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

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Acknowledgements

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4th meeting of beam-beam workgroup, Nov. 25, 2021, KEK

Outline

- Updates on beam-beam simulations for SuperKEKB
  - BBSS ν_x scan with vertical fractional tune $[\nu_y] = .61.$
  - BBWS tune scan
  - Benchmark of beam-beam simulations
- Recent machine status related to beam-beam
- Summary

Updates on beam-beam simulations

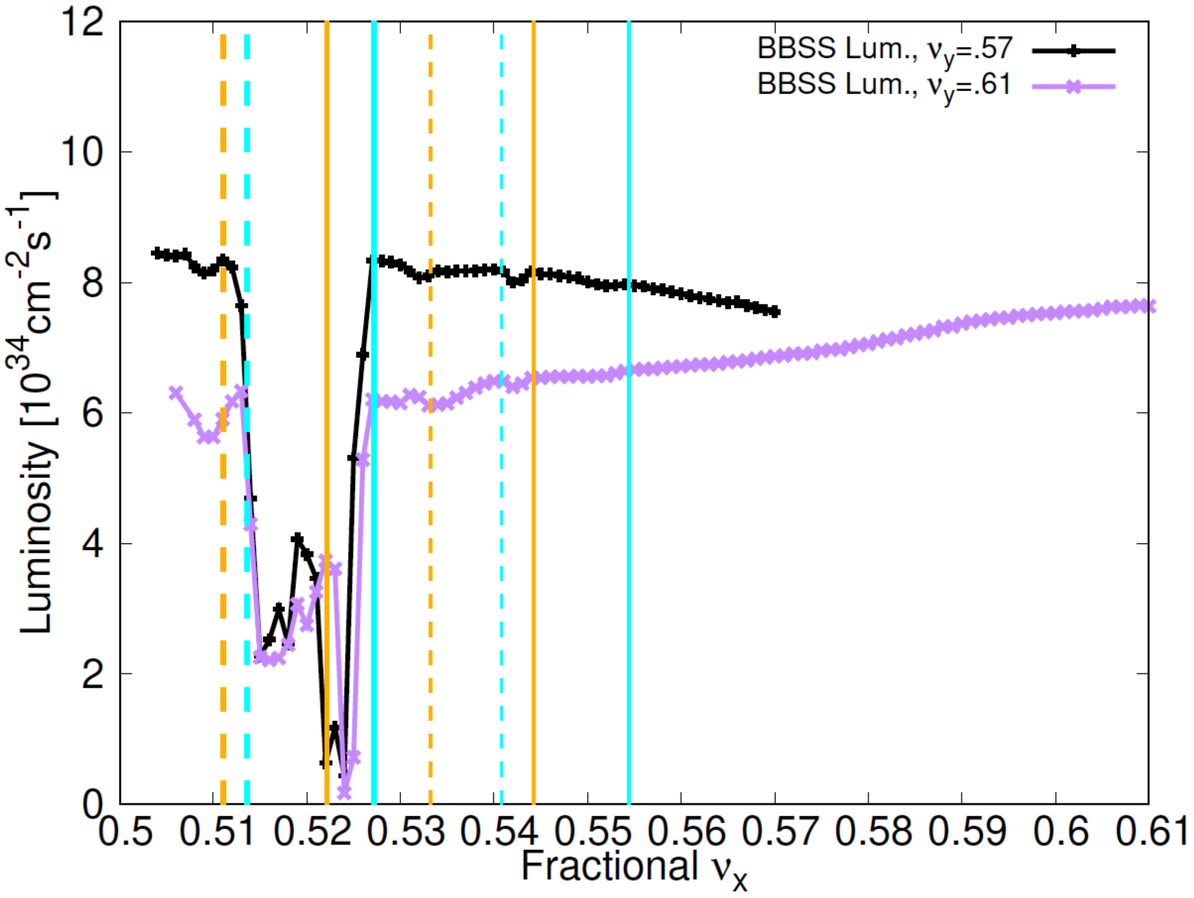
- Tune scan with longitudinal pseudo-Green function wakes
  - Beam parameters similar to observations on 2021.07.01.

	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

- Tune scan using BBSS with longitudinal pseudo-Green function wakes
  - Assume equal ν_x for HER and LER. Fractional vertical tune set as $\nu_y = .57/.61$, scan ν_x. Track 2e6 macro particles to 12000 turns.
  - Plots: Luminosity and beam sizes (the data at the last turn) as a function of ν_x.
  - Data for $0.513 < \nu_x < 0.526$ do not arrive at equilibrium.
  - For $\nu_y = .61$, luminosity decreases when horizontal tune moves from $\nu_x = 0.61$ to $\nu_x = 0.54$. This is caused by vertical blowup of HER beam, and should be related to beam-beam resonance of $-\nu_x + 4\nu_y + \alpha = N$ with insufficient HER crab waist strength (40%) (see p.10 for BBWS tune scan).

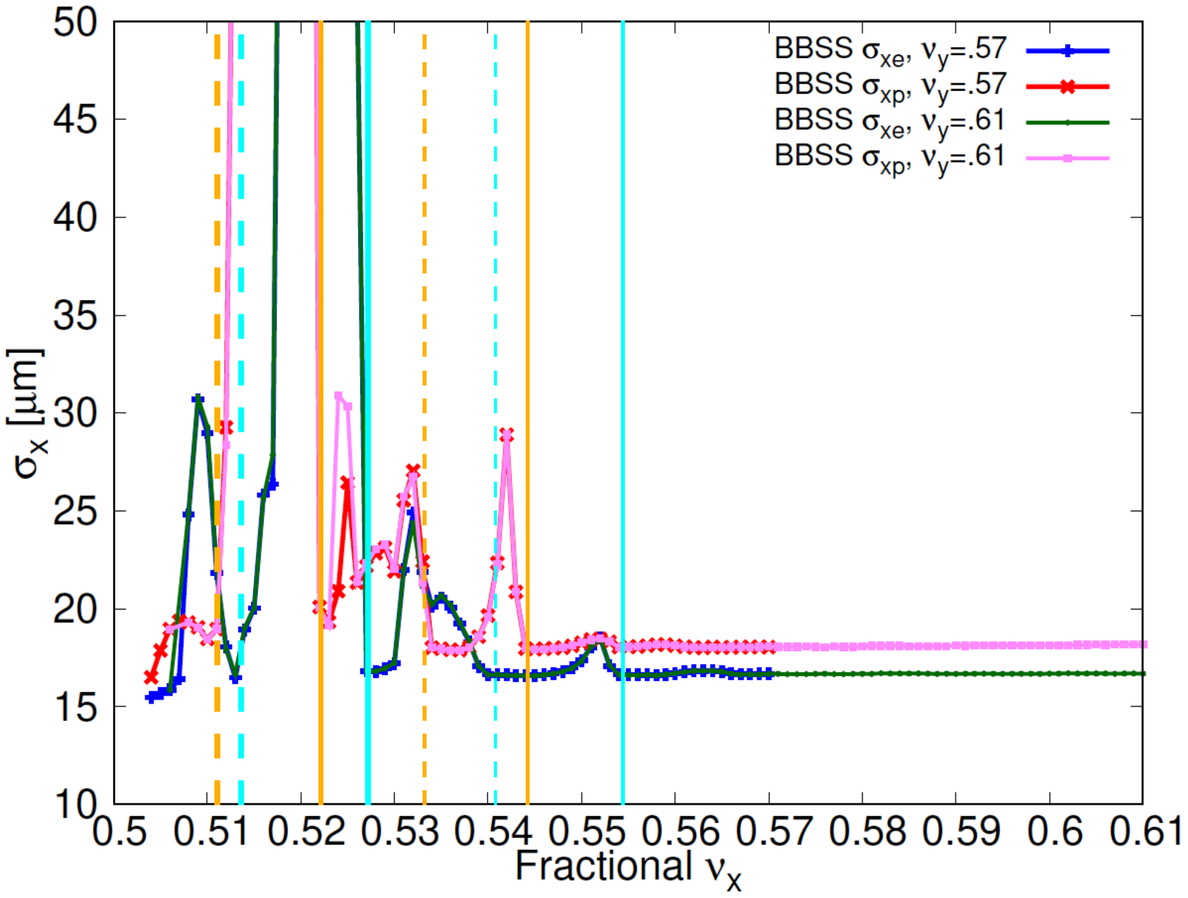
Synchro-betatron resonances: $\nu_x - k\nu_s/2 = N/2$
Odd k: Dashed lines; Even k: Solid lines
Orange lines: LER; Cyan lines: HER



Updates on beam-beam simulations

- Tune scan with longitudinal pseudo-Green function wakes (cont'd)
  - Tune scan with $\nu_y = 0.61$ finished. It reproduces the resonances seen in the tune scan with $\nu_y = 0.57$ on the left of $\nu_x - 2\nu_s = N/2$.

