Updates on beam-beam simulations and recent machine studies related to beam-beam

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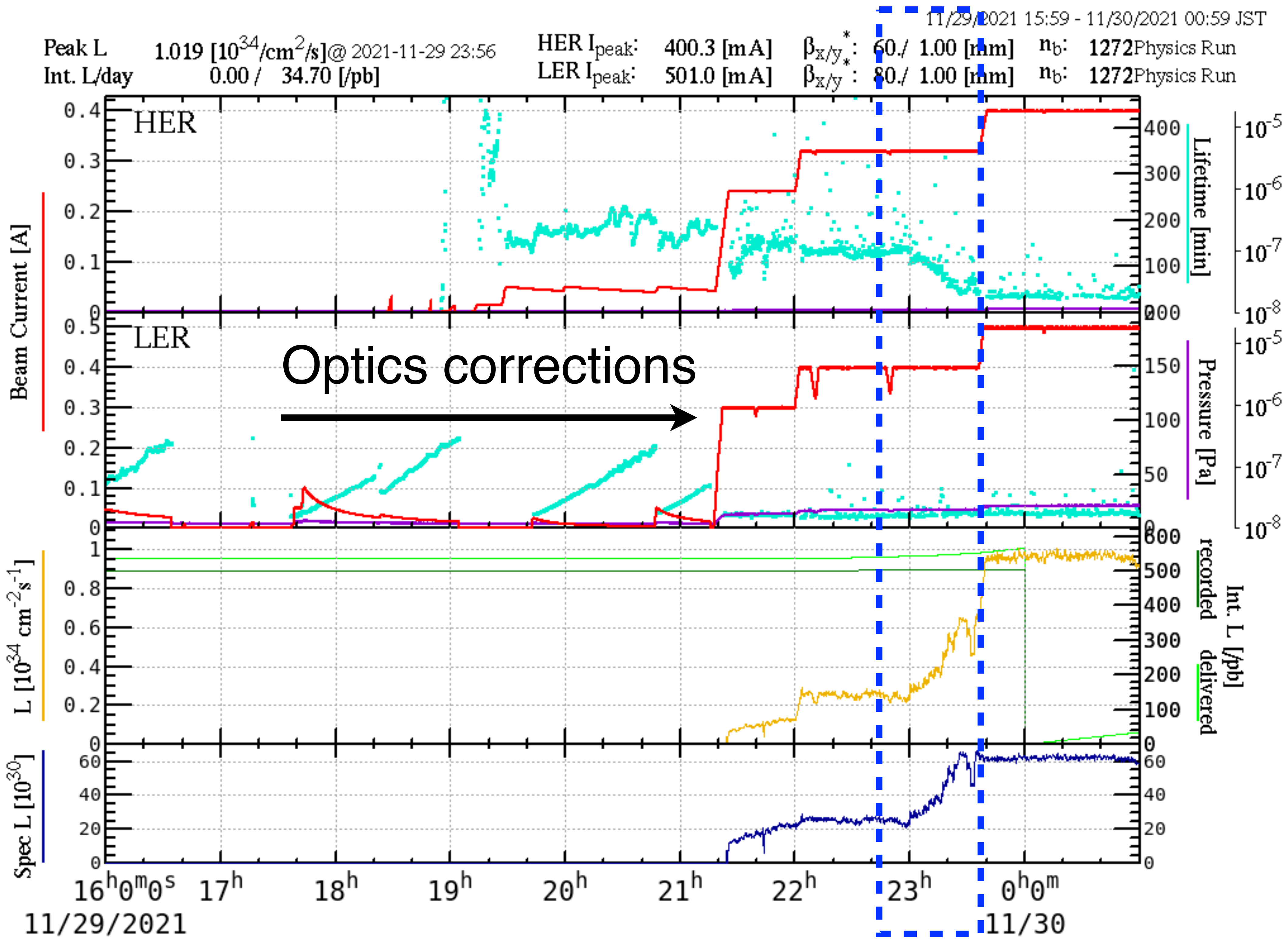
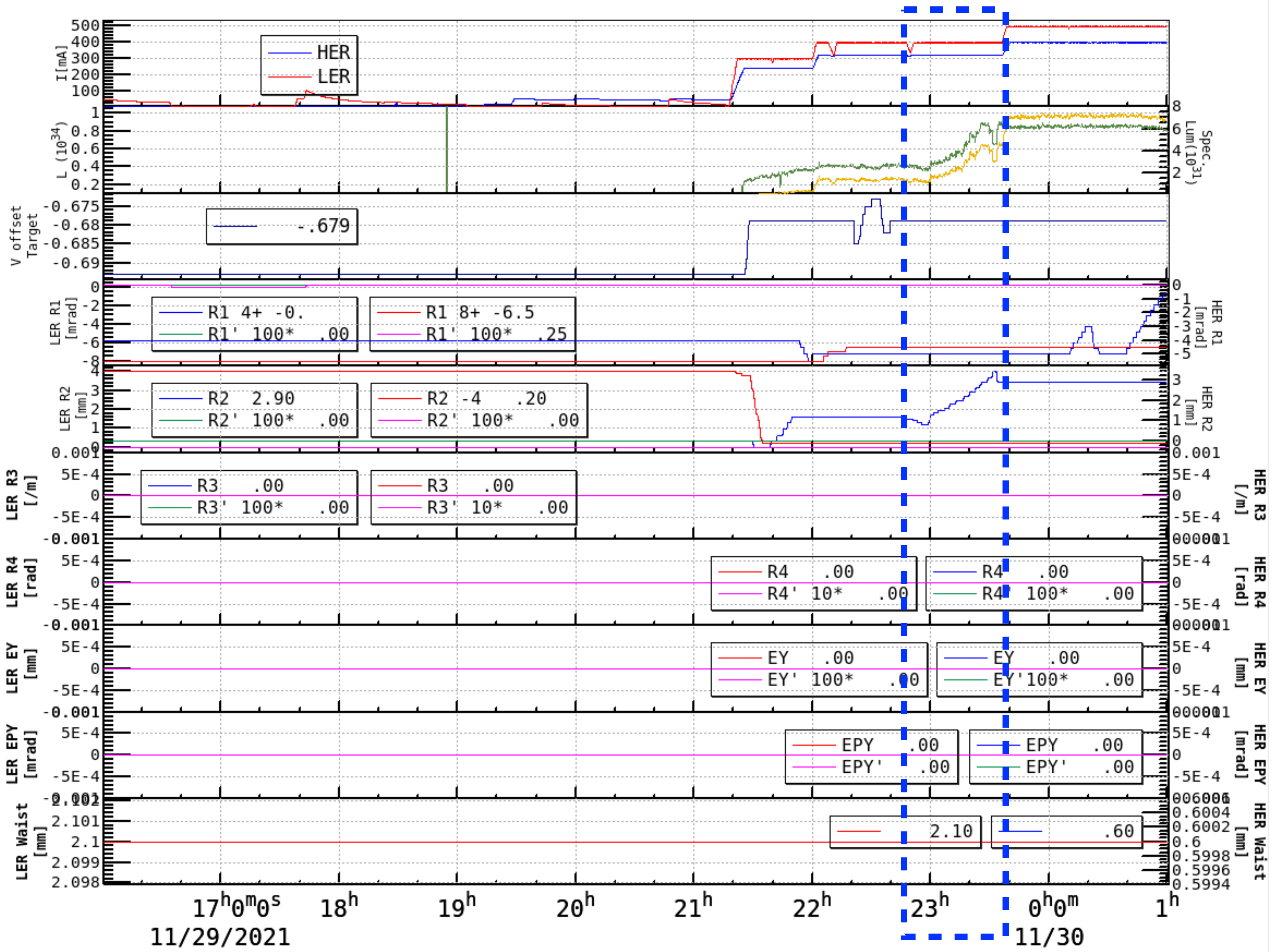
Outline

- Updates on beam-beam simulations for SuperKEKB
    - BBSS simulations of IP knobs (R1 and R2)
- Recent machine study related to beam-beam
- Luminosity performance
- Summary

Machine tunings

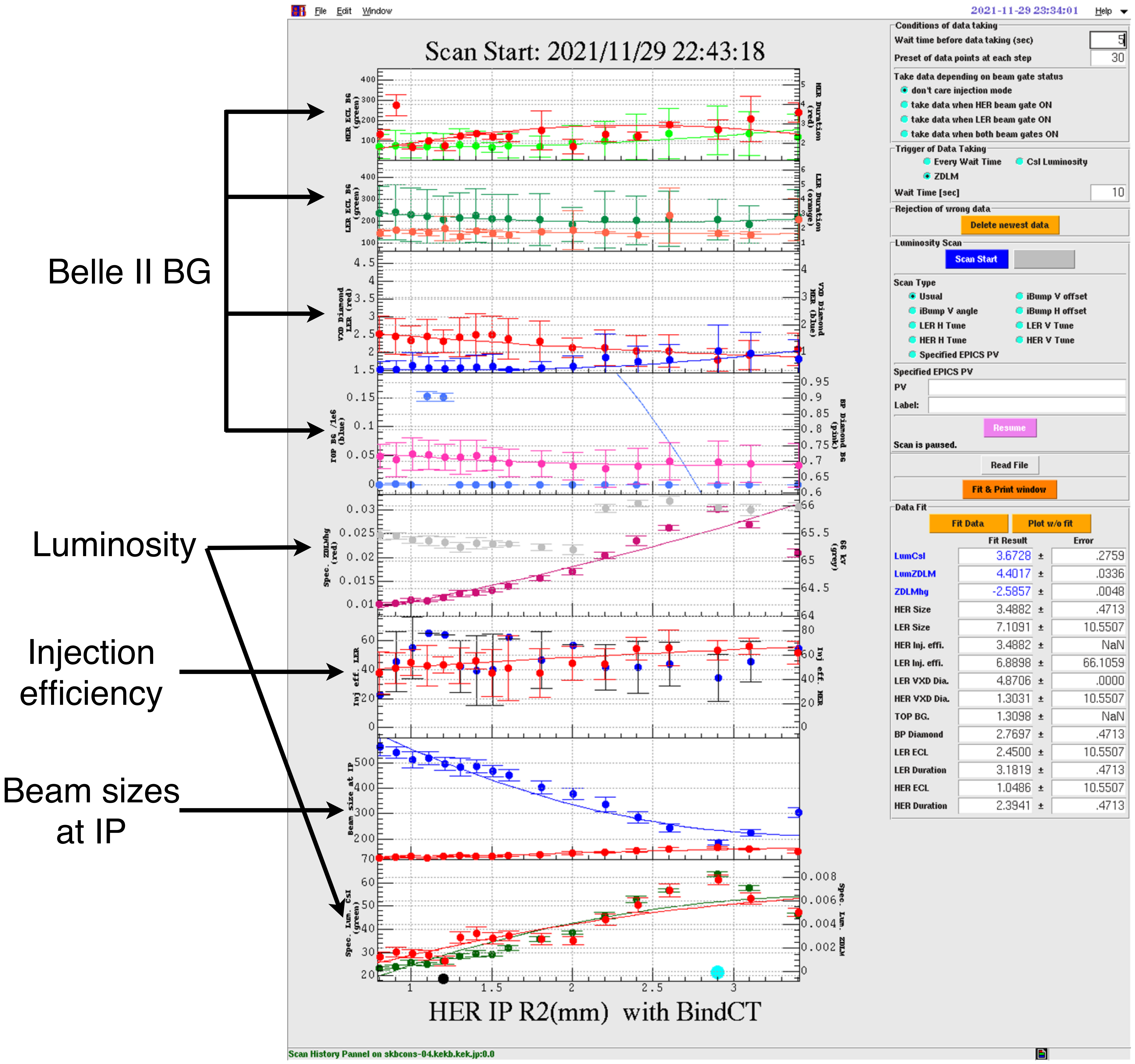
- Luminosity optimization with IP knobs are frequently done by KCG shifters.
- The IP knobs are usually successful after fresh global optics correction (beta functions, coupling, dispersion).
- The global optics corrections do not control the optics parameters at IP well. So IP knobs serve as a next-step fine tuning. Usually R1 and R2 scans are successful. R3 and R4 scans are more related to Belle2 background.





Machine tunings

- An example of successful HER IP R2 knobs is shown.
- Online luminosity optimization is a challenging task.



Updates on beam-beam simulations

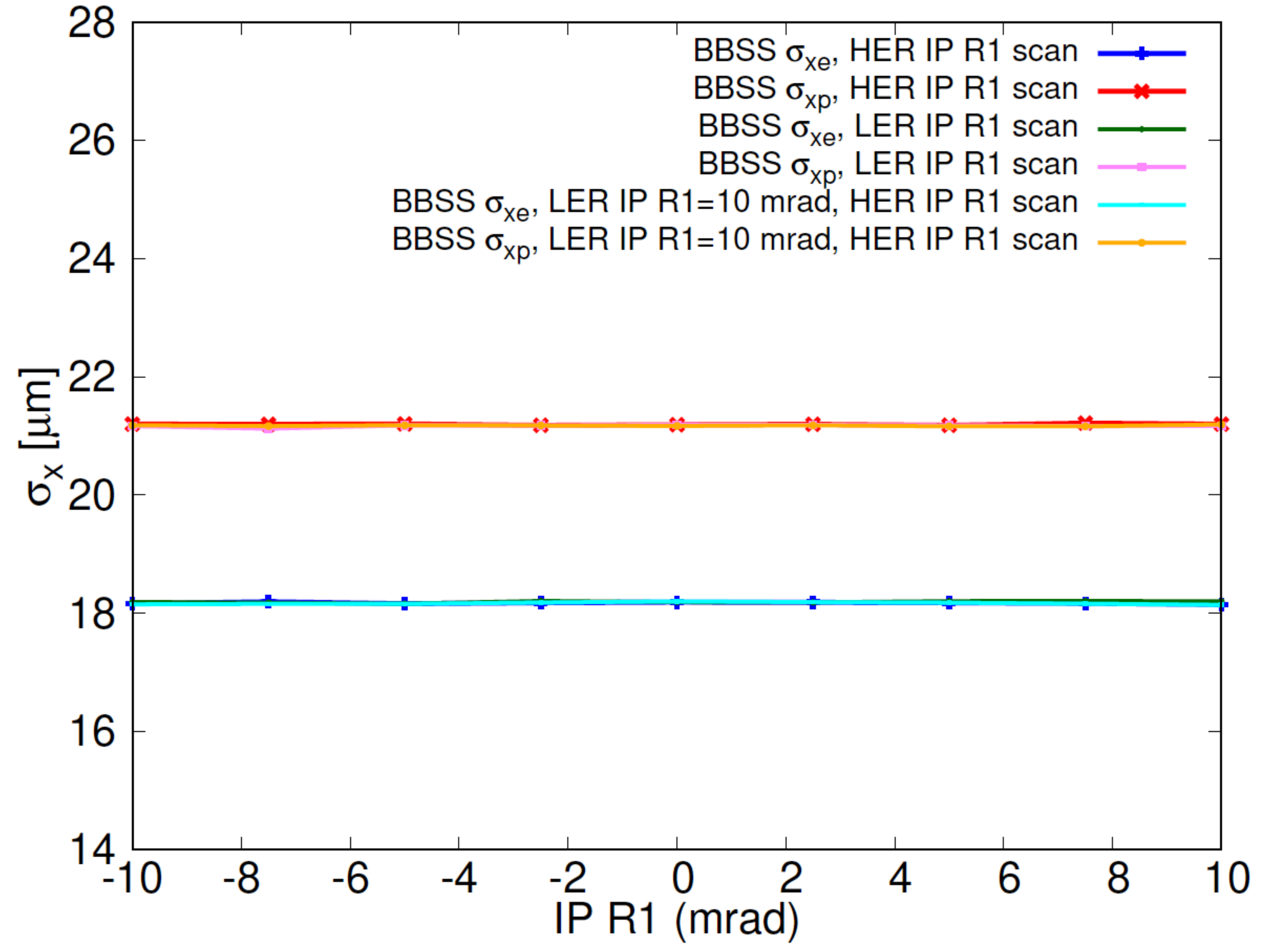
- Simulations of IP knobs (R1 and R2) with longitudinal pseudo-Green function wakes
  - Beam parameters similar to observations on 2021.07.01.

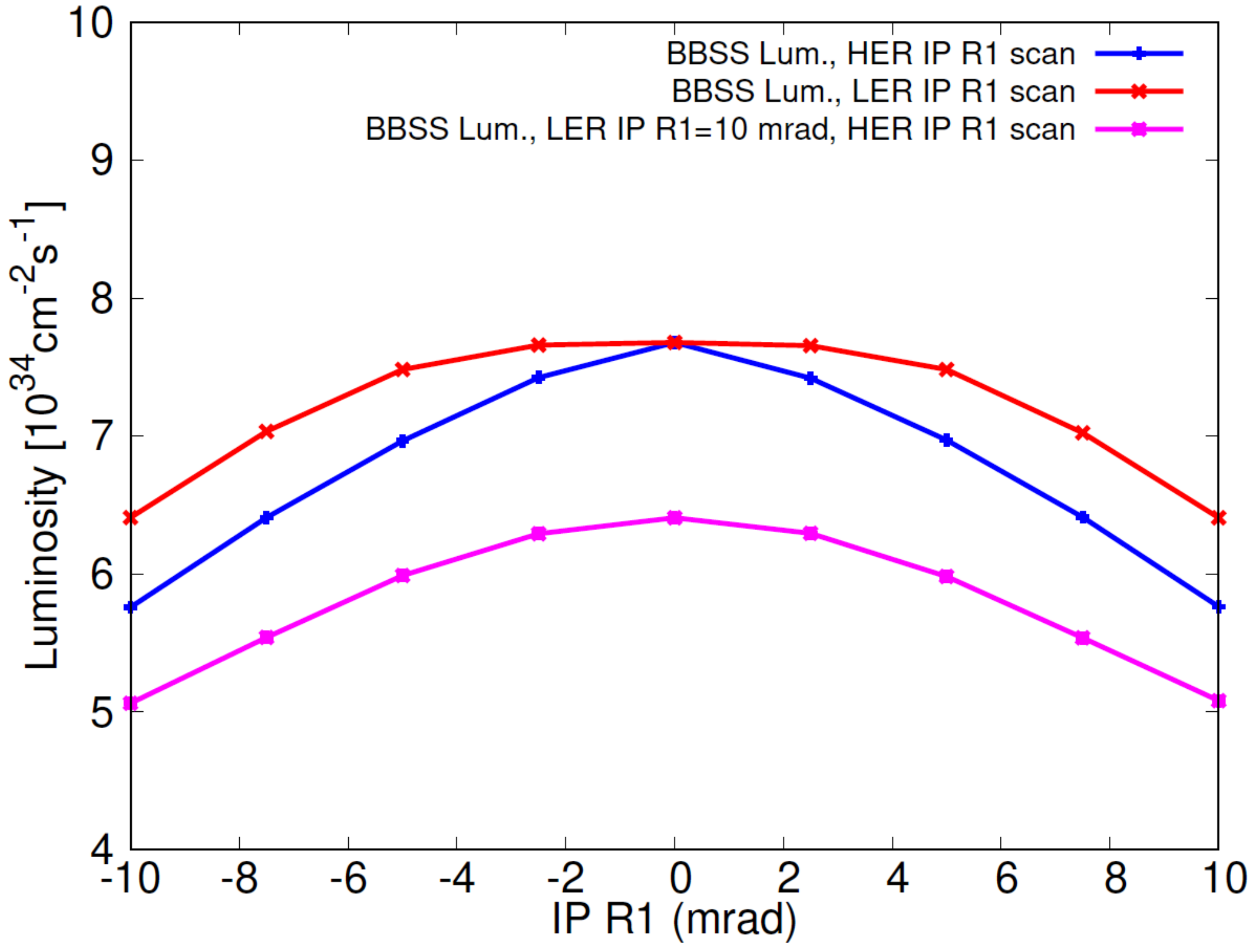
	2021.07.01		Comments
	HER	LER	
I_{bunch} (mA)	0.80	1.0	
# bunch	1174		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	23	23	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured 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

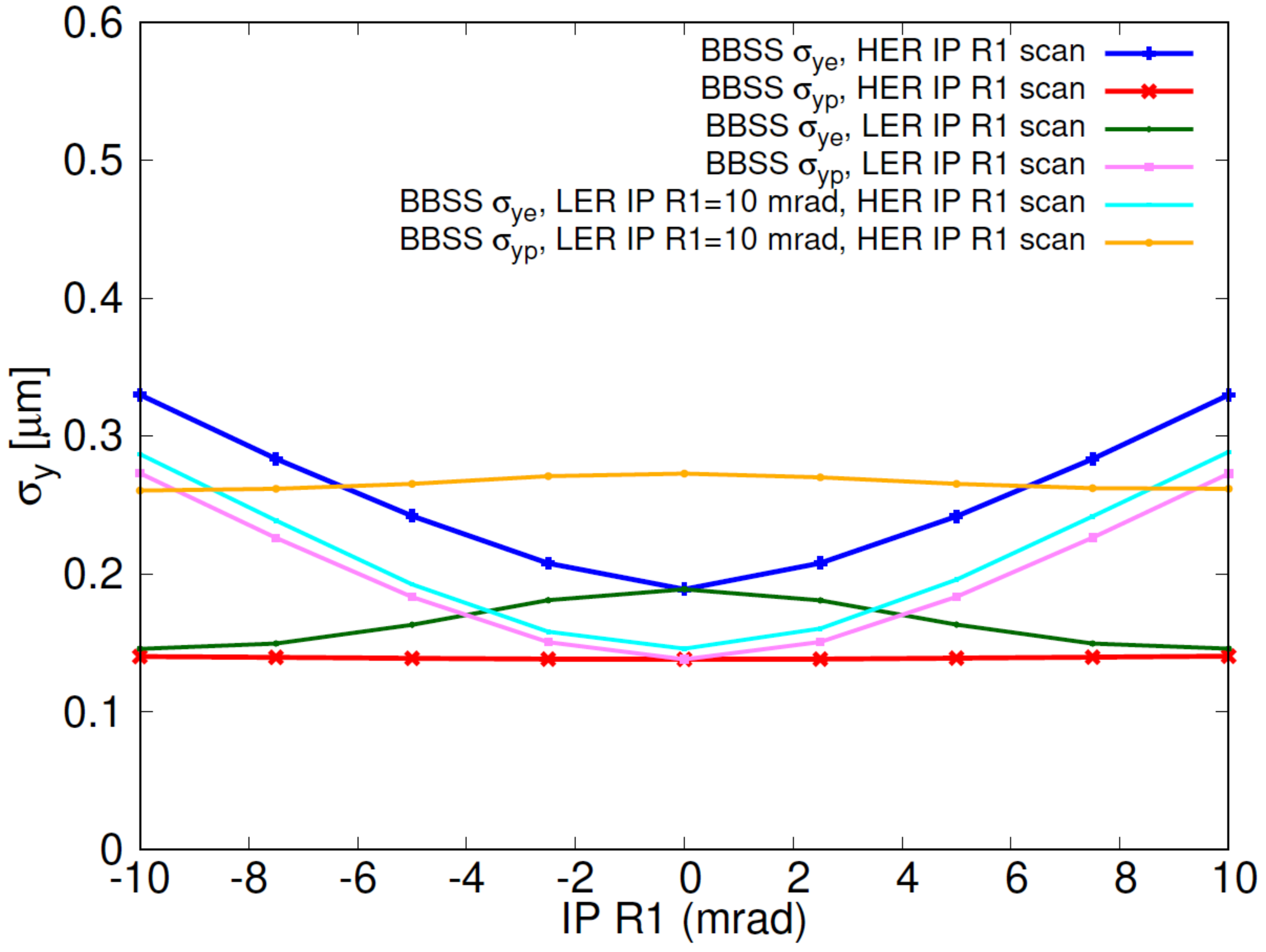
Updates on beam-beam simulations

- IP R1 scan
  - Simulations were done using simple one-turn matrix.
  - With $\epsilon_y = 23$ pm and $\beta_y^* = 1$ mm, changing R1 of one beam has small effect on the other beam.
  - σ_y^* of electron beam has correlation with IP R1 of LER, this is because the crab waist ratio of HER is 40%. Beam-beam blowup (due to BB resonances) of HER beam is relaxed with the LER beam size becomes larger (it means weaker beam-beam force).
  - With LER IP R1=10 mrad, the best luminosity is found at HER IP R1=0. This seems to justify the principle of IP knobs:

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





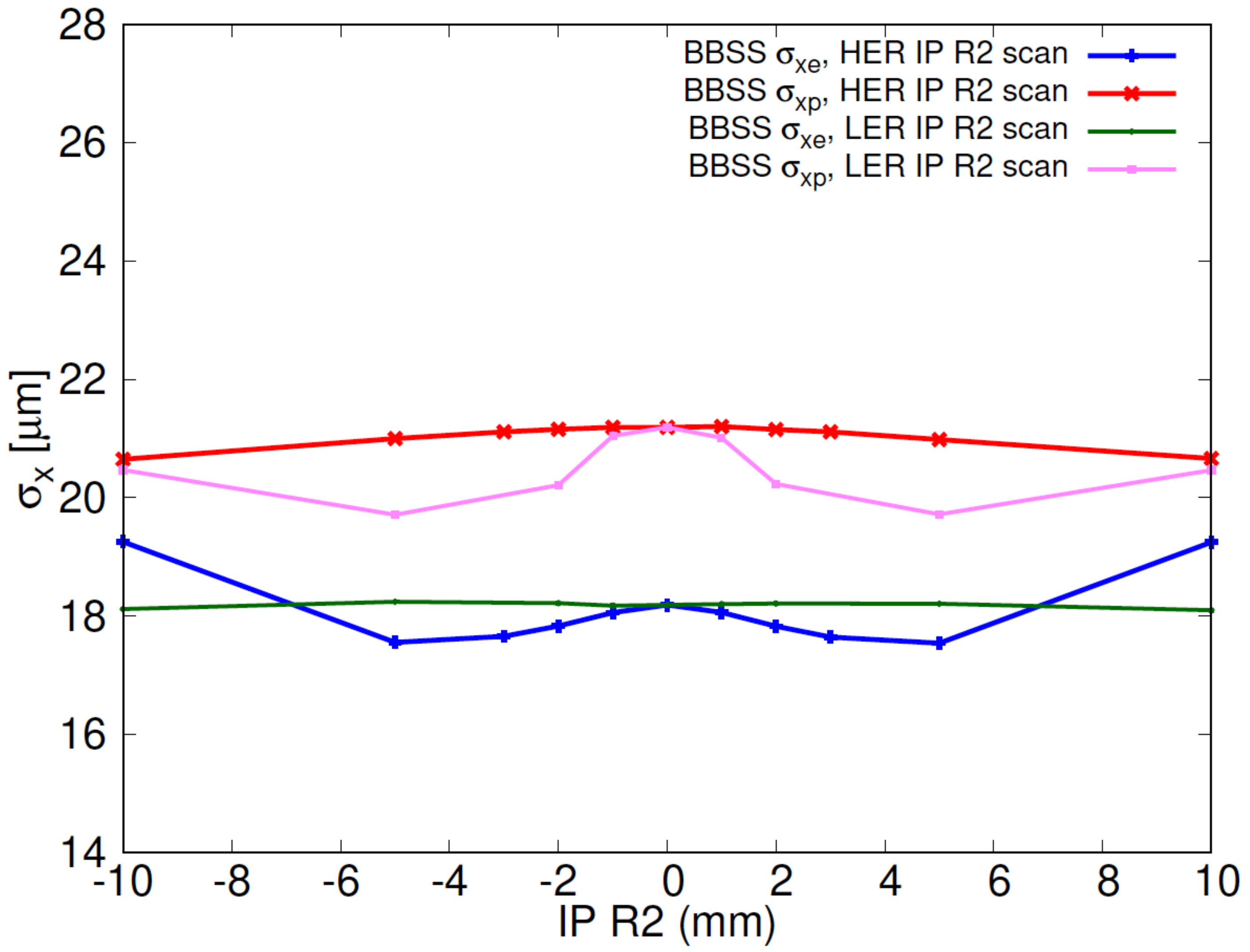


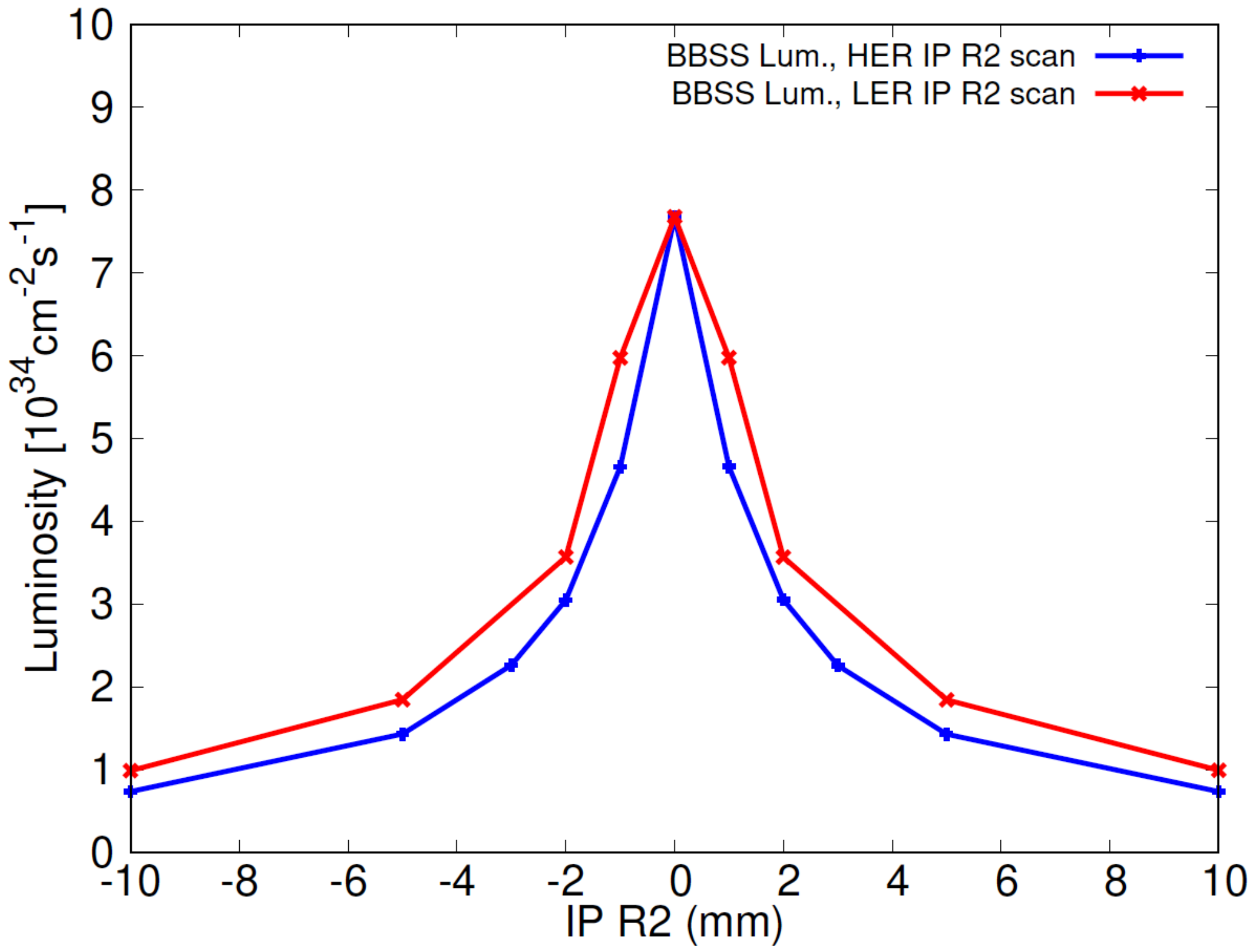
Updates on beam-beam simulations

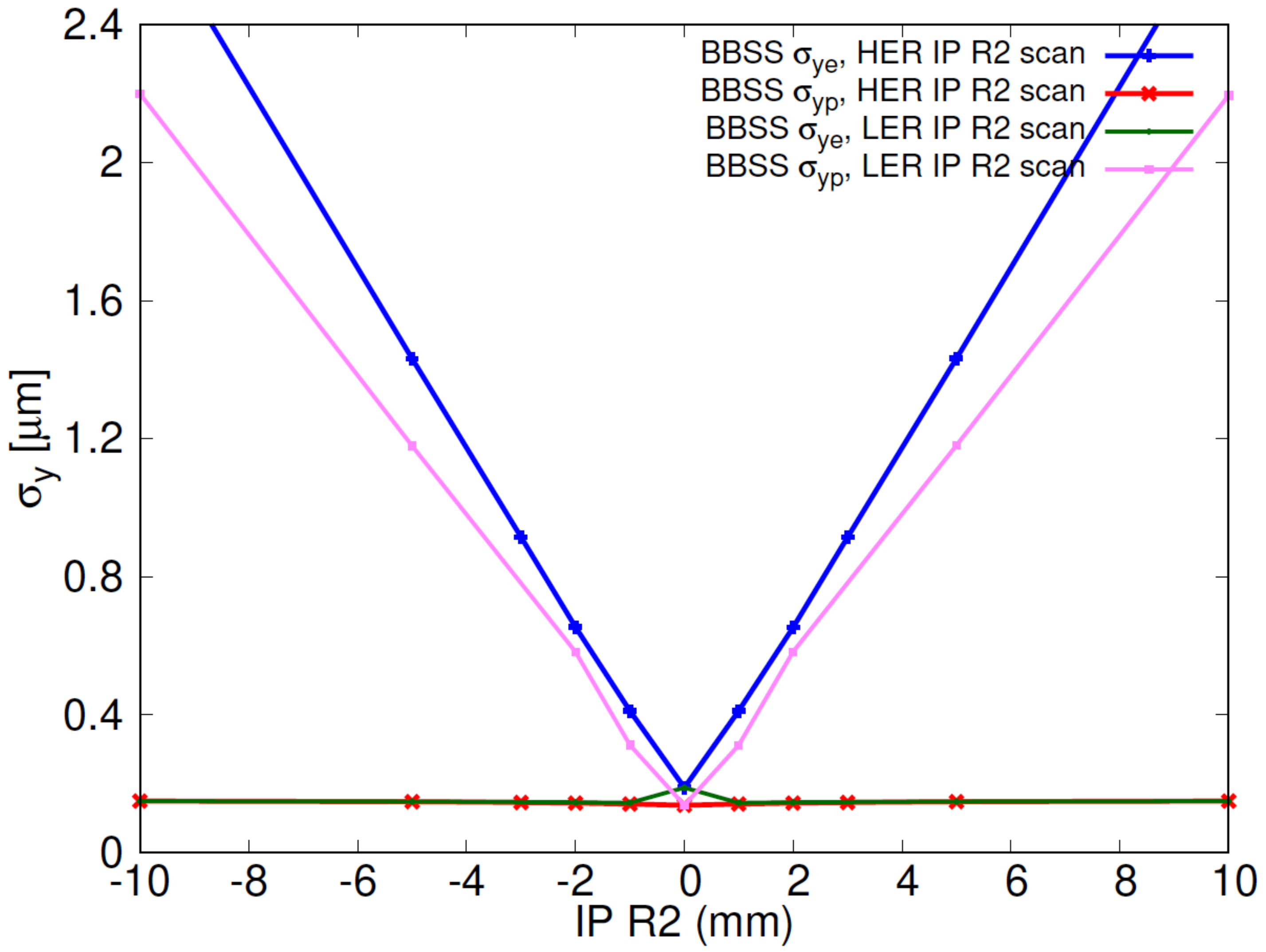
- IP R2 scan
  - Simulations of IP R2 scan show similar results of IP R1 scan.
  - The scaling law of vertical beam sizes at IP follows [1]:

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

  - Δs is the deviation of vertical waist position.
  - Luminosity looks to be sensitive to R2, but it is related to $\beta_x^* \ll 1$ m.



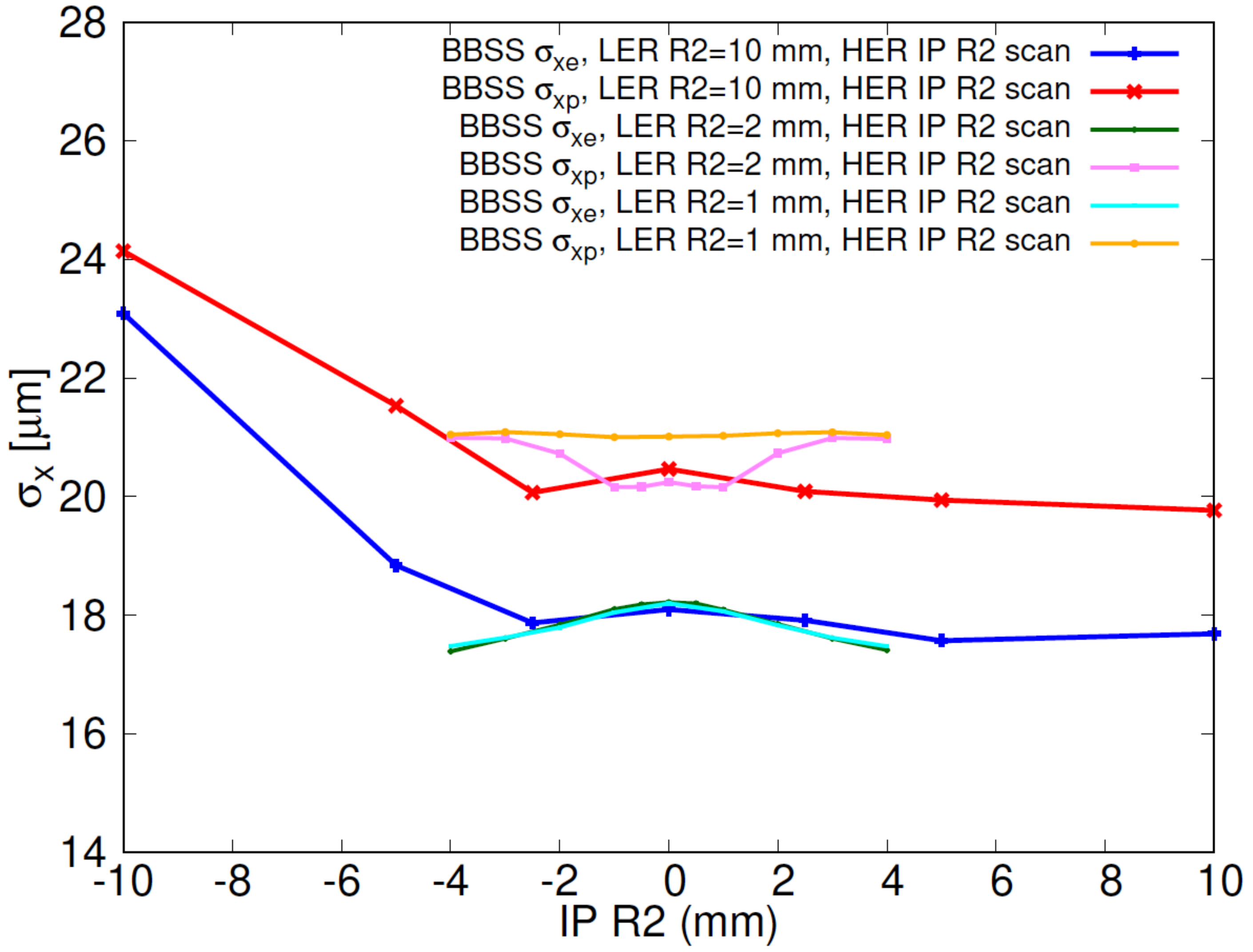


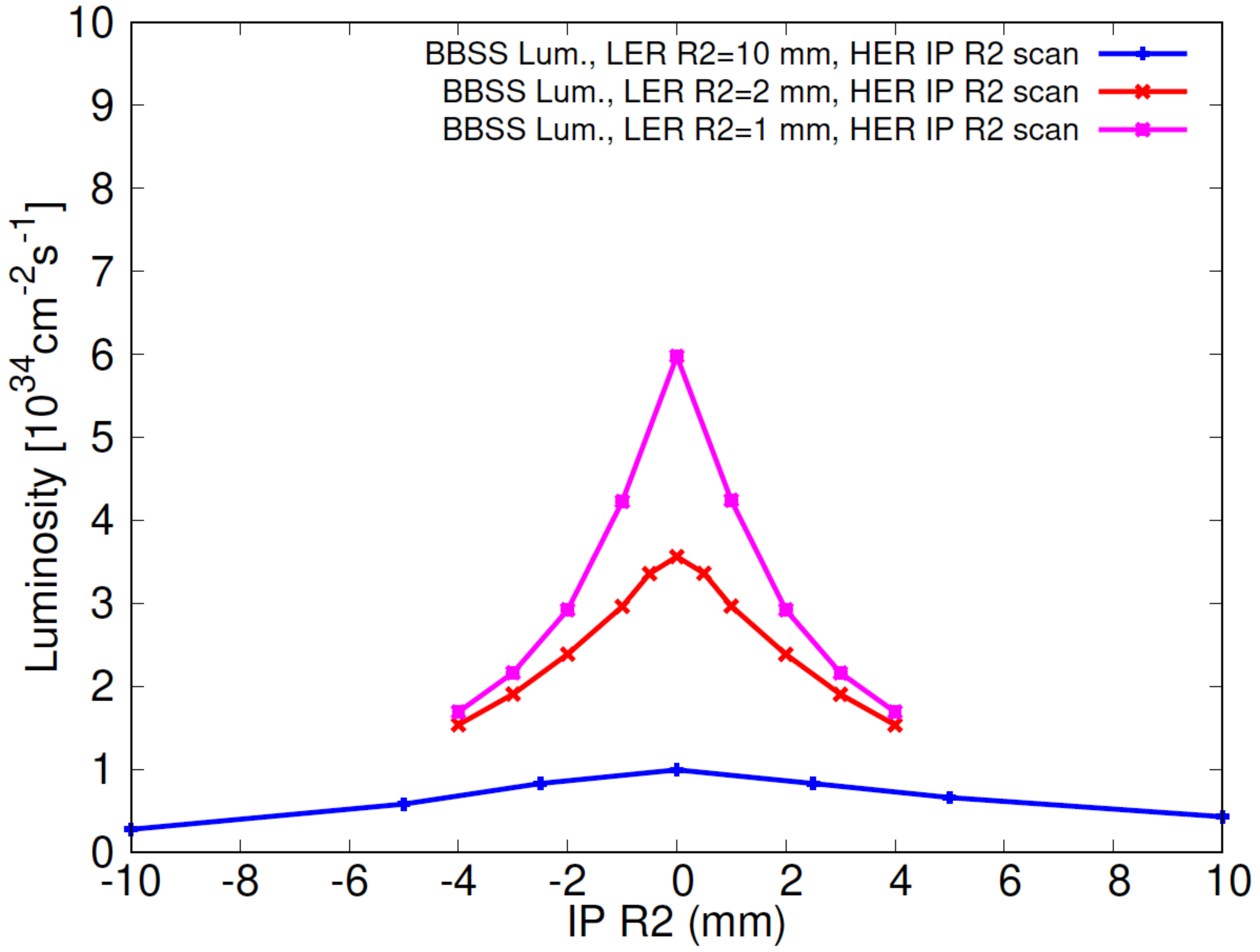


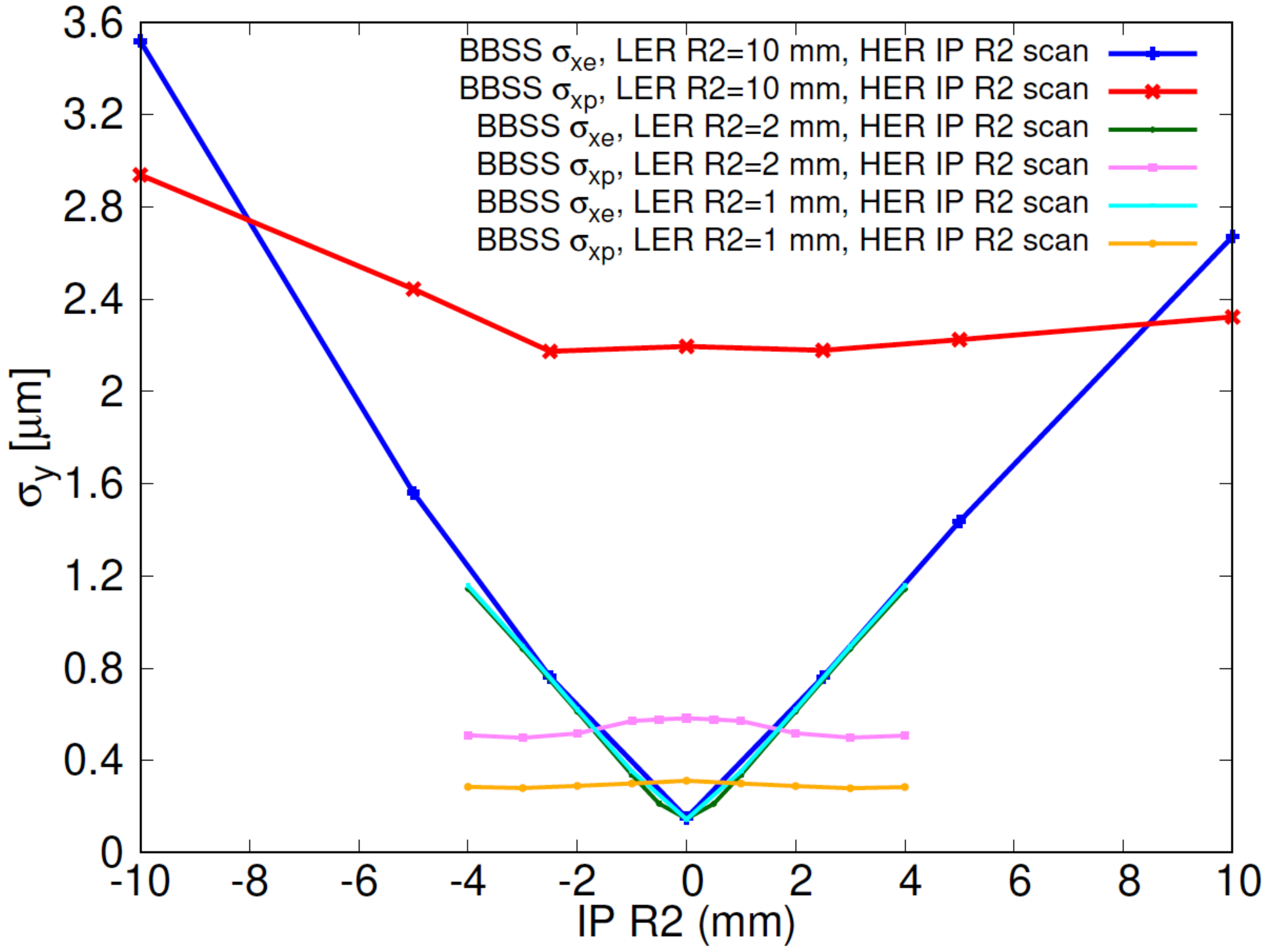
[1] Y. Ohnishi et al., The European Physical Journal Plus 136, 1023 (2021)

Updates on beam-beam simulations

- HER IP R2 scan with nonzero LER IP R2
  - Peak luminosity is found at R2(e-)=0 even R2(e+) is large.
  - The realistic IP knobs are more complicated depending on machine conditions.

