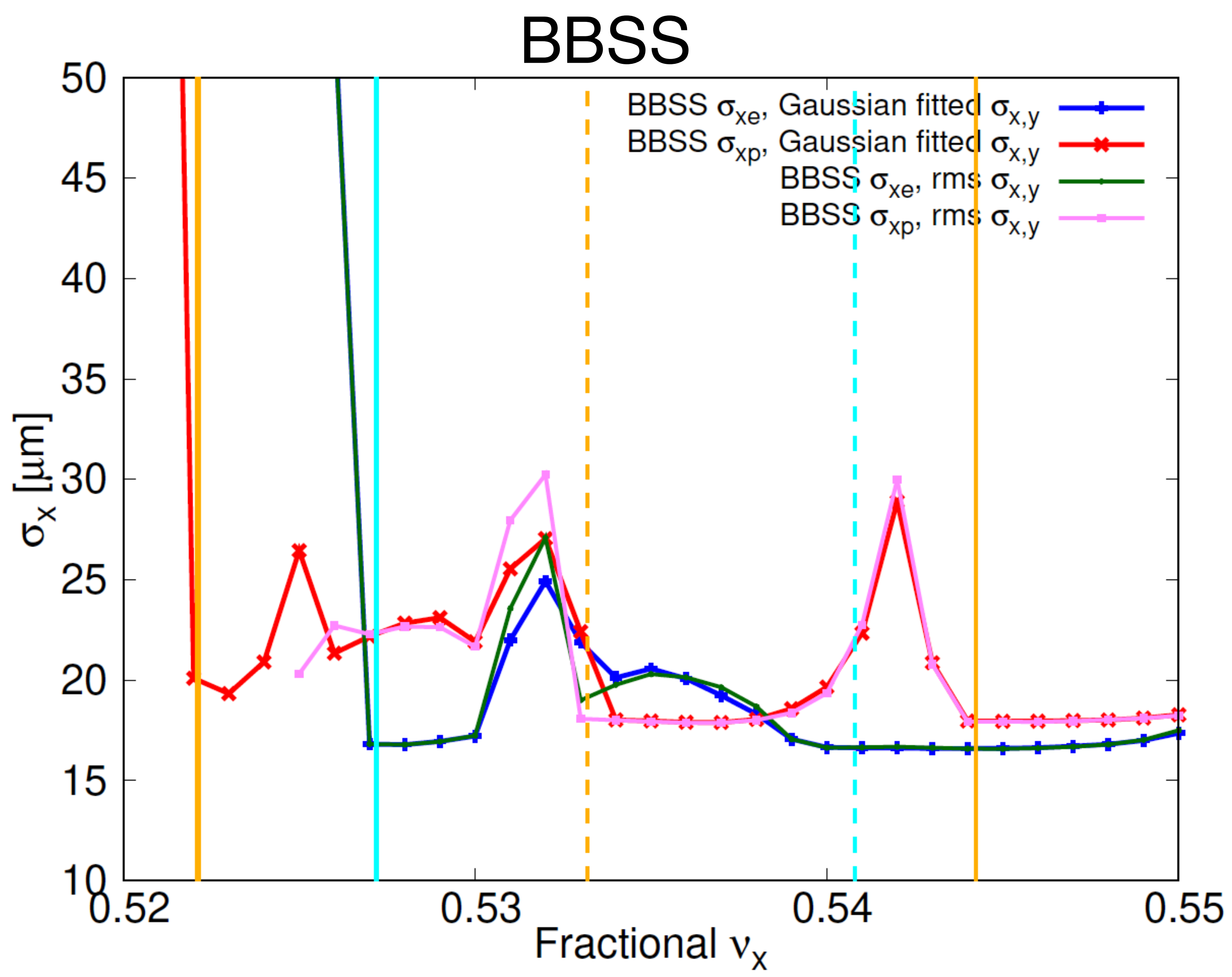


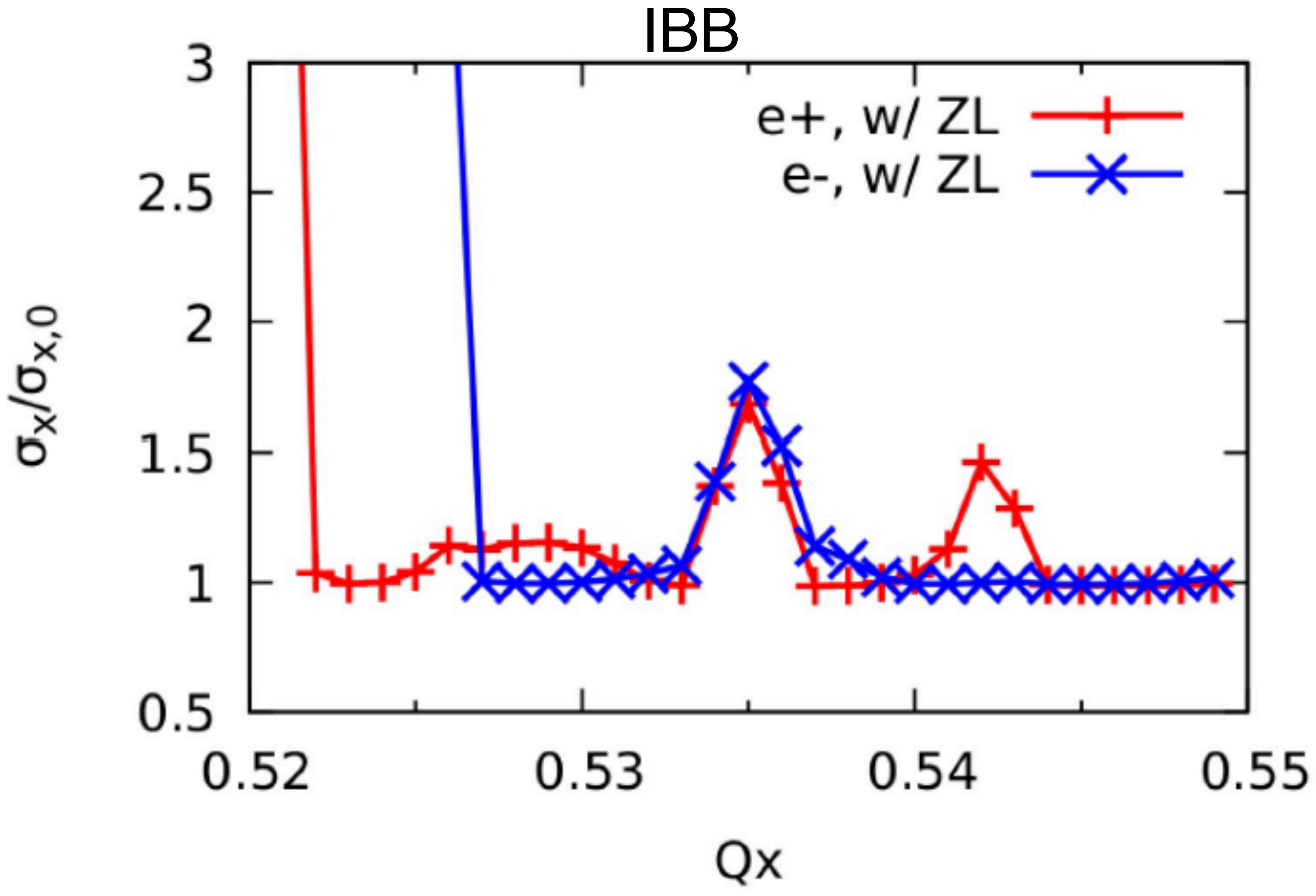


[2] D. Zhou, Talk presented at the 4th ITF-BB subgroup meeting, KEK, Nov. 25, 2021, https://kds.kek.jp/event/40237/.

Beam-beam: simulations vs observations

- Jul. 01, 2021: HBCC study
  - ν_x dependent σ_x^* blowup was also seen in an independent simulation using IBB by Y. Zhang.
  - Discrepancy was also seen in blowup behavior.
  - Beam-beam simulations showed that it is hard to avoid σ_x^* blowup when ν_x is chosen to be between resonances $\nu_x - \nu_s = N/2$ and $\nu_x - 2\nu_s = N/2$.
  - According to D. Shatilov [3], σ_x^* blowup will cause σ_y^* blowup due to betatron coupling. It is not well confirmed yet in experimental observations at SuperKEKB.





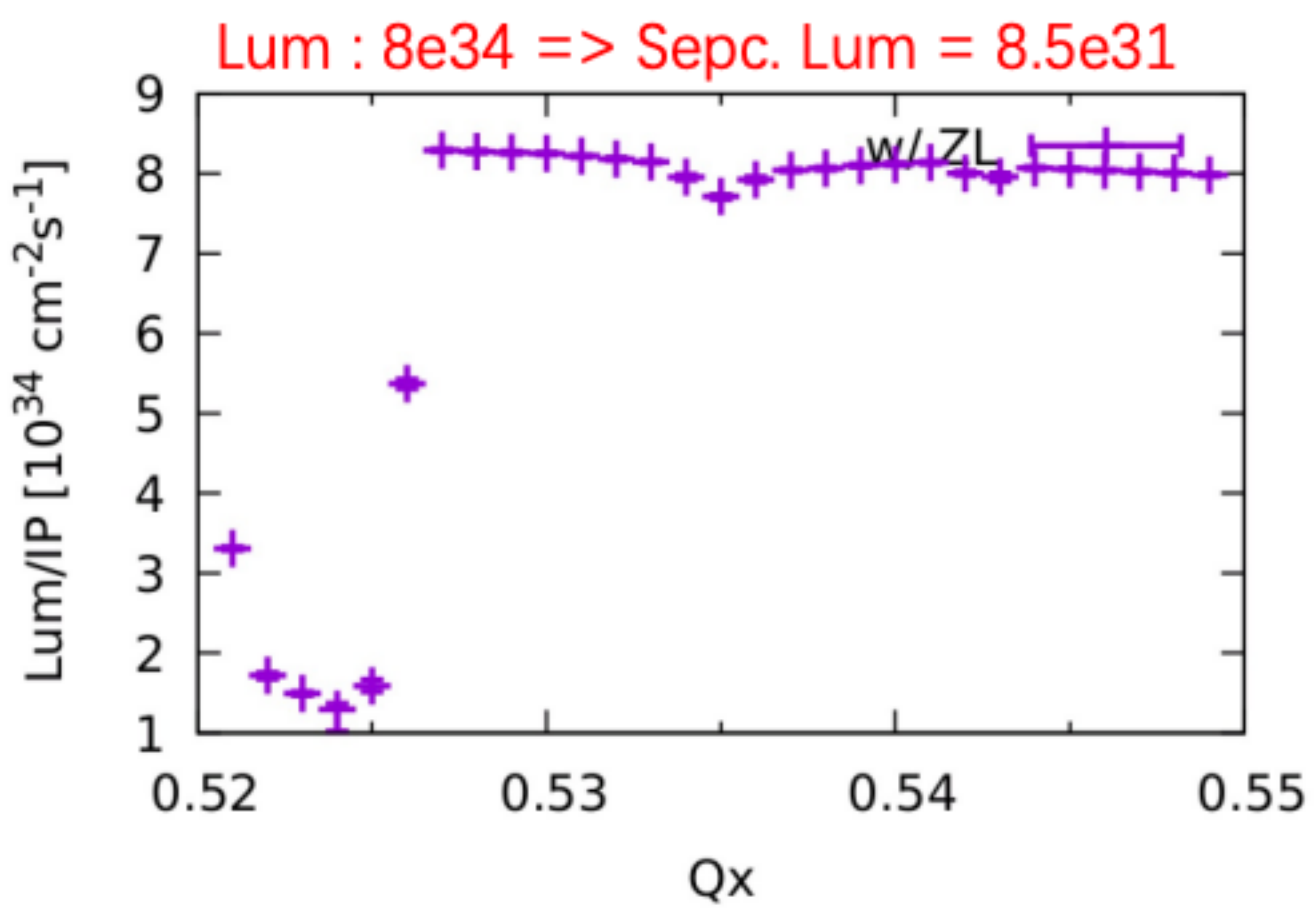
[2] D. Zhou, Talk presented at the 4th ITF-BB subgroup meeting, KEK, Nov. 25, 2021, https://kds.kek.jp/event/40237/.

[3] D. Shatilv, Talk presented at the 3rd ITF-BB subgroup meeting, KEK, Oct. 28, 2021, https://kds.kek.jp/event/39831/.

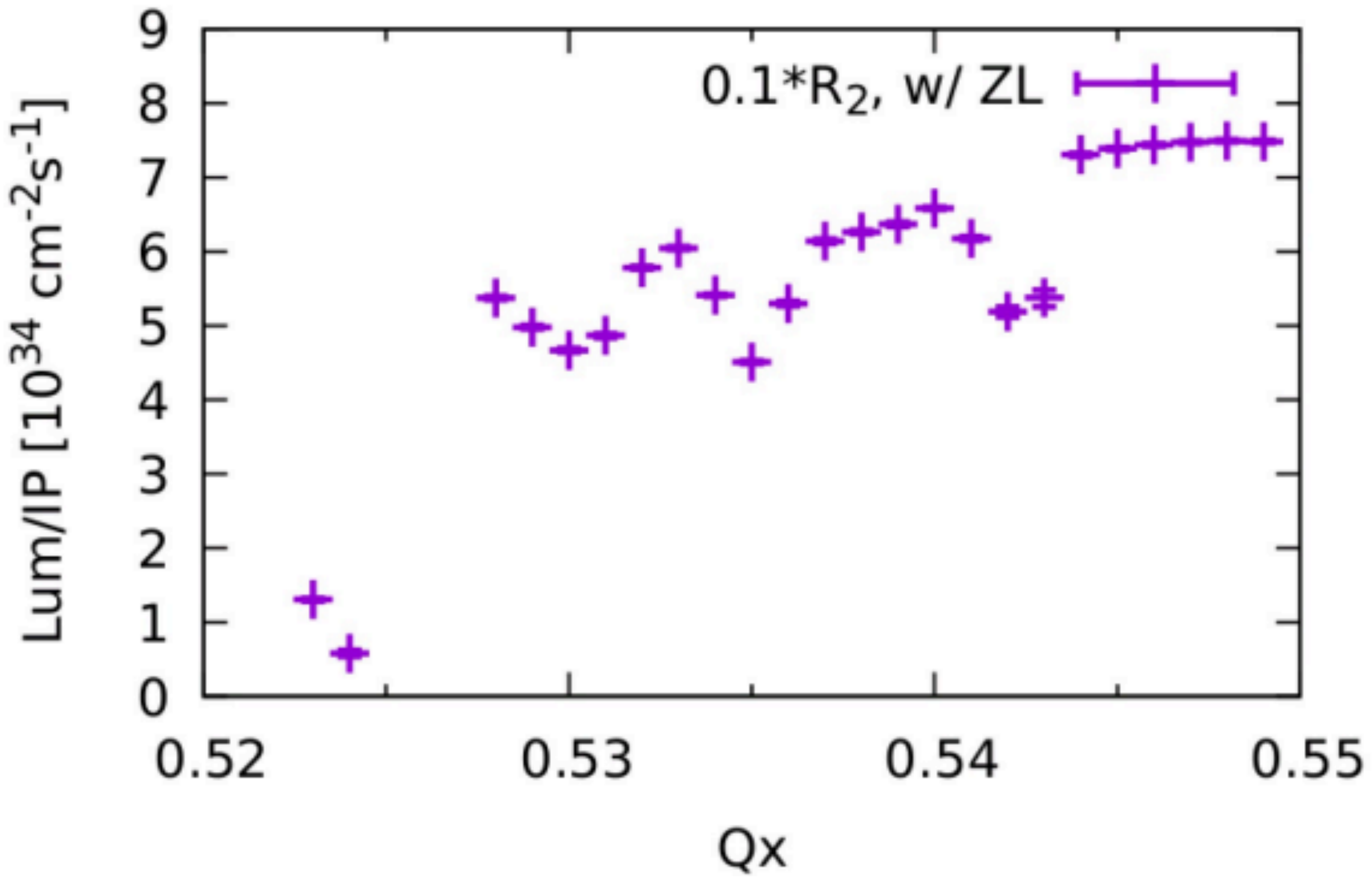
Beam-beam: simulations vs observations

- Jul. 01, 2021: HBCC study
  - Beam-beam simulations with inclusion of chromatic coupling in LER (using IBB by Y. Zhang) showed direct luminosity loss might appear with the current configuration of SuperKEKB (β_y^* =1 mm with crab waist).
  - IBB simulations were done with the same $\nu_{x,y}$ for LER and HER. Only chromatic coupling in LER (extracted from TbT measurements) was considered.
  - Correction of chromatic coupling using rotatable sextupoles in LER was successfully demonstrated.

IBB simulation w/o chromatic coupling



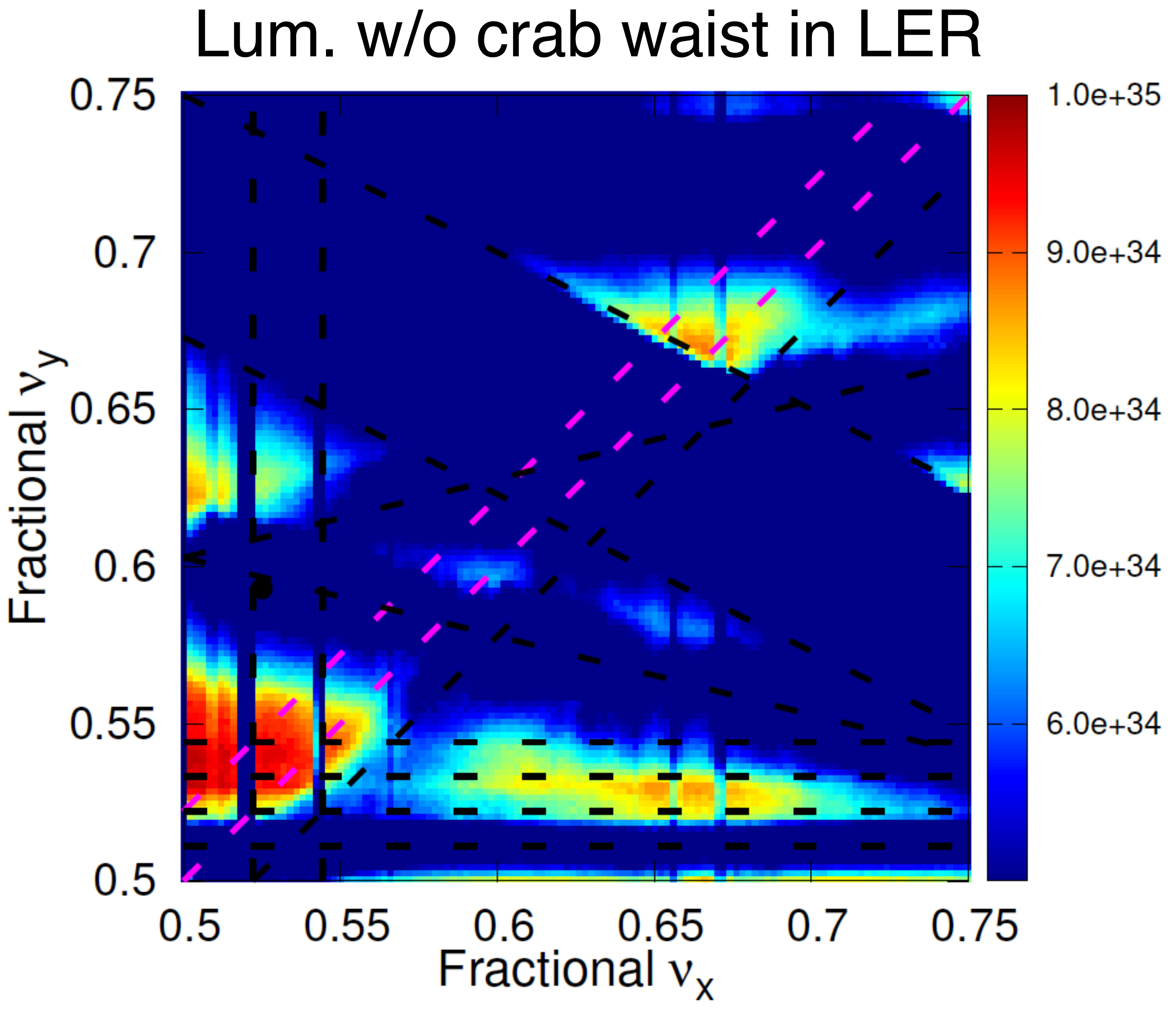
IBB simulation w/ chromatic coupling

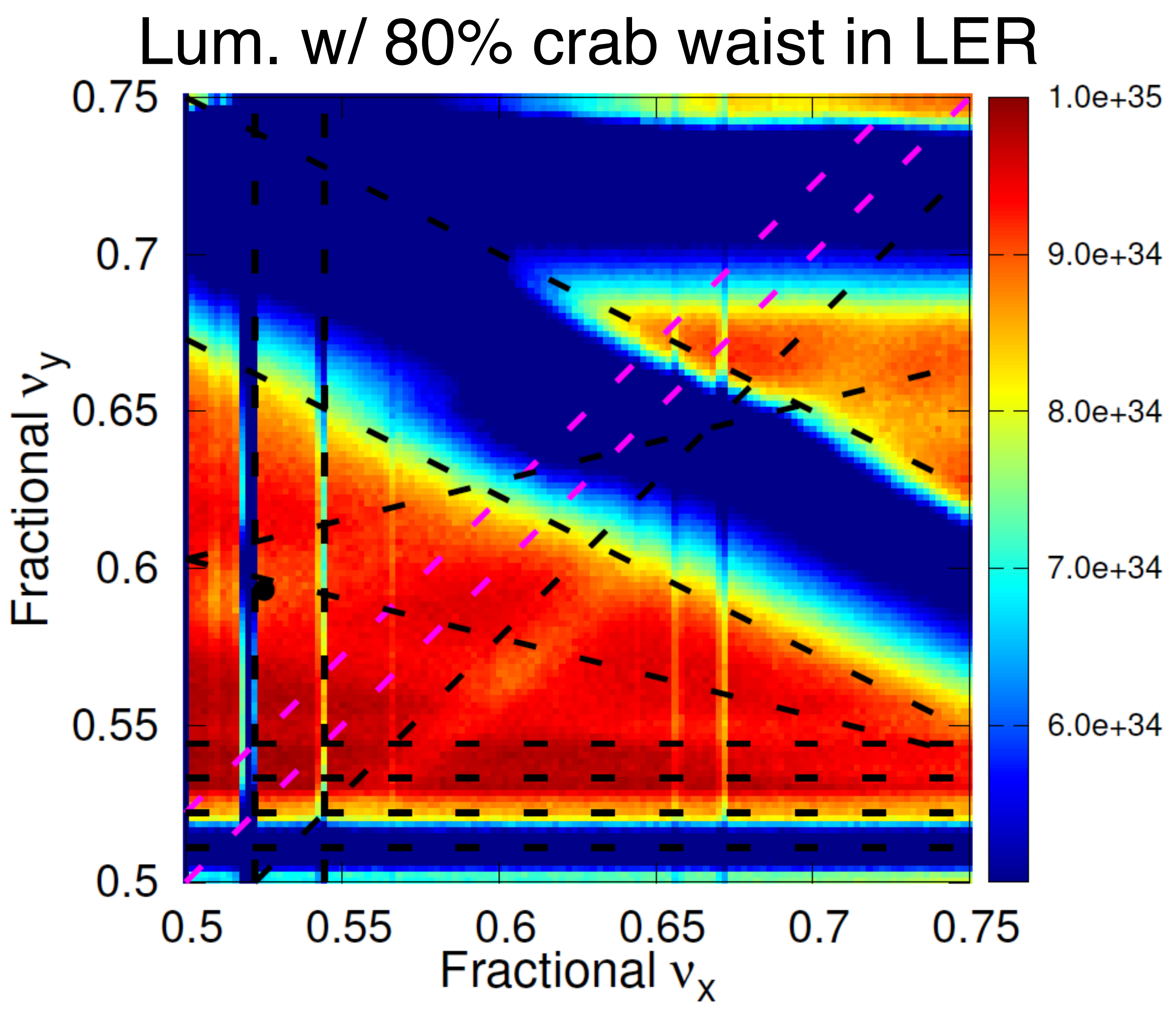


[4] Y. Zhang, Talk presented at the 5th ITF-BB subgroup meeting, KEK, Dec. 15, 2021, https://kds.kek.jp/event/40470/.

Beam-beam: simulations vs observations

- Jul. 01, 2021: HBCC study
  - Tune scan using BBWS showed that 80% crab waist ratio in LER is effective in suppressing vertical blowup caused by beam-beam resonances (mainly $\nu_x \pm 4\nu_y + \alpha = N$).
  - Moving ν_y downward to 0.57 should be better, but it was not verified in the beam-beam machine study on Dec. 21, 2021. One reason is that enough CW makes luminosity to be insensitive to ν_y. Another reason might be that σ_y^* blowup driven by transverse impedance (see talks by T. Ishibashi and K. Ohmi in this meeting) does not prefer moving ν_y downward to 0.57.

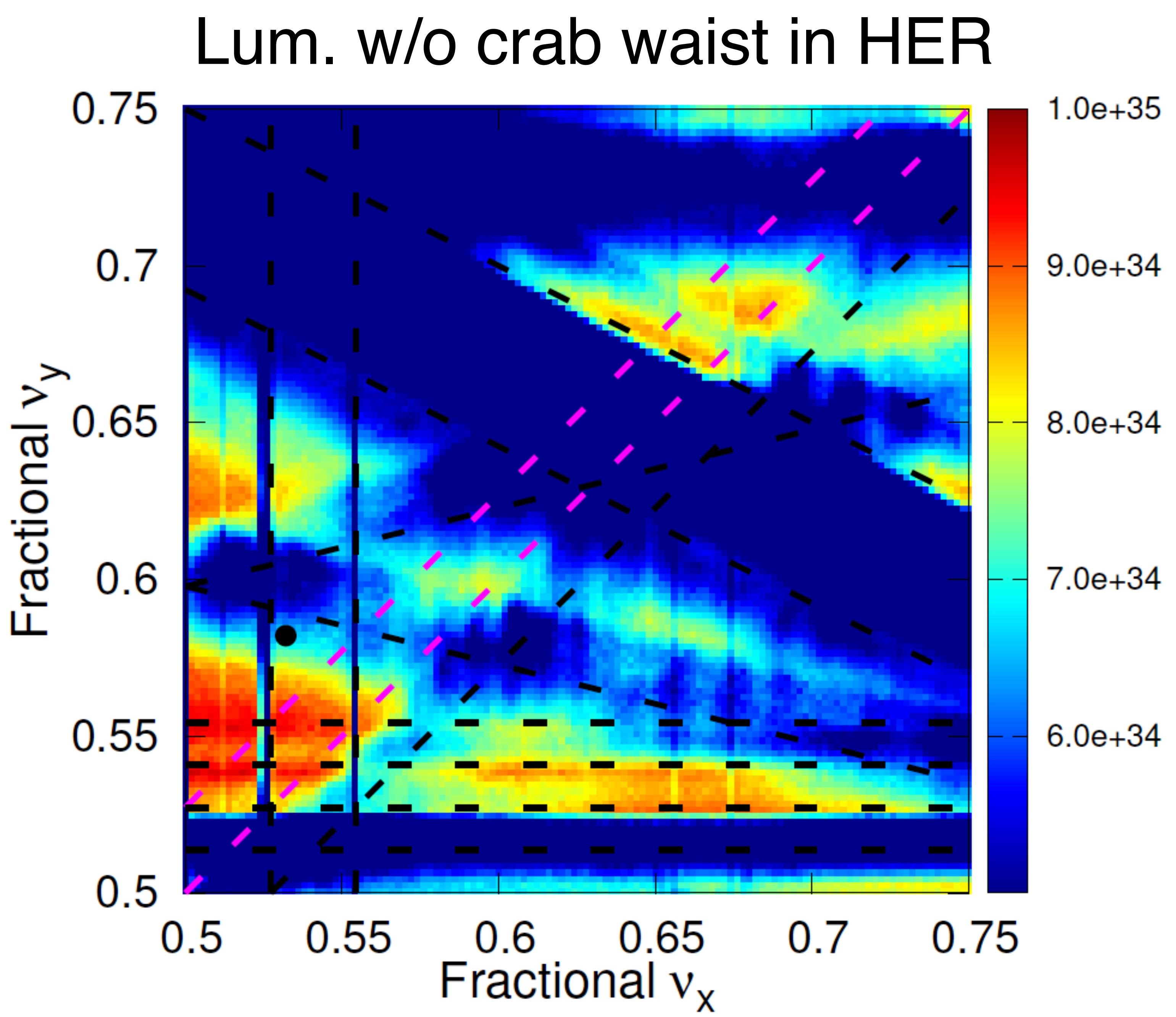


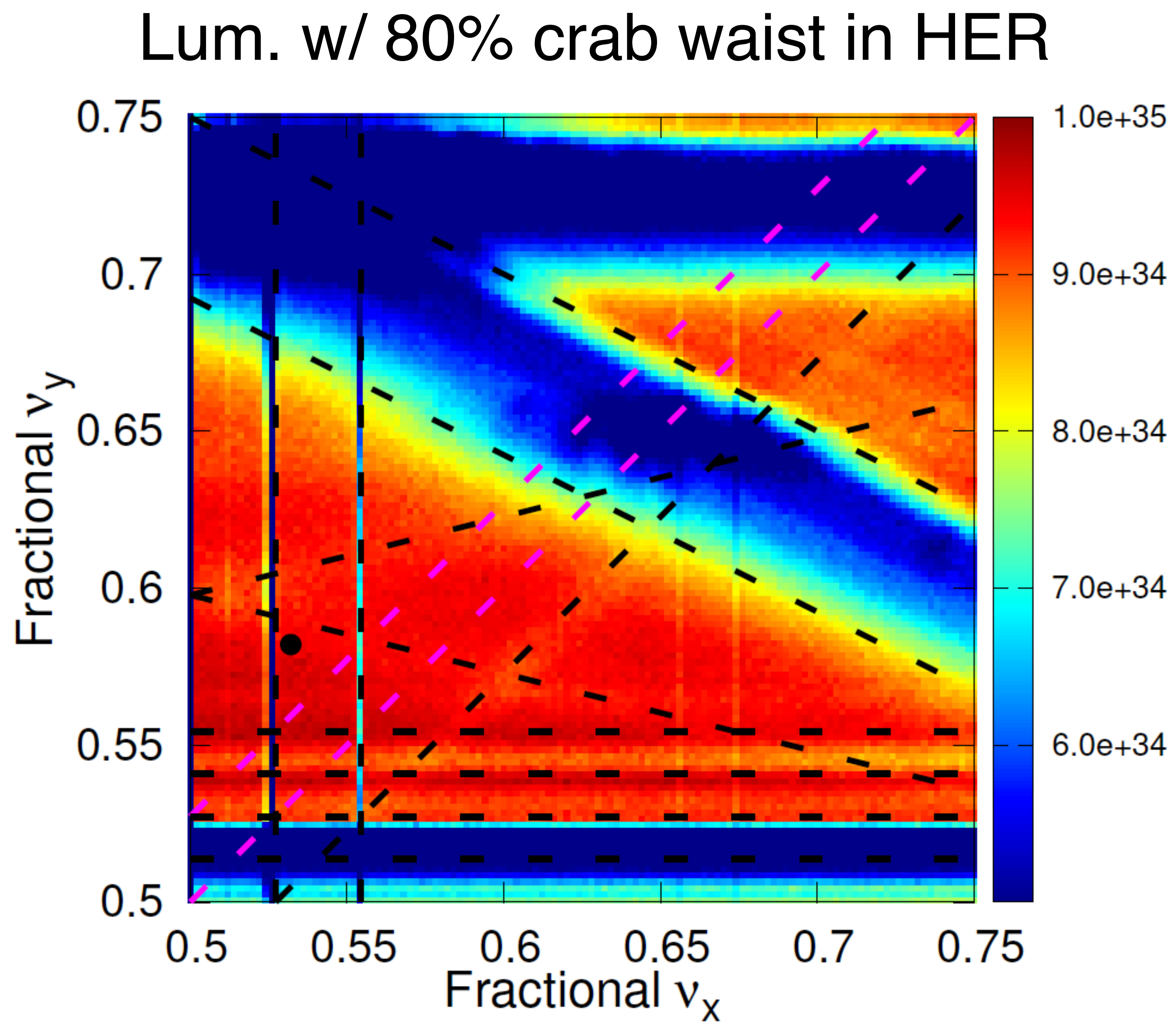


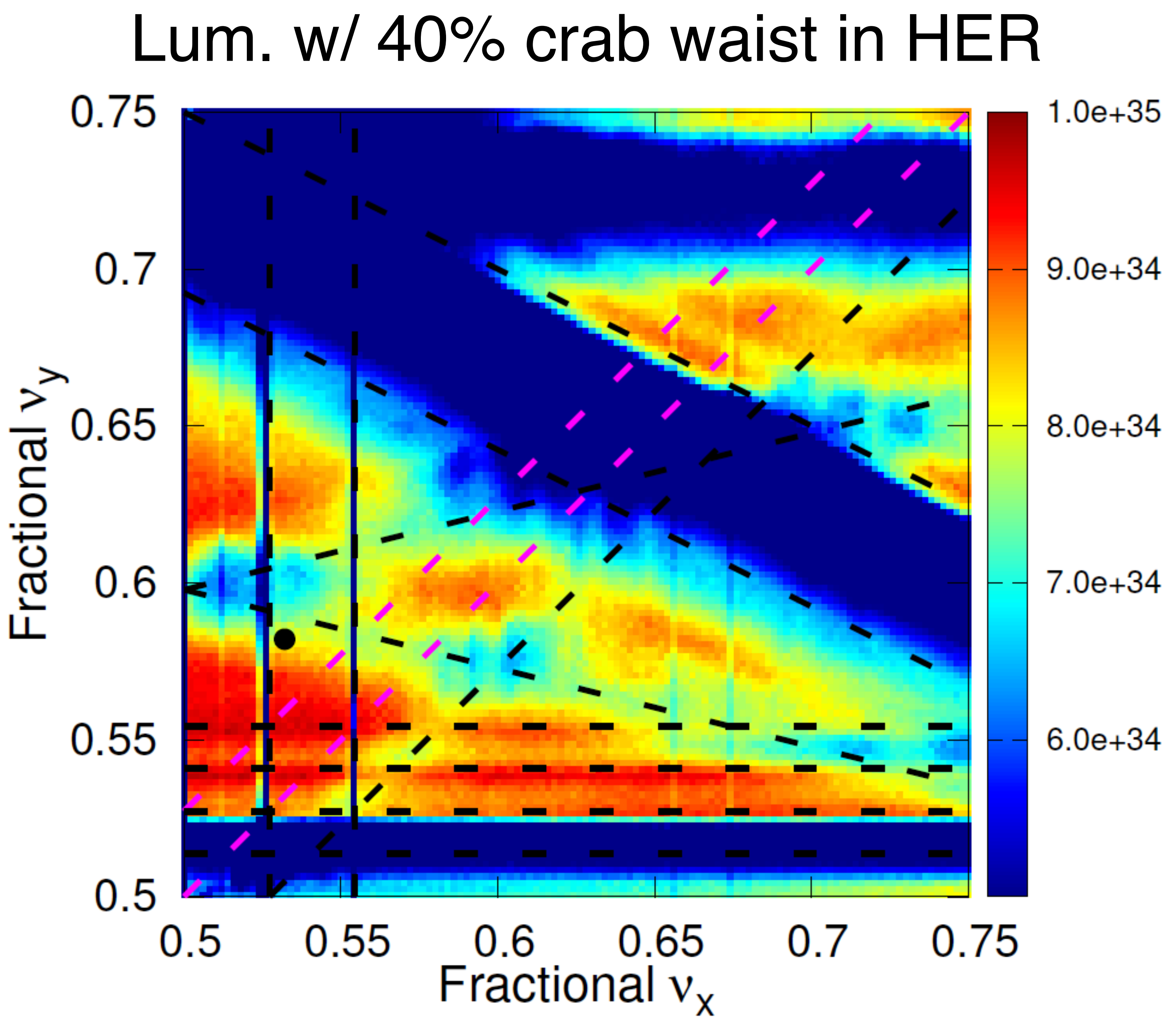
[2] D. Zhou, Talk presented at the 4th ITF-BB subgroup meeting, KEK, Nov. 25, 2021, https://kds.kek.jp/event/40237/.