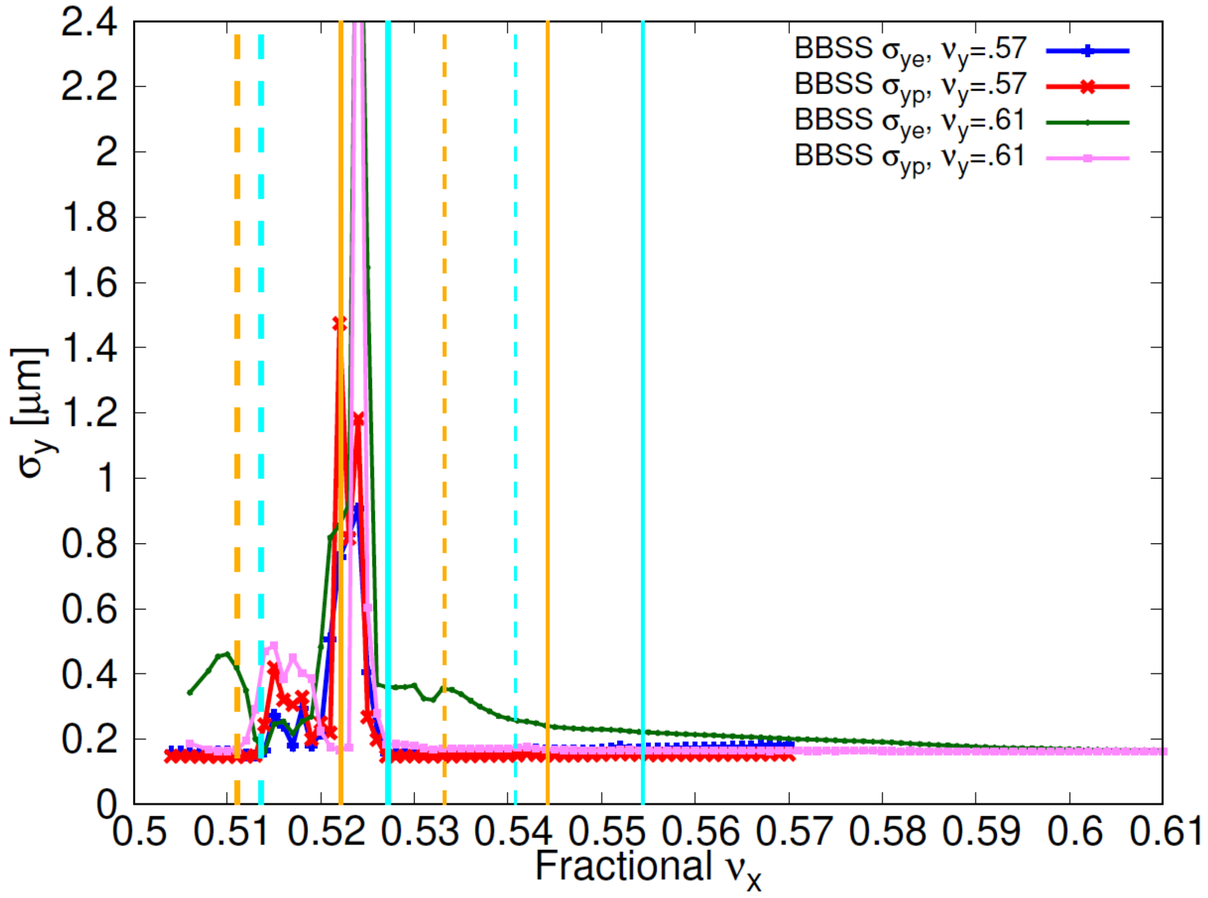
Synchro-betatron resonances: $\nu_x - k\nu_s/2 = N/2$
Odd k: Dashed lines; Even k: Solid lines
Orange lines: LER; Cyan lines: HER



New results

- Tune scan with longitudinal pseudo-Green function wakes (cont'd)
  - Vertical blowup of HER beam with $\nu_y = 0.61$ should be related to $\nu_x + 4\nu_y + \alpha = N$ with insufficient HER crab waist strength (40%).
  - "In collision schemes with ϕ >> 1, an increase in εx itself does not have a noticeable impact on luminosity. However, this leads to a proportional increase in εy due to the betatron coupling, so eventually the luminosity will decrease several times." [2]

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

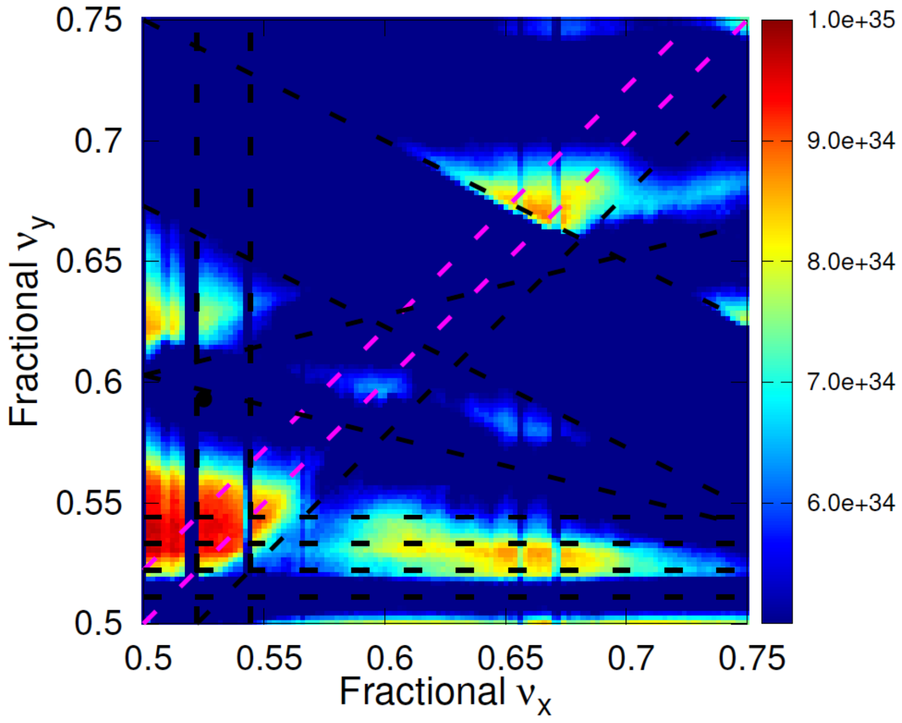


[2] D. Shatilov, "FCC-ee Parameter Optimization", ICFA Beam Dynamics Newslett. 72 (2017) 30-41.

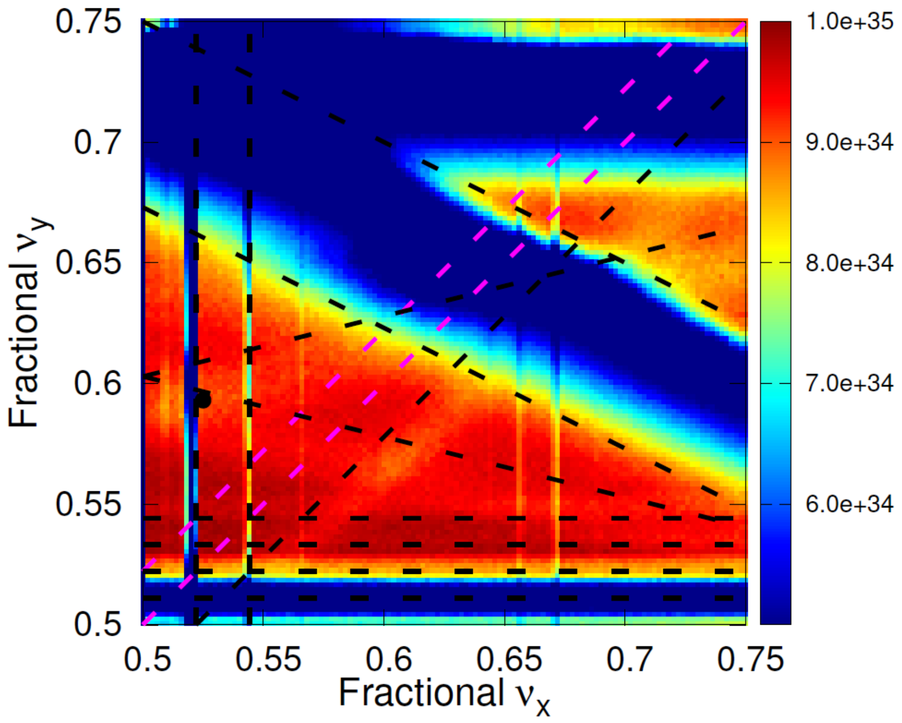
Updates on beam-beam simulations

- Tune scan using BBWS without longitudinal wakes
  - Luminosity with weak positron beam (LER): Beam-beam resonances of $\nu_x \pm 4\nu_y + \alpha = N$ are well suppressed by crab waist (80%).