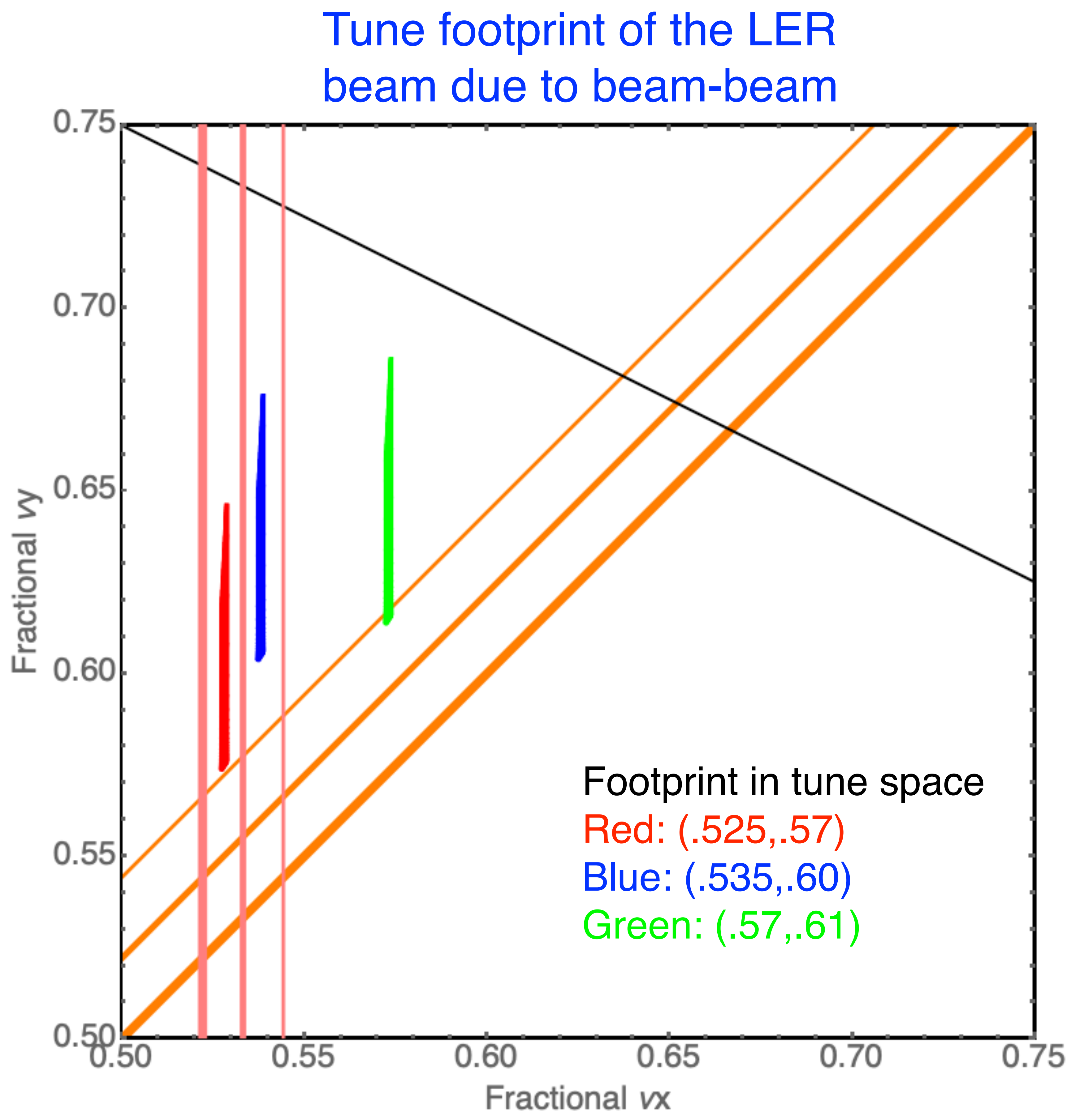






Tune survey machine study

- Motivation
  - Effects from beam-beam, impedance and lattice nonlinearity can extend the footprint of the beam (especially at high bunch currents). Avoiding overlap of beam's tune footprint with important resonances (here, I mean all types of resonances $m\nu_x + n\nu_y + k * \nu_s = N$) is useful to minimize the beam blowup.
  - Even without overlap of beam's tune footprint with resonances, there are still beam blowup due to interplay of beam-beam, impedance and lattice nonlinearity. Studying resonances through tune survey machine study is still useful for the purpose of better understanding machine imperfections.
  - Tune survey with single-beam and collision will detect the potential important resonance lines. Therefore it will help search for the best choice of working point.



Tune survey machine study

- Motivation [2]
  - K. Ohmi and K. Hirosawa developed a simpler method [3] to calculated the nonlinear terms. Good agreements were found with PTC results.
  - Then perturbation maps were made via MAP element in SAD to simulate luminosity loss. Finally, the term of $p_x^2 p_y$ was found to be important. Its sources were also well understood. Other chromatic terms can also be important in addition to chromatic couplings.
  - **Finally we arrived at a clear picture for the luminosity loss in beam-beam simulations (weak-strong model plus design lattice): The sources are beam-beam resonances and nonlinearity of the IR. But, the remedy is far from apparent.**
  - **I don't understand Ohmi-san's conclusion "Interference with the Beam-beam force does not appear in the luminosity performance, but does appear in the lifetime". Is there anything inconsistent?**

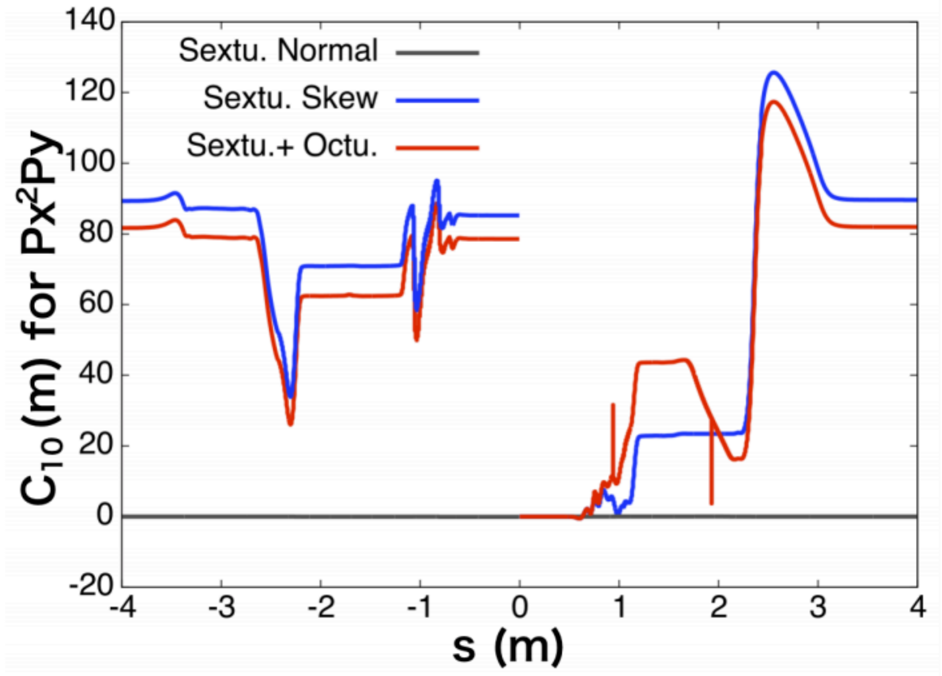


Figure 4: Coefficient of $P_X^2 P_Y$ caused by skew sextupole (SK_2) and octupole ($K_3 + SK_3$) fields.

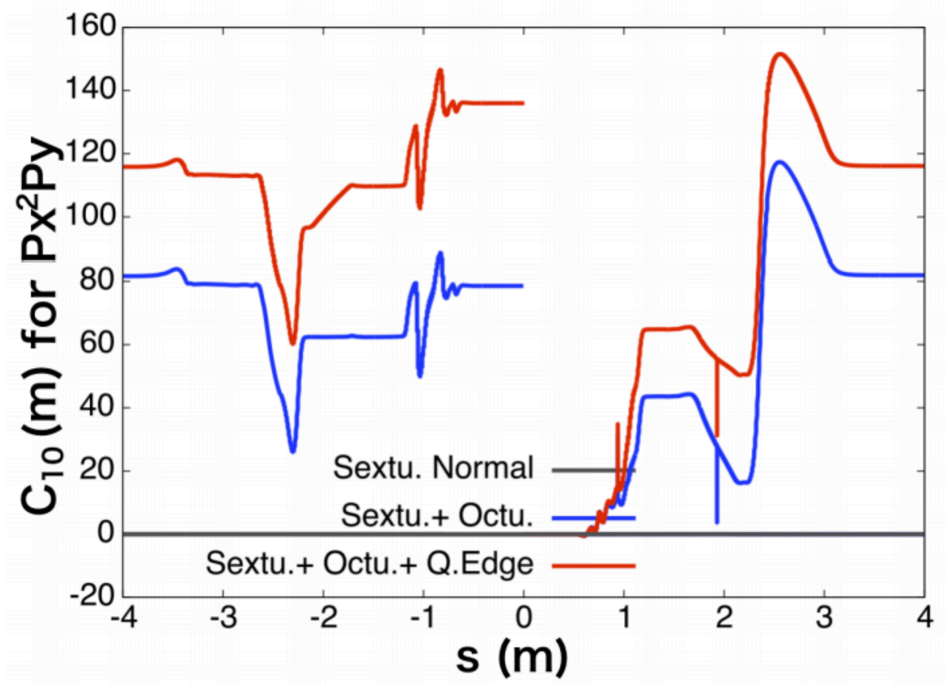


Figure 5: Coefficient of $P_X^2 P_Y$ for sextupole and octupole ($SK_2 + K_3 + SK_3$) and quadrupole hard-edge fringe ($SK_2 + K_3 + SK_3 + Q.edge$) fields.

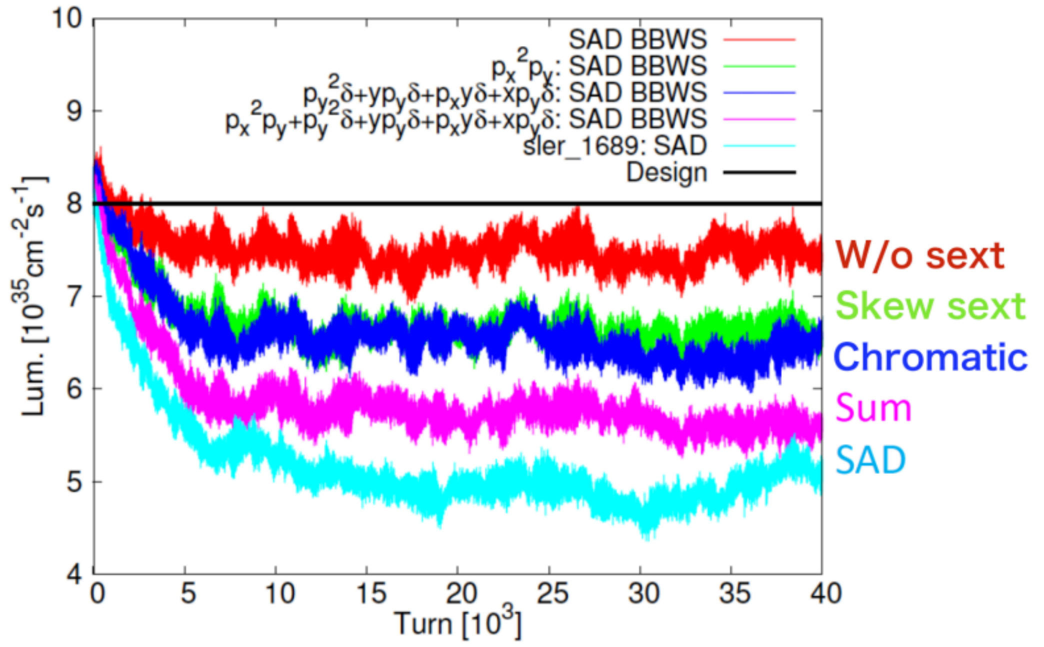
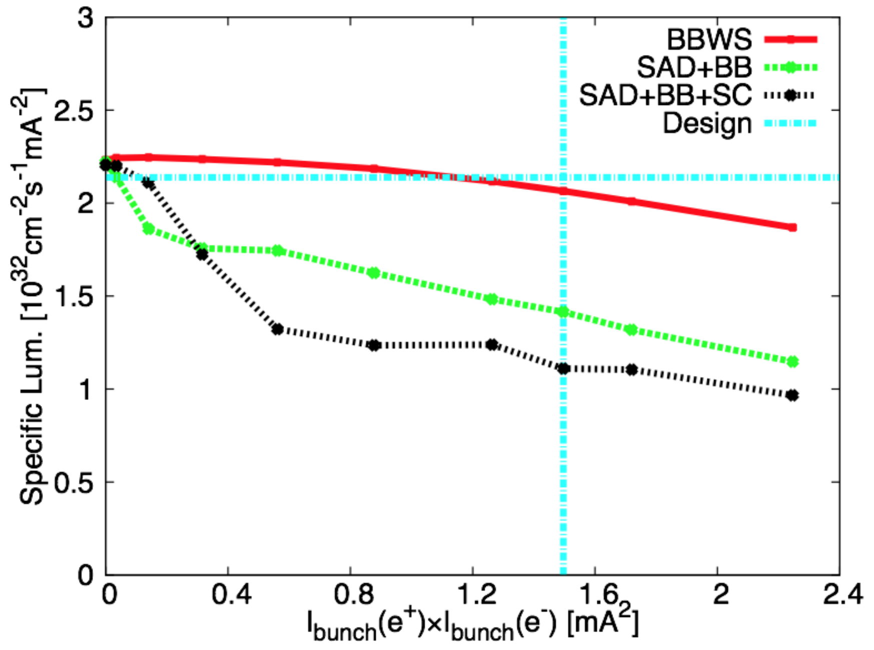
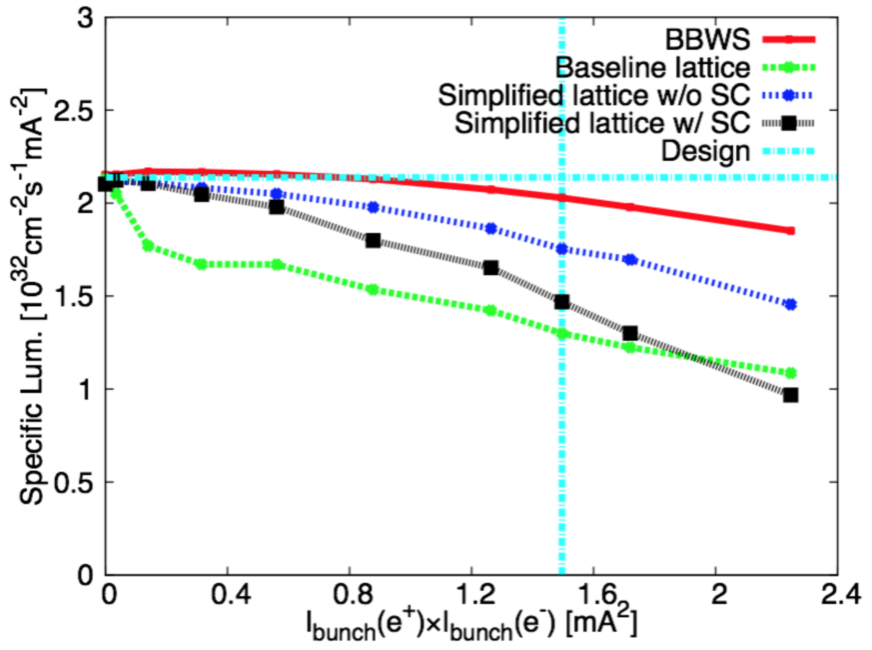


Figure 6: Luminosities for sextupole term (: $P_X^2 P_Y$), chromatic twiss, and SAD.



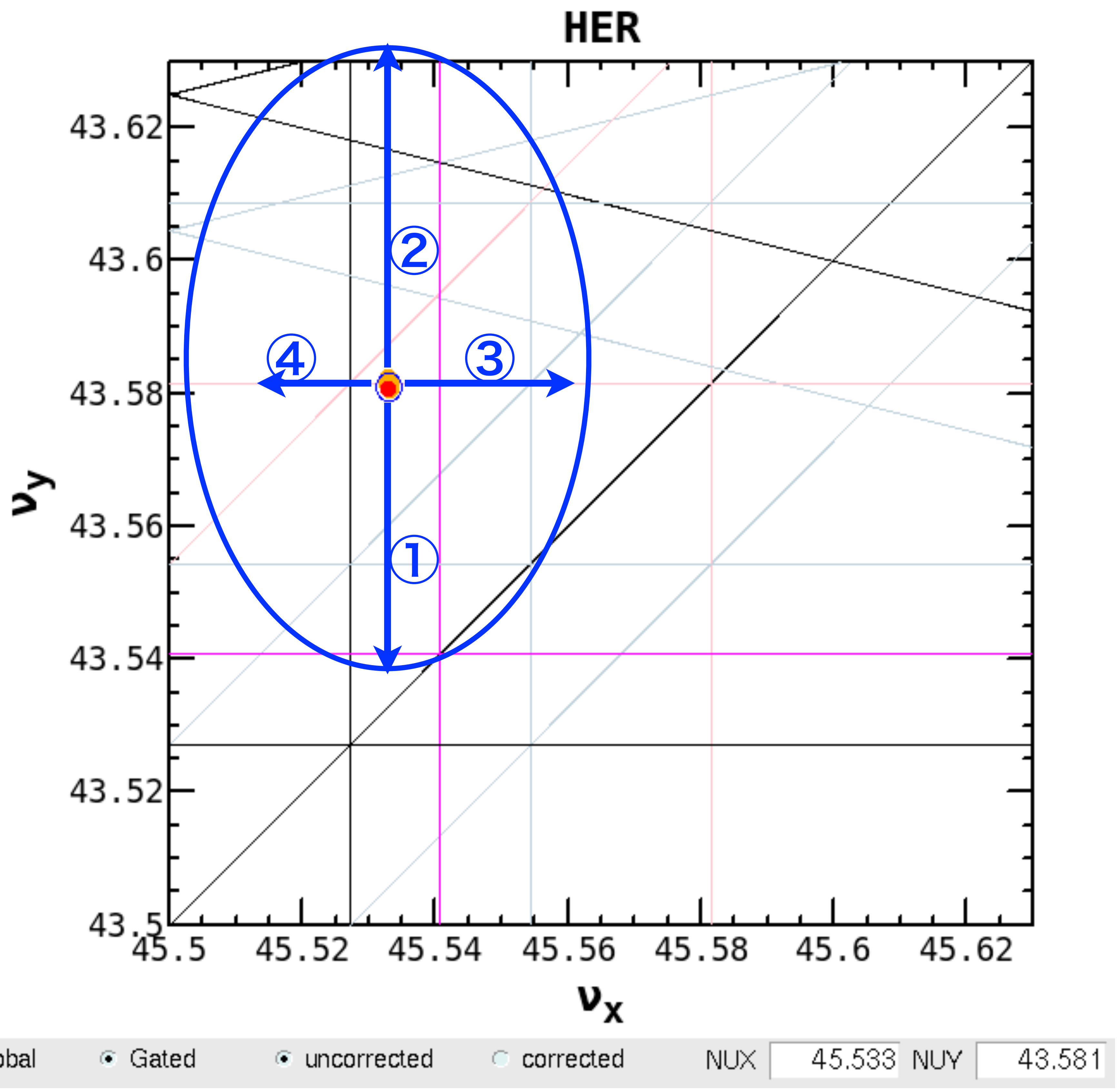


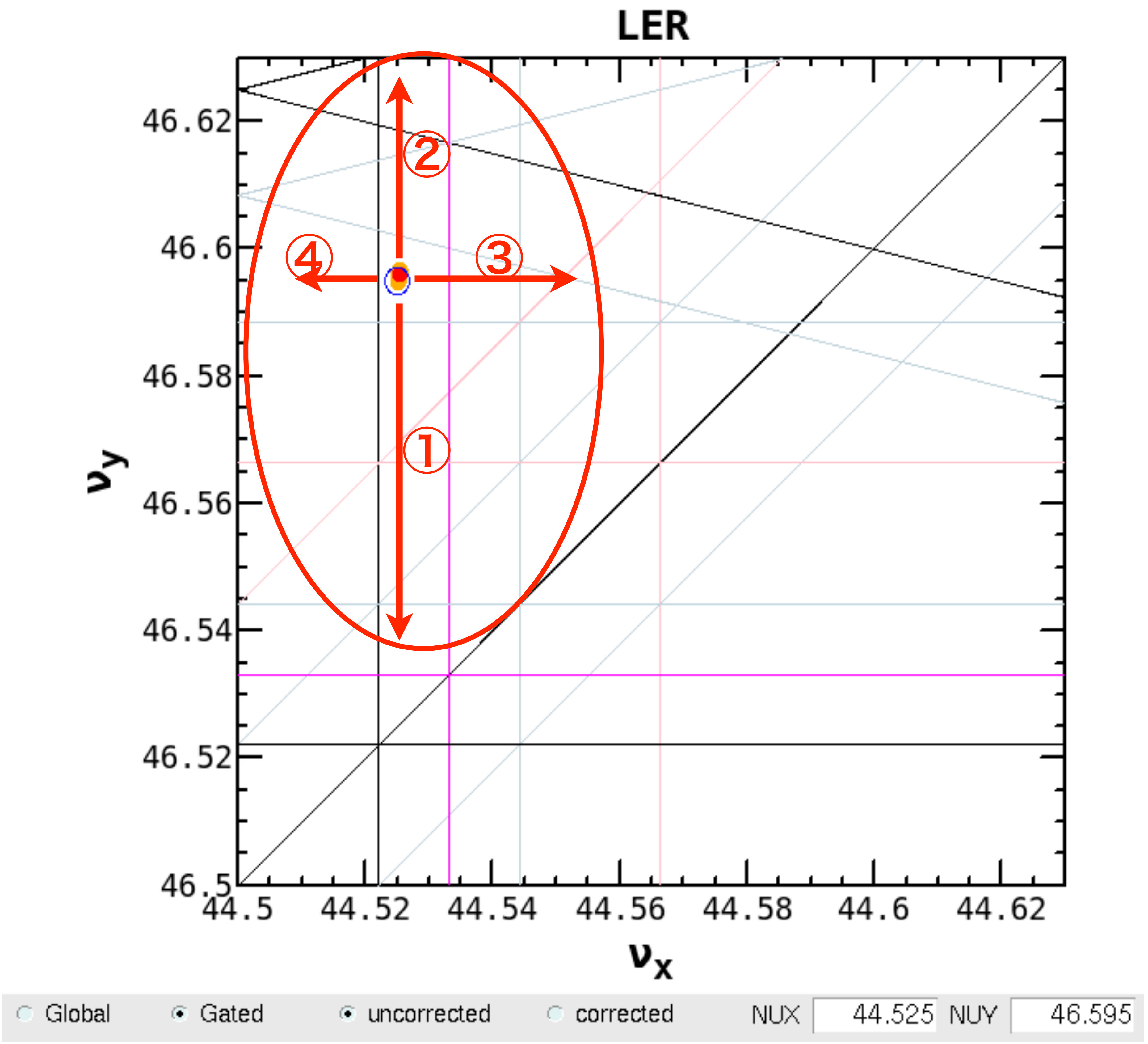
[2] D. Zhou, talk presented in the 1st itf-bb subgroup meeting, https://kds.kek.jp/event/39142/.
[3] K. Hirosawa et al., The influence of higher order multipoles of IR magnets on luminosity for SuperKEKB, in Proceedings of IPAC'18, Vancouver, BC, Canada, 2018.