Beam-beam: simulations vs observations

- Jul. 01, 2021: HBCC study
  - Tune scan using BBWS showed that 40% crab waist ratio in HER might not be enough for suppressing vertical blowup caused by beam-beam resonances (mainly $\nu_x \pm 4\nu_y + \alpha = N$).
  - Moving ν_y downward to 0.57 should give better luminosity, and it was verified in the beam-beam machine study on Dec. 21, 2021.



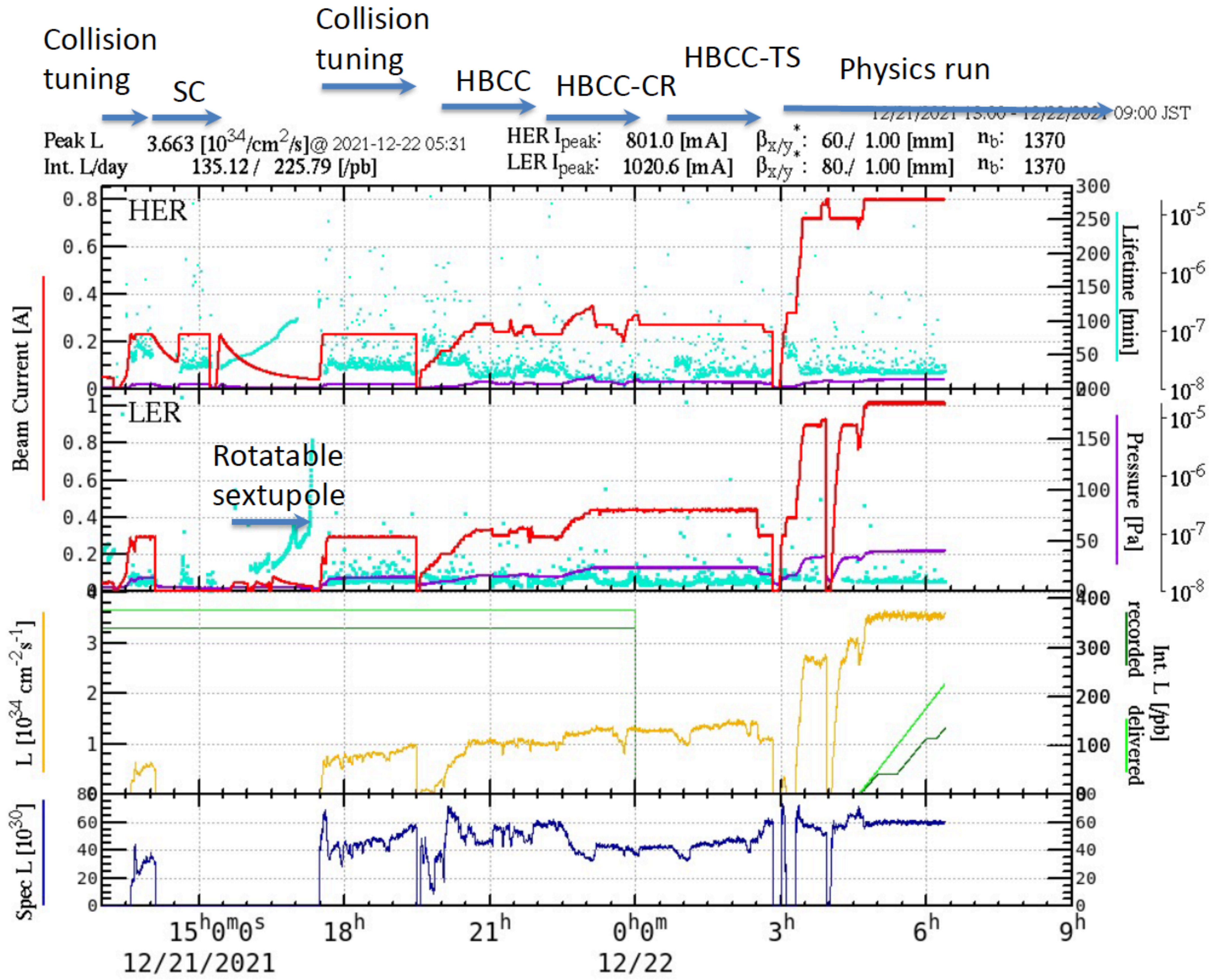


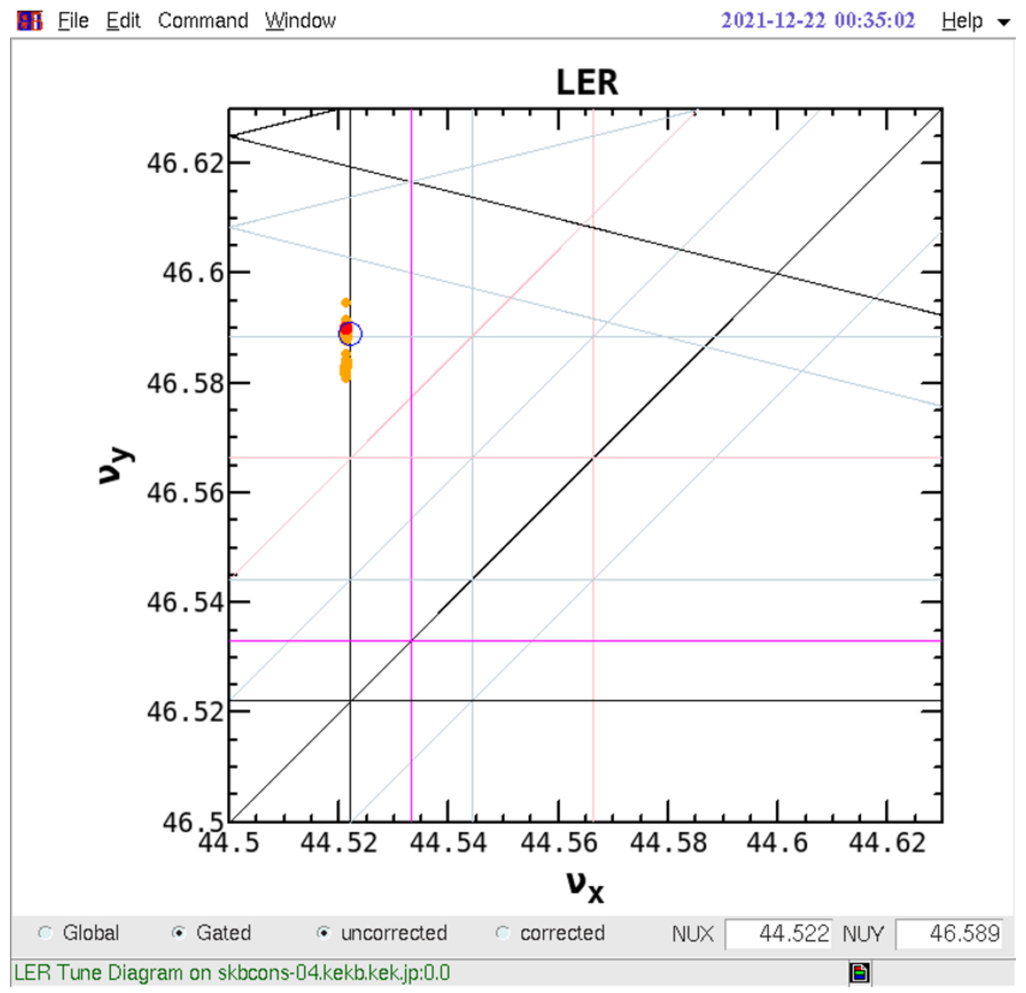


[2] D. Zhou, Talk presented at the 4th ITF-BB subgroup meeting, KEK, Nov. 25, 2021, https://kds.kek.jp/event/40237/.

Beam-beam: simulations vs observations

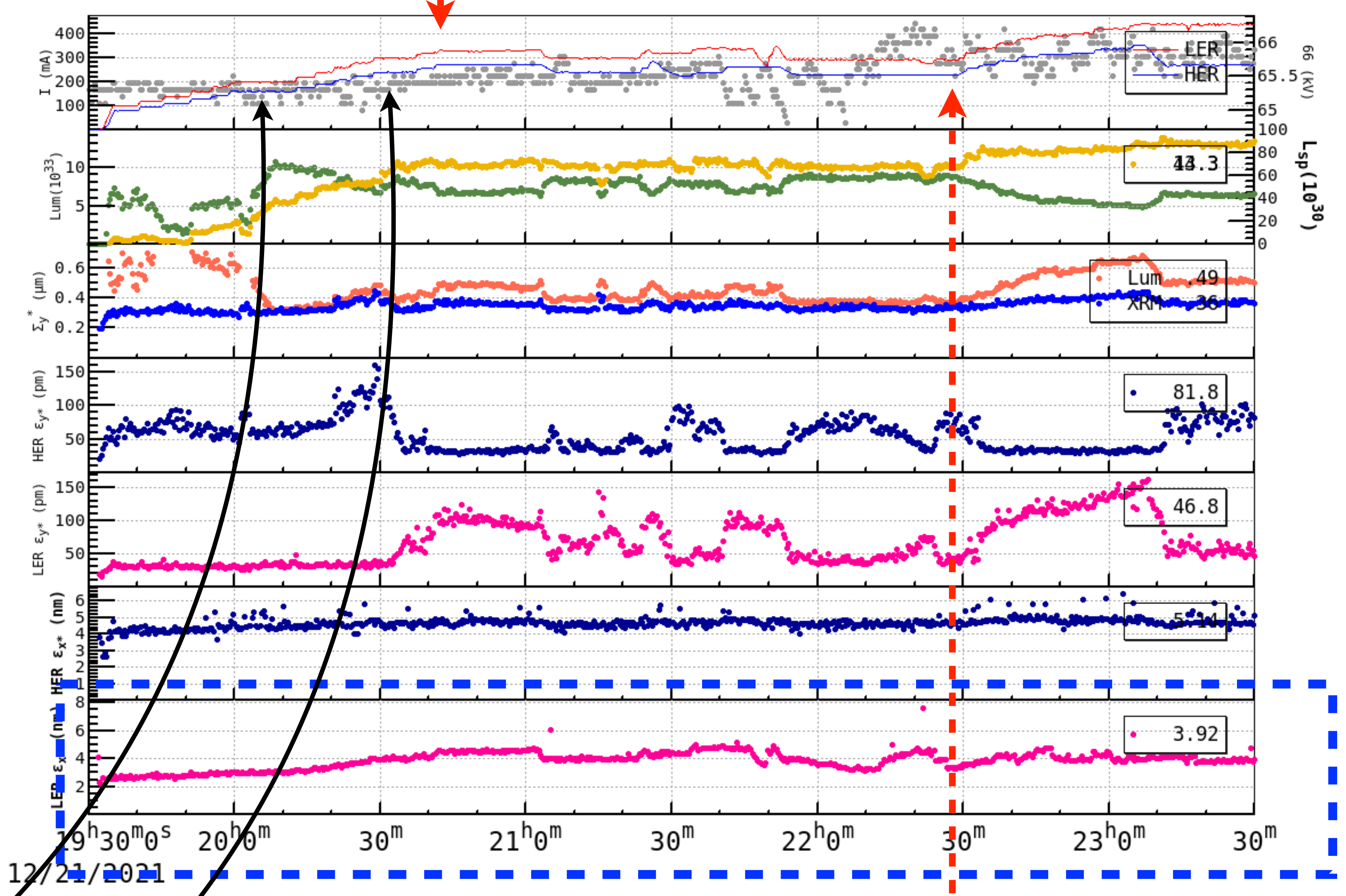
- Dec. 21-22, 2021: Beam-beam study overview
  - The beam-beam machine study was very successful with several important findings.
  - LER horizontal ϵ_x blowup was verified: It is driven by beam-beam and sensitive to LER ν_x. It is not simply coherent BBHTI. It can be a phenomenon of beam-beam driven 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.

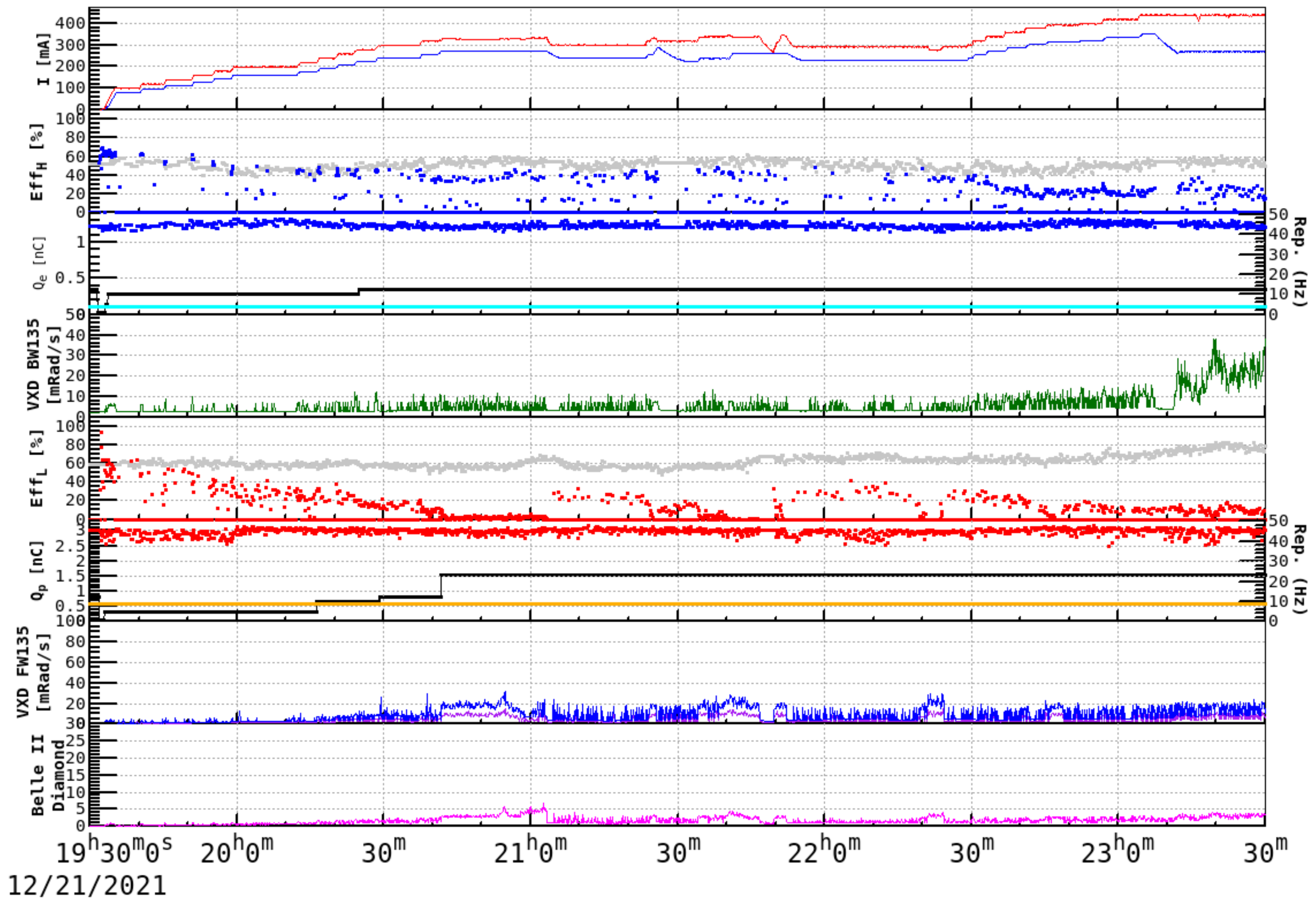


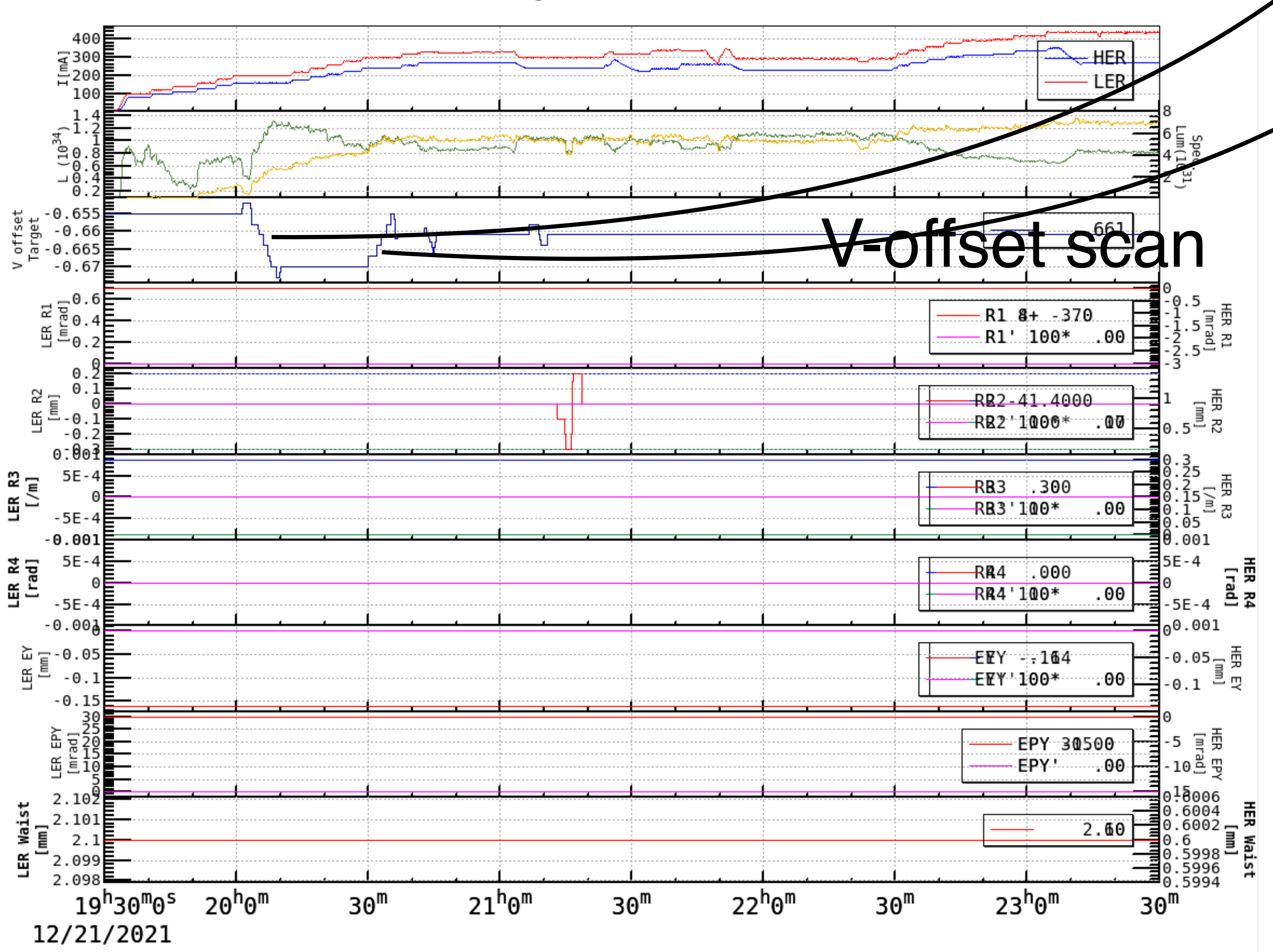


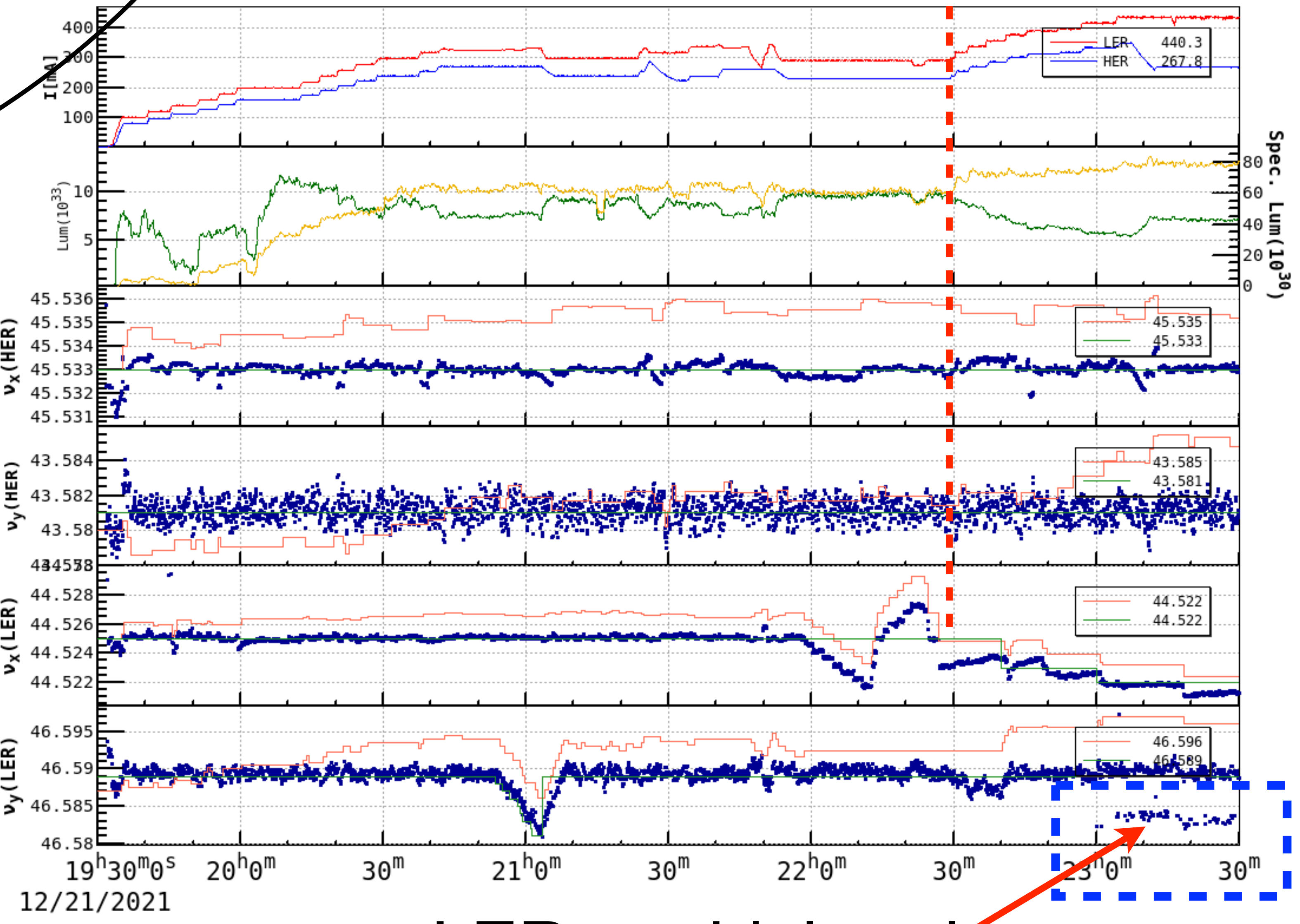
Beam-beam: simulations vs observations

- 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. It's better to do HBCC study immediately after physics run?
  - 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.









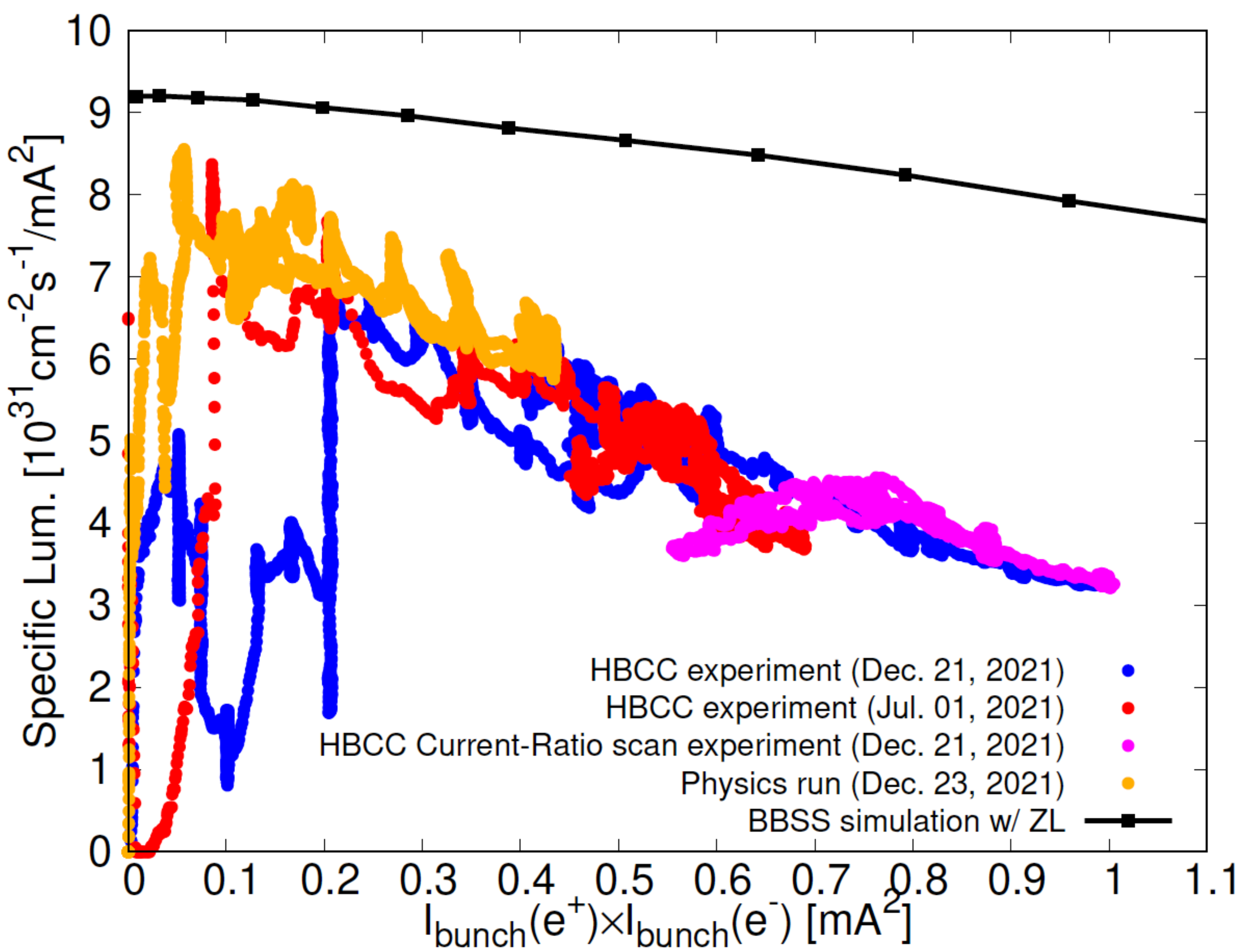
Beam-beam: simulations vs observations

- 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

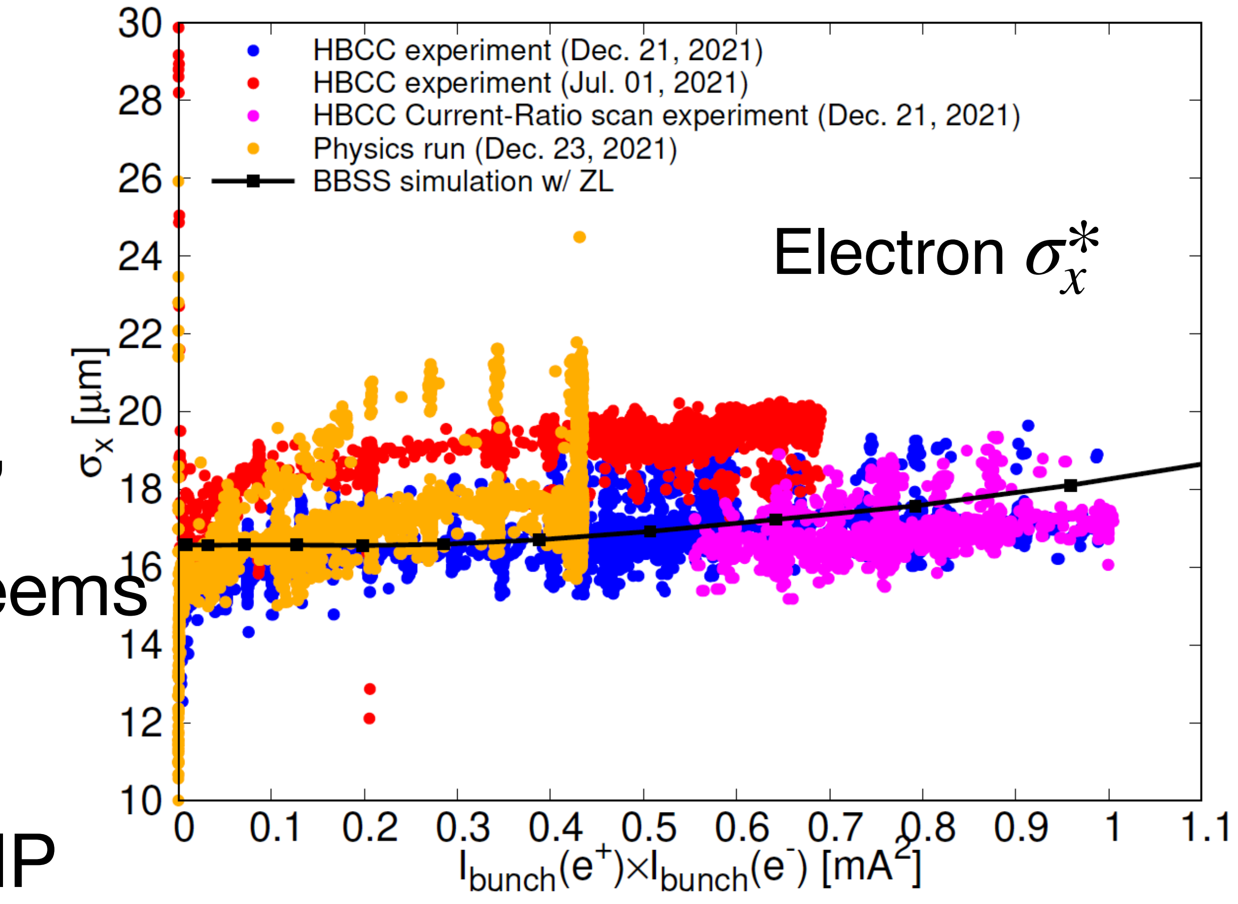
	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	
# bunch	393		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	20	35	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured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

