Beam-beam related issues

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Acknowledgments

K. Ohmi, Y. Ohnishi, Y. Zhang, K. Matsuoka, S. Uehara,
and members of the SuperKEKB commissioning group

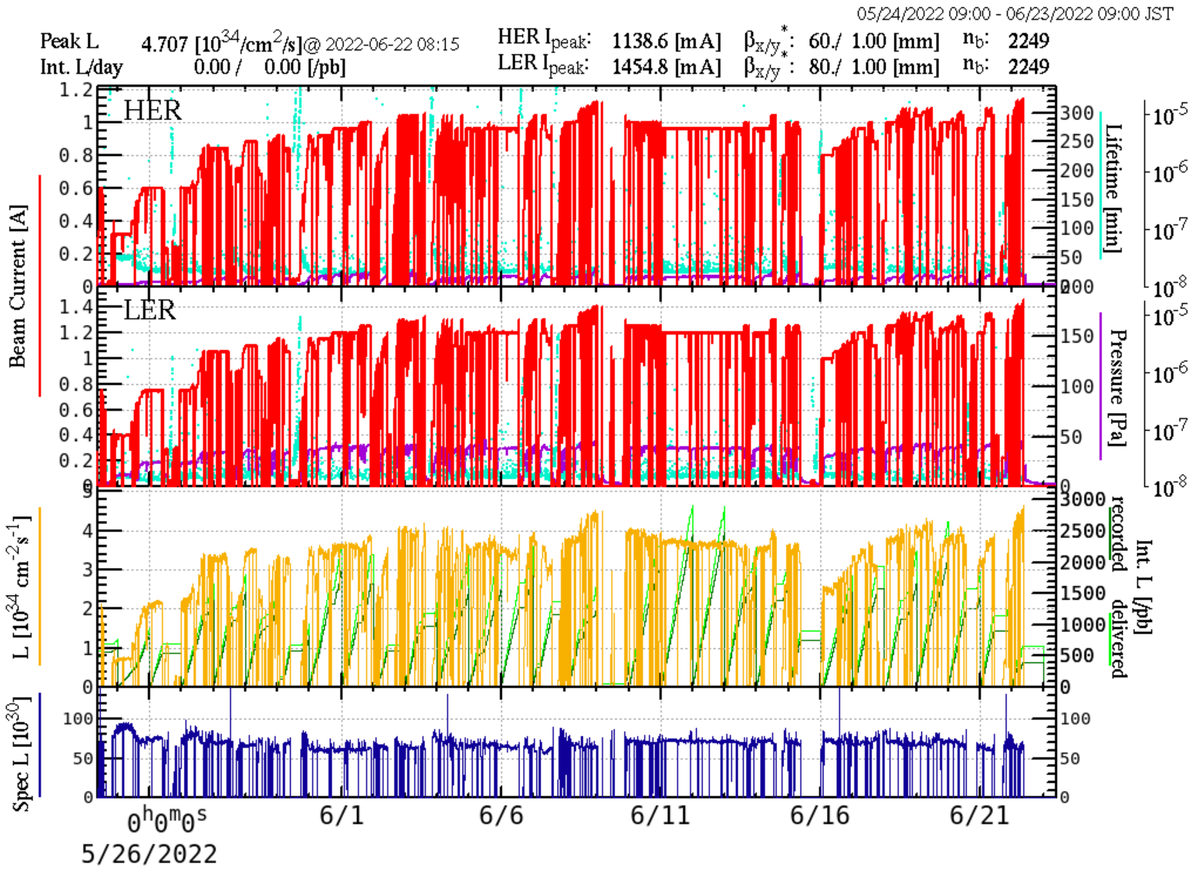
10th meeting of beam-beam workgroup, Jun. 30, 2022, KEK

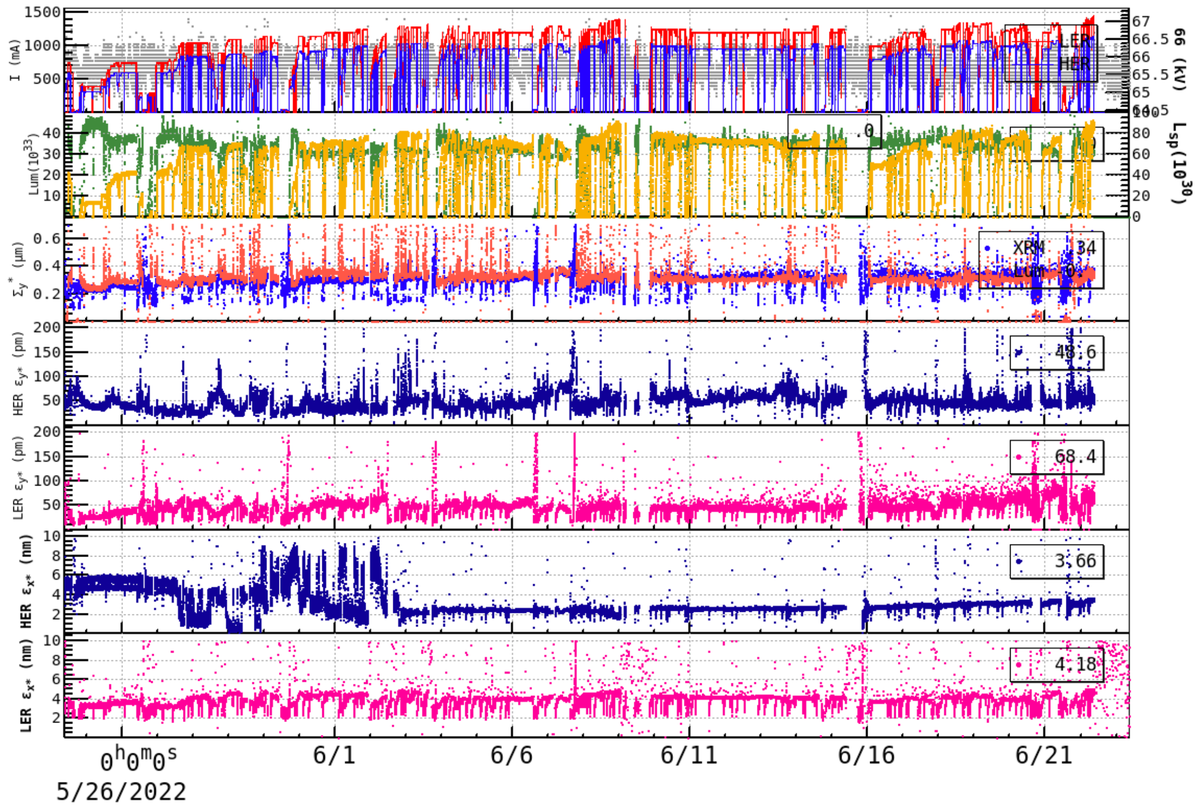
Outline

- Recent machine status
- Identified issues limiting luminosity performance
- Updates on beam-beam simulations

Recent machine status

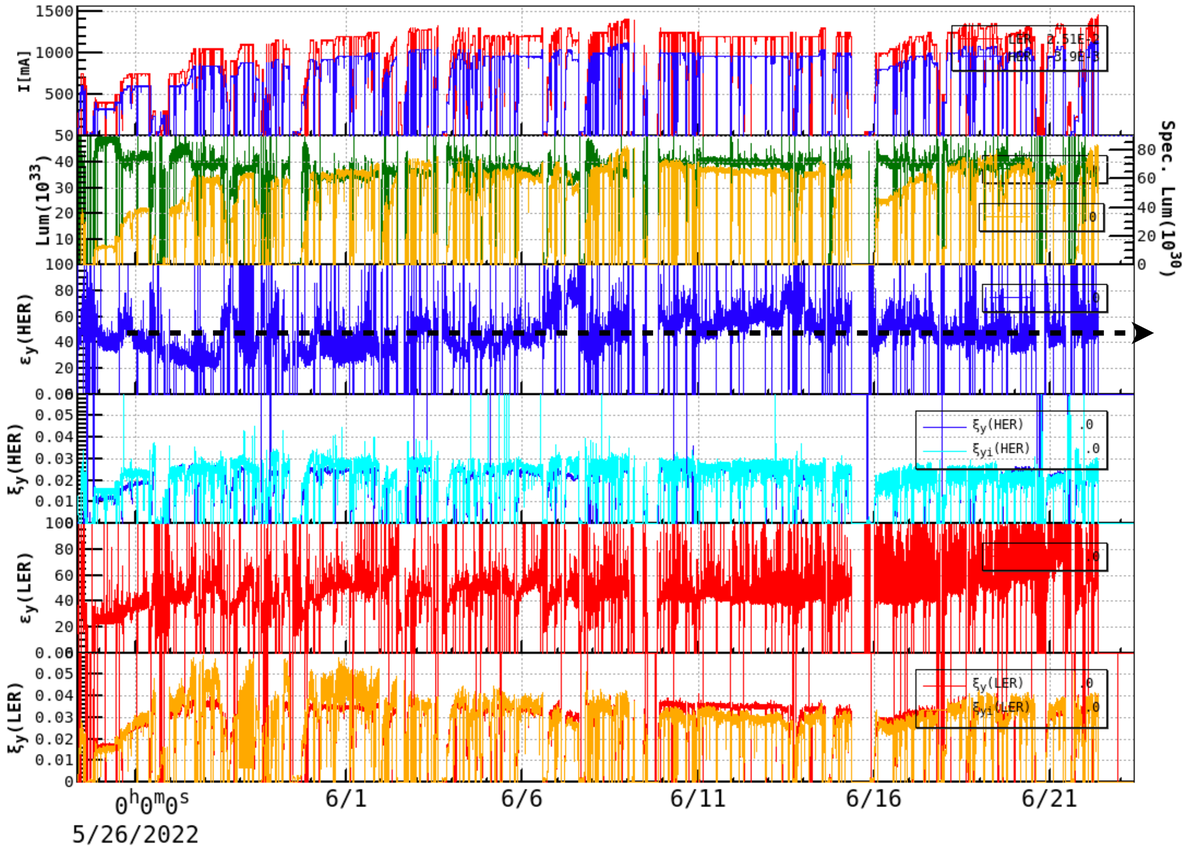
- 30 days of machine status
  - Luminosity record: 4.707e34 $cm^{-2}s^{-1}$.