Tune survey machine study

- Routines for tune survey
  - Currently the machine is operating around (45.533,43.581) for HER and (44.525, 46.595) for LER.
  - The tune survey was done with reference to the HER/LER tune diagram. The tune diagram shows the main resonances that might cause emittance blowup, such as chromatic coupling $\nu_x - \nu_y + k\nu_s =$ Integer, synchro-beta resonances $m\nu_x - k\nu_s =$ Integer and $n\nu_y - k\nu_s =$ Integer.

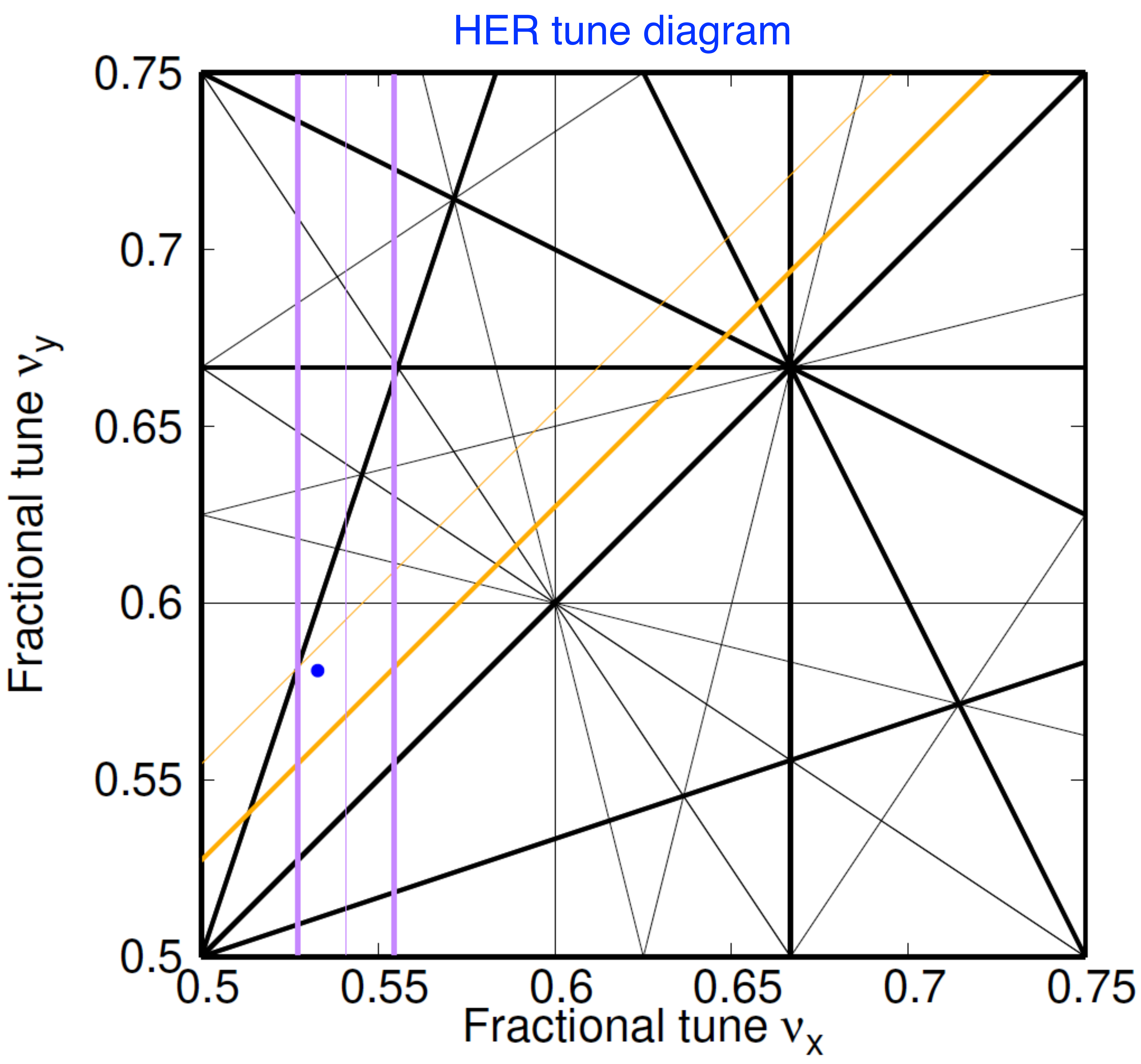
	HER	LER
ε_x (nm)	4.6	4.0
ε_y (pm)	23	23
β_x (mm)	60	80
β_y (mm)	1	1
σ_{z0} (mm)	5.05	4.84
ν_x	45.533	44.525
ν_y	43.581	46.595
ν_s	0.0272	0.0233
Crab waist	40%	80%

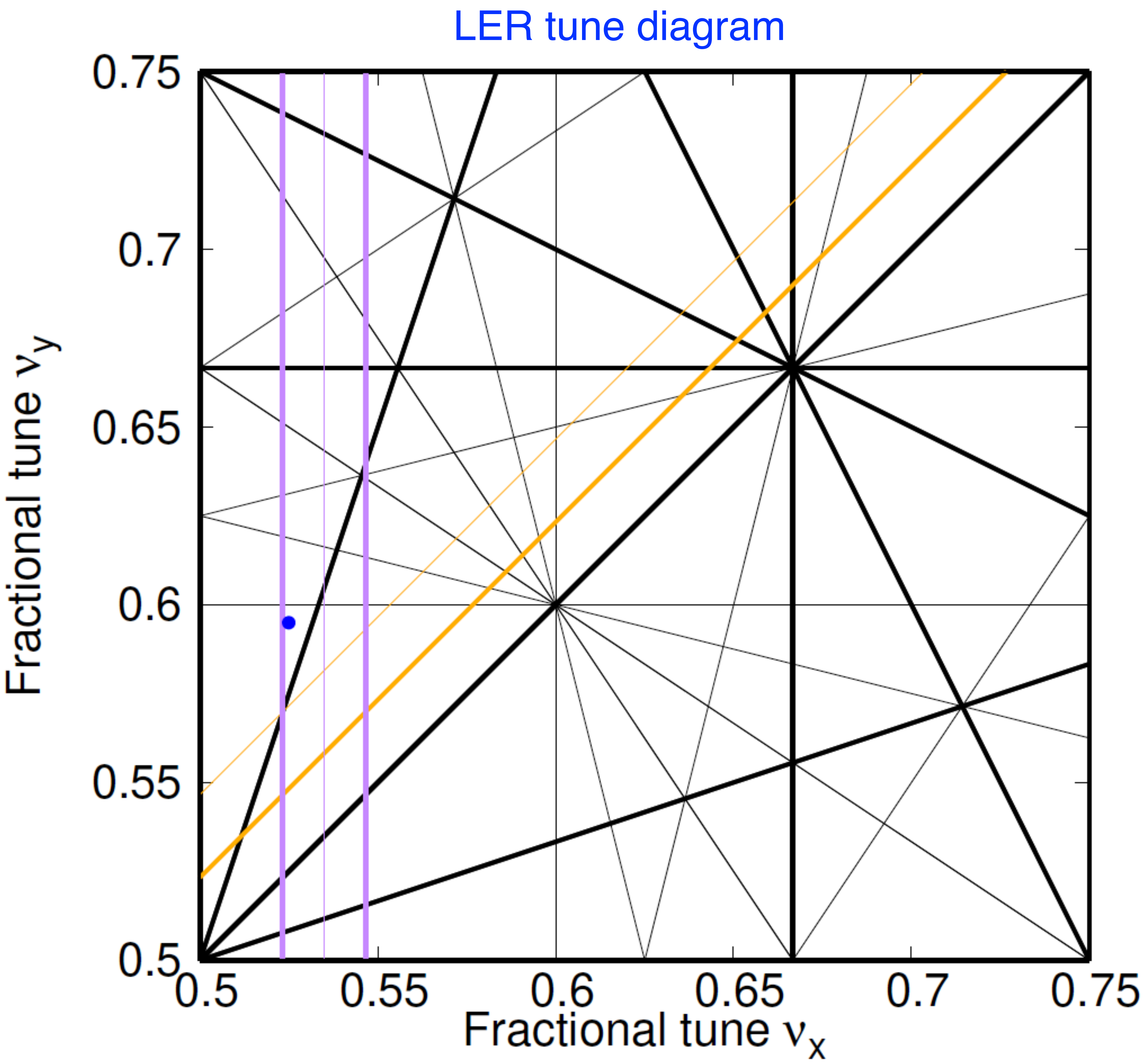




Tune survey machine study

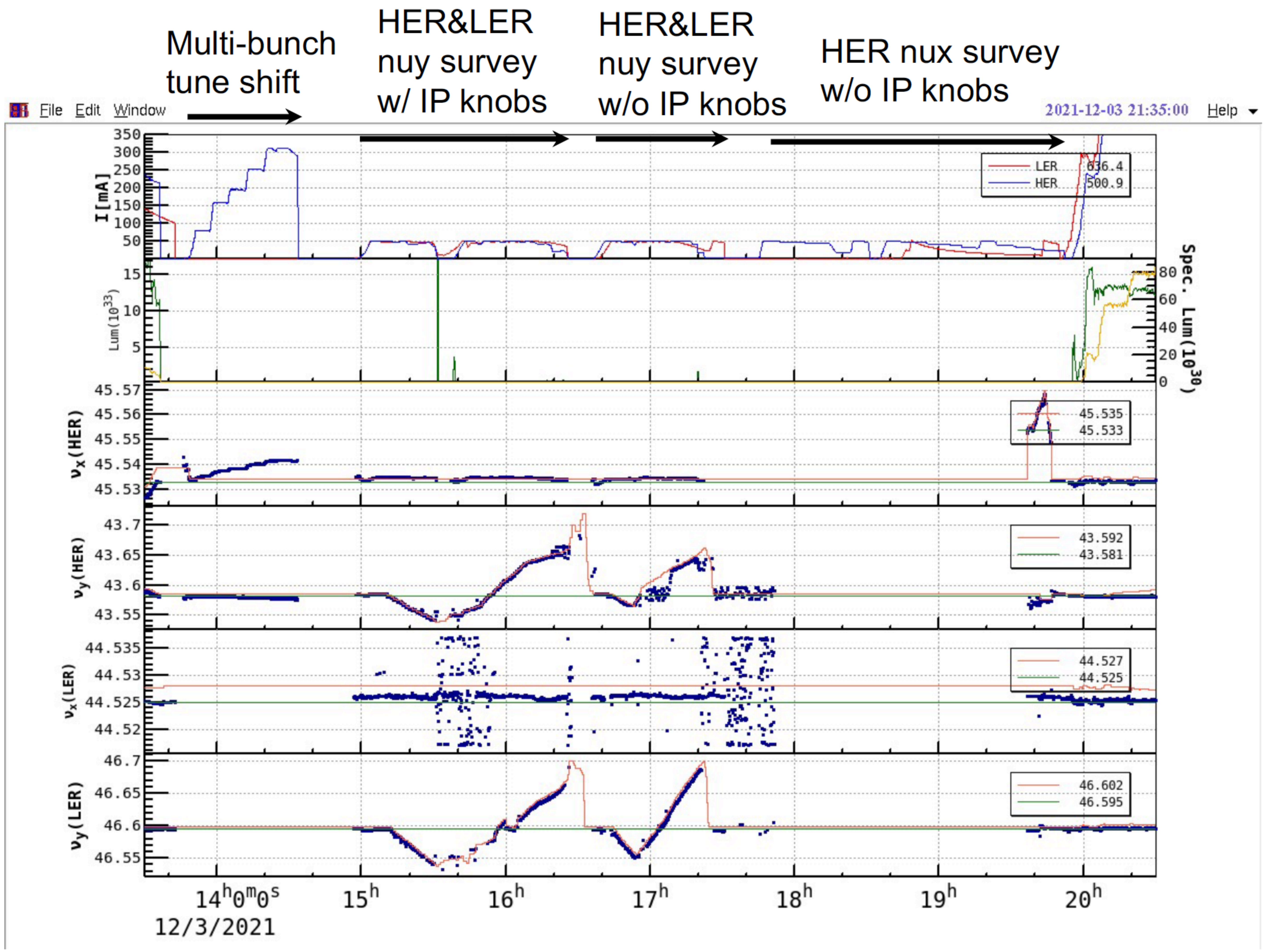
- Resonances to be identified
  - Note that LER/HER are operated above/below $\nu_x - \nu_y + 2\nu_s = N$ and $3\nu_x - \nu_y = N$, respectively.





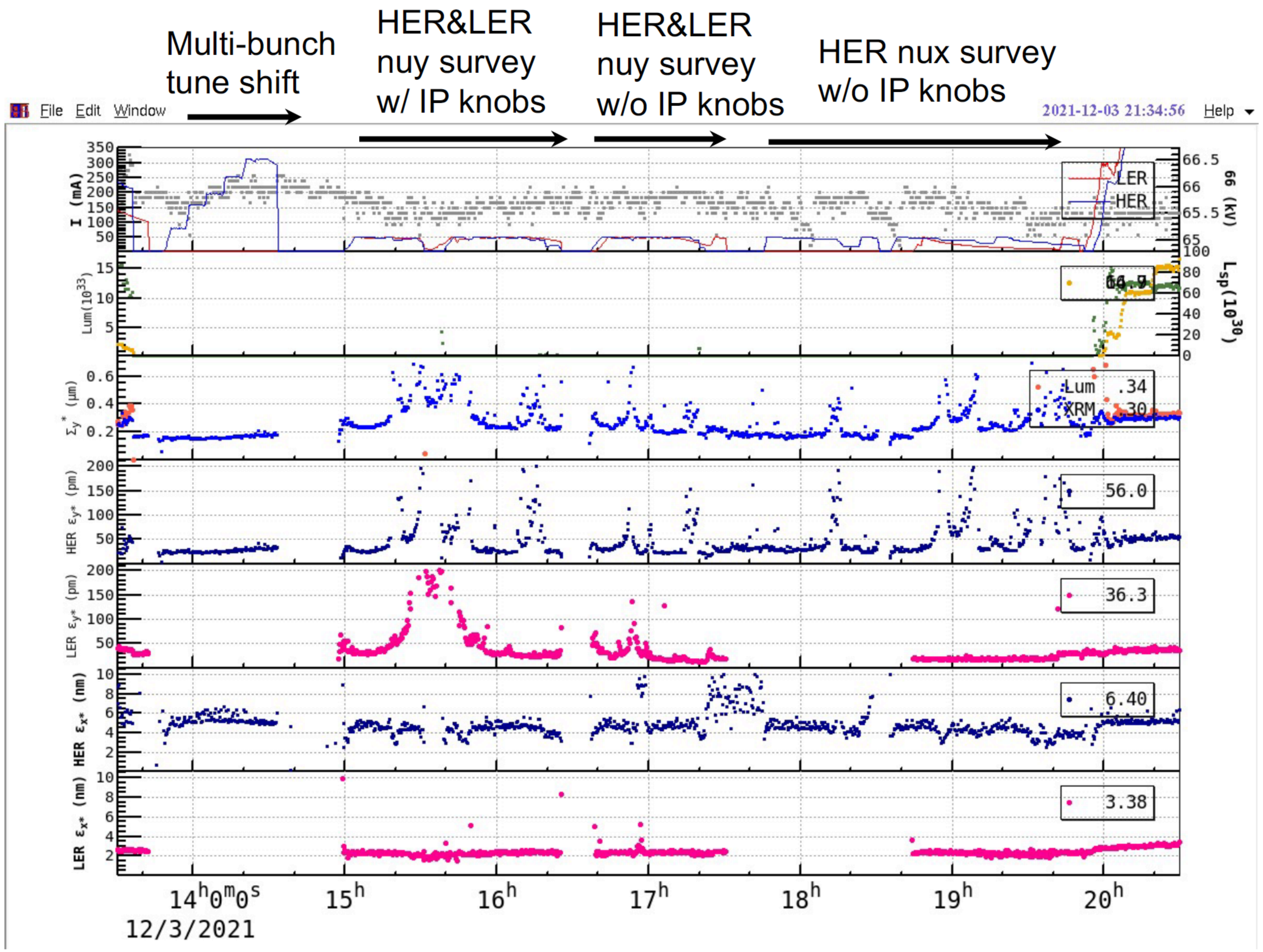
Tune survey machine study done on Dec. 3, 2021

- 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

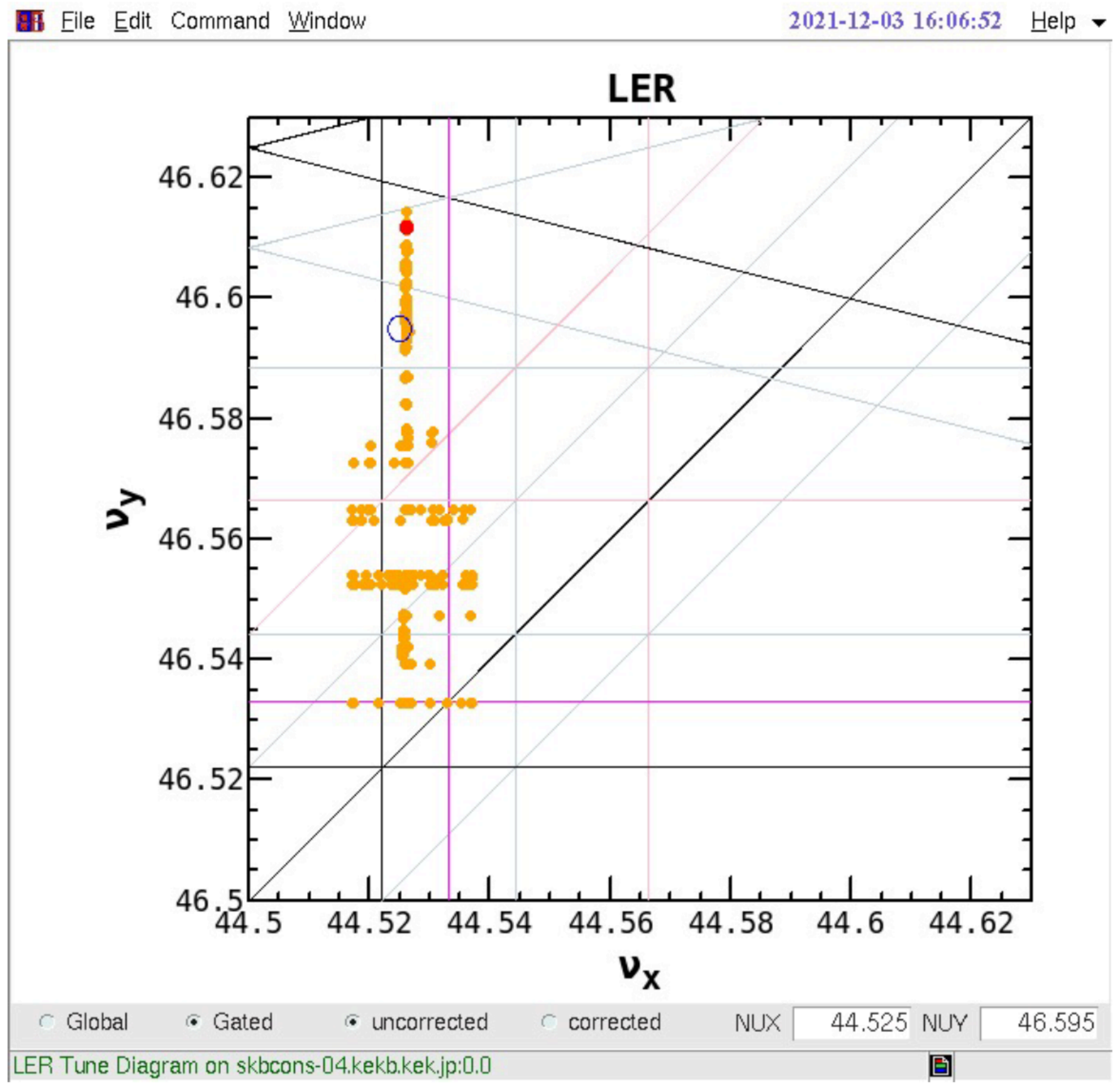
- Data taking
  - Beam emittances from XRMs