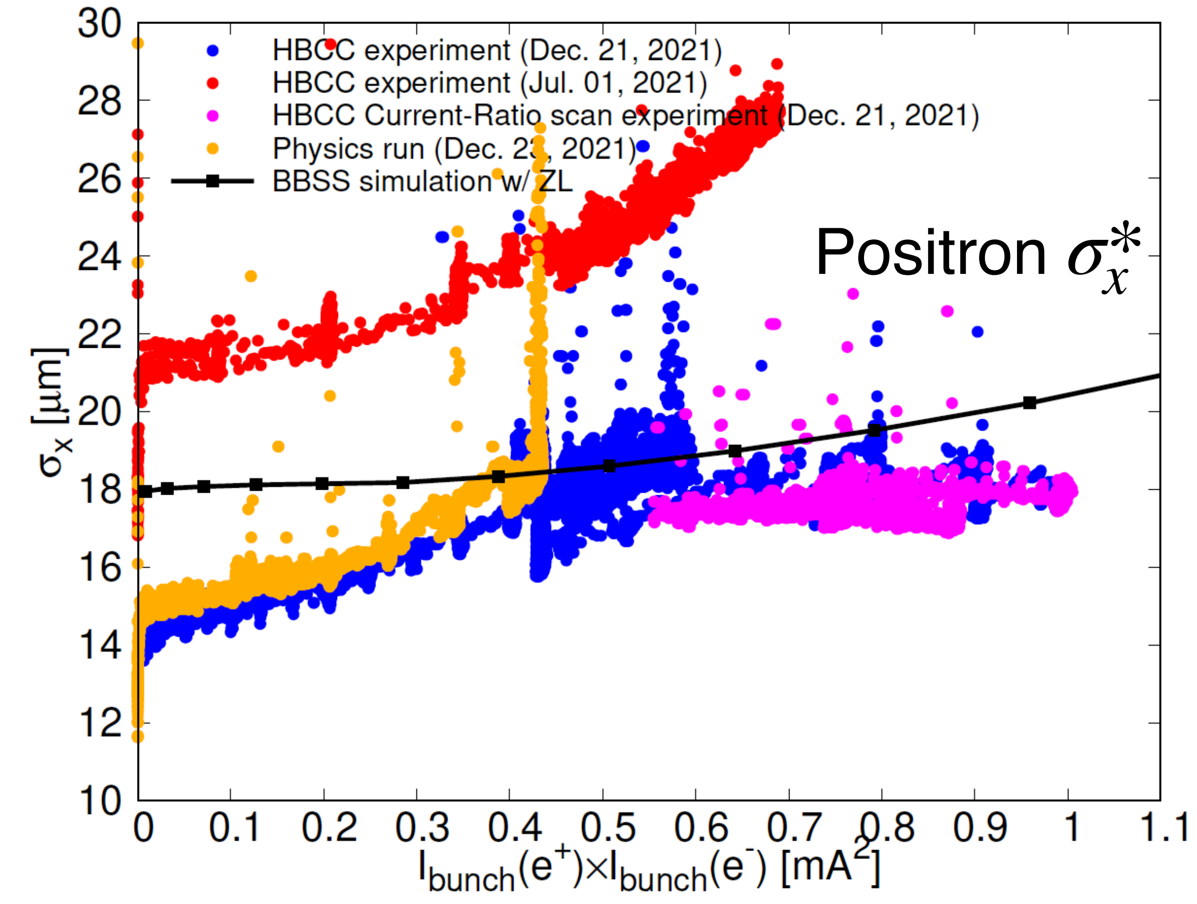
Lsp: BBSS simulations vs observation



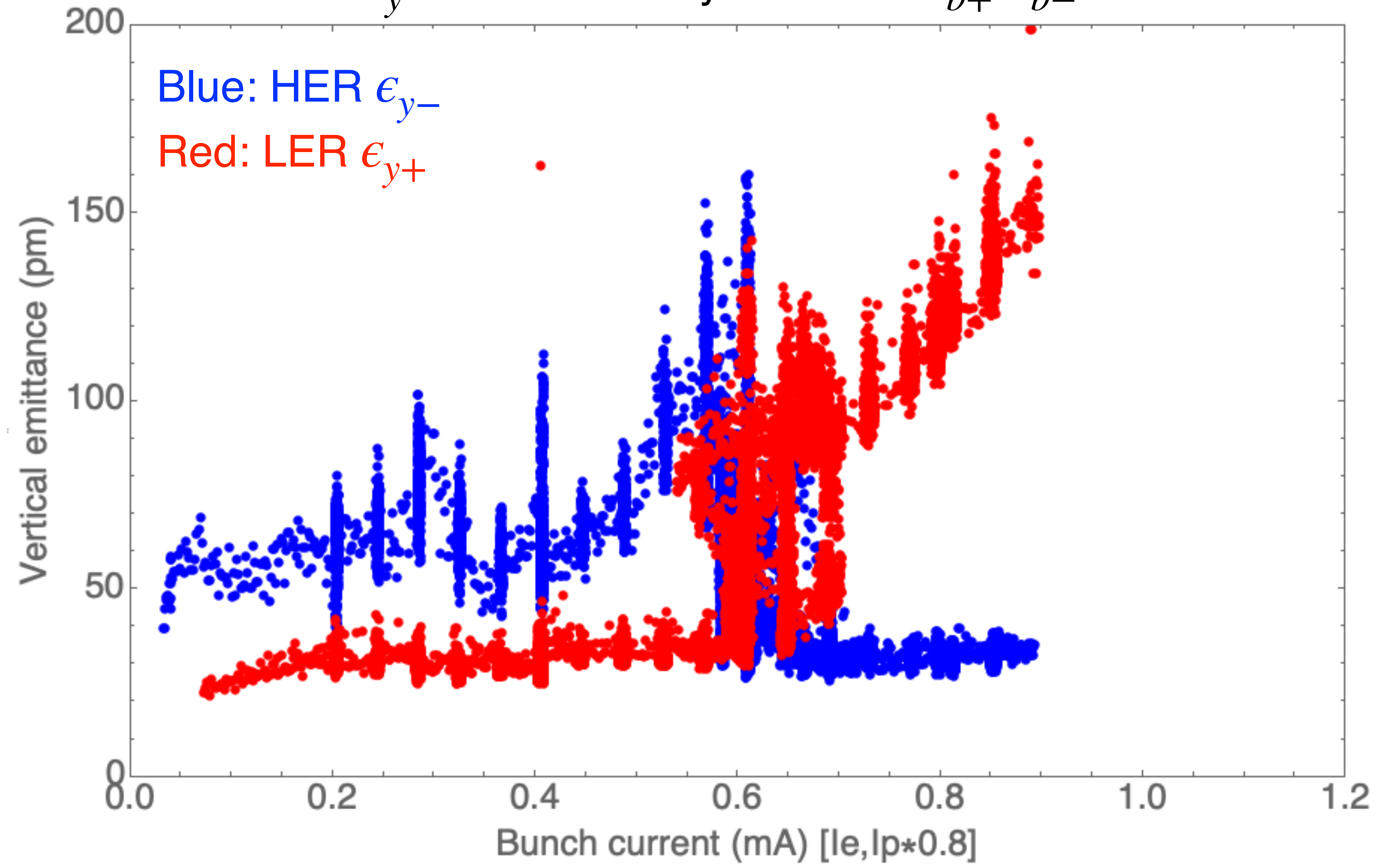
Beam-beam: simulations vs observations

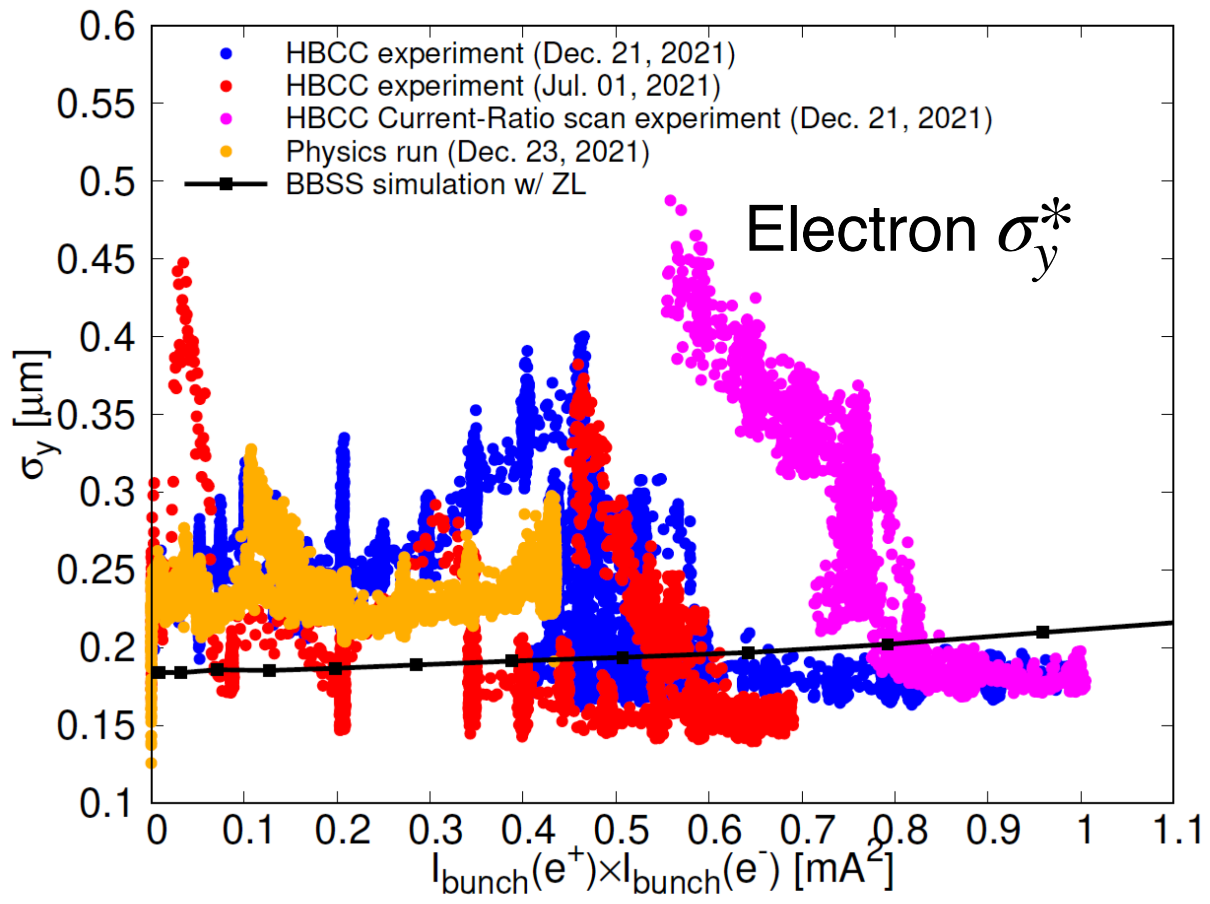
- Dec. 21-22, 2021: HBCC study
  - LER σ_x^* blowup was partially mitigated by reducing LER ν_x.
  - It was hard to achieve balanced collision ($\sigma_{y+}^* \approx \sigma_{y-}^*$) when $I_{b+}I_{b-} > 0.45$ mA².
  - When bunch current ratio is fixed with I_{b+}/I_{b-}=1.25, a "flip-flop" phenomenon 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.

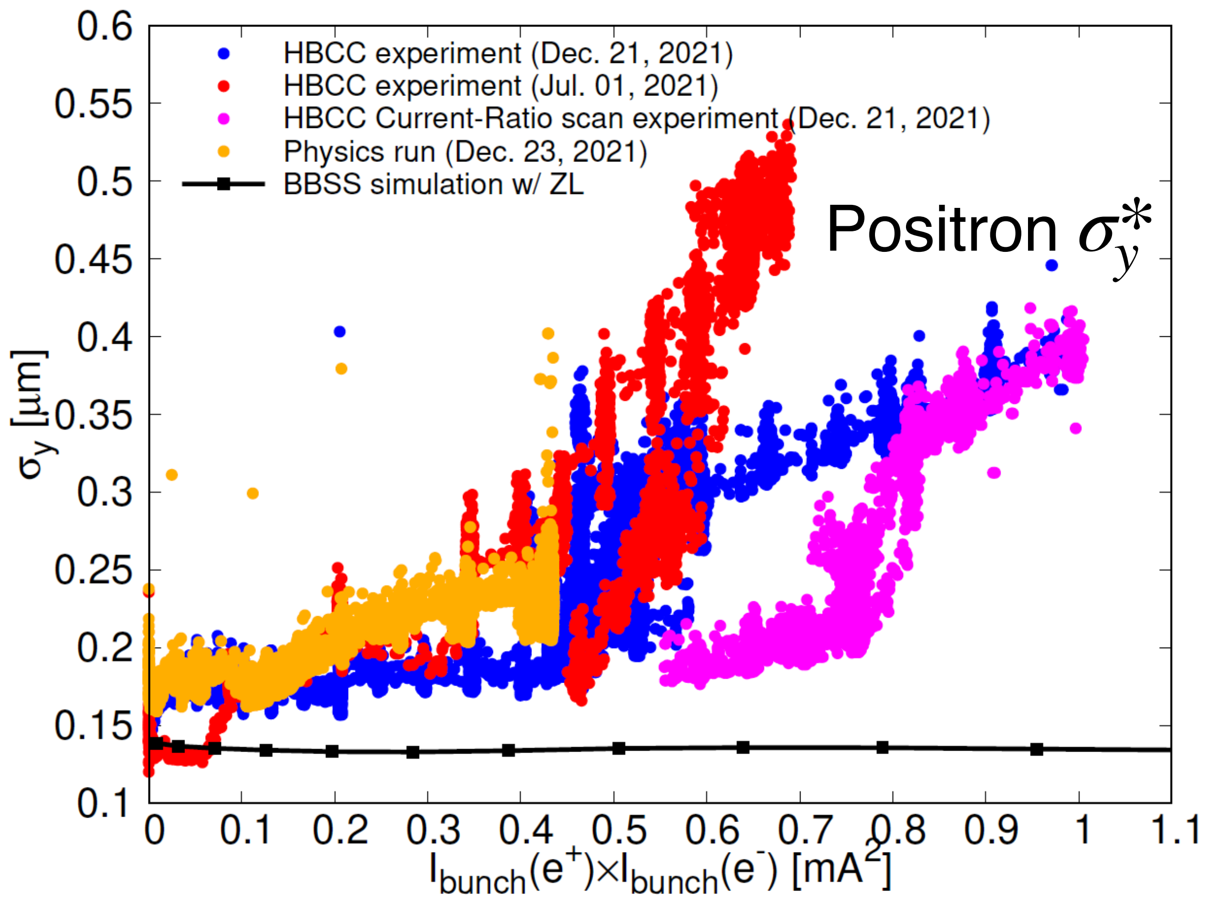




Vertical ϵ_y for HBCC study with fixed I_{b+}/I_{b-}=1.25

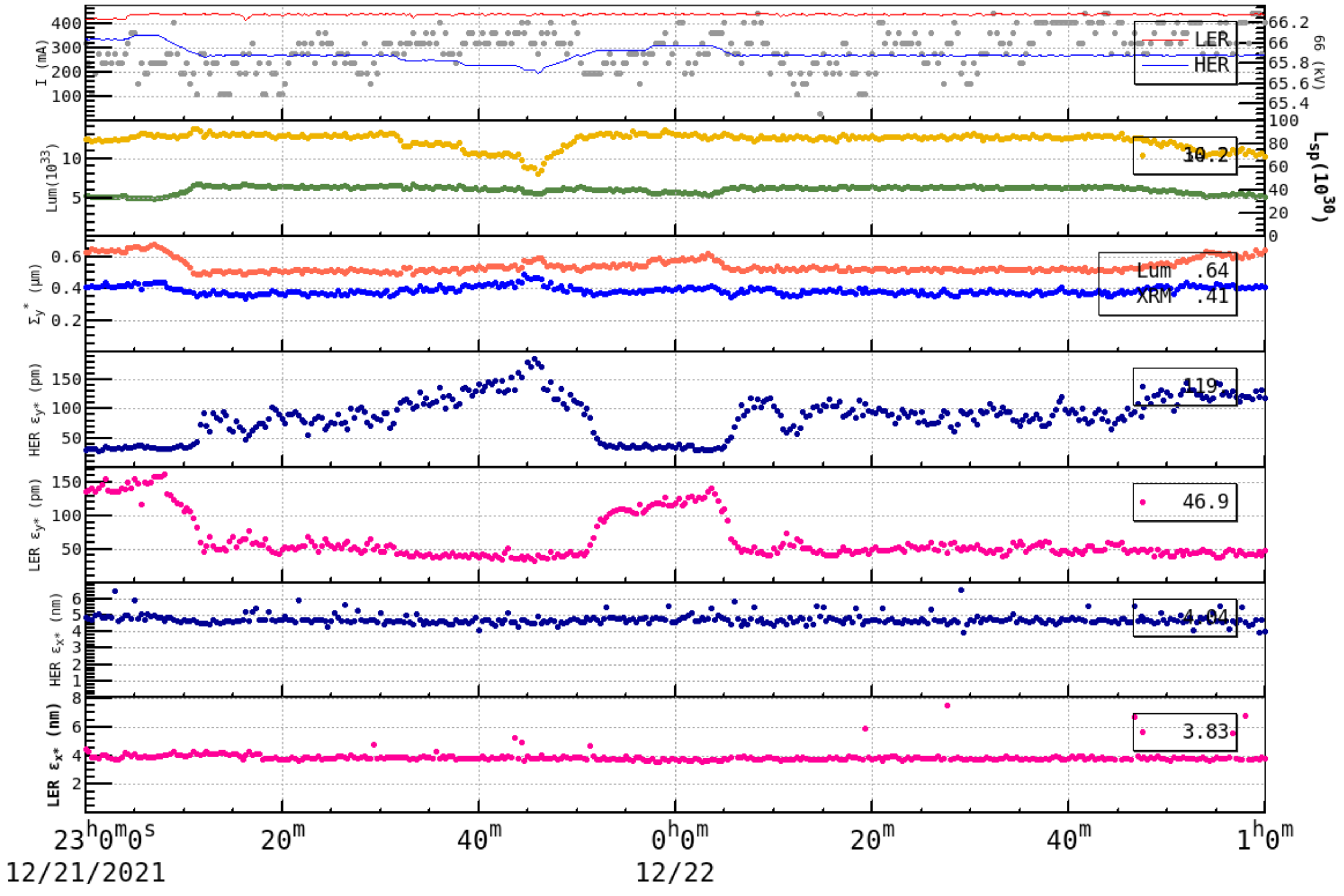


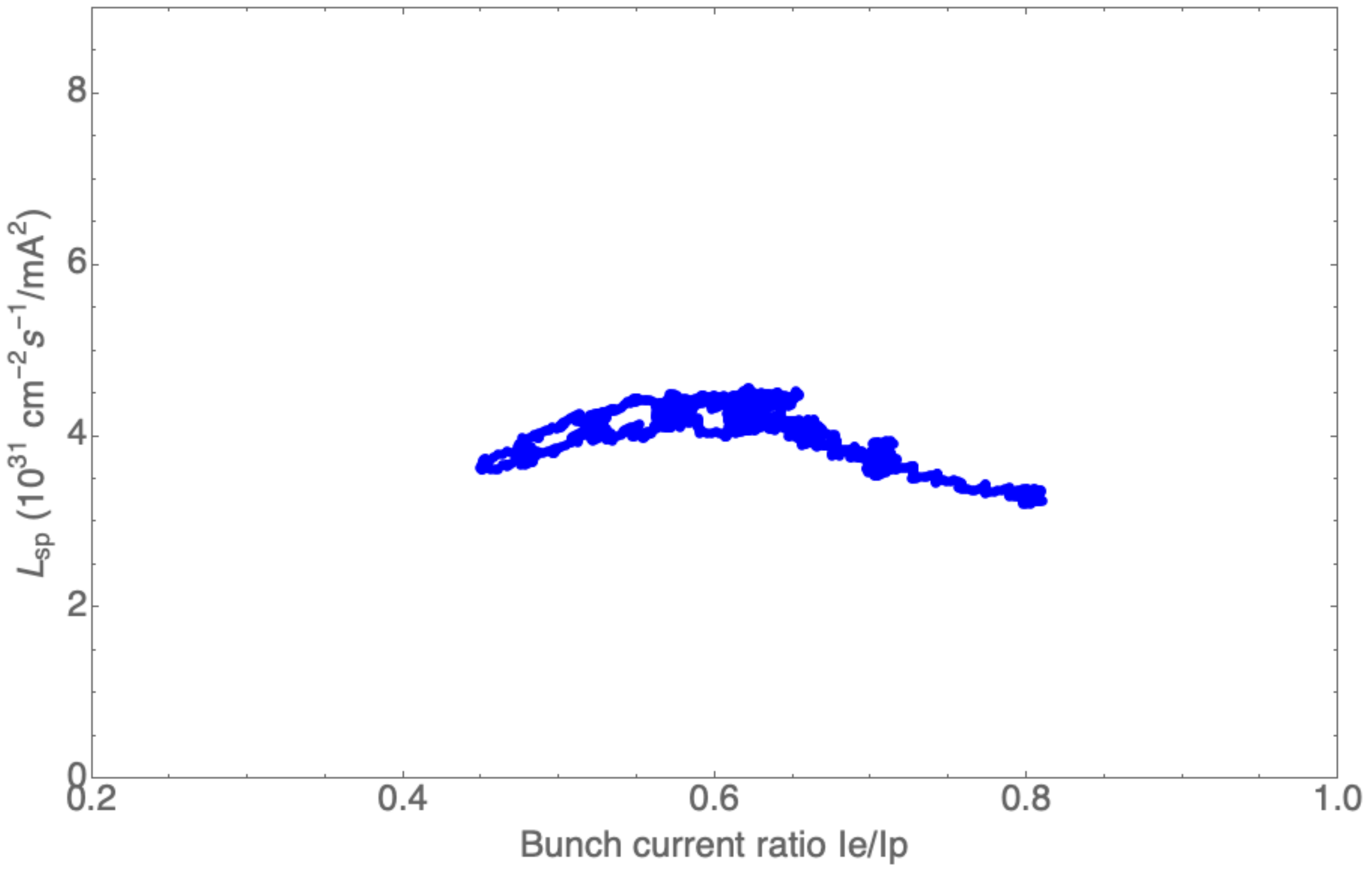


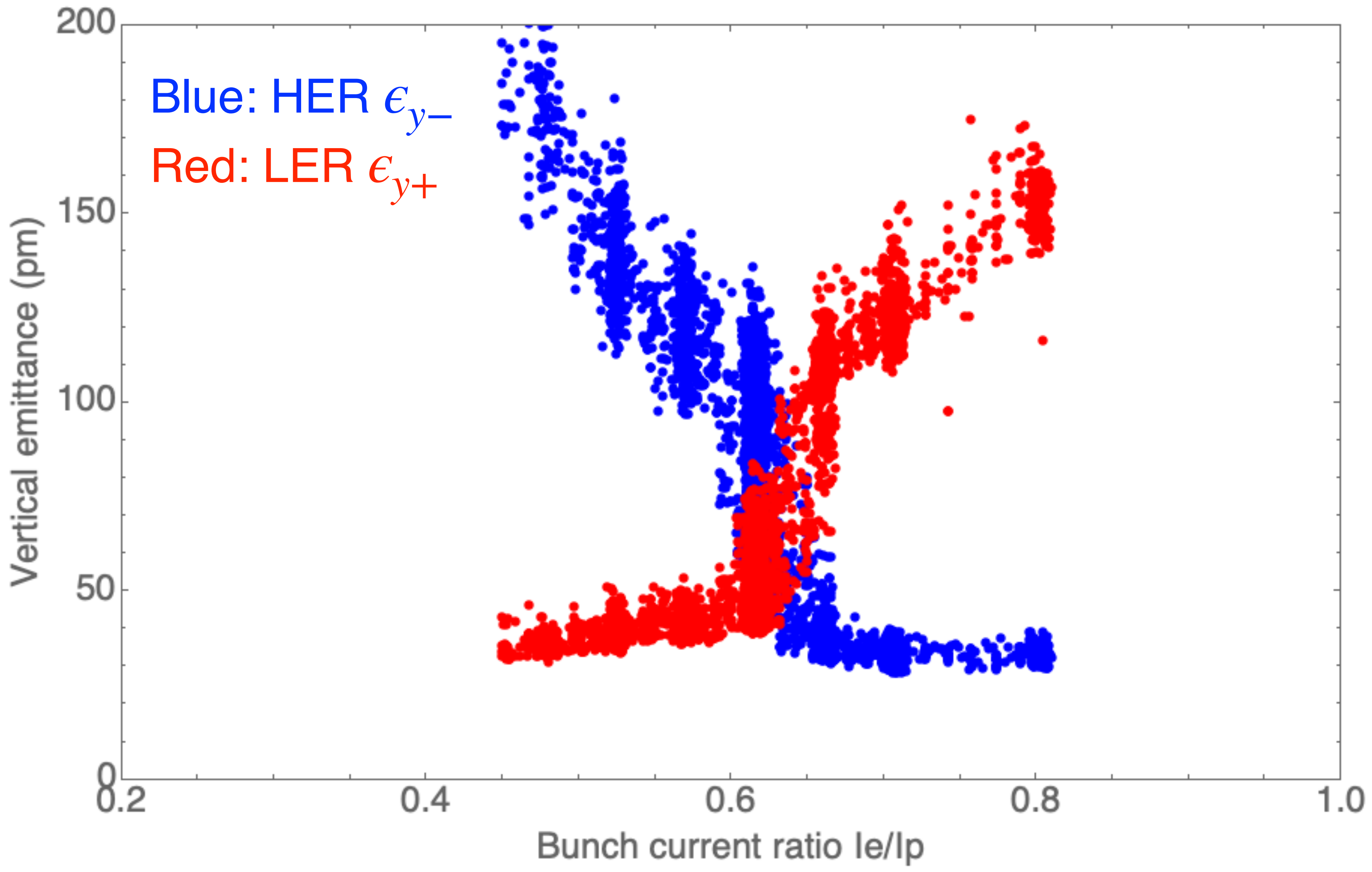


Beam-beam: simulations vs observations

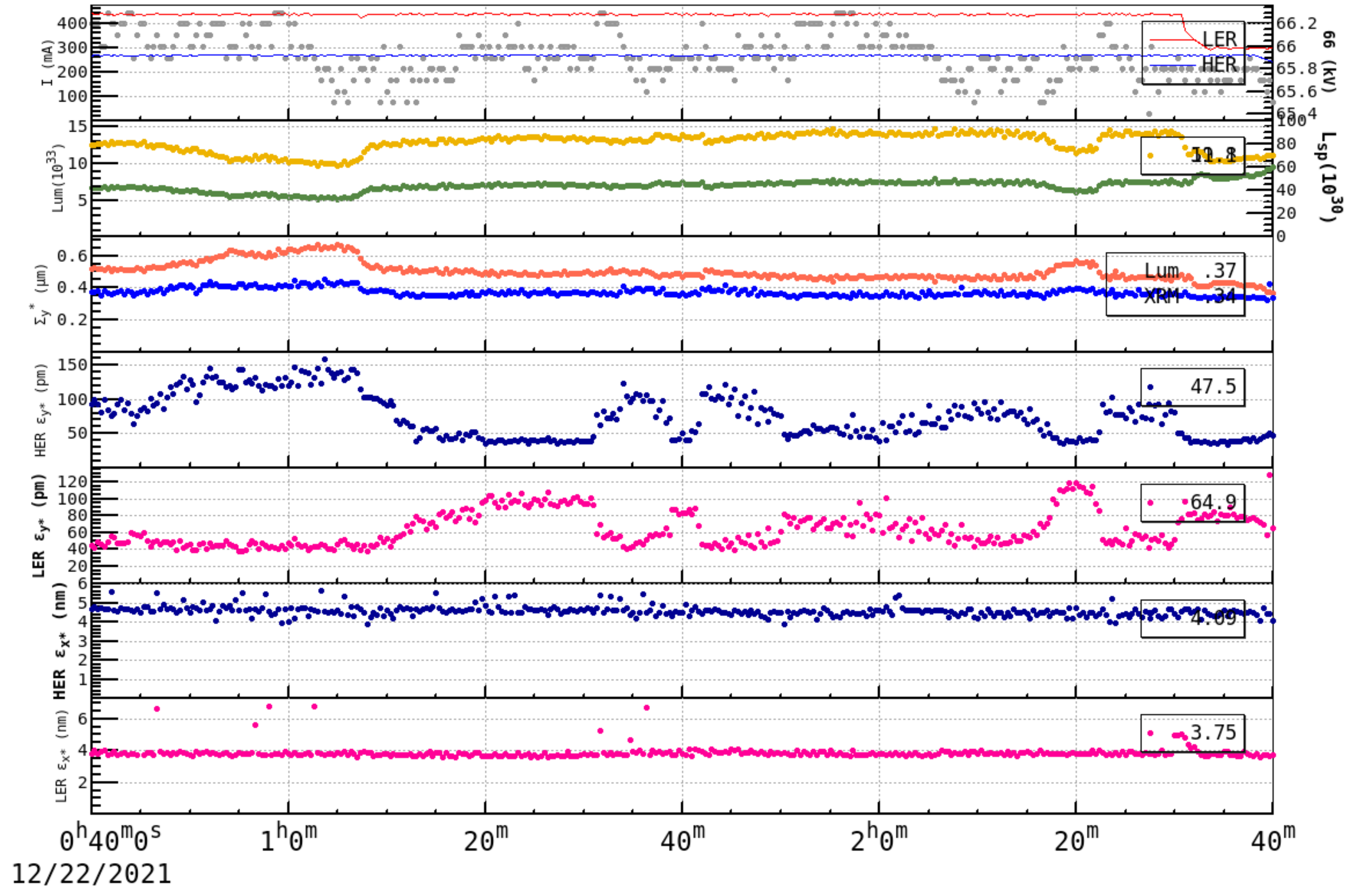
- Dec. 21-22, 2021: HBCC current-ratio study
  - When the LER beam current is fixed at 440 mA (393 bunches), the optimum current ratio ("optimum" means maximum Lsp with $\sigma^*_{y+} \approx \sigma^*_{y-}$) was found at $I_{b+}/I_{b-} \approx 1.7$, close to the energy transparency condition $I_{b+}/I_{b-}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



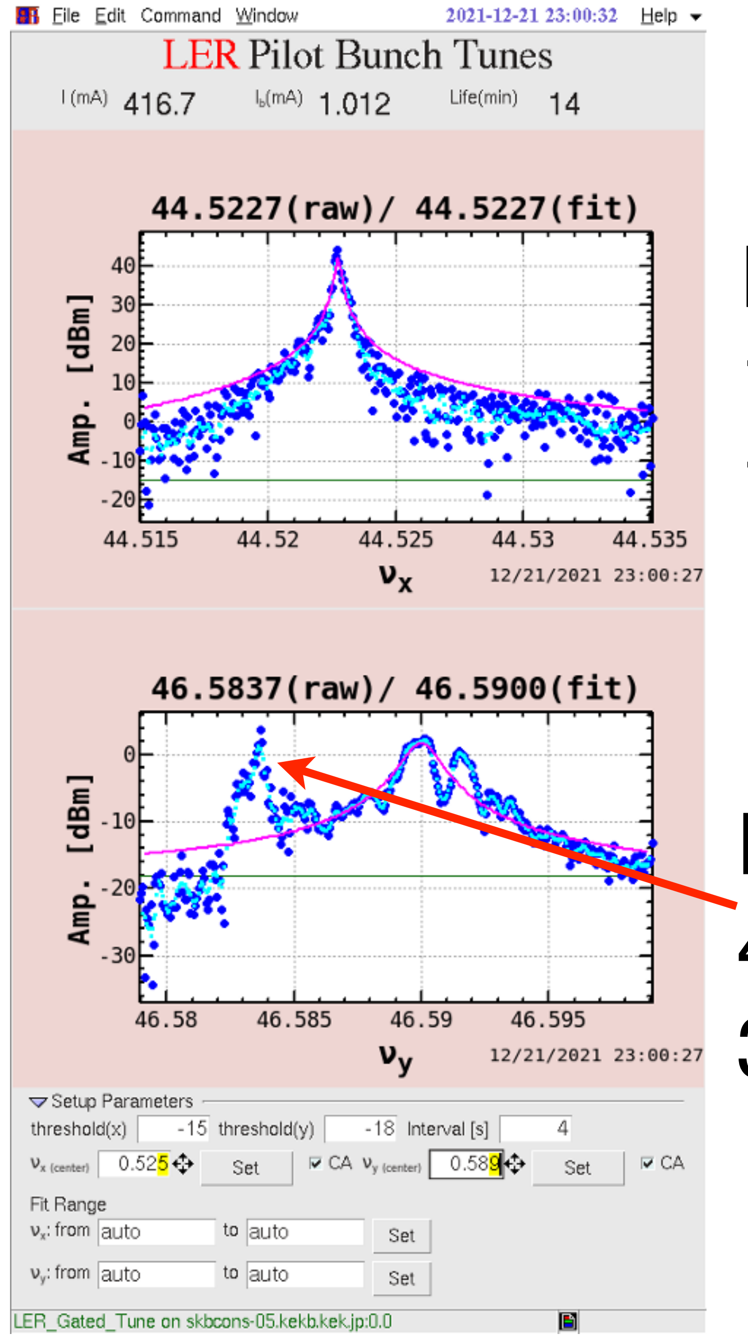


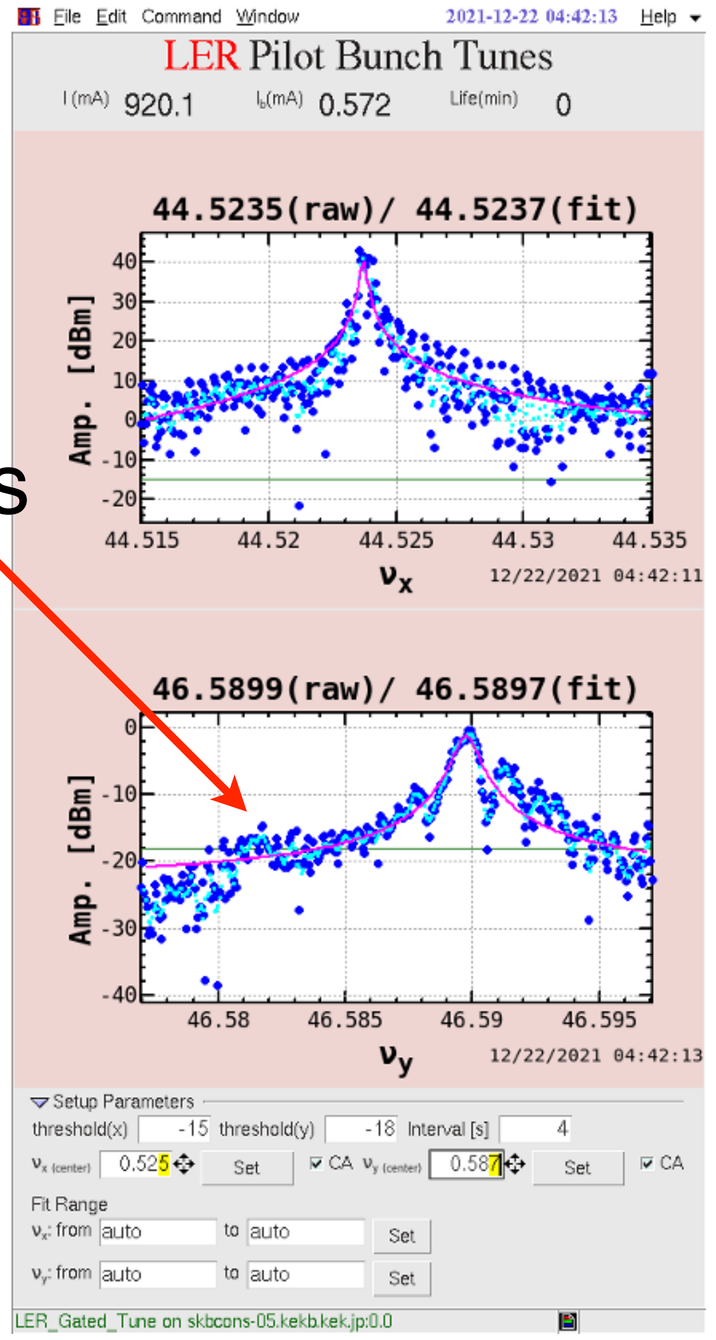


Beam-beam: simulations vs observations



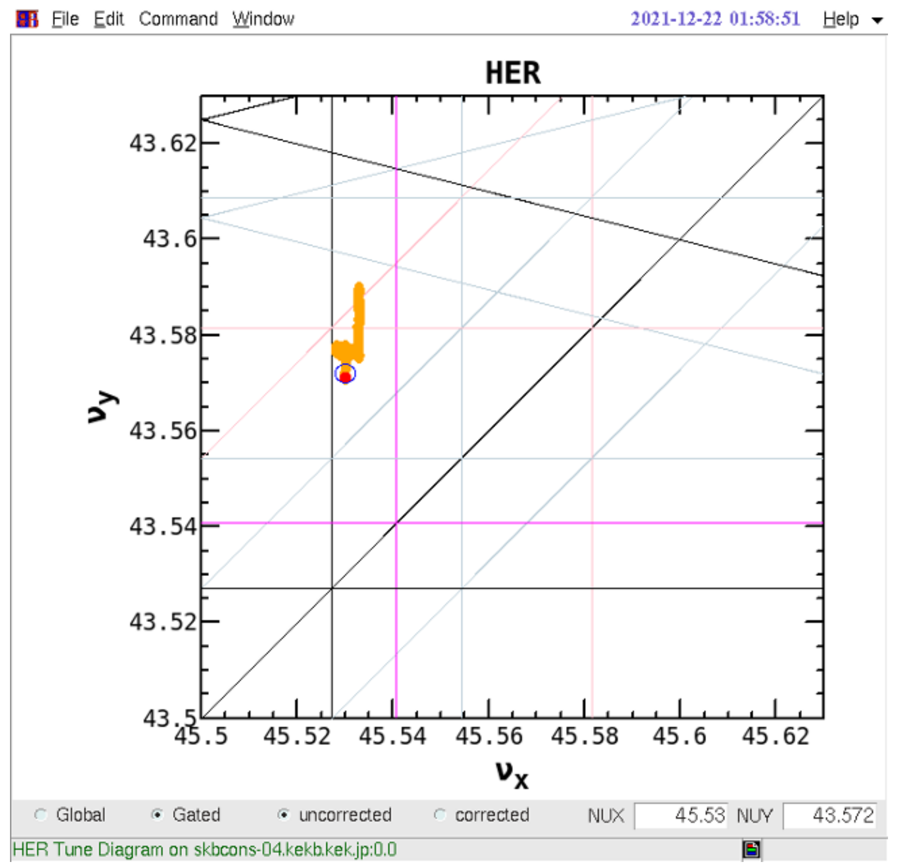
- Dec. 21-22, 2021: HBCC tune-survey study
  - Tune survey was done with fixed beam current I_{+}/I_{-}=440/352 mA (393 bunches).
  - With I_{b+}>1 mA, sideband of LER ν_y (-1 mode) was alway seen.
  - Changing HER ν_y from 43.582 to upper side cause HER vertical blowup and luminosity loss, down side 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).