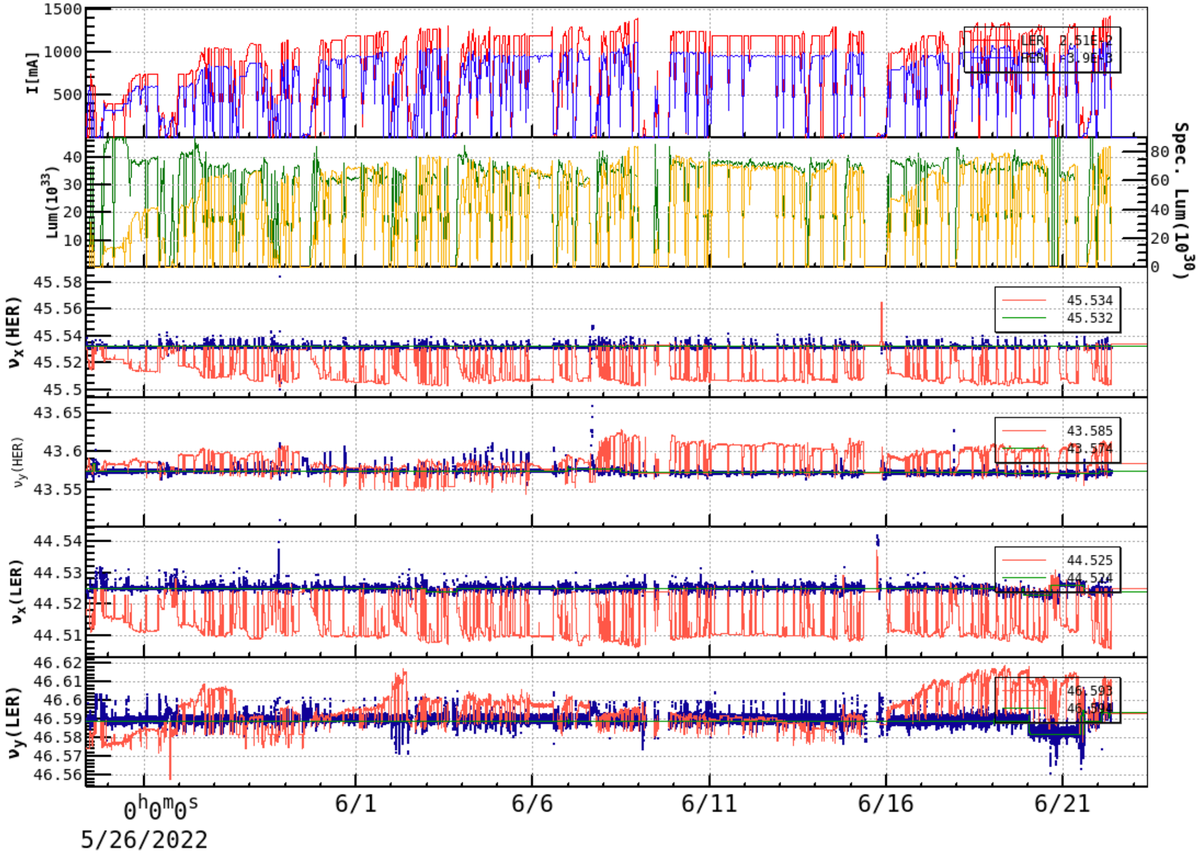




Recent machine status

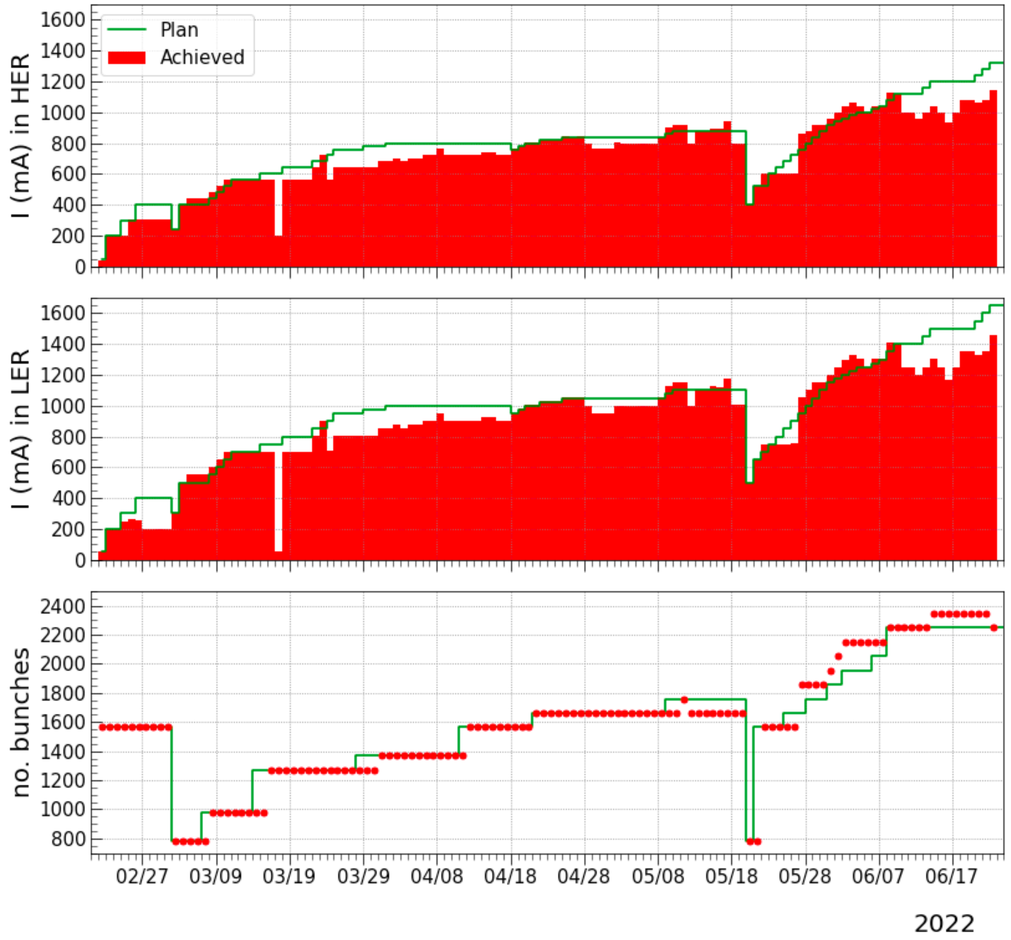
- 30 days of machine status
  - In addition to beam-beam effects, other factors affected machine performance: SR-heading induced optics distortion; Impedance effects (damaged collimators) in LER; Long-term (~1 week) stability of optics; Total currents limited by fast beam losses; …

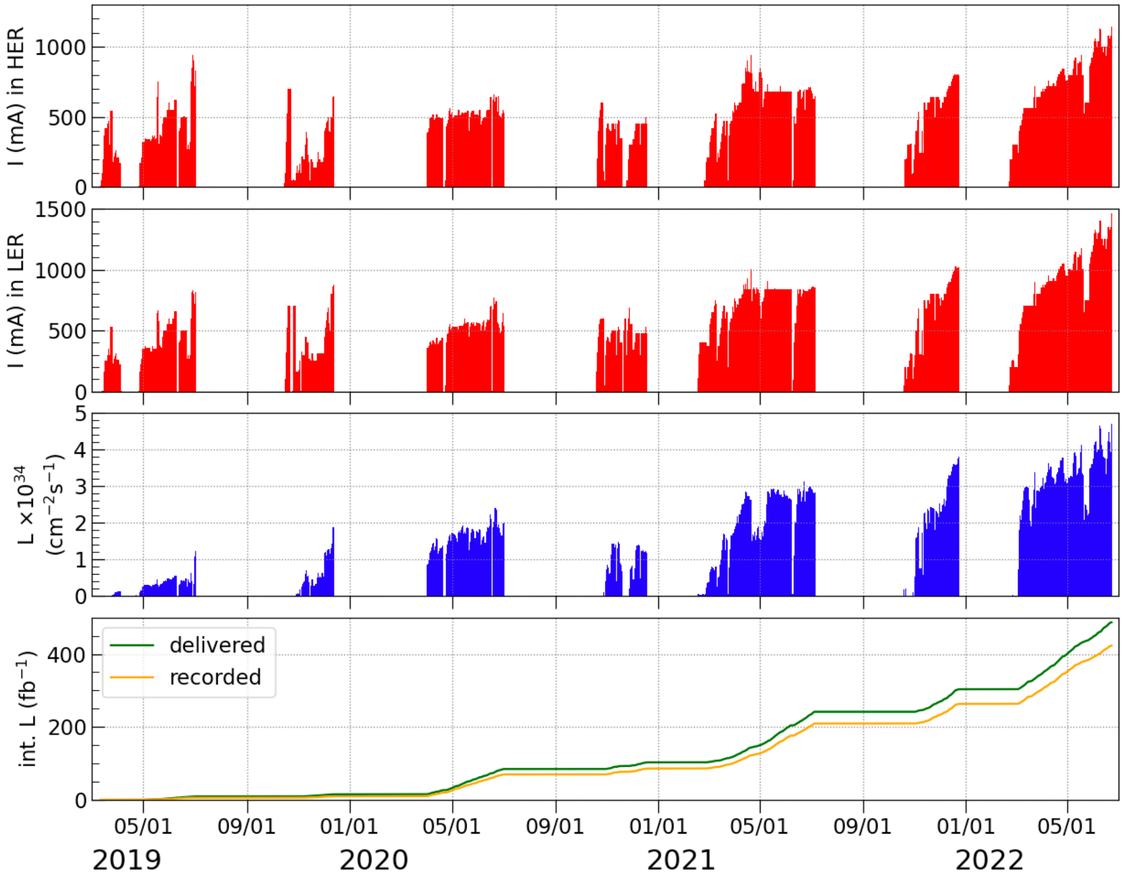




Recent machine status

- Beam currents and luminosity history [1]
  - Achievements in 2022ab run: Maximum bunches stored: 2346; Maximum beam currents: 1.46/1.14 A.





[1] Y. Ohnishi, https://www-linac.kek.jp/skekb/status/web/status_plan.md.html

Recent machine status

- Luminosity records [1]

- Peak luminosity 4.65 x10^{34} ($cm^{-2}s^{-1}$), June 8, swing, 2022
- Belle II HV ON

parameter	LER	HER	unit
Beam current	1321	1099	mA
Number of bunches	2249		
Bunch current	0.587	0.489	mA
Beam-Beam parameter ξ_y	0.0407	0.0279	
Σ_y^*	0.303		μm
σ_y^*	0.215		μm
Tunes (x/y)	44.525 / 46.589	45.532 / 43.573	
Specific luminosity (x10^{31})	7.21		$cm^{-2}s^{-1}/mA^2$
Luminosity (x10^{34})	4.65		$cm^{-2}s^{-1}$

- Peak luminosity 4.71 x10^{34} ($cm^{-2}s^{-1}$), June 22, day, 2022
- Belle II HV OFF

parameter	LER	HER	unit
Beam current	1363	1118	mA
Number of bunches	2249		
Bunch current	0.606	0.497	mA
Beam-Beam parameter ξ_y	0.0398	0.0278	
Σ_y^*	0.315		μm
σ_y^*	0.223		μm
Tunes (x/y)	44.524 / 46.594	45.532 / 43.574	
Specific luminosity (x10^{31})	6.95		$cm^{-2}s^{-1}/mA^2$
Luminosity (x10^{34})	4.71		$cm^{-2}s^{-1}$

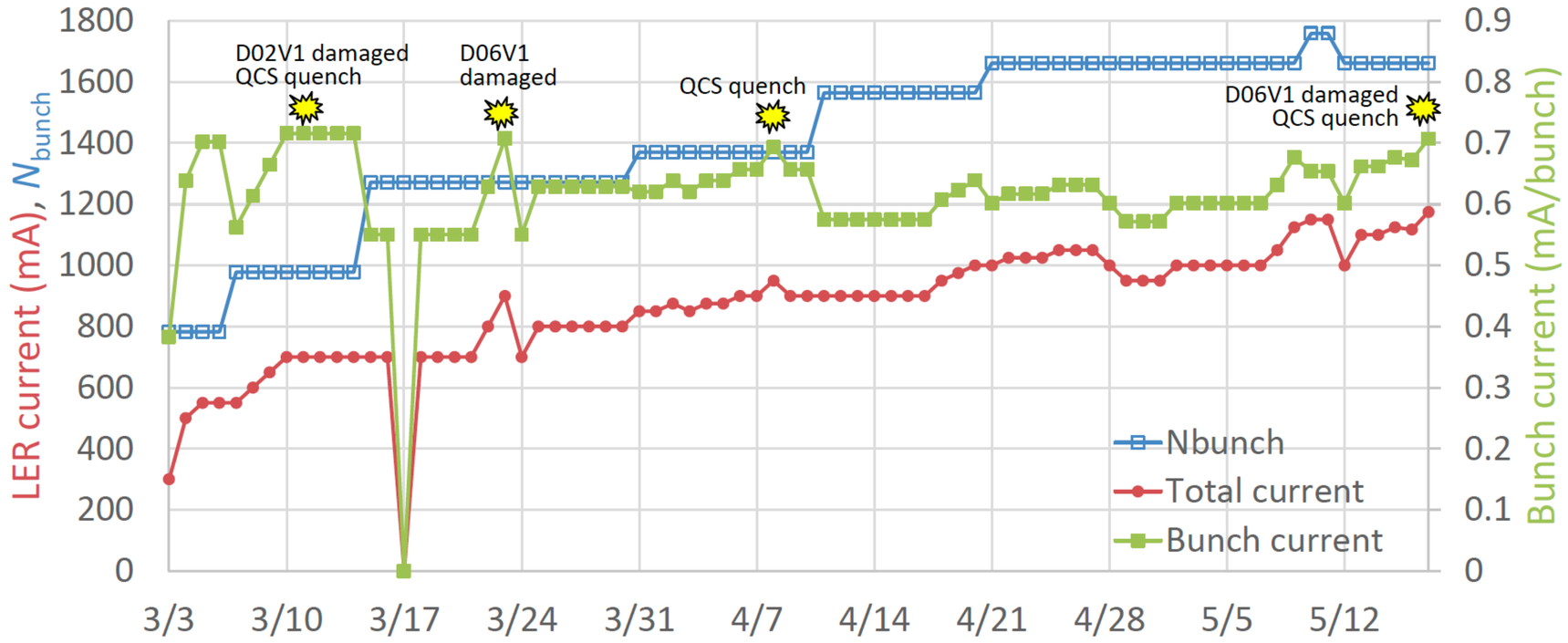
[1] Y. Ohnishi, https://www-linac.kek.jp/skekb/status/web/status_plan.md.html

Issues identified: Limit of bunch current $I_{b+} \lesssim 0.7$ mA in physics run mode

- Severe machine failures happened when $I_{b+} > 0.7$ mA during the physics run

Courtesy of K. Matsuoka

Beam loss accidents and bunch current

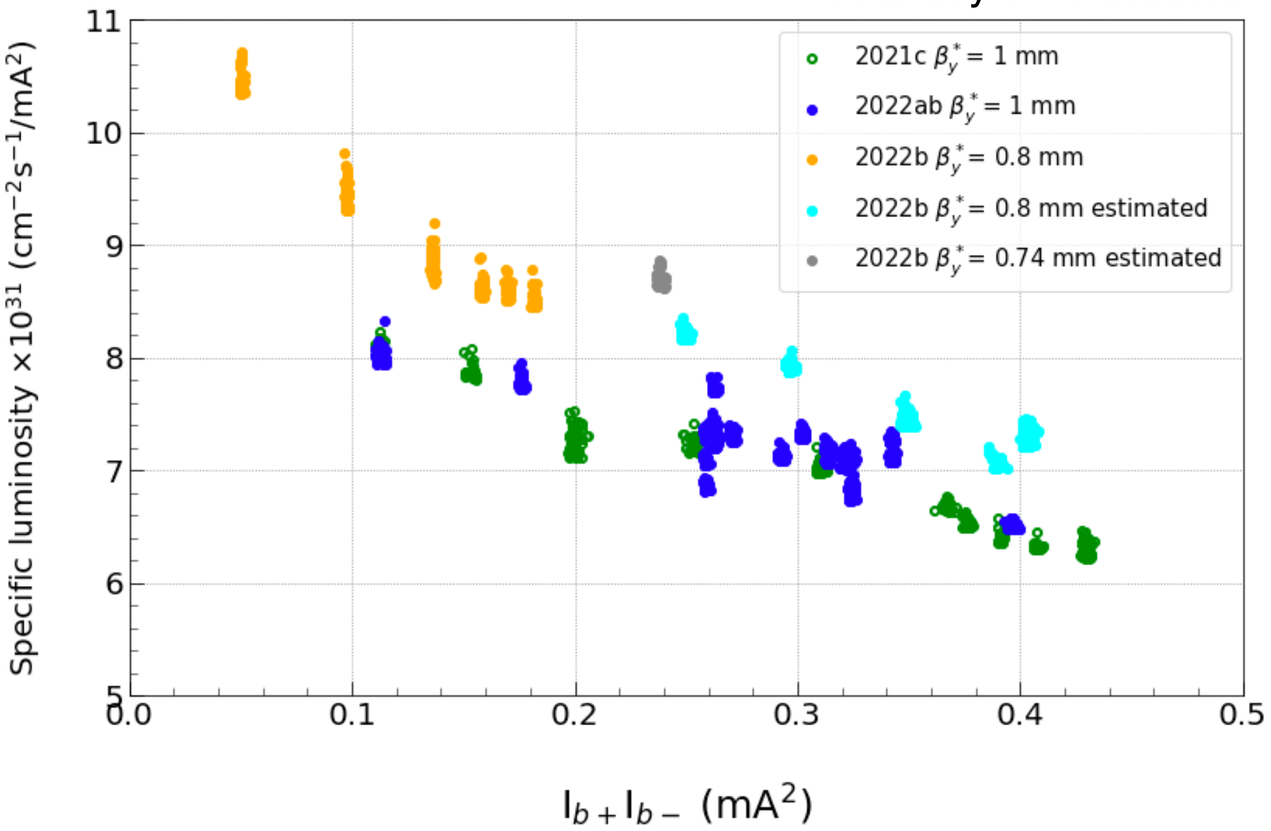


The three big accidents of LER beam loss in 2022 happened at $I_b \gtrsim 0.7$ mA/bunch within a day after increasing the beam current at the three different N_{bunch}.