No crab waist



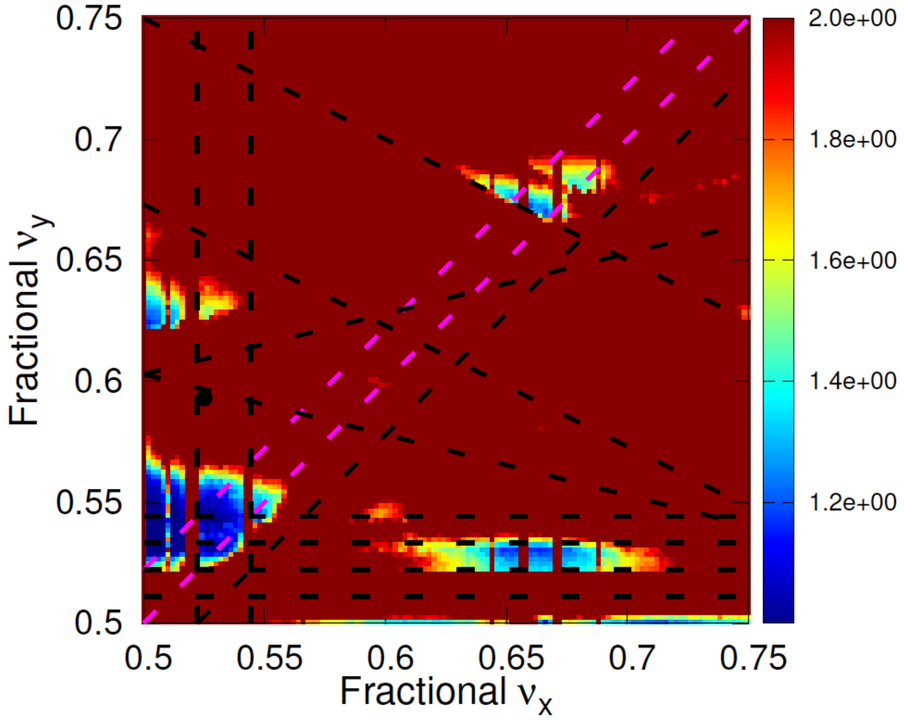
80% crab waist



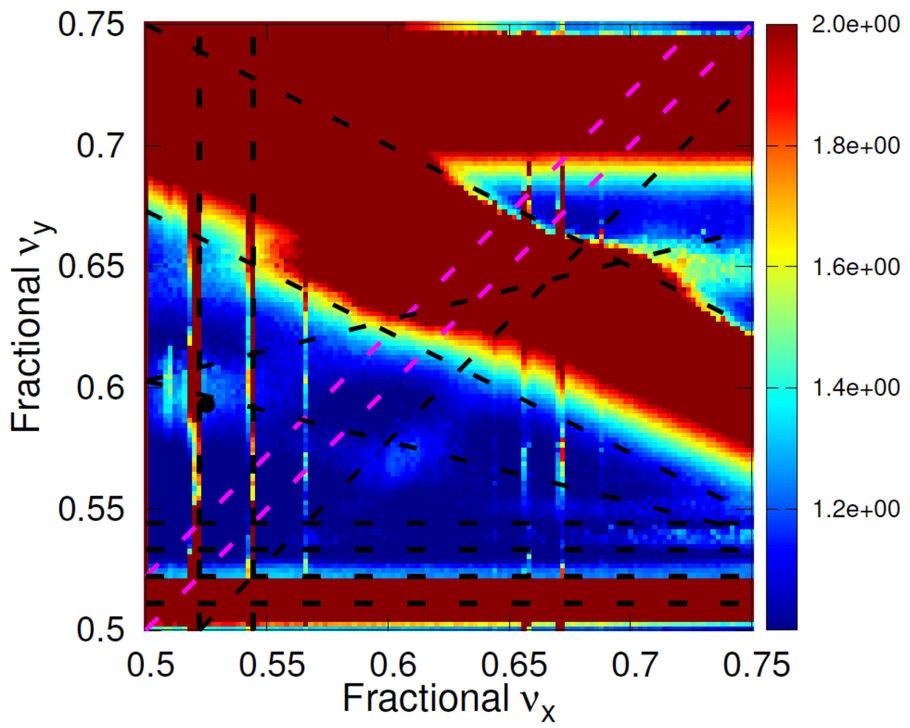
Updates on beam-beam simulations

- Tune scan using BBWS without longitudinal wakes
  - Vertical beam size (normalized by nominal value) with weak positron beam (LER): Beam-beam resonances of $\nu_x \pm 4\nu_y + \alpha = N$ are well suppressed by crab waist (80%).

No crab waist



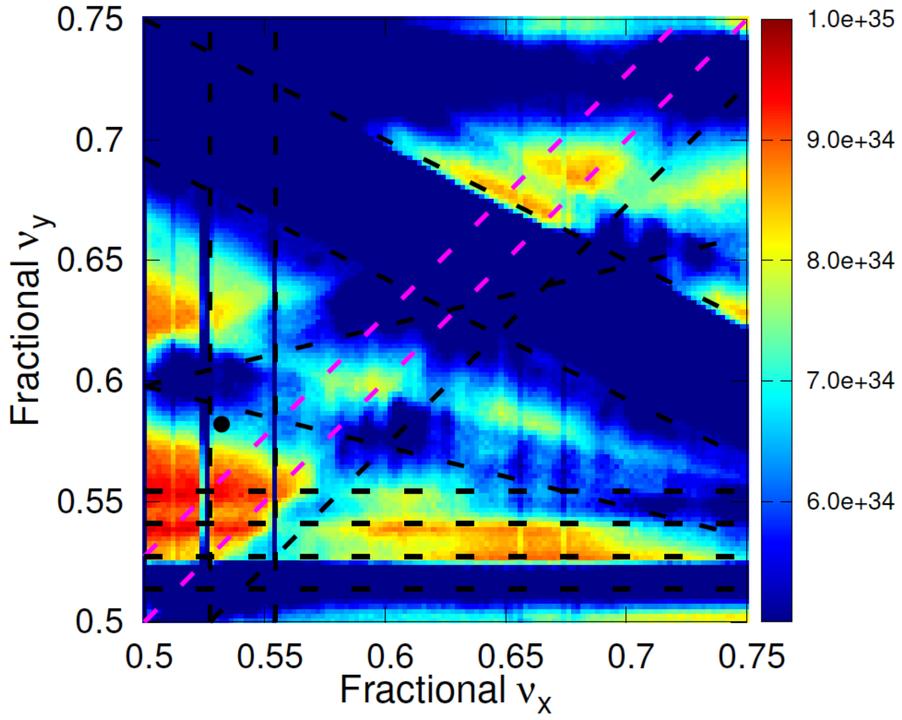
80% crab waist



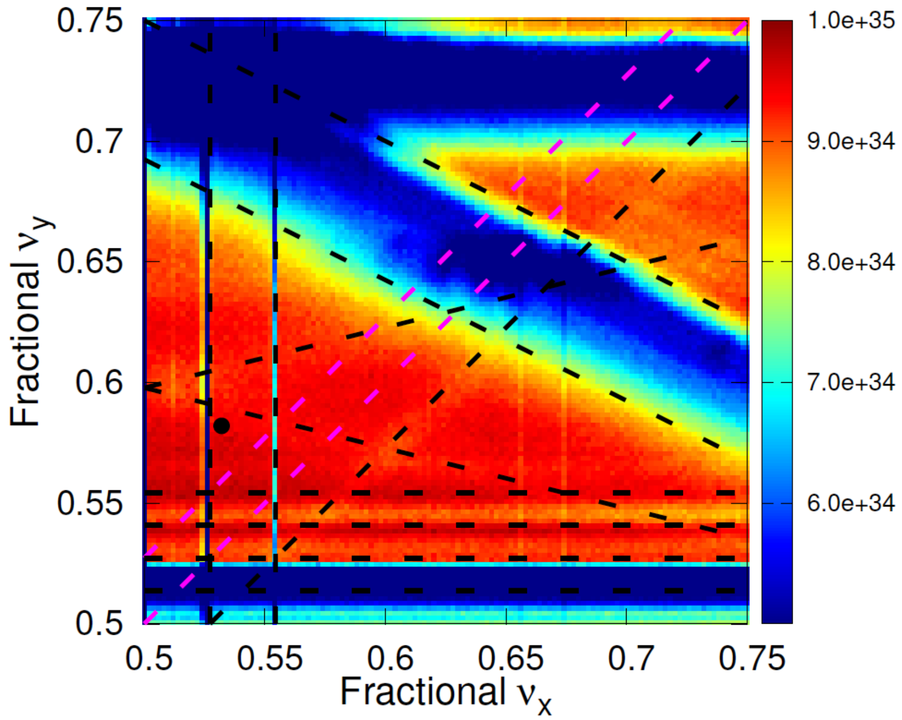
Updates on beam-beam simulations

- Tune scan using BBWS without longitudinal wakes
  - Luminosity with weak electron beam (HER): Beam-beam resonances of $\nu_x \pm 4\nu_y + \alpha = N$ are well suppressed by crab waist (80%).