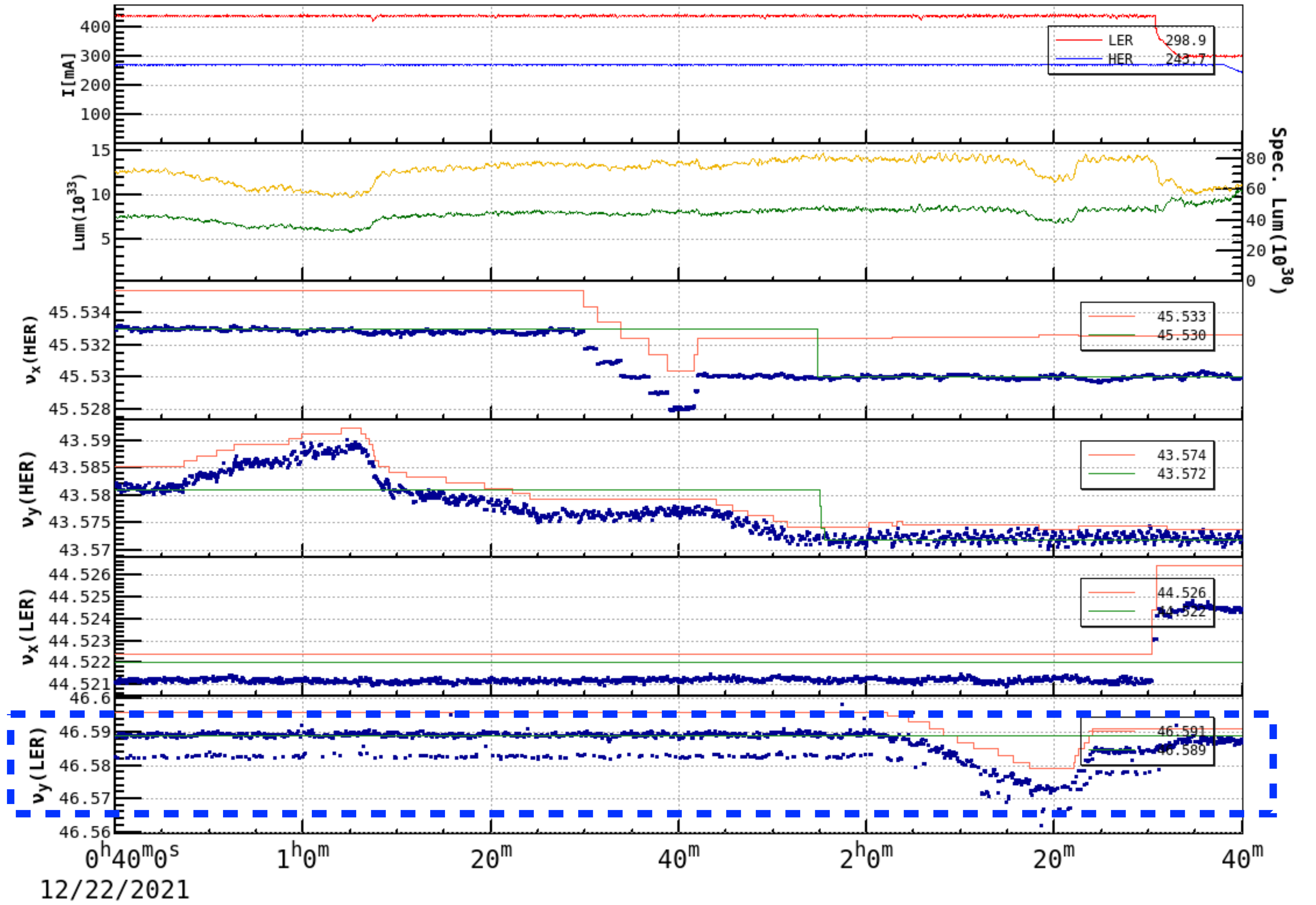




Physics run
1020 mA
1370 bunches

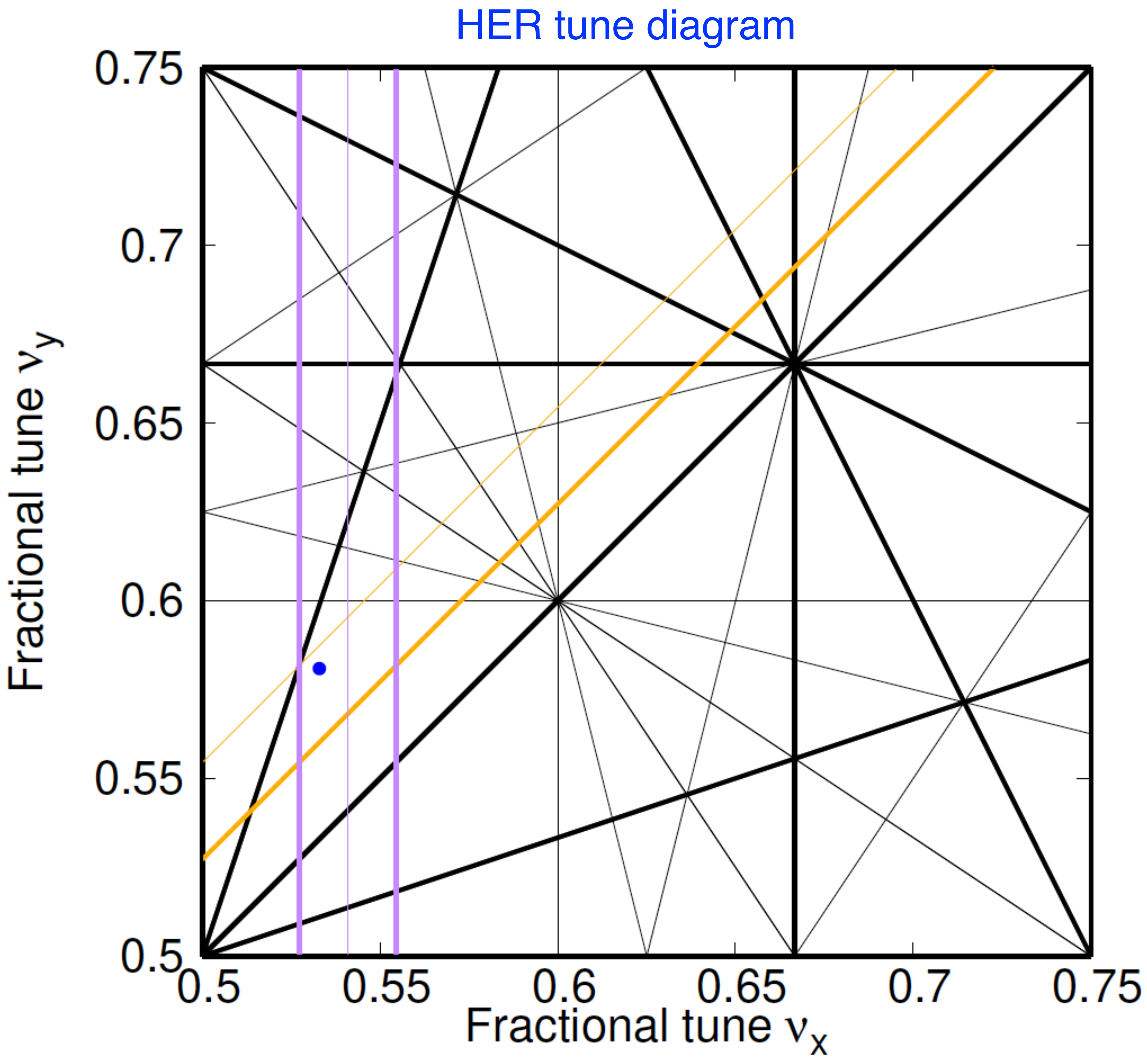
HBCC
440 mA
393 bunches

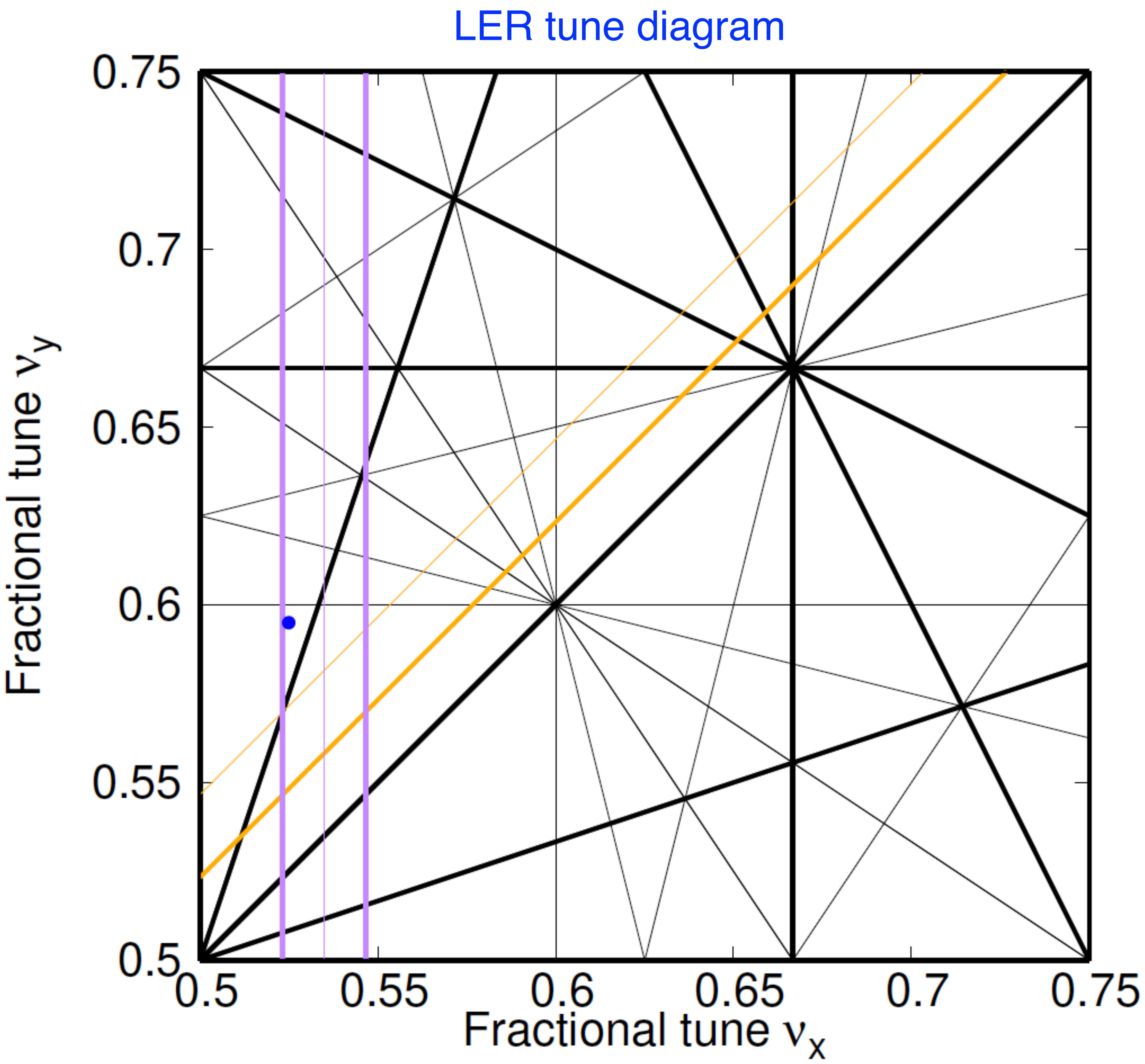




Resonances and tune survey

- Resonances to be identified
  - Note that LER/HER are operated above/below $\nu_x - \nu_y + 2\nu_s = N$ and $3\nu_x - \nu_y = N$, respectively.

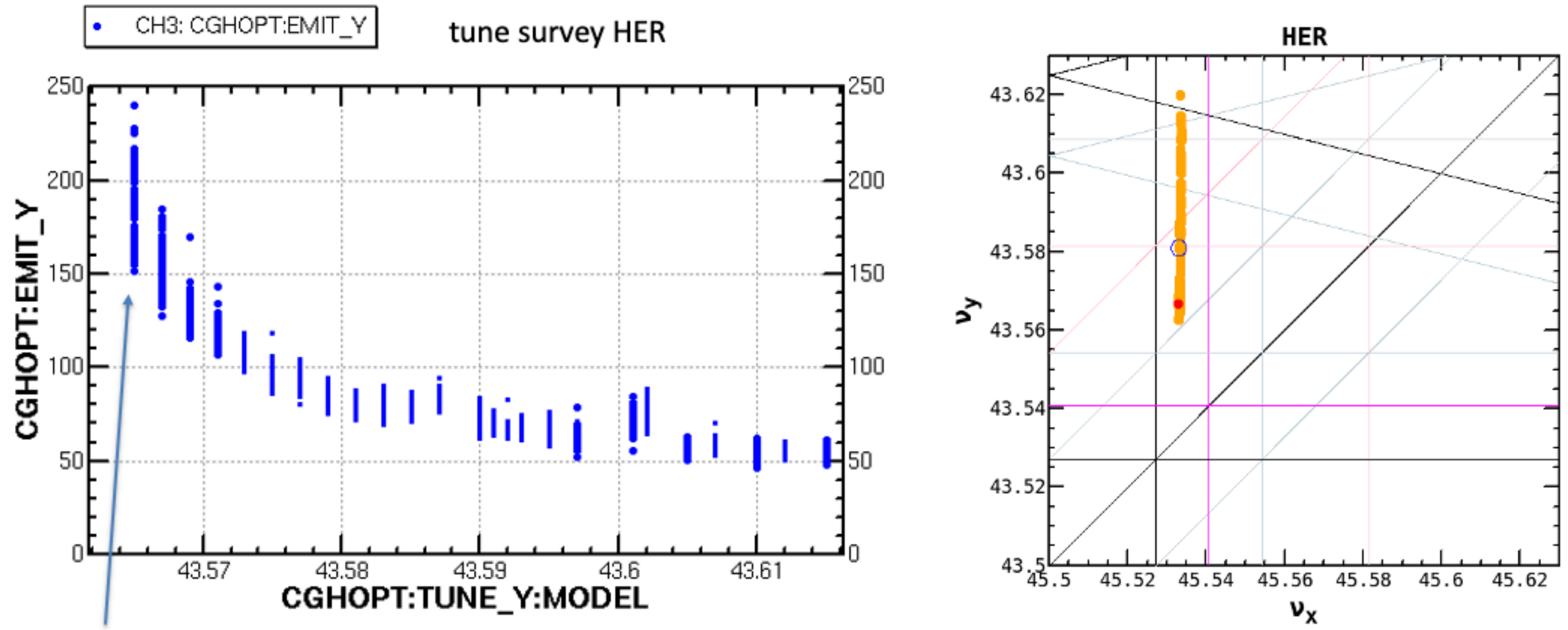




Resonances and tune survey

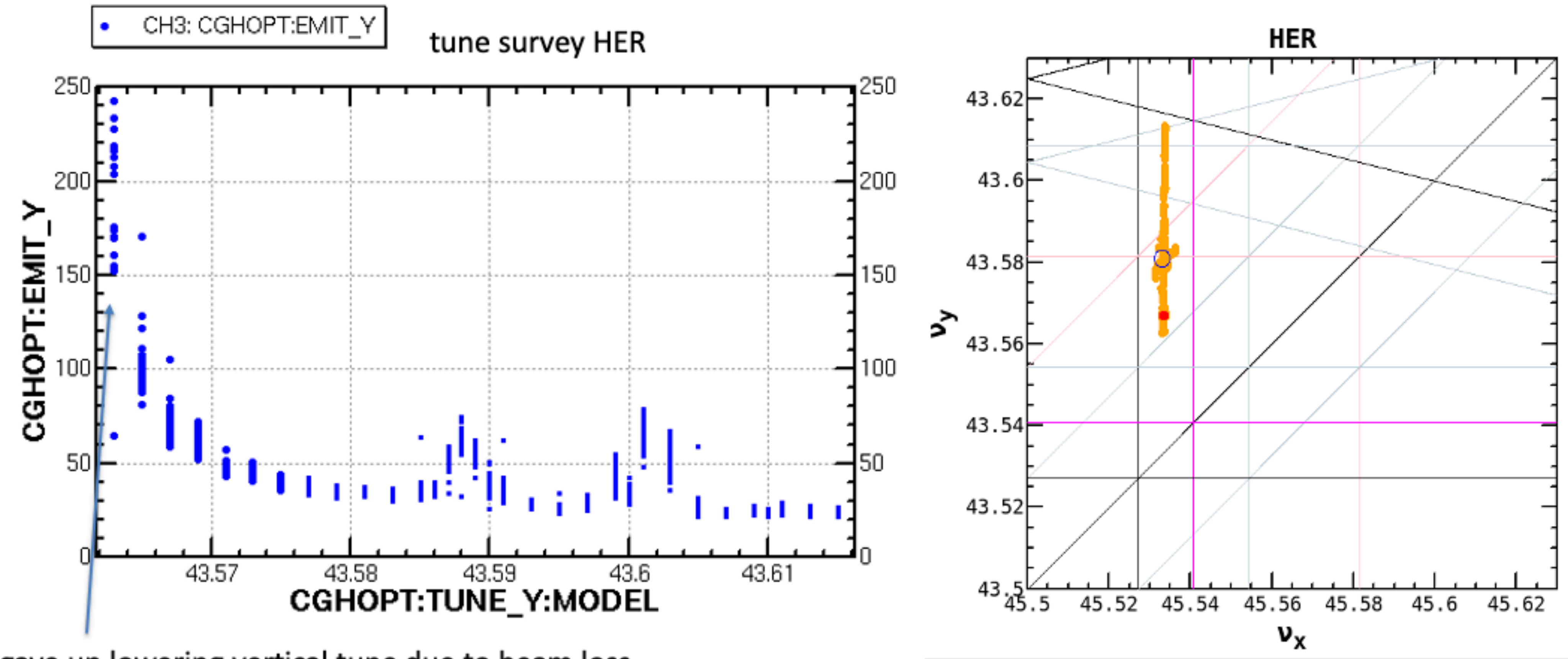
- HER tune survey done on Nov. 8, 2021
  - The study was done with LER trouble with injection kickers. So the beam time of HER was available for such study.
  - More details about the study can be found from shift report (2021_11_08_0900_Ueda_Funakoshi).
  - Post analysis of the experimental data showed clear emittance blowup caused by chromatic couplings of $\nu_x - \nu_y + \nu_s =$ Integer and $\nu_x - \nu_y + 2\nu_s =$ Integer. Because bunch current was very low in this study, the synchrotron tune ν_s can be taken as the zero-current ν_s calculated from design lattice.
  - This study showed, during physics run, the global emittance coupling of the rings might change with time.
  - Because HER is operating below the second chromatic coupling resonance $\nu_x - \nu_y + 2\nu_s =$ Integer, the footprint of the beam (with collective effects from impedance and beam-beam) will overlap this line and side effects should be seen.

HER tune scan (vertical) before optics correction knob on



gave up lowering vertical tune due to beam loss

HER tune scan (vertical) after optics correction knob off



gave up lowering vertical tune due to beam loss

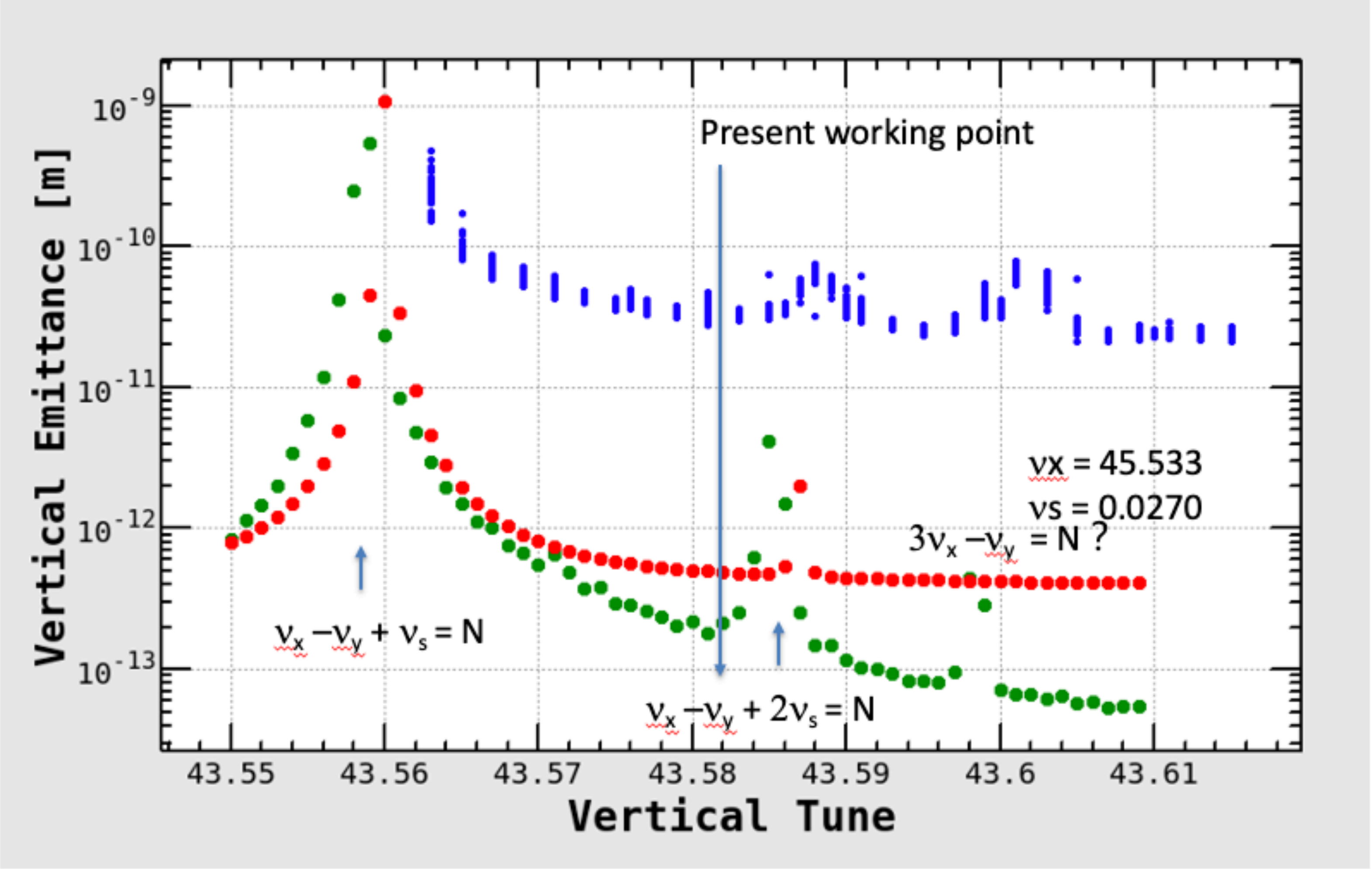
From Y. Funakoshi's report

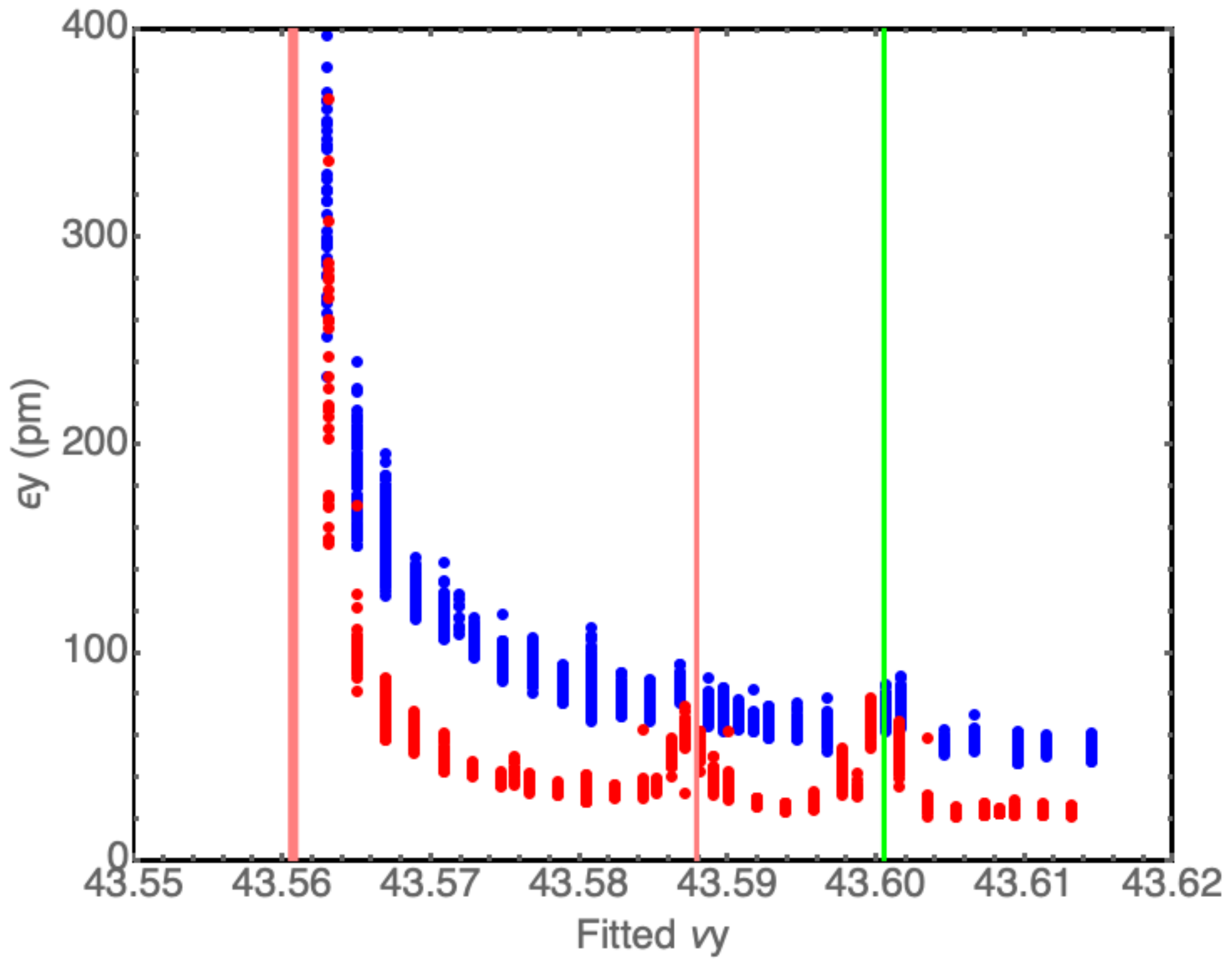
Resonances and tune survey

From Y. Funakoshi's report

- HER tune survey done on Nov. 8, 2021
  - The measured tune-dependent emittances were compared with simulations using ideal lattice (without machine errors) by Funakoshi-san.
  - The peak positions of chromatic couplings had good agreement.
  - But, off from the resonances, the measured emittances were much higher than simulations. It indicated the global emittance coupling is important.
  - Also, both simulations and measurements showed the existence of $3\nu_x - \nu_y =$ N resonance (to be confirmed).

Simulation on synchro-beta emittance (HER)



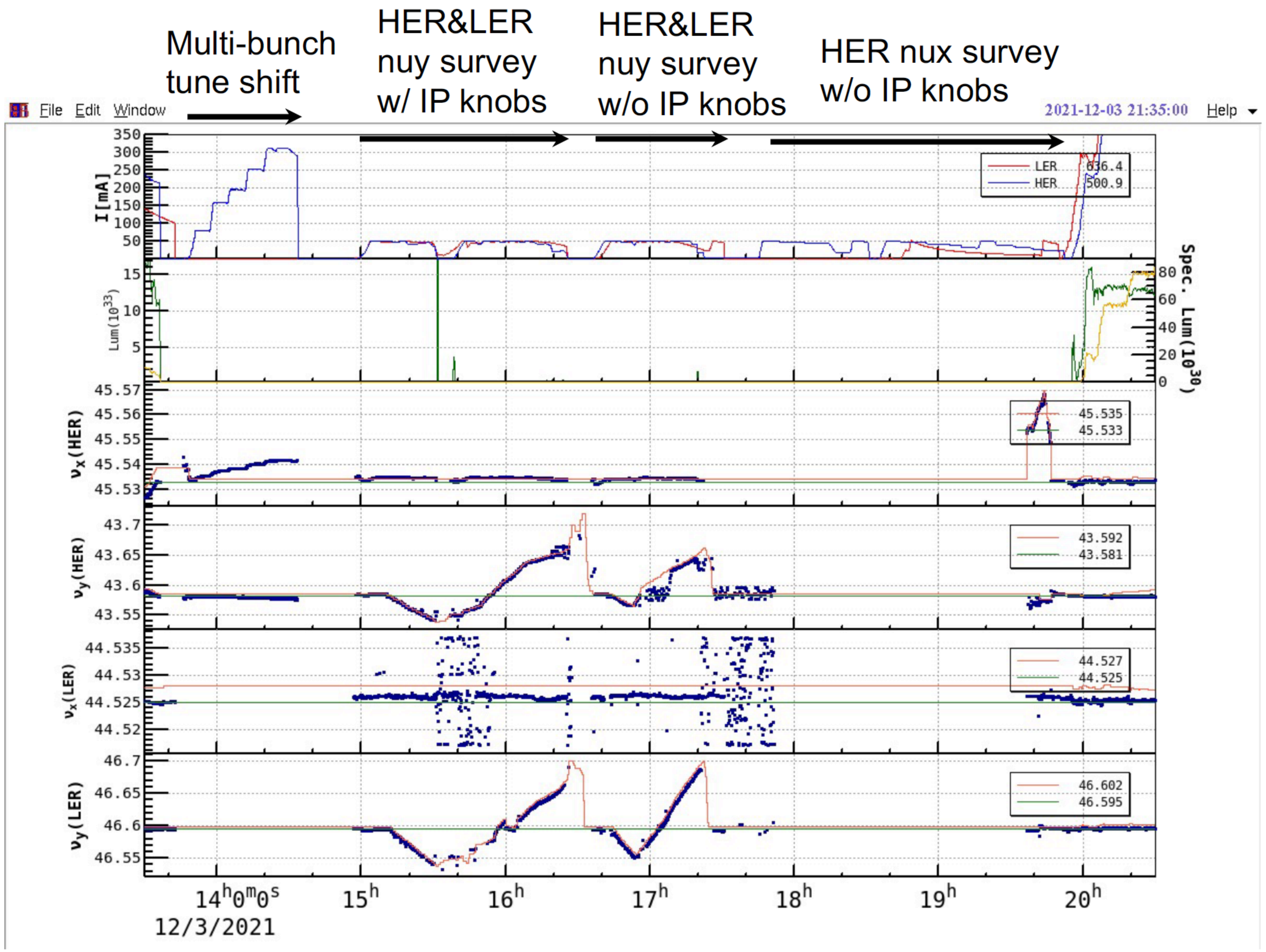


Blue dots: ν_y scan before optics correction

Red dots: ν_y scan after optics correction

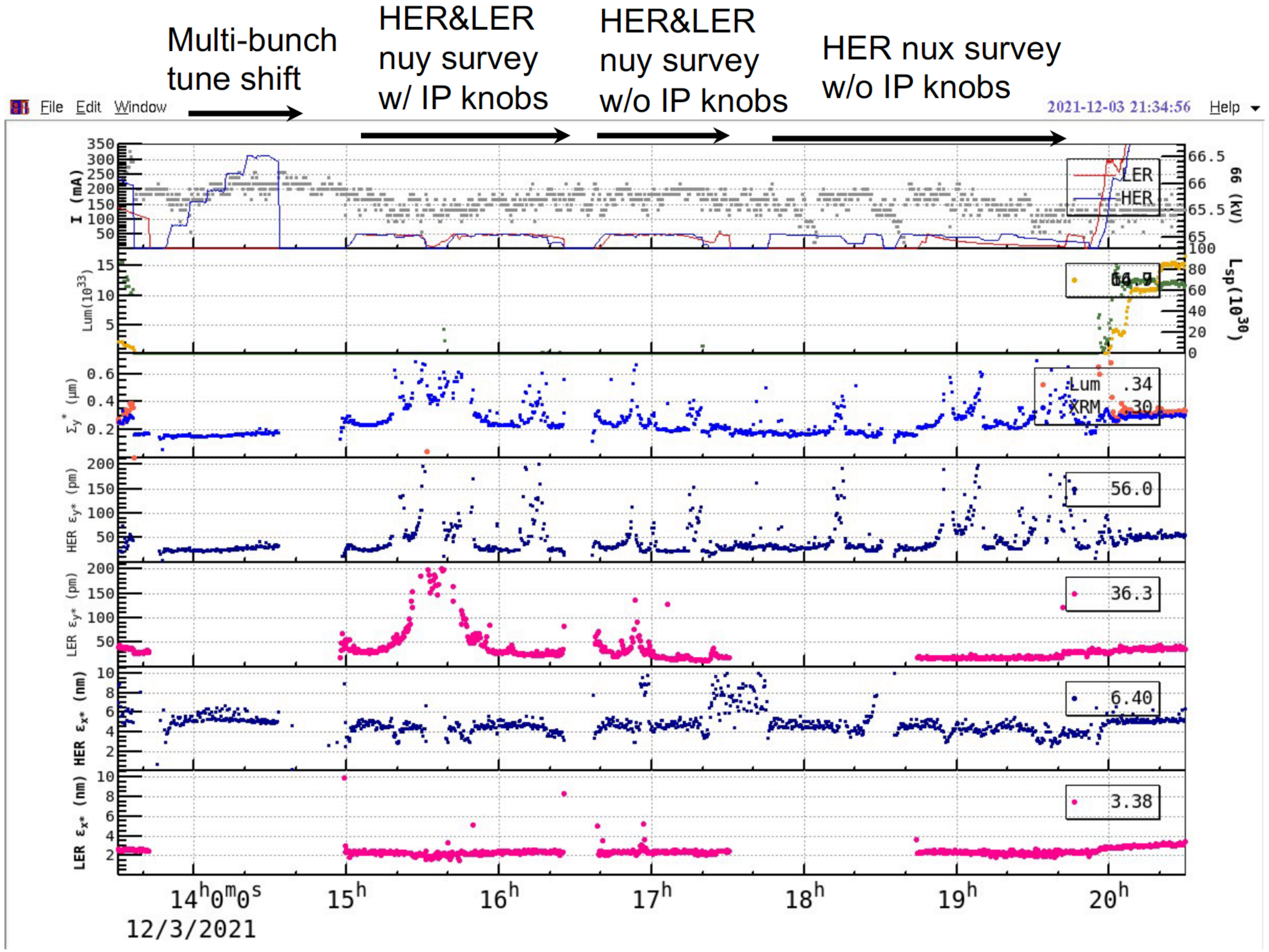
Resonances and tune survey

- Tune survey study on Dec. 3, 2021: Machine conditions and study items
  - Number of bunches: 783; Beam current: 50 mA
  - Tune feedback OFF; BxB FB on
  - HER/LER vertical tune survey: [nuy] .55 → .70
  - HER horizontal tune survey: [nux] .51 → .56