Issues identified: Optics distortion by SR heating

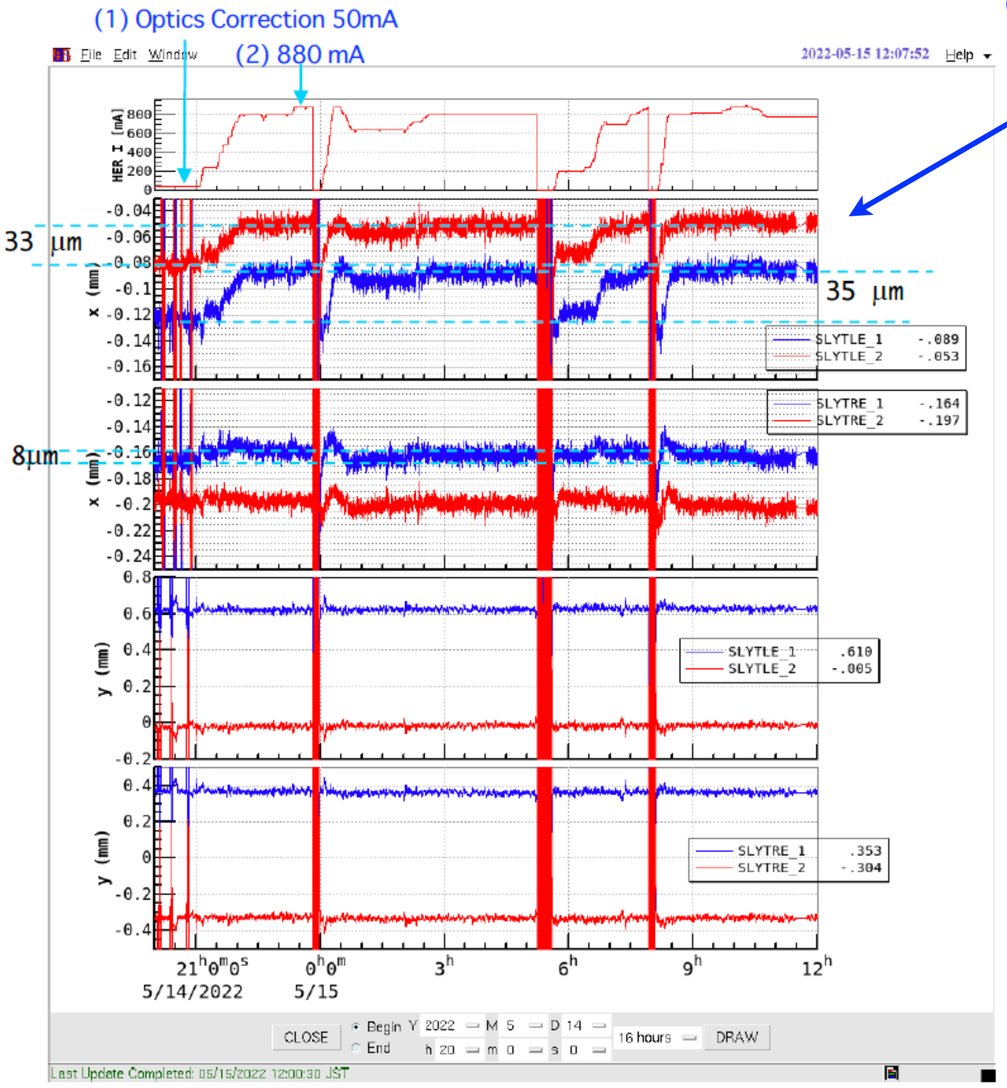
- Current-dependent optics distortion
  - SR heating causes orbit distortion.
  - Beta-beat and global coupling get worse at high currents.
  - An unexpected β_y^* squeeze explains the Lsp gain.

Courtesy of Y. Ohnishi



Issues identified: Optics distortion by SR heating

- Current-dependent orbit offsets at SLY* magnets



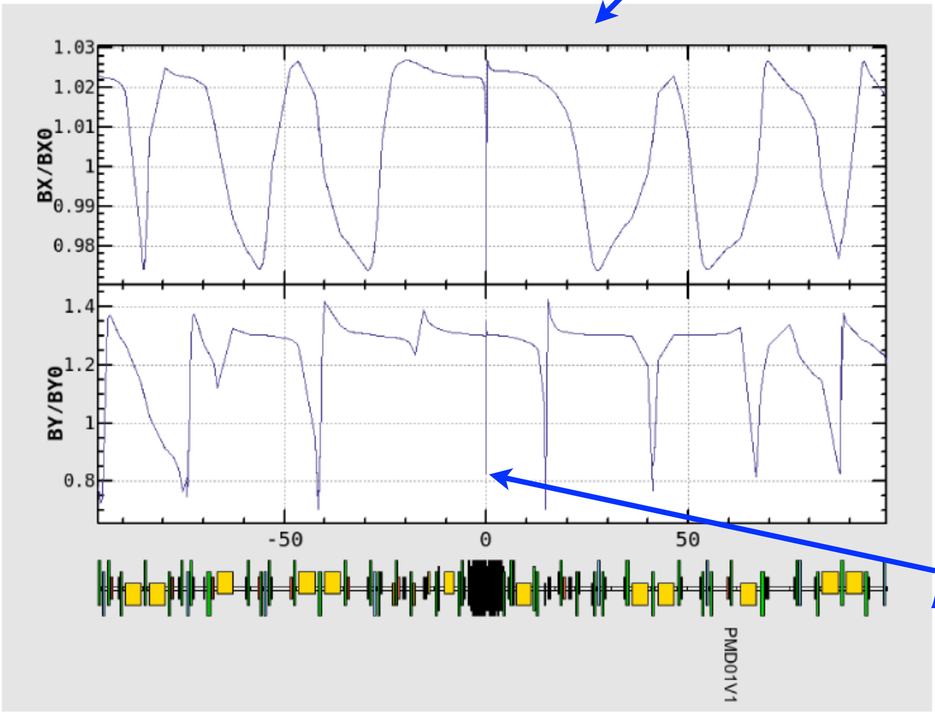
Observed offsets

Courtesy of H. Koiso

SLYが以下のように水平方向にずれたときの
beta beat 推定値

SLYTRE1	-8 μm
SLYTRE2	0
SLYTLE1	-35 μm
SLYTLE2	-33 μm

Resulting beta-beat (SAD simulation)

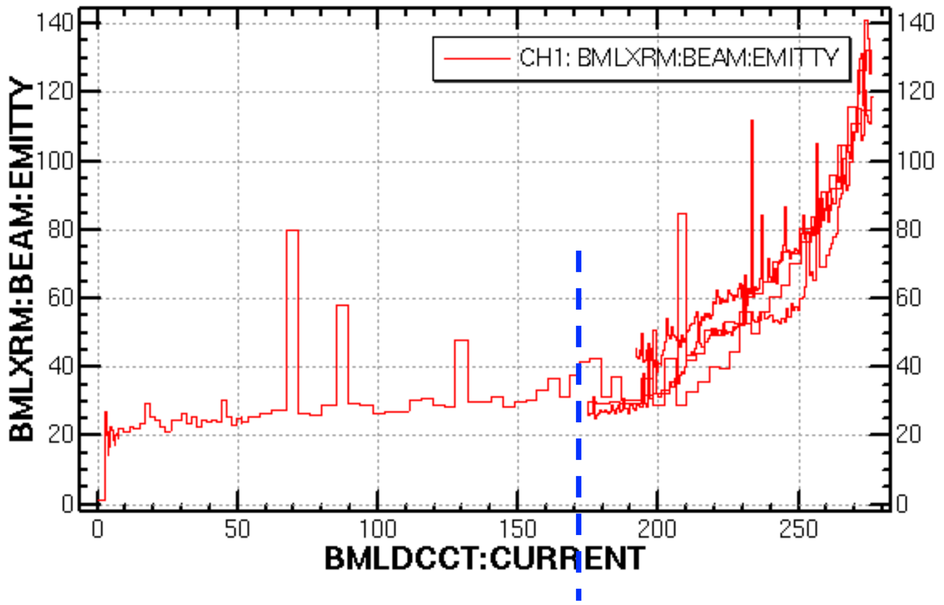


β_y^* **squeezed**

Issues identified: Impedance effects in LER

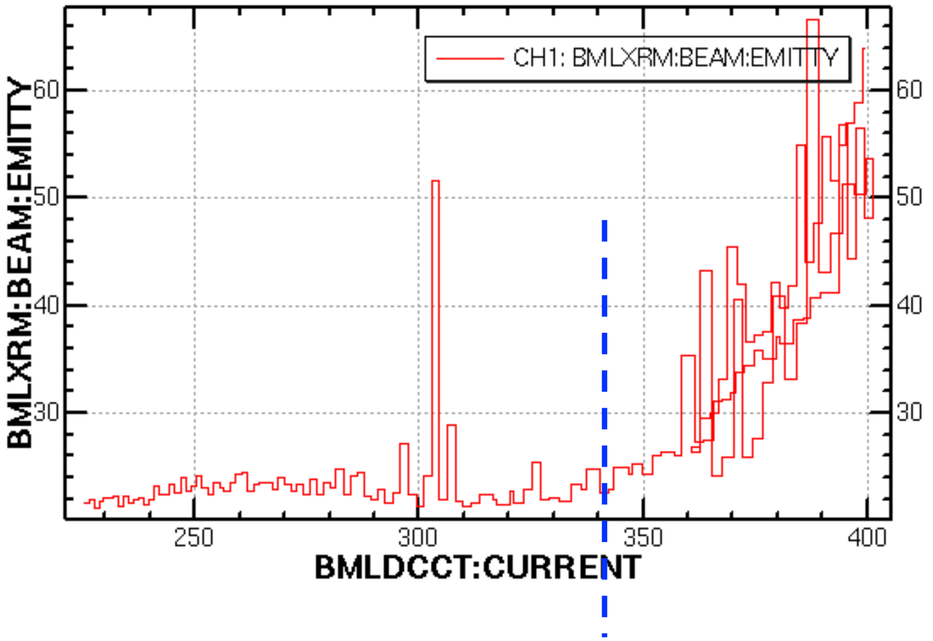
- Current-dependent single-beam blowup in LER
  - This problem was solved by fine-tuning of FB system in Mar. 2022. But it appeared again, mainly due to new damages to collimators (D06V1 and D02V1).
  - On Jun. 21, 2022, tunings were done to improve the blowup threshold: Vertical tune ν_y .582 → .595; Gap of D06V1: TOP 4.2 mm, BTM -5.1 → -8.0 mm.