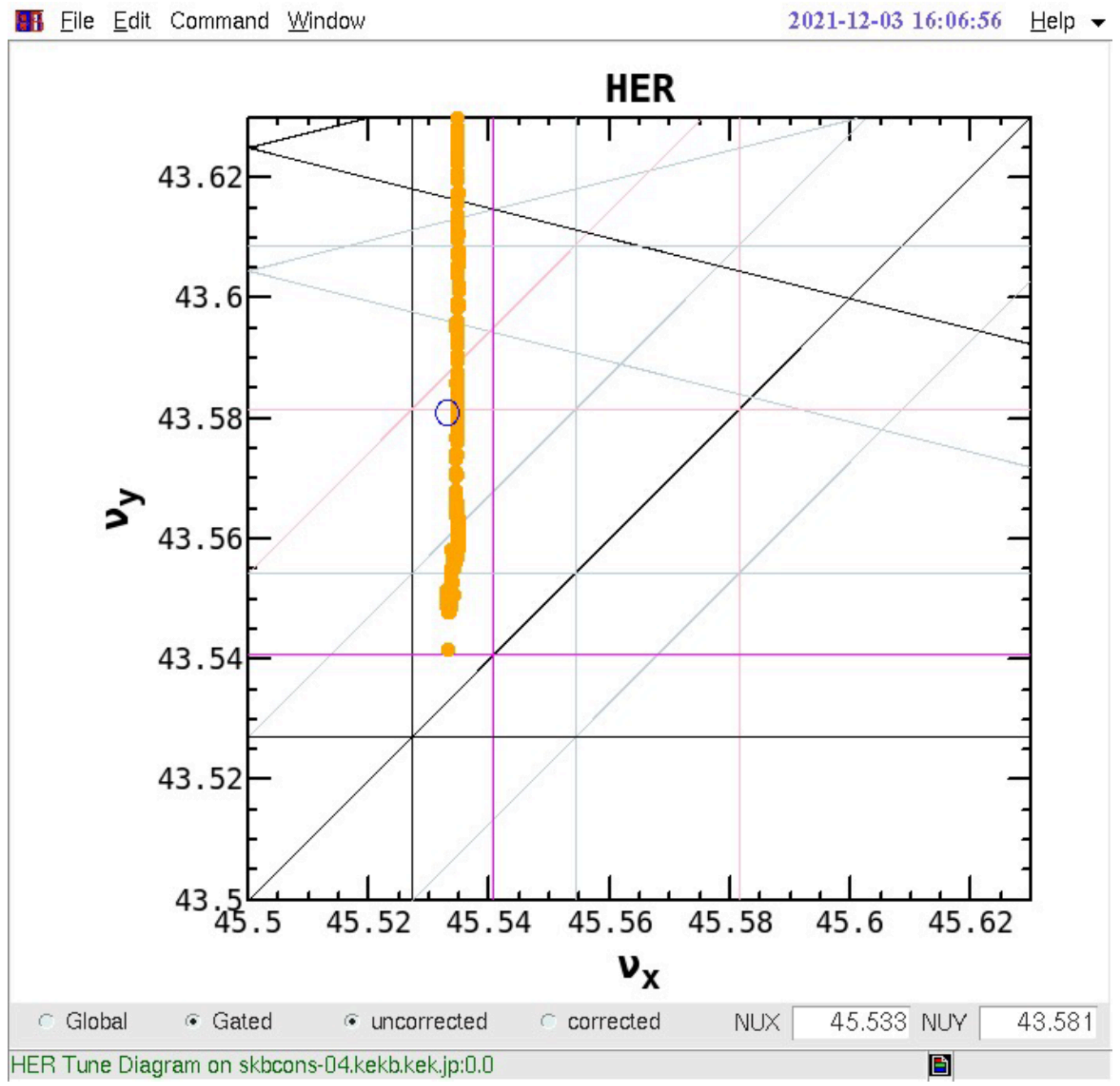
Tune survey machine study done on Dec. 3, 2021

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

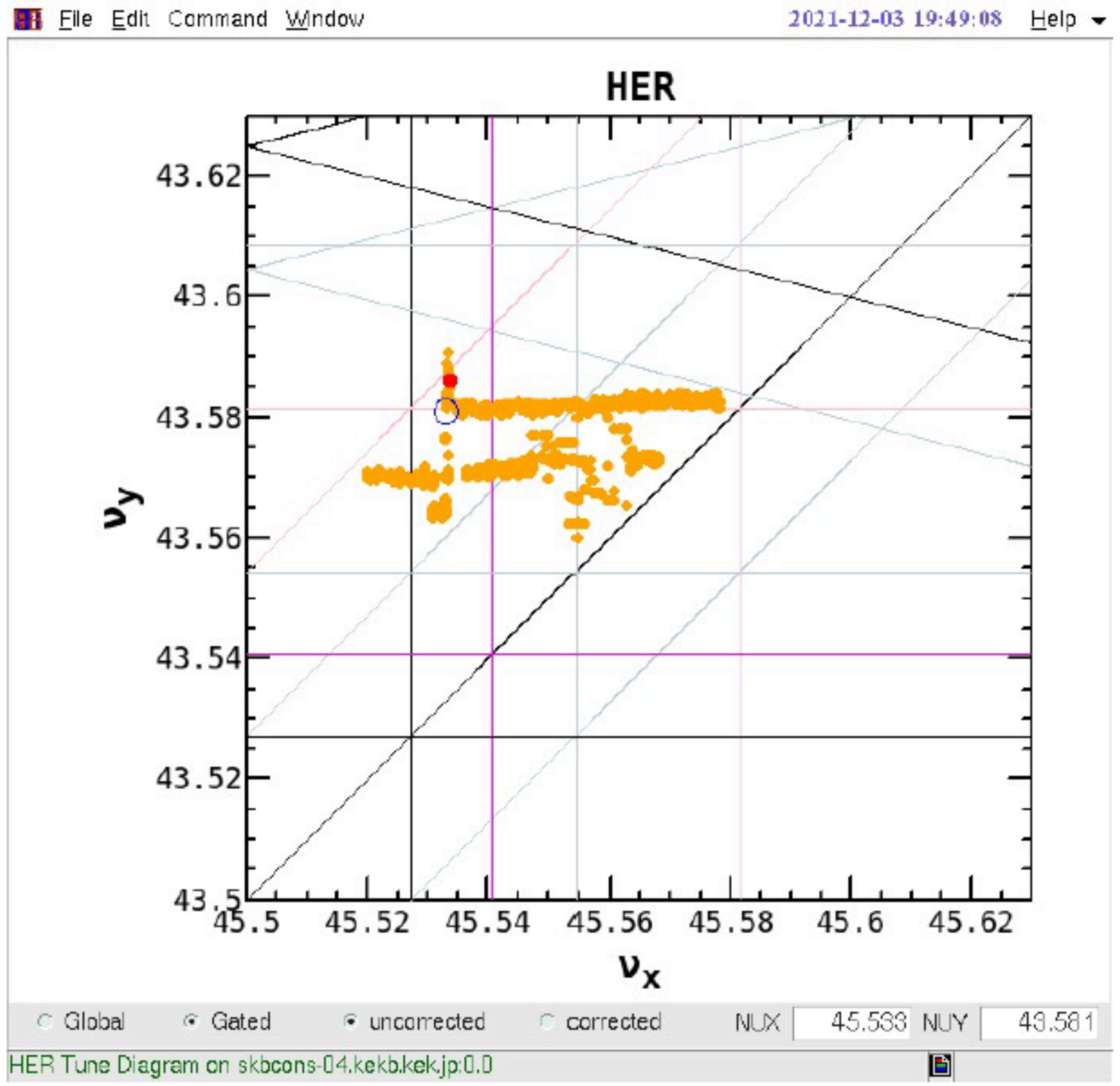
LER nuy survey



HER nuy survey

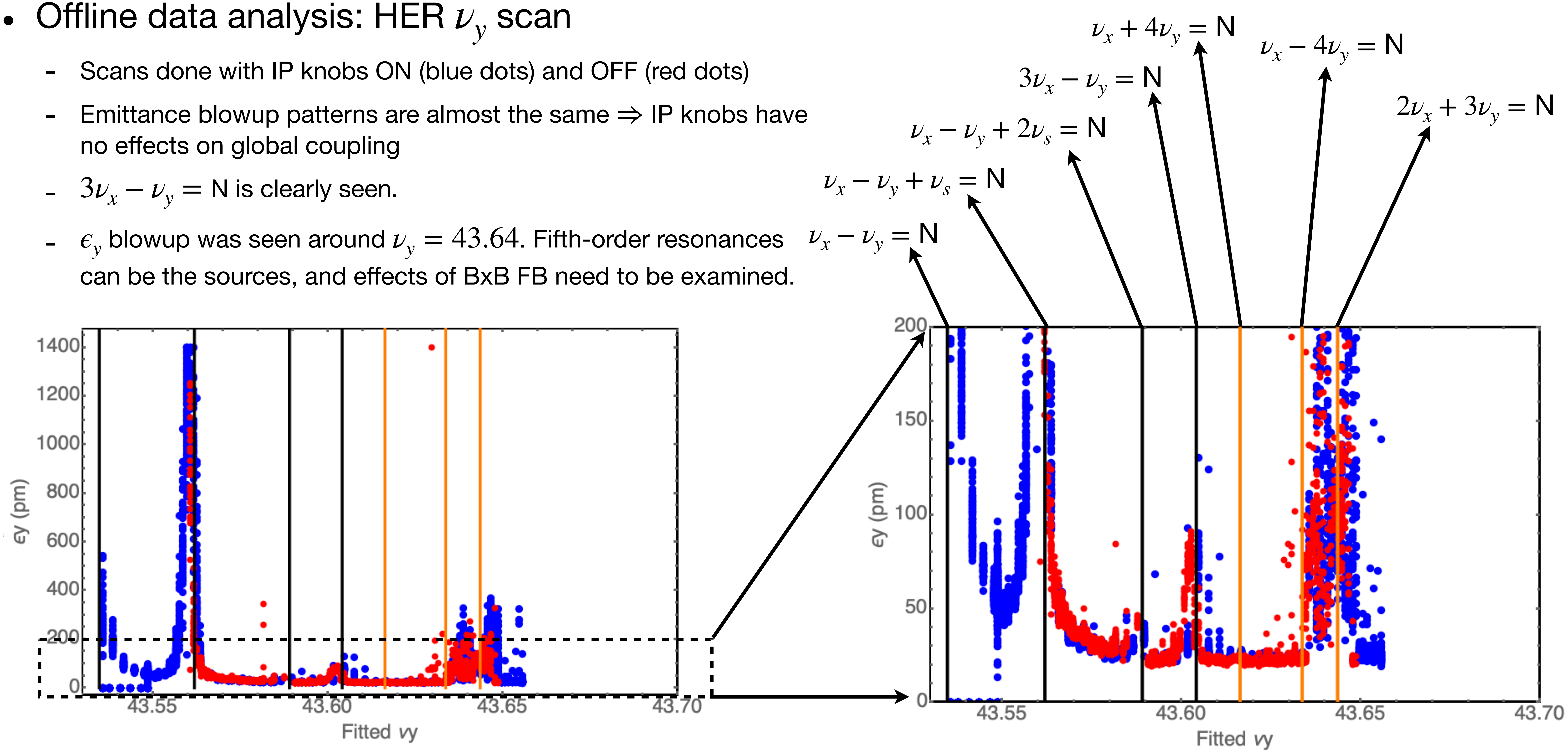


HER nux survey



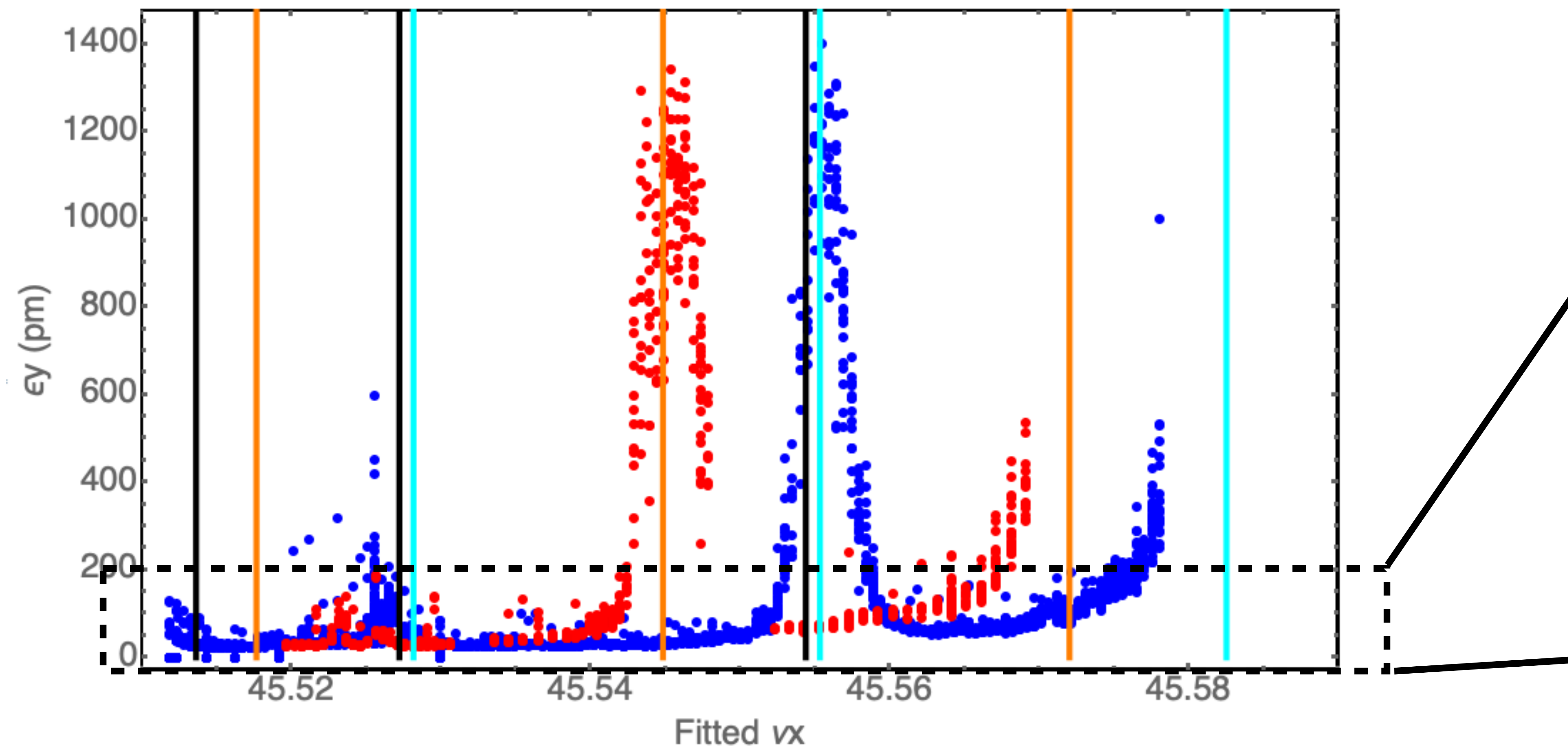
Tune survey machine study done on Dec. 3, 2021

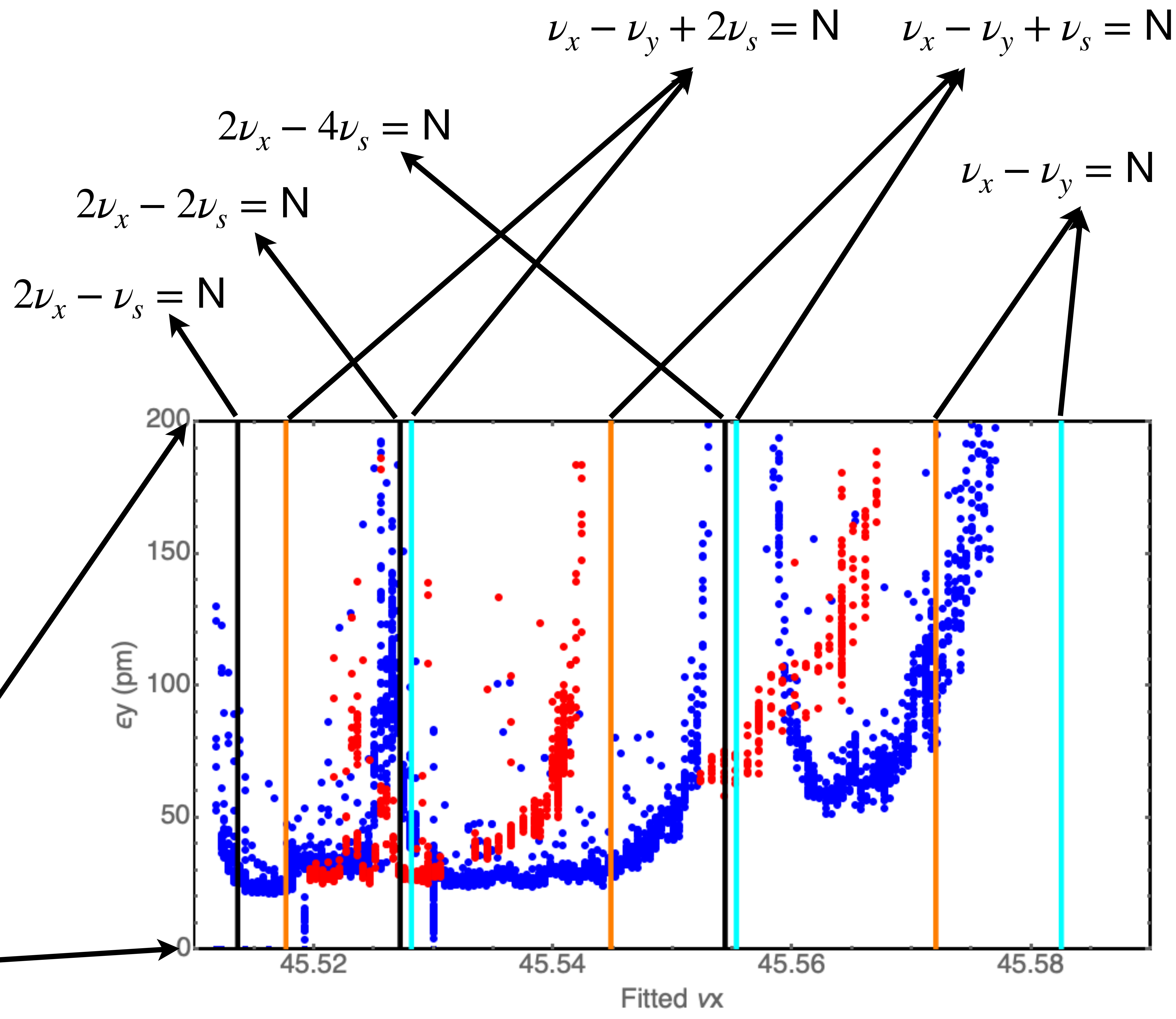
- Offline data analysis: HER ν_y scan
  - Scans done with IP knobs ON (blue dots) and OFF (red dots)
  - Emittance blowup patterns are almost the same ⇒ IP knobs have no effects on global coupling
  - $3\nu_x - \nu_y =$ N is clearly seen.
  - ϵ_y blowup was seen around $\nu_y = 43.64$. Fifth-order resonances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



Tune survey machine study done on Dec. 3, 2021

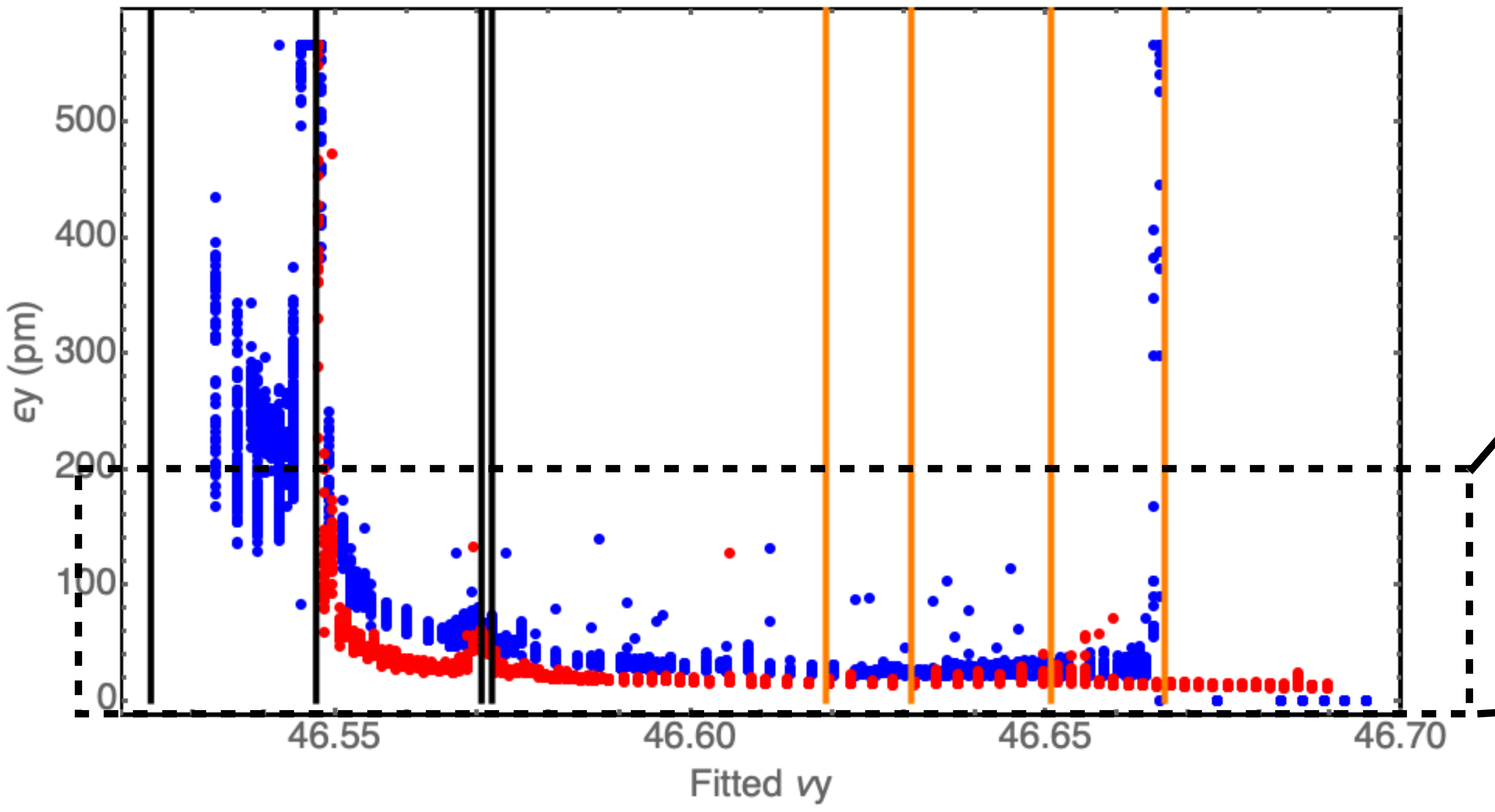
- Offline data analysis: HER ν_x scan
  - Scans done with IP knobs OFF, and model tune $\nu_y = 43.586$ (blue dots) and $\nu_y = 43.576$ (red dots)
  - Changing ν_y shifts resonances $\nu_x - \nu_y + k\nu_s =$ N
  - $2\nu_x - 3\nu_s =$ N and $2\nu_x - 4\nu_s =$ N were not clearly seen in this study.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