Tune survey machine study done on Dec. 3, 2021

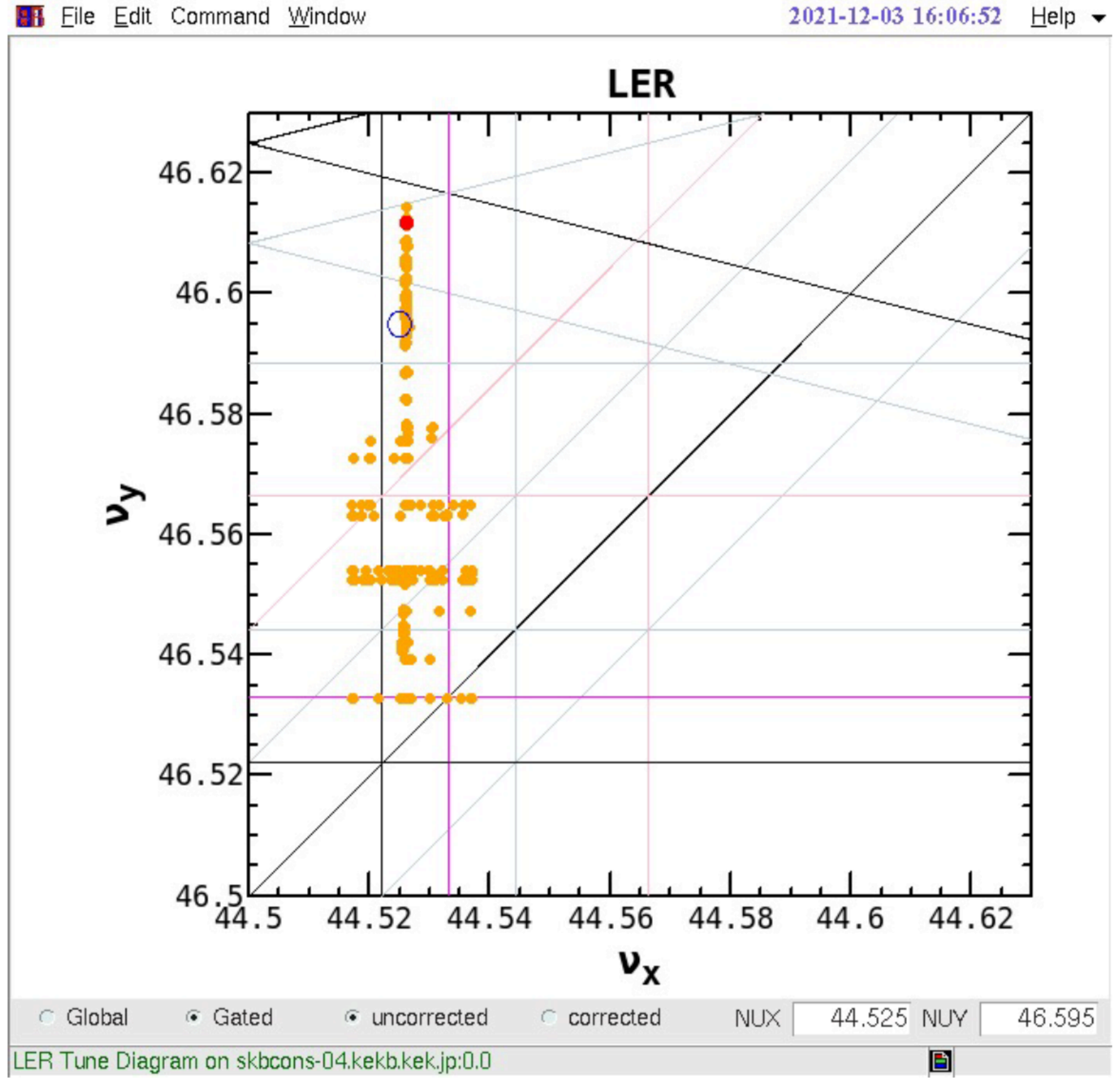
- Data taking
  - Beam emittances from XRMs



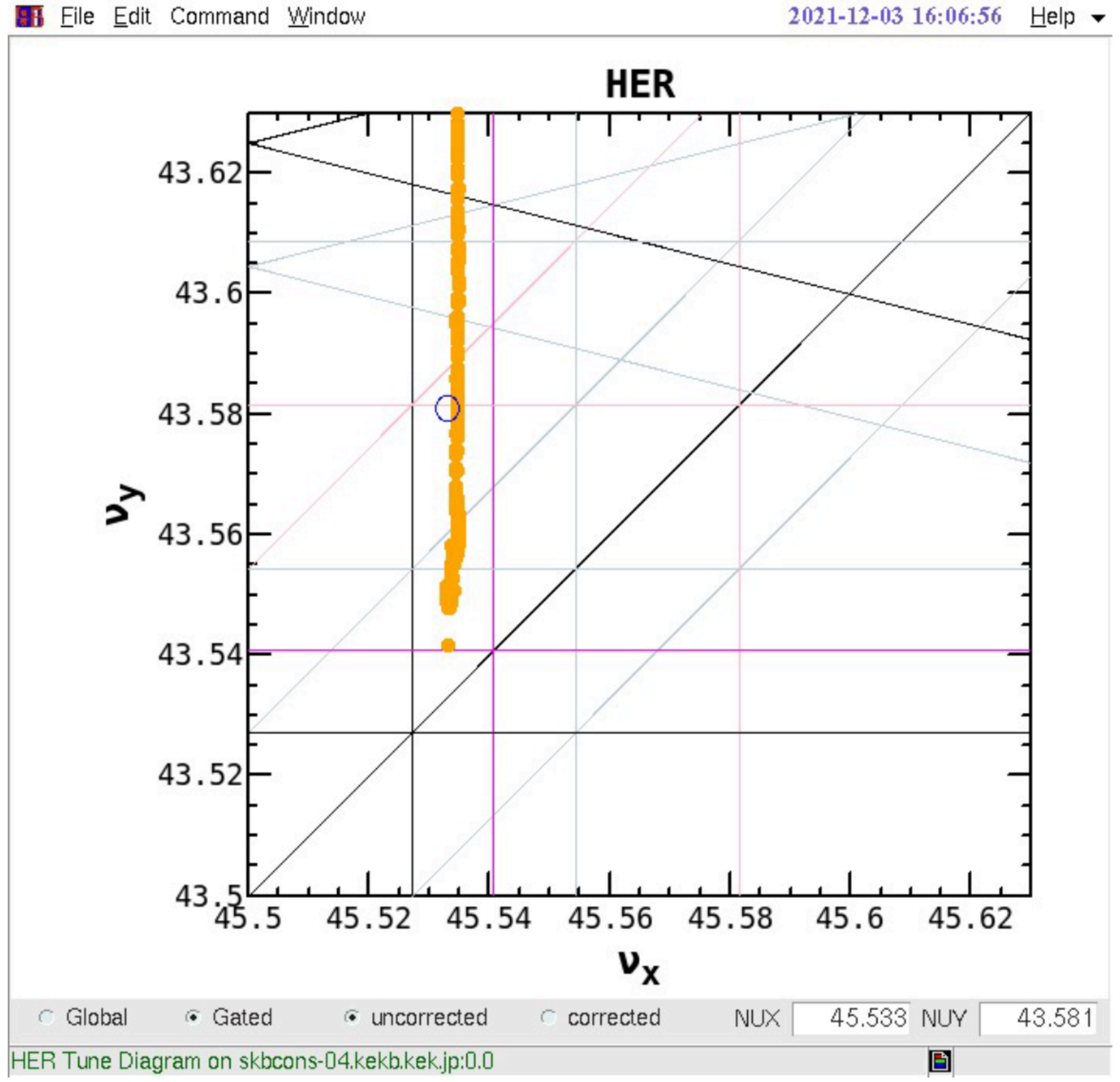
Tune survey machine study done on Dec. 3, 2021

- Study items
  - 1) HER ν_y scan
  - 2) LER ν_y scan
  - 3) HER ν_x scan

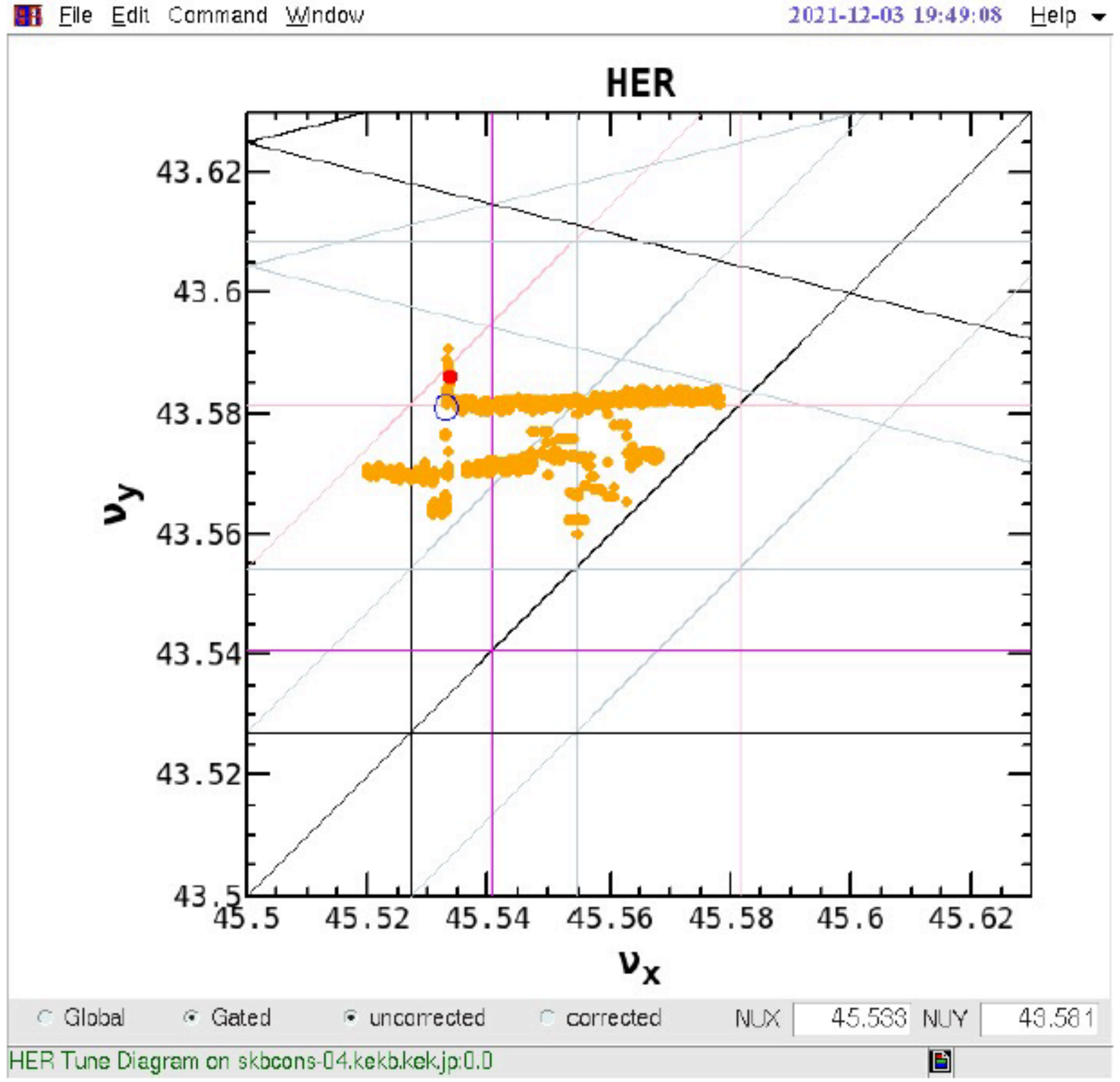
LER nuy survey



HER nuy survey

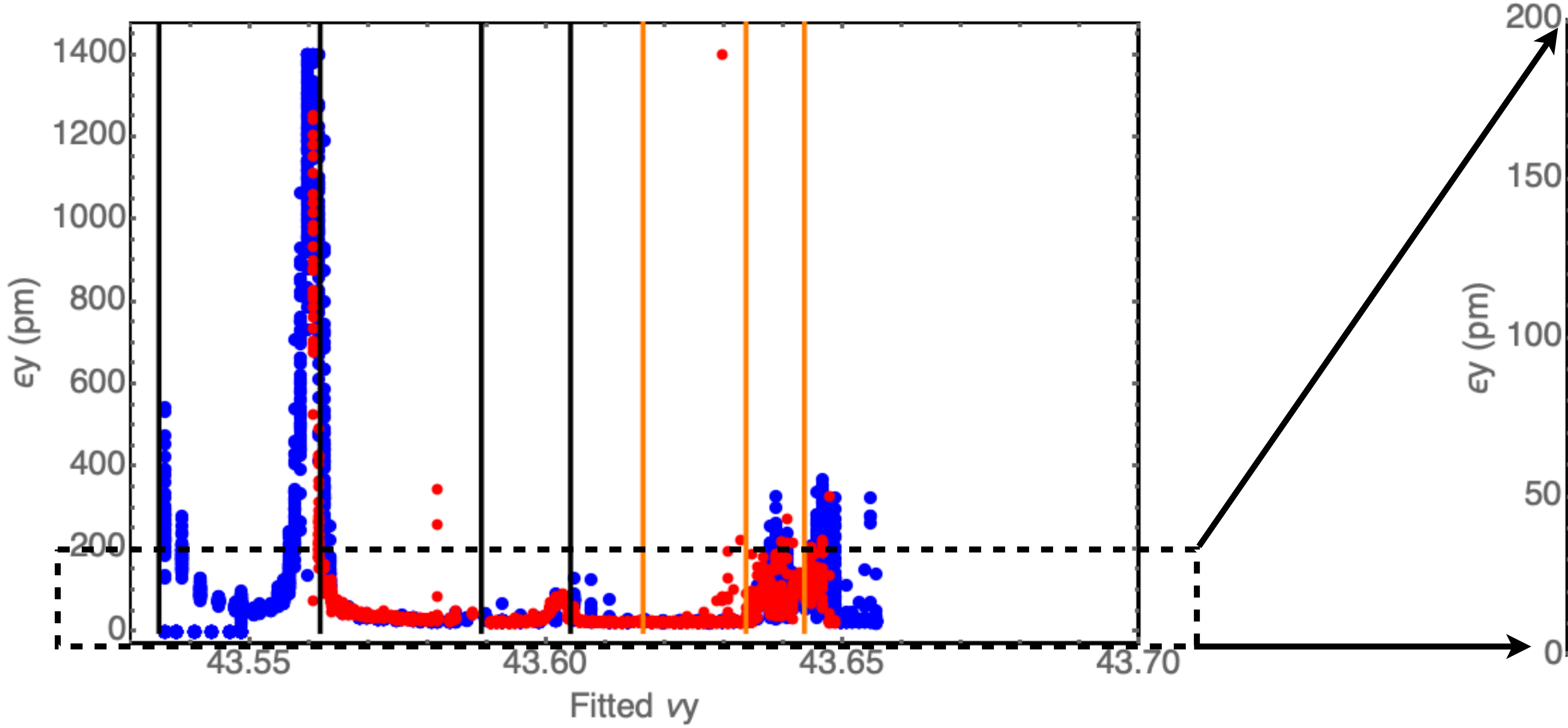


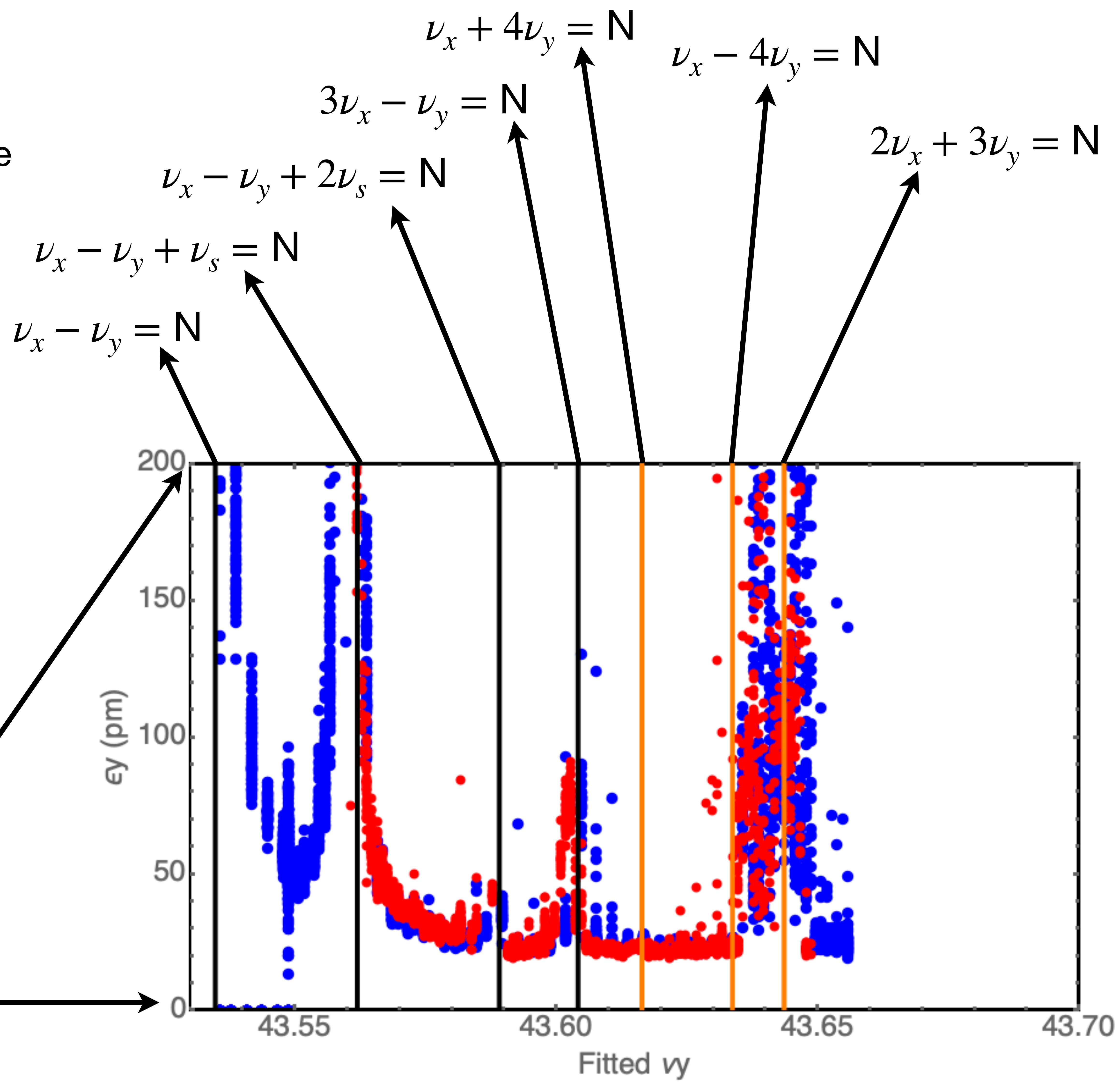
HER nux survey



Tune survey machine study done on Dec. 3, 2021

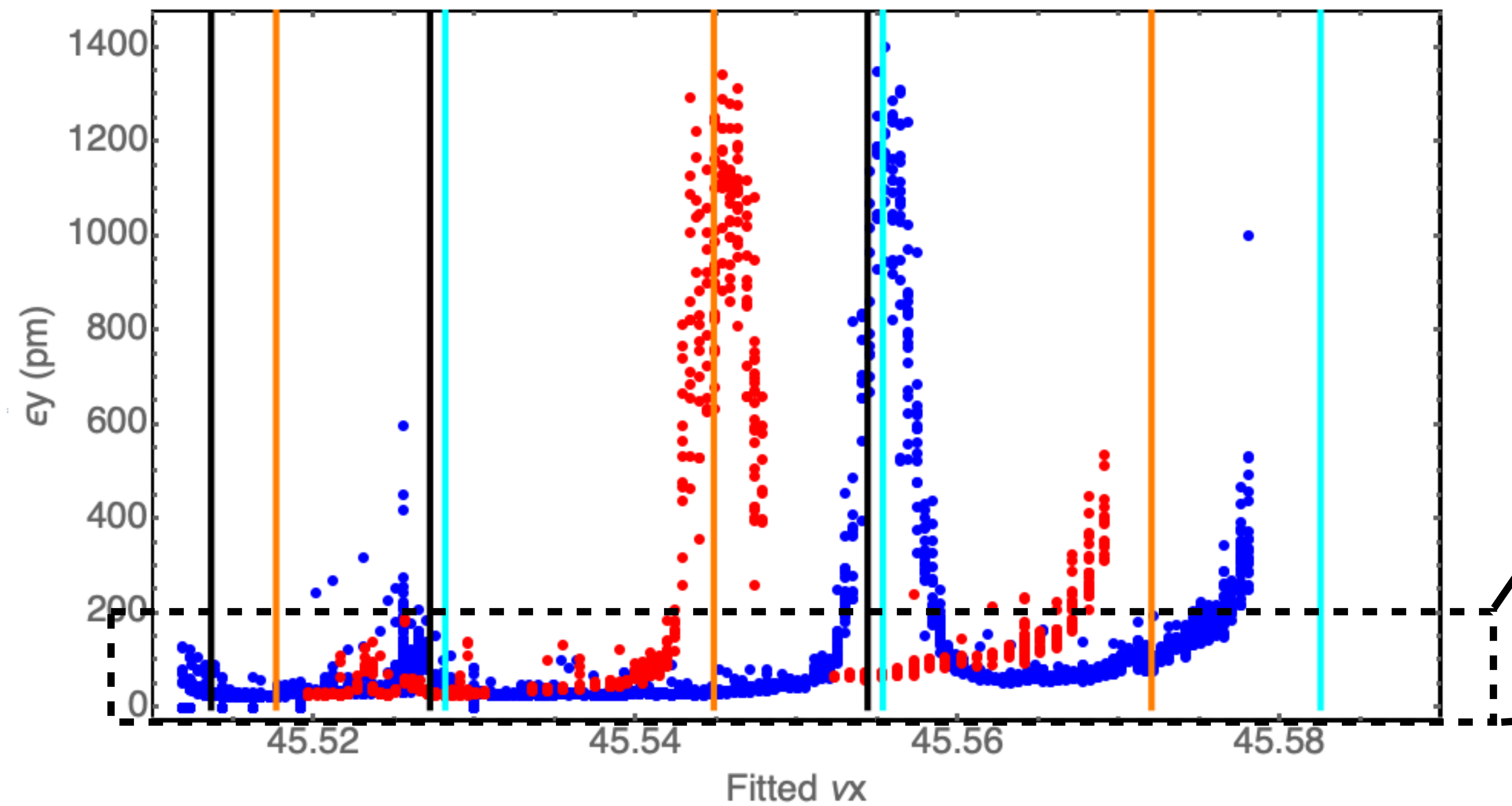
- Offline data analysis: HER ν_y scan
  - Scans done with IP knobs ON (blue dots) and OFF (red dots)
  - Emittance blowup patterns are almost the same $\Rightarrow$ IP knobs have no effects on global coupling
  - $3\nu_x - \nu_y =$ N is clearly seen.
  - ϵ_y blowup was seen around $\nu_y = 43.64$. Fifth-order resonances can be the sources, and effects of BxB FB need to be examined.

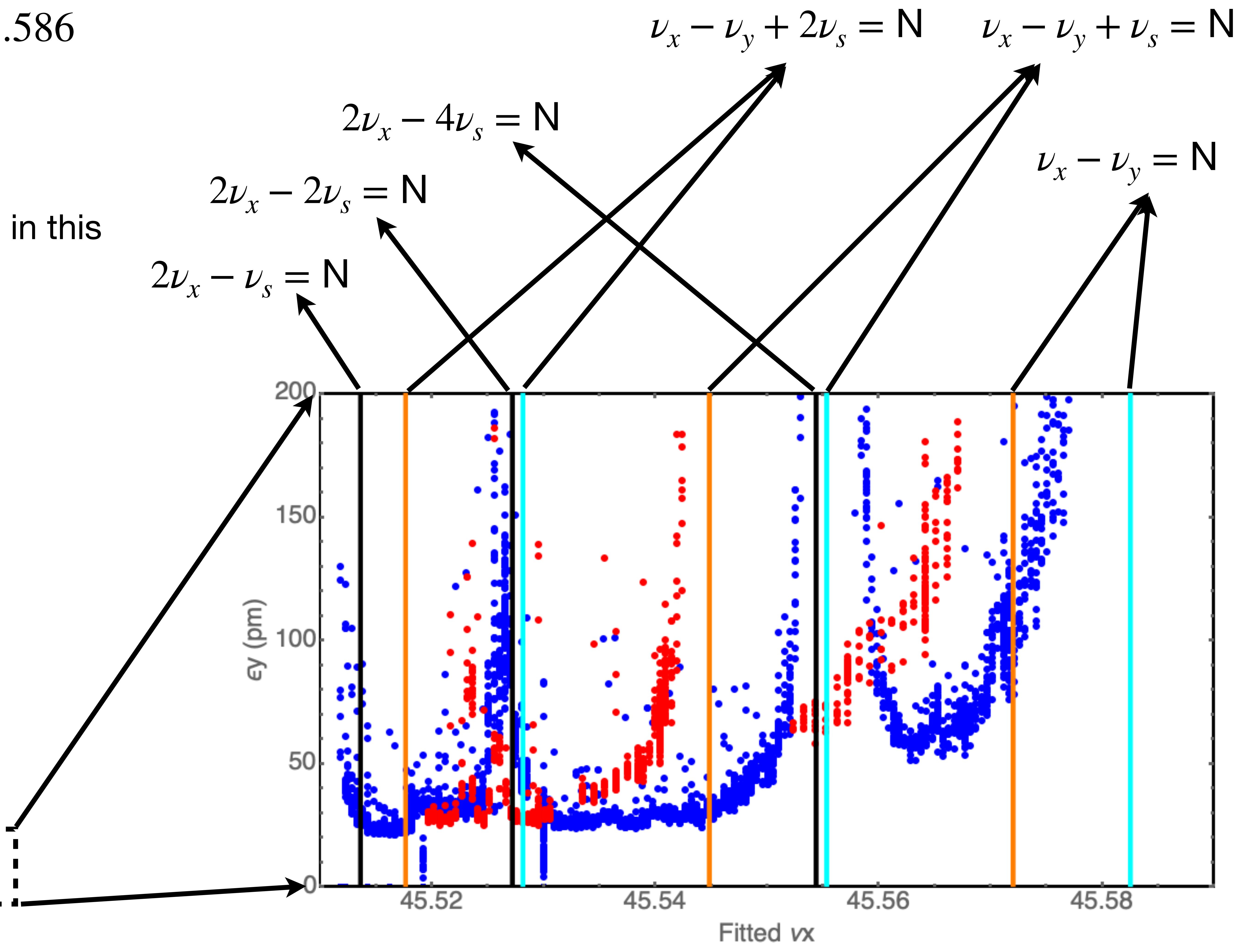




Tune survey machine study done on Dec. 3, 2021

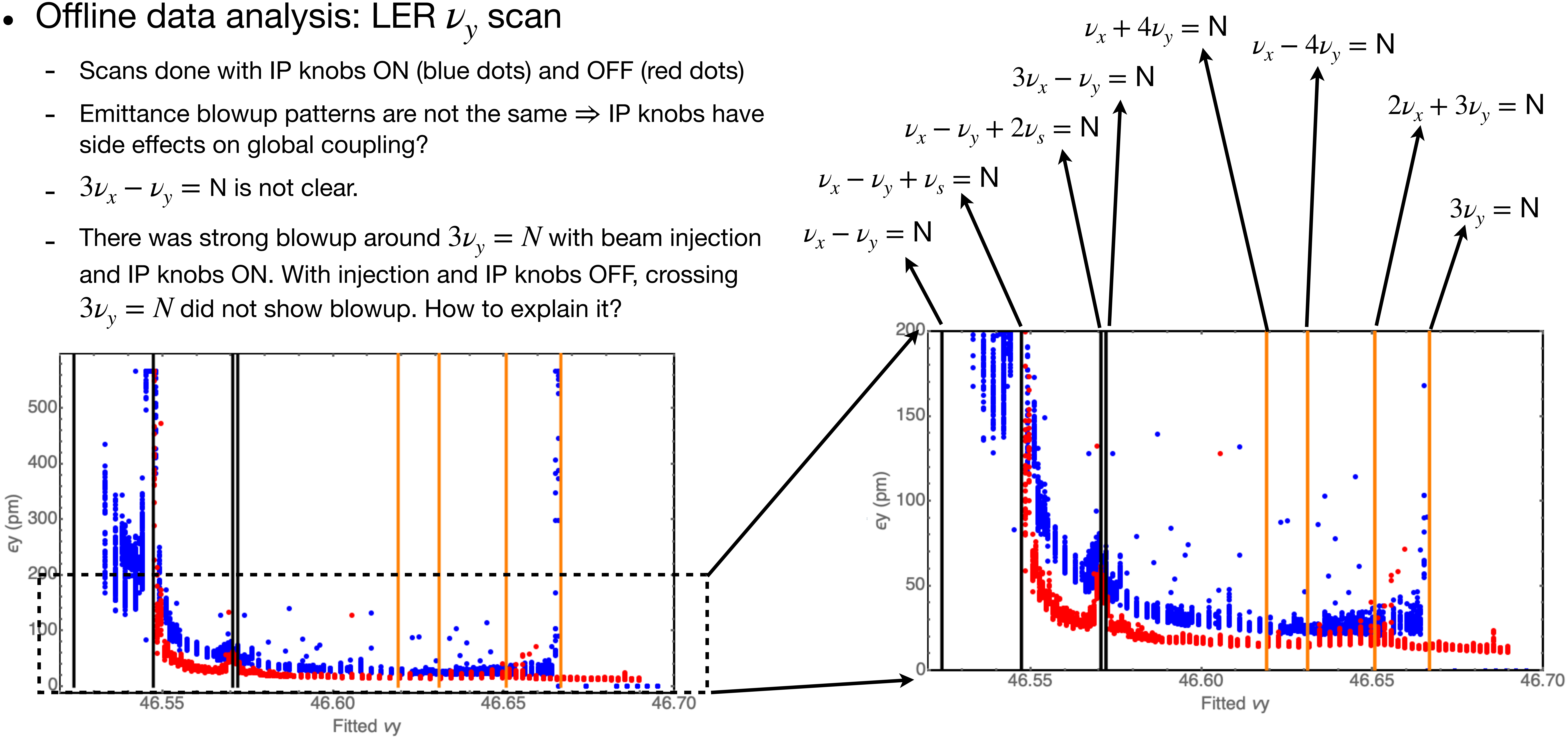
- Offline data analysis: HER ν_x scan
  - Scans done with IP knobs OFF, and model tune $\nu_y = 43.586$ (blue dots) and $\nu_y = 43.576$ (red dots)
  - Changing ν_y shifts resonances $\nu_x - \nu_y + k\nu_s =$ N
  - $2\nu_x - 3\nu_s =$ N and $2\nu_x - 4\nu_s =$ N were not clearly seen in this study. Maybe they are mainly excited by beam-beam?





Tune survey machine study done on Dec. 3, 2021

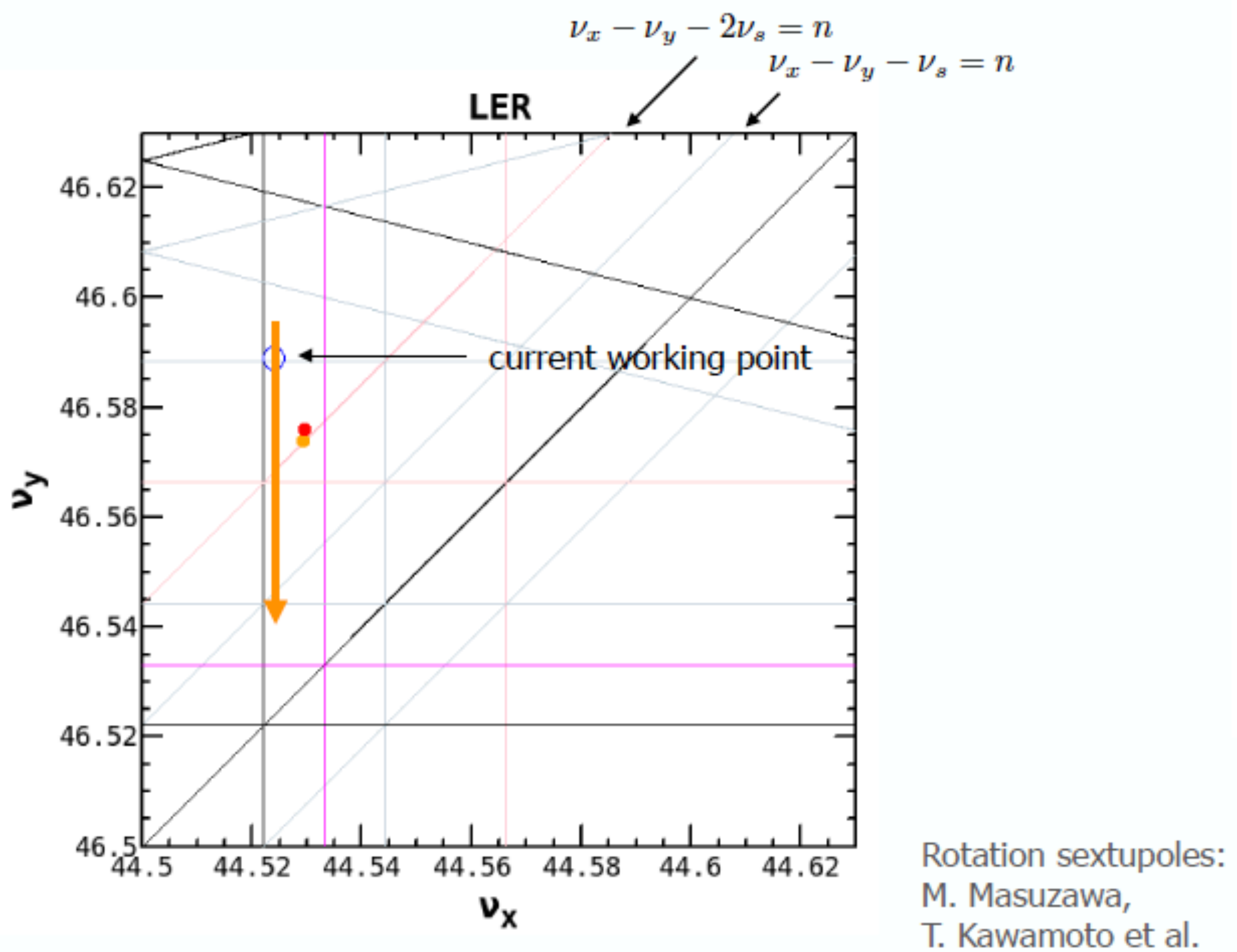
- Offline data analysis: LER ν_y scan
  - Scans done with IP knobs ON (blue dots) and OFF (red dots)
  - Emittance blowup patterns are not the same ⇒ IP knobs have side effects on global coupling?
  - $3\nu_x - \nu_y =$ N is not clear.
  - There was strong blowup around $3\nu_y = N$ with beam injection and IP knobs ON. With injection and IP knobs OFF, crossing $3\nu_y = N$ did not show blowup. How to explain it?