Machine conditions:
Single-beam, 393 bunches



Threshold <0.5mA/bunch

KCG shift report on LER vertical blowup study
By S. Terui, T. Ishibashi, K. Yoshihara, M. Nishiwaki
Jun. 21, 2022



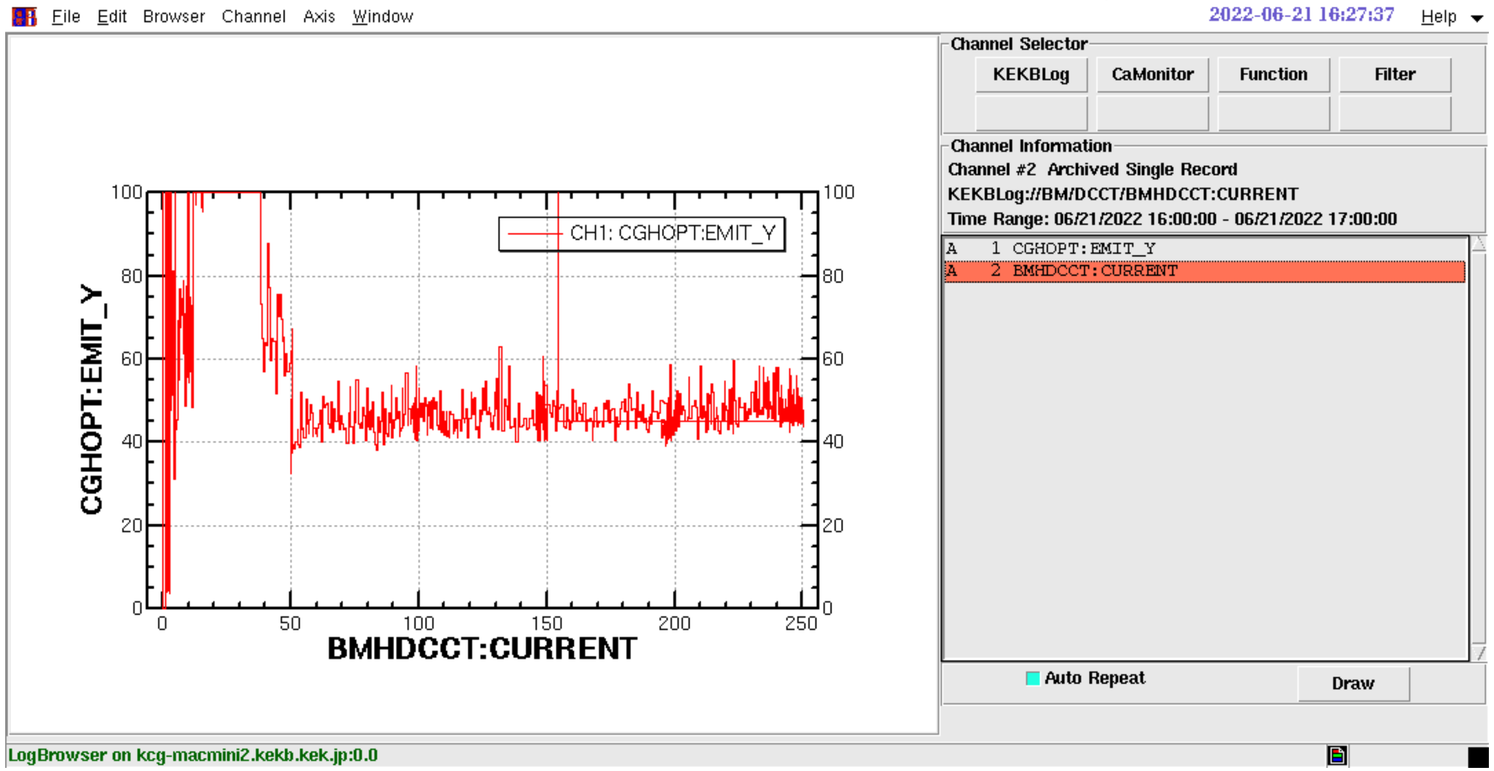
After tunings ~0.87mA/bunch

Issues identified: Impedance effects in HER

- Current-dependent single-beam vertical emittance in HER
  - No clear evidence of single-beam blowup (up to 0.64 mA/bunch) in HER

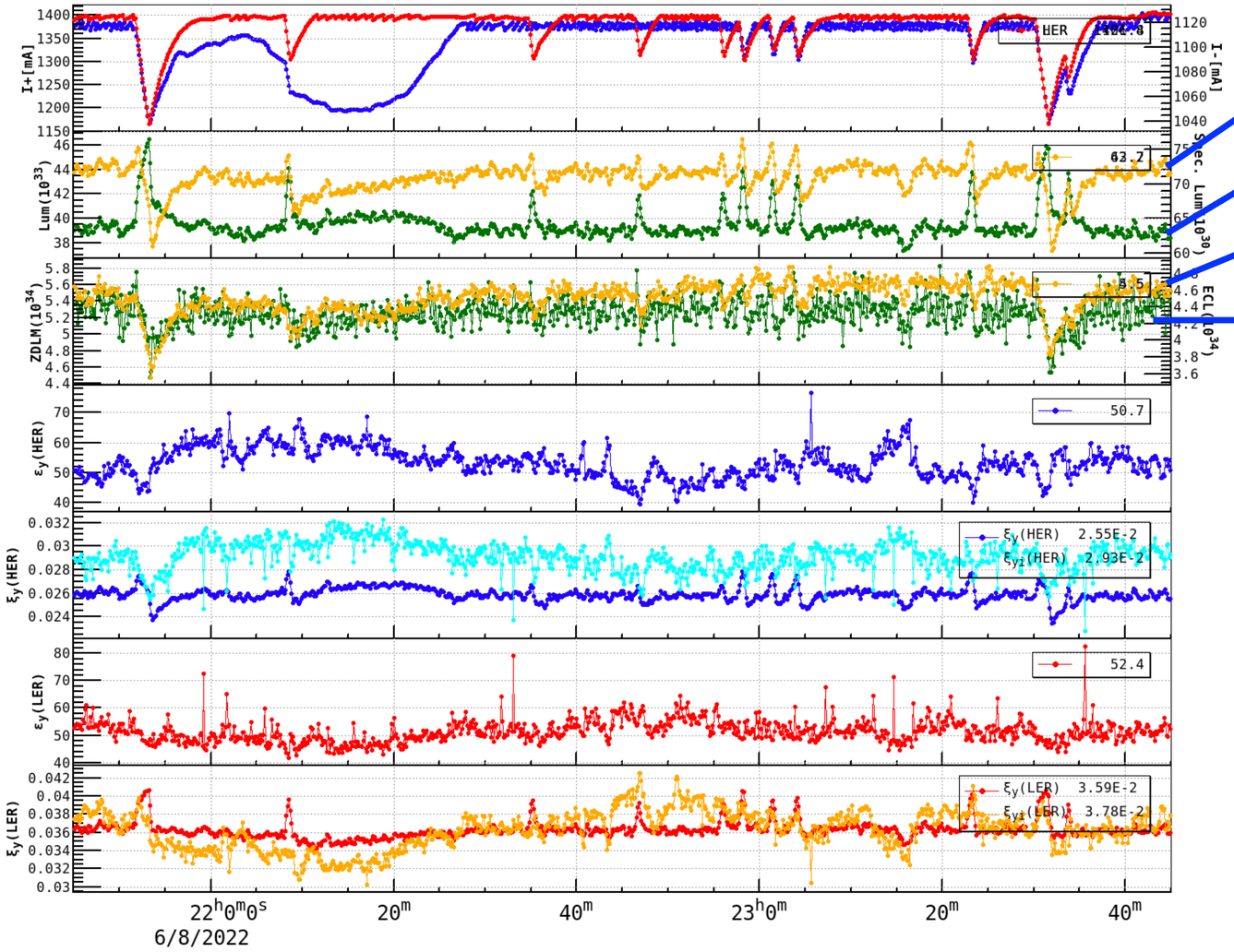
Machine conditions:
Single-beam, 393 bunches

KCG shift report on high bunch-current collision study
By D. Zhou, R. Ueki, M. Nishiwaki
Jun. 21, 2022



Issues identified: Lsp-Injection correlation

- The injection was intentionally stopped to achieve the new record of 4.65e34 luminosity with Belle II HV ON (Jun. 8, 2022).



Yellow: Total luminosity ECL (20-second average)

Green: Specific luminosity (Lsp)

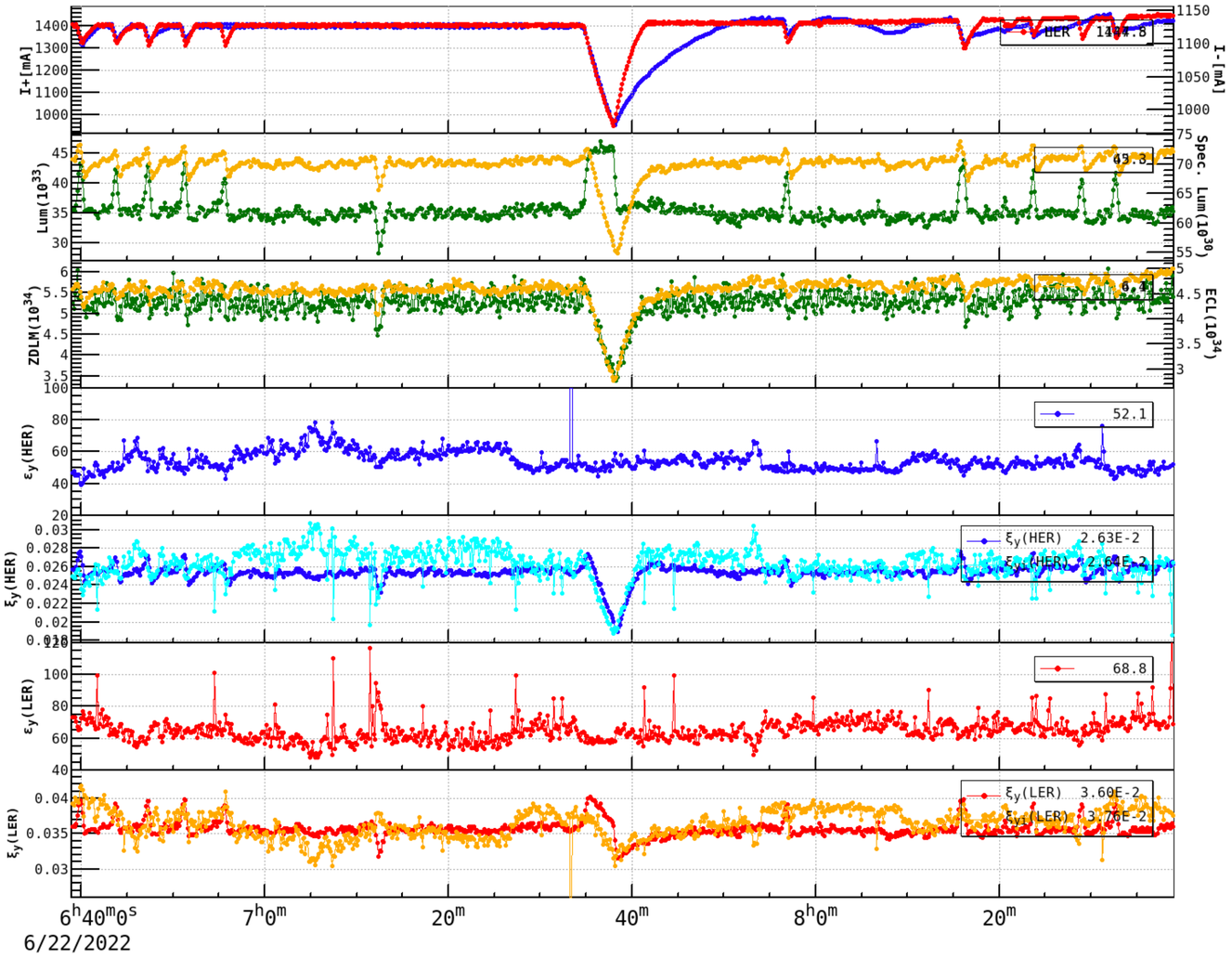
Yellow: Total luminosity ZDLM

Green: Total luminosity ECL (updated per 2.5 second)

* Peak luminosity always appears after injection stopped
* Lsp always jump up after injection stopped

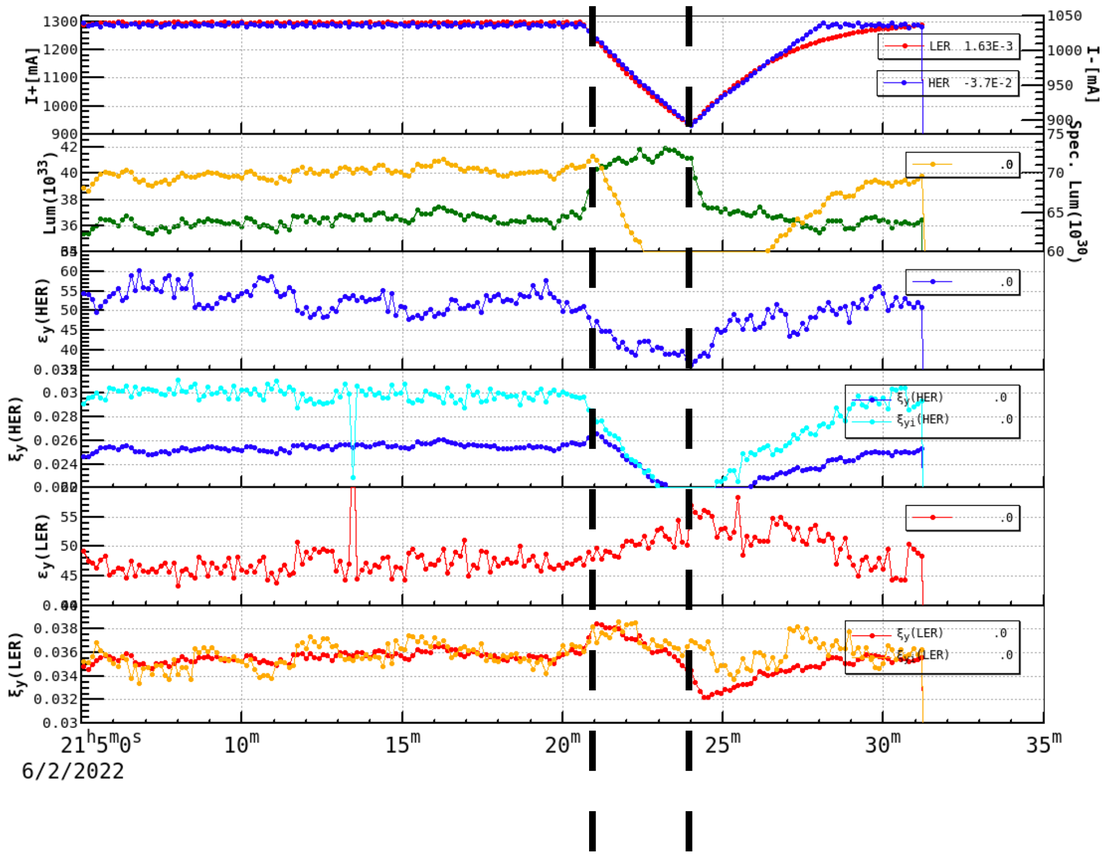
Issues identified: Lsp-Injection correlation

