Status Of SuperKEKB 2021ab

February 16 – July 5, 2021

Y. Ohnishi

Revised: July 9

Overview of Machine Performance

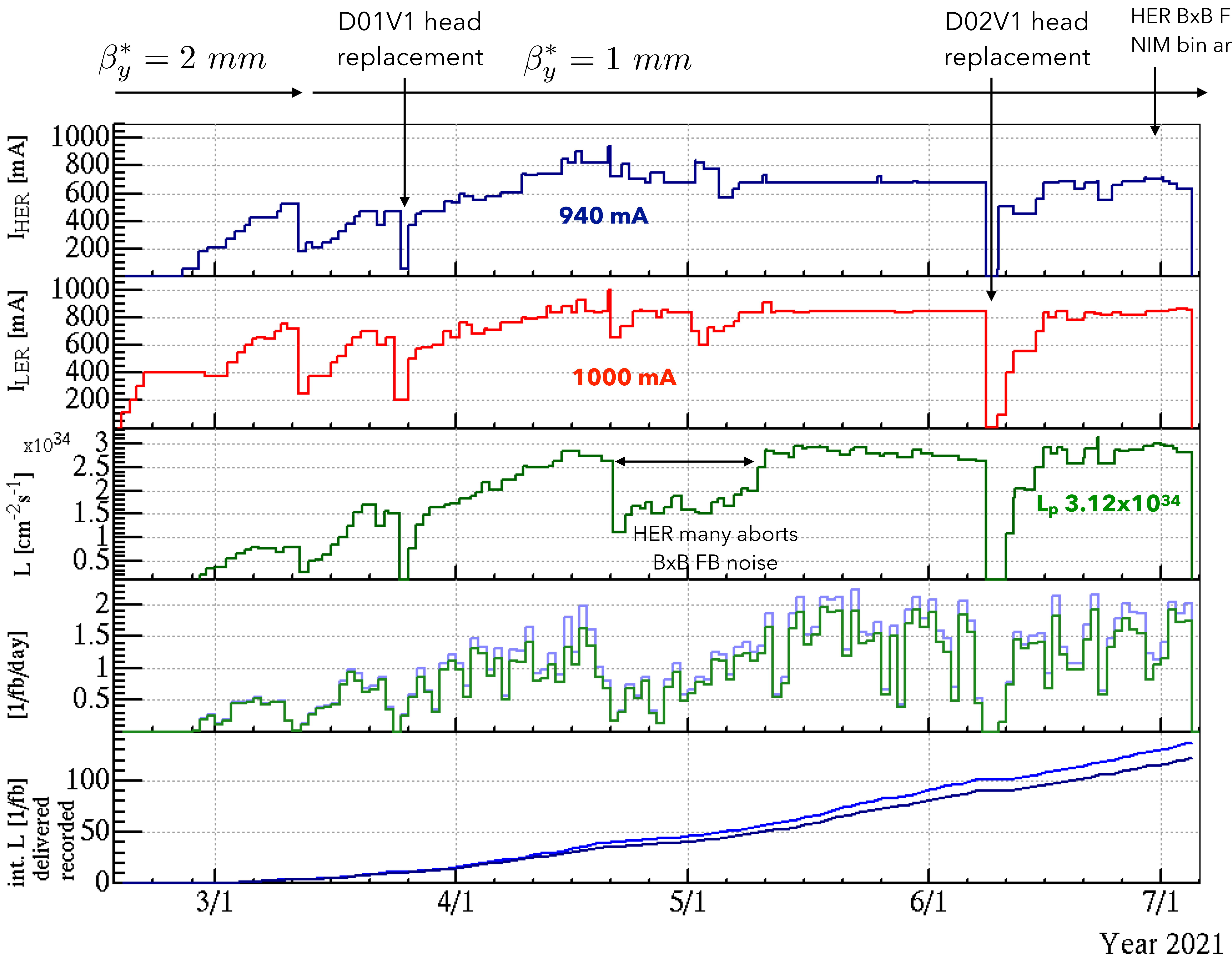
Keeping performance

Improvement of performance

Many effort is devoted to keep performance.

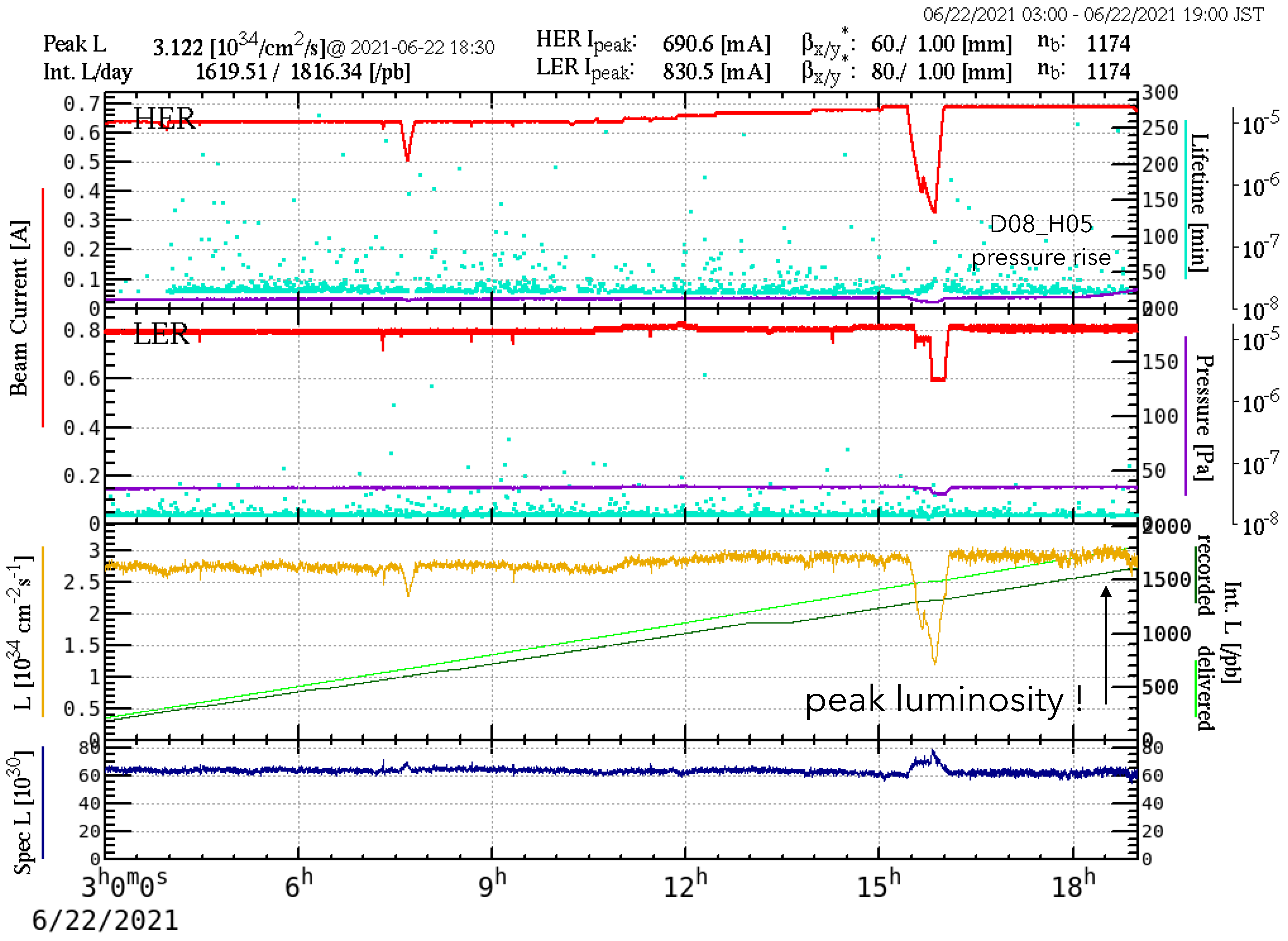
stability of machine, aging of devices and infrastructures

2021ab Operation Summary



- The 2021a run started on 16th February and operated for 140 days (4 months and half).
- The first ten days were devoted to the vacuum scrubbing.
- We operated with β_y^* = 2 mm to check hardwares and to test high current operation safely.
- Calibrations of BPM and collimator head positions, etc. were also performed by using beams during the first two weeks.
- D01V1(HER) head was replaced. The top jaw was short for the LER collimator head (March 23).
- We squeezed β_y^* down to 1 mm on 10th March. Beam currents increased with "baking run". 1000 mA / 940 mA w/o physics run
- HER many aborts from April 20 to May 3.
- D02V1(LER) head was replaced due damage (June 7).

Peak Luminosity : 3.12 x 10^{34} $cm^{-2}s^{-1}$



	int. L recorded	int. L delivered
Shift	747.2 pb^{-1} May 18 swing	787.6 pb^{-1} June 22 swing
Day	1.964 fb^{-1} May 18	2.233 fb^{-1} May 22
7 days May 14 - 20	12.141 fb^{-1}	13.482 fb^{-1}
30 days May 18 - June 23	42.319 fb^{-1}	47.370 fb^{-1}
2021ab 140 days	123.2 fb^{-1}	138.6 fb^{-1}

* online data

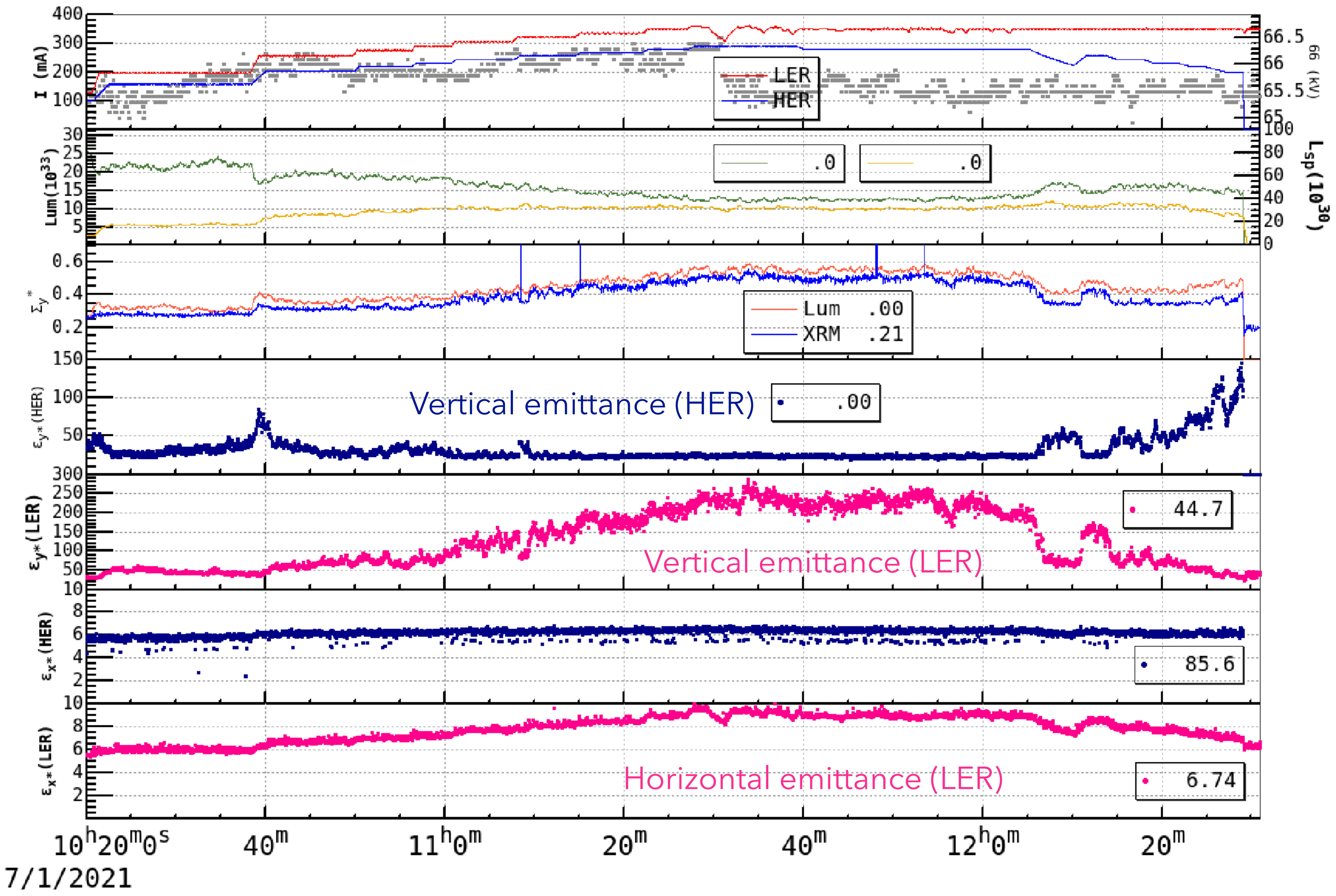
Machine Parameters

	2020b : June 21, 2020		2021b : June 22, 2021		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	nm
Beam Current	712	607	**790**	**687**	mA
Number of bunches	978		1174		
Bunch current	0.728	0.621	0.673	0.585	mA
Lifetime	760	1270	540	1320	sec
Horizontal size σ_x*	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.403		0.324		μm*1
Vertical size σ_y*	0.285		0.229		μm*2
Betatron tunes ν_x / ν_y	45.523 / 43.581	44.531 / 41.577	44.524 / 46.596	45.532 / 43.581	
β_x* / β_y*	80 / 1.0	60 / 1.0	80 / 1.0	60 / 1.0	mm
Piwinski angle	10.7	12.7	10.7	12.7	
Crab Waist Ratio	80	40	80	40	%
Beam-Beam parameter ξ_y	0.039	0.026	0.046	0.030	
Specific luminosity	5.43×10^{31}		6.76×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.40×10^{34}		**3.12×10^{34}**		$cm^{-2}s^{-1}$

*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2

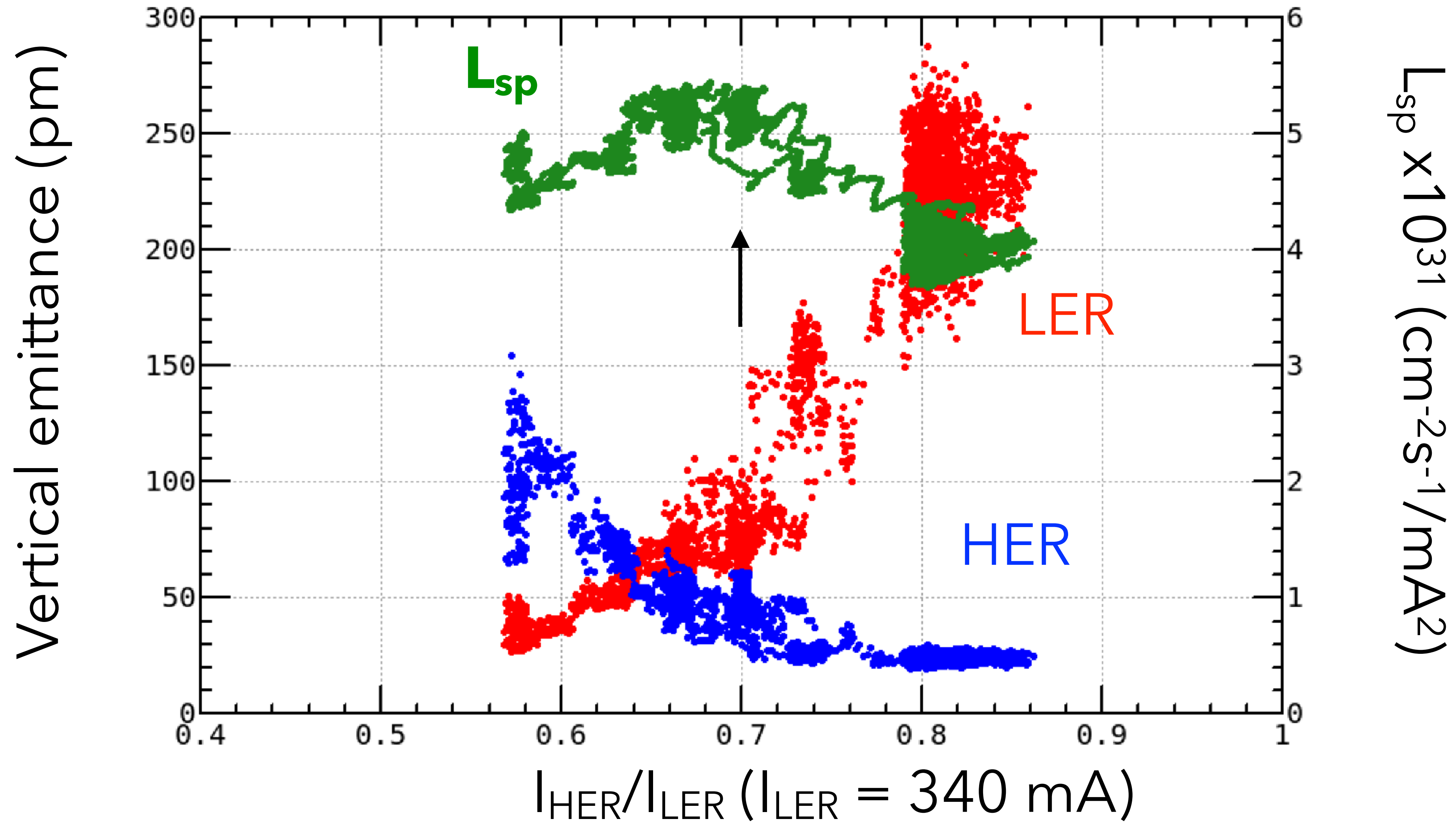
High Bunch Current Collision

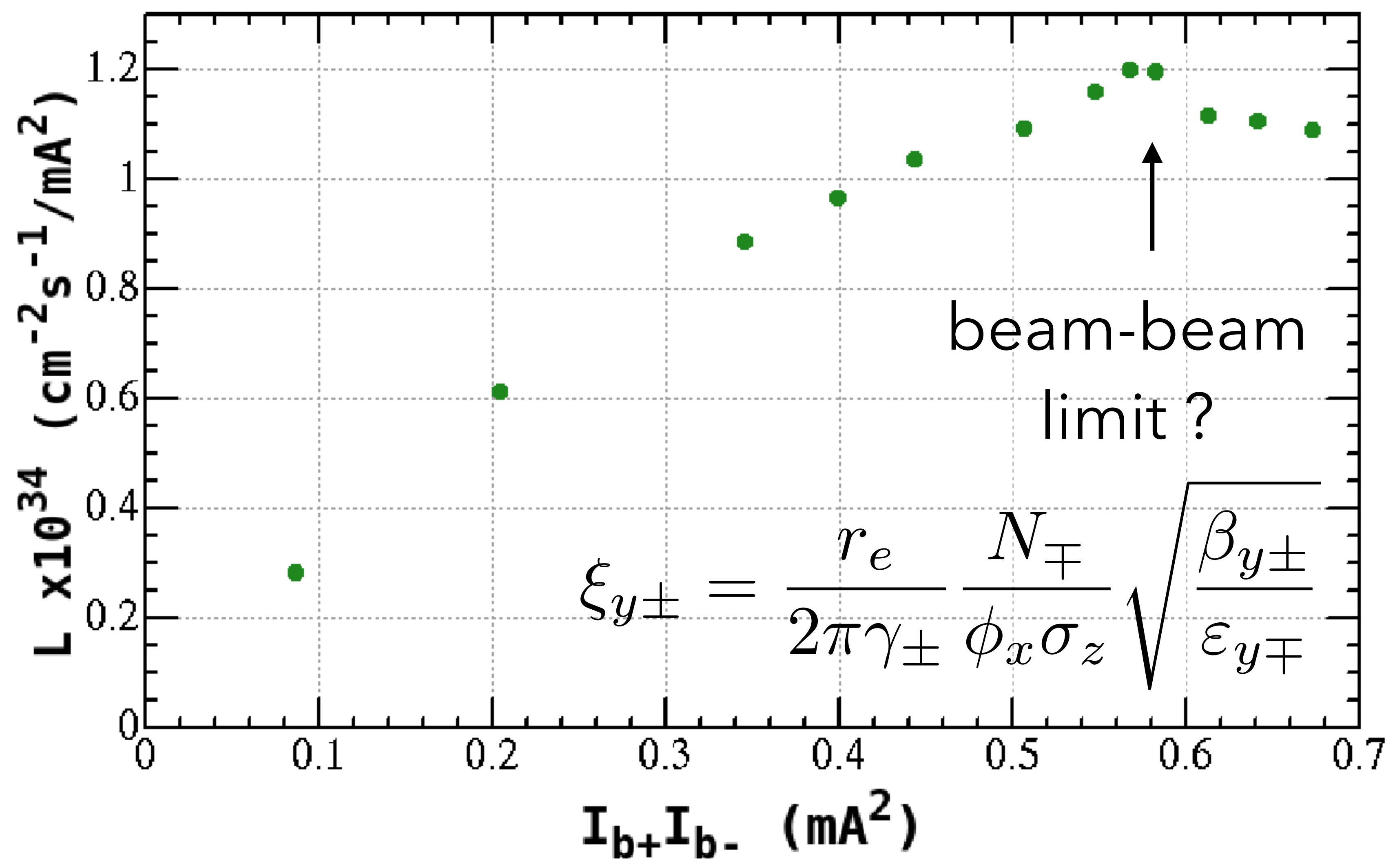
n_b : 393



- We observed large beam-beam blowup in the LER. (40 pm w/o collision)
- It depends on the HER beam current.
- Horizontal emittance also increases.

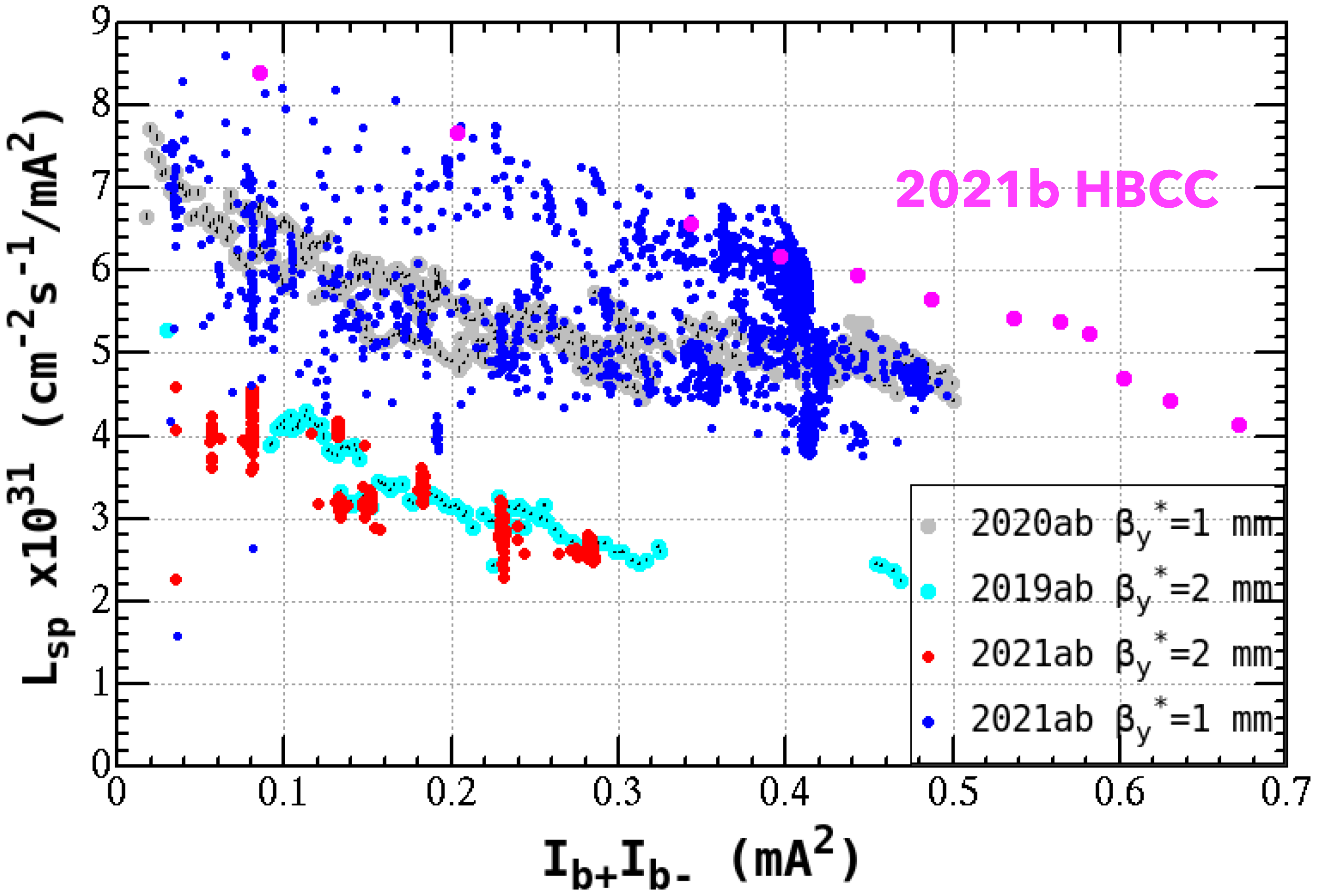
We consider coherent beam-beam head-tail instability and/or dynamic beta/emittance effect.

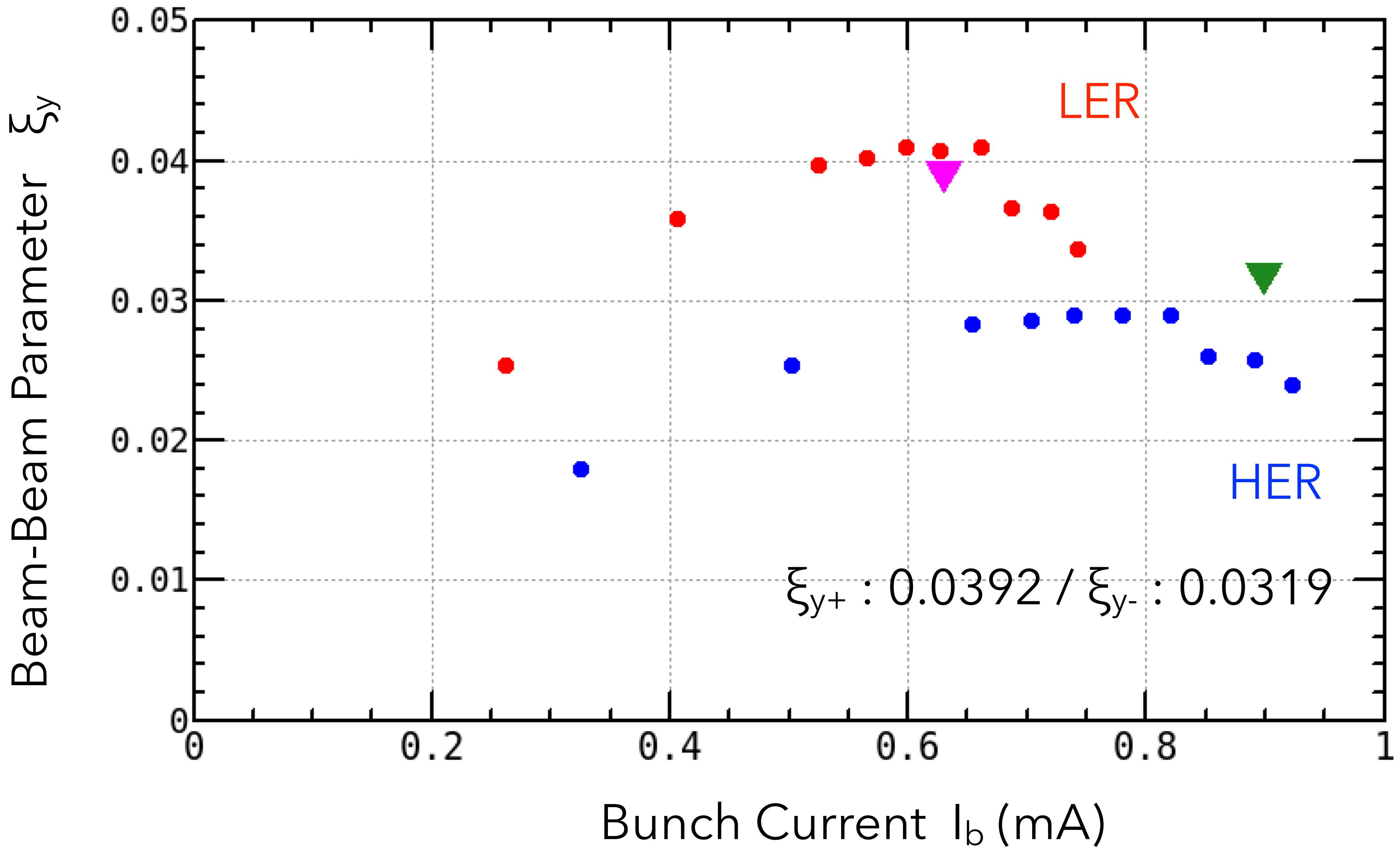




1.2 x10^{34} cm^{-2}s^{-1} at 0.57 mA^2 (393 bunches)

4.78 x 10^{34} cm^{-2}s^{-1} is expected for 1565 bunches.
(I_{LER} : 1.4 A / I_{HER} : 1.0 A)





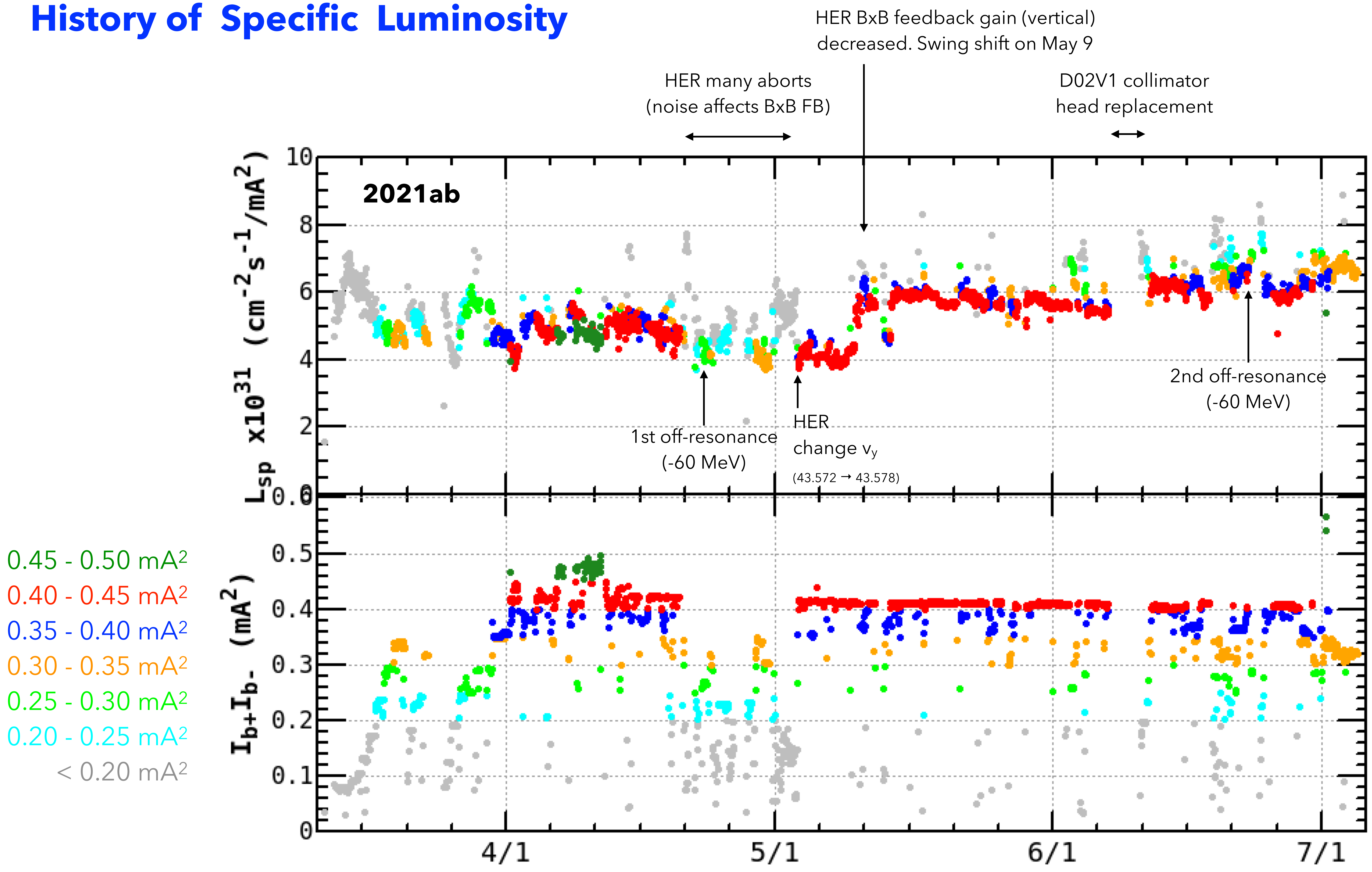
$$L_{sp} = \frac{L}{n_b I_{b+} I_{b-}}$$

$$\xi_{y\pm} = \frac{2er_e\beta^*_{y\pm}L}{\gamma_\pm I_\pm} \qquad \xi_{y\pm} = \xi_{y\pm}(I_{b\mp})$$

- Specific luminosity for β_y^* = 2 mm reproduces that of 2019 ab.
- Specific luminosity for β_y^* = 1 mm is improved compared to that of 2020ab.
- Bunch current product is achieved larger than 0.5 mA^2.

- The beam current ratio is kept to be I_{LER} : I_{HER} = 5 : 4 (circle)
- Beam-beam limit was observed at around 0.03 for HER.
- The bunch current ratio can be optimized to improve luminosity.
- The optimized ratio of beam current is 10 : 7 (triangle) at I_{b+} > 0.8 mA.