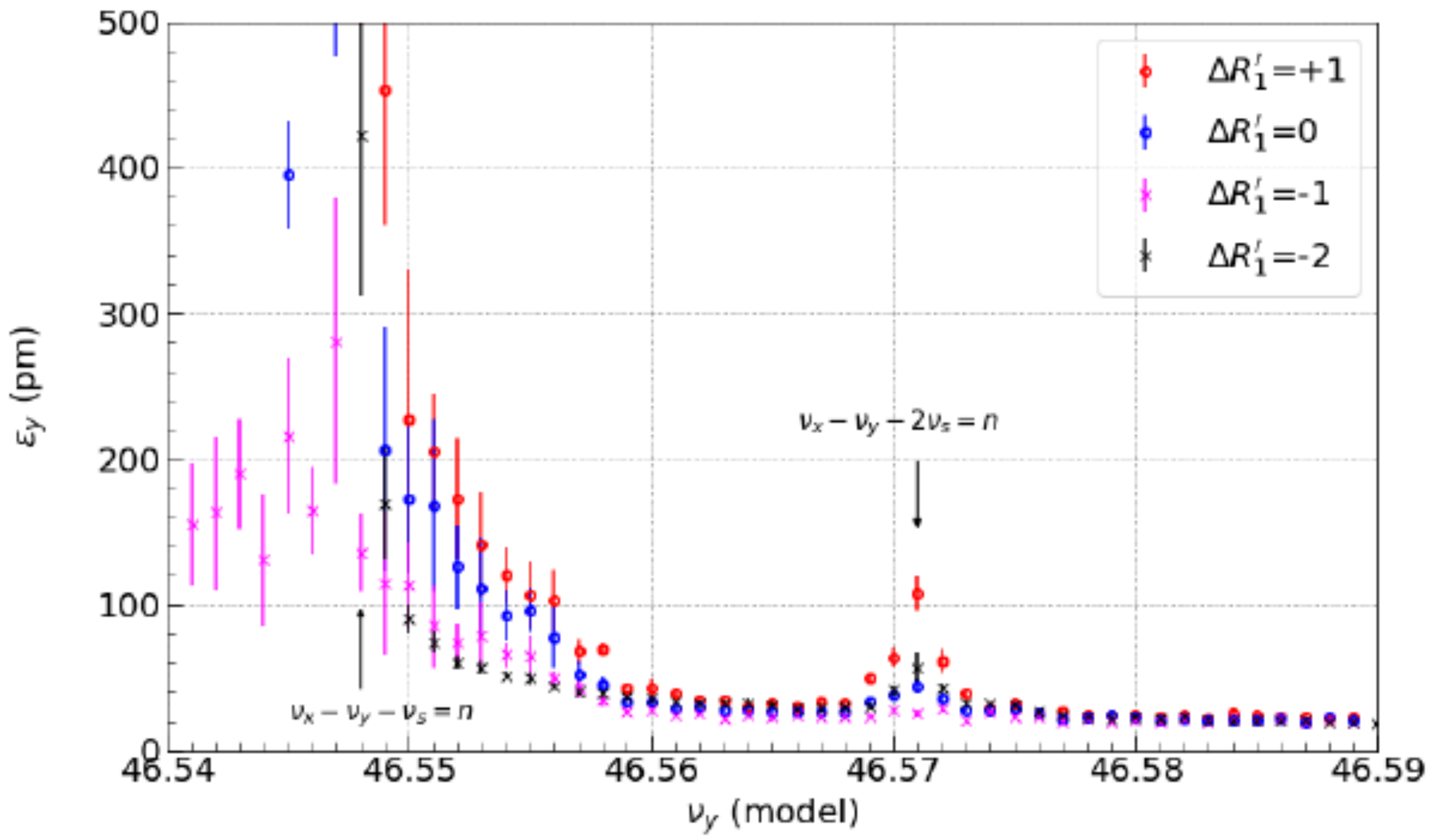
Tune survey for rotation sextupole study on Dec. 20-21, 2021

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

Chromatic X-Y Coupling Correction with Rotation Sextupole Magnets

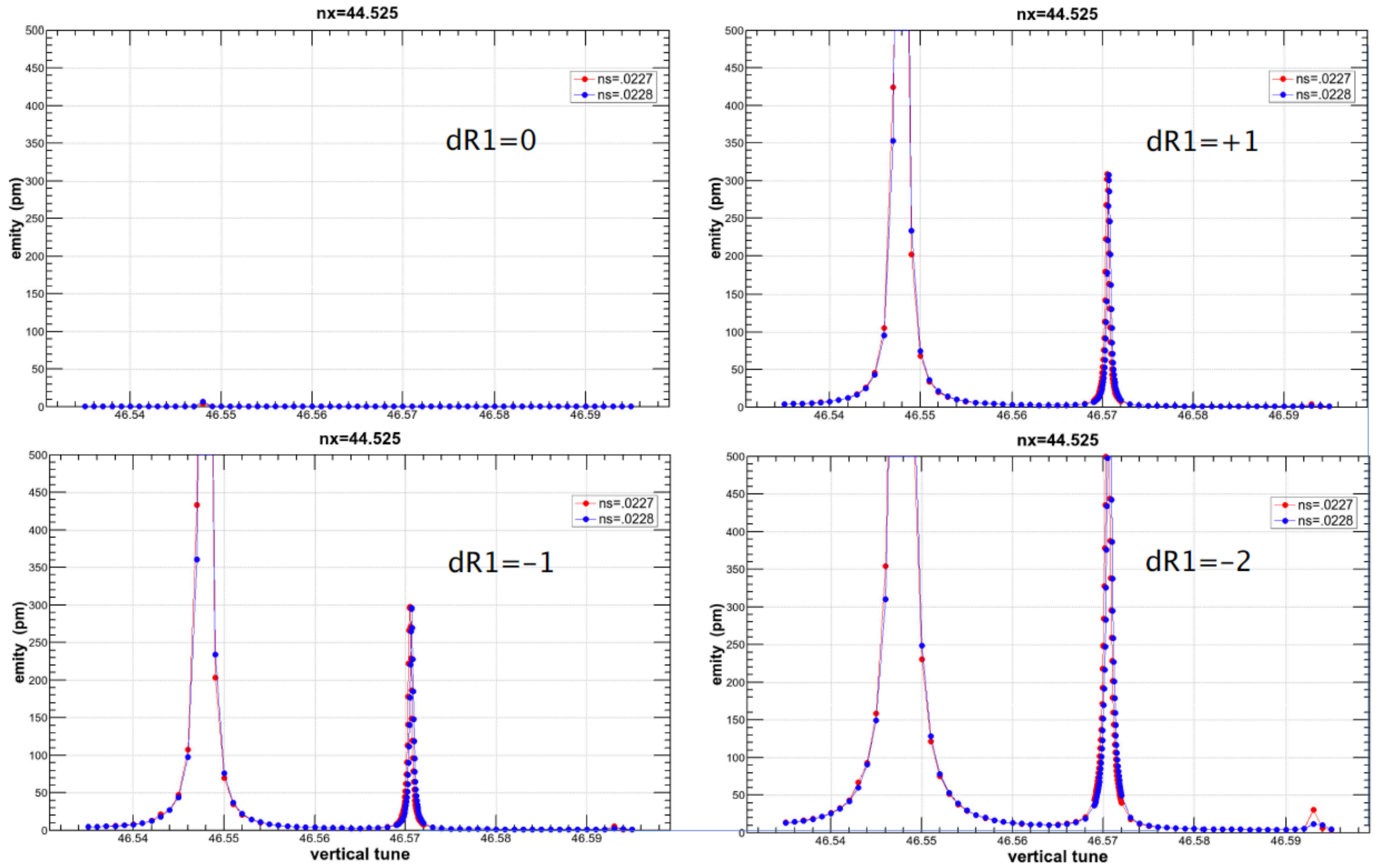


Rotation sextupoles:
M. Masuzawa,
T. Kawamoto et al.



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.)

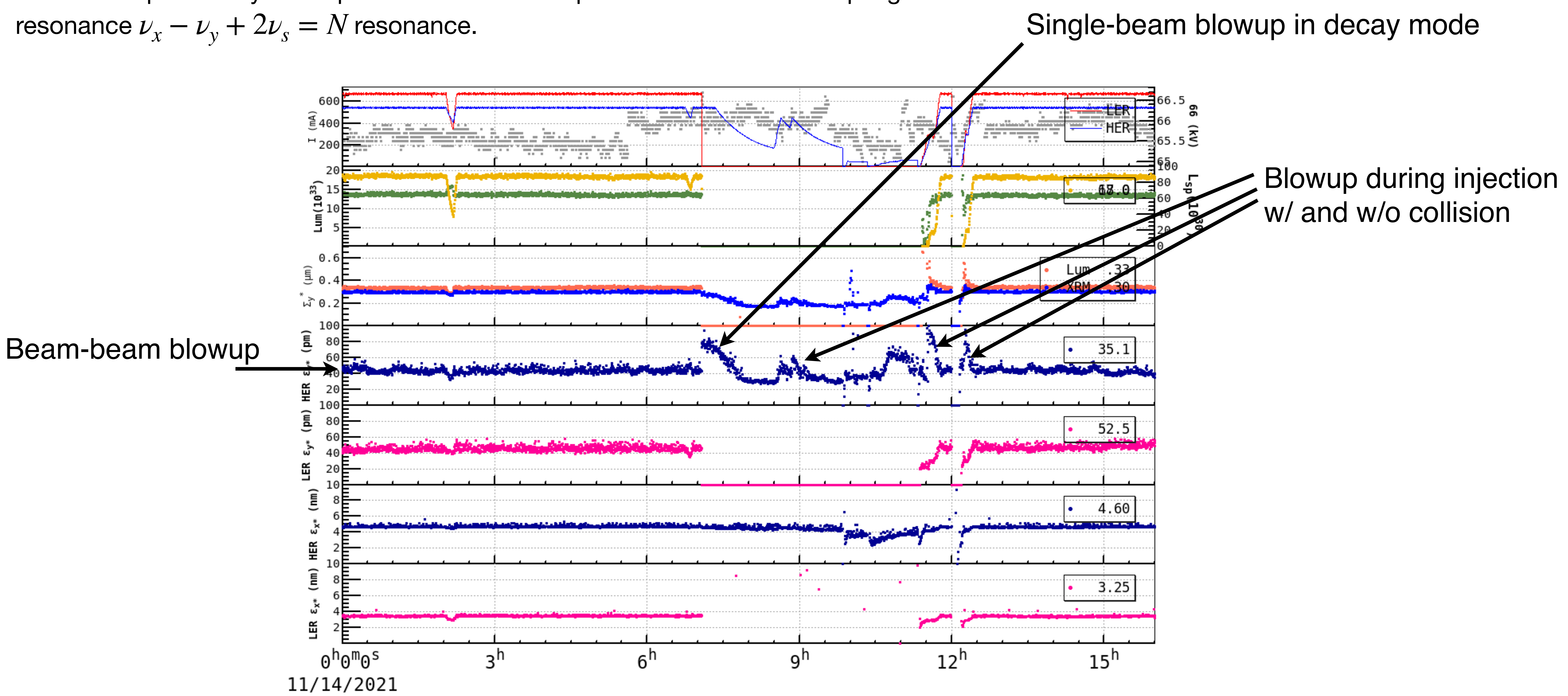


SAD calculation
H. Koiso

Courtesy of Y. Ohnishi

Resonances and tune survey

- HER single-beam study done on Nov. 14, 2021
  - In HER, we observe abnormal vertical emittance blowup.
  - It can be explained by overlap of beam's tune footprint with chromatic coupling resonance $\nu_x - \nu_y + 2\nu_s = N$ resonance.



Longitudinal impedance model of SuperKEKB LER

- Use GdfidL wake data of 2021 from Ishibashi-san.
- Assume collimator settings on Jun. 30, 2021.
- The table is for σ_z=5 mm.

	Number of items	Total loss factor (V/pC)	Total Resistance (Ohm)	Total inductance (nH)
ARES	22	10.2	601	0
Comb bellows	1047	1.4	83	4.7
MO flange	2000	0.01	0.5	1.1
Pumping port (m)	2200/0.4	0	0	0
SR mask	1000	0	0	0
IR duct	1	0.002	0.1	0.6
BPM	445	0.1	8.5	0.6
Transverse FB kicker	2	0.4	26	0
Transverse FB BPM	12	0.02	1.0	0.03
Longitudinal FB kicker	2	1.8	105	0
Grooved beam pipe (m)	520/0.4	0.1	6.3	0.9
Tapers	25	0.01	0.4	0.06
Clearing electrode (m)	150/0.8	0.1	4	11
Collimators	-	0.7	44	13.4
Resistive wall	-	3.9	230	5.7
Total	-	18.8	1112	37.6

Longitudinal impedance model of SuperKEKB LER

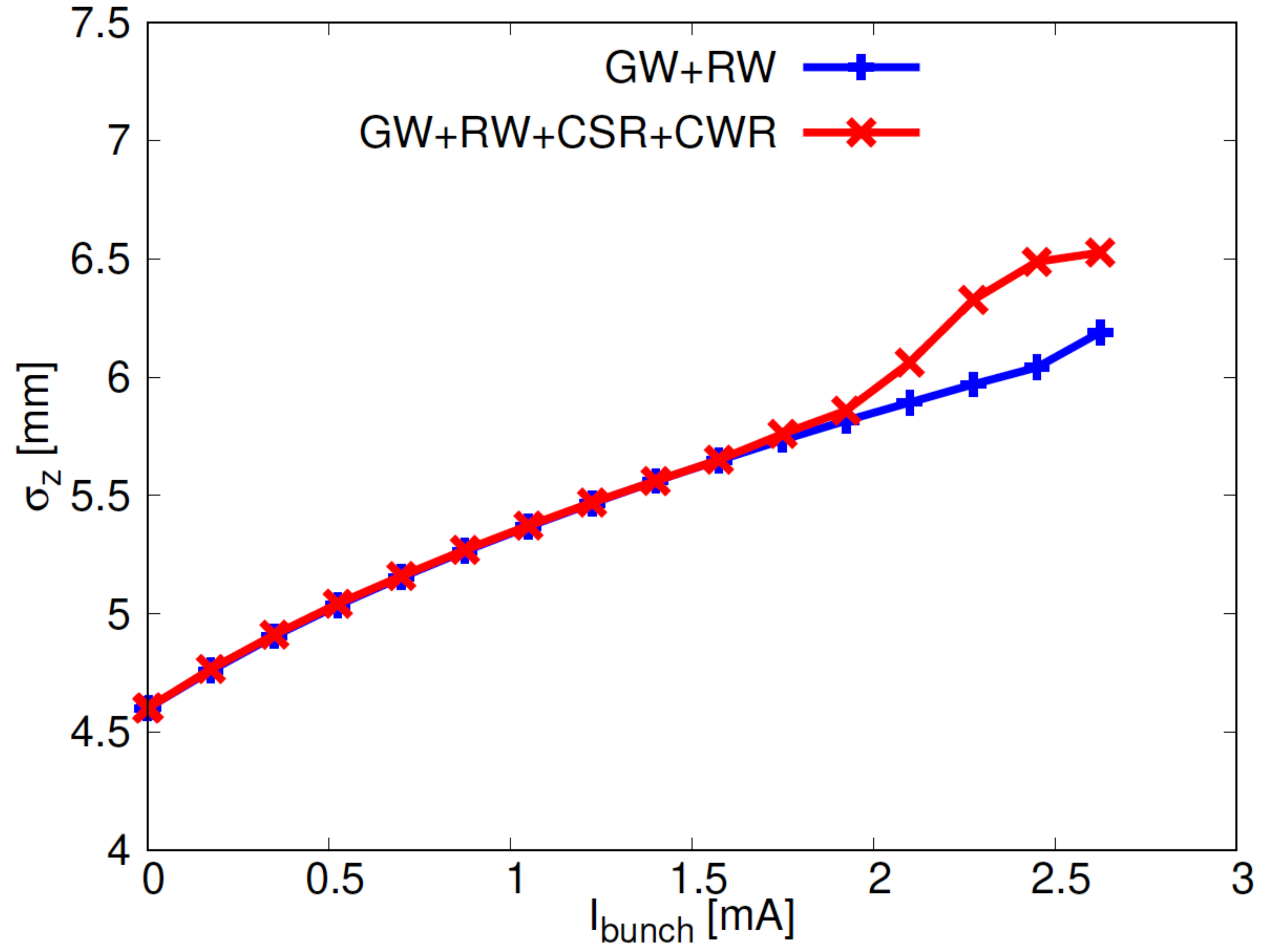
- Assume collimator settings at 13:30 PM, Dec. 22, 2021.
- Updates (by Ishibashi-san)
  - Welding gaps (new impedance sources)
  - Collimator wakes by ECHO3D
  - Resistive wall, using impedance with TiN coating ($\sigma_c = 5e4$ S/m)
- The table is for σ_z=5 mm.
- The updates do not change the longitudinal impedance budget much.

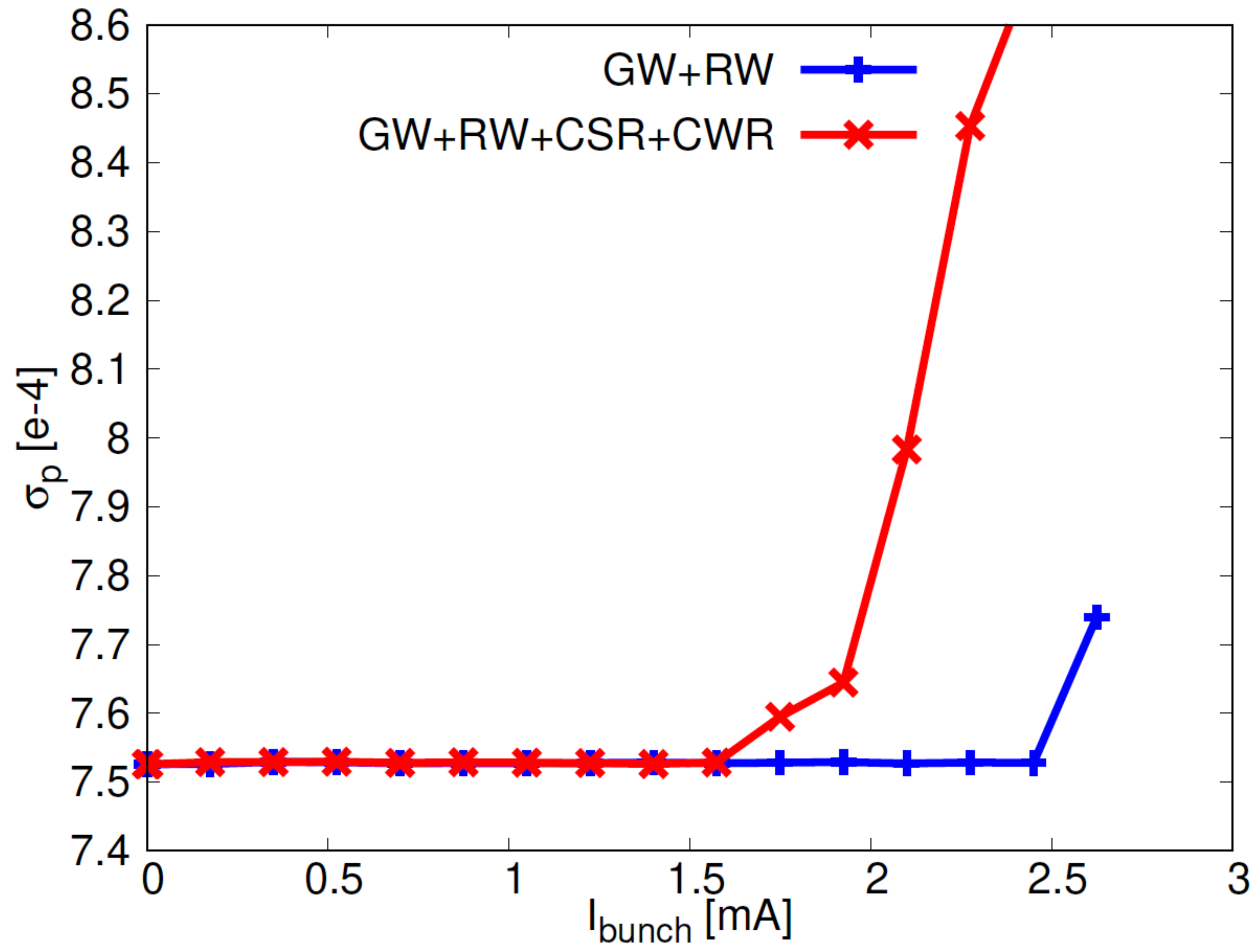
	Number of items	Total loss factor (V/pC)	Total Resistance (Ohm)	Total inductance (nH)
ARES	22	10.2	601	0
Comb bellows	1047	1.4	83	4.7
MO flange	2000	0.01	0.5	1.1
Pumping port (m)	2200/0.4	0	0	0
SR mask	1000	0	0	0
IR duct	1	0.002	0.1	0.6
BPM	445	0.1	8.5	0.6
Transverse FB kicker	2	0.4	26	0
Transverse FB BPM	12	0.02	1.0	0.03
Longitudinal FB kicker	2	1.8	105	0
Grooved beam pipe (m)	520/0.4	0.1	6.3	0.9
Tapers	25	0.01	0.4	0.06
Clearing electrode (m)	150/2.	0.1	4	11
Collimators	-	0.7	41.5	12.1
Welding gaps	2000	0.1	4.8	4.7
Resistive wall	-	3.9	232	8.4
Total	-	18.8	1112	37.5

Simulation of bunch lengthening and microwave instability by Vlasov solver

- Use beam parameters of Dec. 22, 2021 ($\beta_y^* = 1$ mm).
- Bunch lengthening and MWI threshold were similar to old simulations.
  - Fitted bunch lengthening is σ_z[mm] $= \sigma_{z0}$[mm] $+ 0.72 I_b$[mA]. The slope $A = 0.72$/mA is still much smaller than streak camera measurement (about 2/mA, see Ikeda-san's talk in this meeting).
  - To-Do list: Benchmark simulations of bunch lengthening(VFP, pyHEADTAIL, BBSS, etc.), search of new impedance source (Ishibashi-san as the leader), etc.

	Values
RF voltage (MV)	9.12
Beam energy (GeV)	4
Natural bunch length (mm)	4.6
Momentum compaction factor (E-4)	2.9690
Longitudinal damping time (ms)	22.84954
Energy spread (E-4)	7.52596
Energy loss per turn (MeV)	1.7621609
Synchrotron tune	0.0232639





Vertical impedance model of SuperKEKB LER

- Assume collimator settings at 13:30 PM, Dec. 22, 2021.
- Updates (by Ishibashi-san)
  - Welding gaps (new impedance sources)
  - Collimator wakes by ECHO3D
  - Resistive wall, using impedance with TiN coating (σ_c = 5e4 S/m)
- $\beta_y \kappa_y$ of IR duct was underestimated according to Ishibashi-san's new calculation.
- The table is for σ_z=6 mm.

	Number of items	Average β_y (m)	β_y*κ_{yD} (V/pC)	β_y*κ_{yQ} (V/pC)
ARES	22	17.7	-455	0
Comb bellows	1047	19.1	-816	178
MO flange	2000	19.1	-86	-2
Pumping port (m)	2200/0.4	19.1	0	0
SR mask	1000	19.1	0	0
IR duct	1	20.8	-545	141
BPM	445	28.0	-74	4.5
Transverse FB kicker	2	7.9	-39	0
Transverse FB BPM	12	19.3	-8	0
Longitudinal FB kicker	2	20.2	-168	0
Grooved beam pipe (m)	520/0.4	19.0	-166	-159
Tapers	25	19.1	0	9
Clearing electrode (m)	150/2.	15.7	-534	-452
Welding gaps	2000	19.1	-147	19
Resistive wall	-	19.1	-1206	-
Total	-	-	-4244	-261

Vertical impedance model of SuperKEKB LER

- Assume collimator settings at 13:30 PM, Dec. 22, 2021.
- The table is for σ_z=6 mm.
- Resistive wall of collimators NOT taken into account (GdfidL calculations showed it is not important).
- Collimators contribute about 90% of total $\beta_y \kappa_y$ w/o considering IR duct.

	Half gap (mm)	Average β_y (m)	$\beta_y * \kappa_{yD}$ (V/pC)	$\beta_y * \kappa_{yQ}$ (V/pC)
D06H1	13.85	5.6	-64	3
D06H3	10.8	5.6	-60	32
D06V1	2.79	67.3	-11475	-3985
D06V2	2.71	20.6	-3682	-1260
D03H1	11.95	3.0	-33	10
D03V1	8	17.0	-500	-292
D02H1	8	24.7	-315	421
D02H2	11.95	13.2	-145	42
D02V1	1.12	11.9	-7762	-1886
D02H3	13.95	55.4	-634	25
D02H4	8.07	13.3	-169	223
Total	-	-	-24838	-6669

Betatron tune shift

- Assume collimator settings at 13:30 PM, Dec. 22, 2021.
- Use beam parameters and lattice on Dec. 22, 2021.
- See Ishibashi-san’s talk for measurements of tune shift.

$$\mathrm{dvdI}[\beta\kappa\_] := \frac{\beta\kappa * 10^{12} * 10^{-3}}{4\pi * (\mathrm{c0}/\mathrm{Cir}) * (\mathrm{Ep} * 10^{9})};$$

Estimate of vertical tune shift (Unit: /mA)

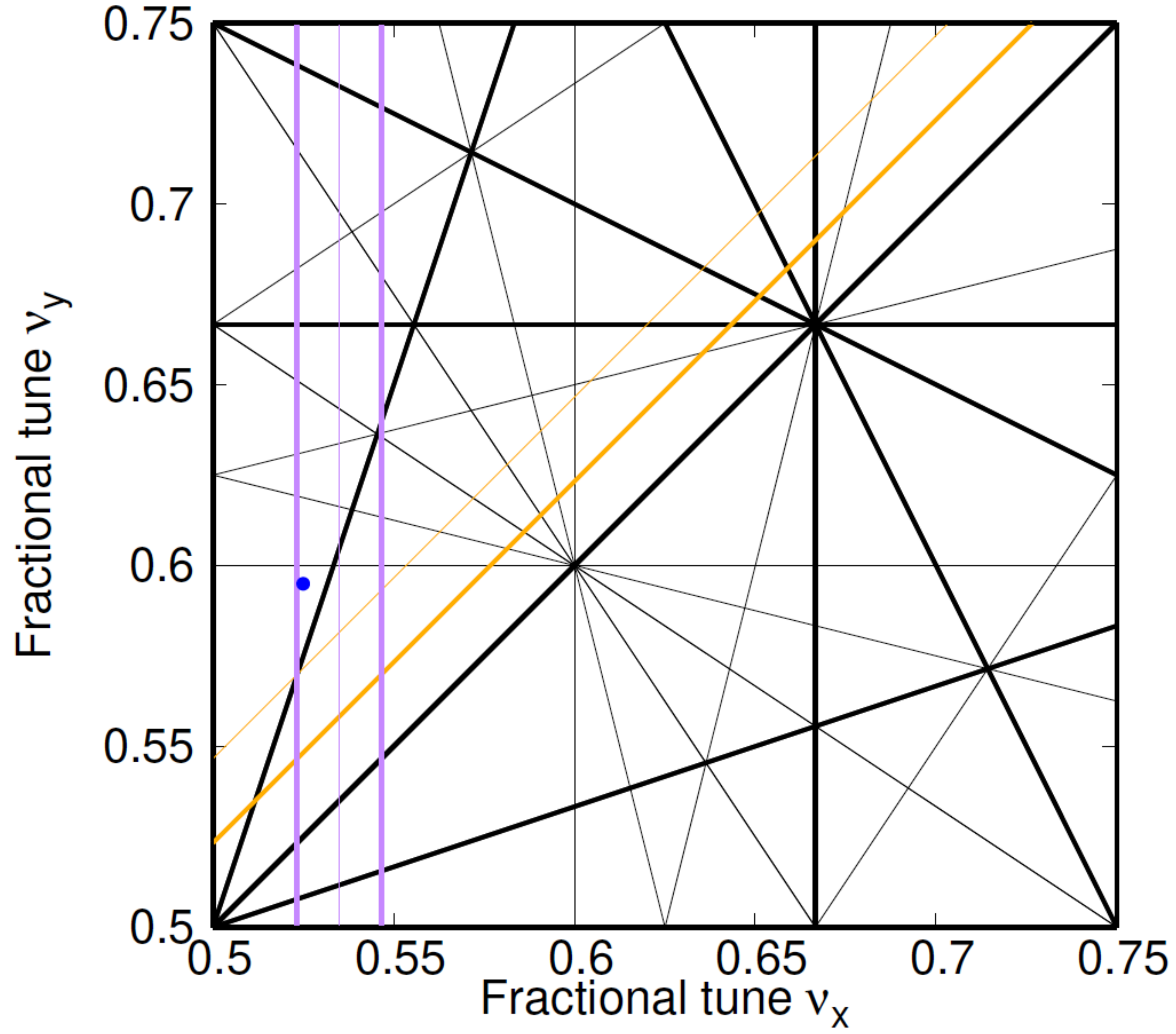
	Ver. Dipolar Collimators	Vert. Dipolar. Others	Vert. Quad Collimators	Hor. Quad. Others	Total
σ_z=5 mm	-0.00541276	-0.000947807	-0.00160797	-0.0000682918	-0.00803683
σ_z=6 mm	-0.00497163	-0.000849563	-0.00133485	-0.000052172	-0.00720822

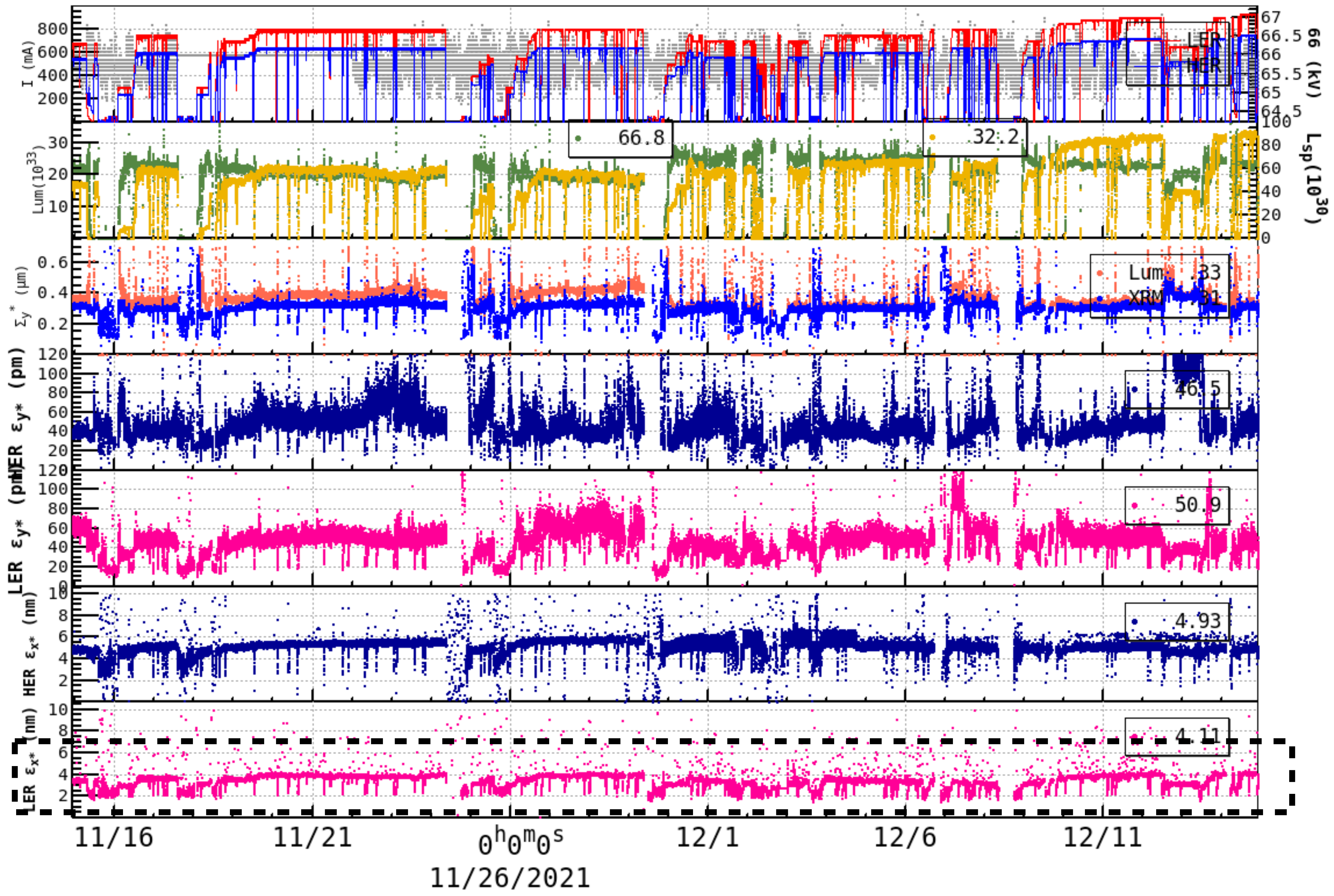
Estimate of horizontal tune shift (Unit: /mA)