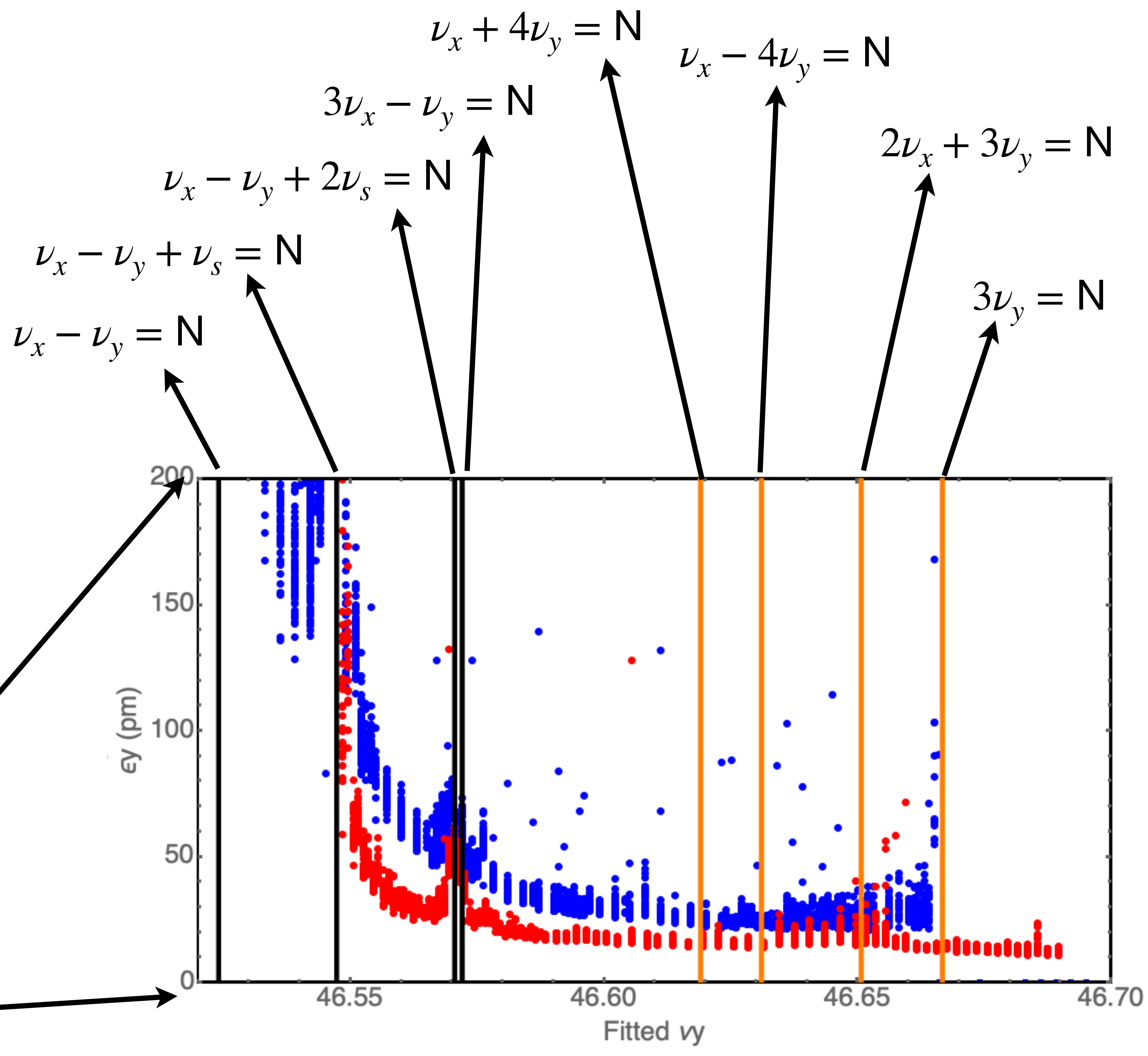




Tune survey machine study done on Dec. 3, 2021

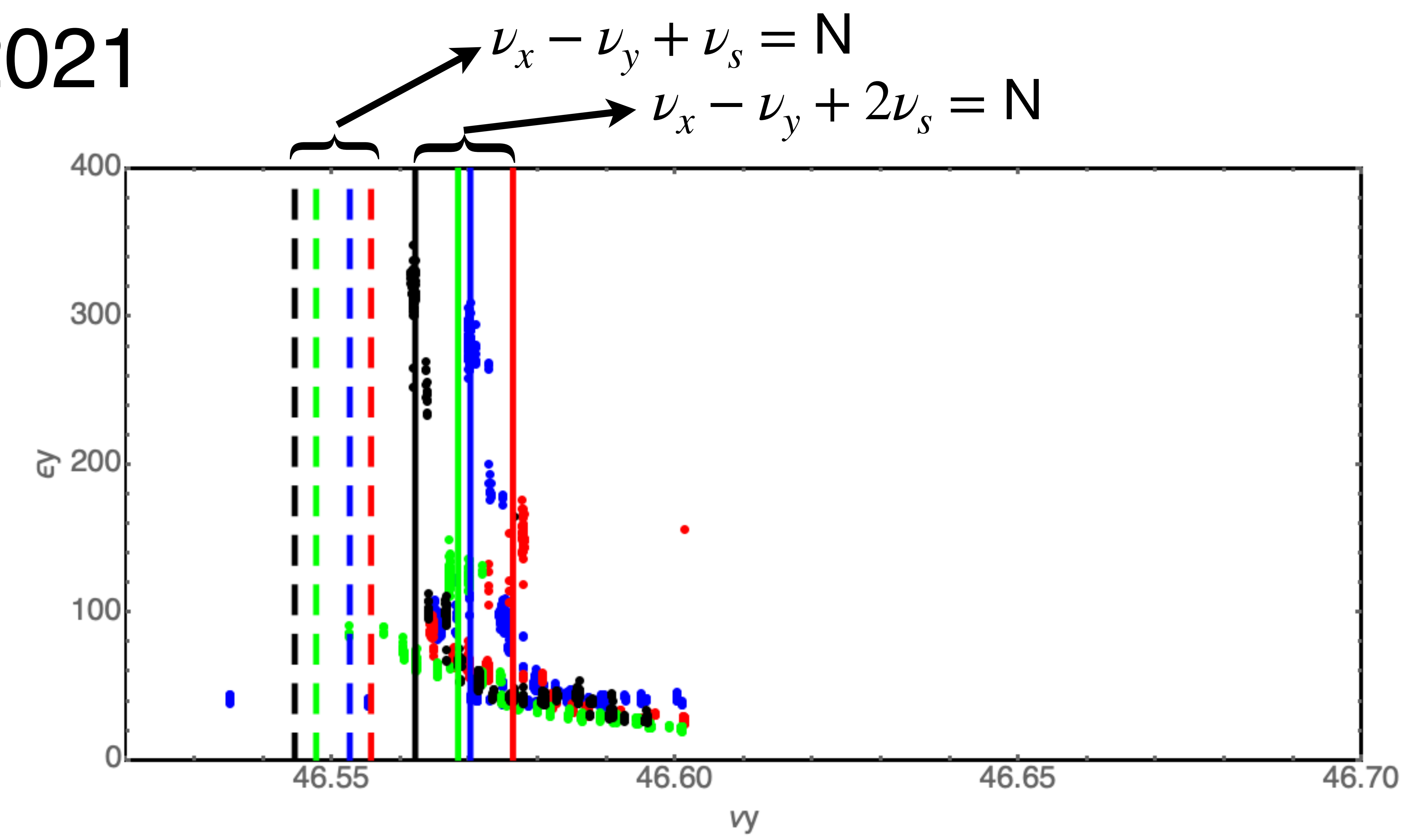
- Offline data analysis: LER ν_y scan
  - Scans done with IP knobs ON (blue dots) and OFF (red dots)
  - Emittance blowup patterns are not the same ⇒ IP knobs have side effects on global coupling?
  - $3\nu_x - \nu_y =$ N is not clear.
  - There was strong blowup around $3\nu_y = N$ with beam injection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

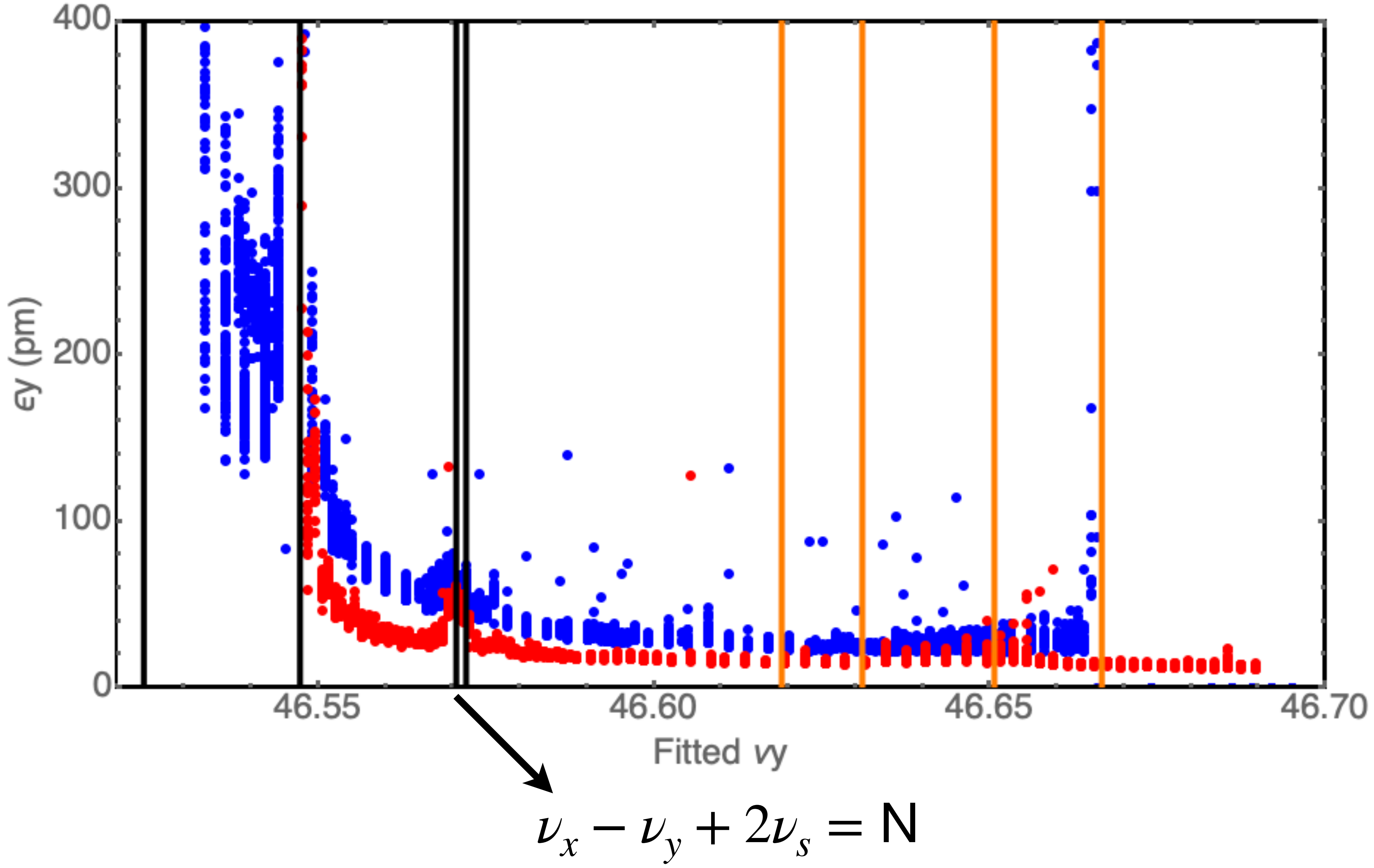




Tune survey machine study done on Dec. 3, 2021

- 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.

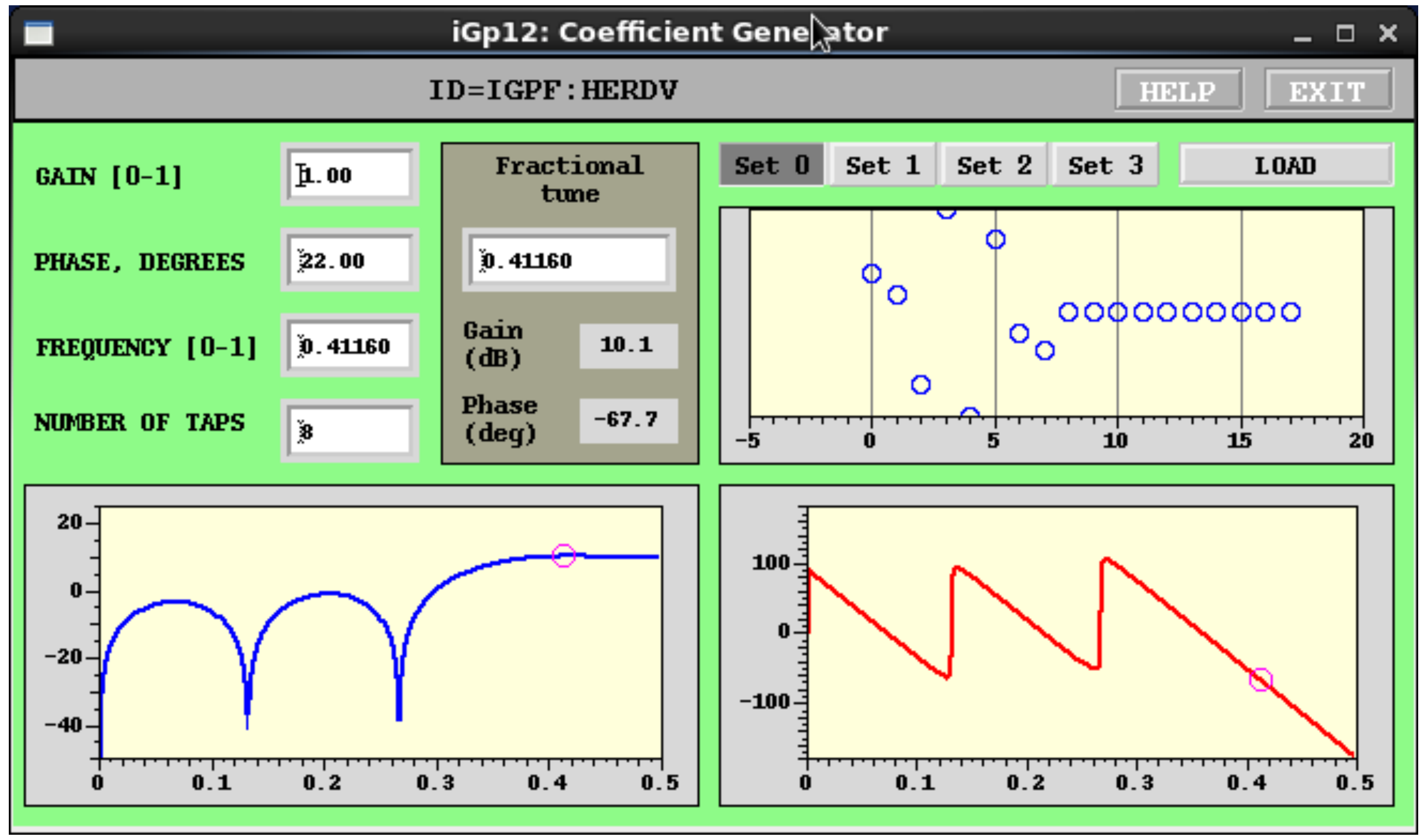


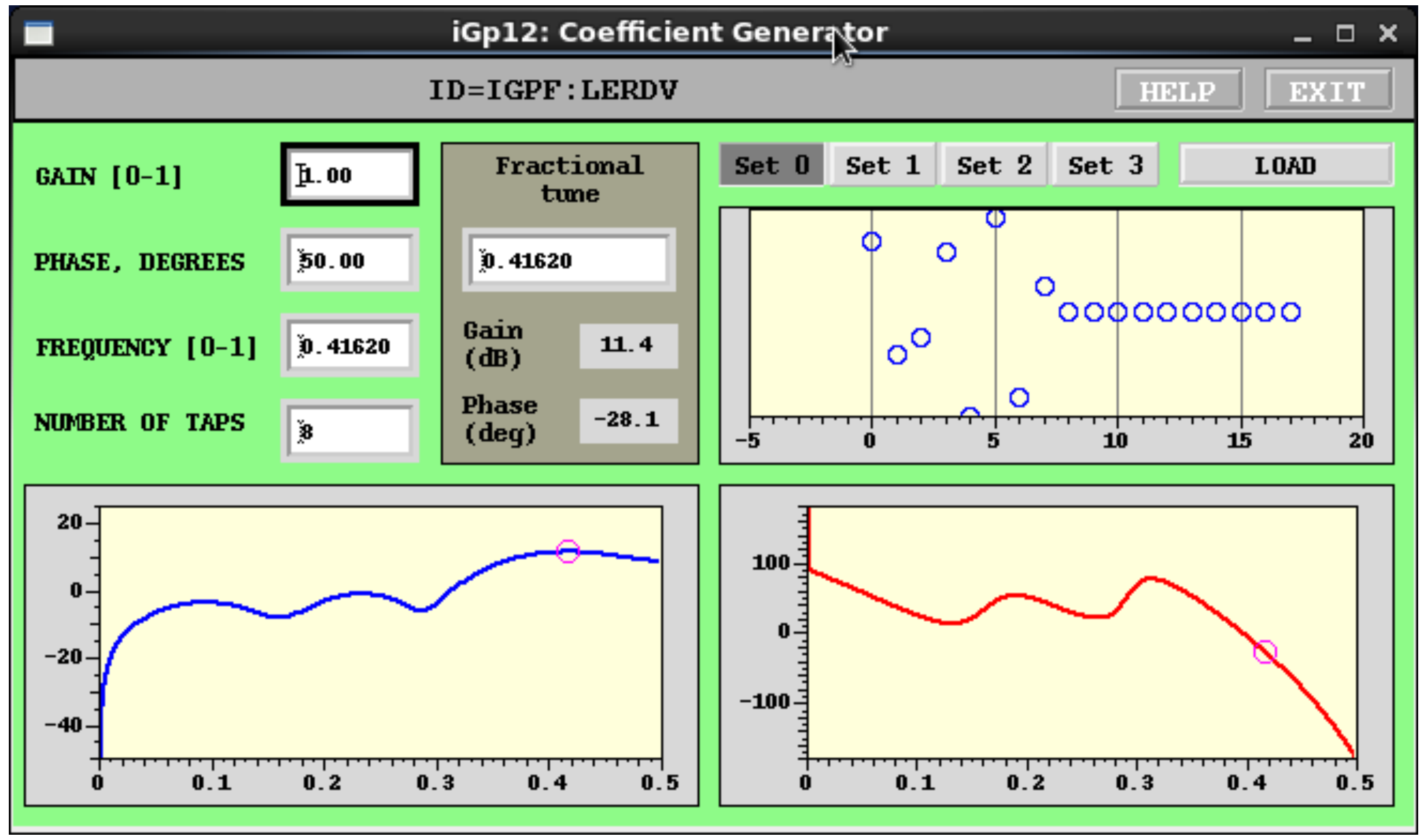


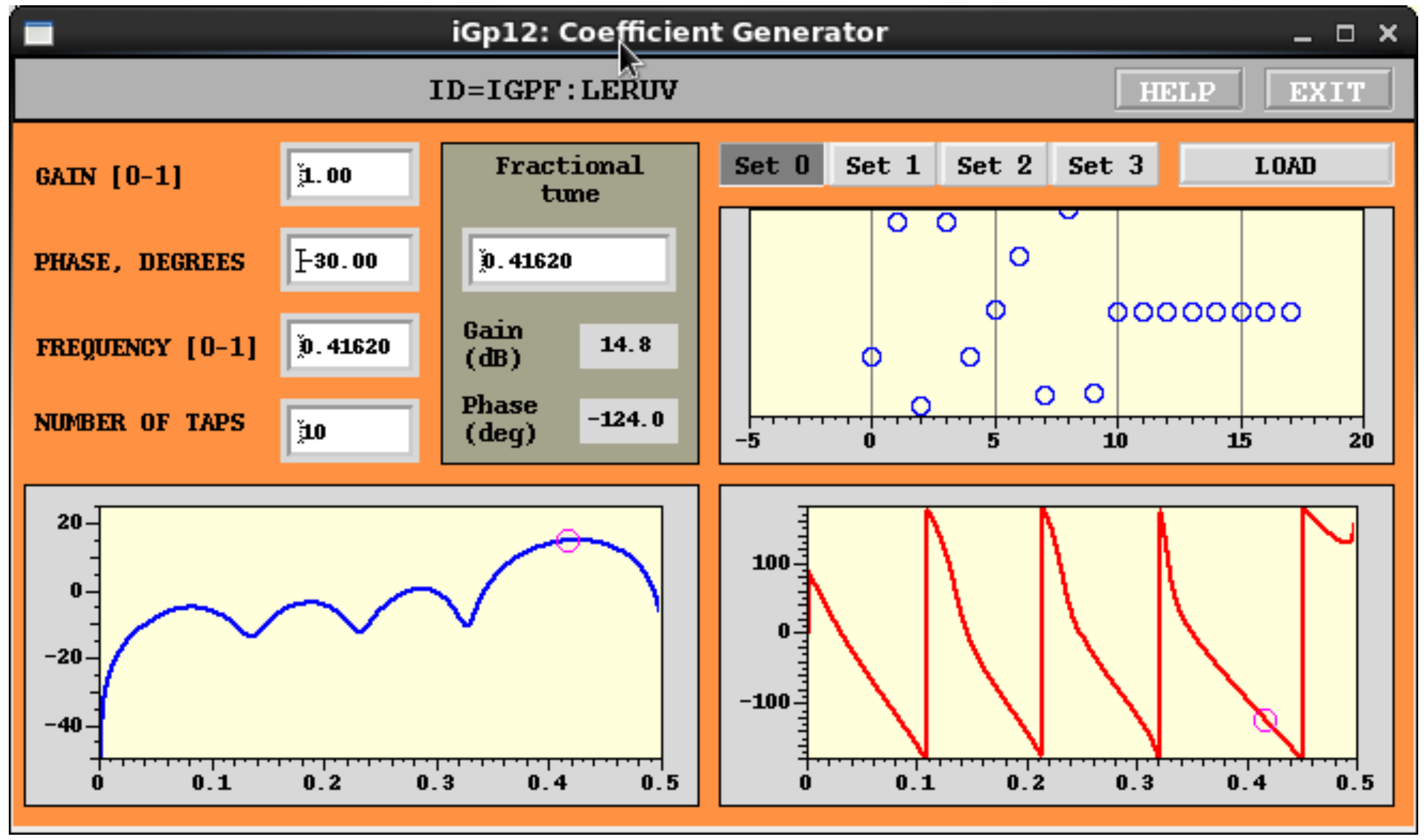
Tune survey machine study done on Dec. 3, 2021