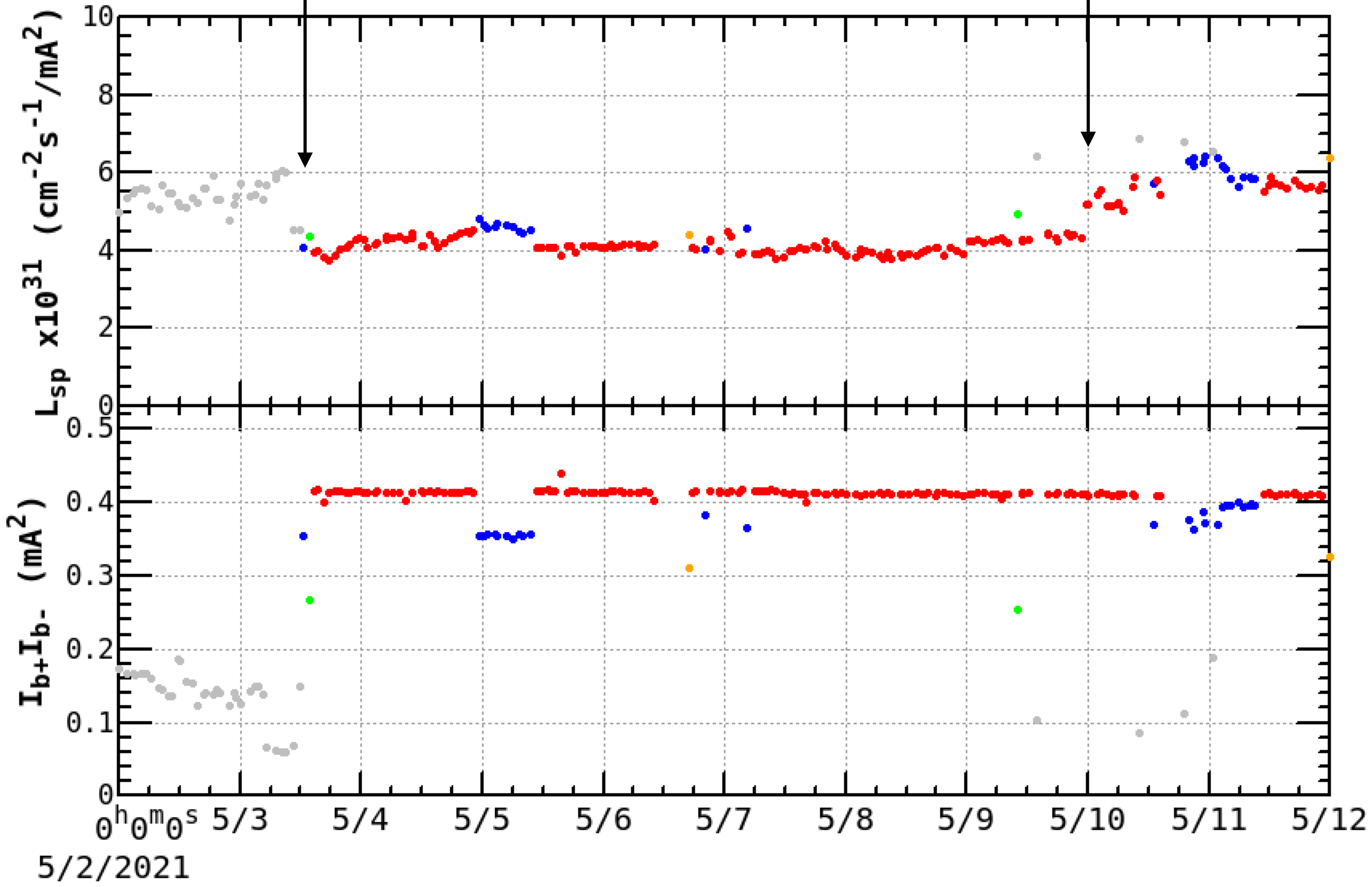
History of Specific Luminosity



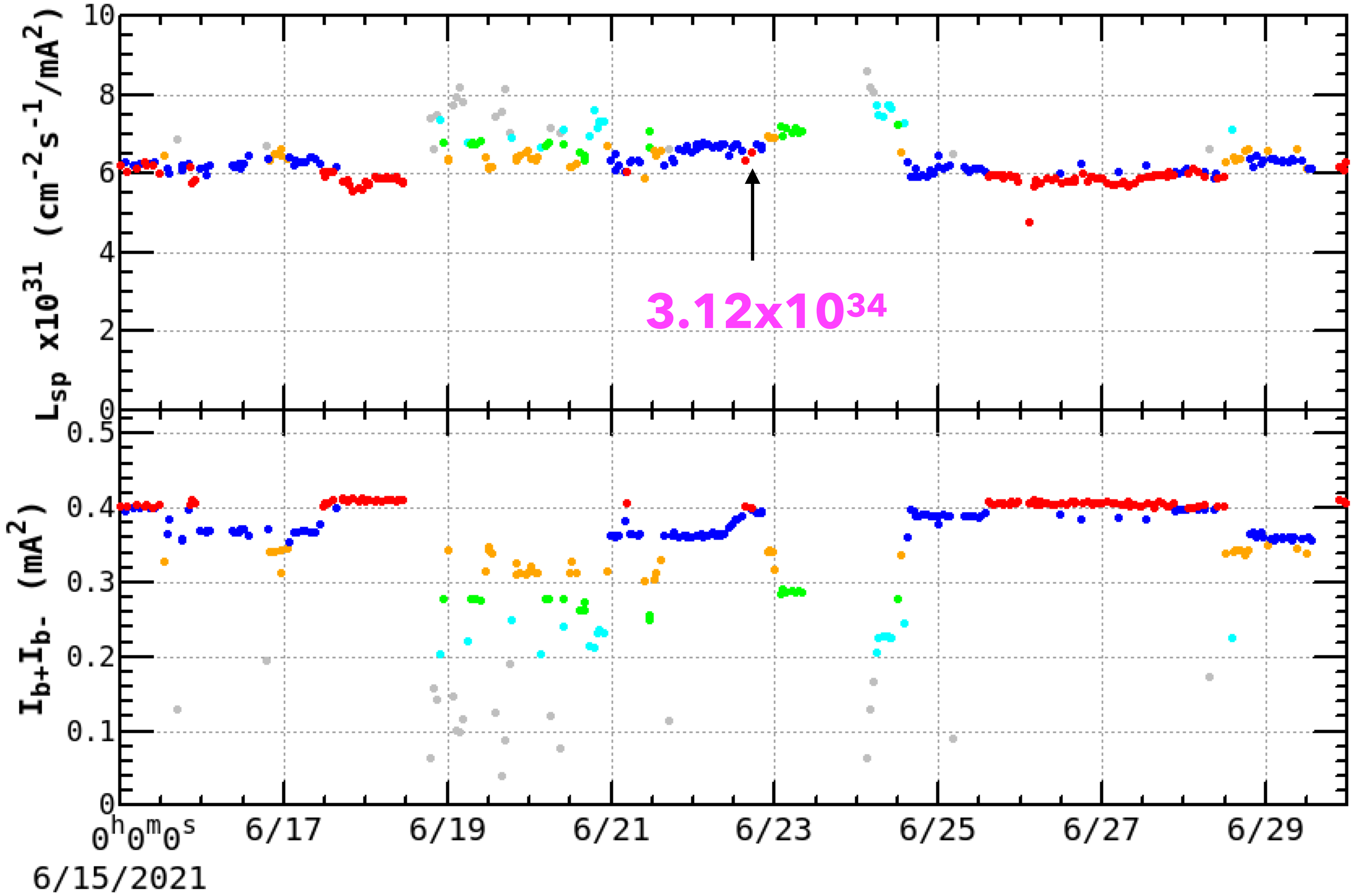
More detail of L_{sp}

HER
change ν_y
43.572 → 43.578

HER BxB Feedback gain (vertical) decreased.
Swing shift on May 9



off-resonance (-60 MeV)



Linac energy FB trouble

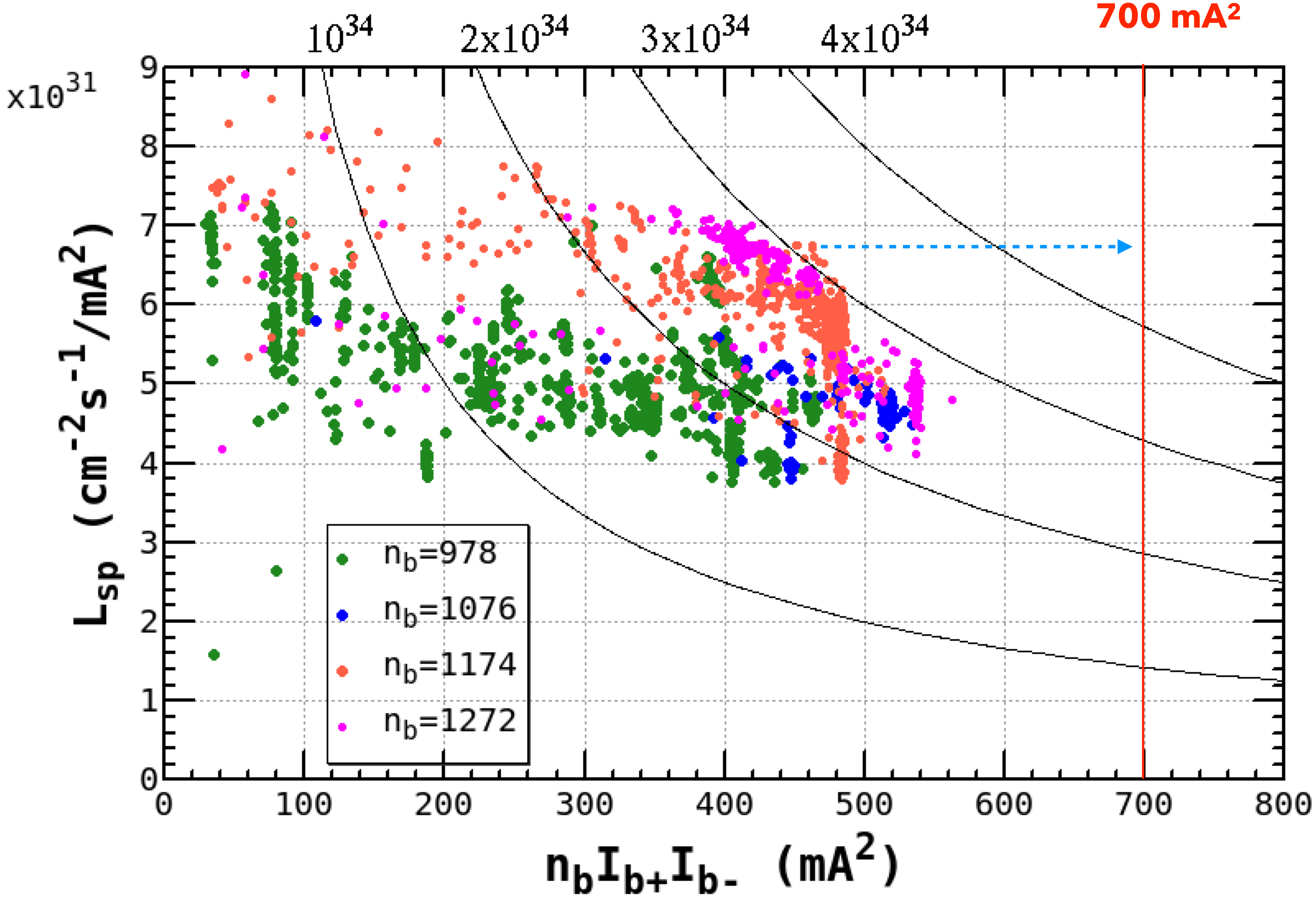
maintenance

Projection of Specific Luminosity

max of $n_b I_{b+} I_{b-}$ is 540 mA²
(840 mA/818 mA, 1272)

target of 2021b
700 mA²

LER / HER : 1.1 A / 1.0 A
n_b = 1565



Beam Aborts and QCS Quench

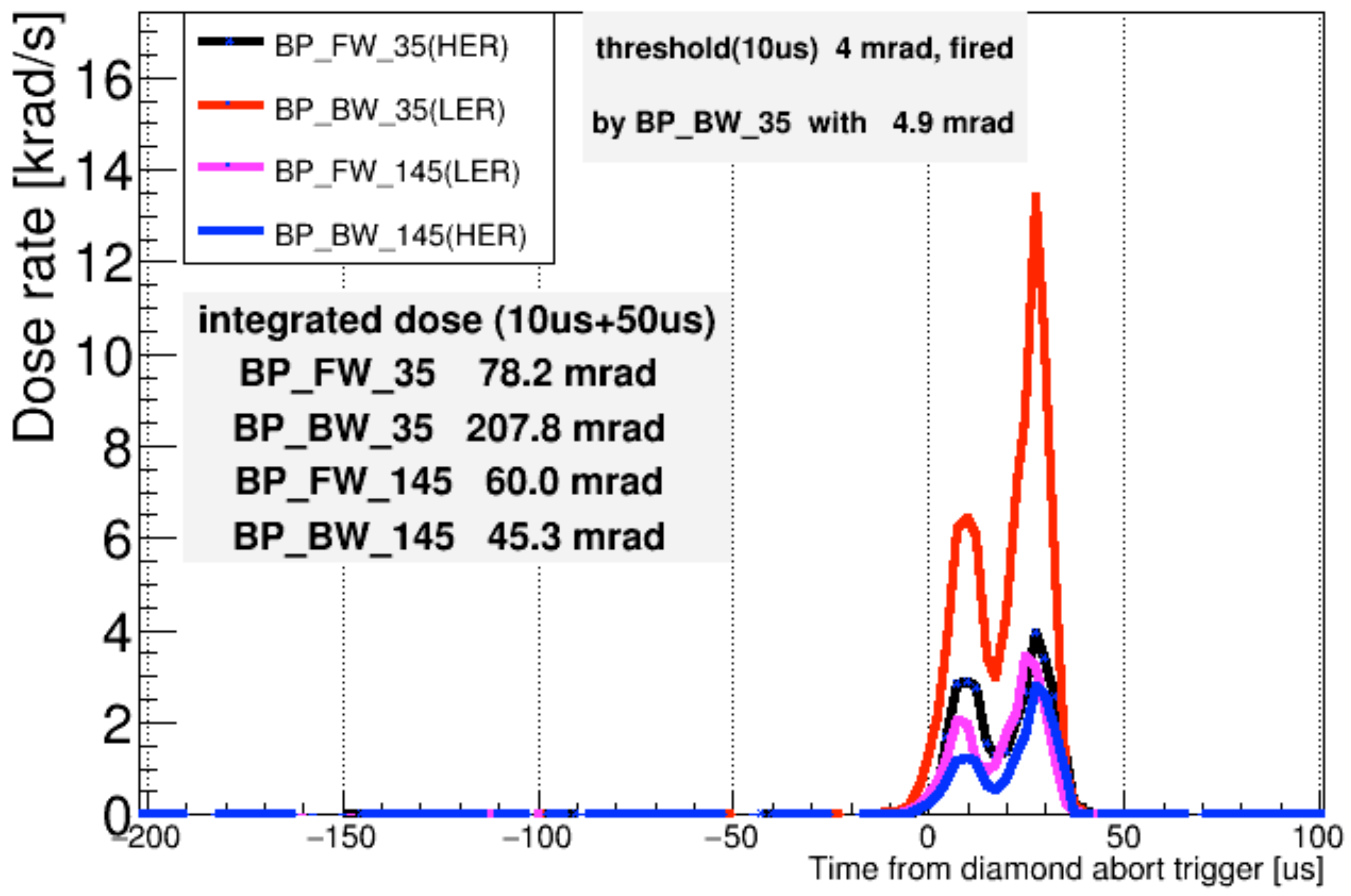
LER and HER Abnormal Beam Abort

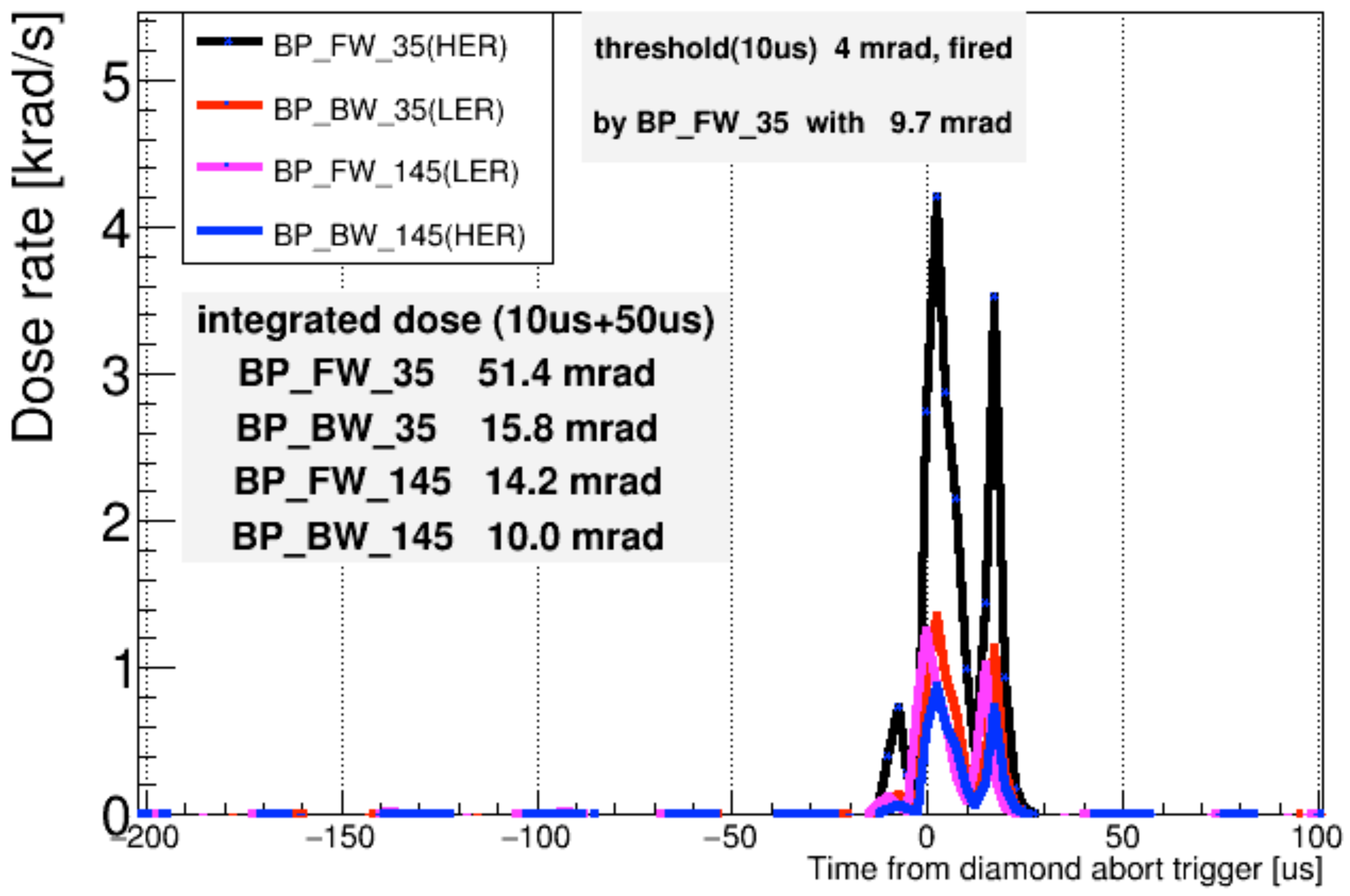
H. Nakayama

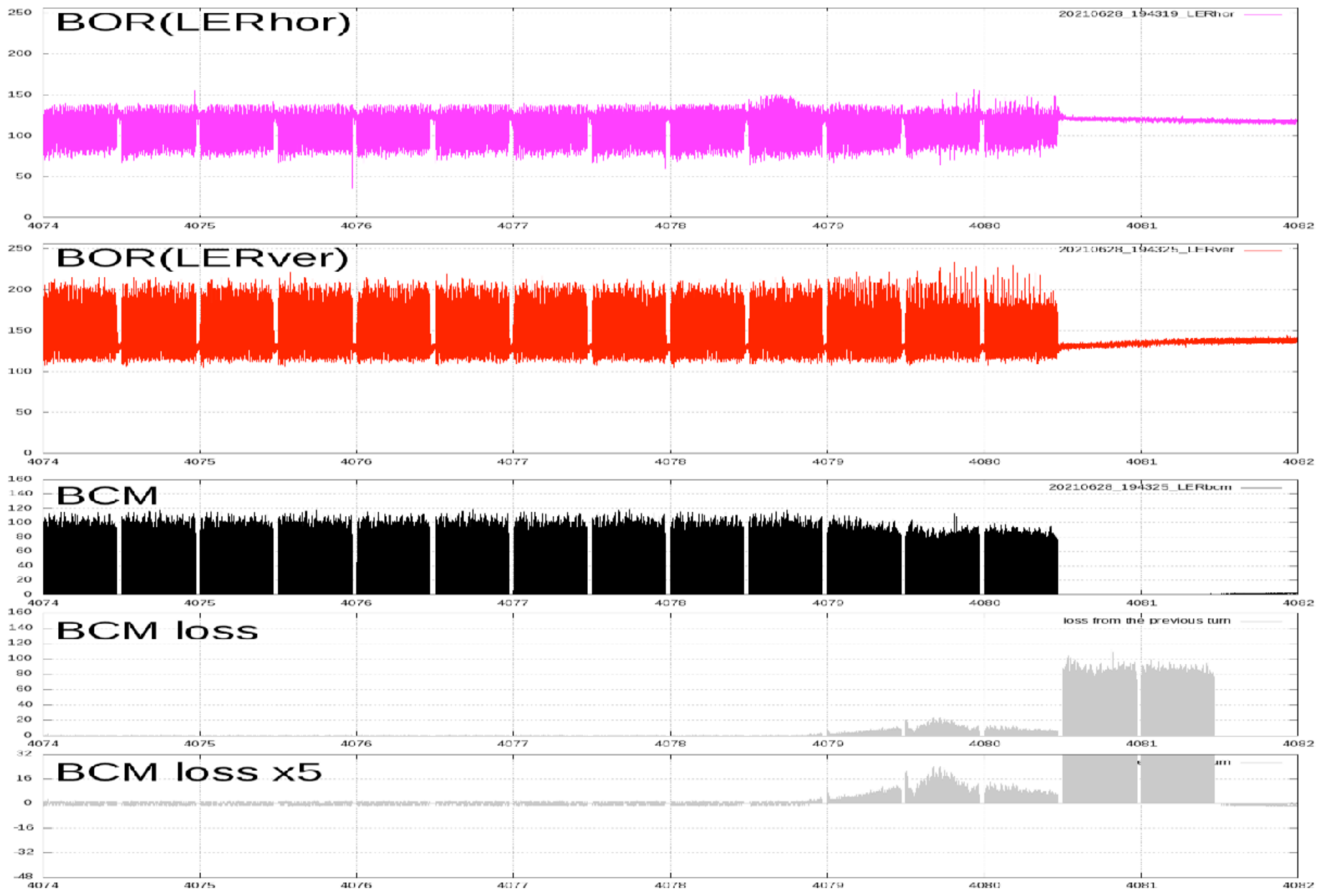
2021-06-28_19-43-19_99839 **835 mA**

typical samples

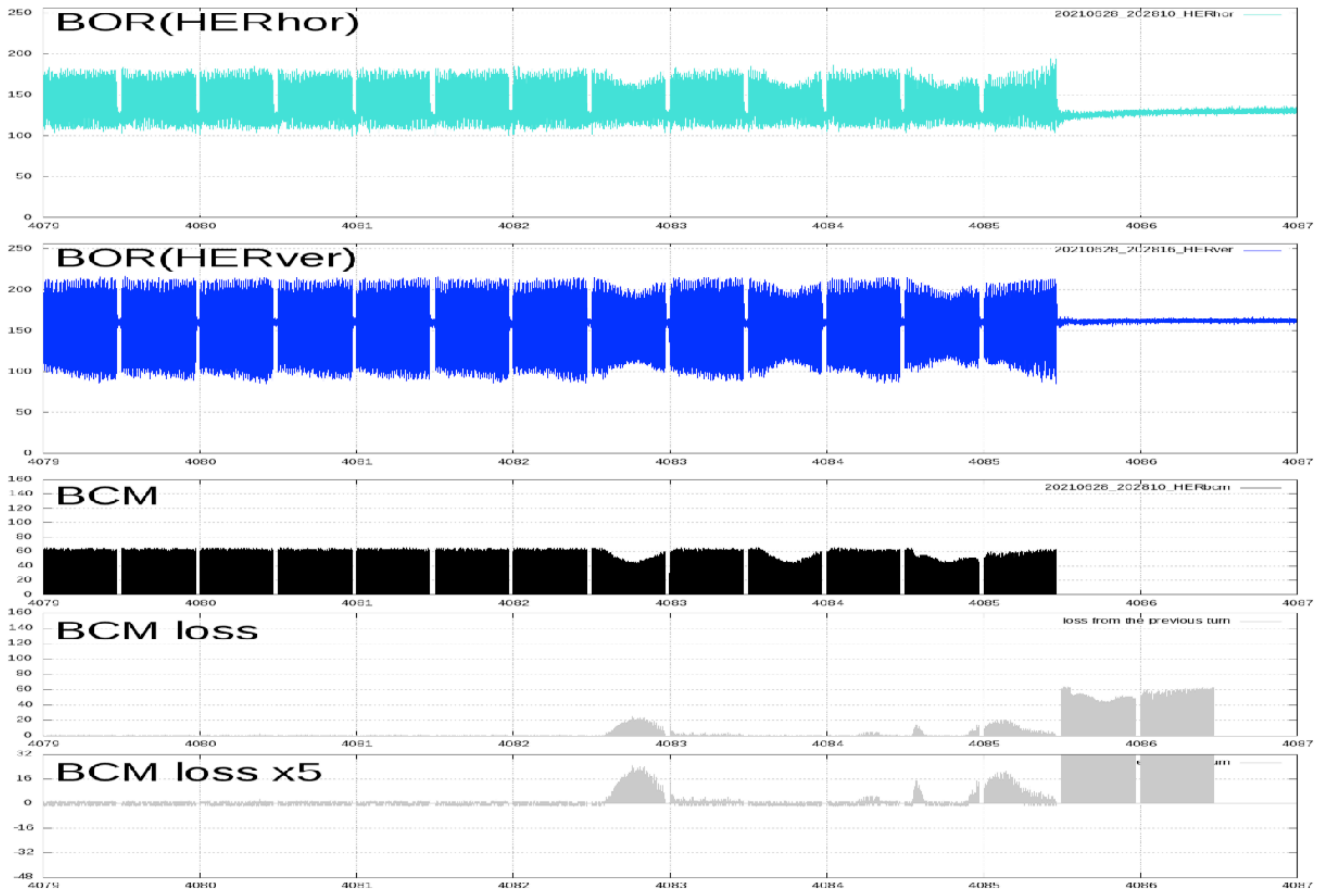
2021-06-28_20-28-10_99845 **709 mA**



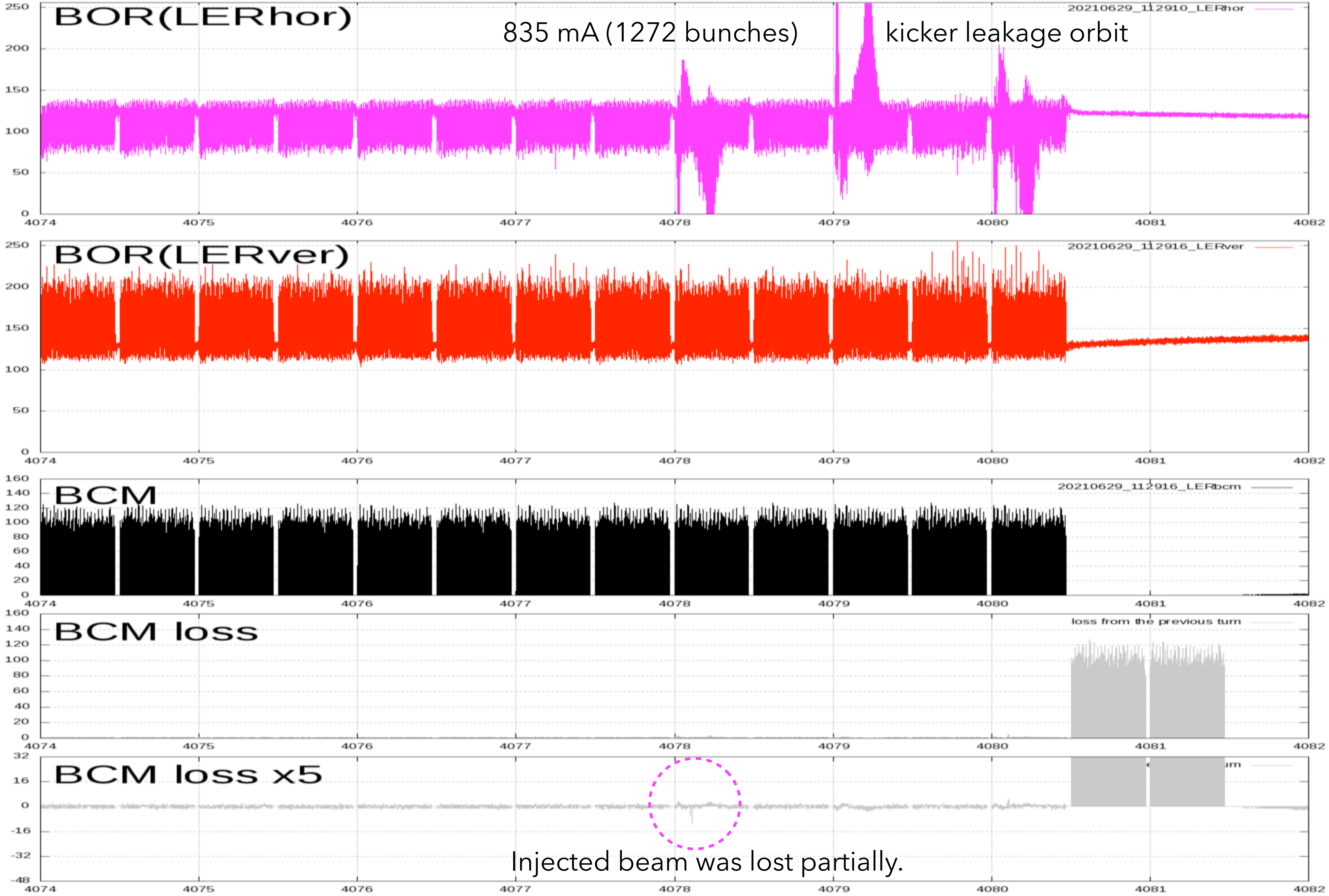




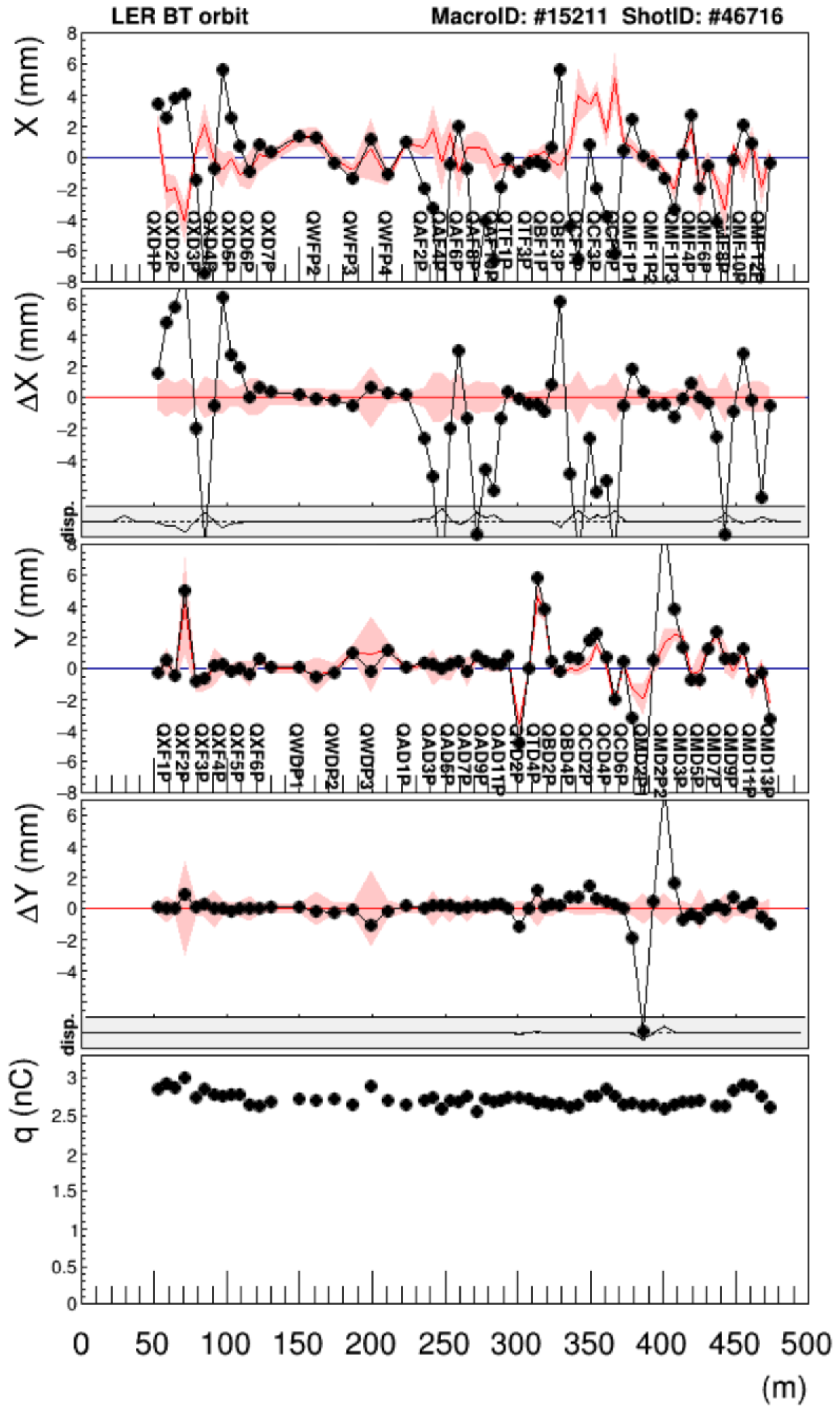
- **No orbit oscillation**
- **Very fast beam loss within a few turns**