	Hor. Dipolar Collimators	Hor. Dipolar. Others	Hor. Quad Collimators	Hor. Quad. Others	Total
σ_z=5 mm	-0.00211063	-0.00072972	0.0010495	0.0000843841	-0.00170647
σ_z=6 mm	-0.0017785	-0.000667095	0.000874458	0.000066171	-0.00150497

Discussion on candidates for vertical emittance blowup

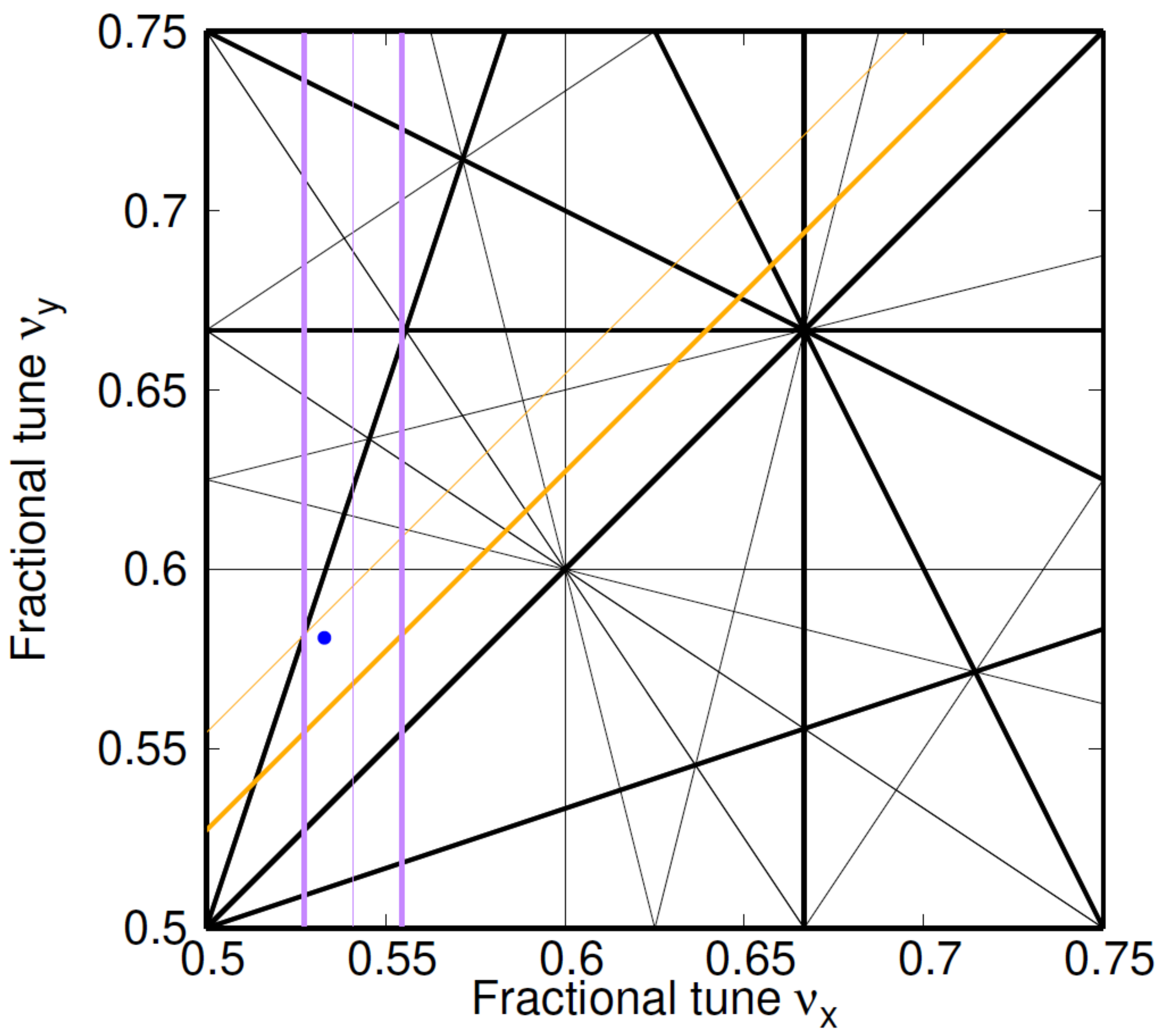
- LER
  - Beam-beam driven synchro-betatron resonance (it means single-beam effect, not BBHTI or X-Z instability which means coherent blowup of both beams. Potential-well distortion cause ν_s spread and increase width of $2\nu_x - k\nu_s = N$ resonances.).
  - “TMCI”: Interplay of beam-beam, impedance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



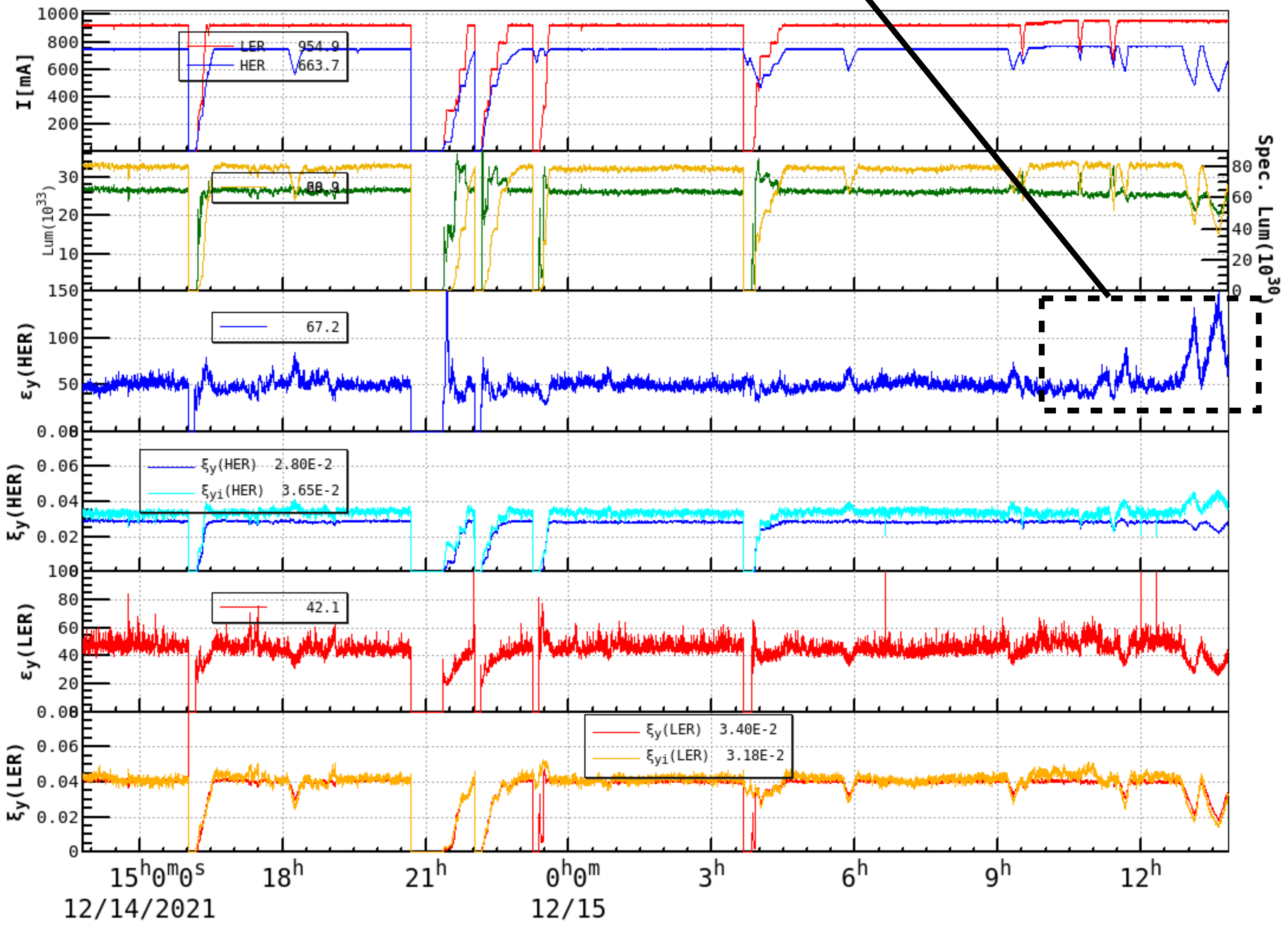


Discussion on candidates for vertical emittance blowup

- 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?
  - Insufficient CW (now 40%, limited by SLY* strengths).
  - Imperfect CW (imperfect phase-advance between SLY* magnets, non-perfect CW for off-momentum particles)
  - Others?

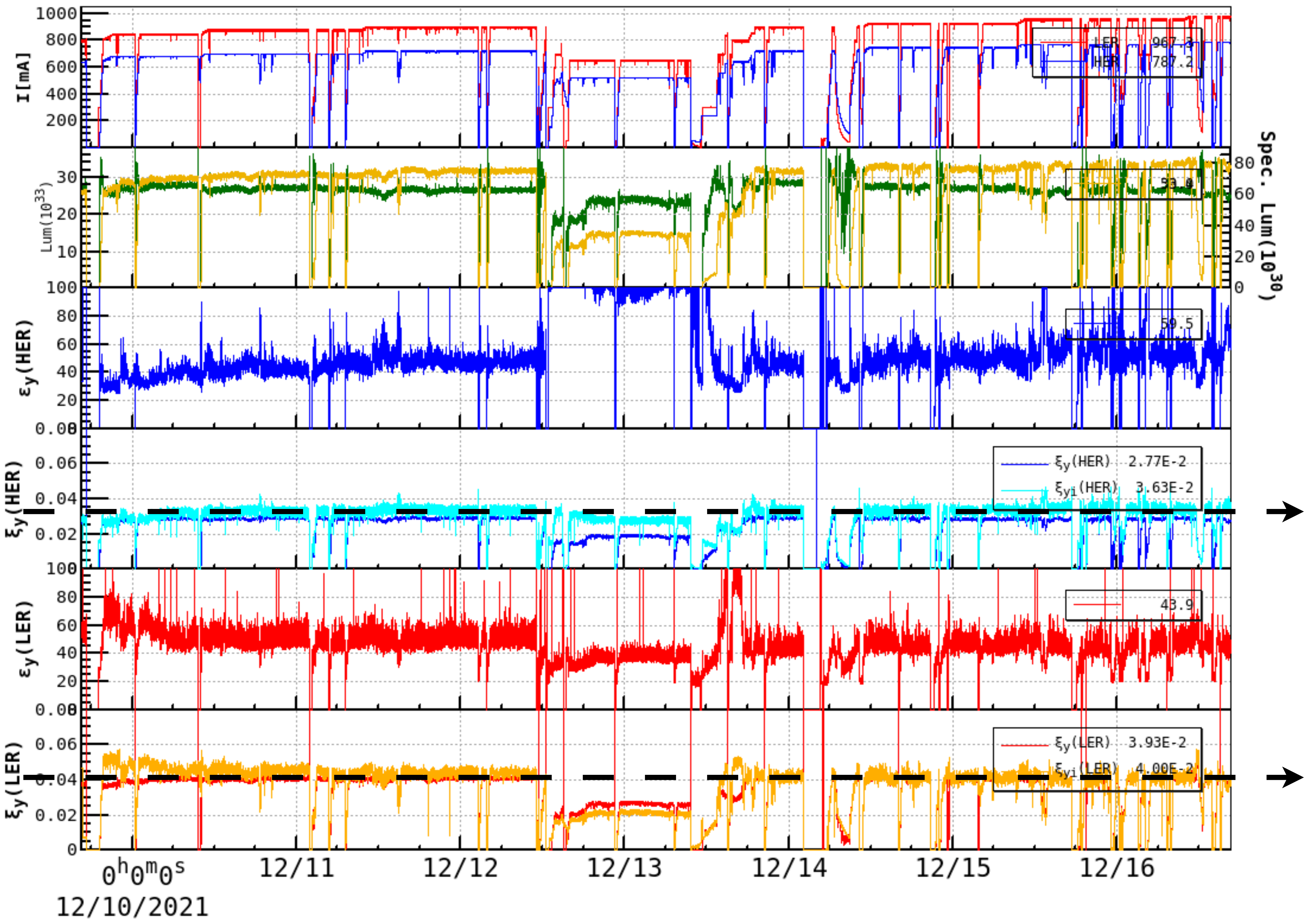


“Threshold” in $\xi_{yi} \approx 0.03$



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.



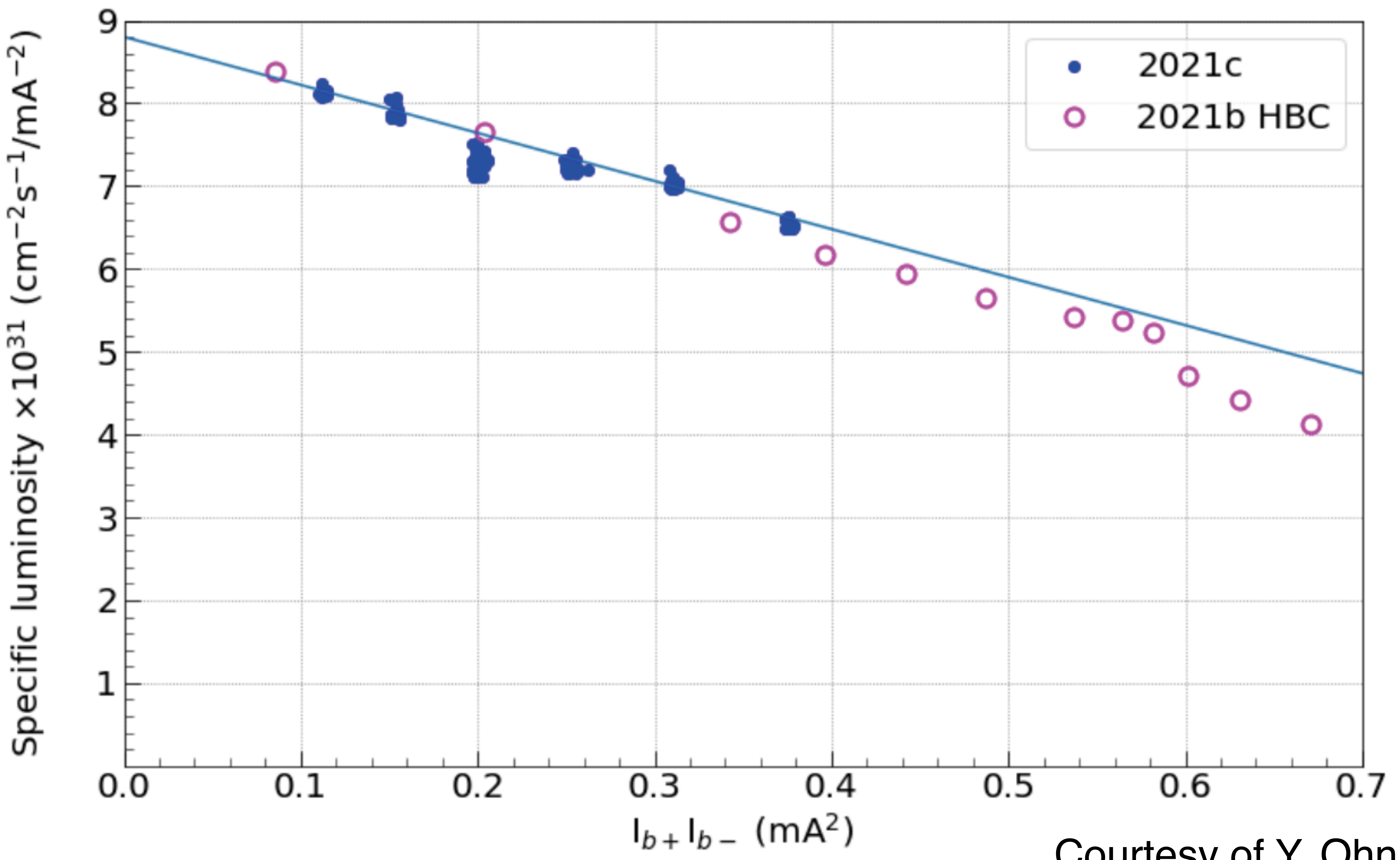
$$L = \frac{1}{2er_e}\frac{\gamma_+ I_+}{\beta^*_{y+}}\xi_{y+} = \frac{1}{2er_e}\frac{\gamma_- I_-}{\beta^*_{y-}}\xi_{y-}$$

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

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

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 3.815E34 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 $L_{sp}[10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}/\mathrm{mA}^2] = 8.8 - 5.8 I_{b+} I_{b-} [\mathrm{mA}^2]$. 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	$I_{b+}I_{b-}$ [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

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

Backup

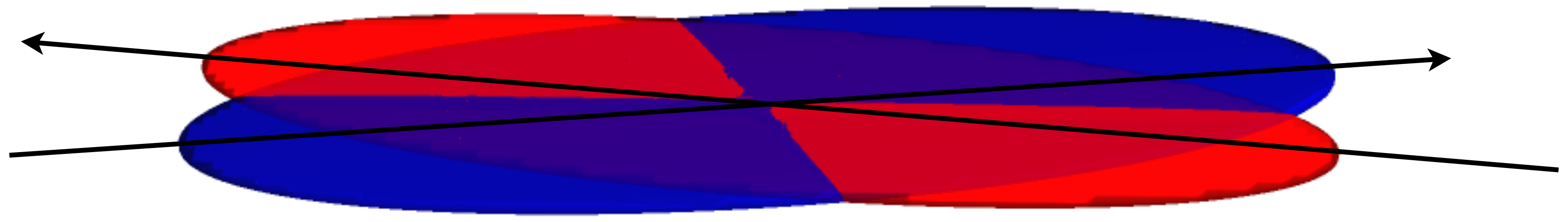
Status of SuperKEKB

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

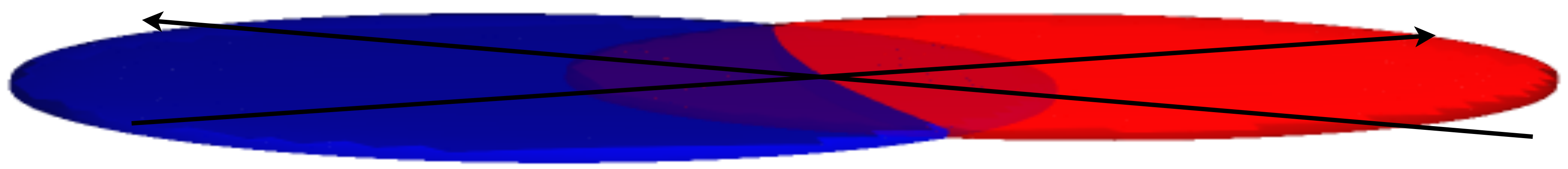
	KEKB (2009.06.17)		SKEKB (2021.12.16)		SKEKB (Final design)	
	HER	LER	HER	LER	HER	LER
I_{beam} (A)	1.2	1.0	0.79	0.98	2.6	3.6
# bunch	1585		1370		2500	
ε_x (nm)	24	18	4.6	4.0	4.6	3.2
ε_y (pm)	150	150	~50	~50	12.9	8.64
β_x (mm)	1200	1200	60	80	25	32
β_y (mm)	5.9	5.9	1	1	0.3	0.27
σ_z (mm)	6	6	5	6	5	6
ν_x	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

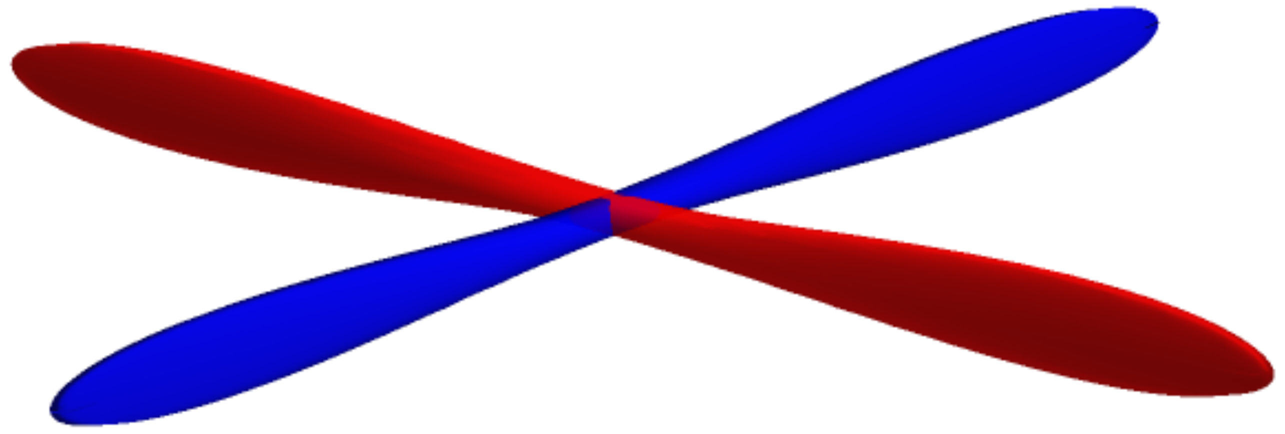
KEKB
(Crossing angle)



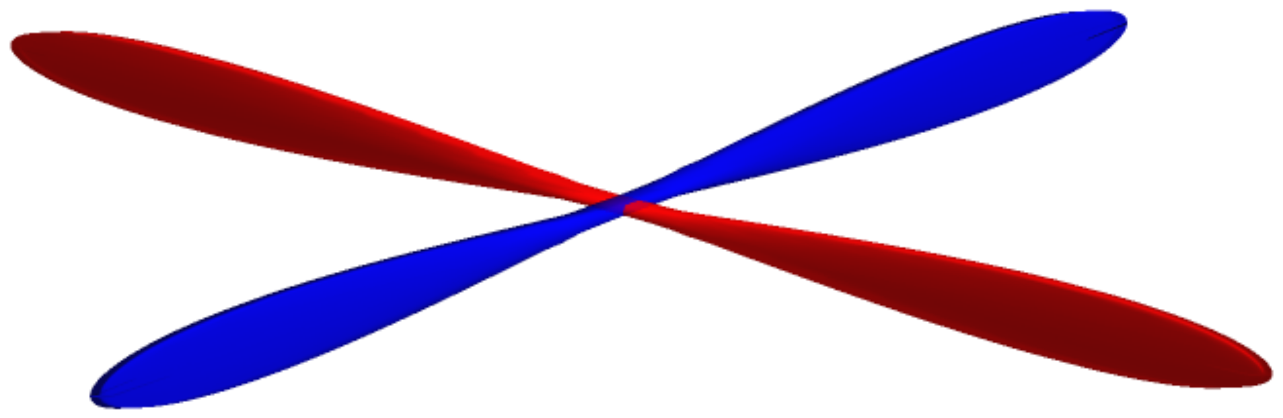
KEKB
(Crab cavity)



SuperKEKB
(2021c)

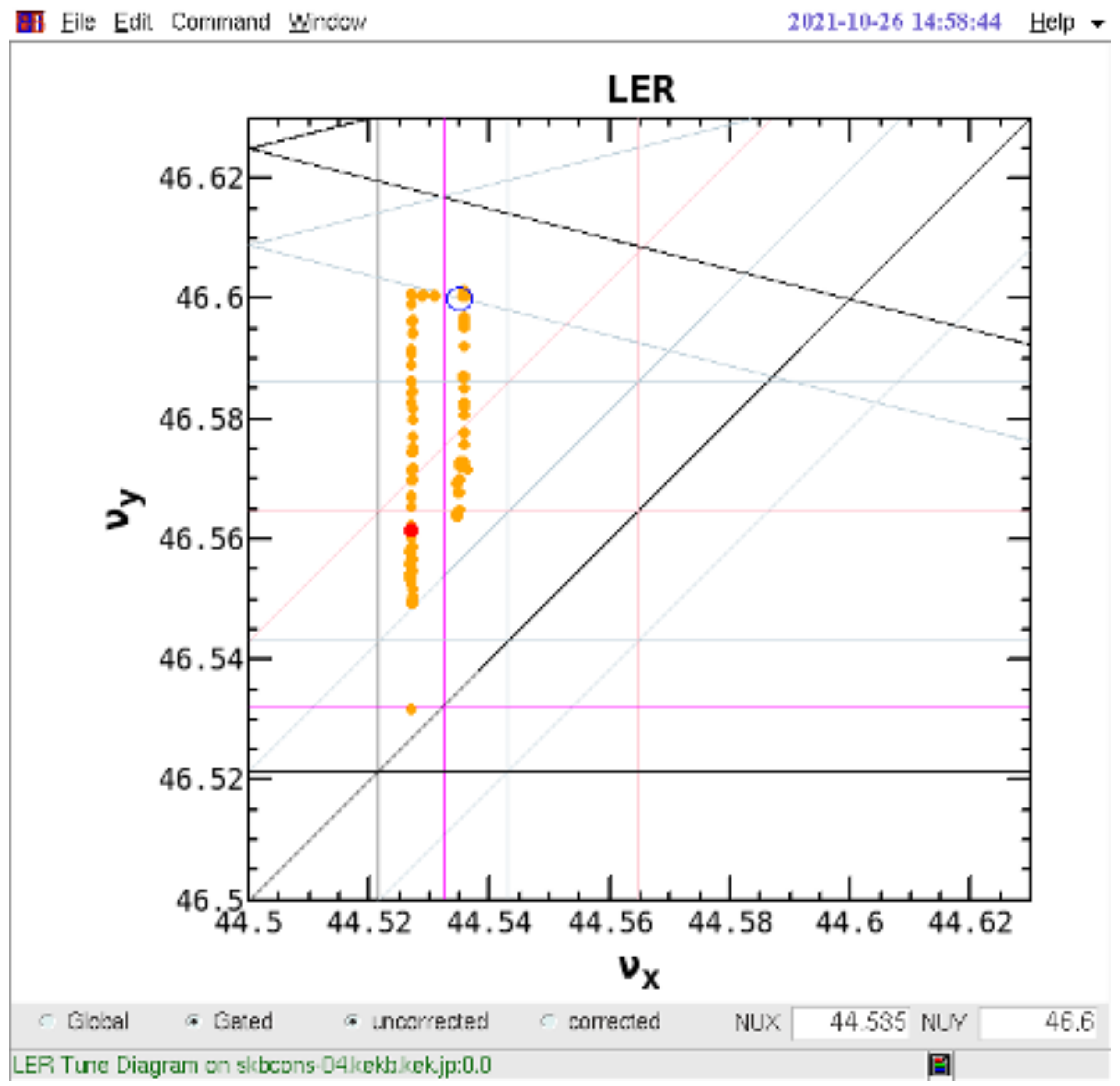


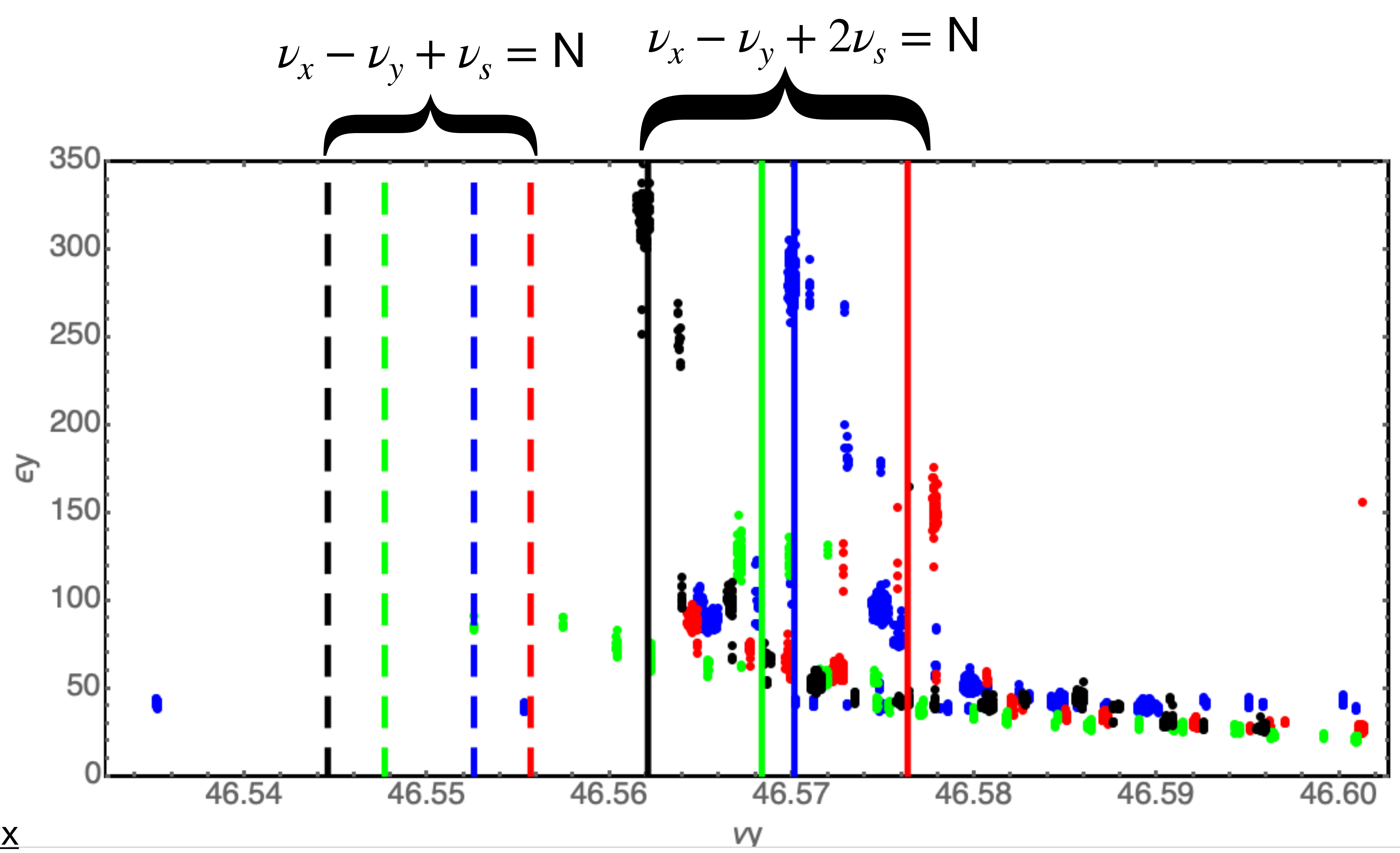
SuperKEKB
(Final design)



Resonances and tune survey

- LER TMCI study done on Oct. 26, 2021
  - A TMCI study in LER was done on Oct. 26, 2021.
  - More details about the study can be found from later reports by Ishibashi-san (for example, see Ref. [6]).
  - Post analysis of the experimental data showed clear emittance blowup caused by chromatic couplings of $\nu_x - \nu_y + \nu_s =$ Integer and $\nu_x - \nu_y + 2\nu_s =$ Integer. Synchrotron tune ν_s depends on bunch current because of potential-well distortion caused by longitudinal coupling impedance. So data analysis needs to take into account this factor.
  - This study showed a possible interplay between localized transverse impedance from collimators and machine imperfections (including linear coupling and chromatic couplings) (See Ohmi-san's report Ref. [7] and this talk in this meeting).