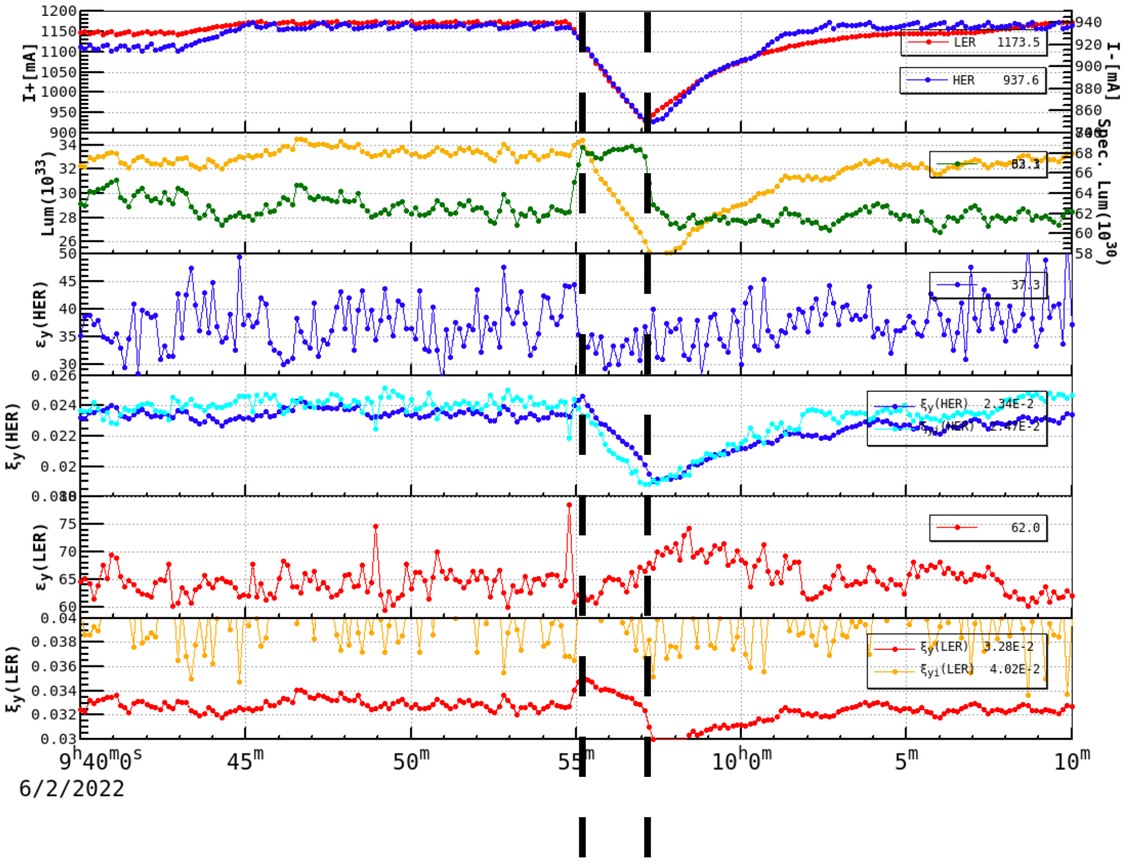
- The injection was intentionally stopped to achieve the new record of 4.71e34 luminosity with Belle II HV OFF (Jun. 22, 2022).



Issues identified: Lsp-Injection correlation

- Analysis of KBlog data shows this phenomenon has been there since Phase-2
  - Lsp degradation (in the order of 10%) due to injection has been clearly observed.
  - A sudden increase of Lsp causes a local peak luminosity. This is why we frequently saw the best luminosity just after injection stopped.

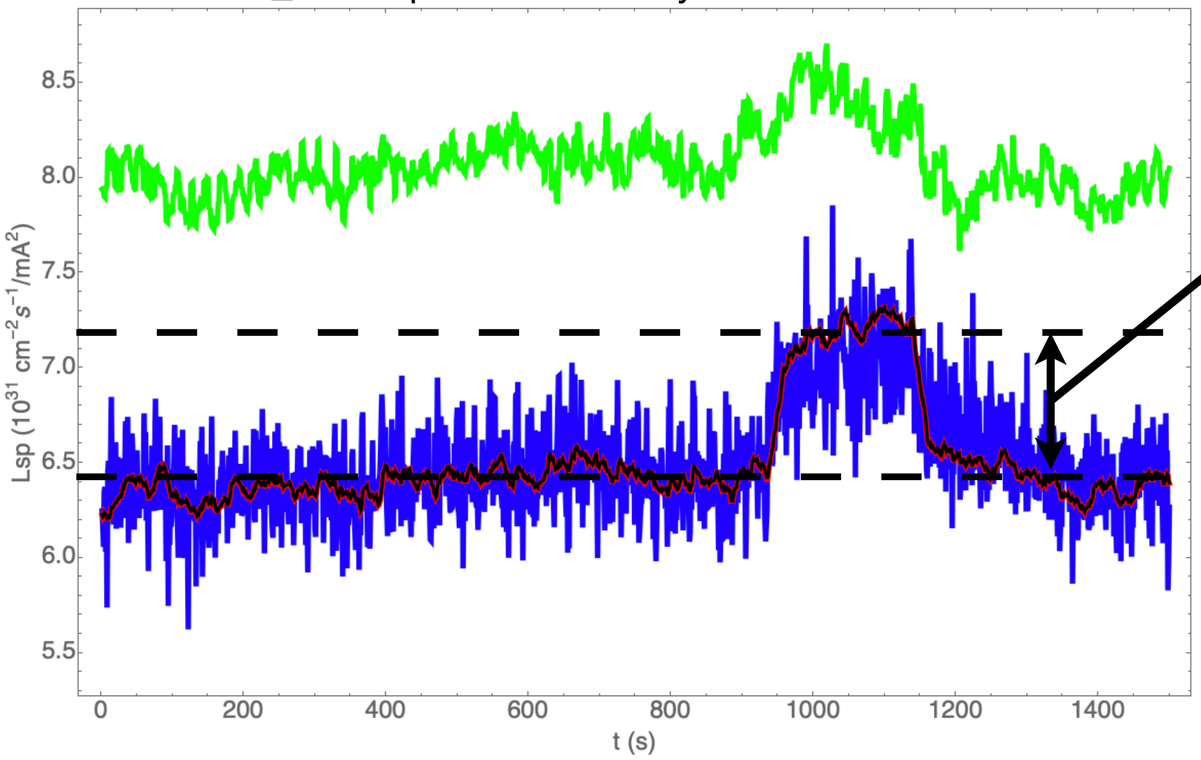




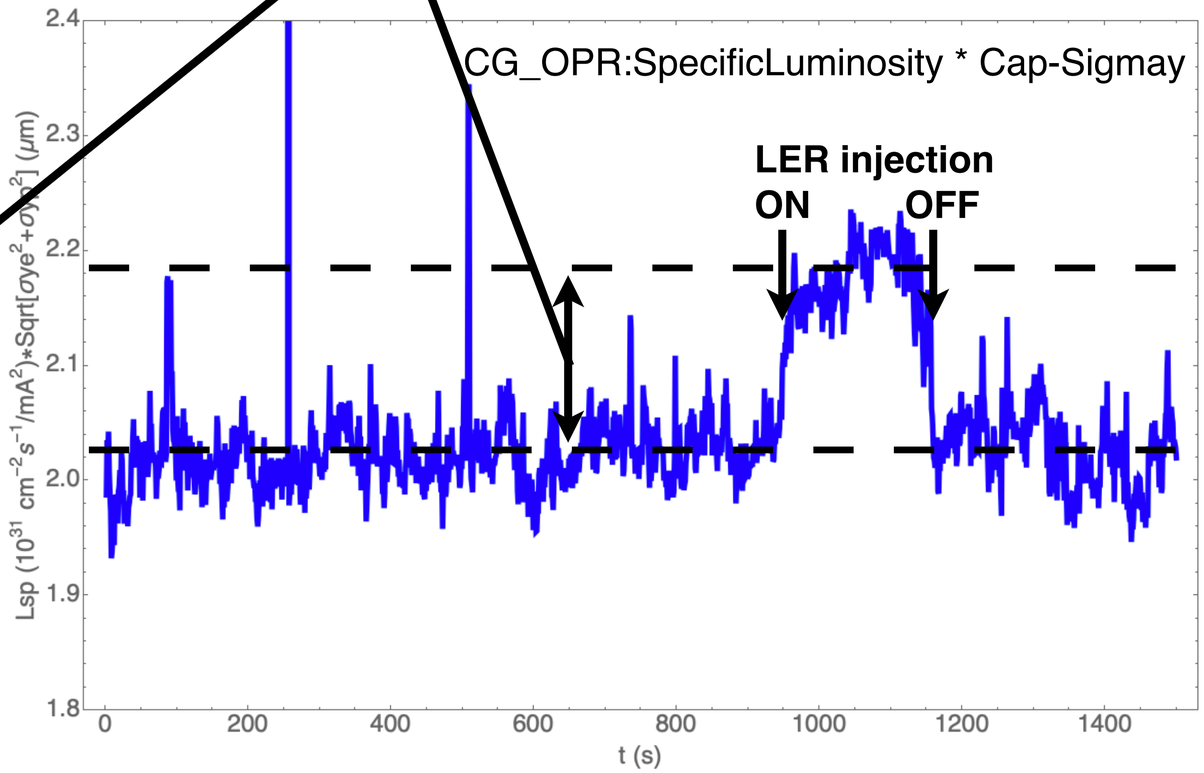
Issues identified: Lsp-Injection correlation

- The phenomenon: 2022-06-02 21:05 PM
  - All luminosity PVs gave a similar jump-response to injection stop/start.
  - $L_{sp} \cdot \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}$ still shows jump-response. It means there is a geometric loss of luminosity.

Blue: B2_nsm:get:ECL_LUM_MON:lum_acc_corrected
Red: B2_nsm:get:ECL_LUM_MON:lum_acc_20
Green: B2_nsm:get:MONZDLMINT:ZDLM_INTVAL:value
Black: CG_OPR:SpecificLuminosity



Lsp degradation by ~10%, independent to vertical emittances

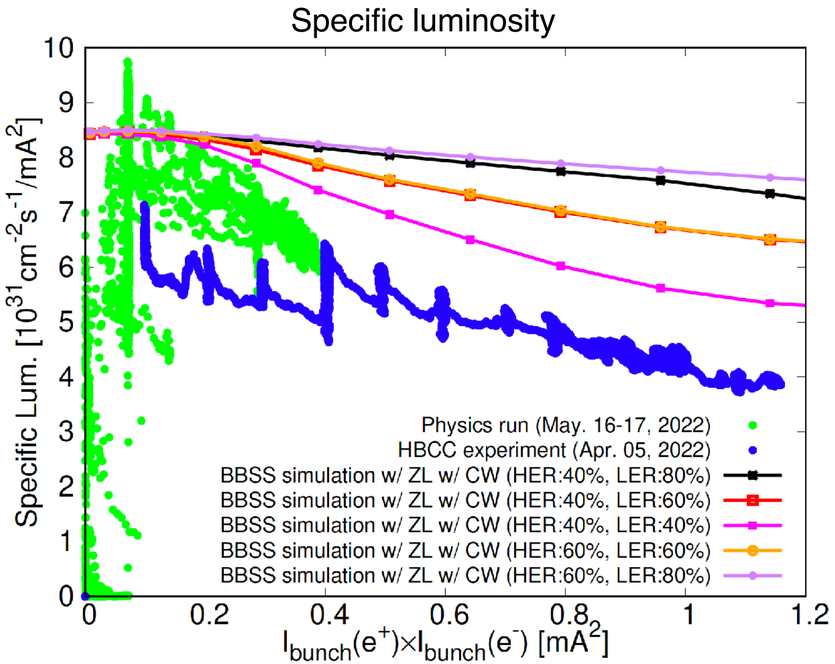


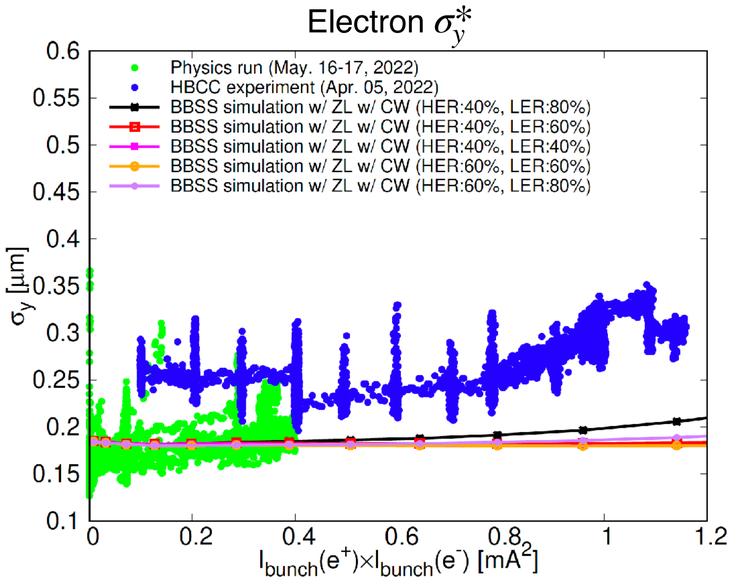
Issues identified: Lsp-Injection correlation