No crab waist



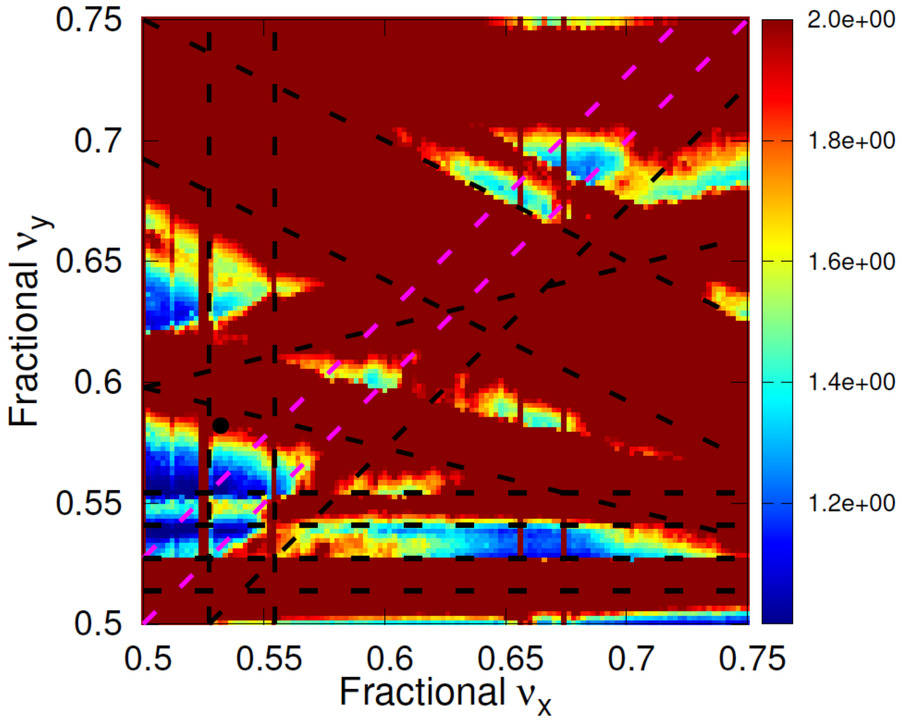
80% crab waist



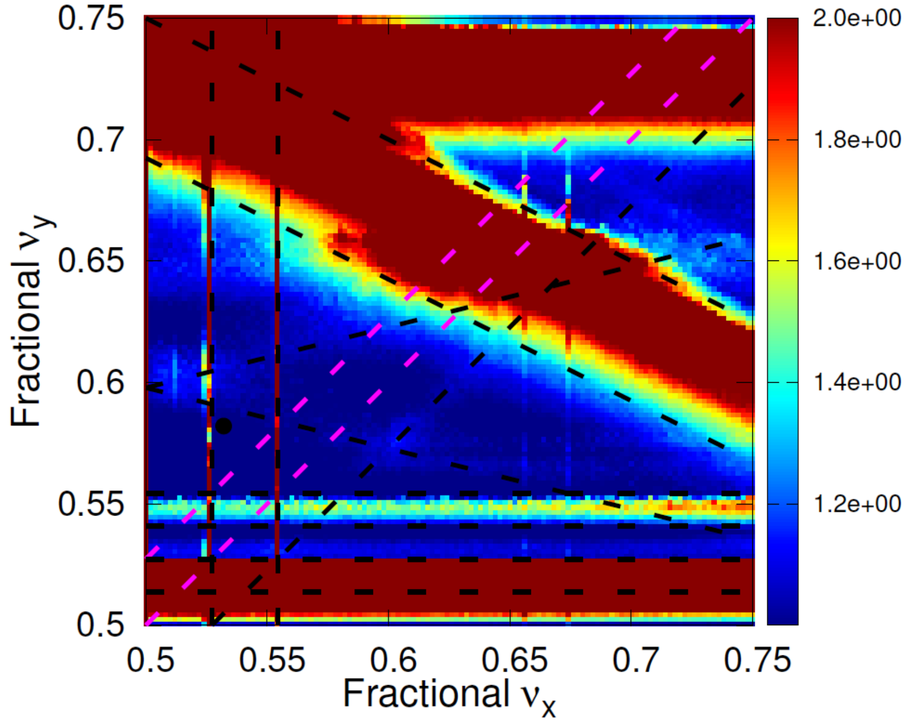
Updates on beam-beam simulations

- Tune scan using BBWS without longitudinal wakes
  - Vertical beam size (normalized by nominal value) with weak electron beam (HER): Beam-beam resonances of $\nu_x \pm 4\nu_y + \alpha = N$ are well suppressed by crab waist (80%).