Blue dots: ν_y scan with $\nu_x = 44.535$ and $I_{\text{bunch}} = 0.91$ mA

Red dots: ν_y scan with $\nu_x = 44.535$ and $I_{\text{bunch}} = 0.31$ mA

Green dots: ν_y scan with $\nu_x = 44.527$ and $I_{\text{bunch}} = 0.31$ mA

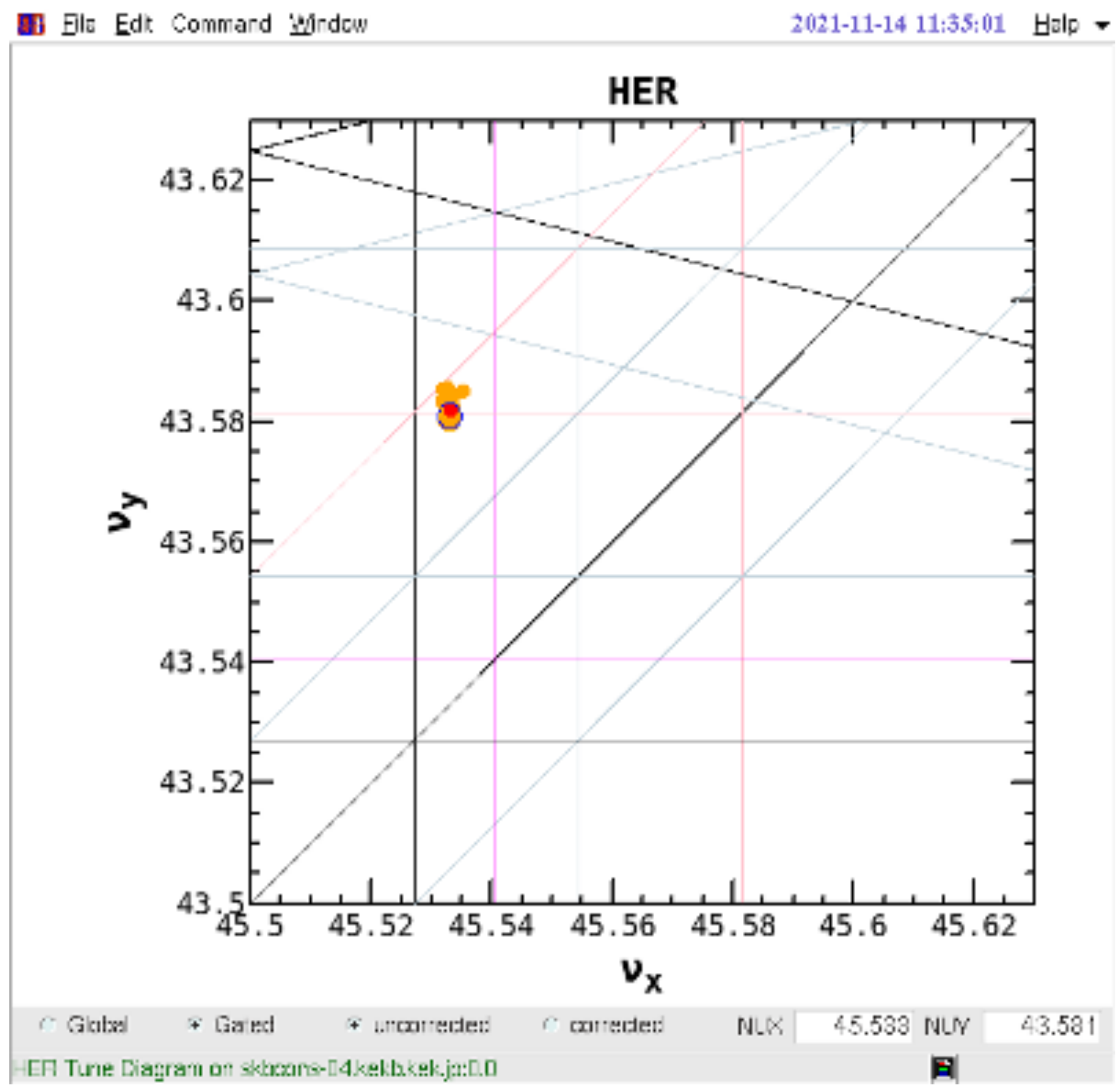
Black dots: ν_y scan with $\nu_x = 44.527$ and $I_{\text{bunch}} = 0.91$ mA

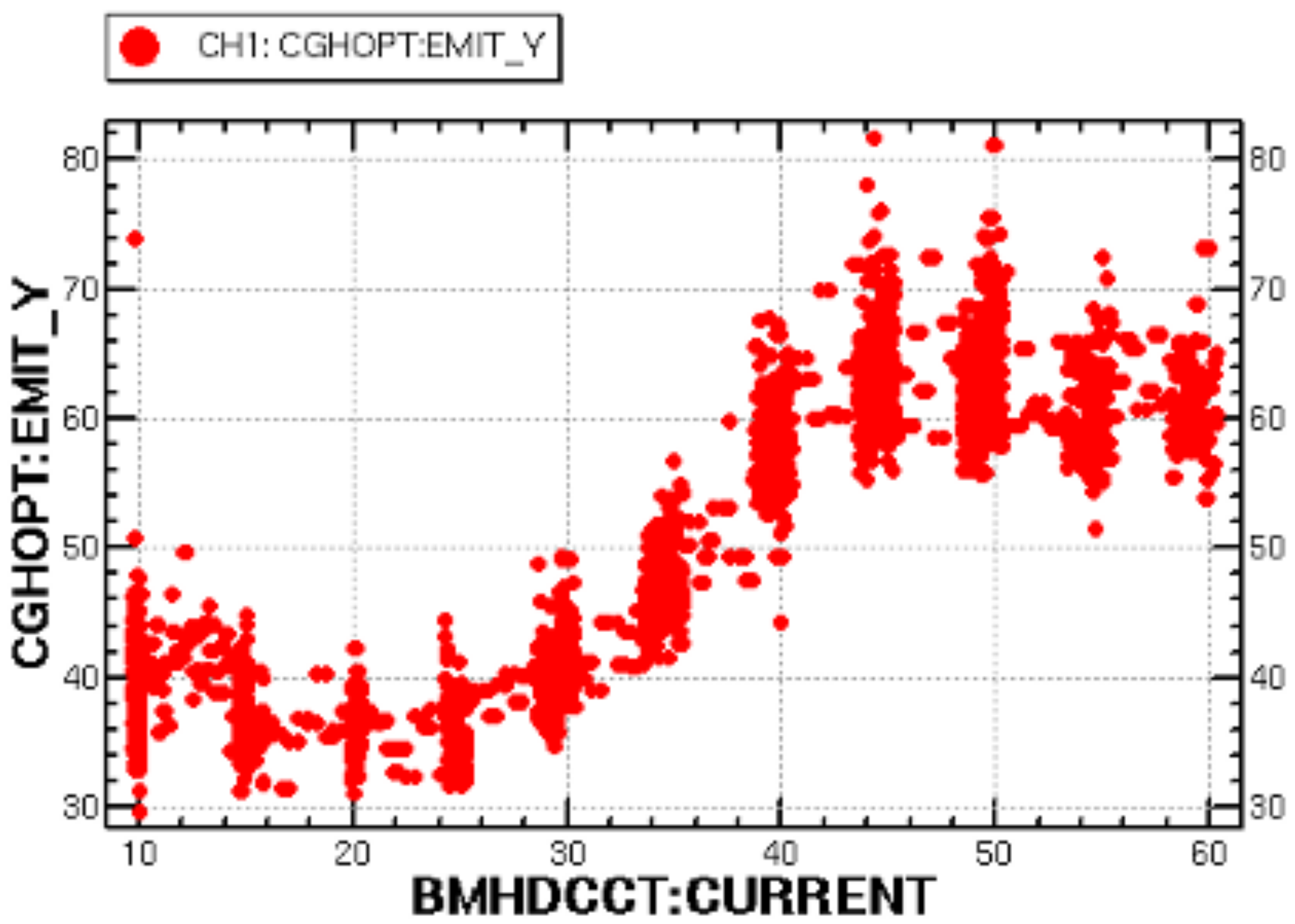
[6] https://kds.kek.jp/event/39972/contributions/199971/attachments/149042/186732/2021c_tmci_study_report.pptx

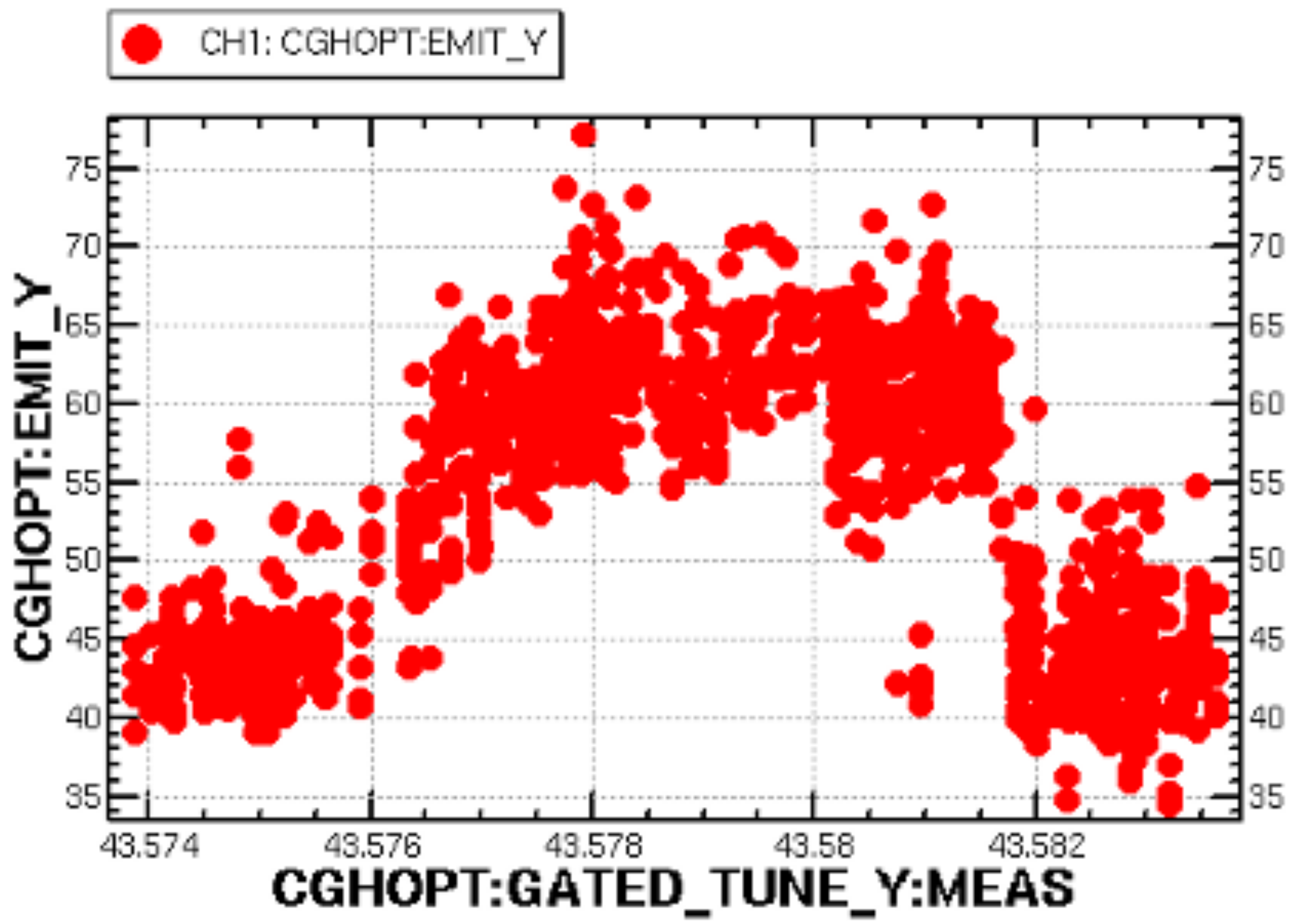
[7] https://kds.kek.jp/event/39972/contributions/200040/attachments/149061/186596/SBR_ChromCoup_Wake.pdf

Resonances and tune survey

- HER single-beam study done on Nov. 14, 2021
  - The study was done with LER trouble with injection kickers. So the beam time of HER was available for such study.
  - More details about the study can be found from shift report (2021_11_14_0900_Suetsugu_Sugimura.pptx) and study report presented by D.Zhou at the KCG meeting of Nov.15, 2021.
  - Post analysis of the experimental data showed clear emittance blowup caused by the second chromatic coupling $\nu_x - \nu_y + 2\nu_s =$ Integer. Because HER's working point (fixed by tune feedback) is close to this resonance, when the bunch current was increased, the synchrotron tune ν_s will decrease. Consequently, the overlap of beam's tune footprint with $\nu_x - \nu_y + 2\nu_s =$ Integer caused emittance blowup.

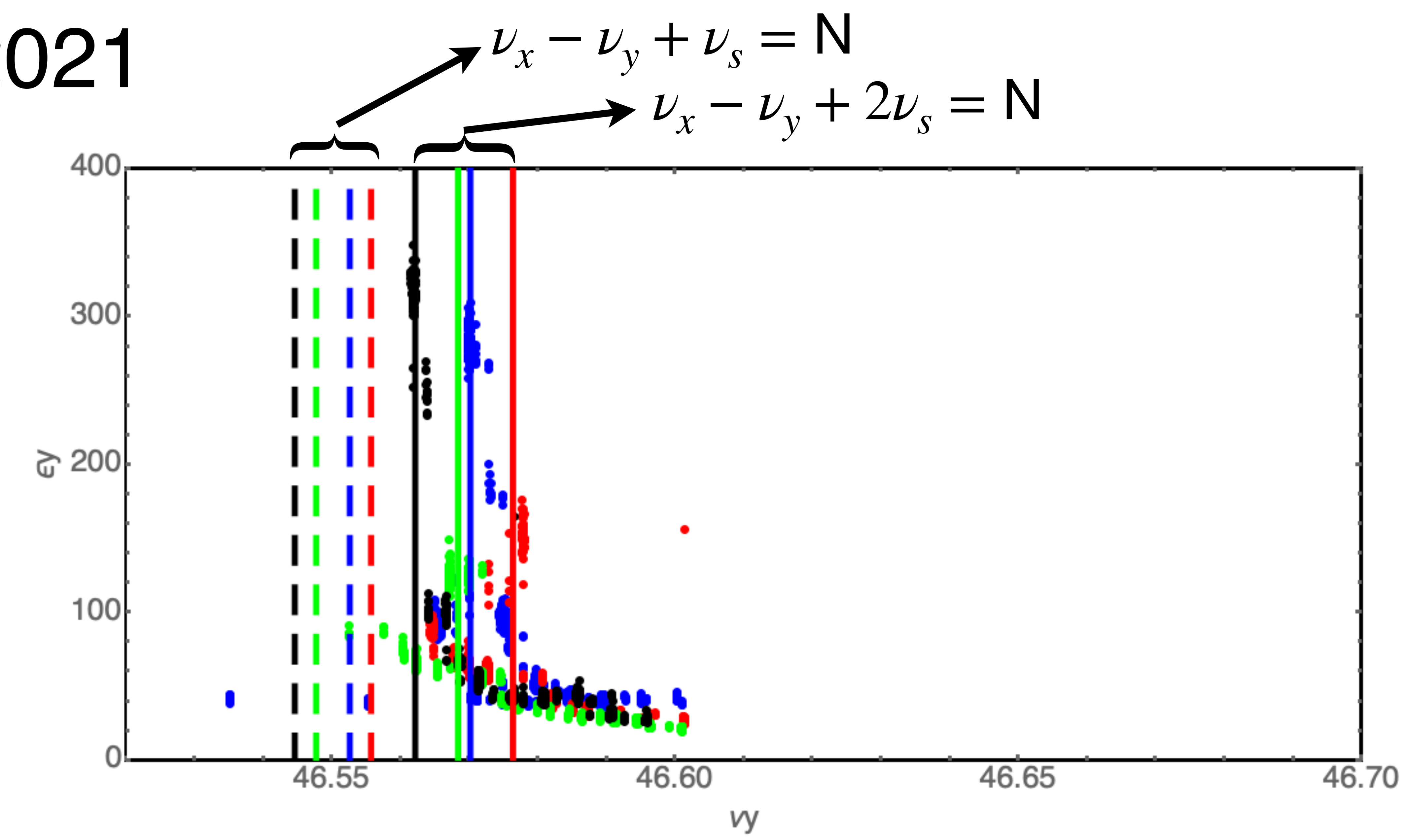


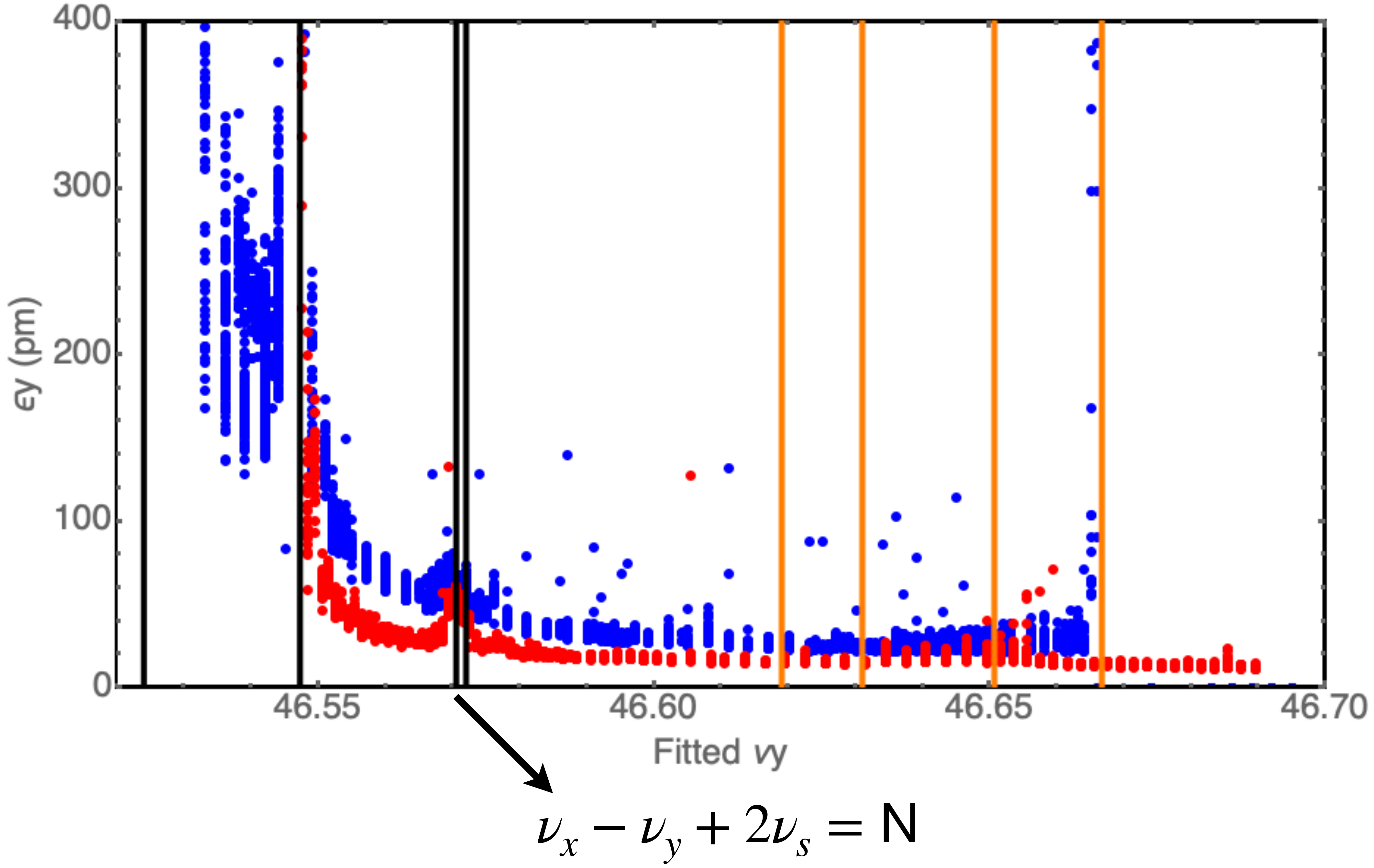




Tune survey machine study done on Dec. 3, 2021

- LER ν_y scan: compare data of 2021.10.26 ($\beta_y^* = 8$ mm) and data of 2021.12.03 ($\beta_y^* = 1$ mm)
  - The tune survey of 2021.10.26 was done with bunch current $I_{b+} =$ 0.31 (red ($\nu_x = 44.535$) and green ($\nu_x = 44.527$) dots of the upper figure) and 0.91 (blue ($\nu_x = 44.535$) and black ($\nu_x = 44.527$) dots of the upper figure) mA. The lattice gives synchrotron tune $\nu_{s0} = 0.0227$.
  - The tune survey of 2021.12.03 was done with very low bunch current (beam current ≤50 mA and bunch number 783). The lattice gives synchrotron tune $\nu_{s0} = 0.0233$.
  - The incoherent synchrotron tune depend on bunch current be of $\nu_s \propto 1/\sigma_z$ due to potential-well distortion due to longitudinal coupling impedance. For data analysis of 2021.12.03, bunch-current dependency of ν_s was neglected ($\nu_{s0} = 0.0233$ was used for the plot).
  - Strength of $\nu_x - \nu_y + 2\nu_s =$ N with $\beta_y^* = 8$ mm seems to be stronger than that with $\beta_y^* = 1$ mm. Effects of rotating sextupoles? To be confirmed by machine study.

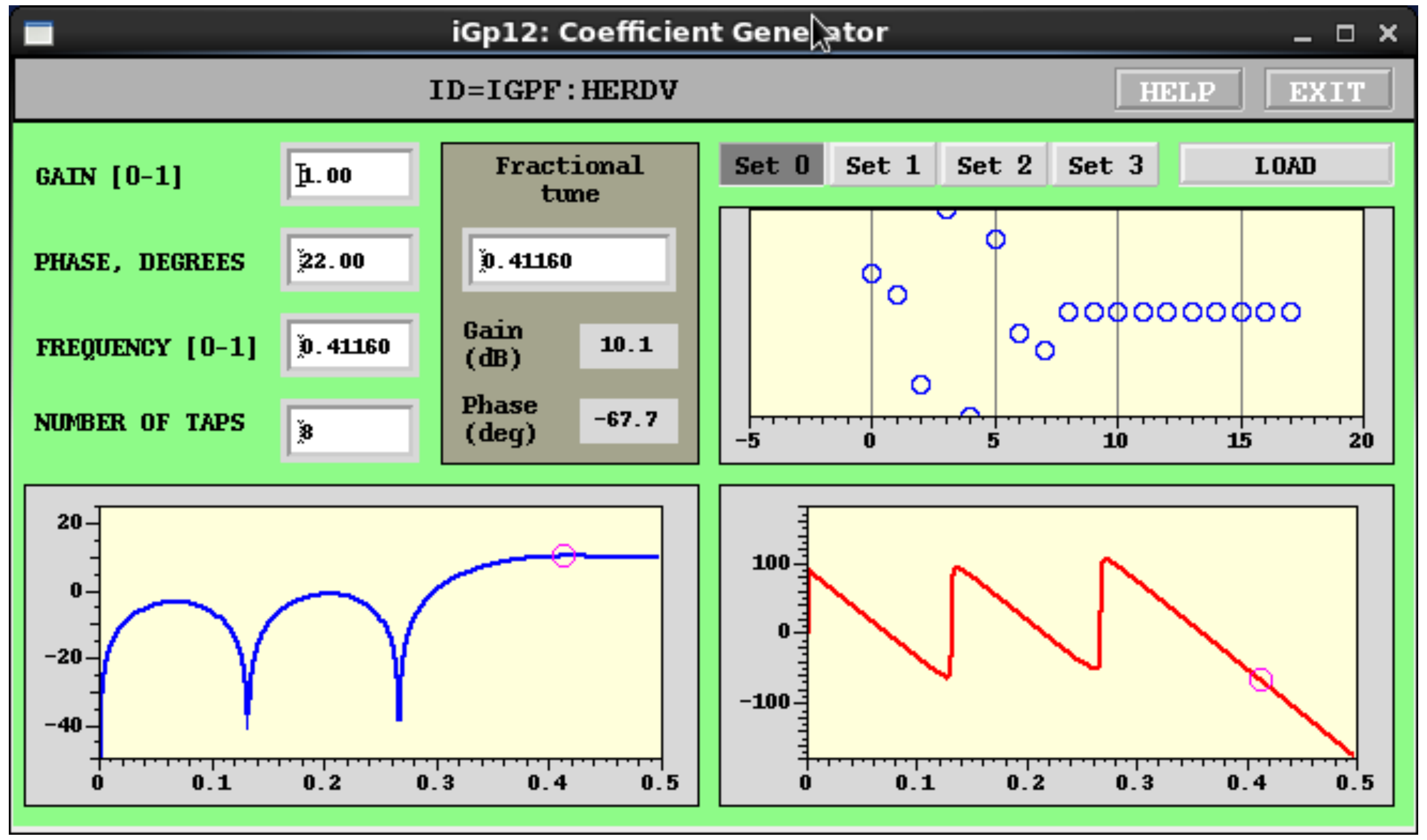


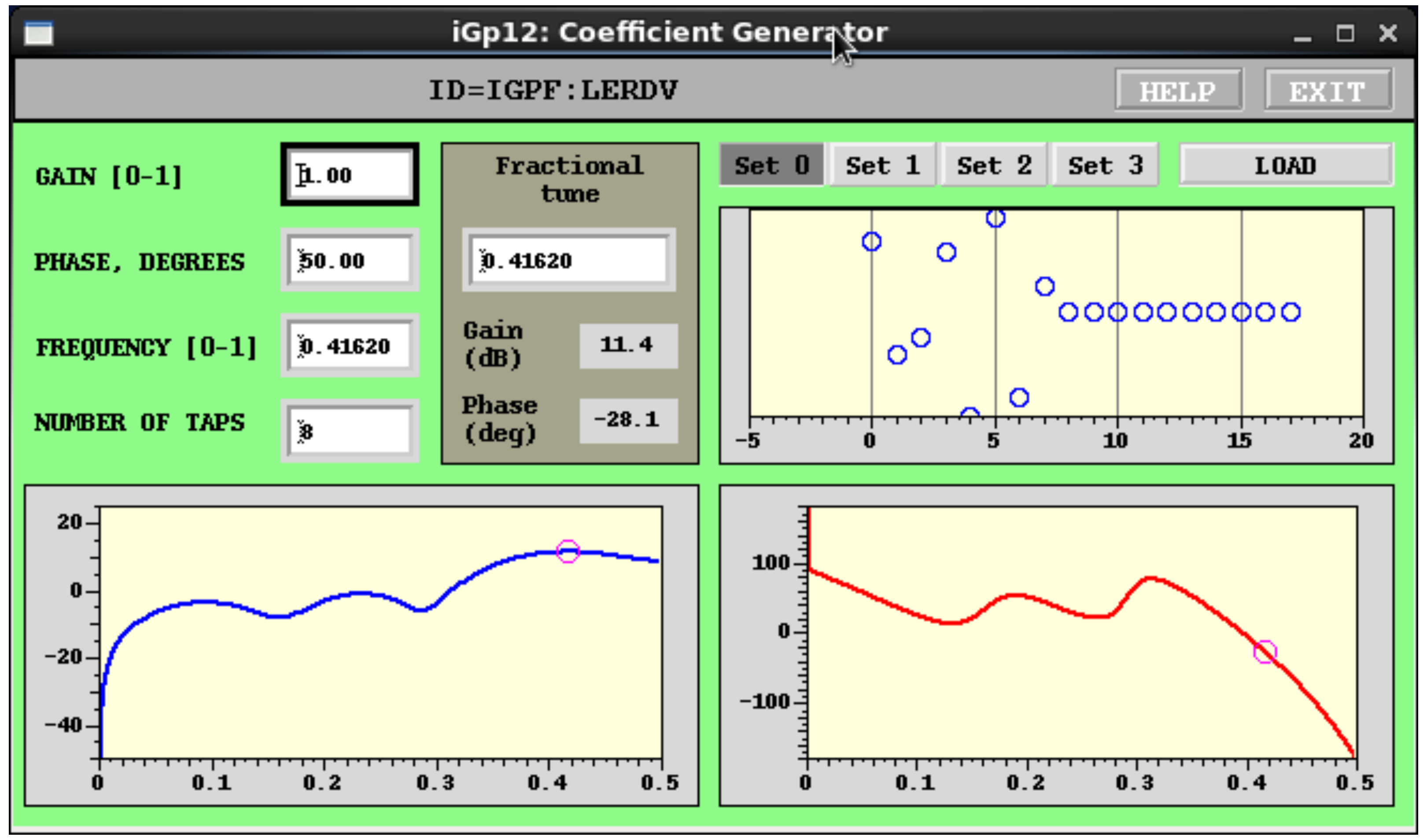


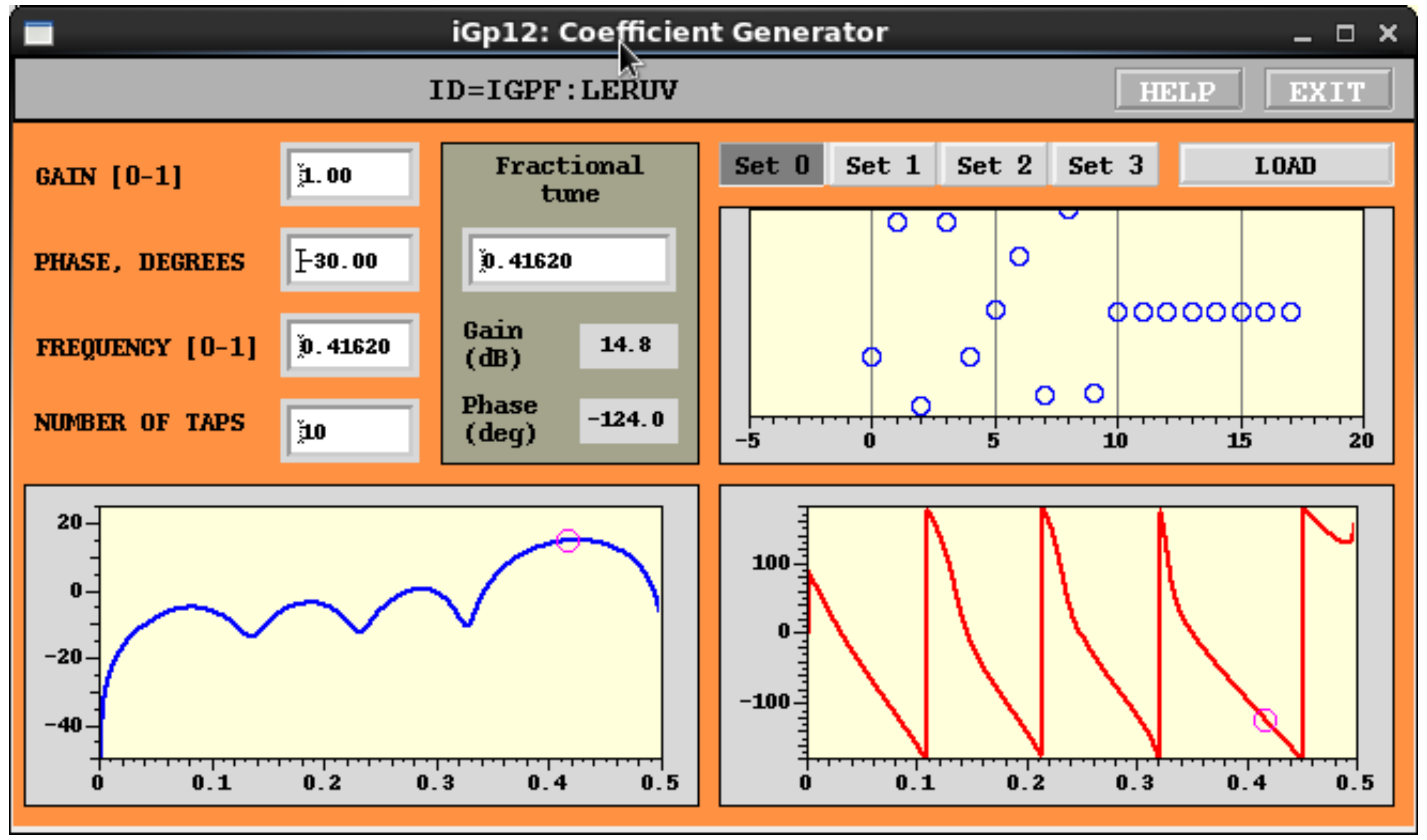
Tune survey machine study done on Dec. 3, 2021

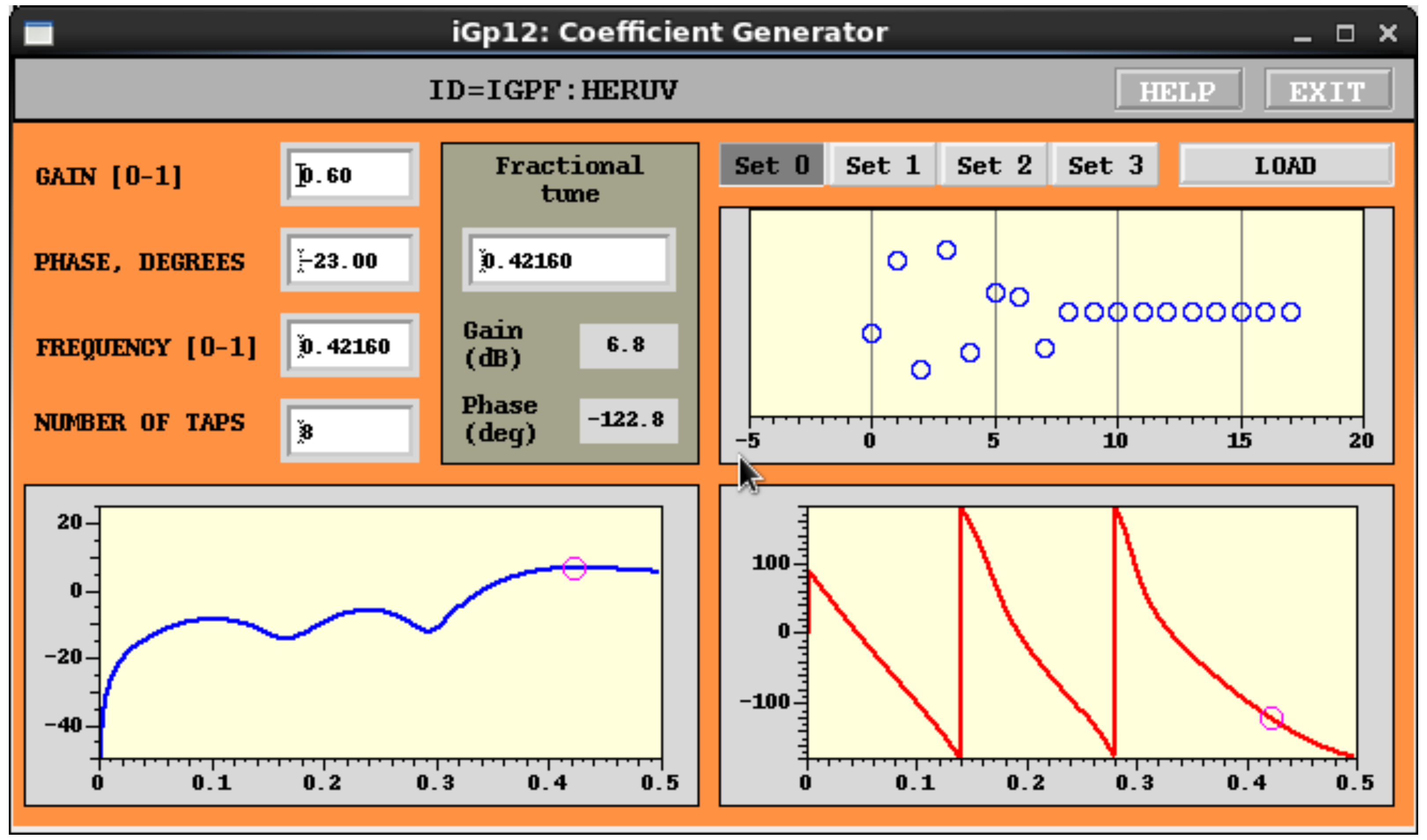
- Effects of BxB FB system
  - For tune survey with fractional ν_y>0.6, one concern is effects of BxB FB.
  - In this study, when ν_y>0.6, injection was difficult, BxB FB had to be turned on to improve injection.
  - Further investigations are necessary.

Courtesy of M. Tobiyama









Horizontal impedance model of SuperKEKB LER

- Assume collimator settings at 13:30 PM, Dec. 22, 2021.
- The table is for σ_z=6 mm.

	Number of items	Average β_x (m)	$\beta_x*\kappa_{xD}$ (V/pC)	$\beta_x*\kappa_{xQ}$ (V/pC)
ARES	22	17.1	-439	0
Comb bellows	1047	15.8	-385	-74
MO flange	2000	15.8	-69	1.7
Pumping port (m)	2200/0.4	15.8	-1.4	0
SR mask	1000	15.8	0	0
IR duct	1	0.34	-11	-3.2
BPM	445	18.9	-53	-3
Transverse FB kicker	2	18.8	-17	-68
Transverse FB BPM	12	24.4	-10	0
Longitudinal FB kicker	2	35.5	-294	0
Grooved beam pipe (m)	520/0.4	11	-461	36
Tapers	25	15.8	-7	-7
Clearing electrode (m)	150/2.	15.6	-64	468
Welding gaps	2000	15.8	-517	-19
Resistive wall	-	15.8	-1003	-
Total	-	-	-3333	331

Horizontal impedance model of SuperKEKB LER

- Assume collimator settings at 13:30 PM, Dec. 22, 2021.
- The table is for σ_z=6 mm.
- Resistive wall of collimators NOT taken into account

	Half gap (mm)	Average β_x (m)	β_x*κ_{xD} (V/pC)	β_x*κ_{xQ} (V/pC)
D06H1	13.85	24.2	-233	-13
D06H3	10.8	24.2	-397	-138
D06V1	2.79	14.6	-826	856
D06V2	2.71	10	-584	602
D03H1	11.95	29	-377	-93
D03V1	8	10.4	-114	178
D02H1	8	20.8	-774	-356
D02H2	11.95	36.5	-475	-117
D02V1	1.12	26.2	-3878	4578
D02H3	13.95	50.8	-483	-23
D02H4	8.07	20.4	-744	-343
Total	-	-	-8885	4369