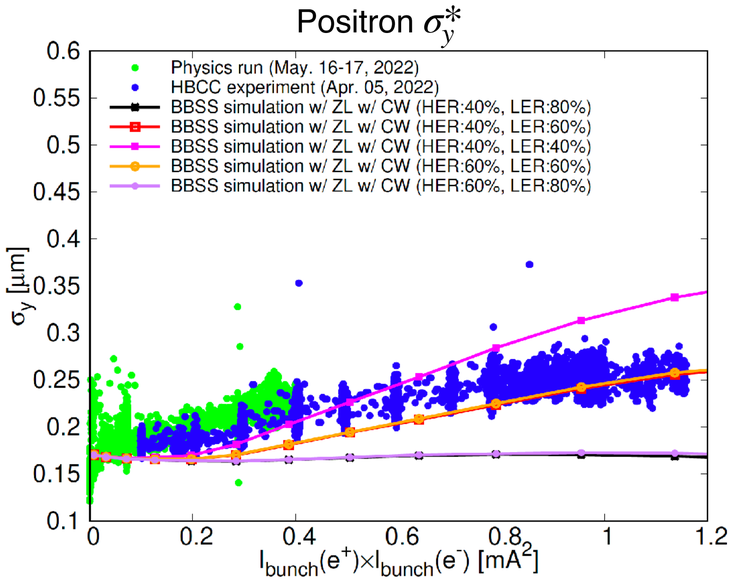
- Investigations are ongoing to understand the sources of Luminosity-Injection correlation
  - LER injection kickers: excite the stored beam and cause luminosity loss. But BxB FB system damps the dipole motion of the excited beam in <200 turns (~2 ms). It's not clear if the injection kickers cause emittance blowup (quadrupole motion) or not.
  - Injection background: It is suspected to affect luminosity measurement. Investigations are ongoing to check this possibility.

Updates on understanding the luminosity performance

- Known sources of luminosity degradation
  - Bunch lengthening; Chromatic couplings; Single-beam blowup in LER (Impedance effects and its interplay with FB); Optics distortion due to SR heating; Luminosity “loss” correlated with injection.
- Sources to be investigated
  - Imperfect crab waist; Beam-beam driven incoherent synchrotron resonances; Interplay of BB, longitudinal and transverse impedances, and feedback system; Interplay of BB and nonlinear lattices; Coupled bunch instabilities.
- For further details, refer to IPAC2022 papers by Y. Funakoshi et al. (MOPLXGD1); D. Zhou et al. (WEPOPT064); M. Masuzawa et al. (TUOZSP2); S. Terui et al. (WEPOTK050).



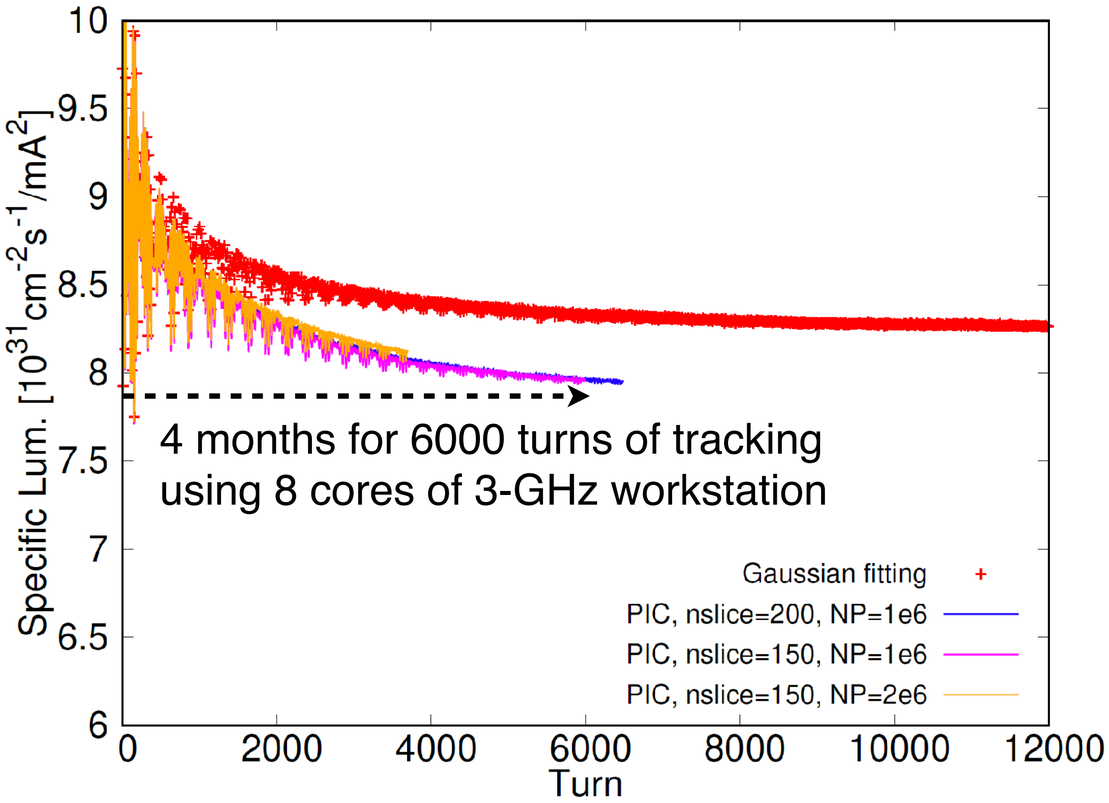




Beam-beam simulations

- BBSS simulations: PIC vs. Gaussian fitting model
  - PIC method predicts lower luminosity (to be verified).
  - One PIC simulation requires ~8 months, and a Gaussian-fitting simulation takes ~1.2 days…
  - Great progress was achieved recently in developing GPU-based BB codes (by K. Ohmi, in collaboration with Y. Zhang and Z. Li (IHEP)). Tests showed a speed-up factor of ~100 for weak-strong and ~4 for strong-strong BB simulations.

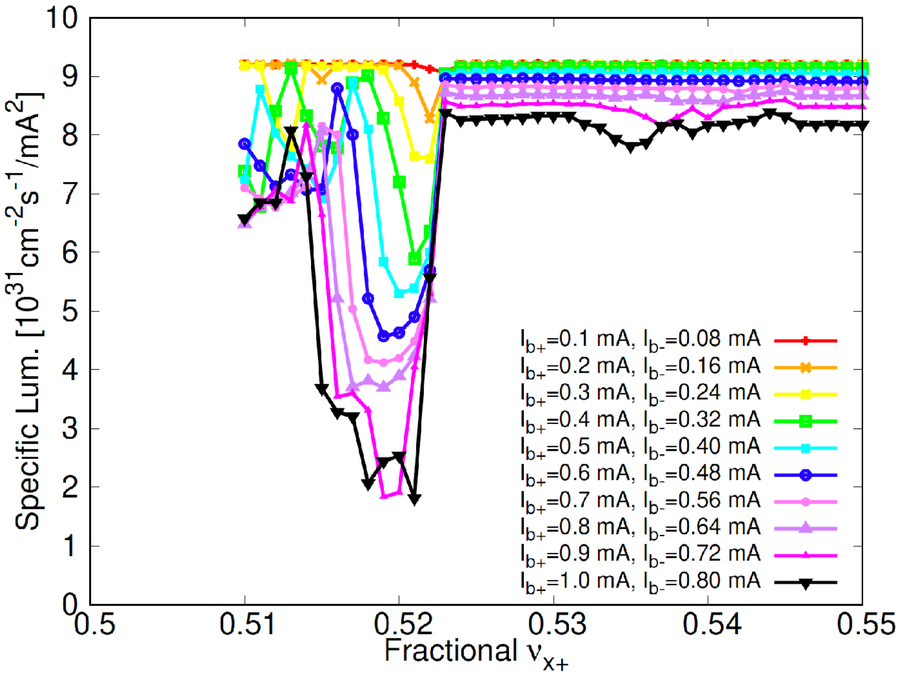
	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	0.8	1.0	
# bunch	-		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	35	20	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured tune 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

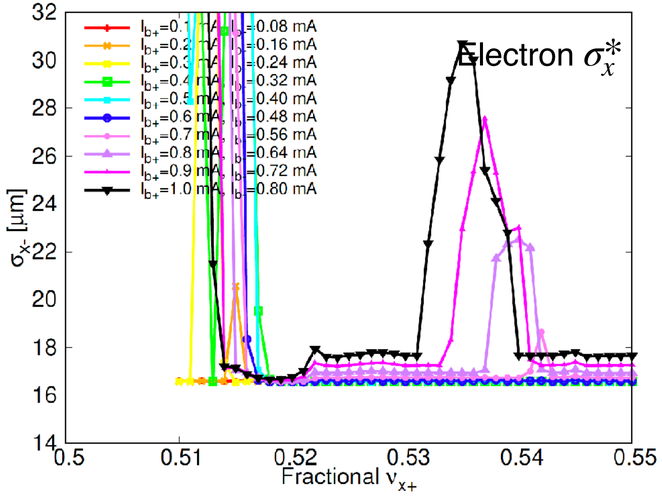


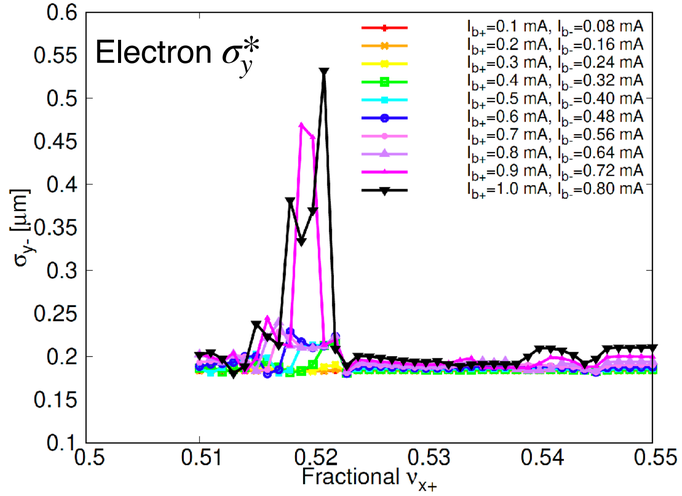
Beam-beam simulations

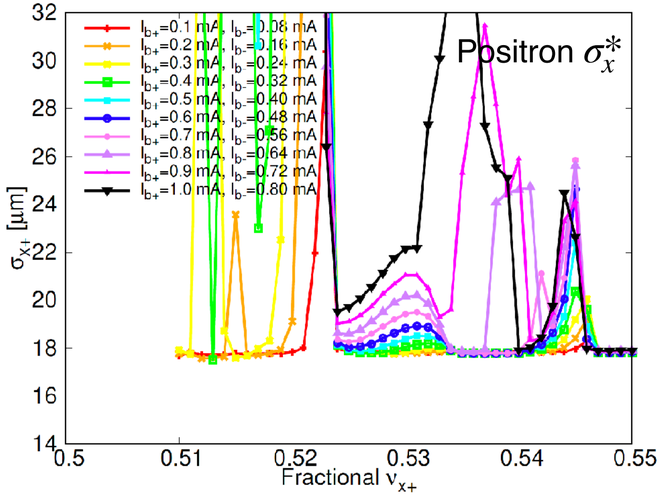
- BBSS simulations: Scan LER ν_x (with LER ν_y and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21)

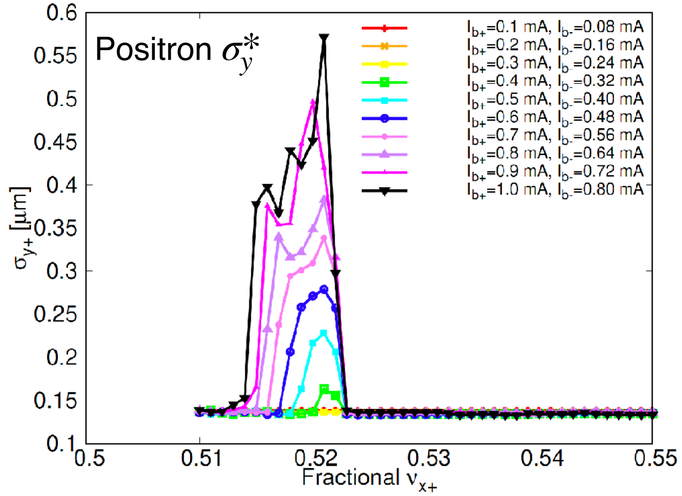
X-Z instability is sensitive to ν_x.