No crab waist

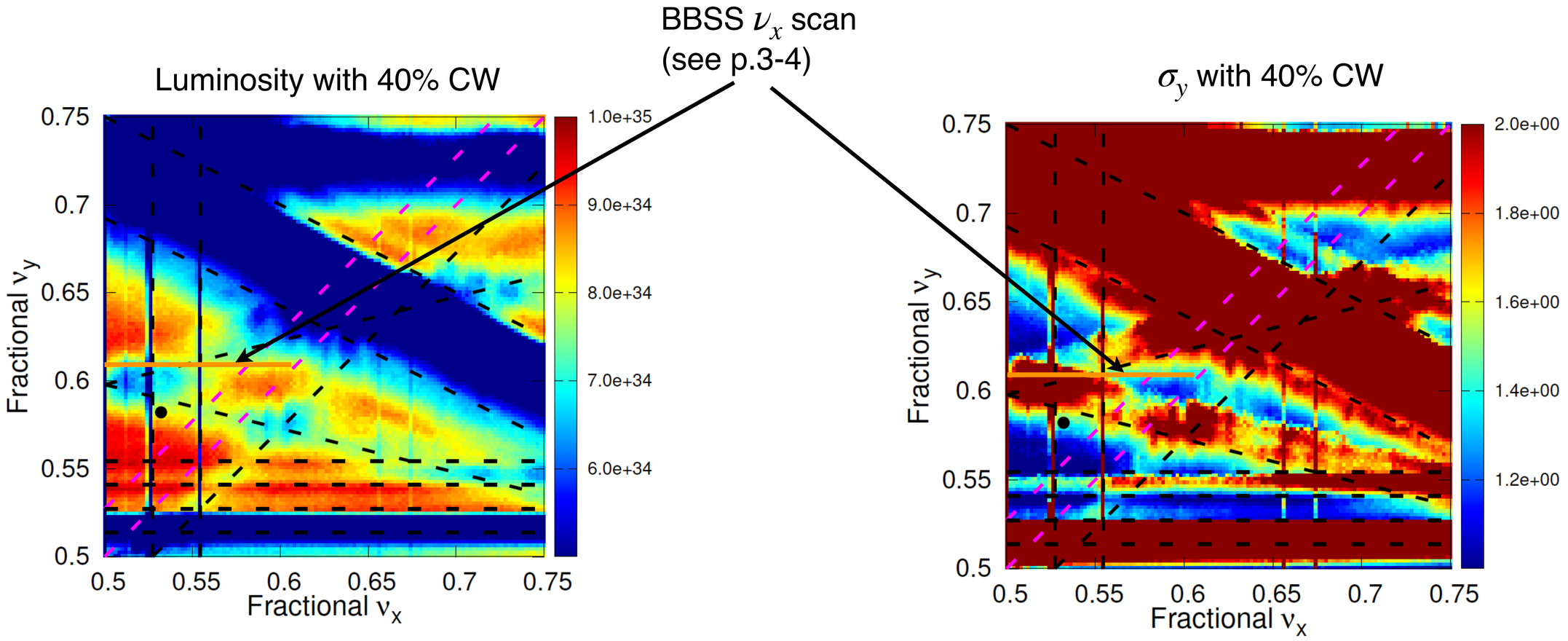


80% crab waist



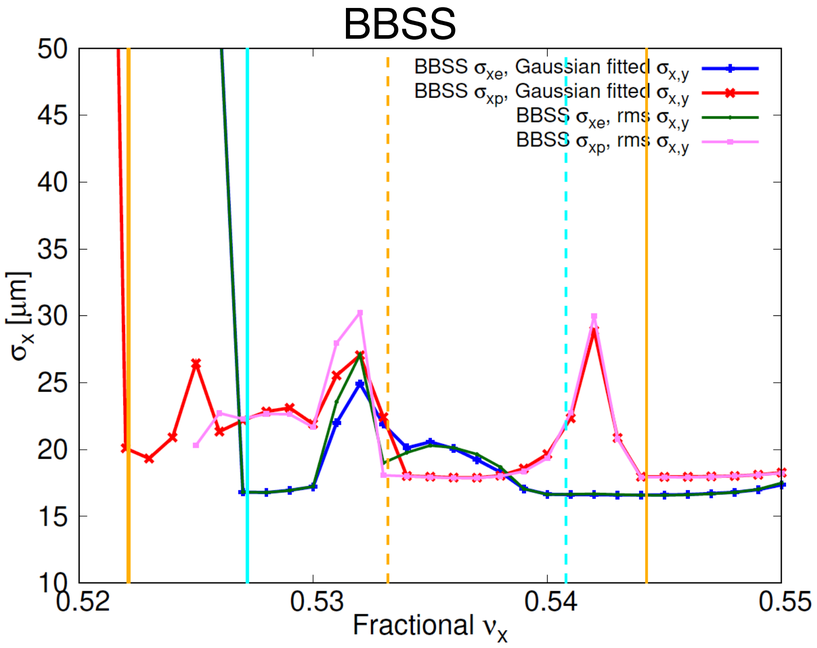
Updates on beam-beam simulations

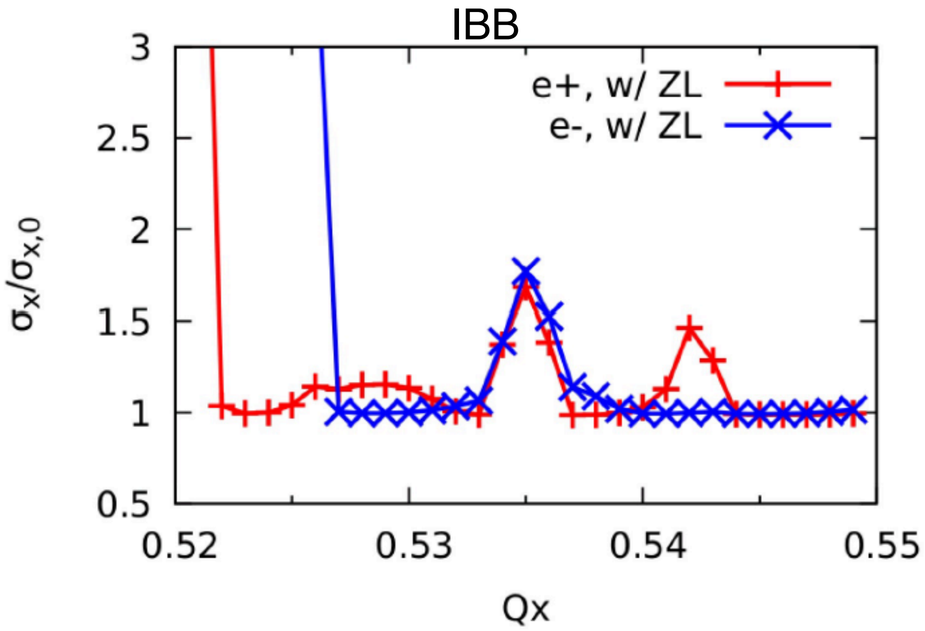
- Tune scan using BBWS without longitudinal wakes
  - However, 40% of crab waist strength is not enough to suppress the beam-beam resonances of $\nu_x \pm 4\nu_y + \alpha = N$ for electron beam (HER).



Updates on beam-beam simulations

- Benchmark simulations
  - In the 3rd ITF-BB workgroup meeting, Y. Zhang showed simulation results of coherent X-Z instability using his IBB code.
  - The horizontal blowup simulated by IBB and BBSS showed different patterns. IBB simulations were done with rms $\sigma_{x,y}$.
  - BBSS simulations using rms $\sigma_{x,y}$ were done, reproducing the pattern of BBSS simulations.
  - To better understand the discrepancy, we plan:
    - To check the impedance modeling of BBSS (BBSS predicts bunch lengthening weaker than VFP simulations).
    - To compare turn-by-turn data of BBSS and IBB.

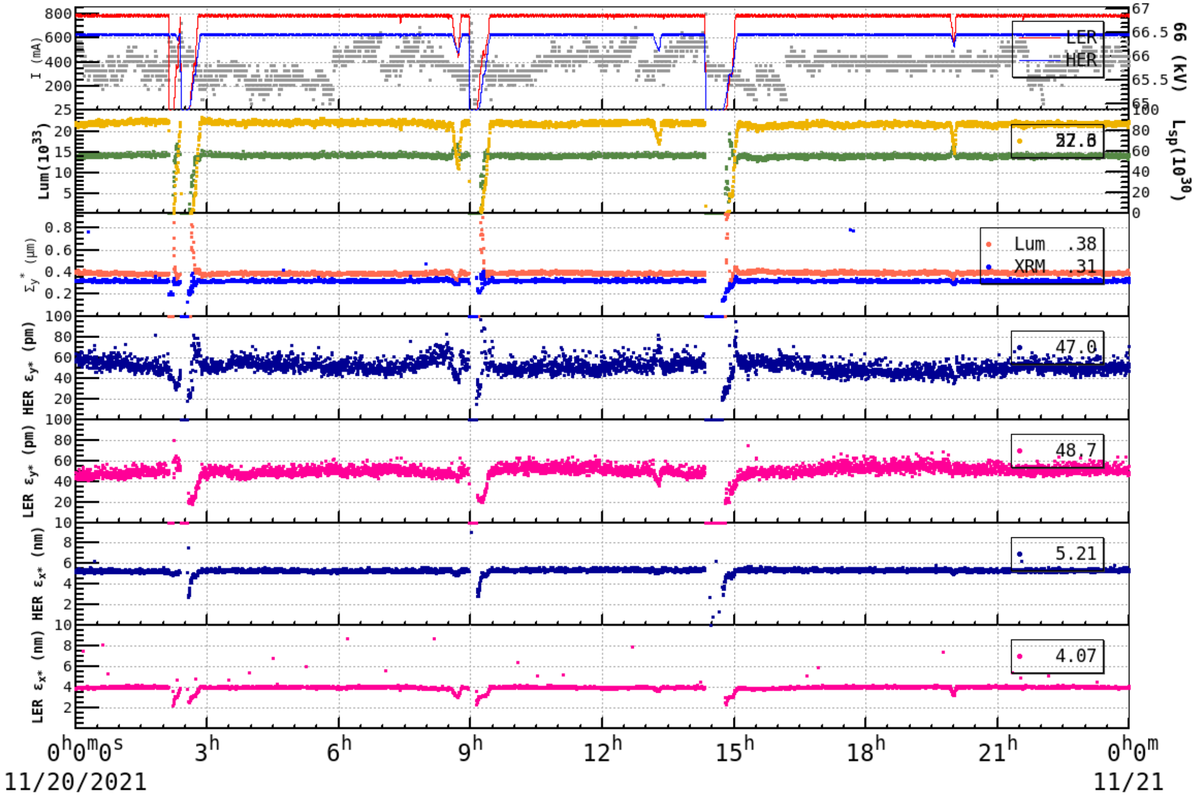




Recent machine status related to beam-beam

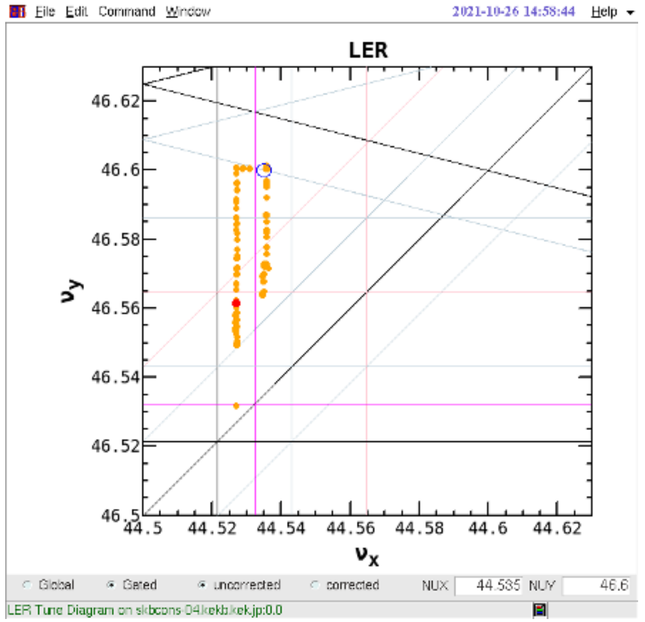
- One day history of luminosity and emittances
  - Stable operation with balanced collision ($\sigma^*_{y+} \approx \sigma^*_{y-}$) was achieved.
  - The vertical emittance blowup ratio ($\epsilon_y/\epsilon_{y0} \approx 2.5$) is still much higher than beam-beam simulations
  - From XRMs, there is visible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