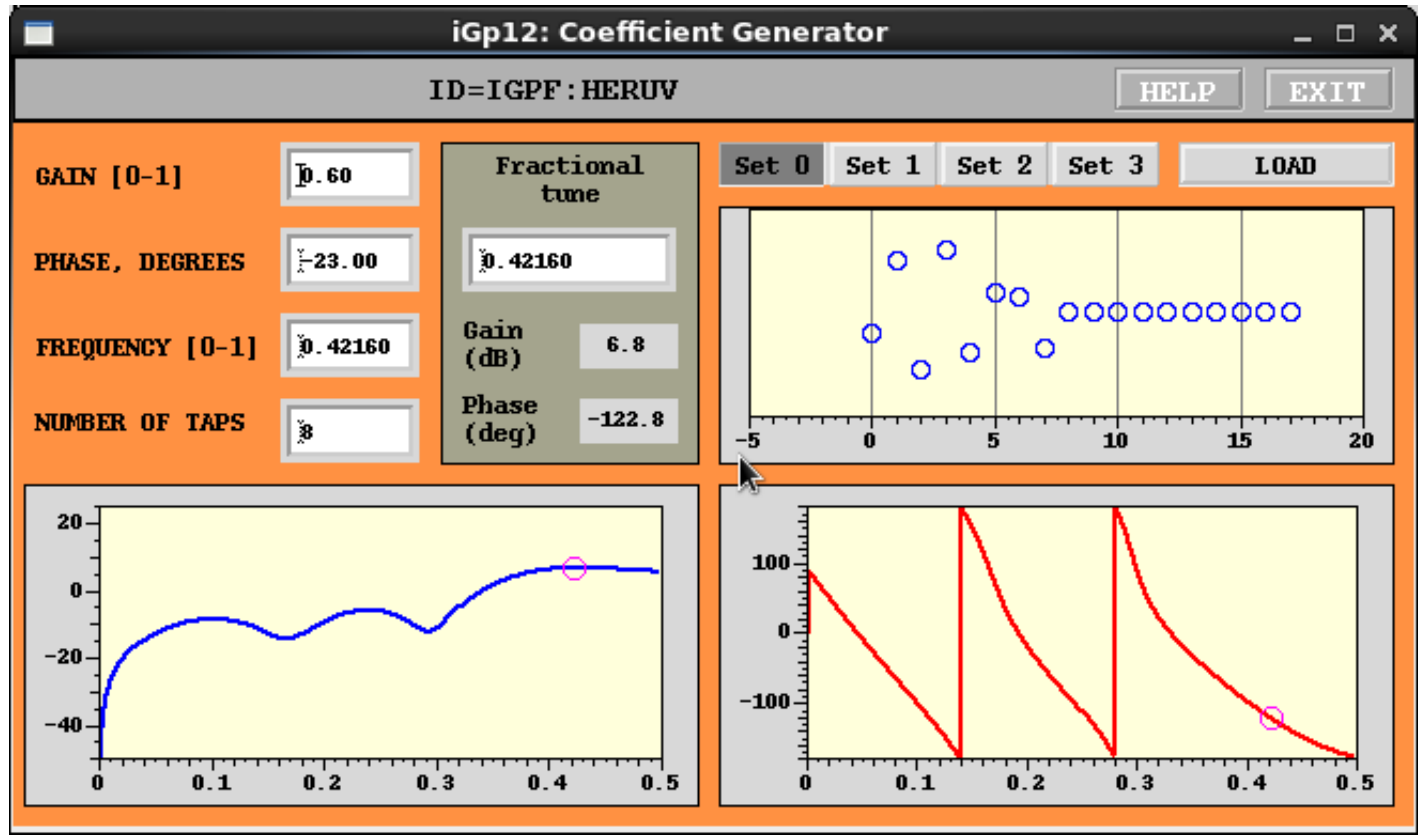
- Effects of BxB FB system
  - For tune survey with fractional ν_y>0.6, one concern is effects of BxB FB.
  - In this study, when ν_y>0.6, injection was difficult, BxB FB had to be turned on to improve injection.
  - Further investigations are necessary.

Courtesy of M. Tobiyama





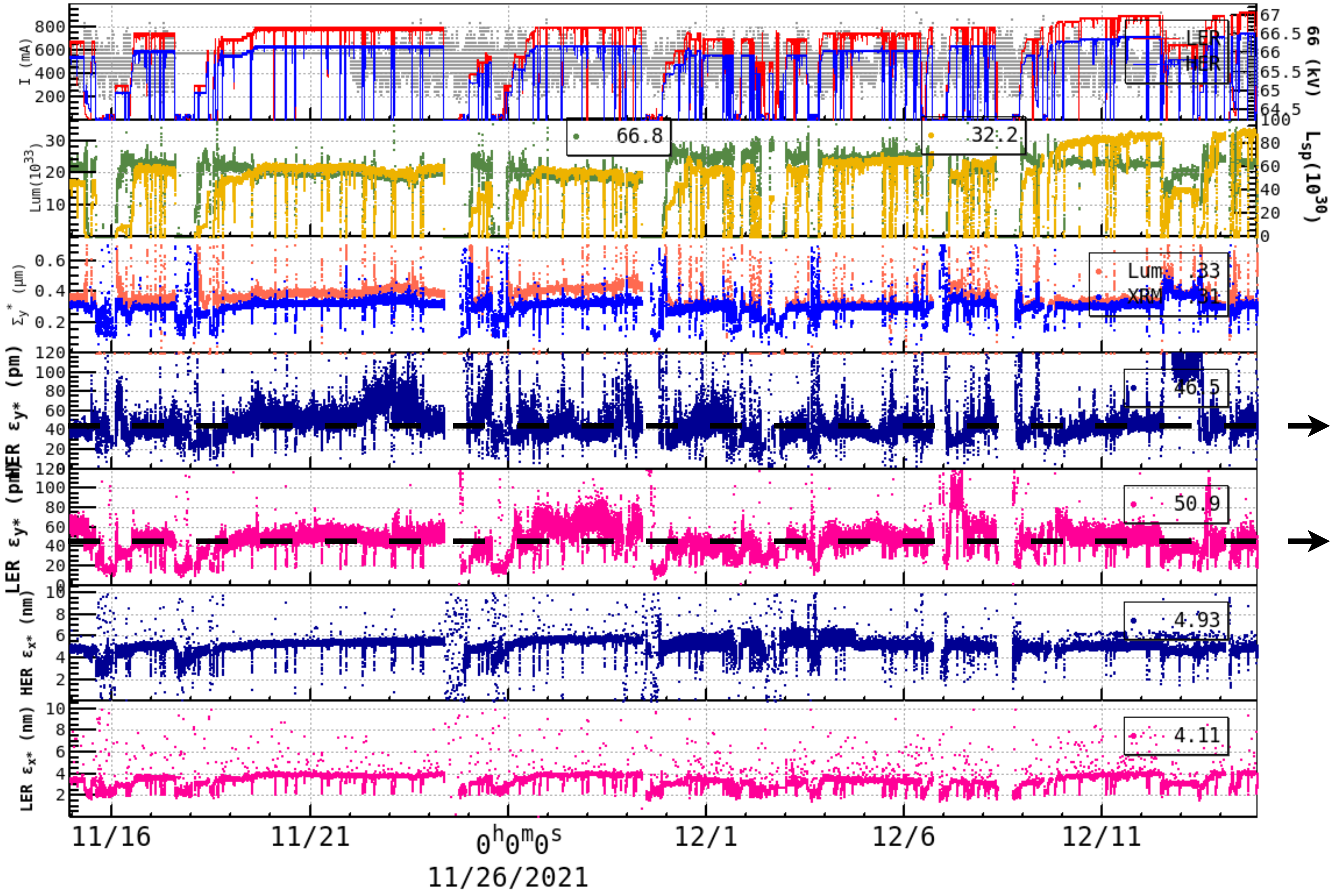




Machine performance

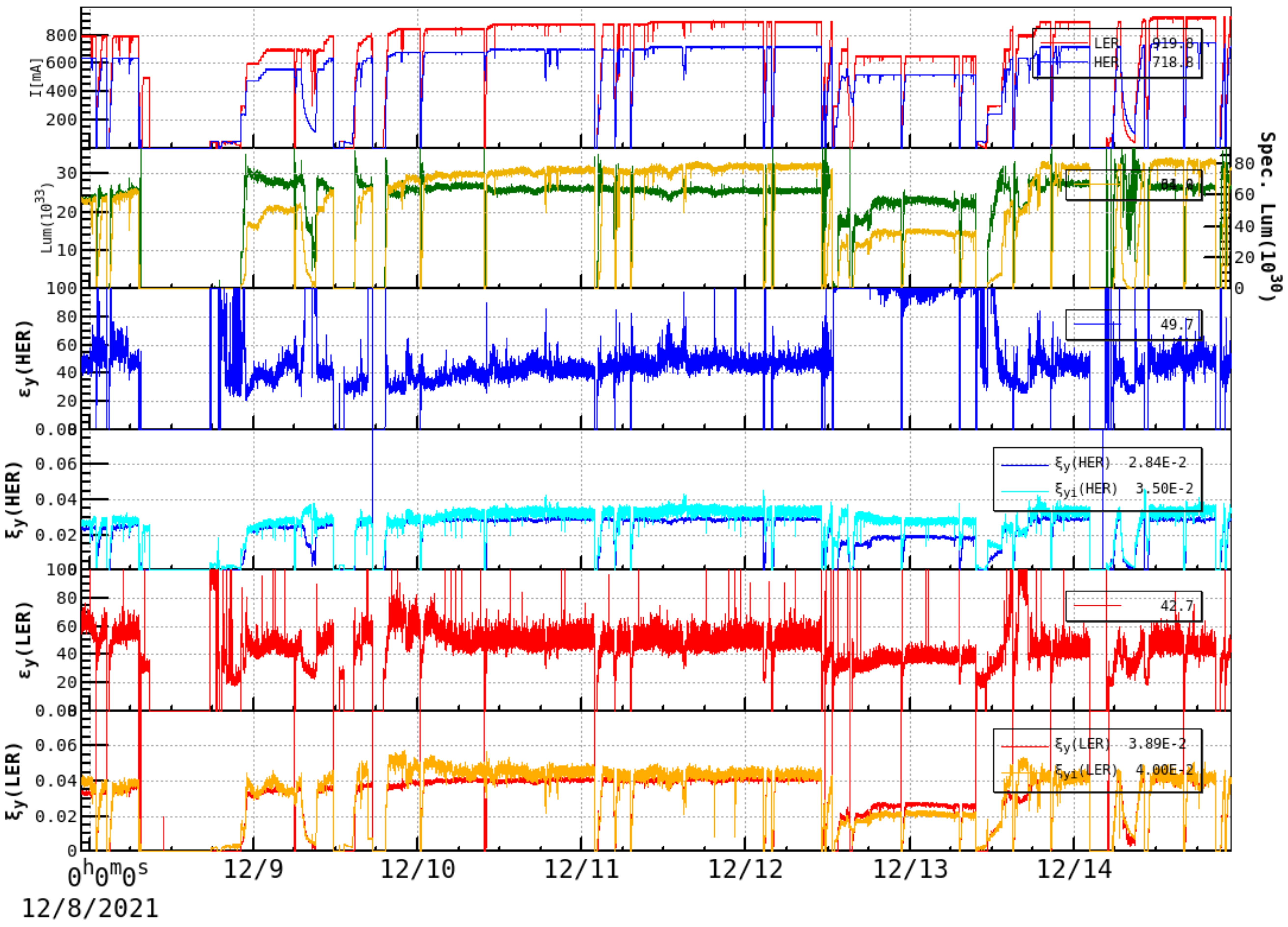
- One month history of luminosity and emittances
  - Stable operation with balanced collision ($\sigma^*_{y+} \approx \sigma^*_{y-}$) was achieved.
  - The vertical emittance blowup ratio ($\epsilon_y/\epsilon_{y0} \approx 2.5$) is still much higher than beam-beam simulations
  - From XRMs, there is visible current dependence of horizontal emittance blowup in LER. Its relation with beam-beam effects is not confirmed yet.

	2021.11.20		Comments
	HER	LER	
I_{beam} (A)	0.75	0.93	
# bunch	1370		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	20	20	Single-beam w/o collision (XRM)
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.61	Natural bunch length (w/o MWI)
ν_x	45.533	44.525	Measured tune of pilot bunch
ν_y	43.581	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design
Luminosity	3.42		10^{34} cm^{-2}s^{-1} (Measured)



Machine performance

- Beam-beam tune shift
  - Under balanced collision ($\sigma^*_{y+} \approx \sigma^*_{y-}$), the two methods for beam-beam parameter (tune shift) are almost equivalent.
  - Note: Natural bunch lengths are used in calculating incoherent beam-beam tune shift.



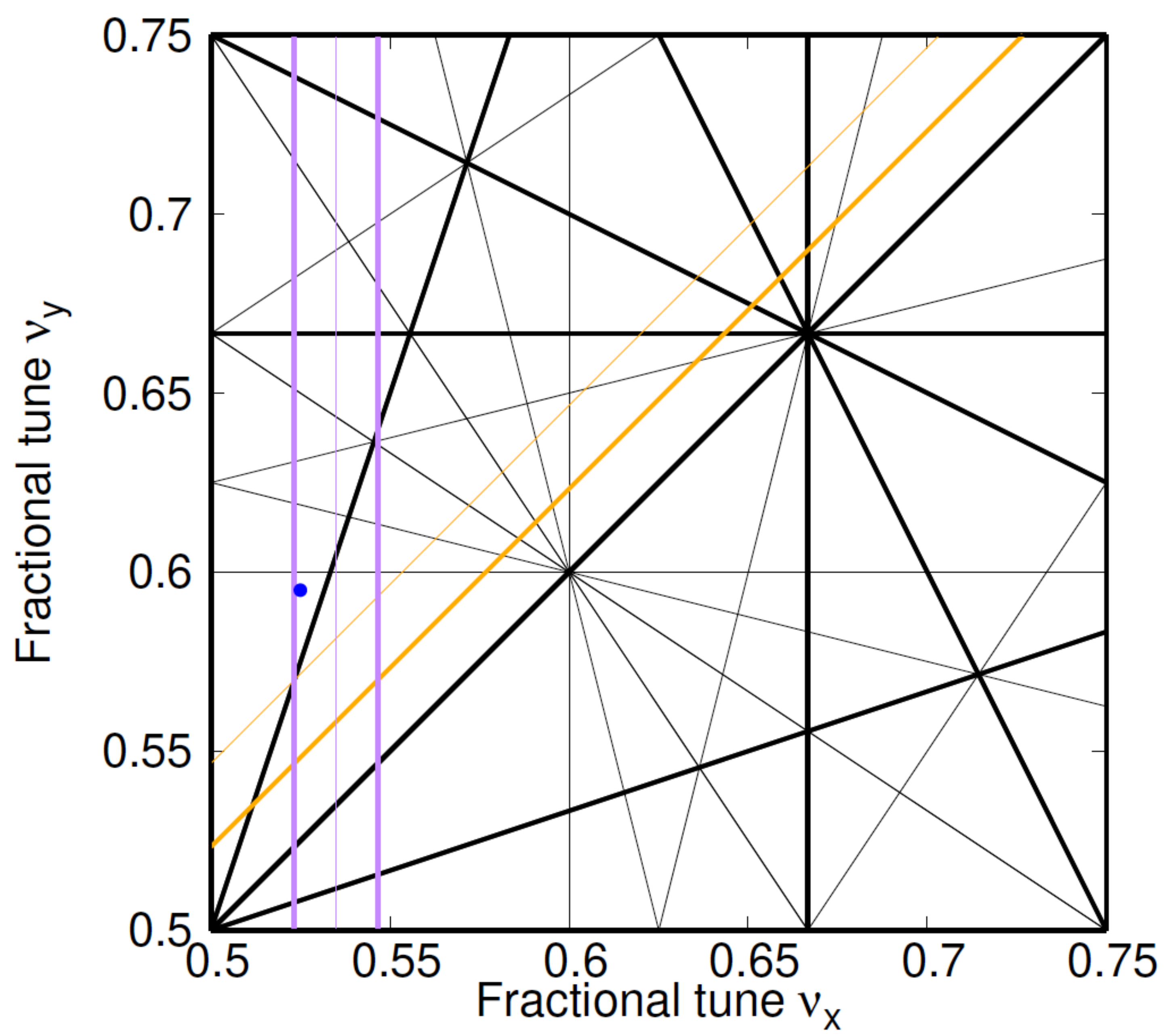
$$L = \frac{1}{2er_e}\frac{\gamma_+ I_+}{\beta^*_{y+}}\xi_{y+} = \frac{1}{2er_e}\frac{\gamma_- I_-}{\beta^*_{y-}}\xi_{y-}$$

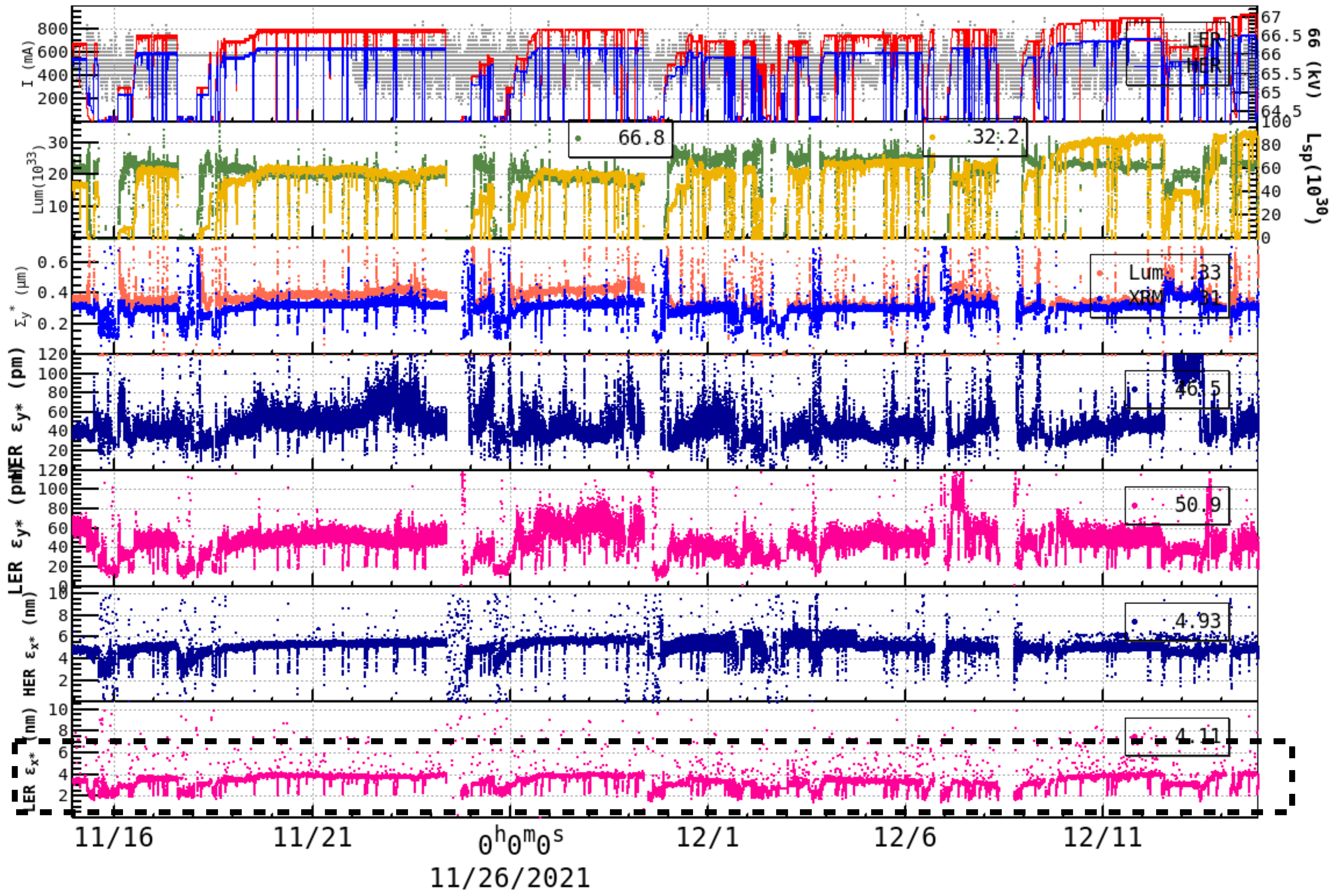
$$\xi^i_{y+} \approx \frac{r_e}{2\pi\gamma_+}\frac{N_-\beta^*_{y+}}{\sigma^*_{y-}\sqrt{\sigma^2_{z-}\tan^2\frac{\theta_c}{2} + \sigma^{*2}_{x-}}}$$