Beam Abort due to Injection Beam

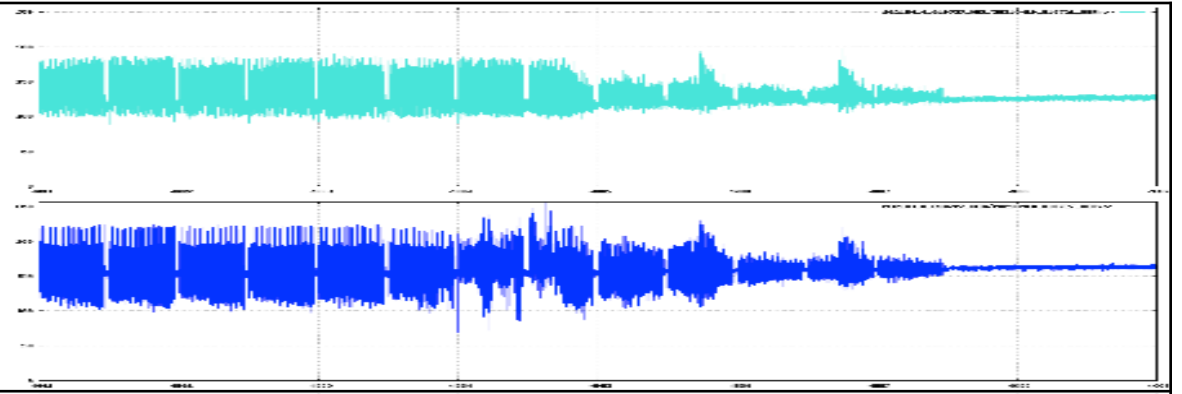
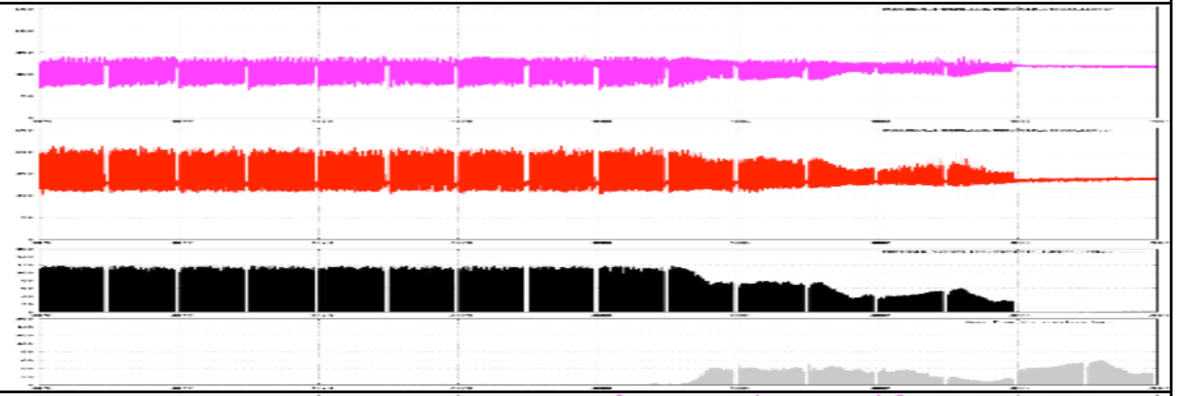
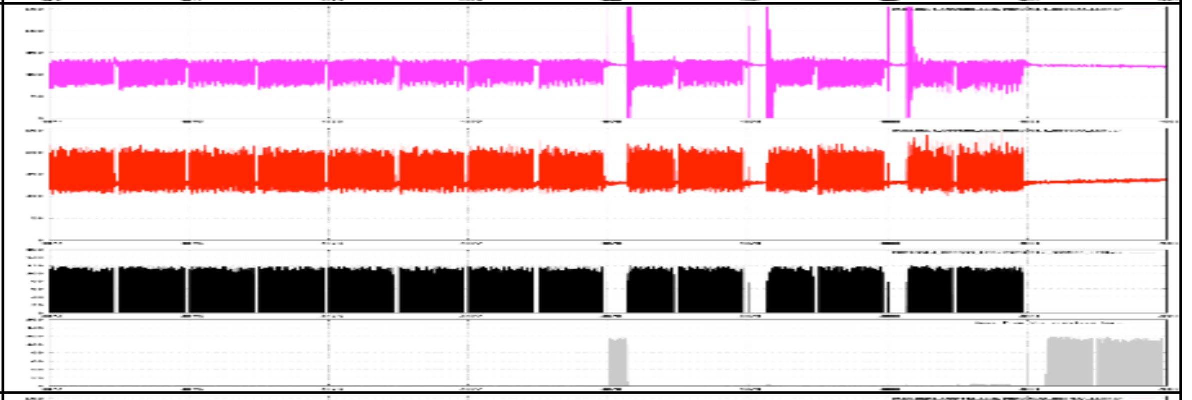
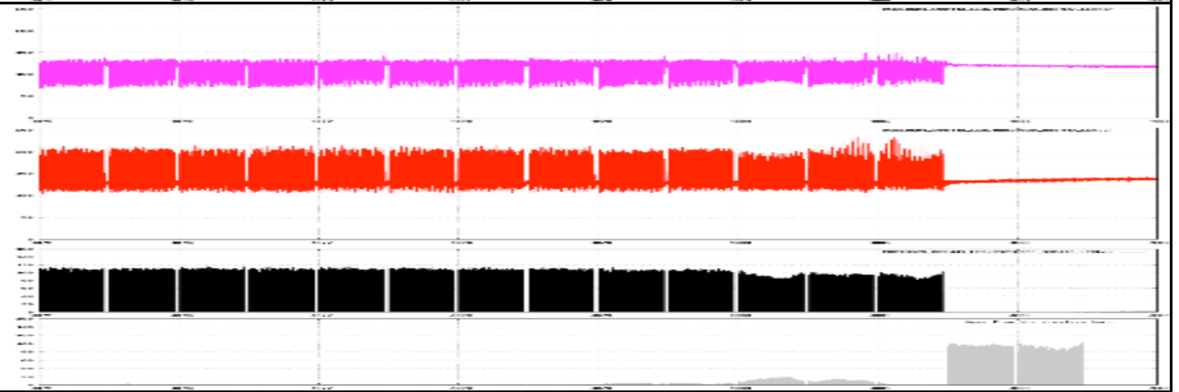
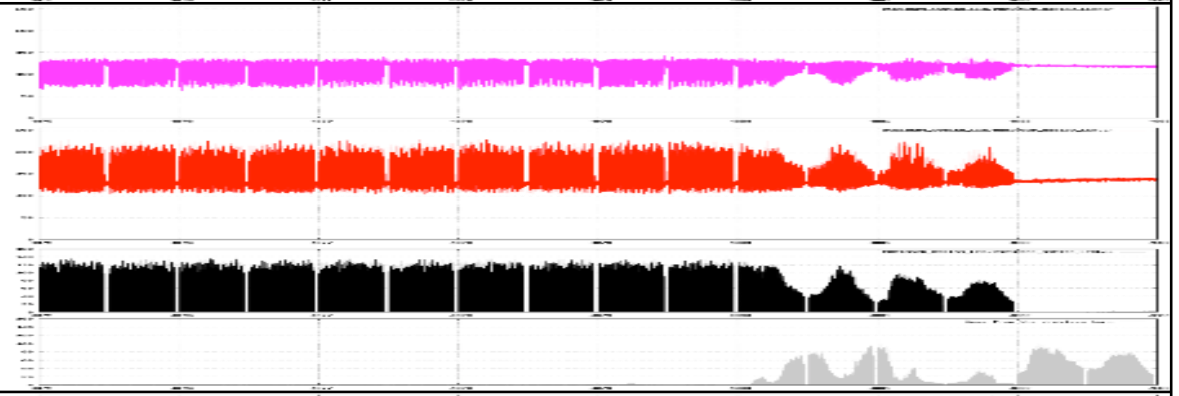
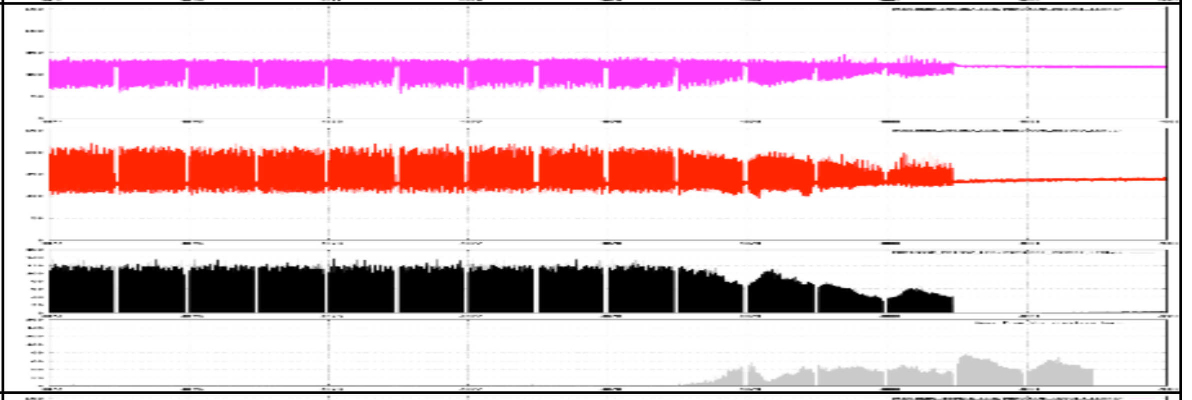
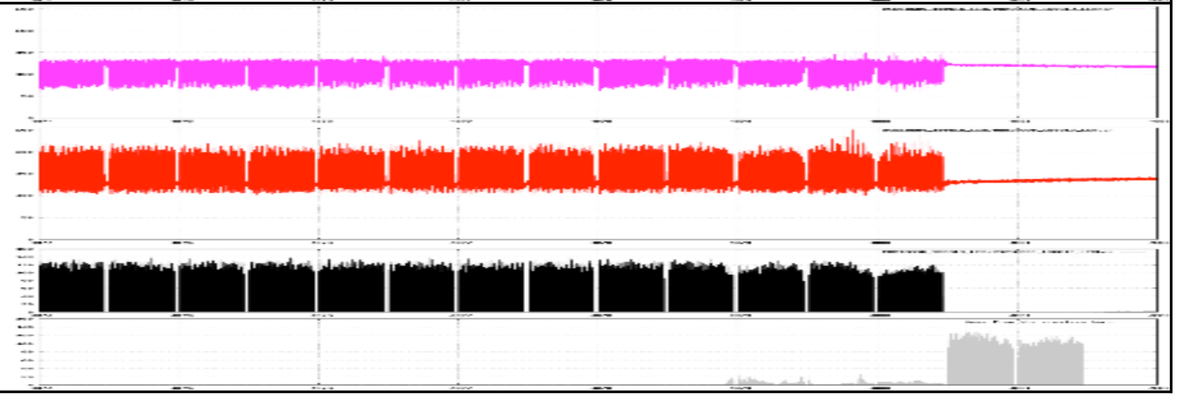


Orbit in beam transport line
Energy deviation was large.

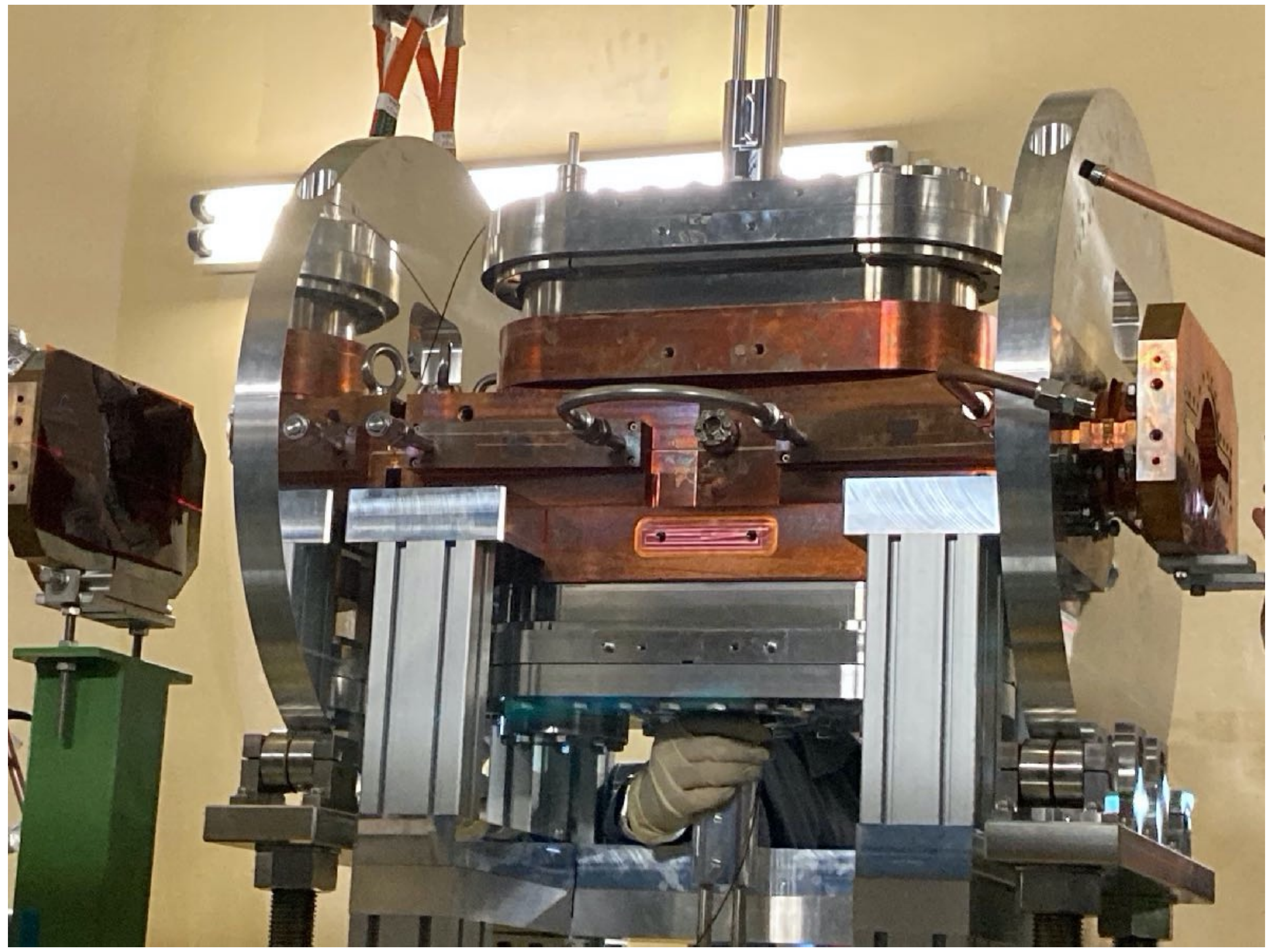


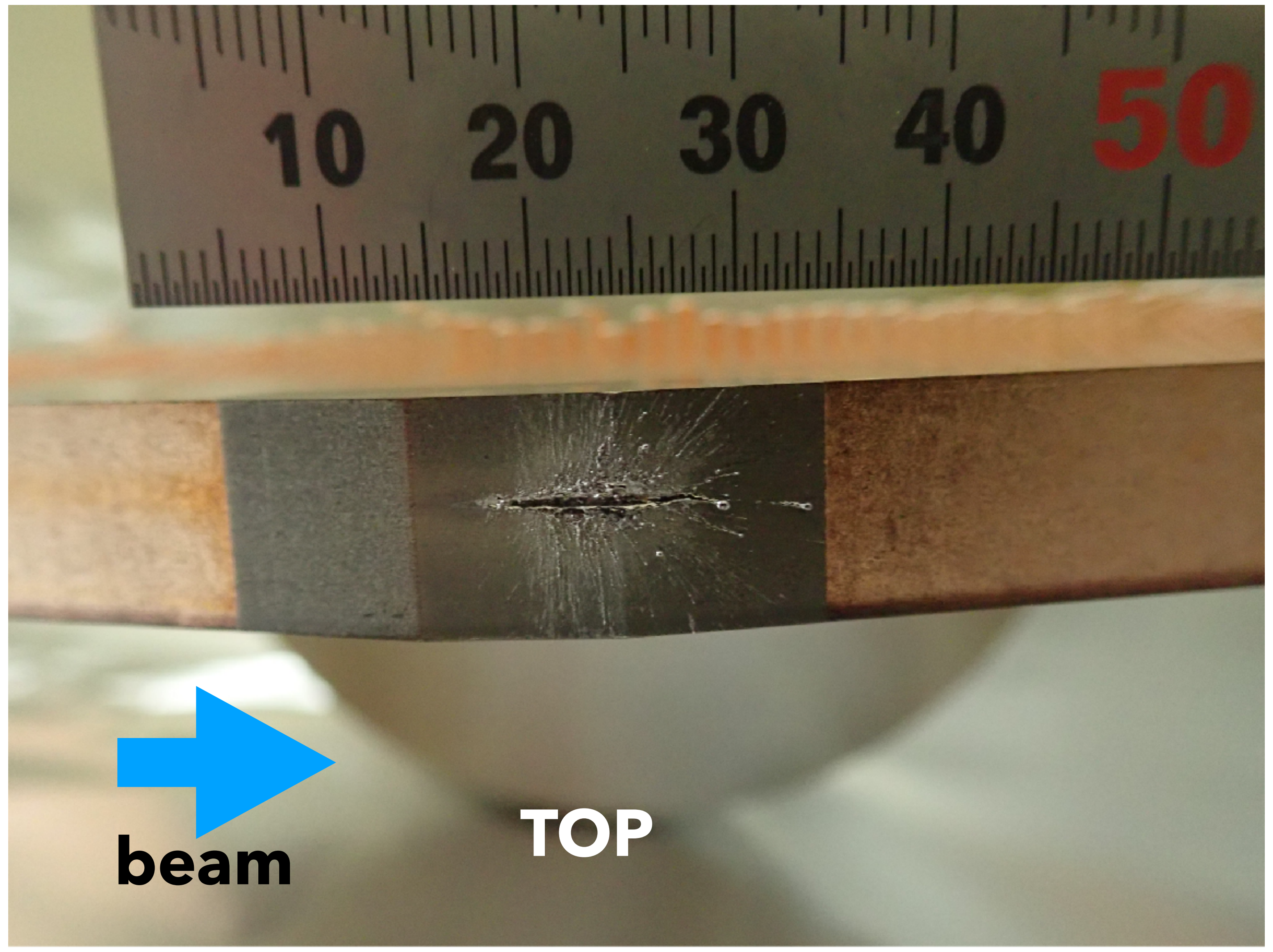
H. Nakayama
H. Kaji

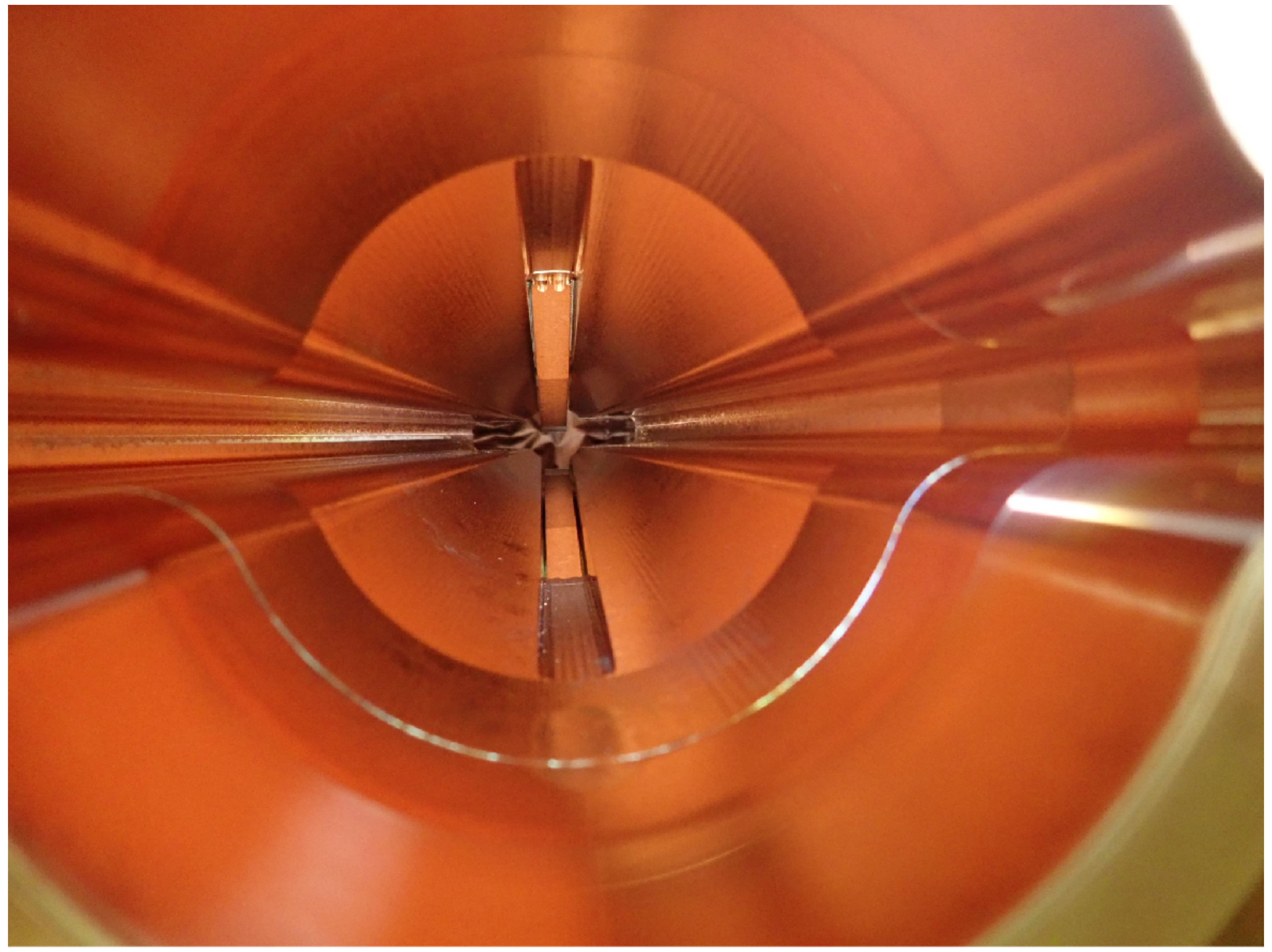
QCS Quench List (except for earthquake and PS trouble)

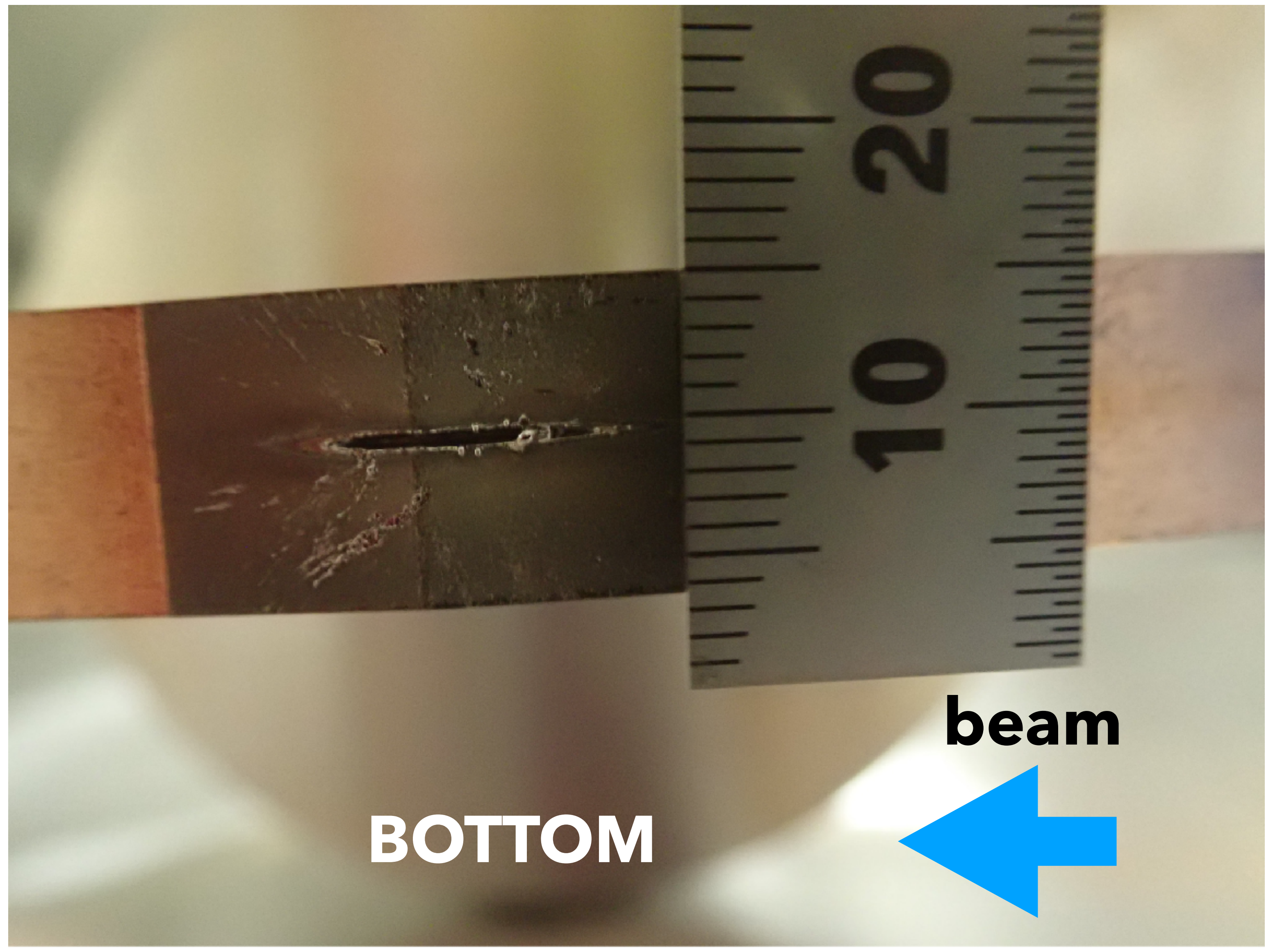
4/19 (MO) Owl	1:07	HER QC1LE	LER: 836 mA / HER: 819 mA HER D09V1 damaged	
5/10 (MO) Day	14:26	LER QC1LP, QC1RP	LER: 906 mA / HER: 726 mA LER D02V1 damaged	
5/14 (FR) Owl	0:35	LER QC1RP	LER: 837 mA / HER: 679 mA LER kicker trouble	
5/23 (SU) Owl	8:24	LER QC1LP, QC1RP	LER: 836 mA / HER: 678 mA LER D06V1 damaged	
5/28 (FR) Owl	3:21	LER QC1RP	LER: 834 mA / HER: 677 mA LER D06V1 damaged	
6/2 (WE) Swing	20:13	LER QC1LP, QC1RP	LER: 840 mA / HER: 678 mA LER D02V1 damaged	
6/6 (SU) Day	16:06	LER QC1LP, QC1RP	LER: 838 mA / HER: 677 mA	

LER D02V1 Collimator Damage and Replacement



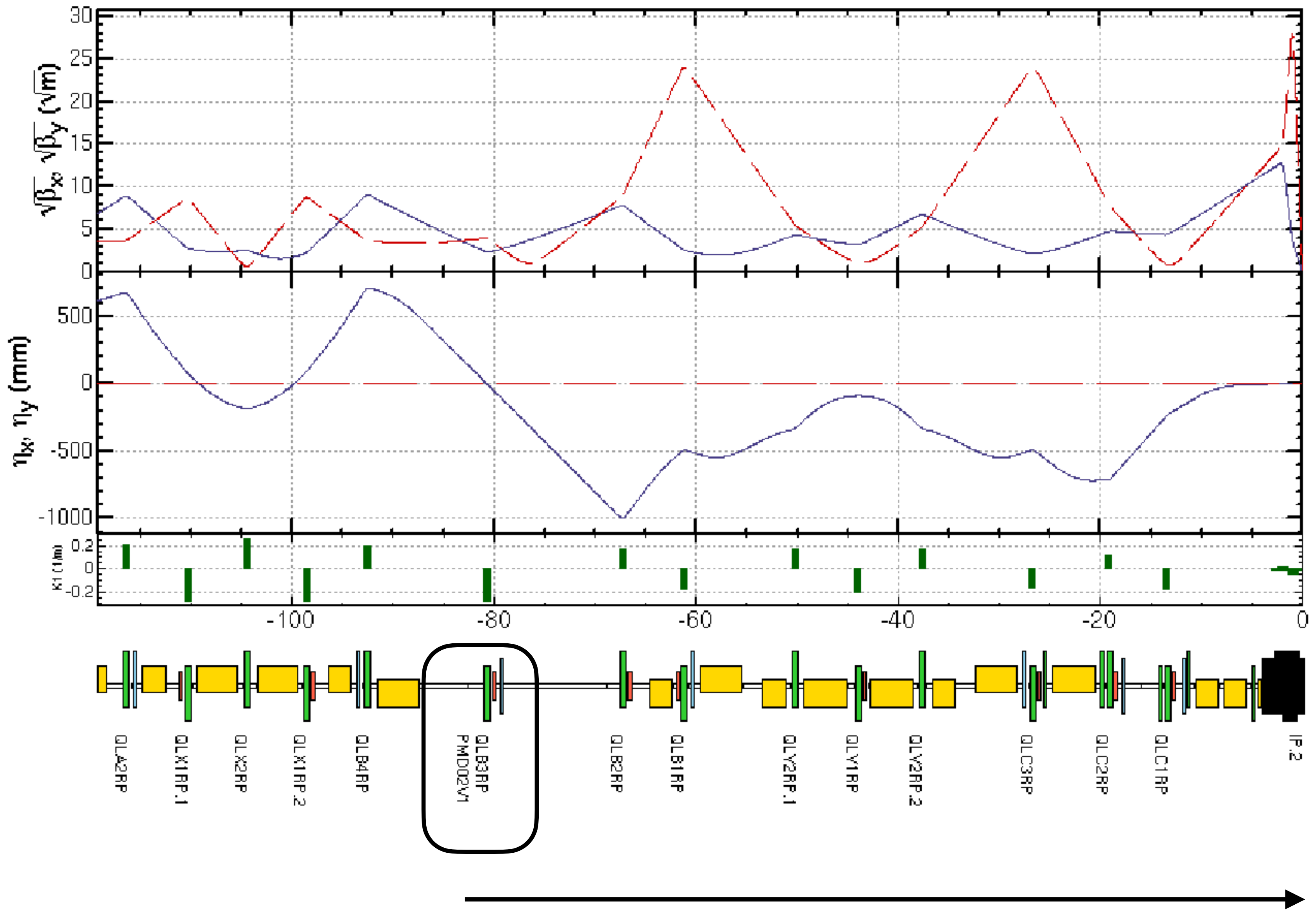






Vertical collimator: D02V1 (LER)