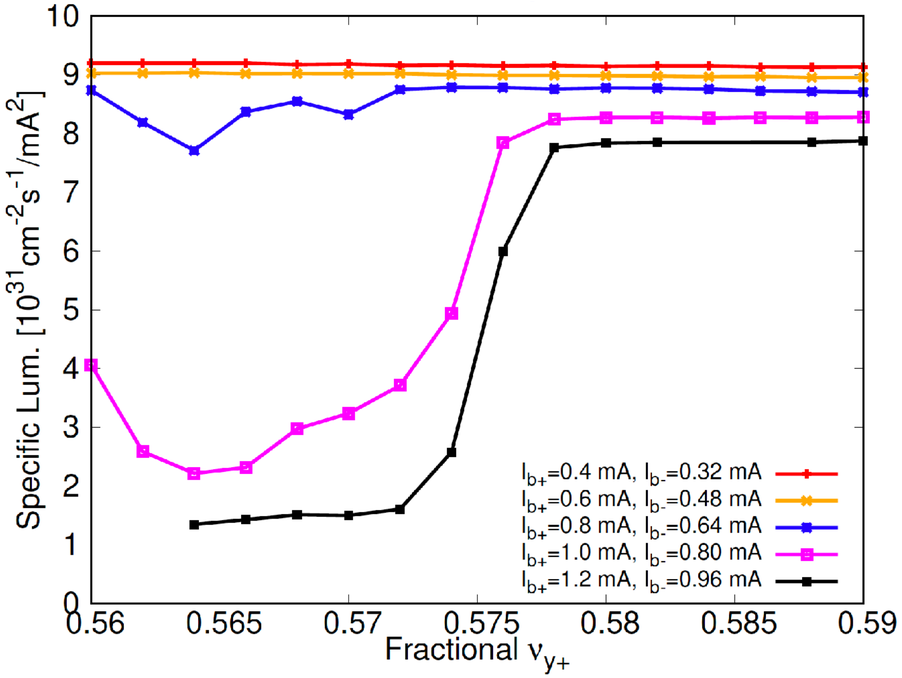


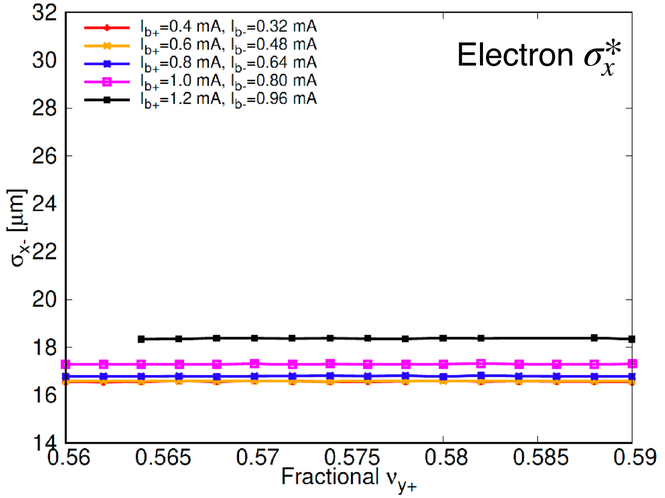


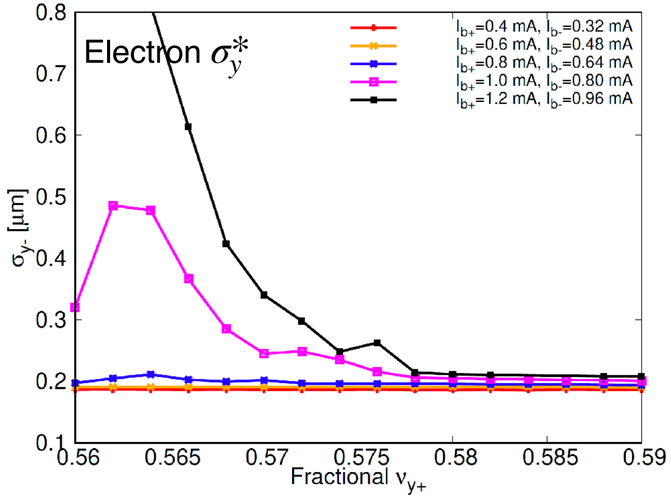
Beam-beam simulations

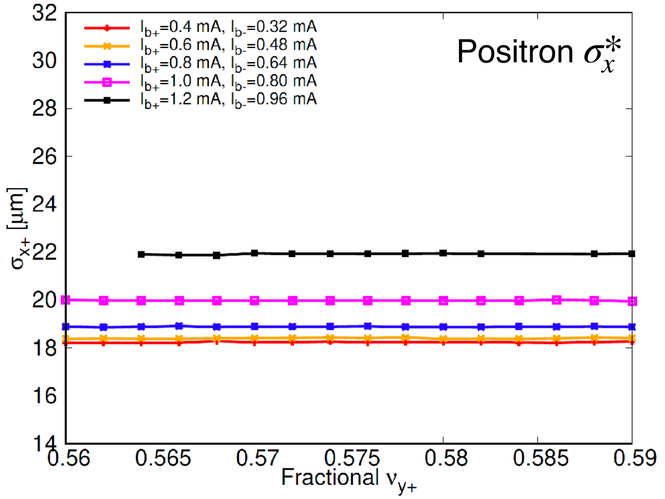
- BBSS simulations: Scan LER ν_y with bunch currents varied (with LER ν_x and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21, BB+Wxy+Wz)

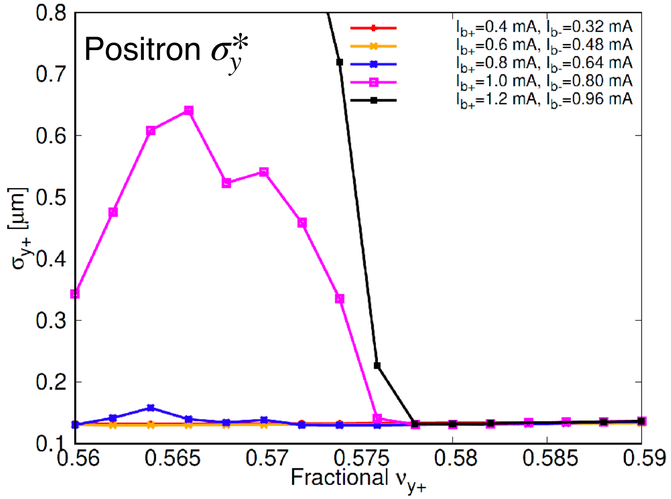
* The interplay of BB+Wxy+Wz causes instability, consistent with Y. Zhang and K. Ohmi's findings.
* This instability has a threshold that is ν_y-dependent.
* This might explain ν_y of LER cannot approach design value .57, which HER has no problem.







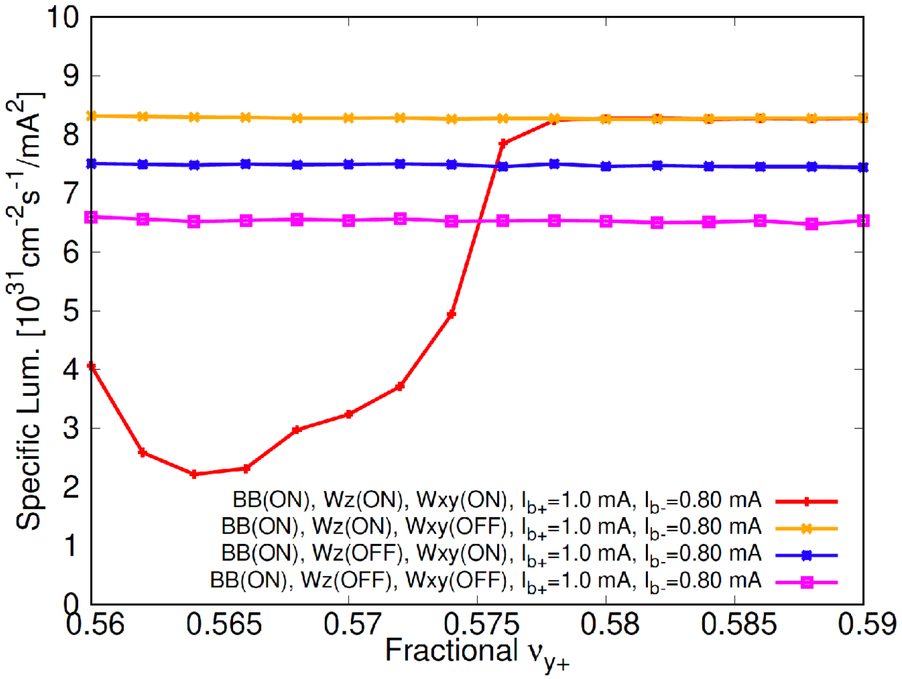


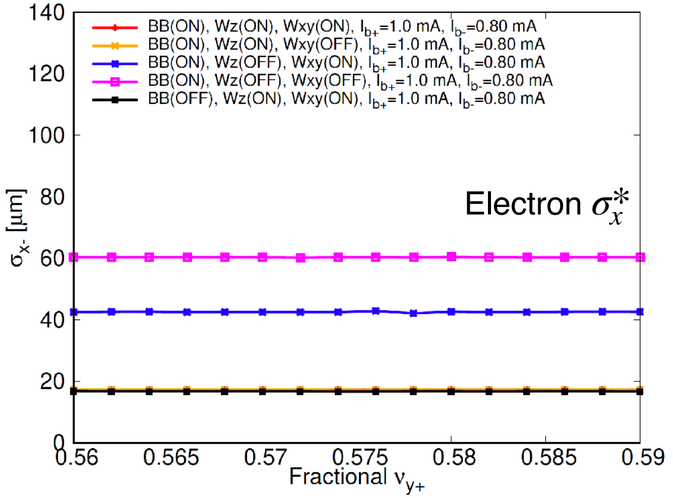


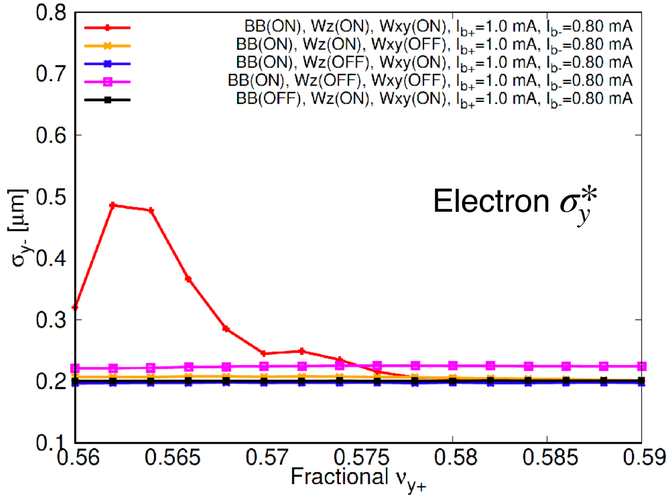
Beam-beam simulations

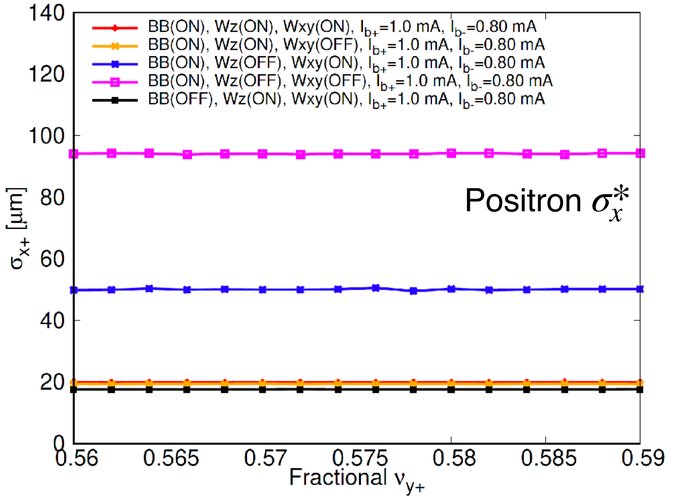
- BBSS simulations: Scan LER ν_y with impedance models varied (with LER ν_x and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21)

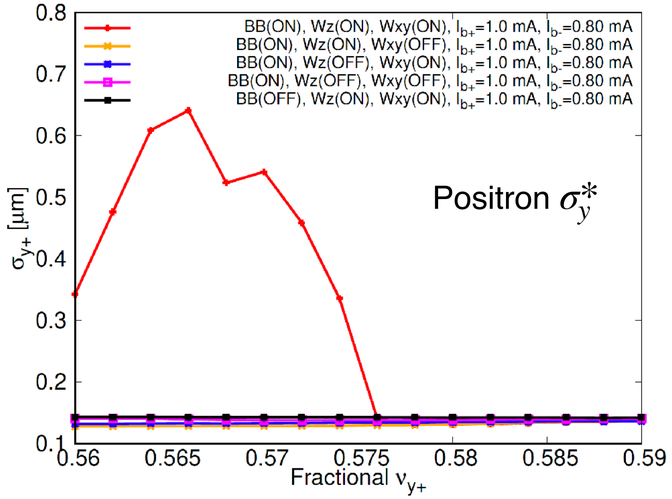
* The vertical instability only appears with BB+Wxy+Wz (physics to be understood).
* With Wz off, X-Z instability appears.