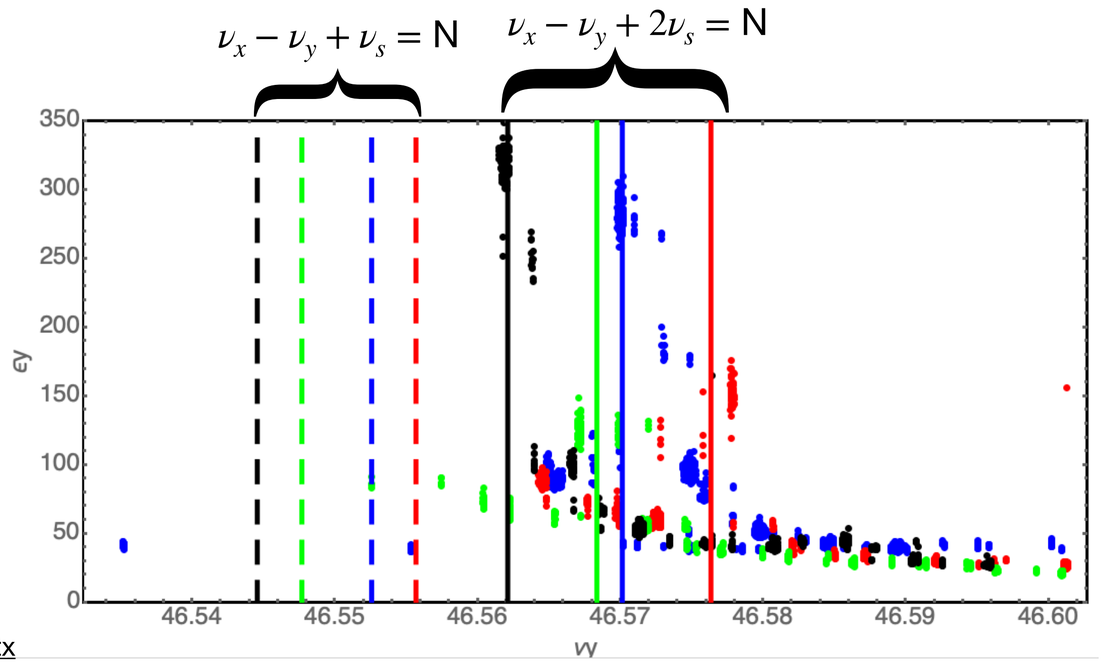
	2021.11.20		Comments
	HER	LER	
I_{beam} (A)	0.64	0.8	
# bunch	1272		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	20	20	Single-beam w/o collision (XRM)
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.61	Natural bunch length (w/o MWI)
ν_x	45.533	44.525	Measured tune of pilot bunch
ν_y	43.581	46.595	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design
Luminosity	2.4		10^{34} cm^{-2}s^{-1} (Measured)



Recent machine status related to beam-beam

- 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. [1]).
  - 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. [2] 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

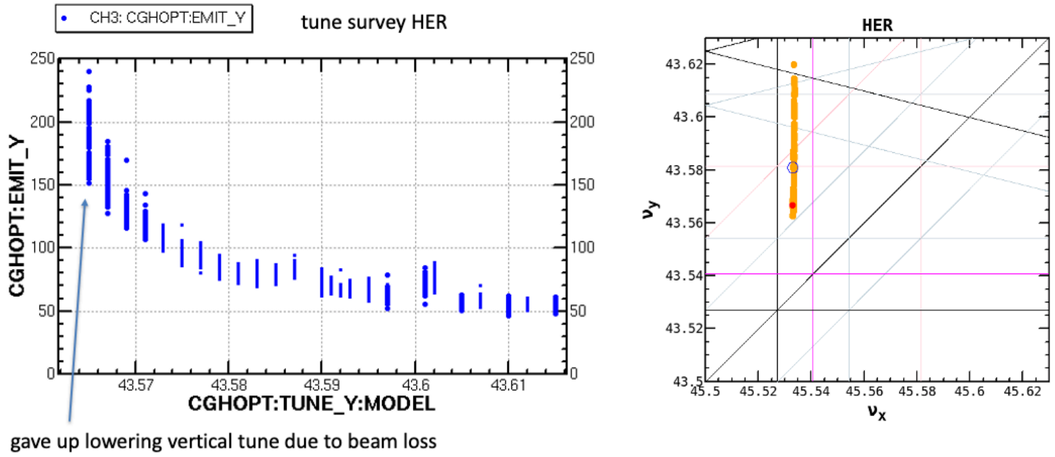
[1] https://kds.kek.jp/event/39972/contributions/199971/attachments/149042/186732/2021c_tmci_study_report.pptx

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

Recent machine status related to beam-beam

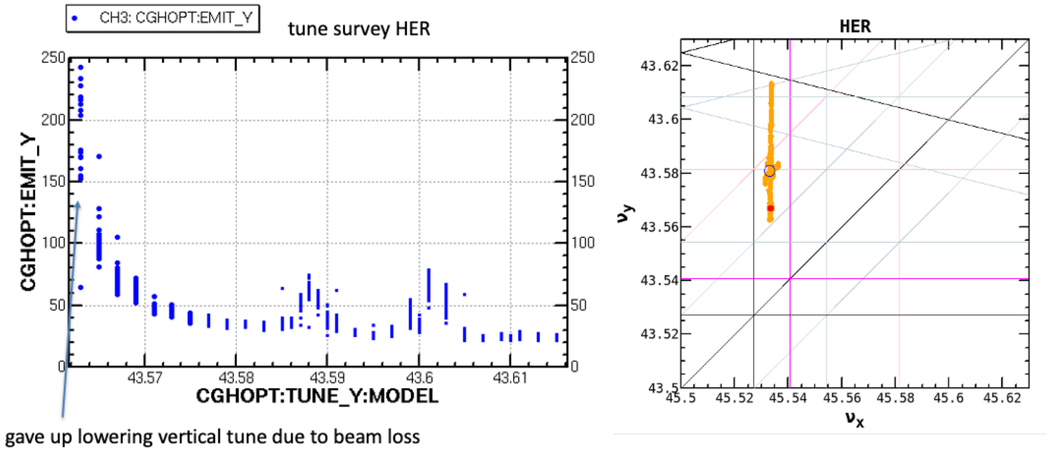
- HER tune survey done on Nov. 8, 2021
  - The study was done with LER trouble with injection kickers. So the beam time of HER was available for such study.
  - More details about the study can be found from shift report (2021_11_08_0900_Ueda_Funakoshi).
  - Post analysis of the experimental data showed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



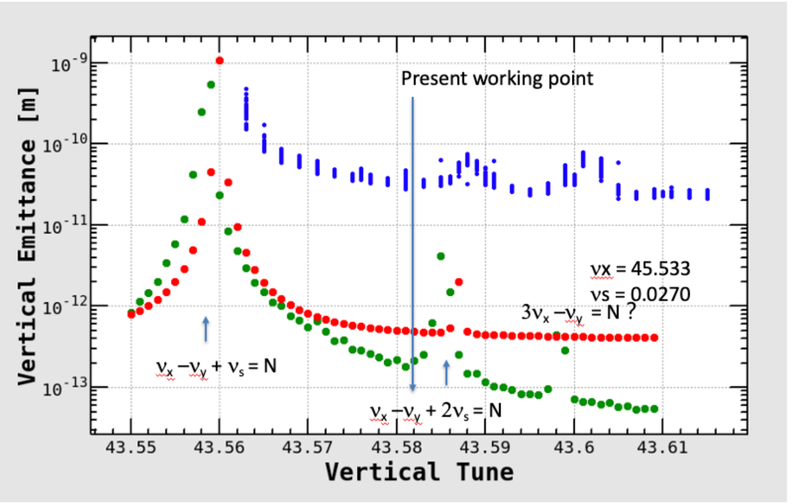
gave up lowering vertical tune due to beam loss