tantalum (Ta) head with 10 mm long tip



82.5 m upper stream of IP

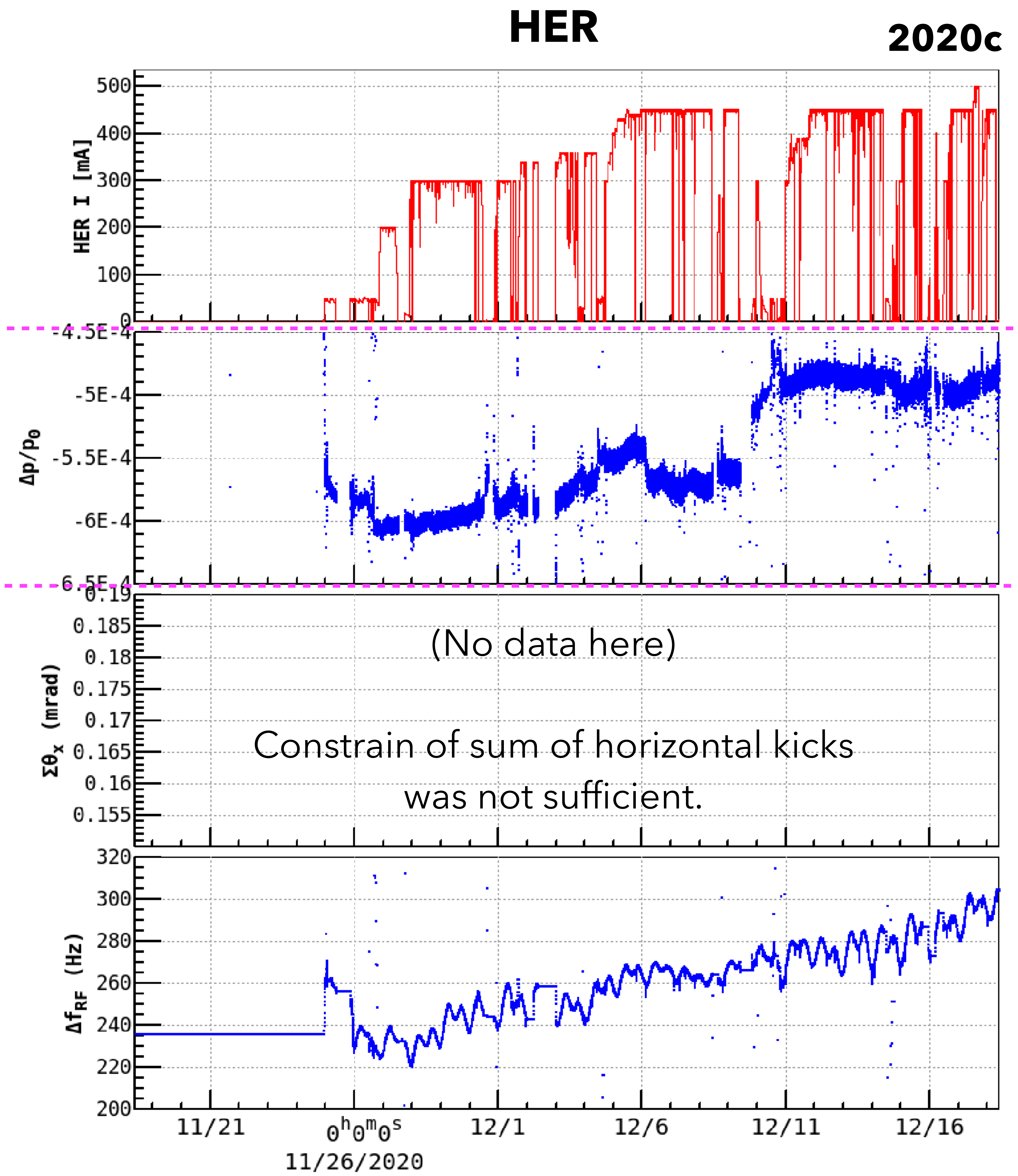
June 8, 2021

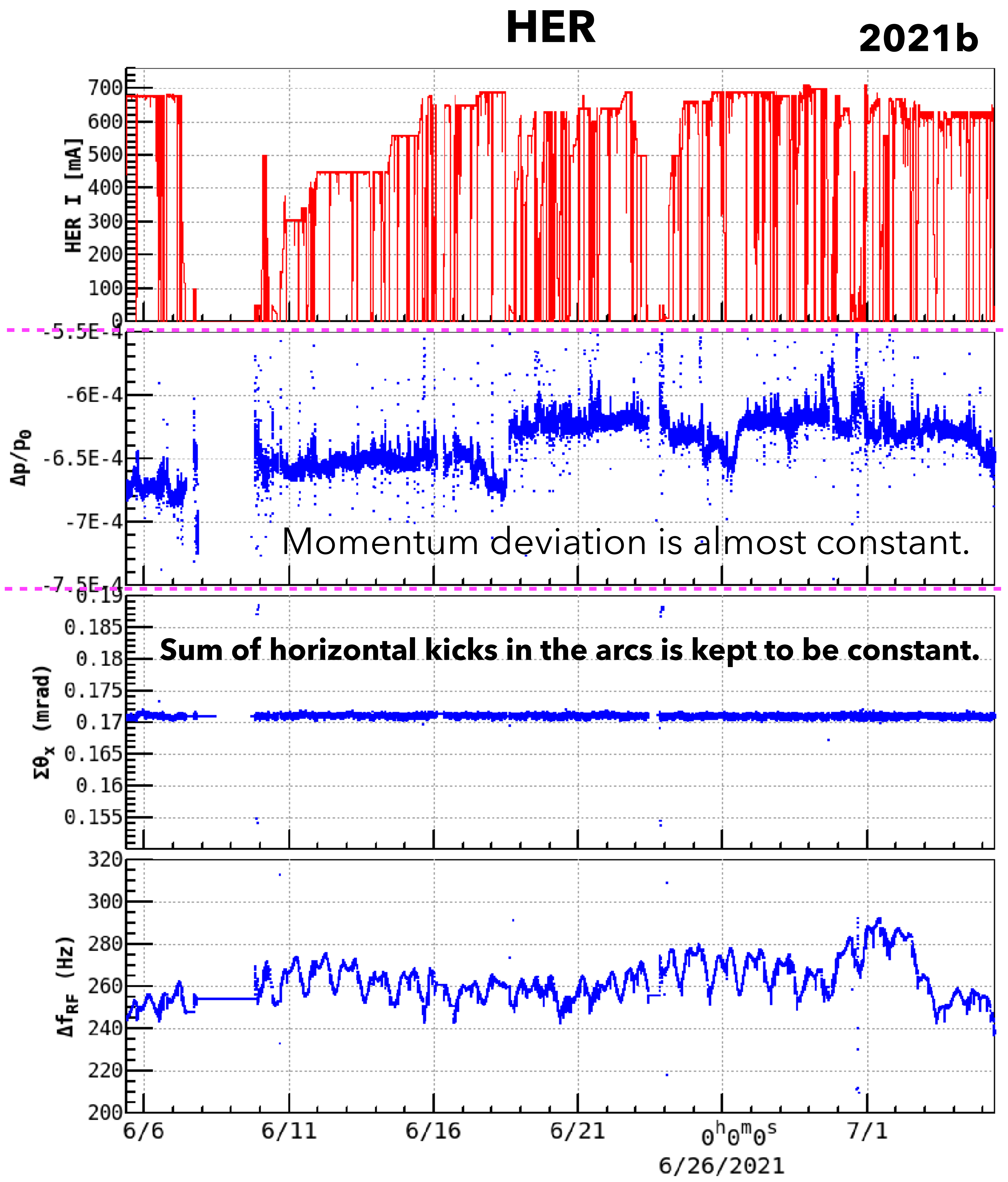
S. Terui
T. Ishibashi
Y. Suetsugu

Improvements and Issues of Machine Performance

Improvement of Continuous Closed orbit Correction (CCC)

We modified the algorithm of orbit correction.





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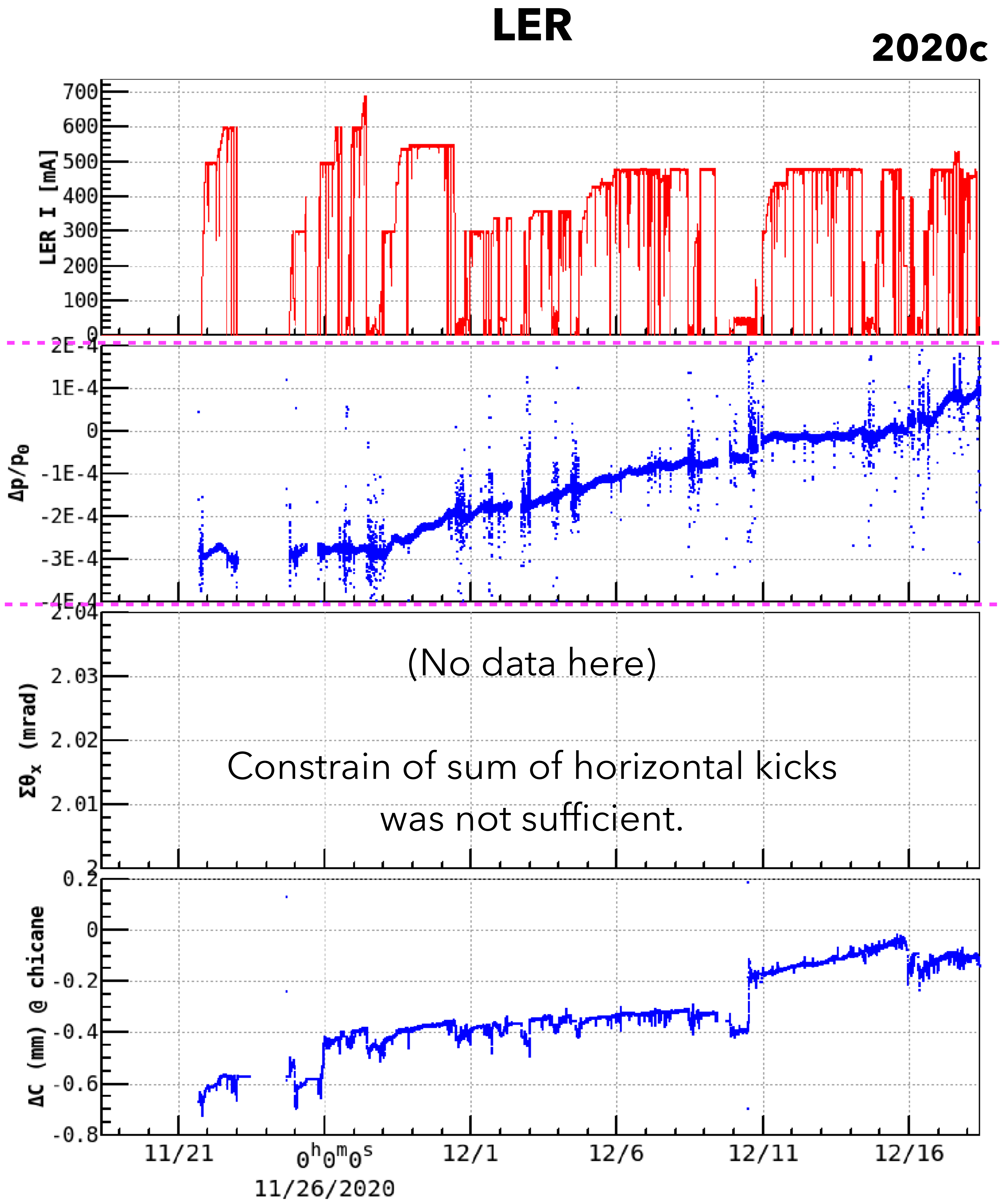
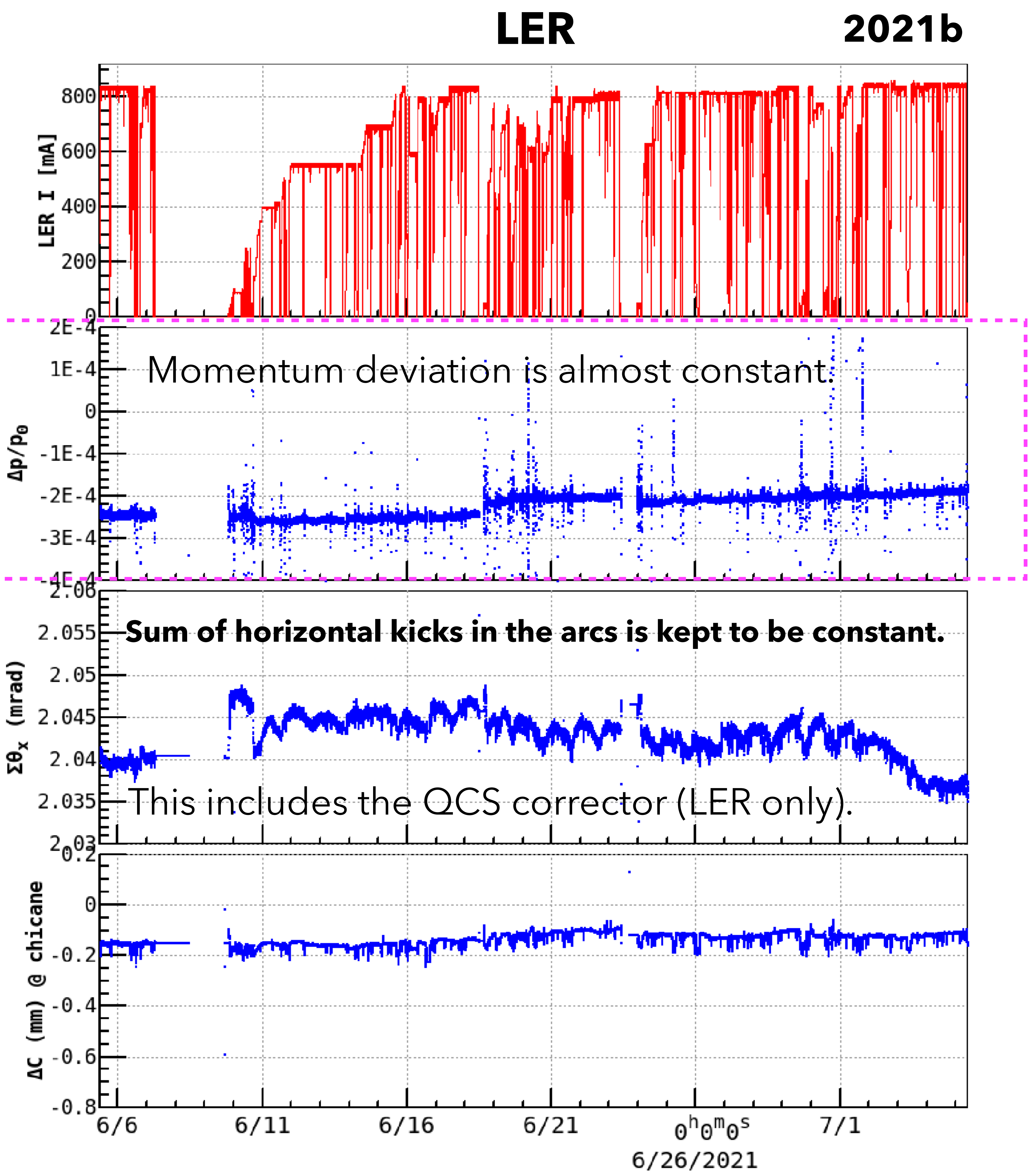
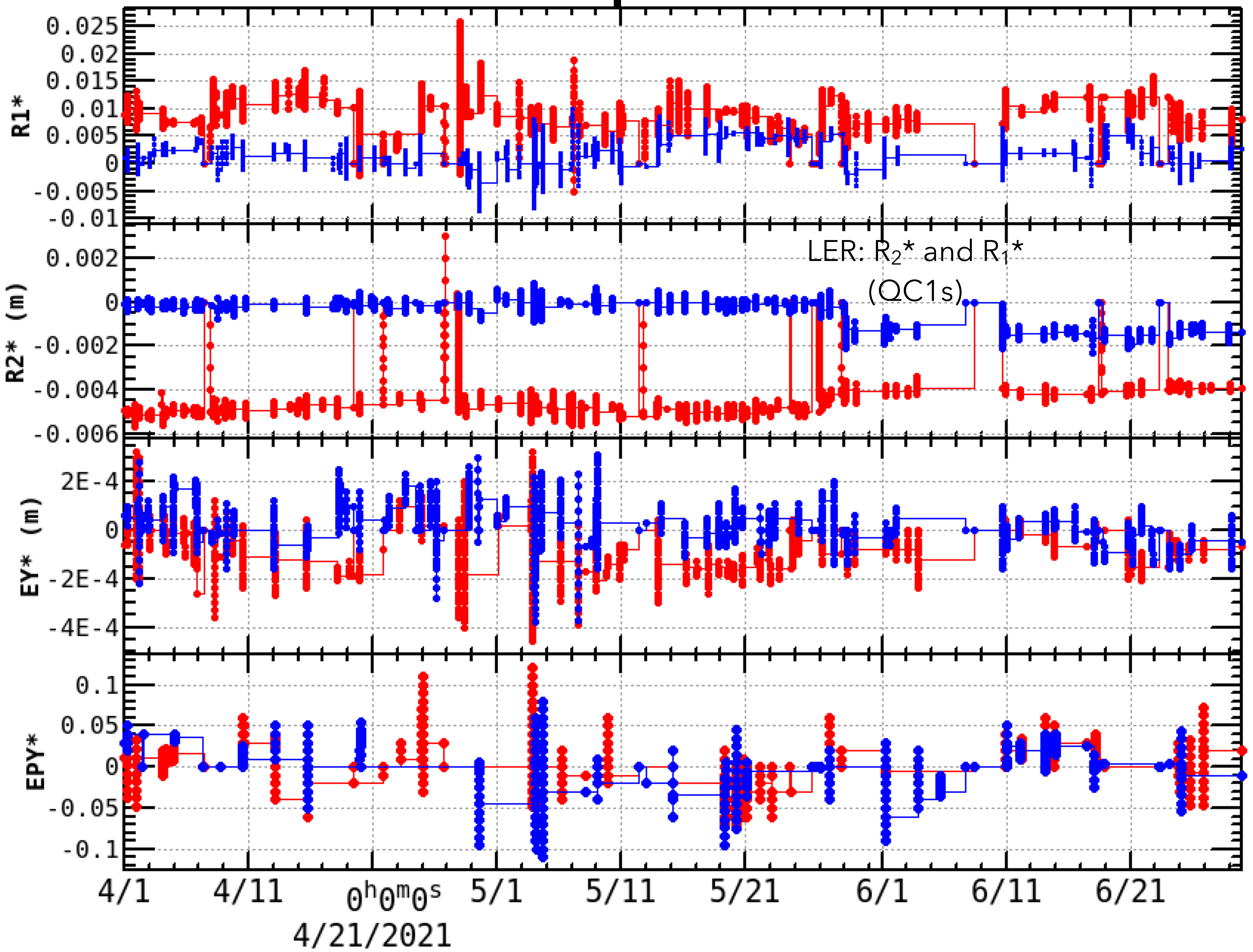


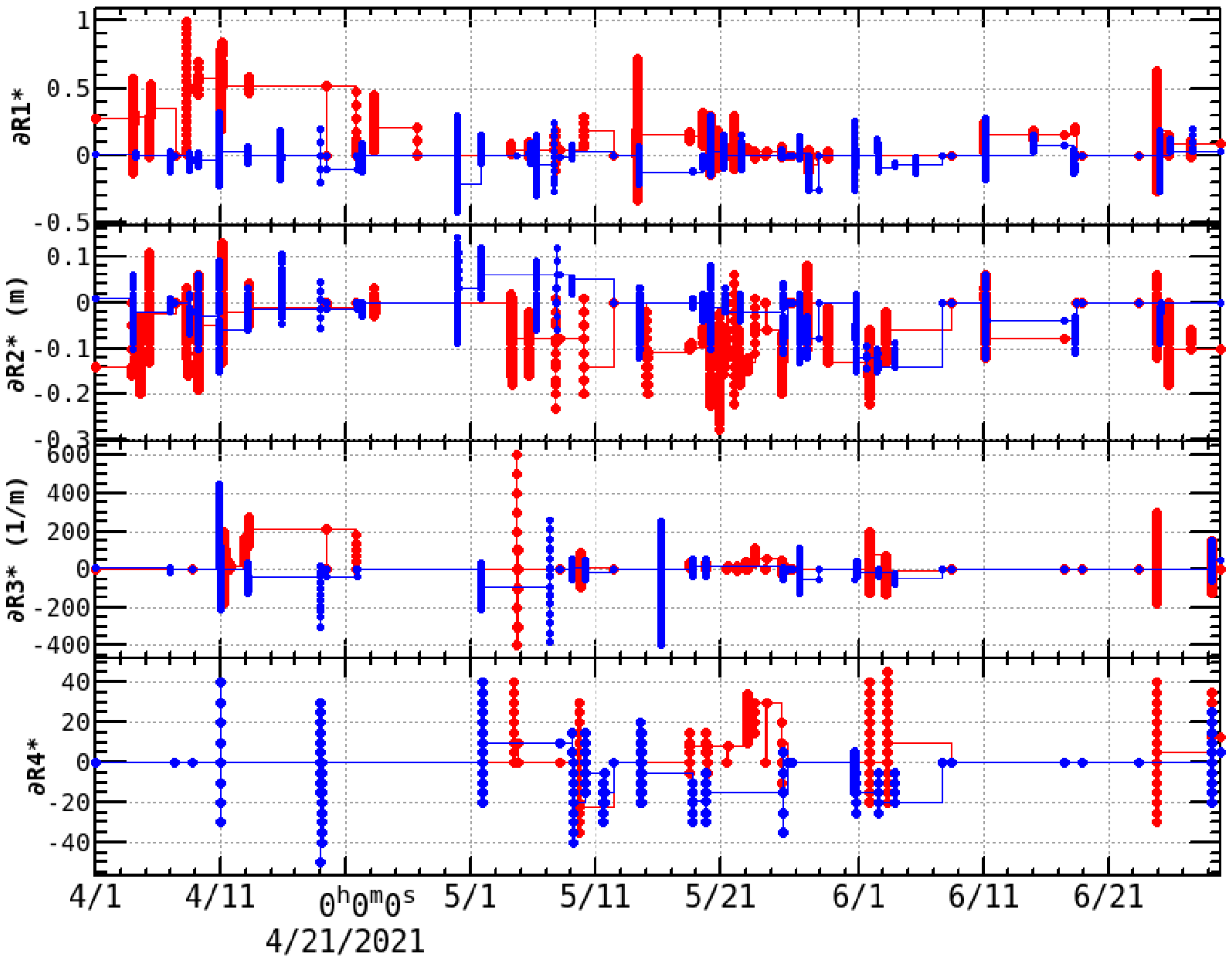


LER / HER

IP X-Y/Dispersion Knobs

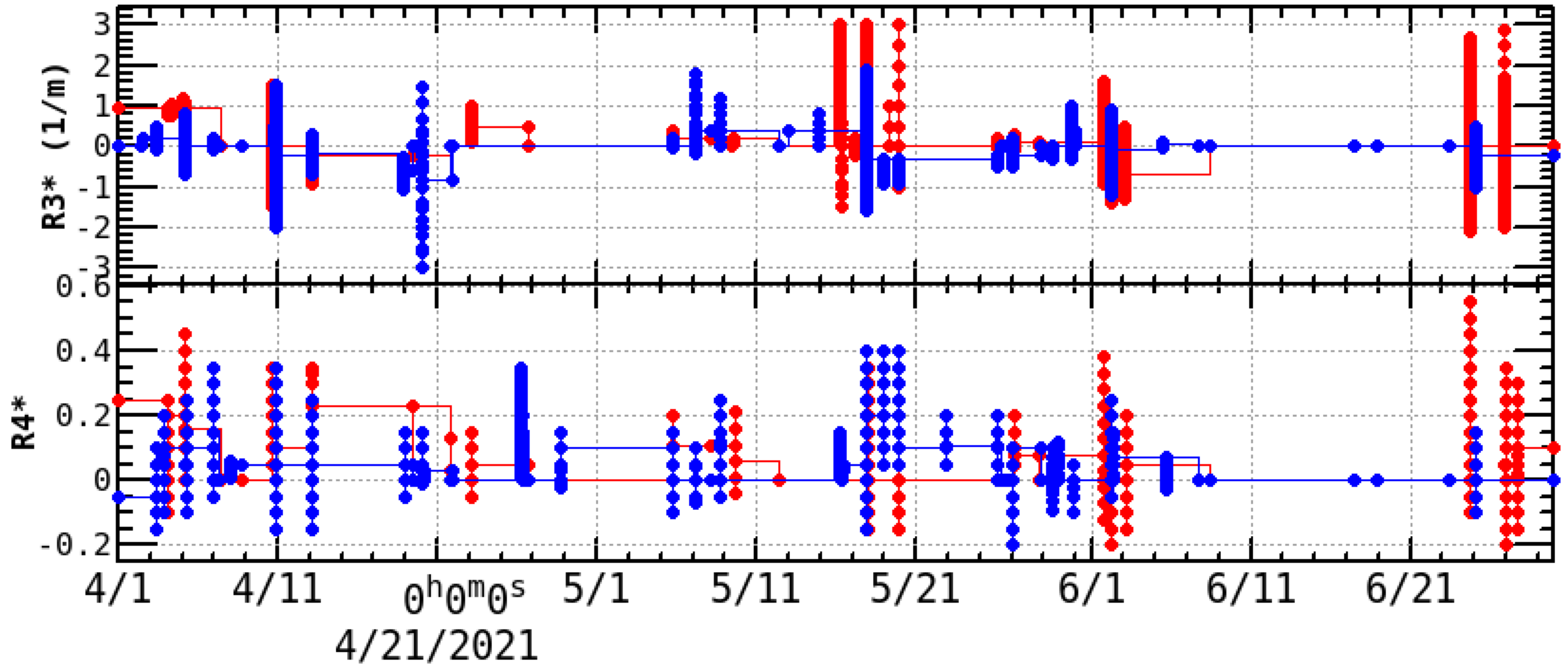


IP Chromatic X-Y Coupling Knobs



IP knob is separated for X-Y coupling and chromatic knobs. (new knobs)

A. Morita



R_1* and R_2* are almost fixed to optimize luminosity.

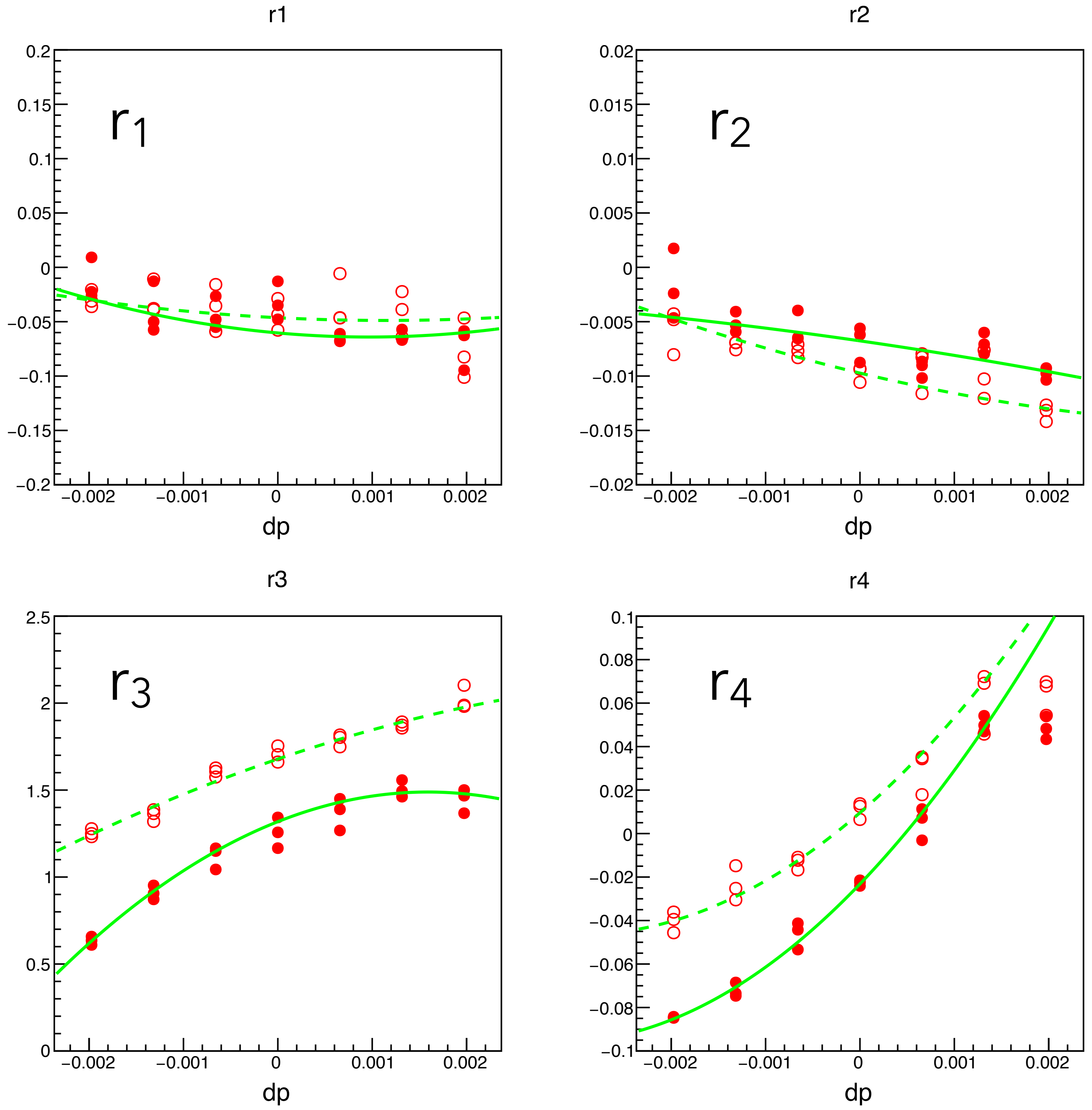
R_3* and R_4* affect beam background.

- Sextupole magnet mounted on rotating table is utilized since March 11 to suppress IP chromatic X-Y (model).
- Corrector strength and/or BG sometime limits the knob.
- Reduction of B-B blowup is not clear so far.

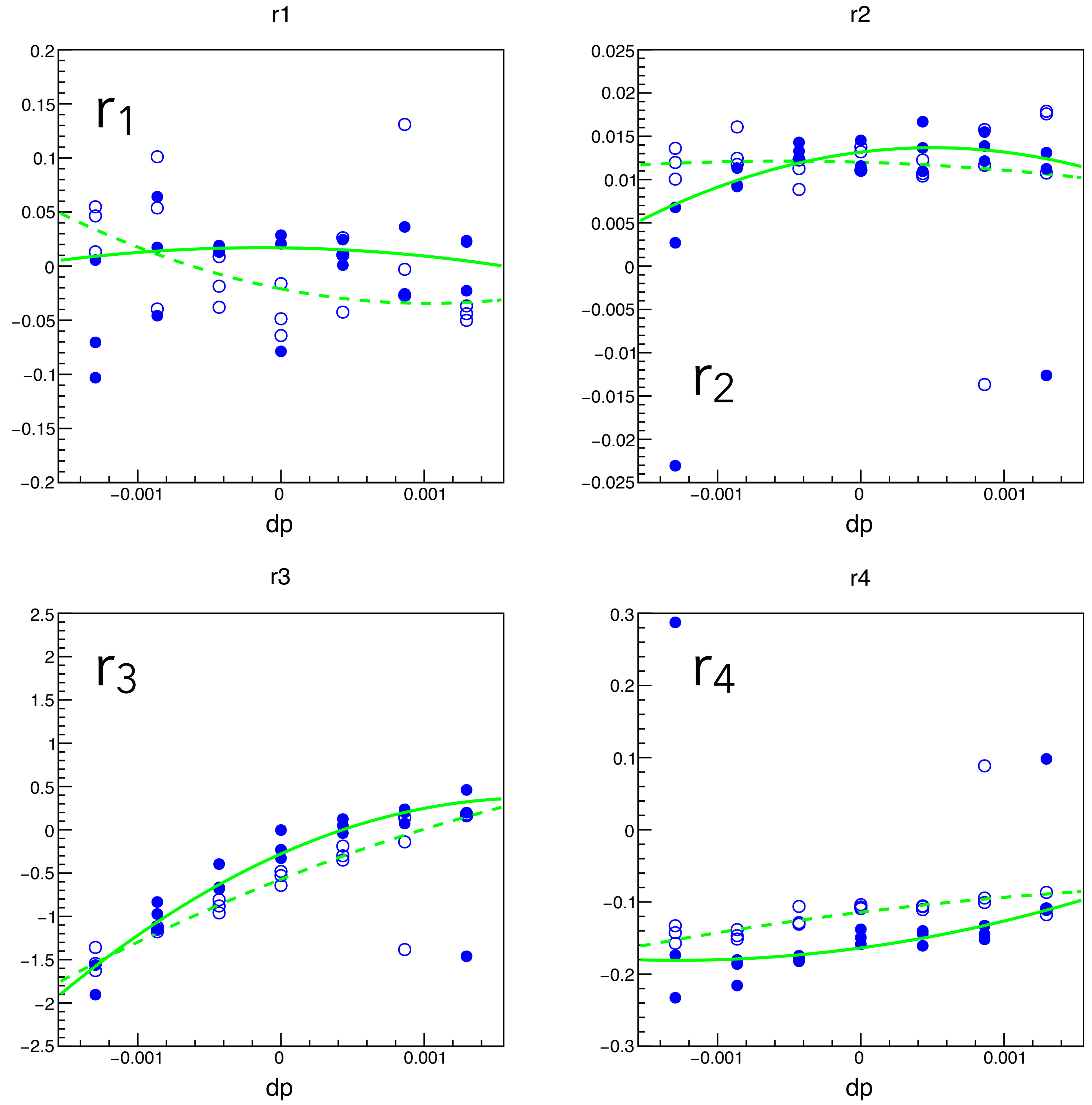
Chromatic X-Y couplings using TBT BPMs

G. Mitsuka

LER



HER



Ohmi-san's criterion

$r_1' < \pm 12$

$r_2' < \pm 3$ m

LER

IP chromatic knob on

r_1	-6.034E-02	**-7.764**	4.012E+03	+0.08
r_2	-6.763E-03	**-1.254**	-8.22E+01	-0.1
r_3	1.318	214.6	-6.755E+04	
r_4	-2.319E-02	45.24	6.998E+03	+13

IP chromatic knob off

r_1	-4.634E-02	-4.379	1.91E+03
r_2	-9.726E-03	-2.079	2.188E+02
r_3	1.678	185.0	-1.746E+04
r_4	9.563E-03	37.54	6.274E+03