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

Discussion on candidates for vertical emittance blowup

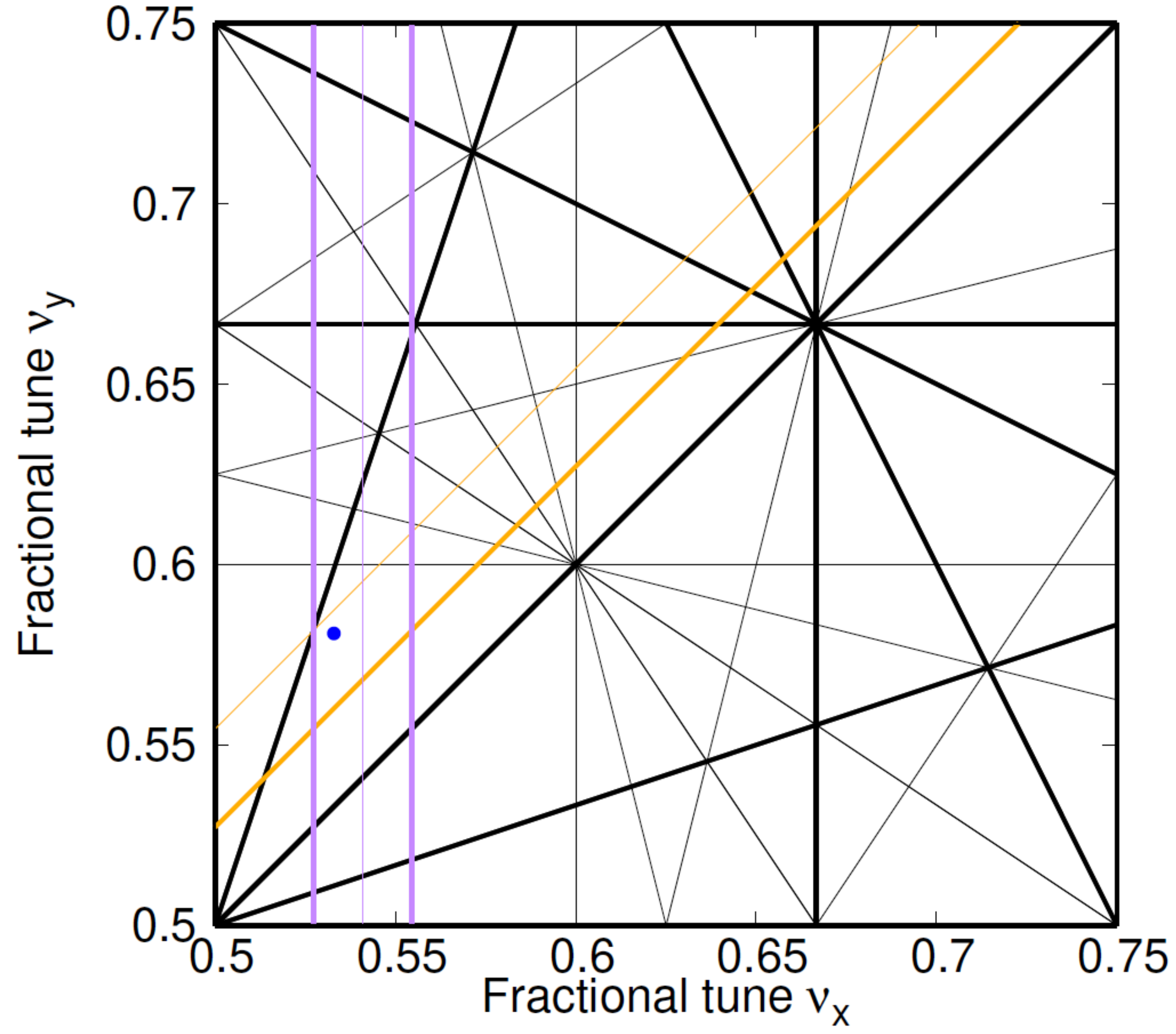
- LER
  - Beam-beam driven synchro-betatron resonance (here I mean single-beam effect, not BBHTI or X-Z instability which means coherent blowup of both beams. Potential-well distortion cause ν_s spread and increase width of $2\nu_x - k\nu_s = N$ resonances.)?.
  - TMCI: Interplay of beam-beam, impedance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



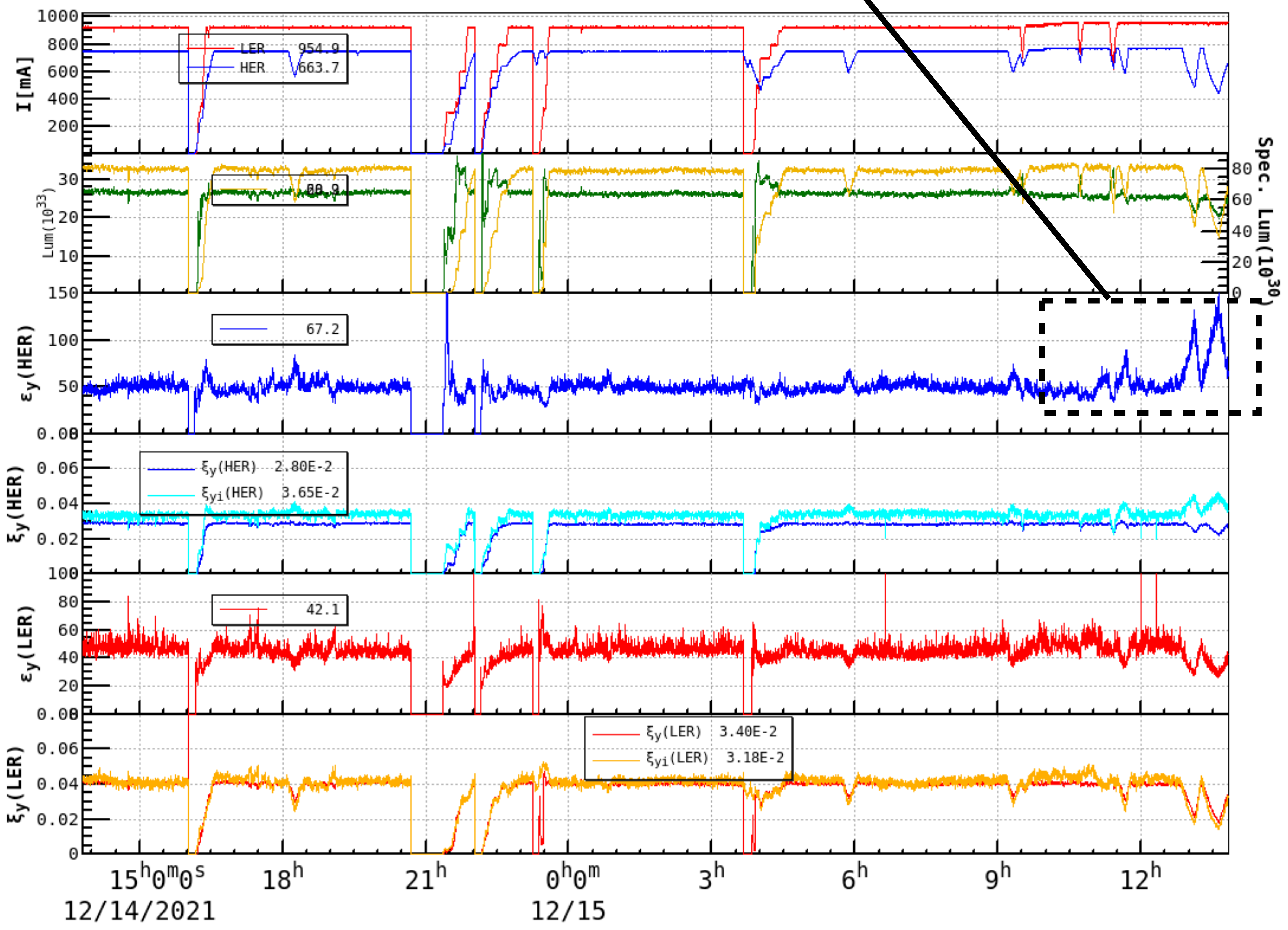


Discussion on candidates for vertical emittance blowup

- 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?



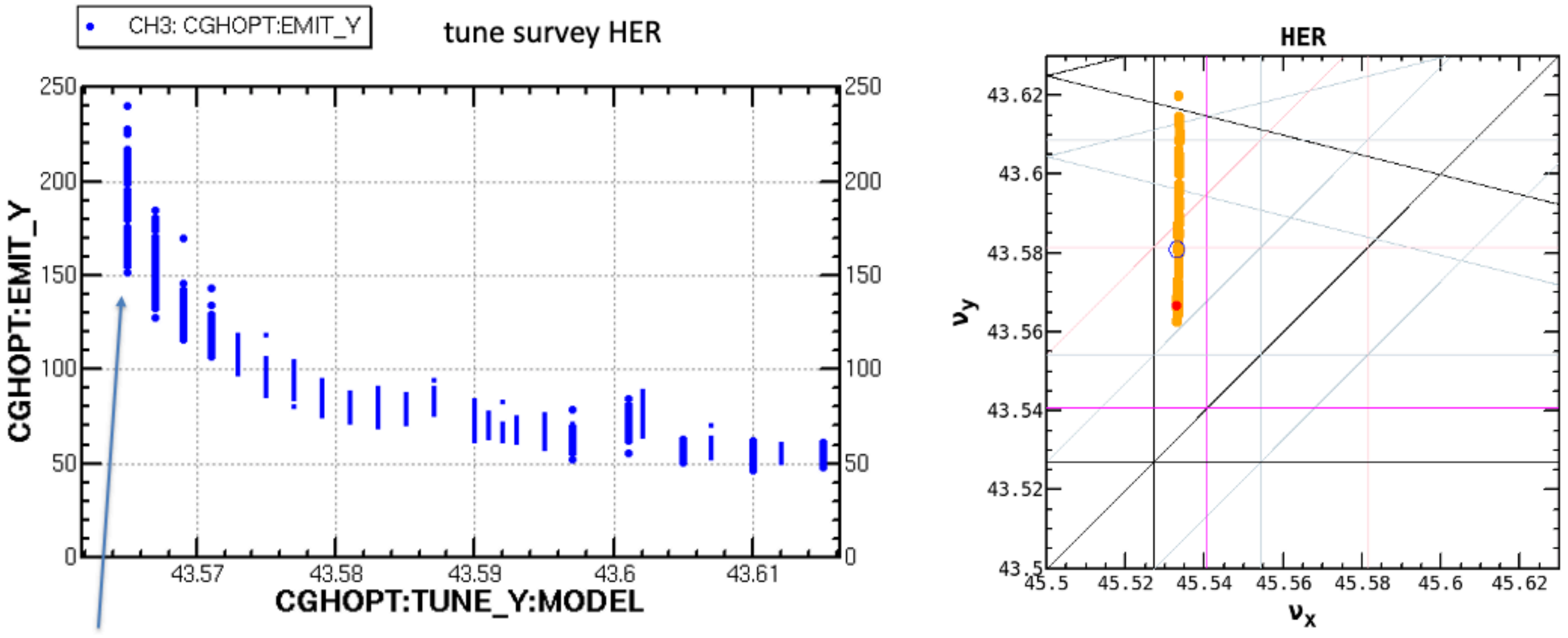
Summary

- BBSS simulation of IP R1 and R2 knobs
  - Seem to justify online IP knobs.
- HER tune survey
  - IP knobs likely 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.
  - $2\nu_x - 3\nu_s =$ N and $2\nu_x - 4\nu_s =$ N were not clearly seen in this study. Maybe they are mainly excited by beam-beam?
- LER tune survey
  - IP knobs have side effects on global coupling?
  - 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?

Backup

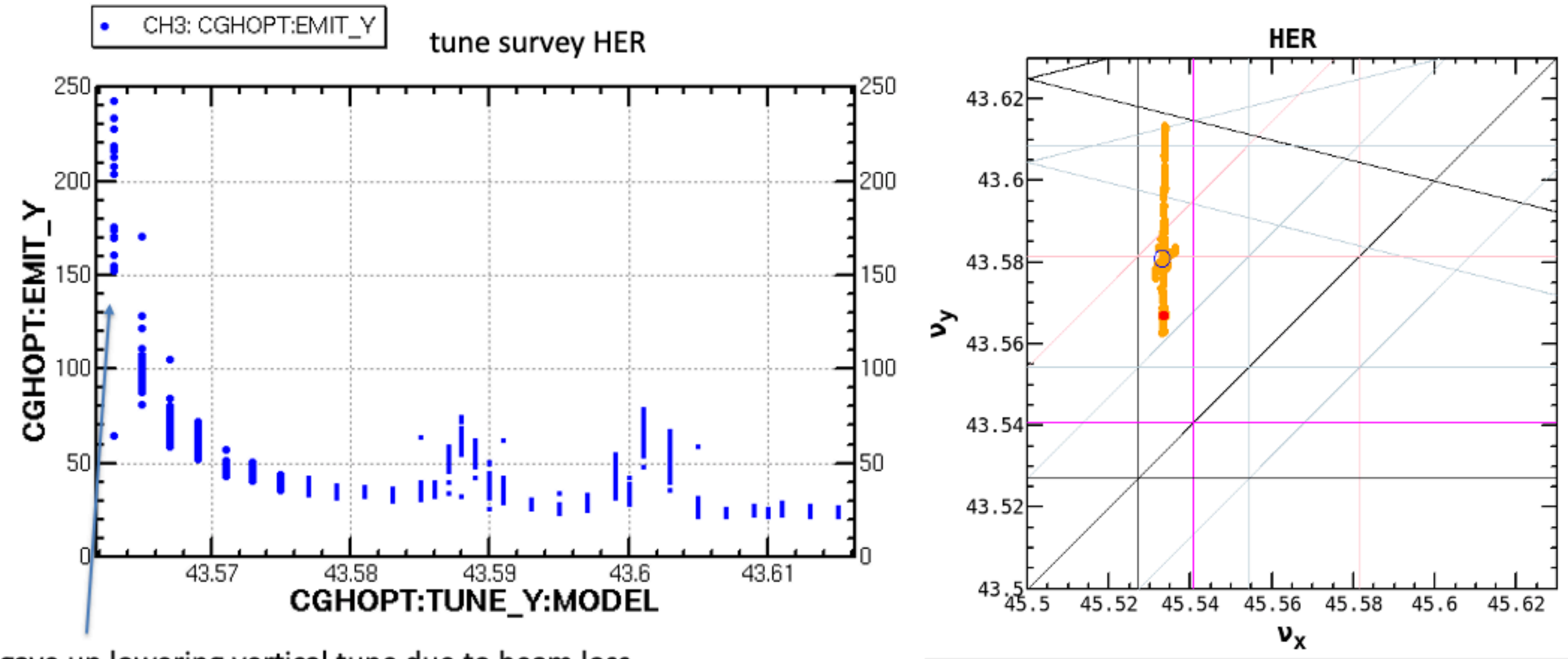
- HER tune survey done on Nov. 8, 2021
  - The study was done with LER trouble with injection kickers. So the beam time of HER was available for such study.
  - More details about the study can be found from shift report (2021_11_08_0900_Ueda_Funakoshi).
  - Post analysis of the experimental data showed 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 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

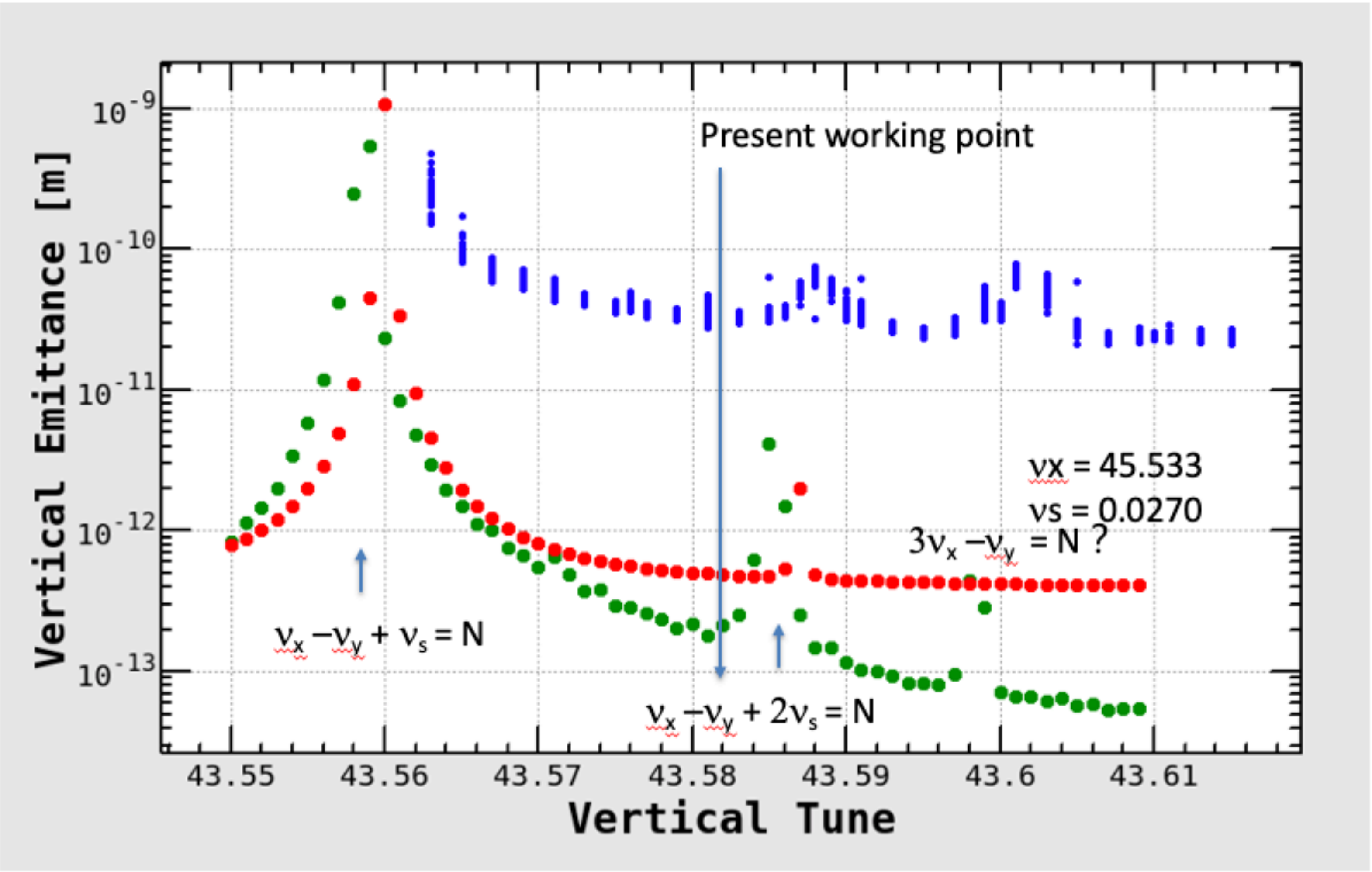


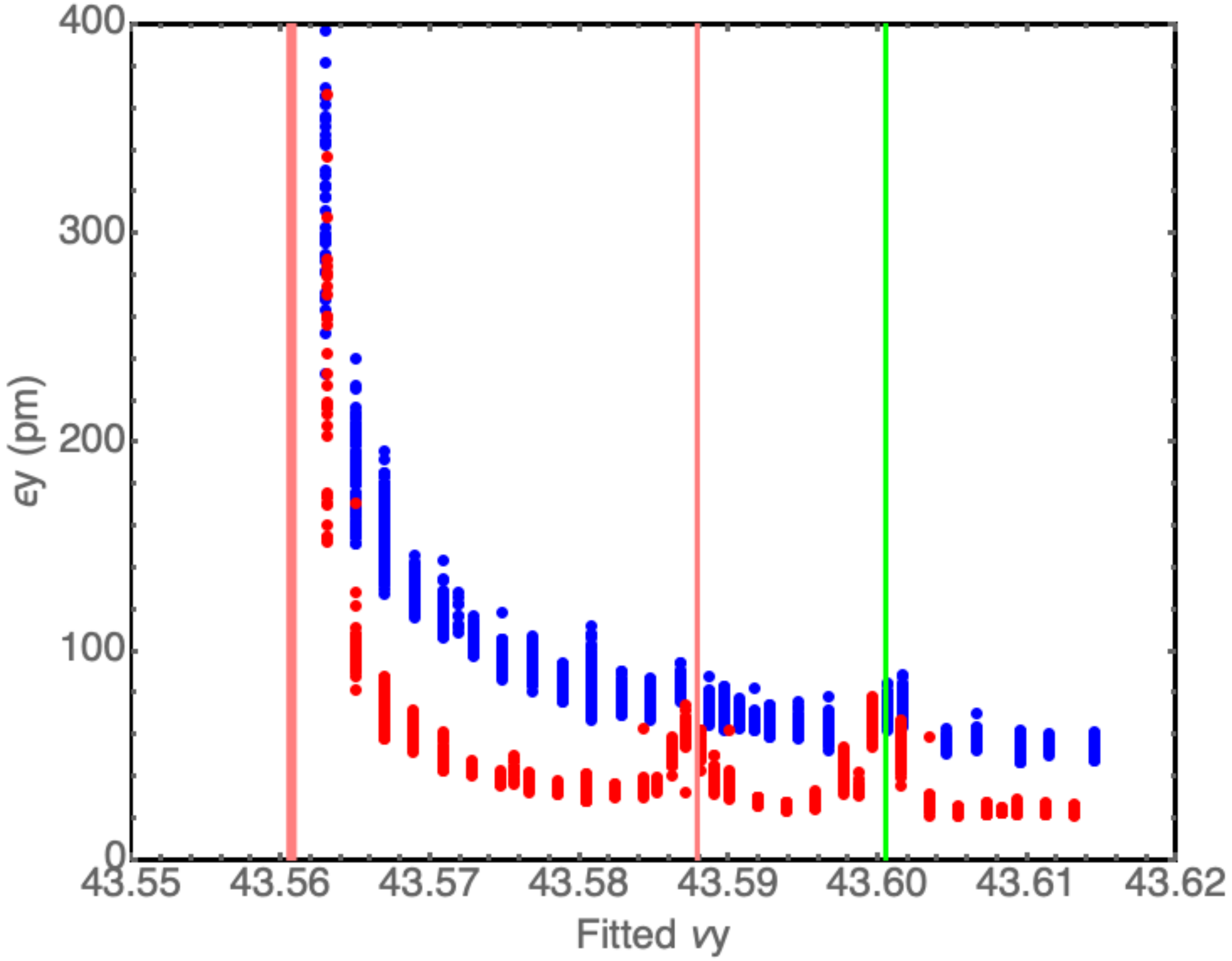
gave up lowering vertical tune due to beam loss

Backup

Simulation on synchro-beta emittance (HER)

- 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).





Blue dots: ν_y scan before optics correction

Red dots: ν_y scan after optics correction

Backup

- 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.