From Y. Funakoshi's report

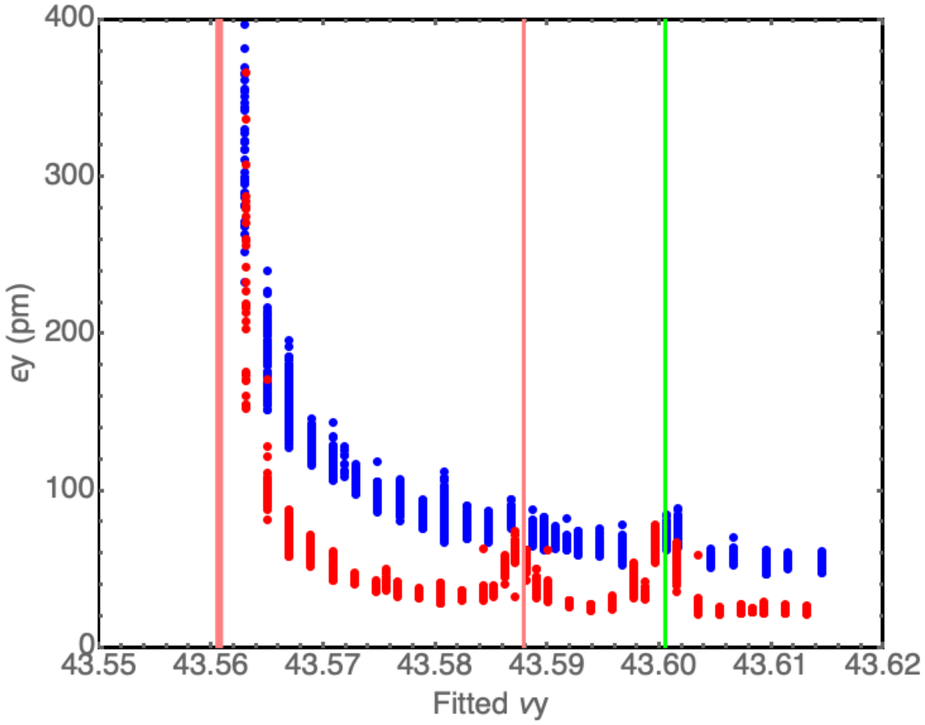
Recent machine status related to beam-beam

From Y. Funakoshi's report

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 $3\nu_x - \nu_y = \mathrm{N}$ resonance (to be confirmed).



Blue dots: ν_y scan before optics correction

Red dots: ν_y scan after optics correction

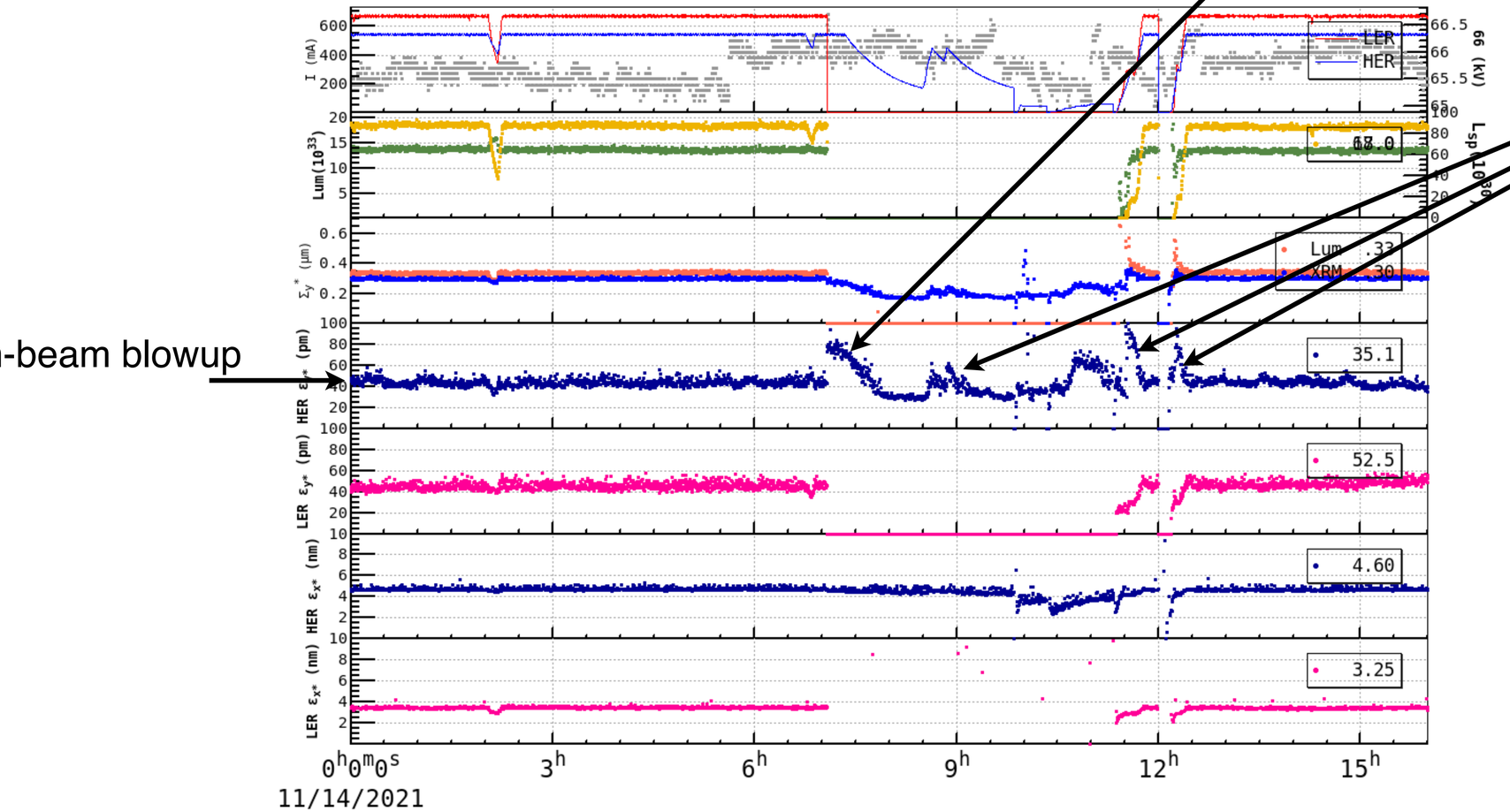
Recent machine status related to beam-beam

- 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.

Single-beam blowup in decay mode

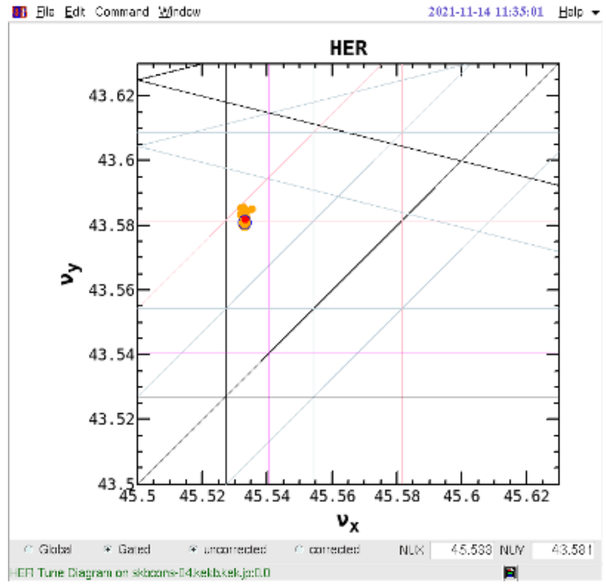
Blowup during injection
w/ and w/o collision