HER

IP chromatic knob on

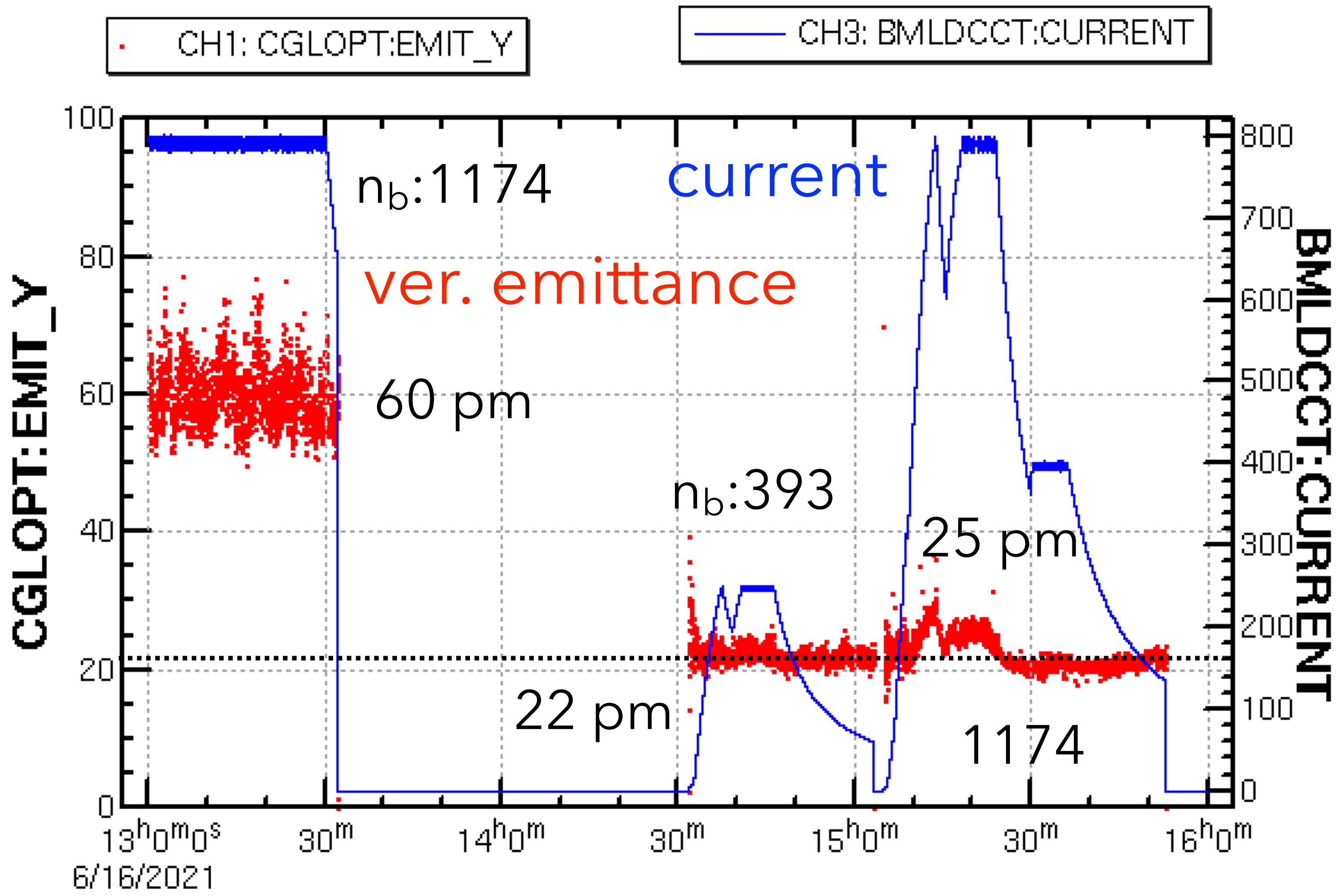
r_1	1.69E-02	**-1.644**	-5.91E+03	+0.03
r_2	1.317E-02	**2.028**	-2.022E+03	
r_3	-2.772E-01	733.0	-2.082E+05	+50
r_4	-1.637E-01	26.81	1.044E+04	+5

IP chromatic knob off

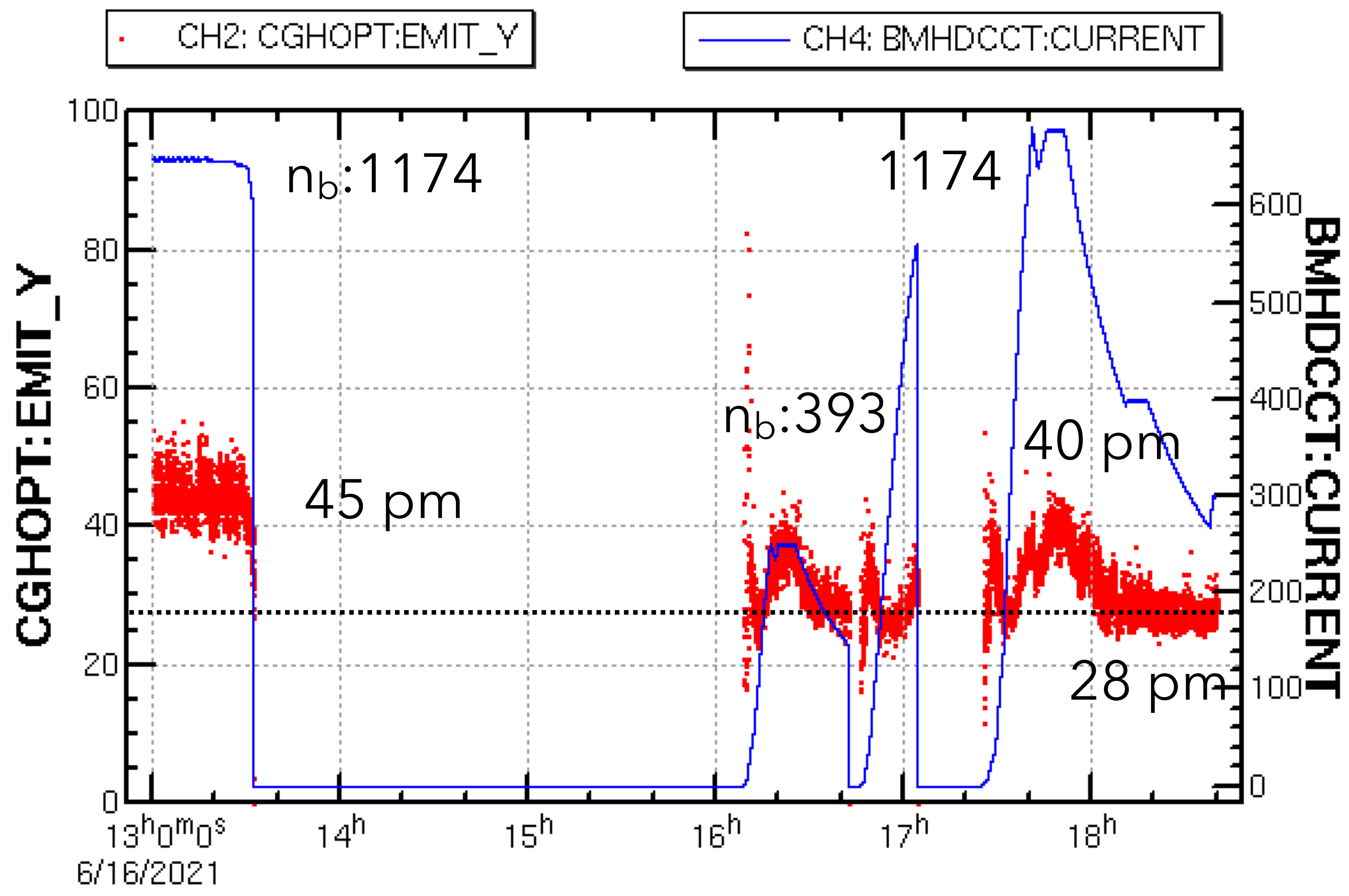
r_1	-2.095E-02	-25.99	1.256E+04
r_2	1.2E-02	-0.4769	-4.409E+02
r_3	-5.715E-01	652.4	-7.325E+04
r_4	-1.142E-01	24.53	-3.876E+03

Beam Lifetime and Vertical Emittance

LER



HER

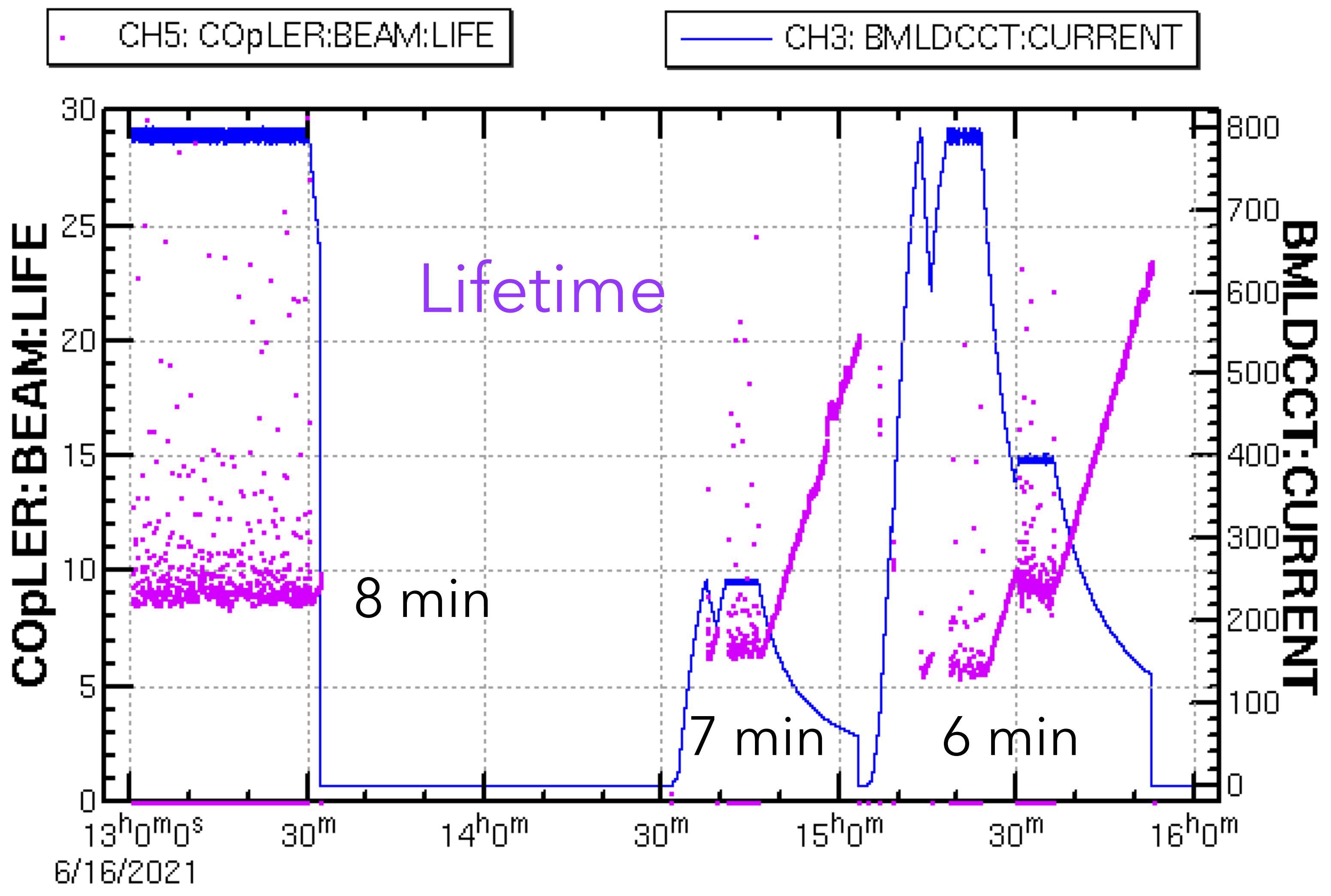


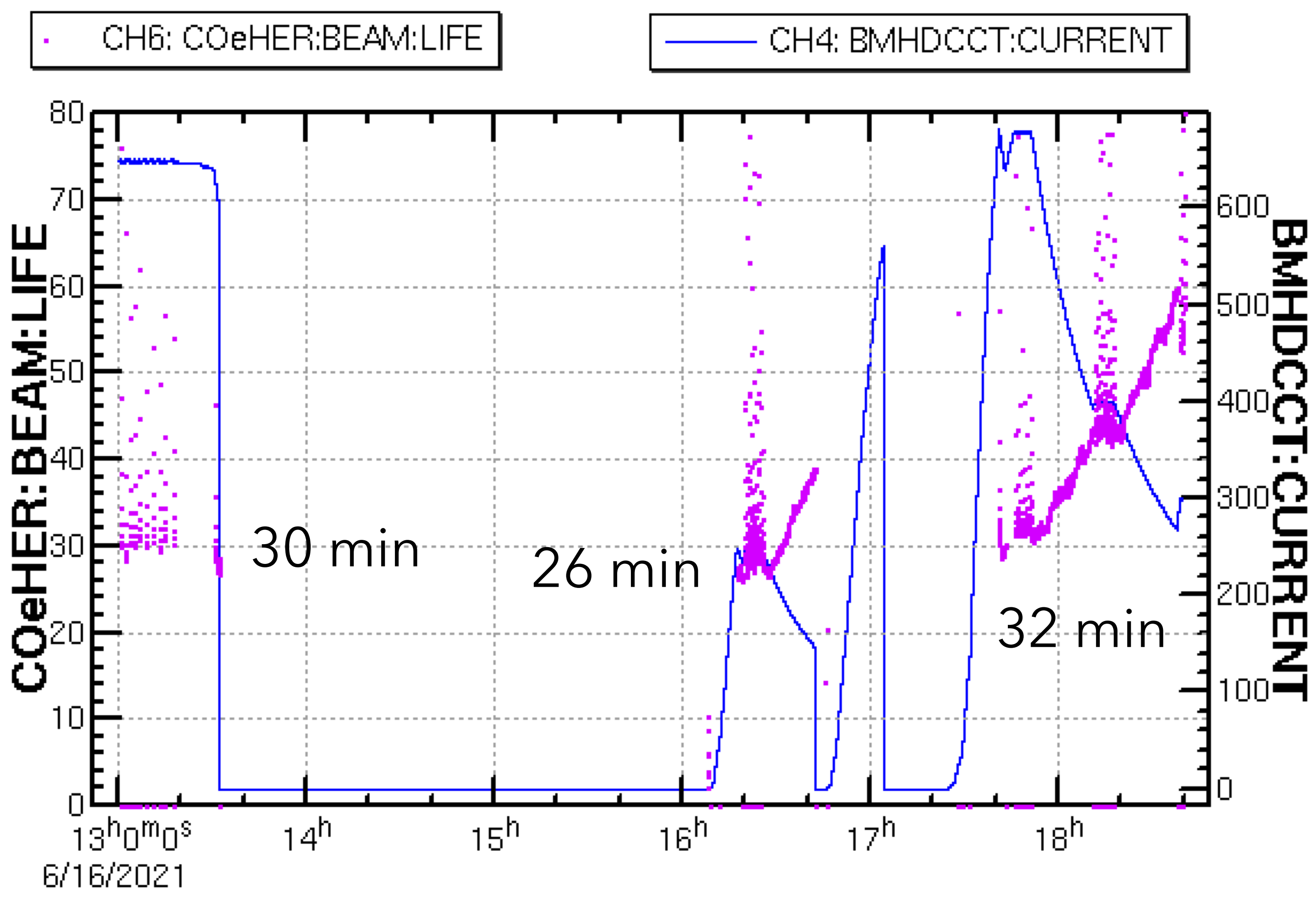
collision **single beam**

collision **single beam**

ε_y depends on bunch current.

	LER	HER
β_x^*	80 mm	60 mm
β_y^*	1 mm	1 mm
I	800 mA	650 mA
n_b	1174	1174
I_b	0.681 mA	0.545 mA
ε_y collision	60 pm	45 pm
ε_y single	25 pm	40 pm
life collision	8 min	30 min
life single	6 min	32 min





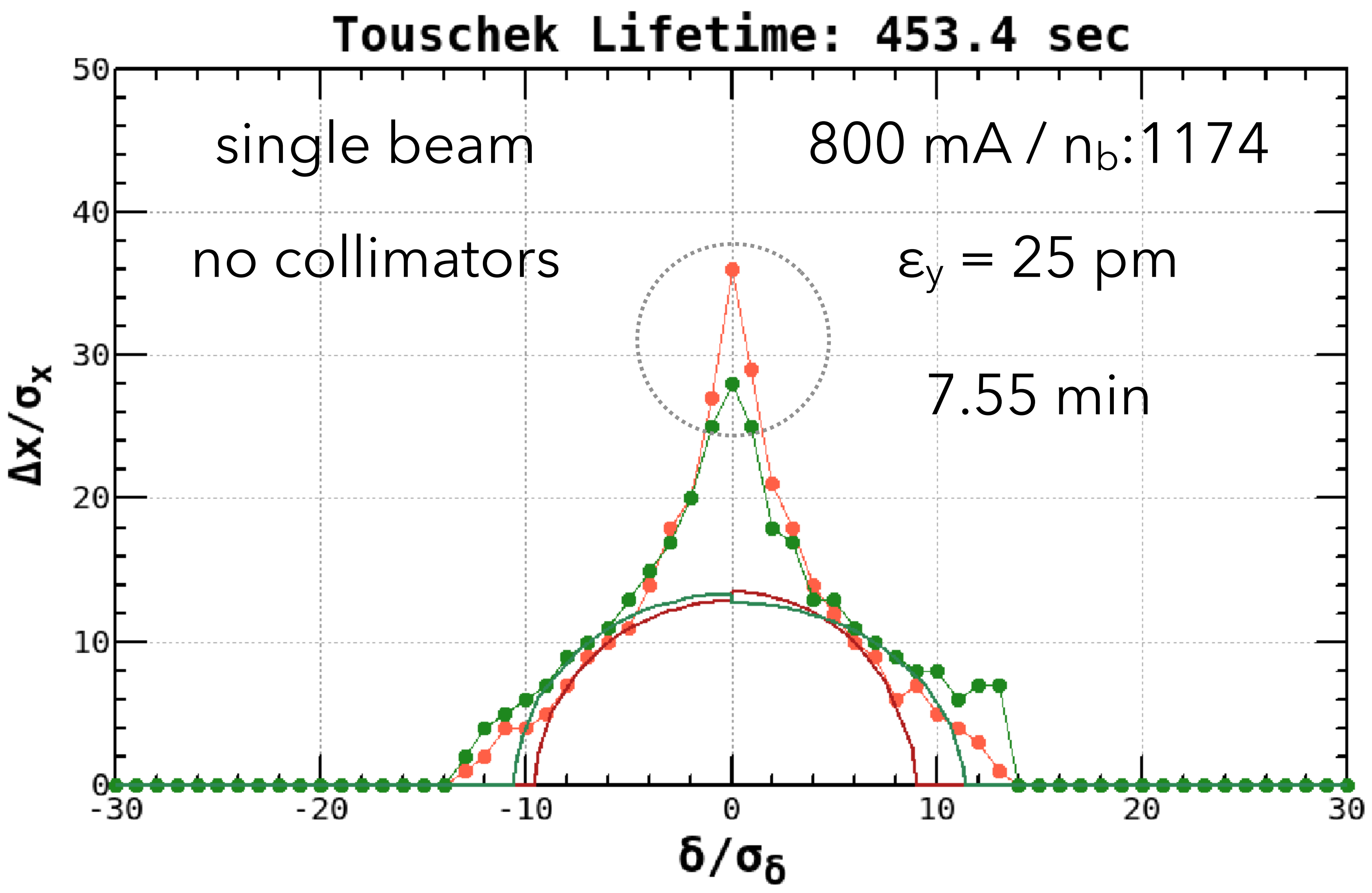
e^+_{inj}: 2 nC x 2 x 12.5 Hz x 80 %

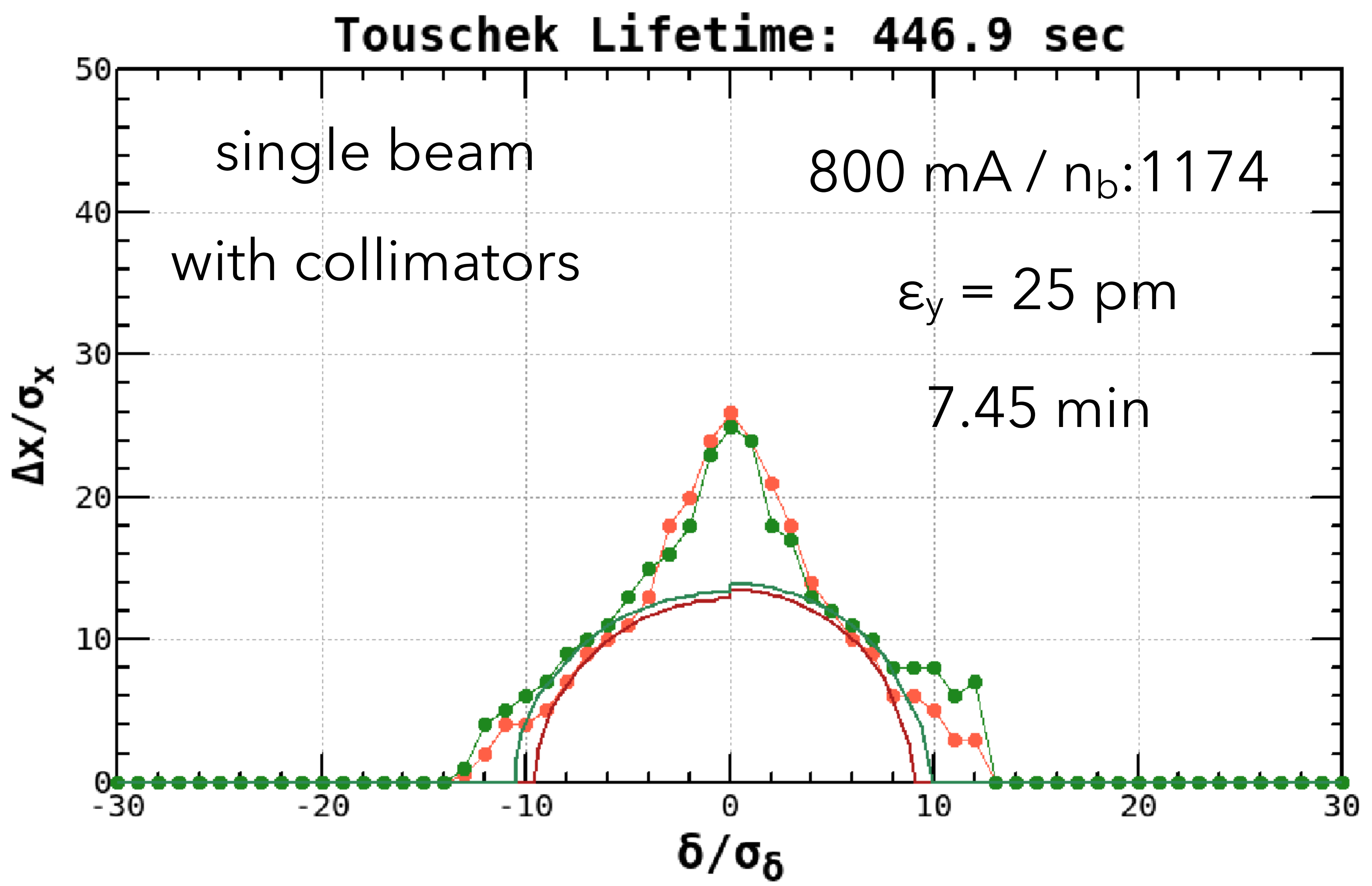
I_{max}= 1.9 A for lifetime: 8 min

(TMCI limit : 1.4 A with n_b:1565)

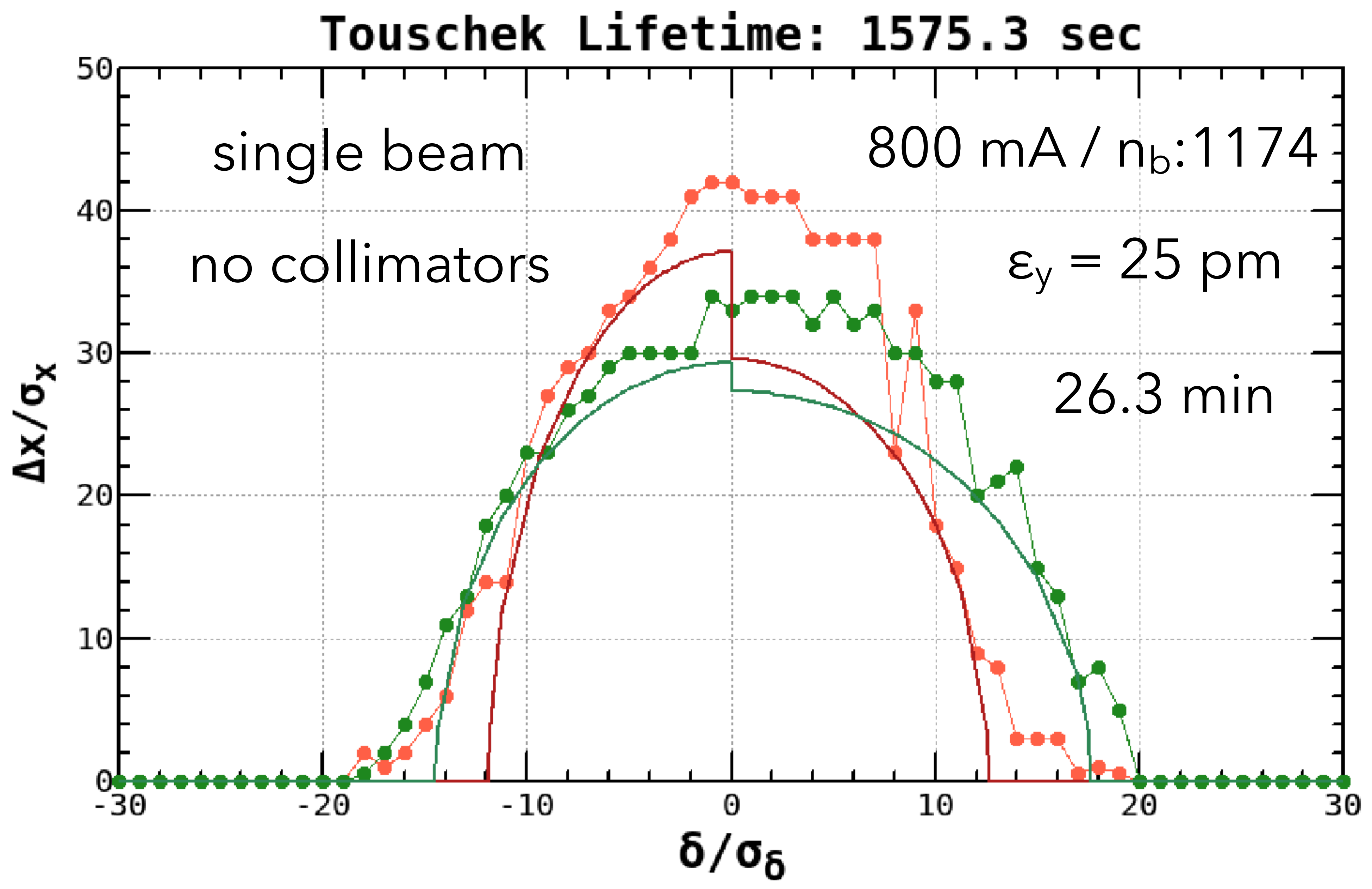
Tracking Simulation
No Machine Error

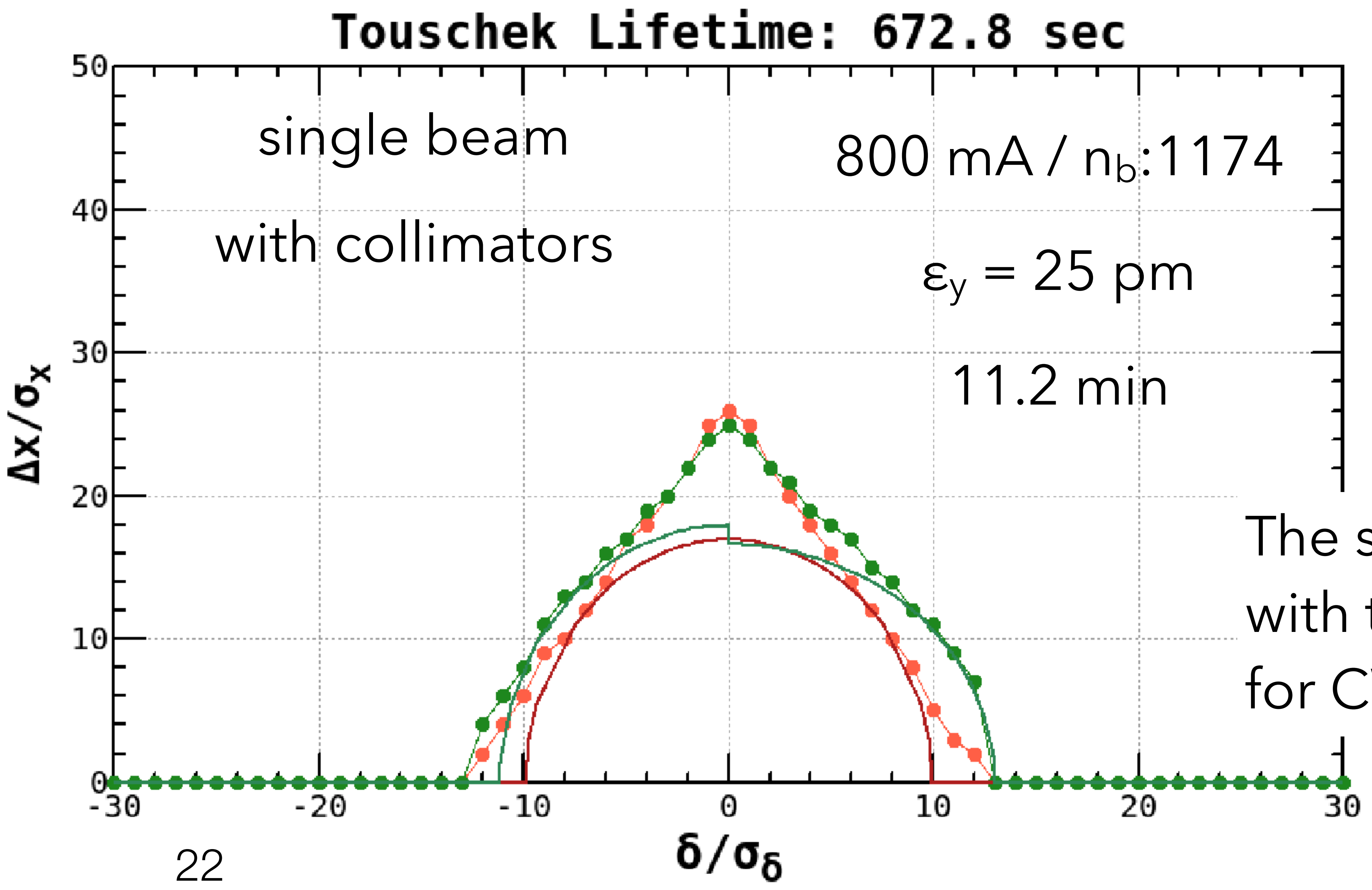
LER : CW 80 %





LER : CW 0 %



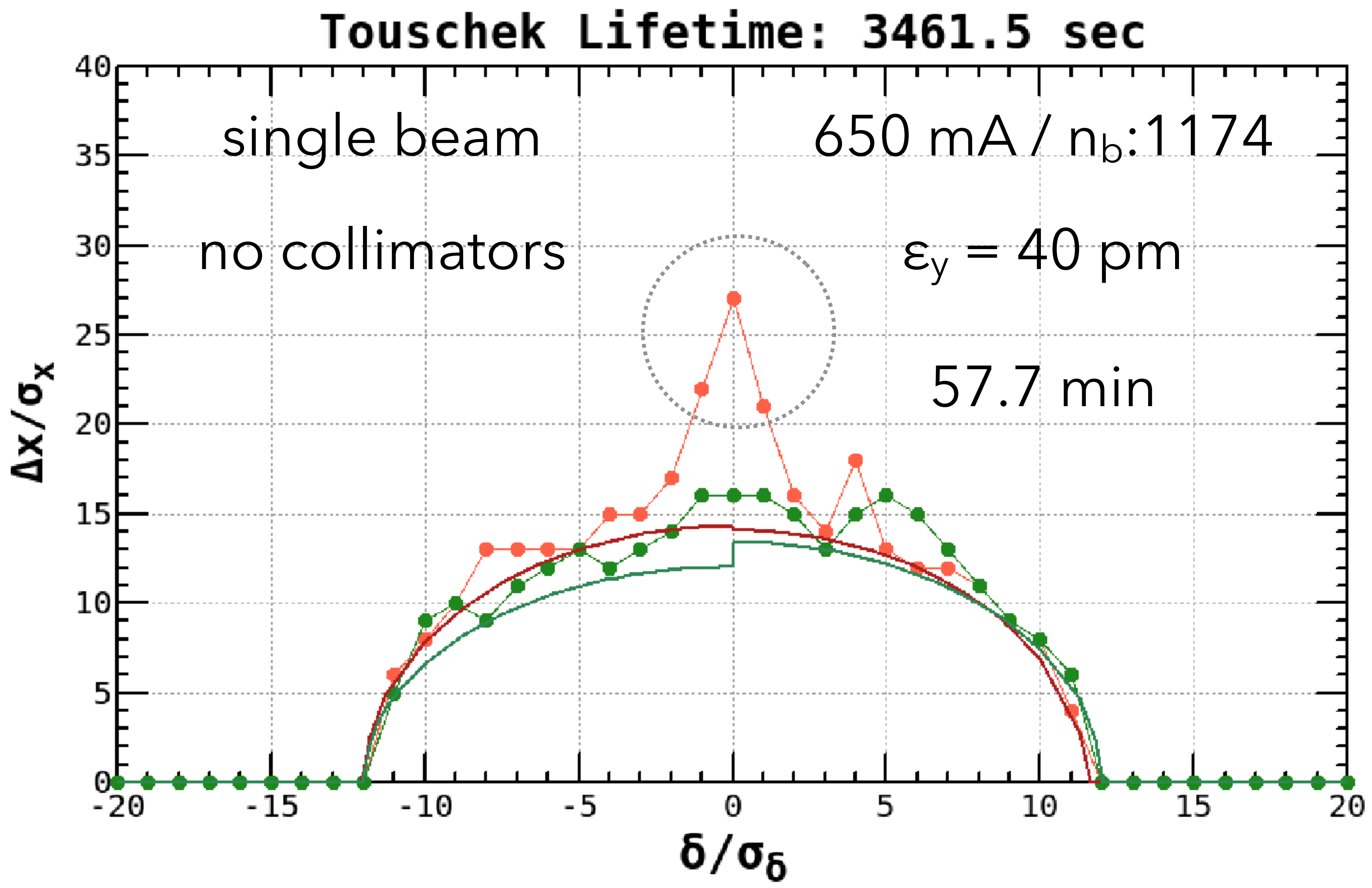


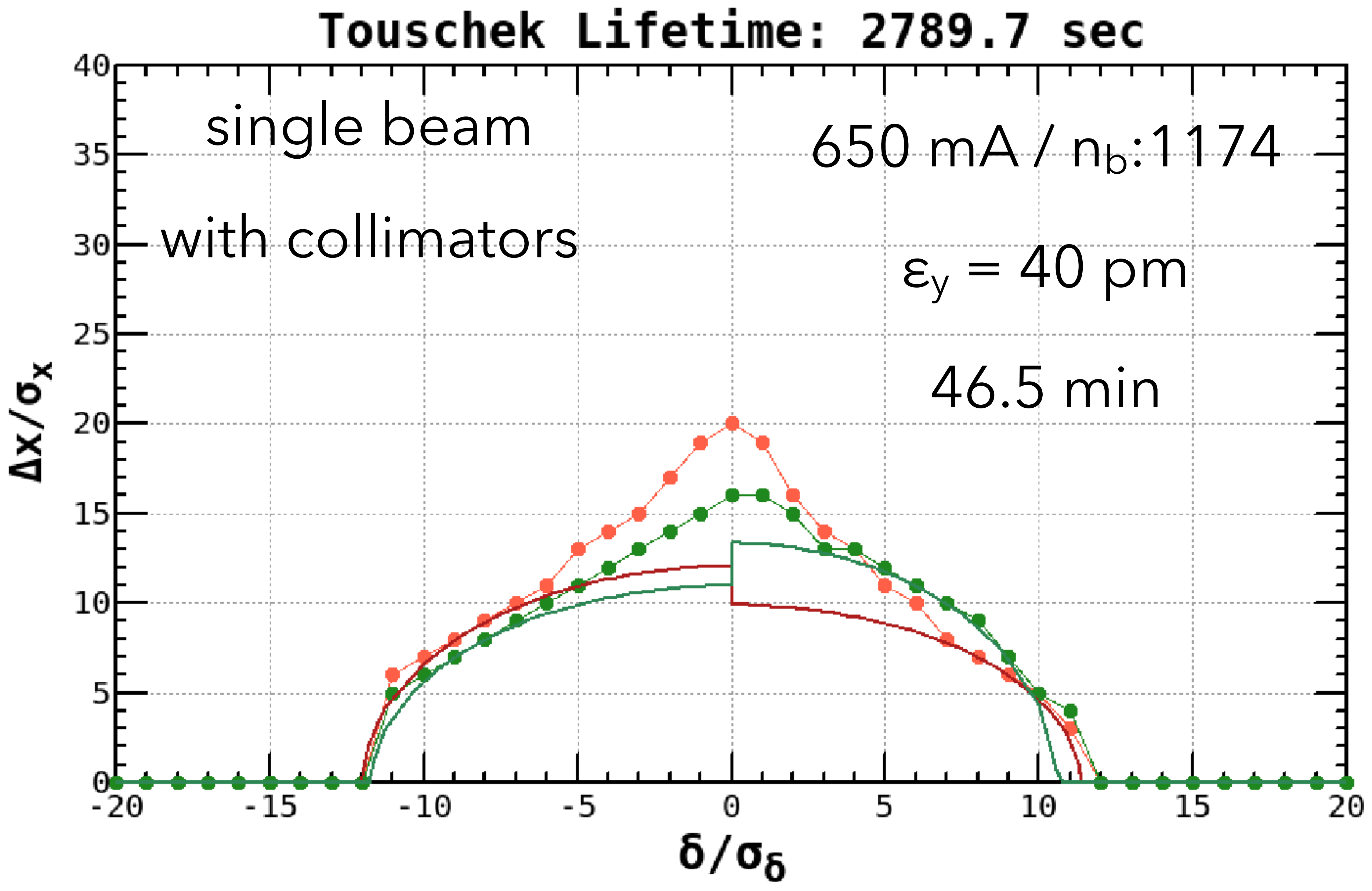
Touschek lifetime is similar to CW 80% with collimators.