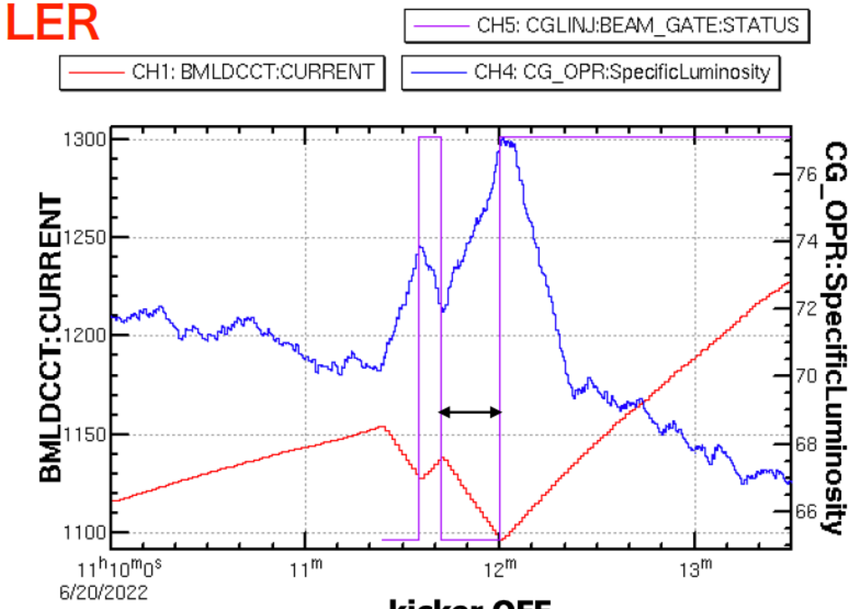
Summary

- A new luminosity record was achieved at the end of 2022b run.
- Some issues limiting luminosity performance: Fast beam losses; Optics distortion caused by SR heating; Single-beam vertical blowup in LER; Lsp-Injection correlation.
- BBSS simulations show vertical instability driven by the interplay of BB+Wxy+Wz (which was discovered by Y. Zhang and K. Ohmi).

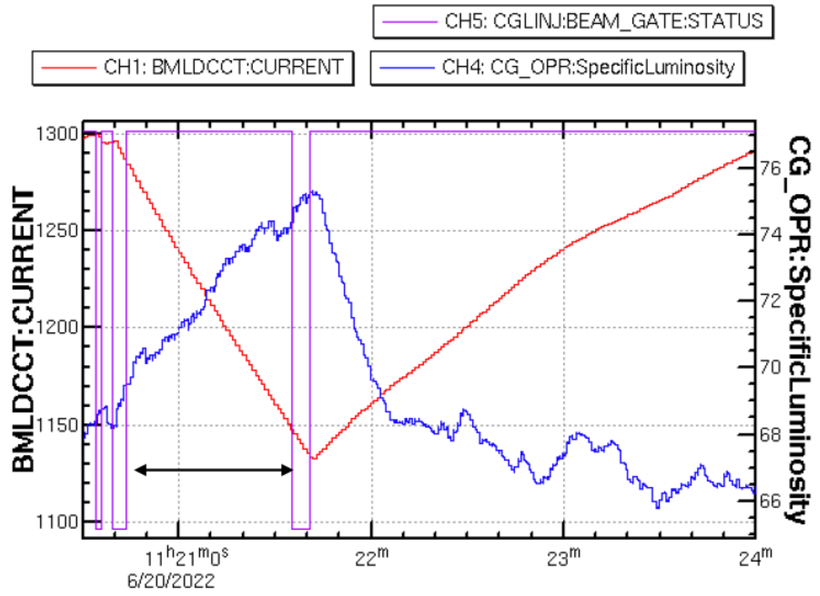
Backup

Y. Ohnishi

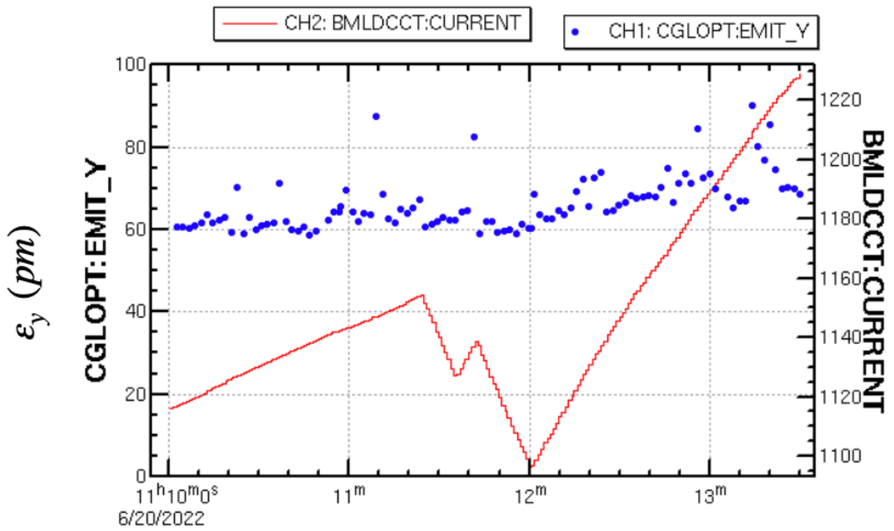
LER



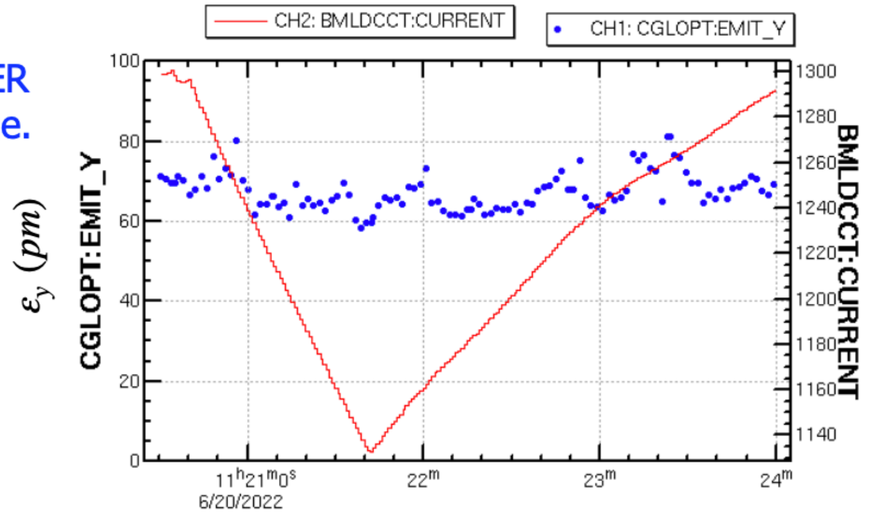
kicker OFF
No injection beam



kicker ON
No injection beam



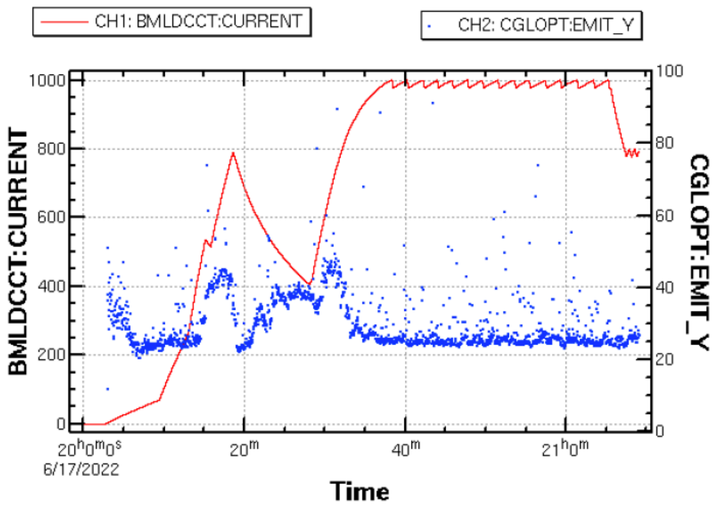
Beam size in LER does not change.



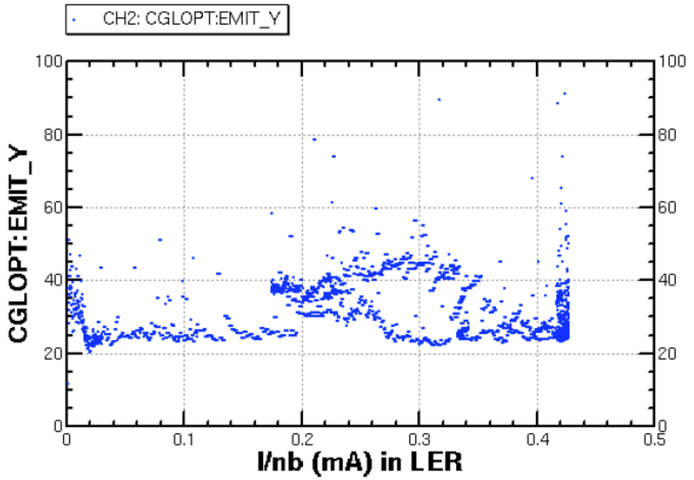
The specific luminosity depends on whether the injection beam on or off.
Injection background affects the online luminosity measurement ?

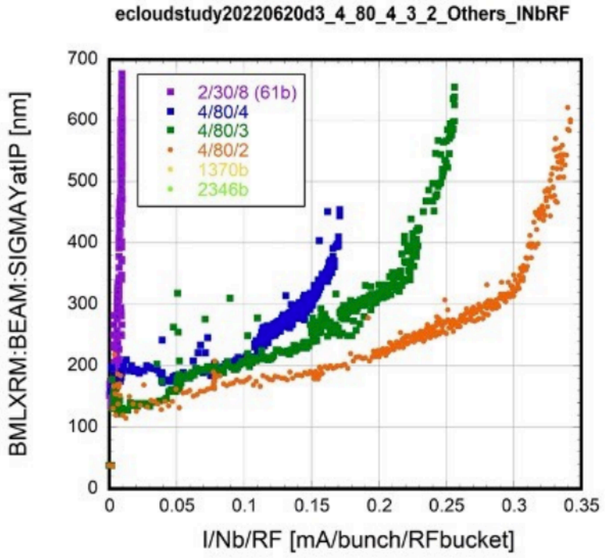
Swing shift on June 17

2346 bunches

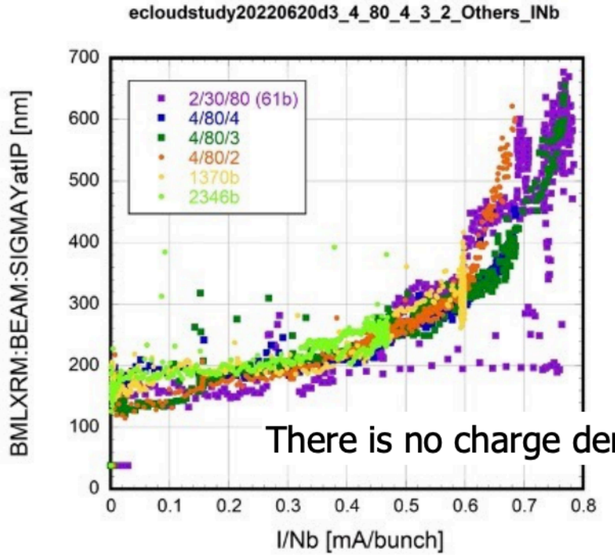


single beam emittance: 25 pm (I_{b+}: 0.4 mA)





There is no electron cloud instability.



There is no charge density dependence.

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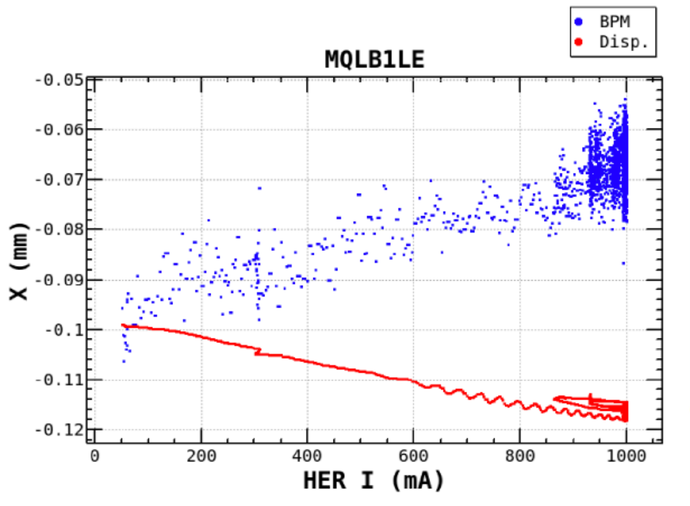
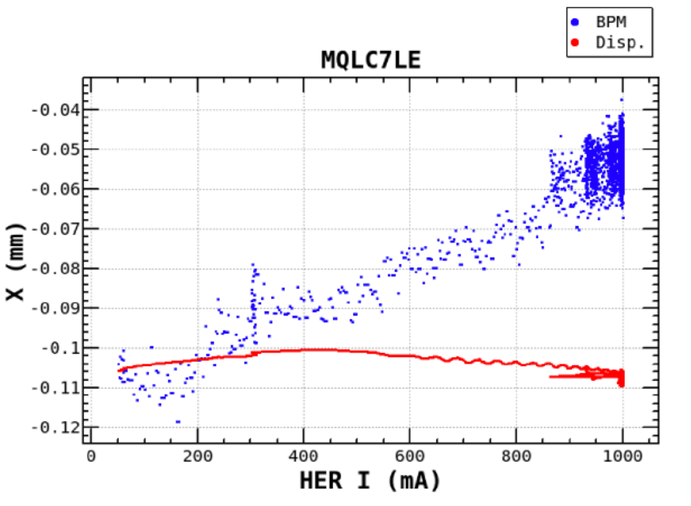
Beam-line deformation due to SR heating in HER



BPM reading

displacement monitor



We adopted horizontal orbit feedback at SLY in HER.