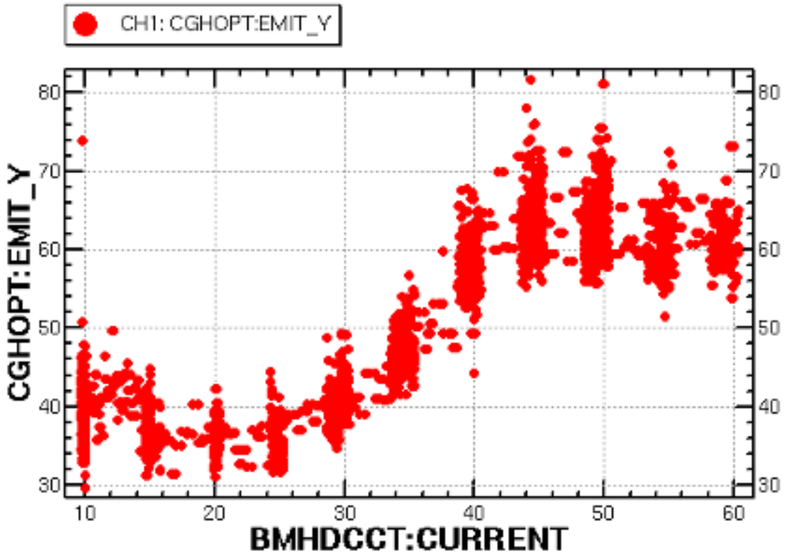
Beam-beam blowup

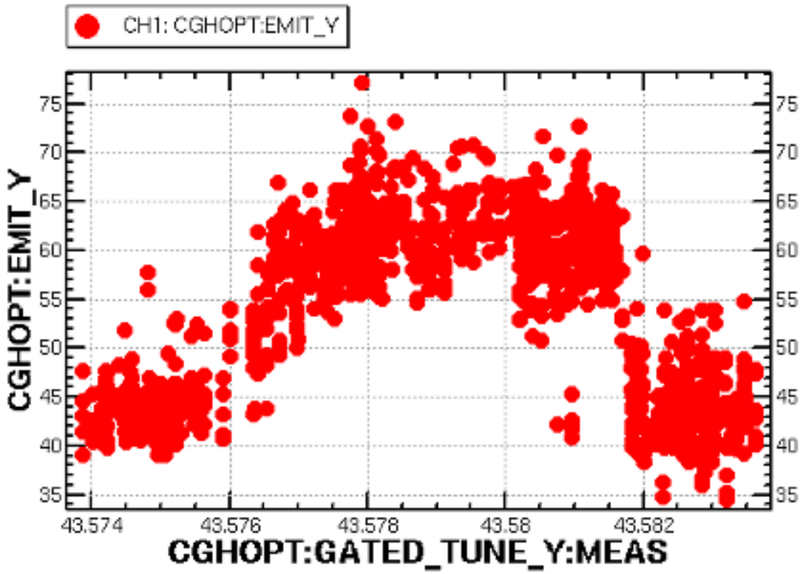


Recent machine status related to beam-beam

- 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.



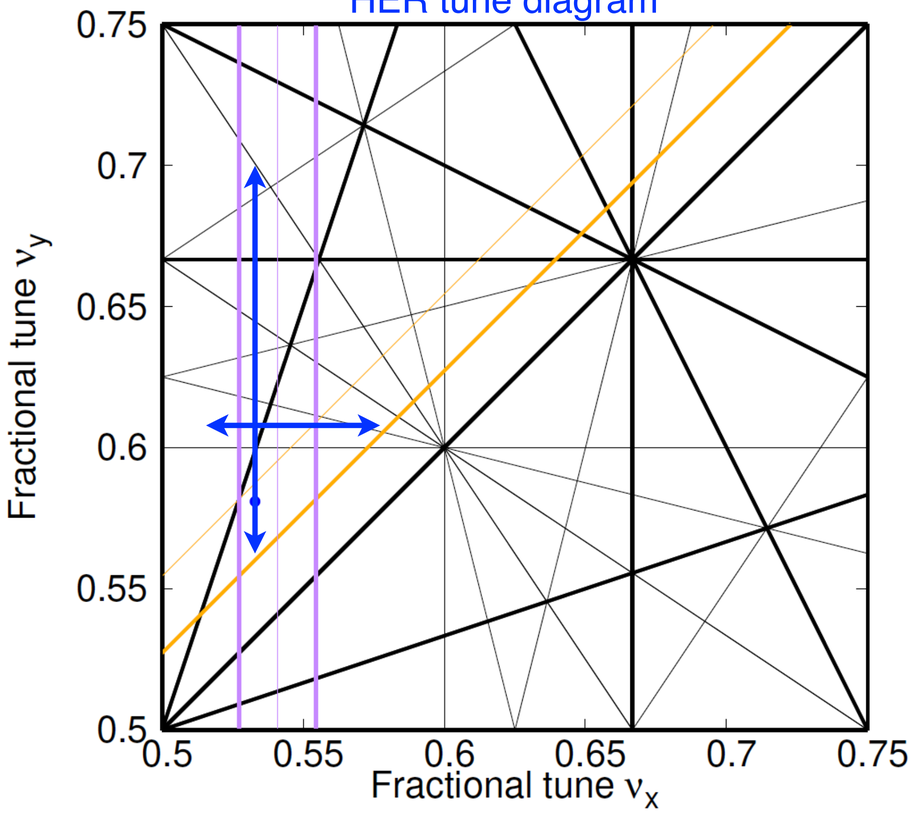




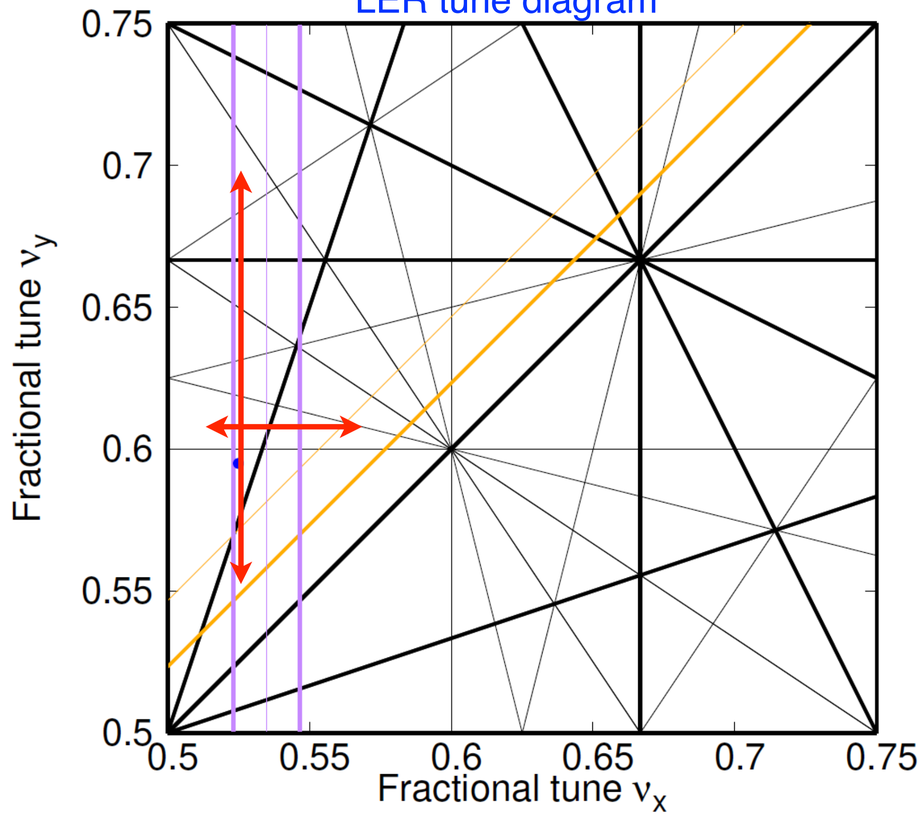
Recent machine status related to beam-beam

- Proposal of tune survey for LER and HER
  - Tune survey to observe single-beam emittance blowup at low bunch current should provide lots of information about nonlinear single particle dynamics.
  - Tune survey to observe single-beam emittance blowup at high bunch current should provide information of impedance effects (such as TMCI).
  - Tune survey to observe collision-beam emittance blowup at high bunch current should provide information of beam-beam effects (coherent X-Z instability, beam-beam resonances, etc.) and its interplay with lattice nonlinearity and impedances.

HER tune diagram



LER tune diagram



Summary

- Beam-beam simulations
  - 40% crab waist strength for HER seems not enough to suppress beam-beam resonances?
  - Impedance effects in BBSS and BBWS need to be improved.
- Recent machine status
  - Machine conditions (many aspects) became more stable compared to 2021ab?
  - Vertical blowup remains to be a big challenge for achieving higher luminosity.
  - Interplay of beam-beam, lattice imperfections (global betatron coupling, chromatic couplings, synchro-beta resonances, high-order geometric resonances, etc.), and impedances looks to be a key issue and requires a better model for beam-beam simulations.