The simulation is consistent with the measured lifetime for CW 80 %.

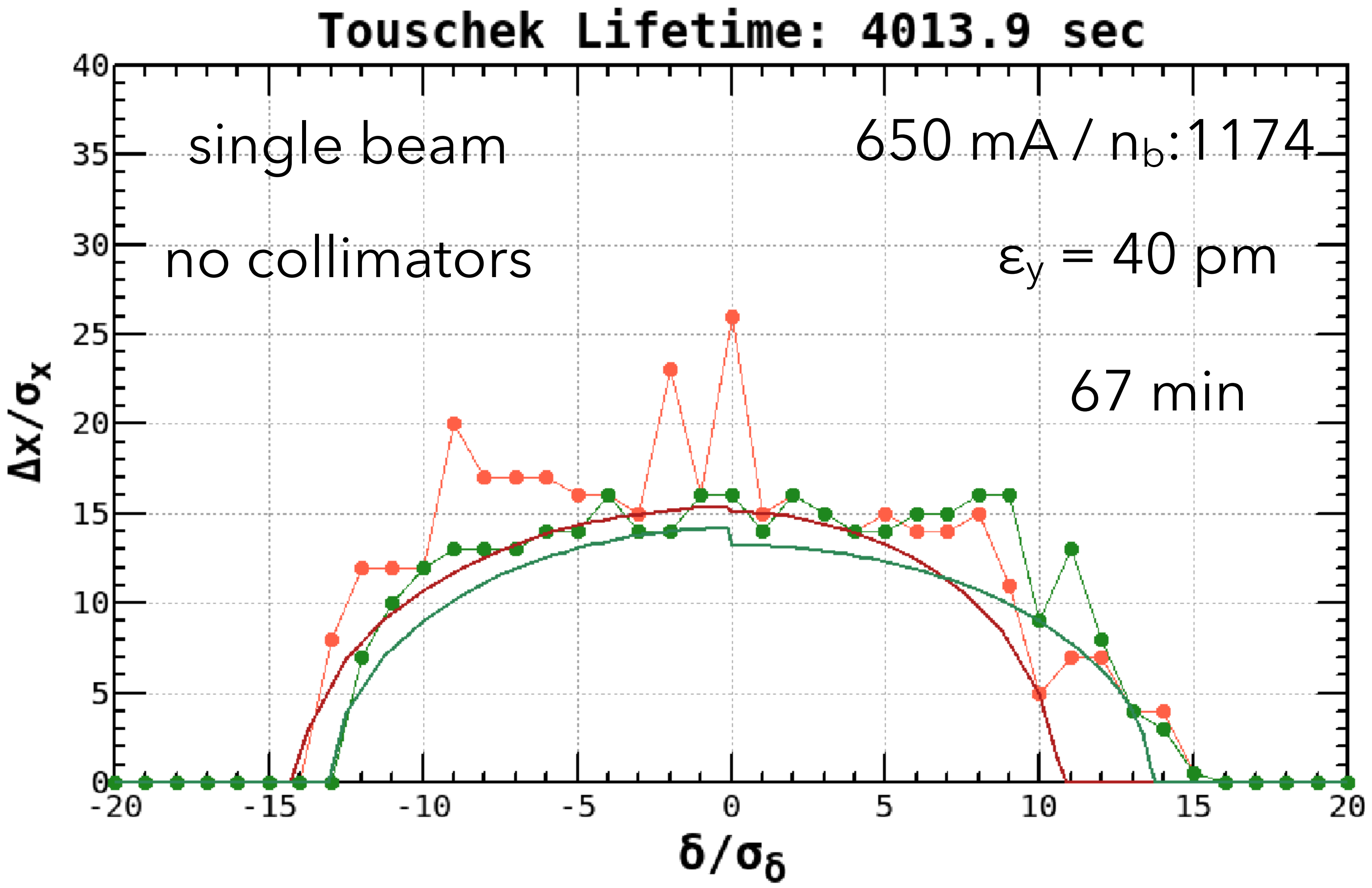
Tracking Simulation
No Machine Error

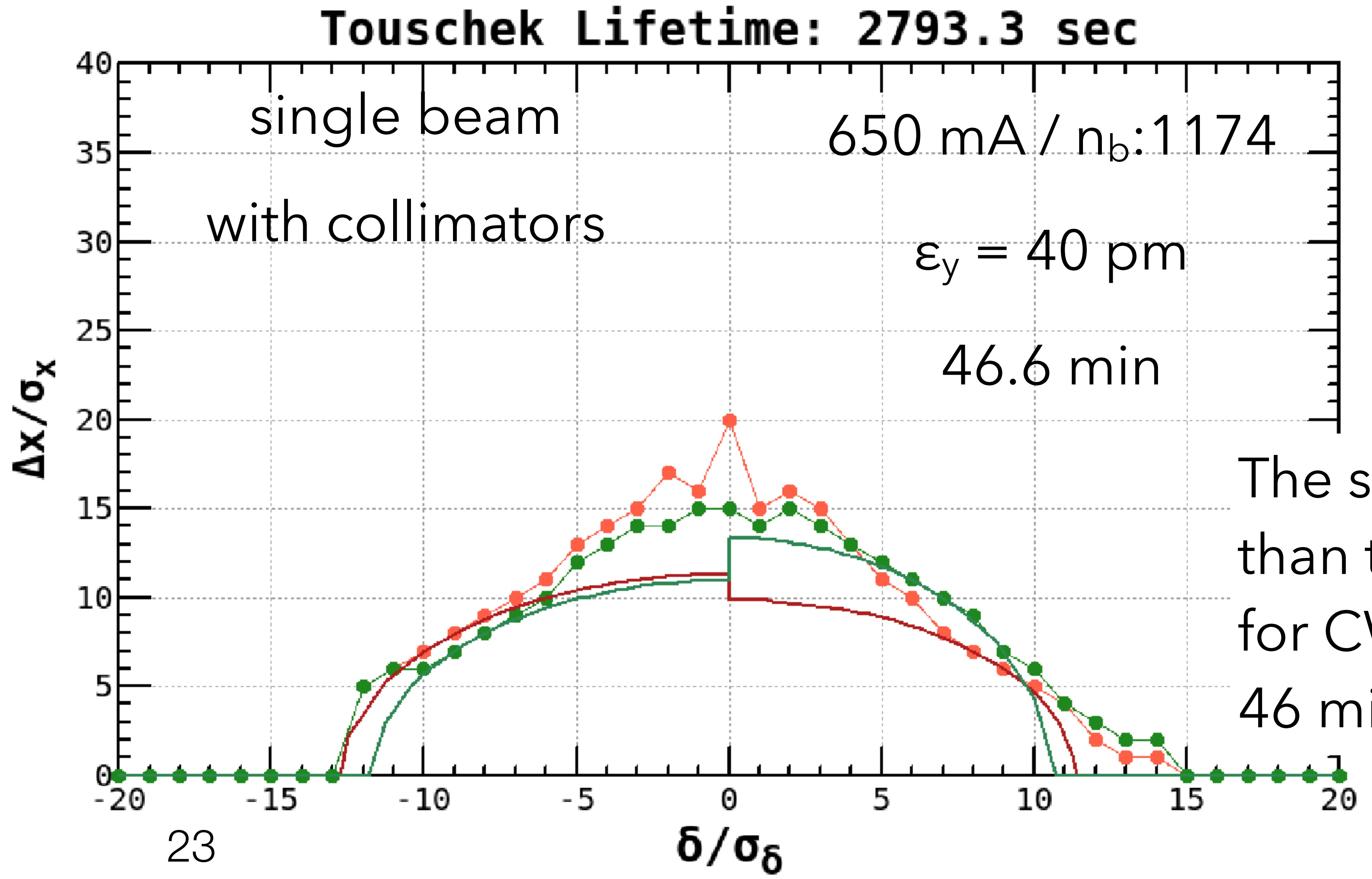
HER : CW 40 %





HER : CW 0 %





Touschek lifetime is similar to CW 40% with collimators.

The simulation is longer than the measured lifetime for CW 40 %.
46 min > 32 min

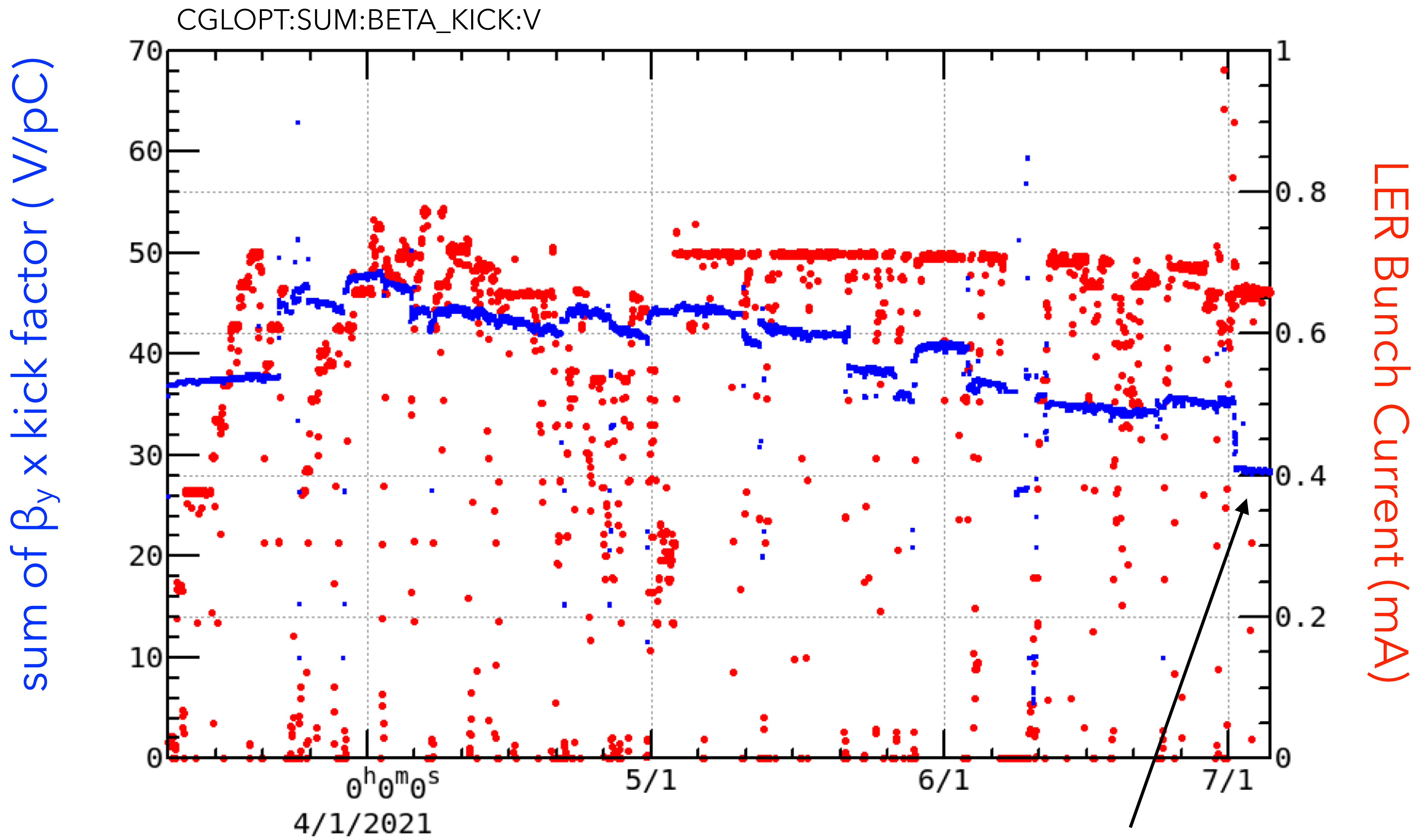
Lifetime and Vertical Emittance

- LER
  - The ε_y is 22 pm - 25 pm for the single beam.
  - The ε_y increases up to 60 pm due to beam-beam blowup at 800 mA(0.68 mA/bunch).
  - The luminosity reduction is 65 %.
  - The DA can almost explain the measured lifetime.
  - The crab waist reduces the DA. But the tight collimators reduce the PA significantly. The collimators make small difference between CW 0 % and CW 80 %.
  - The lifetime is about 8 min for collision at 800 mA. It is quit shorter than what we expected.
- HER
  - The ε_y is 28 - 40 pm which depends on the bunch current.
  - Beam-beam blowup is mild. It is from 40 pm to 45 pm at 650 mA(0.55 mA/bunch).
  - The collimators reduce the DA significantly. It is same as the LER
  - The measured lifetime is shorter than the simulation. (32 min < 46 min; vacuum lifetime not included)

LER Collimator Impedance

Transverse Mode Coupling Instability (TMCI)

Kick factor (vertical) depends on D02V1, D03V1, D06V2, D06V1.

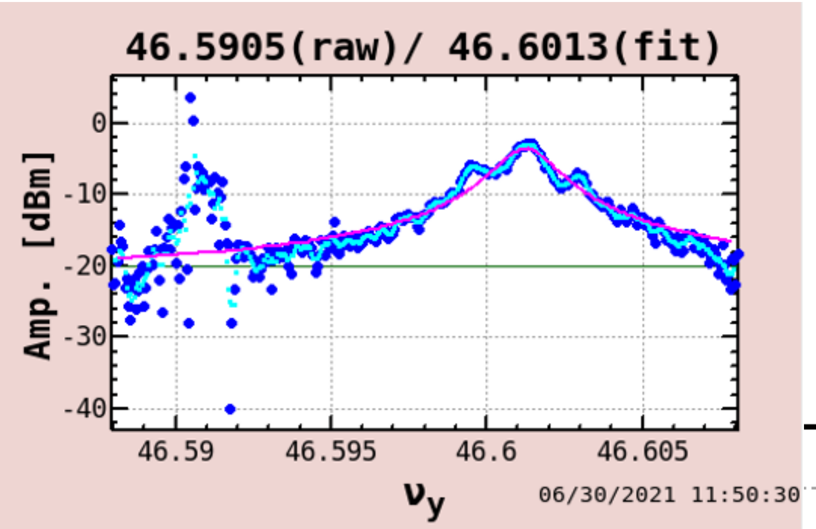


collimator opened (test)

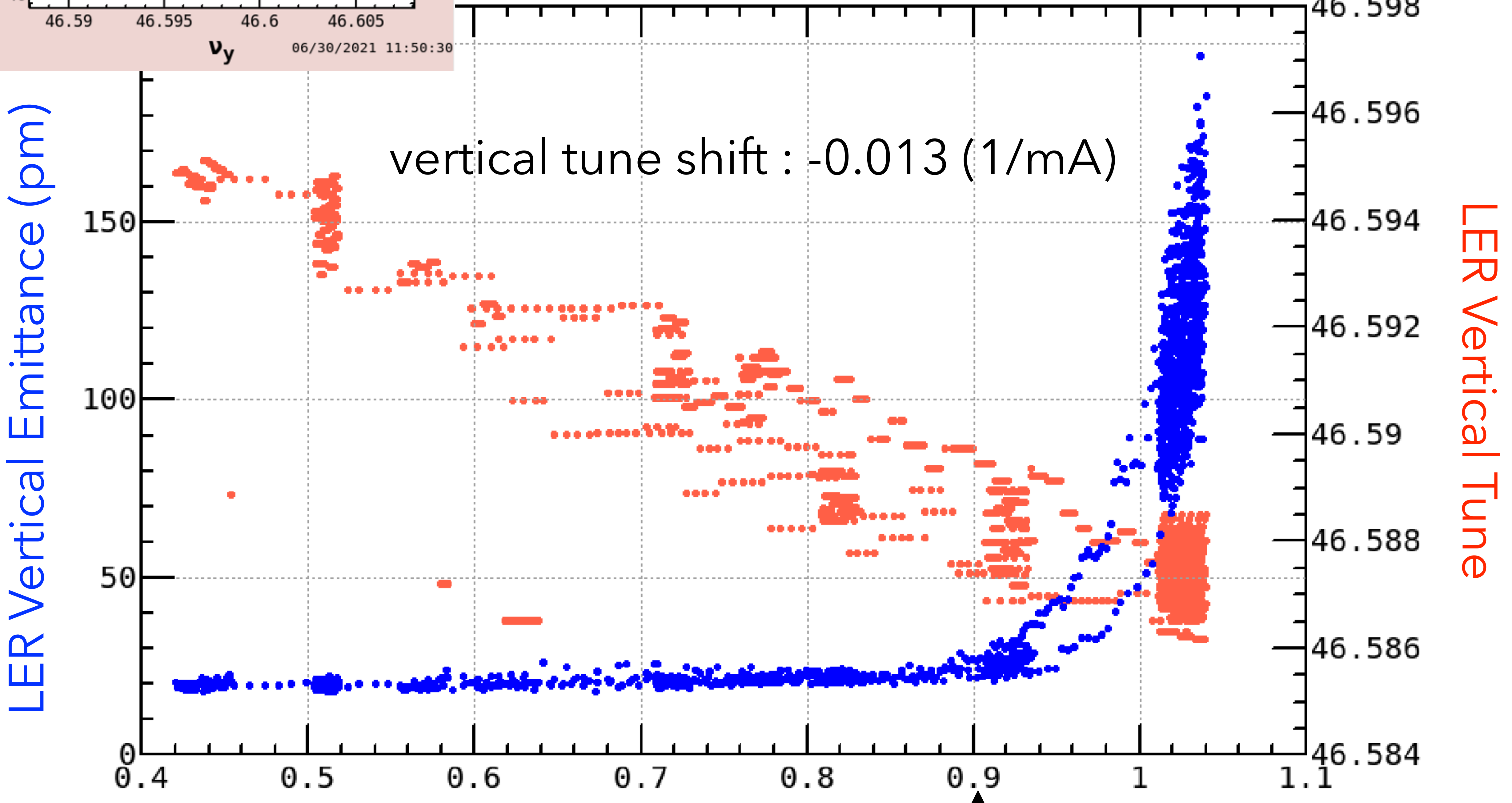
$$\Delta\nu_{y,th} = \frac{T_0 I_{th} \sum_i \beta_{yi}\kappa_i}{4\pi E/e} = \frac{\nu_s}{2}$$

$$f_s = \frac{\nu_s}{T_0}$$

f_s = 2.3325 (kHz)*



Σ β_y κ = 36 (V/pC) on June 30



$$I_{th} = \frac{2\pi f_s (E/e)}{\sum_i \beta_{yi}\kappa_i}$$ = 1.6 mA > 0.9 mA (measured)

The theoretical threshold is factor of 1.8 to the measured threshold.

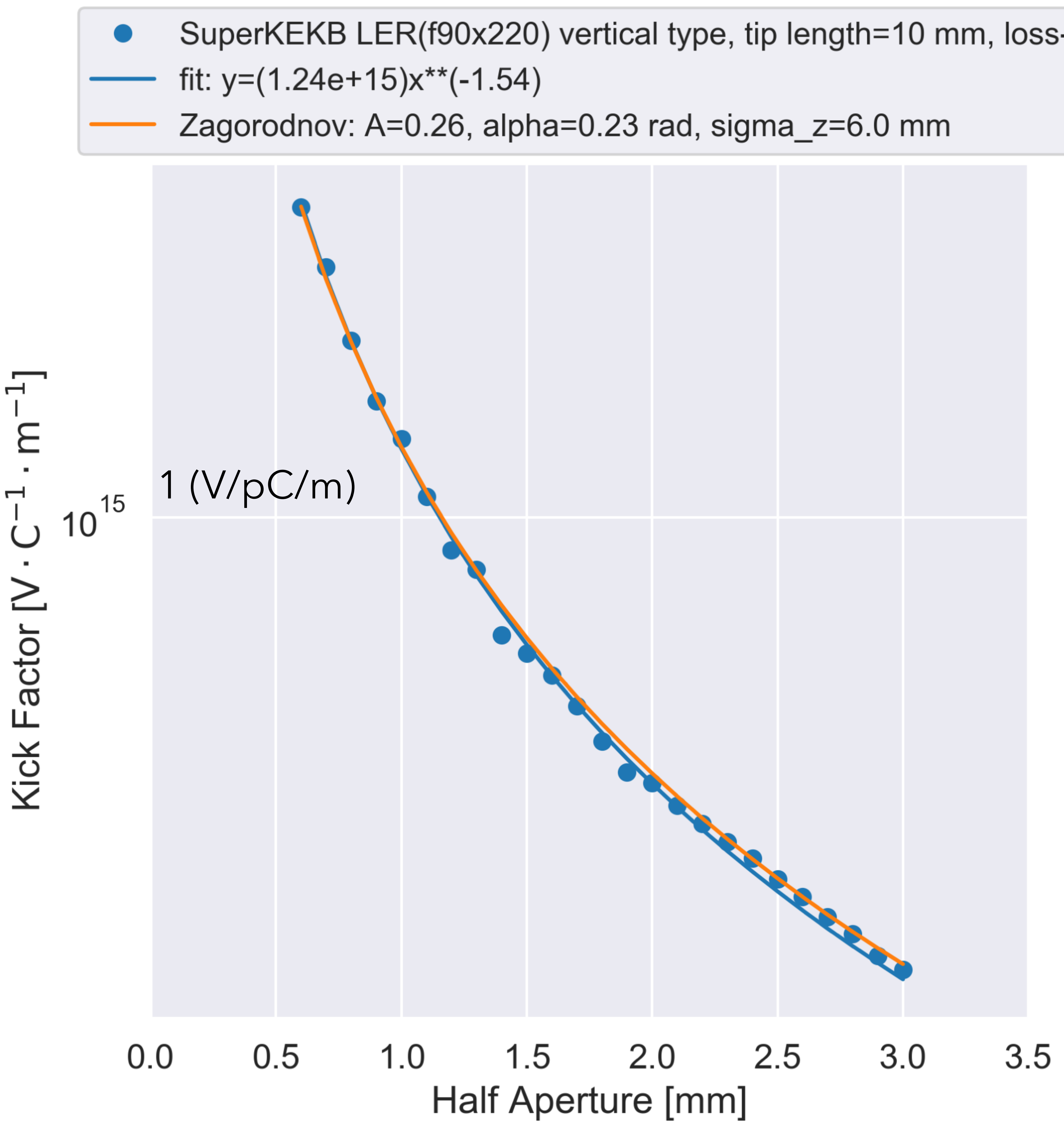
The measured kick factor is 1.8 times larger than the ***GdfidL*** simulator.

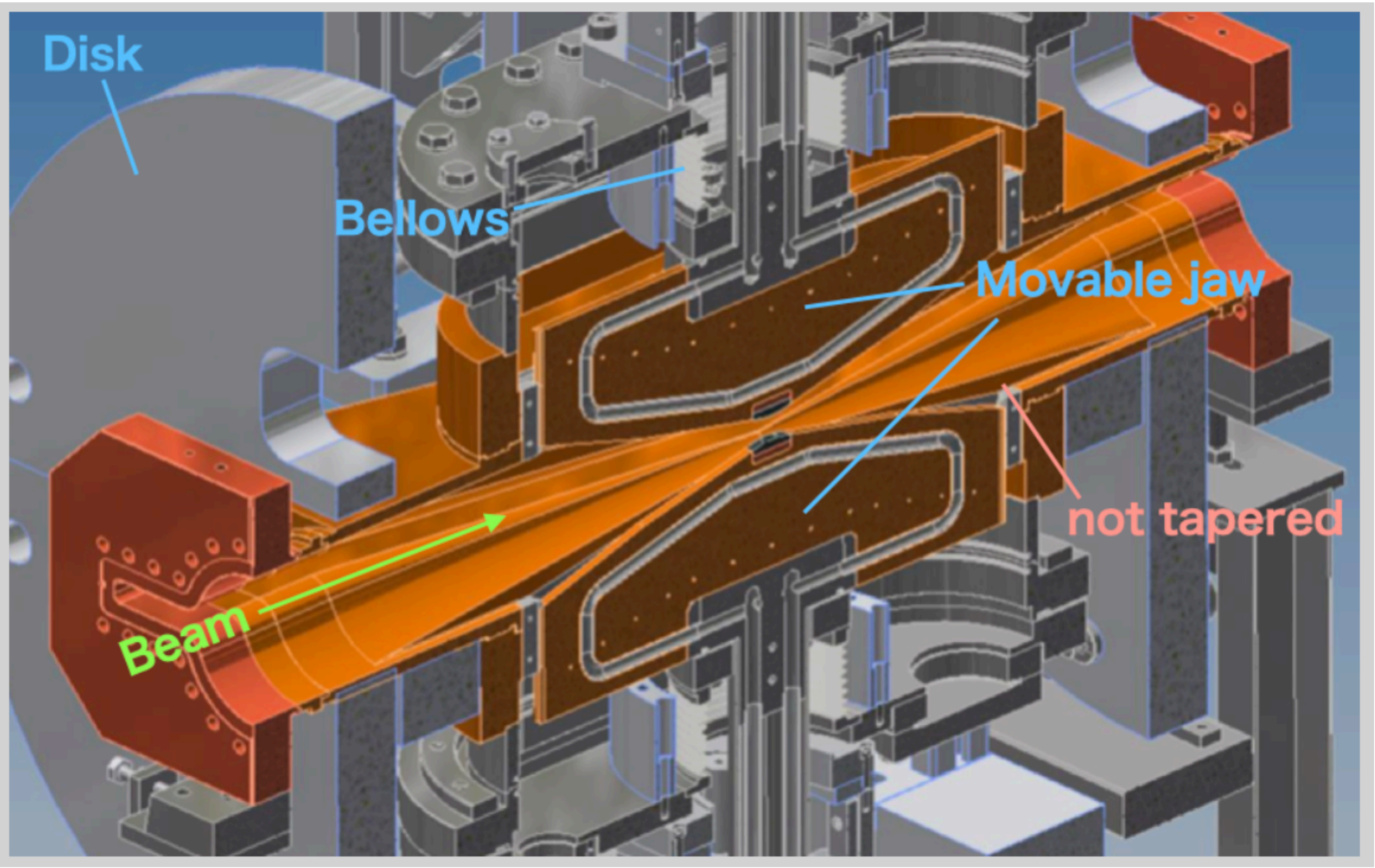
* measured value (M. Tobiyama)

Calculation of GdfidL Electromagnetic Field Simulator

T. Ishibashi

Length(along beam axis) of head : 10 mm





Zagorodnov's equation

$$k_{\perp} = 0.215 A Z_0 c \sqrt{\frac{\alpha}{\sigma_z d^3}}$$

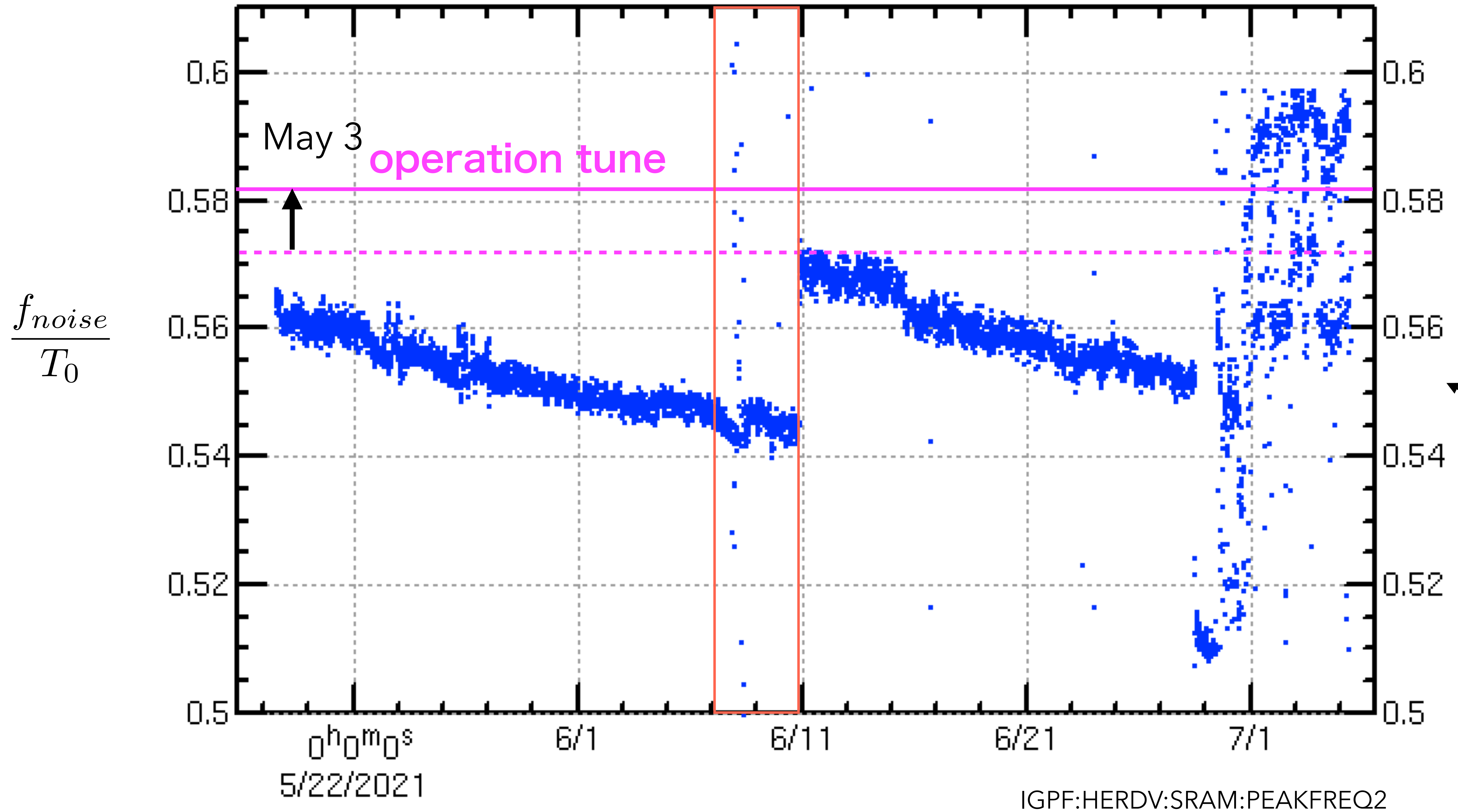
[I. Zagorodnov, Wakefield Calculations for 3D Collimators, EUROTeV-Report-2006-074.]

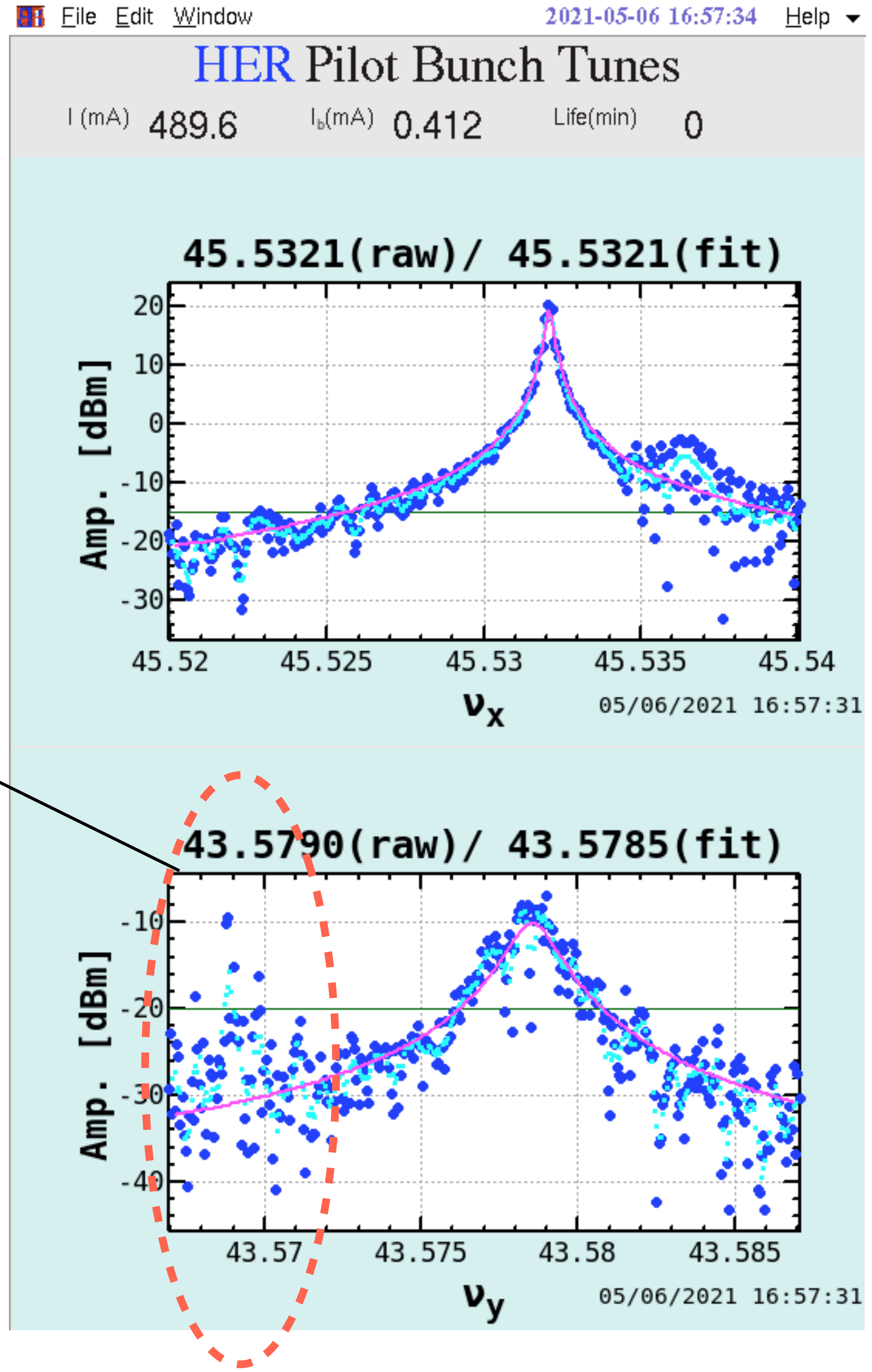
BxB Feedback Noise in HER

May 6

HER BxB FB noise is fixed on June 30.
NIM bin and fanout replacement

D02V1 replacement
and maintenance



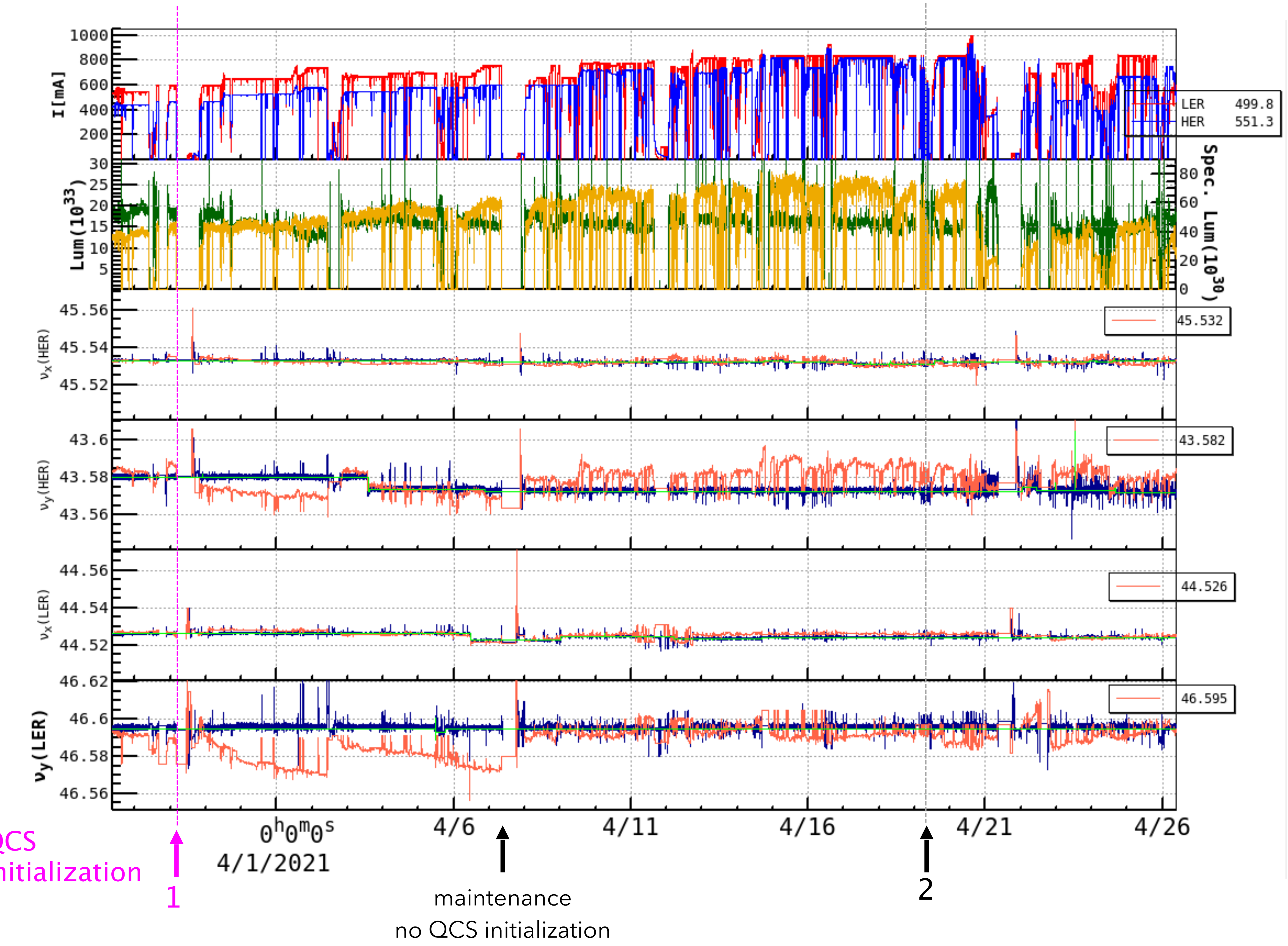


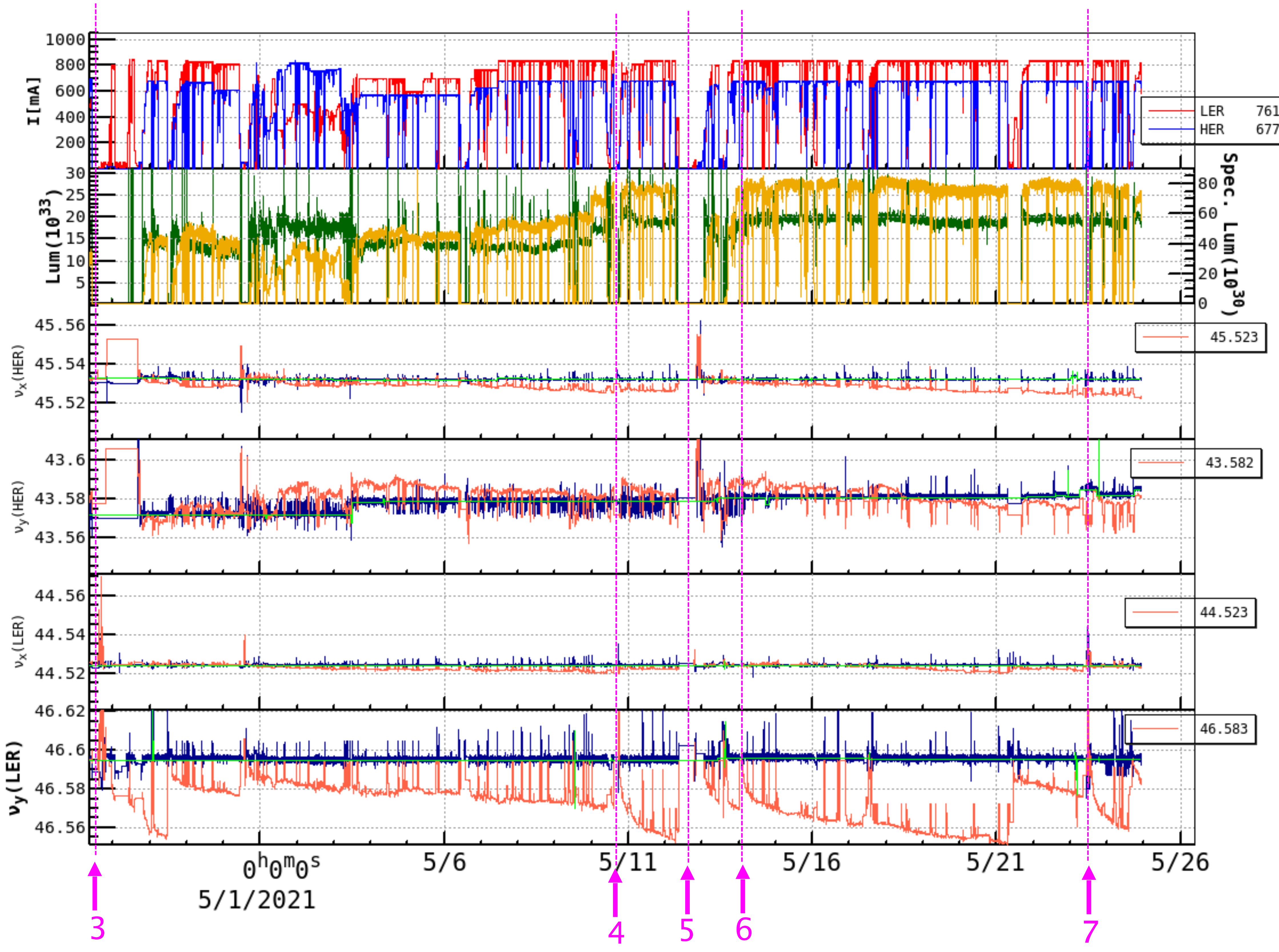
M. Tobiyama

The noise moved away from the working point on May 14.

Tune History: Optics degradation

H. Koiso





1. 3/28 Magnet PS QC1LE Charging Volt I/L Trouble
2. 4/19 QC1LE quench
   (4/21 On -> Off-resonance)

3. 4/26 Off -> On-resonance
4. 5/10 QC1RP & QC1LP quench
5. 5/12 Maintenance
6. 5/14 QC1RP quench
7. 5/23 QC1RP & QC1LP quench

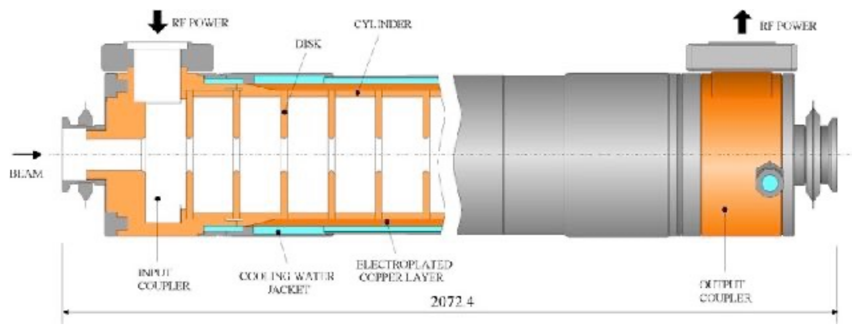
Discrepancy between model and measurement of ν_y increases rapidly after QCS initialization with optics corrections.
When we skip the QCS initialization, the discrepancy becomes small. QCS coils move slowly or field/orbit drifting ?

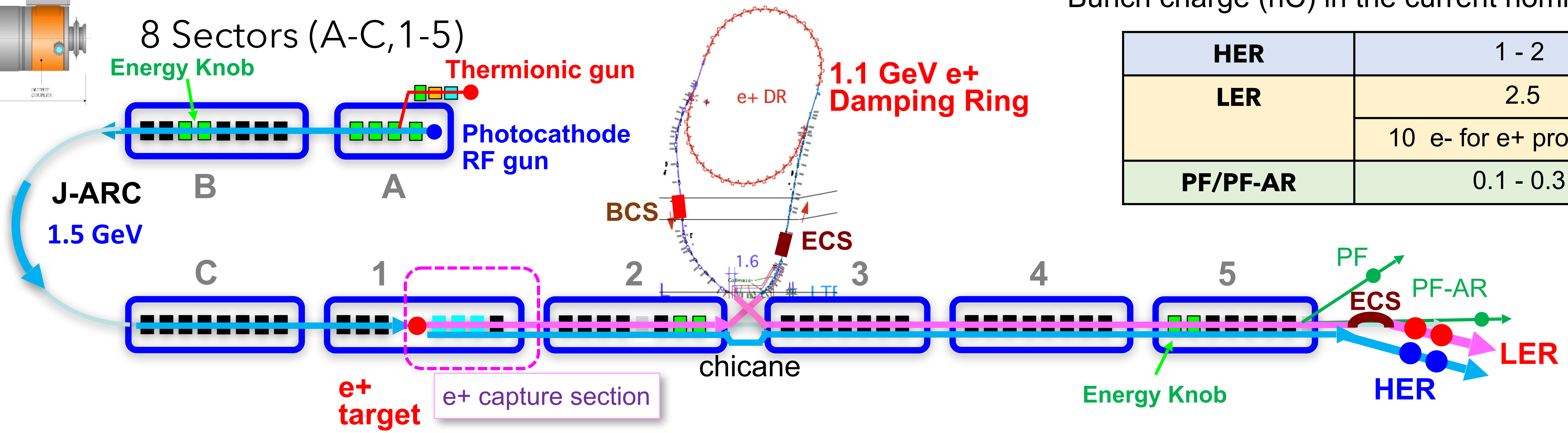
Injector Linac, Beam Transport, Injection System

Injector Linac

M. Satoh

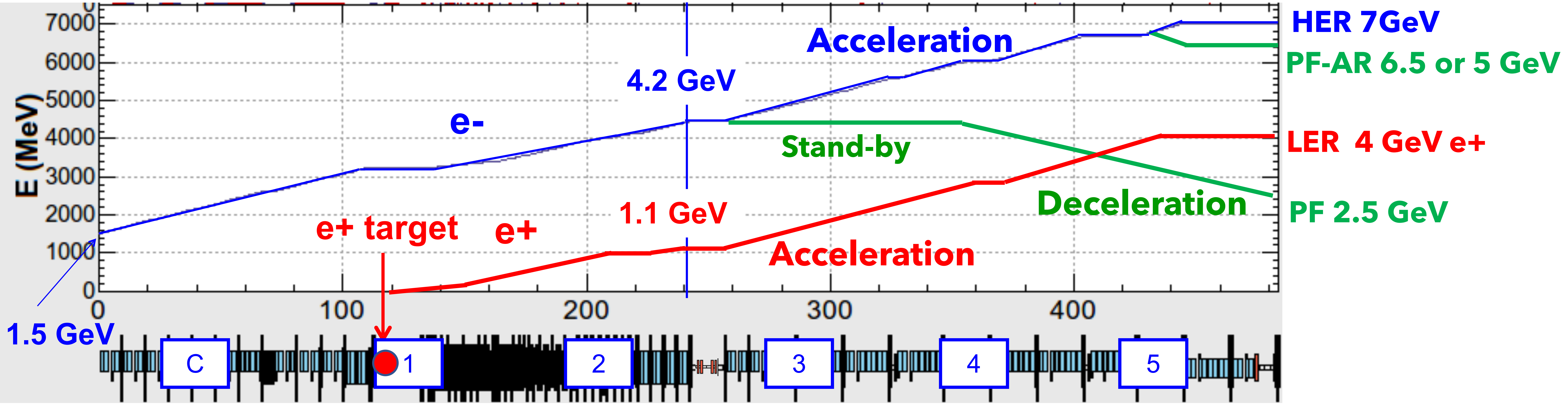
60 klystron units
240 accelerating structures (S-band 2-m-long)





Bunch charge (nC) in the current nominal operation

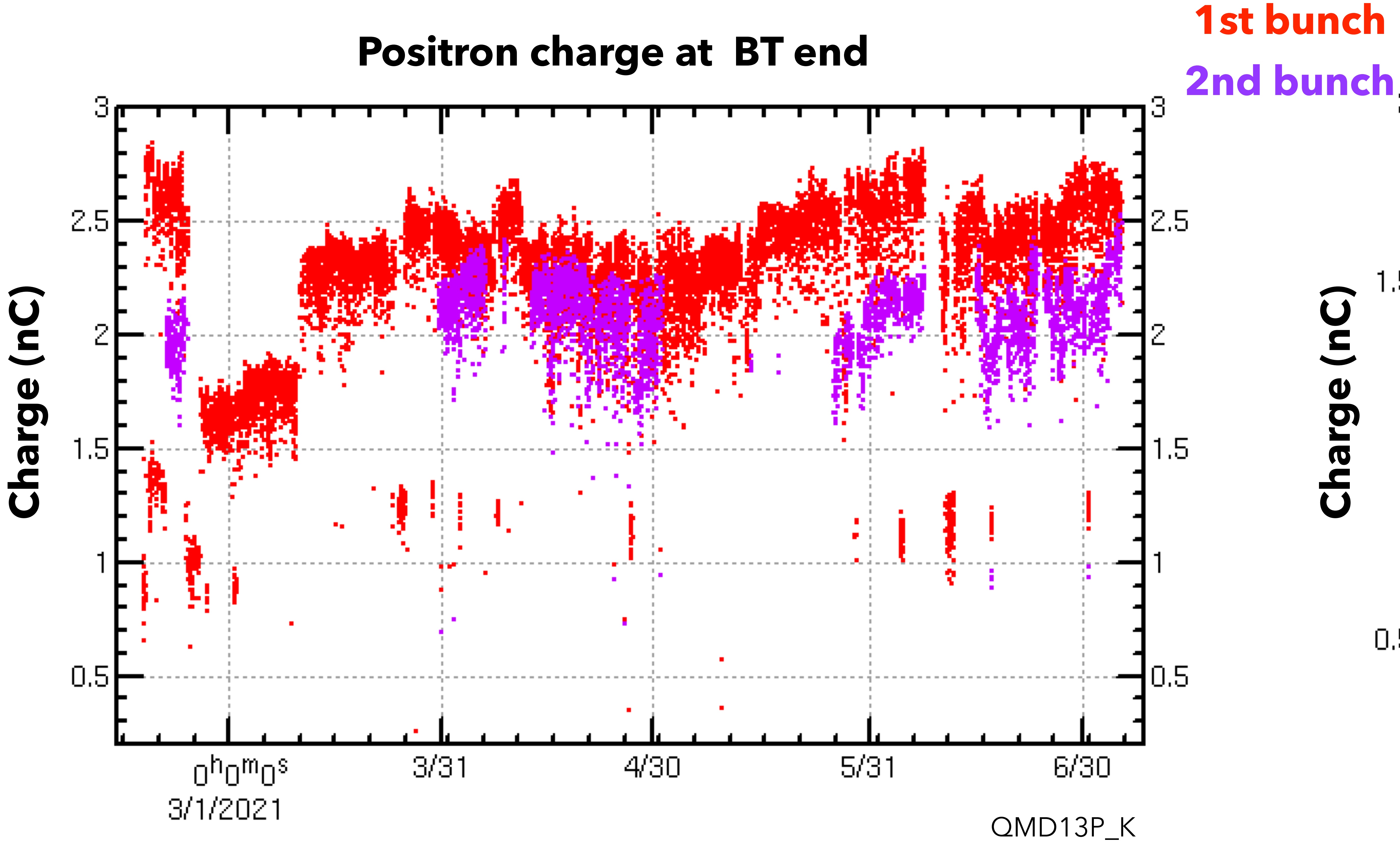
HER	1 - 2
LER	2.5
	10 e- for e+ production
PF/PF-AR	0.1 - 0.3

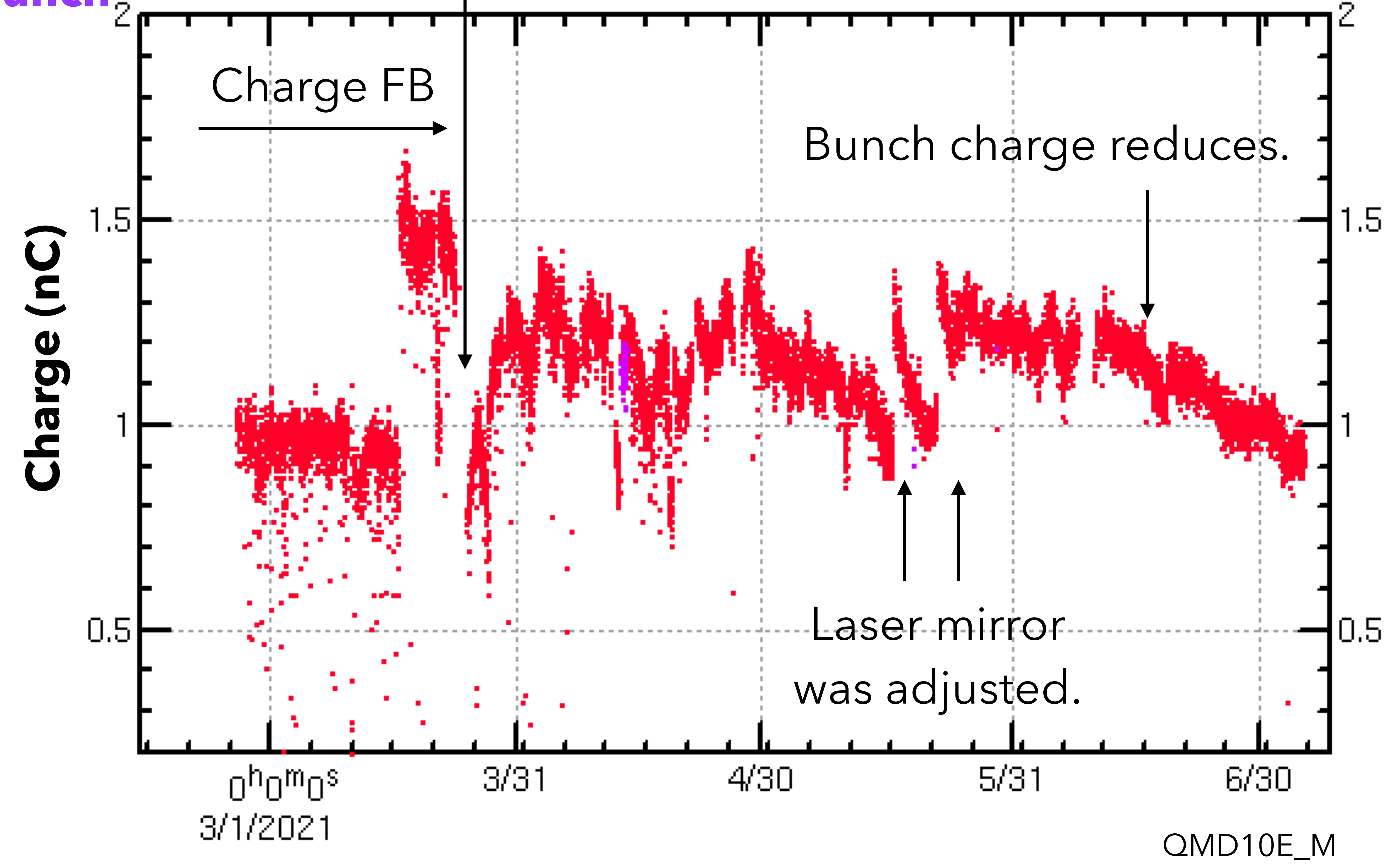


Beam energy for each beam mode along the beam line after the J-ARC.

Bunch Charge from Injector Linac

QE decreased due to human error (end of March)
Bunch charge feedback was stopped
because laser power reached 100 %.





Average charge is ~ 2.4 nC/bunch for 1st bunch
2nd bunch is lower than 1st bunch.

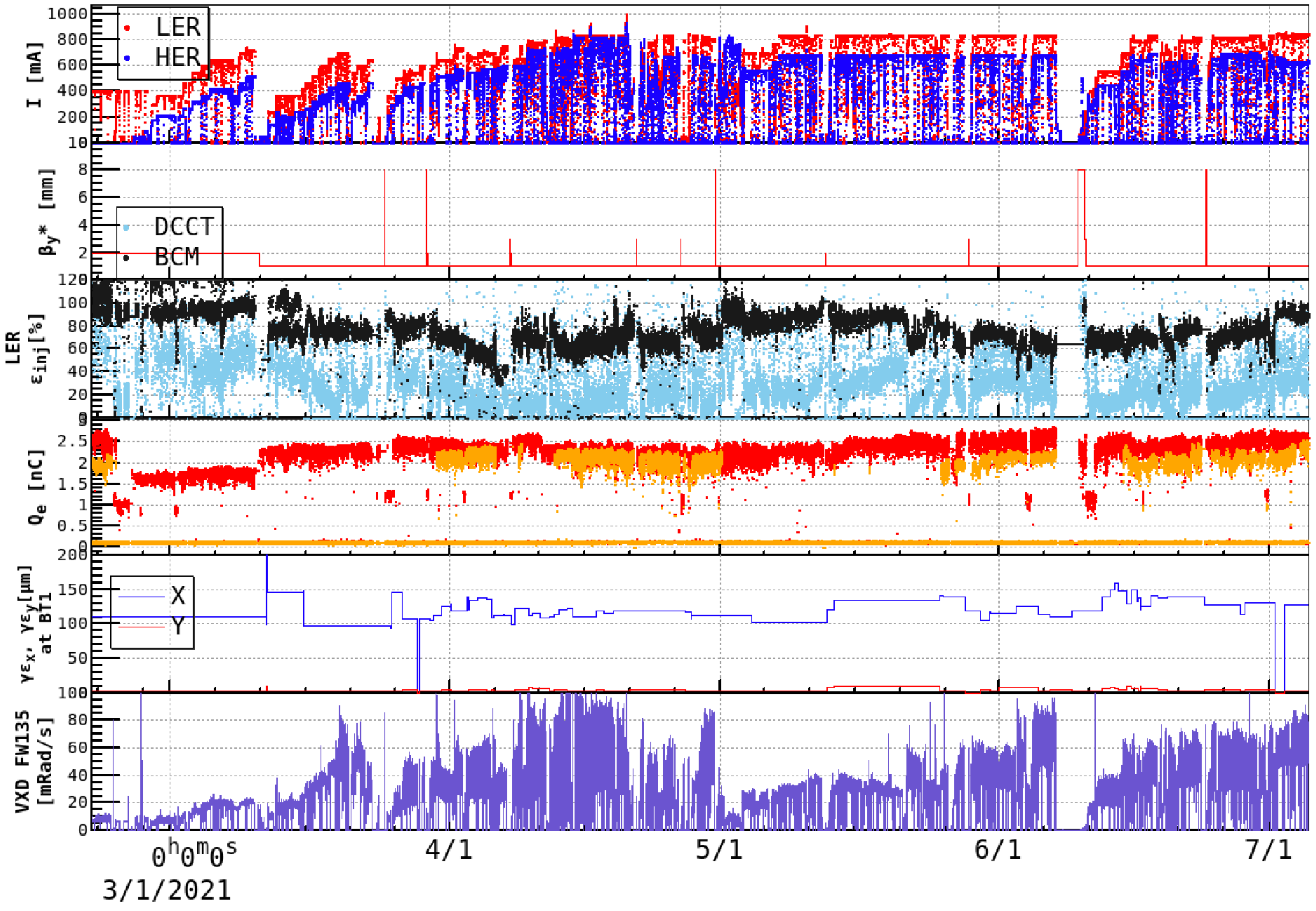
Average charge is ~ 1.2 nC/bunch
Stability of charge is poor.
2-bunch injection is not available so far because
the emittance of 2nd bunch is larger than 1st bunch.

Injection and emittance

N. Iida

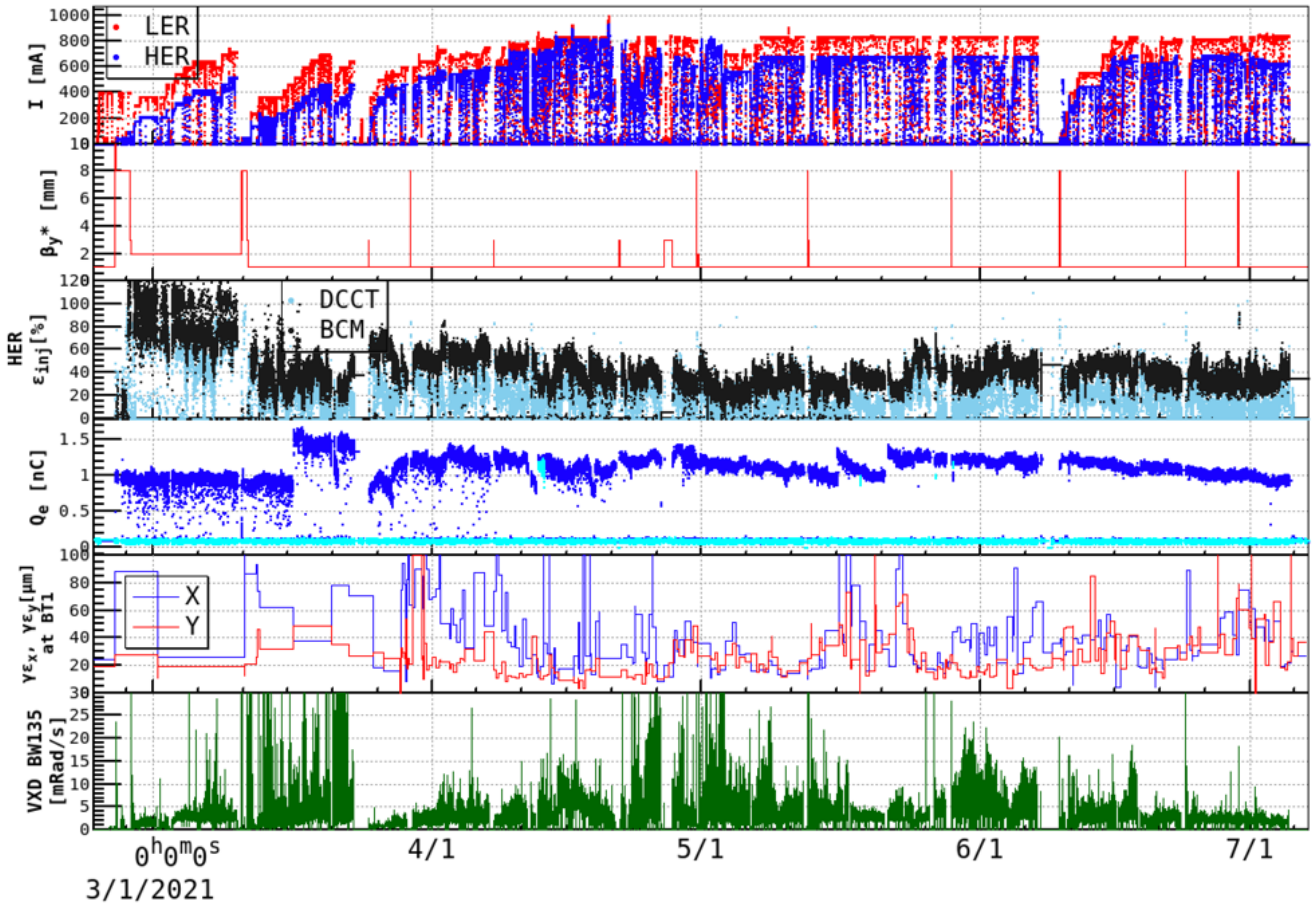
β_y^* = 2 mm

LER



β_y^* = 2 mm

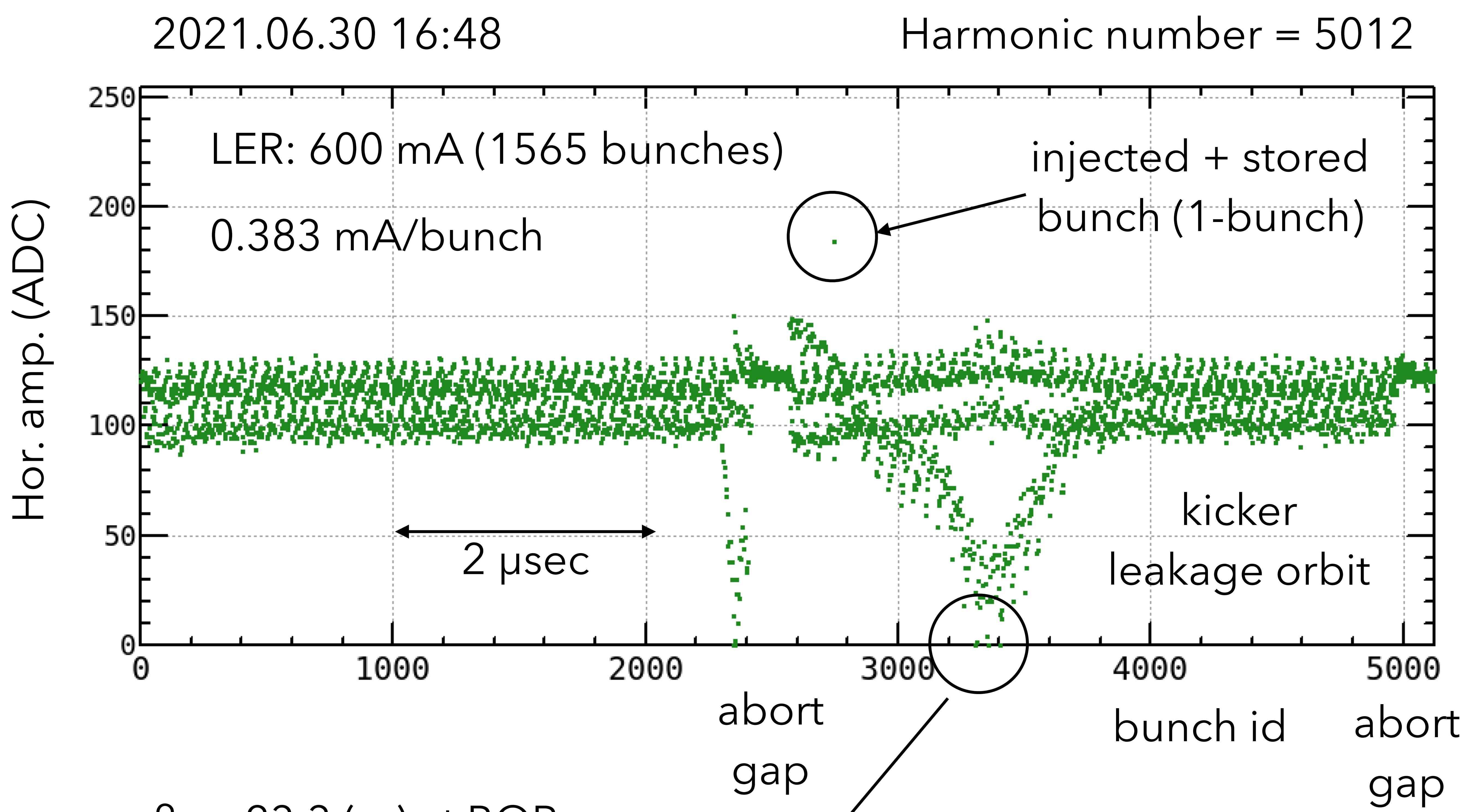
HER

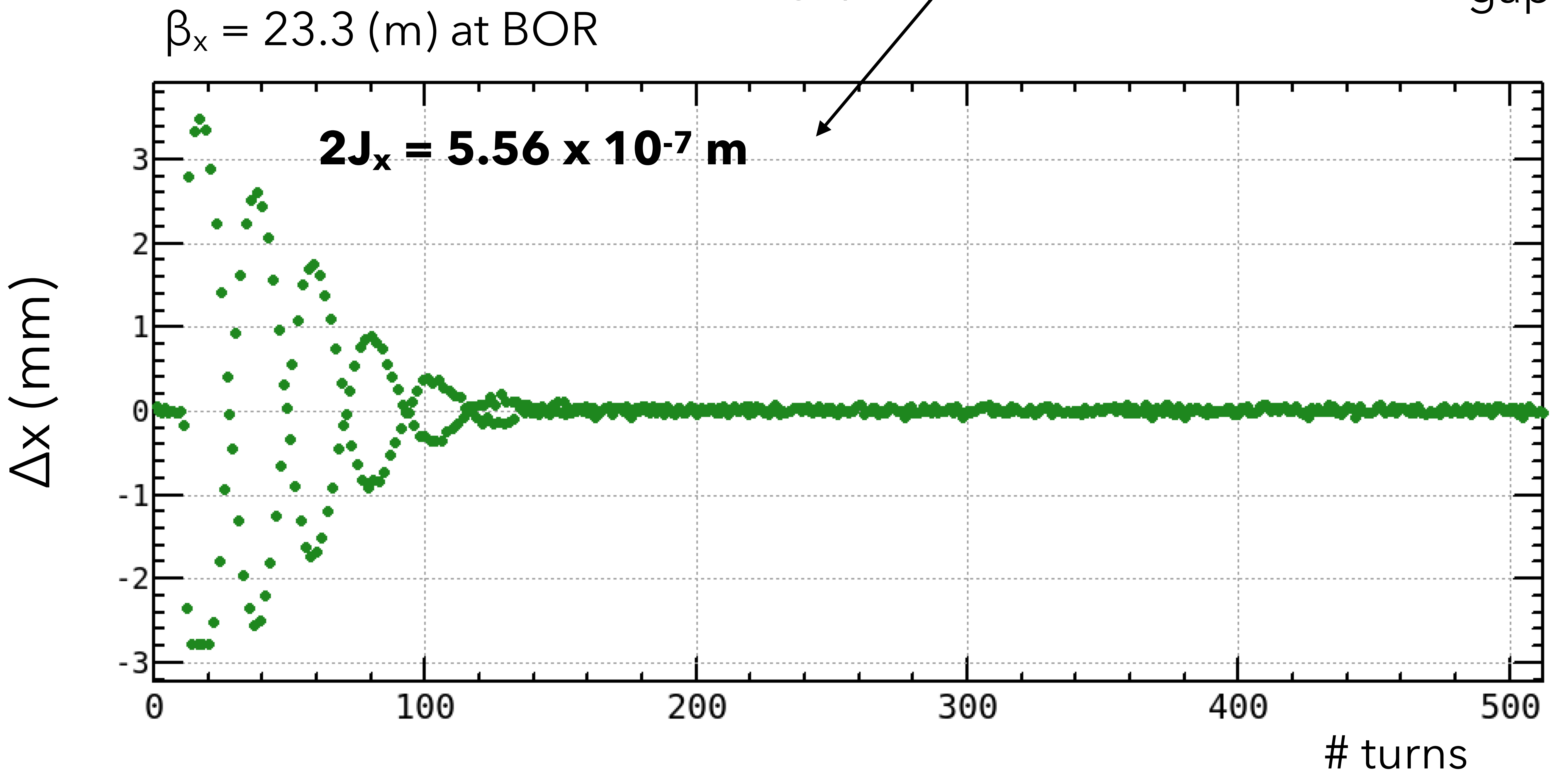


Issues of injection

- HER
  - The injection efficiency("raw") is insufficient. It is 40~60%.
  - The blowup of emittances in the e- BT line is still serious issue.
    - The normalized emittance($\gamma\varepsilon_{x,y}$) blows up from 20 μm in BT1 to 100~200μm in BT2.
  - Injection efficiency can not be kept without tuning of the horizontal orbit at the injection point.
  - Septum angle and position have to change.
    - After an abort, the septum angle has to reduce 2×10^{-4} rad and it should be resumed at the full current.
  - Bunch charge of e- beam is getting lower from 1.4nC to 1.0nC during short term.The 2-bunch-injection is not available.
  - The emittances of the 2nd beam become larger than 1st bunch after the positron target.
- LER
  - The injection efficiency and beam backgrounds for the 2nd bunch are worse than 1st bunch.

Data of Bunch Oscillation Recorder (BOR)

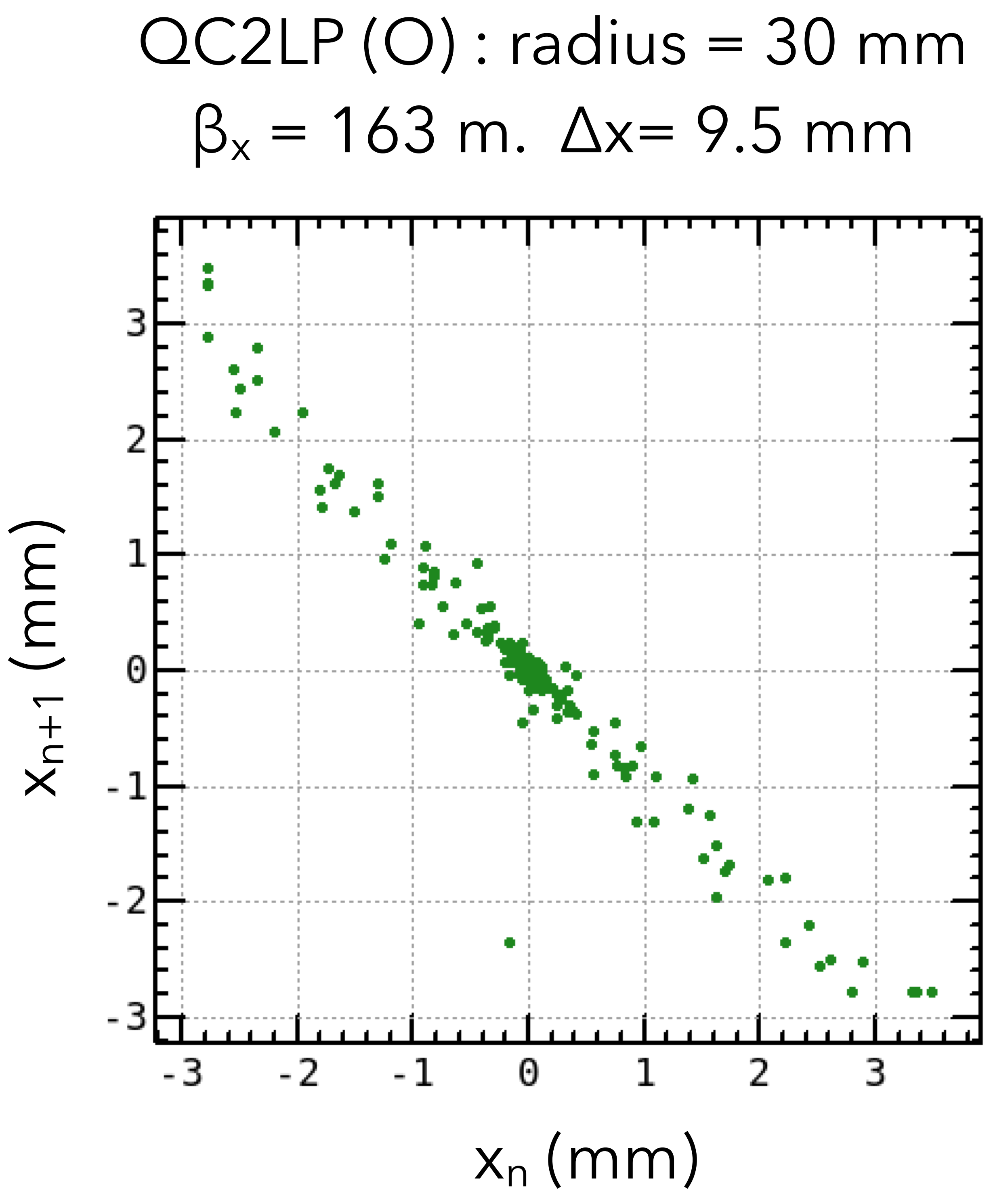




Large orbit leakage due to injection kickers is observed in the horizontal plane after injection in the LER.

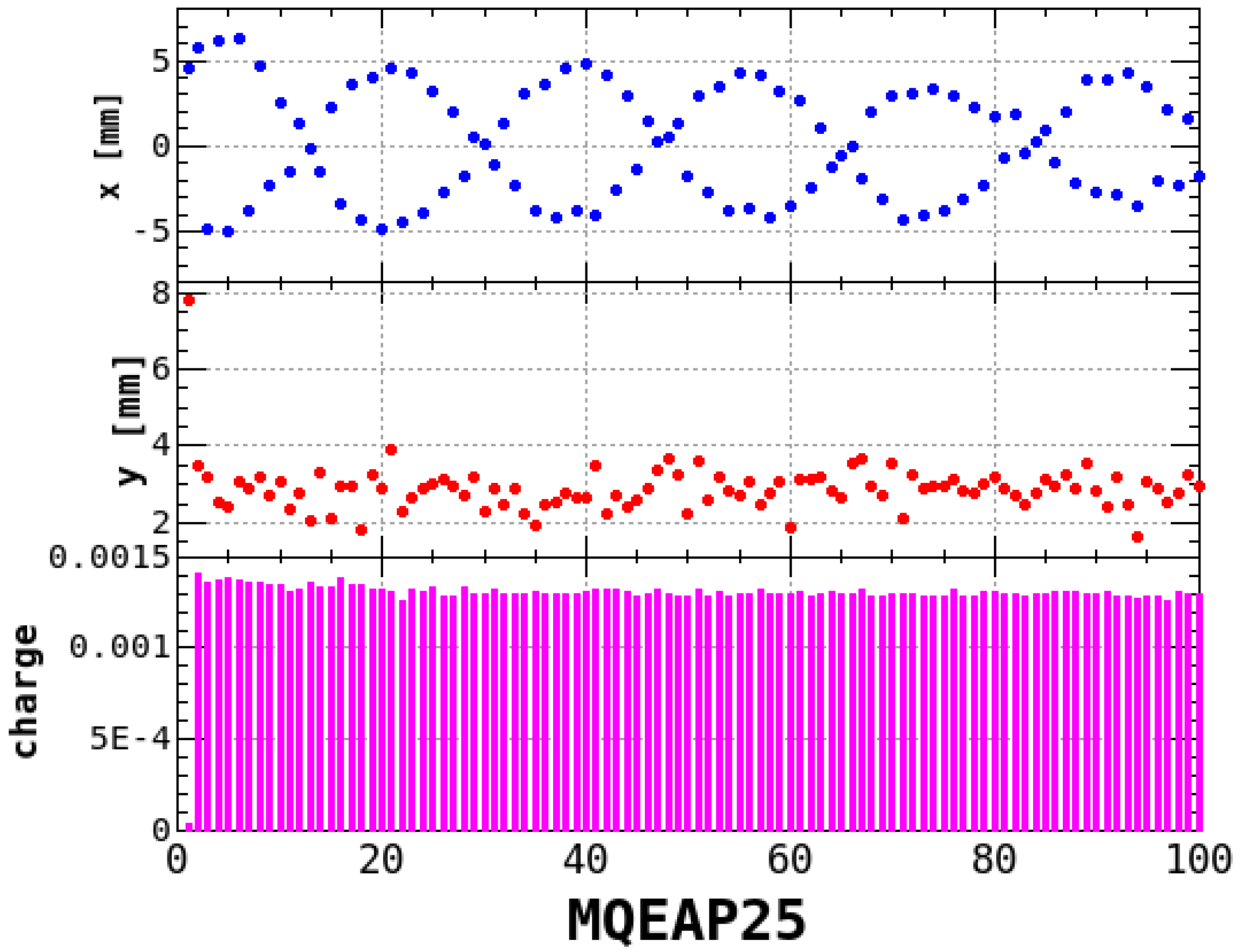
Problem is that pulse shapes (half sine) are different among six kickers.

This might be **beam loss (BG)** at higher beam current and **source of instabilities**.



Data of Injection Beam using TBT BPMs in LER

sample-1 βx =24.42 m



Horizontal injection error:

$2J_x$ = 1.47x10^{-6} m

QC2LP (O) : radius = 30 mm
β_x = 163 m. Δx= 15.5 mm

D06V1 : half width = 6 mm
β_x = 14.6 m. Δx= 4.6 mm

Kicker leakage orbit (stored beam):

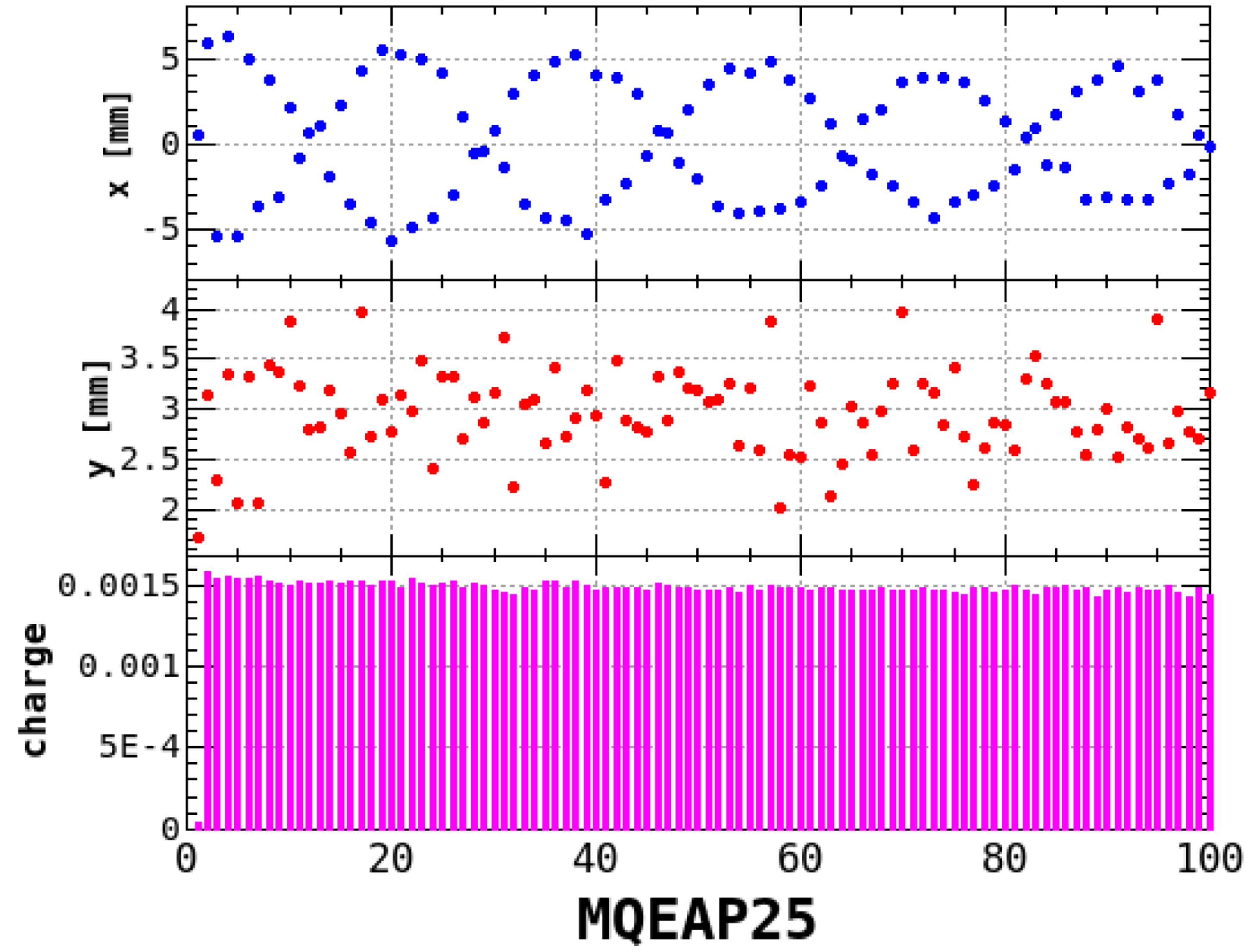
$2J_x$ = 5.56 x 10^{-7} m 1/3 of injection error

QC2LP (O) : radius = 30 mm
β_x = 163 m. Δx= 9.5 mm

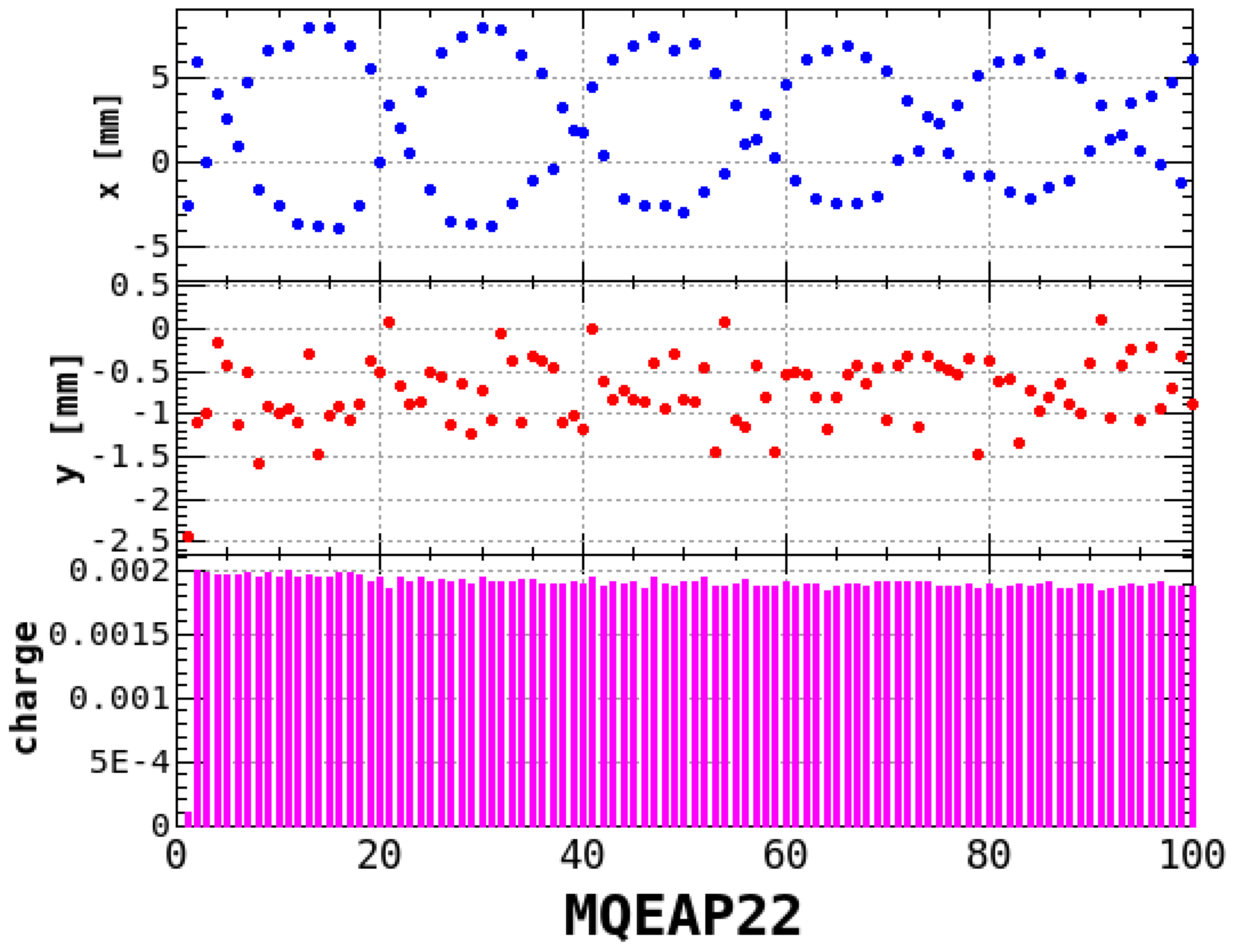
D06V1 : half width = 6 mm
β_x = 14.6 m. Δx= 2.9 mm

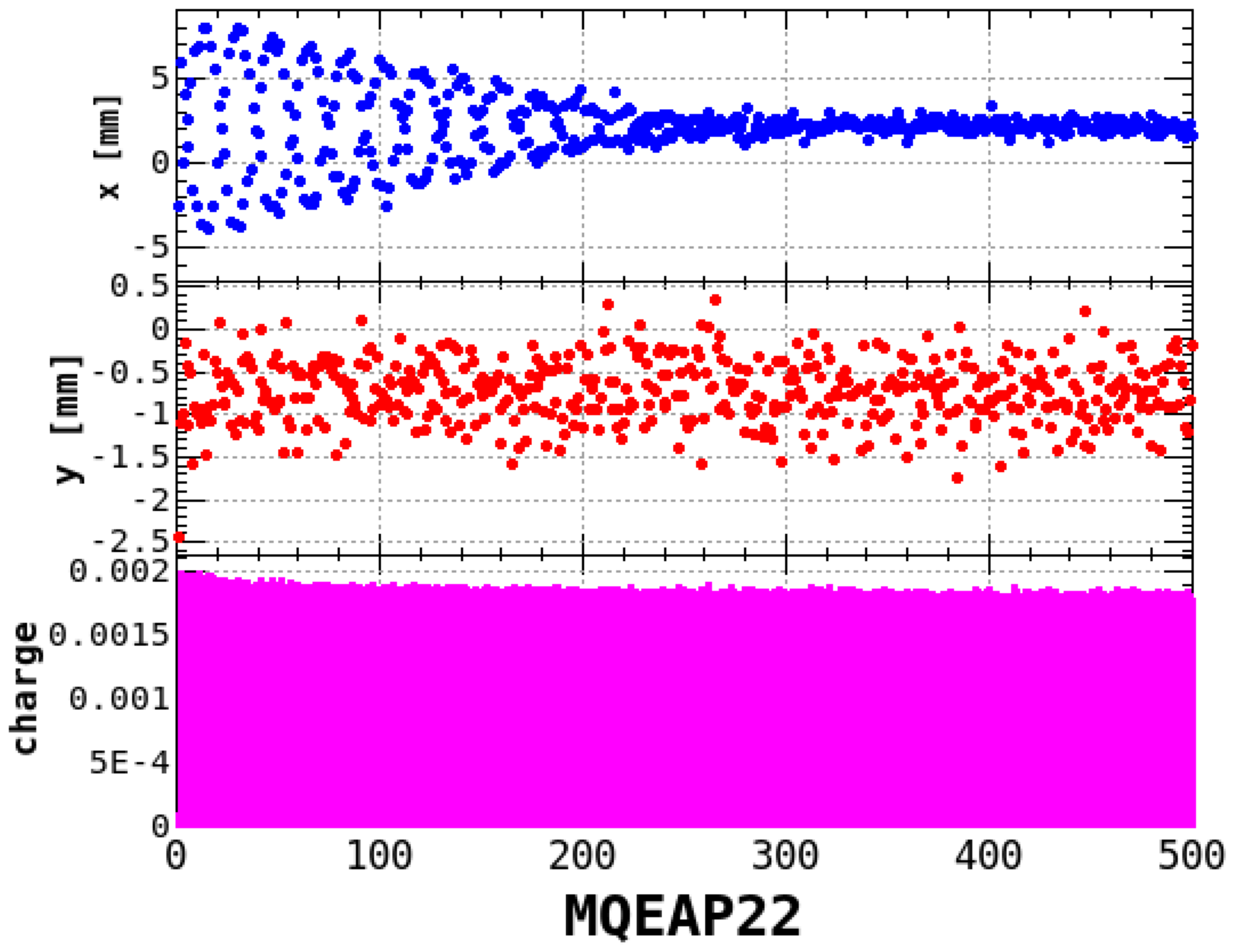
Oscillation is damped in 250 turns owing to BxB feed back system.

sample-2



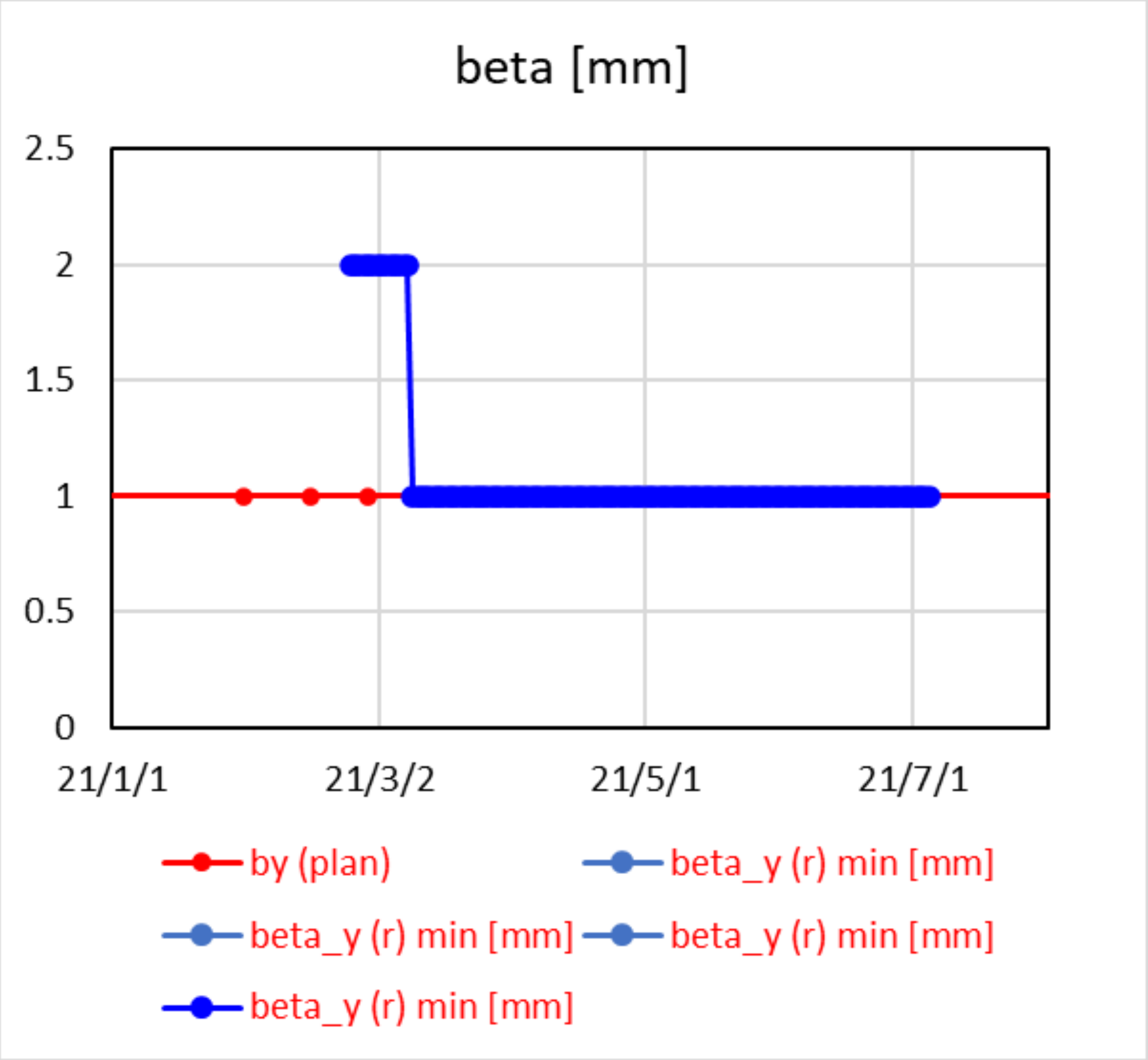
sample-3 βx =24.42 m

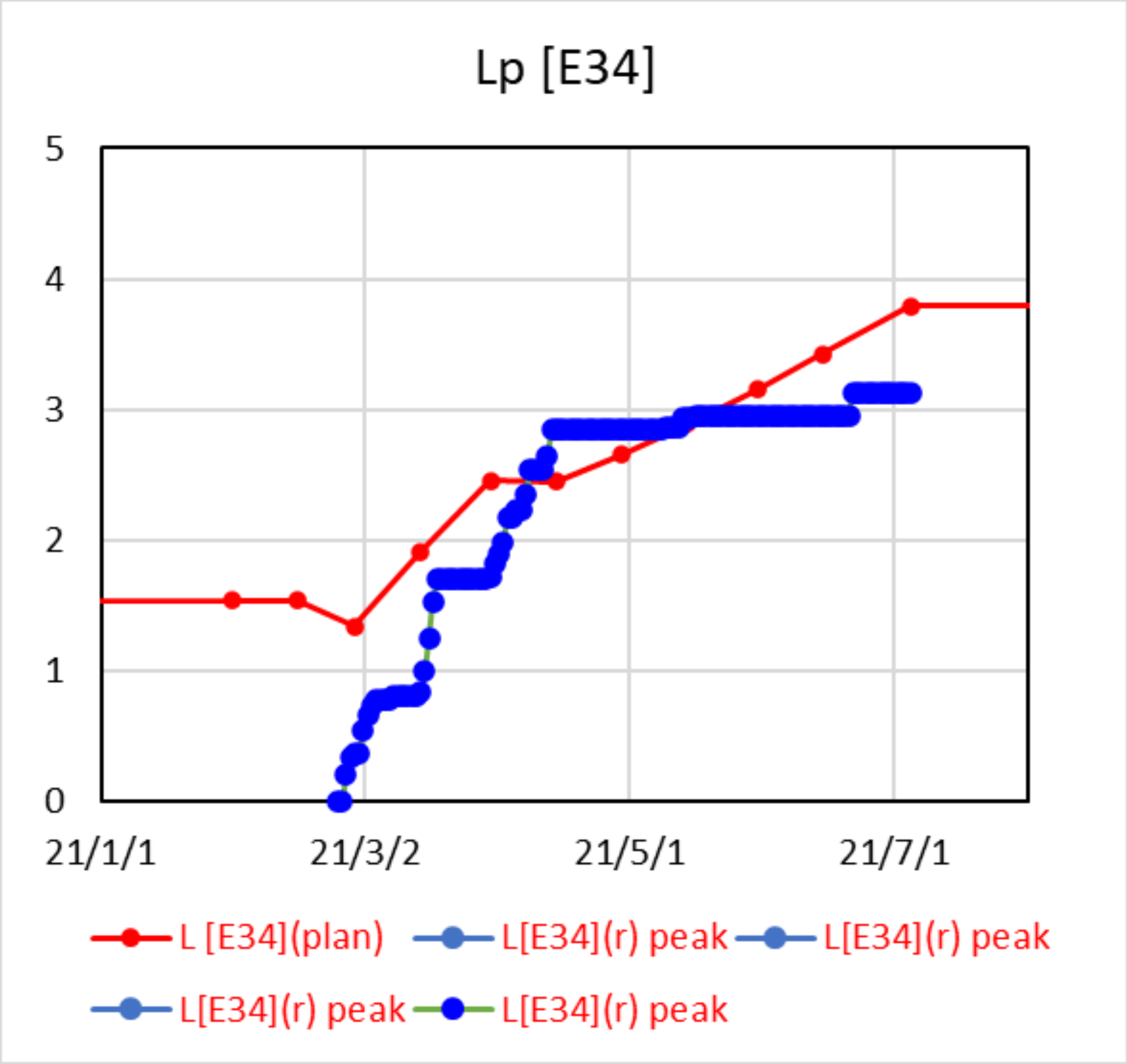


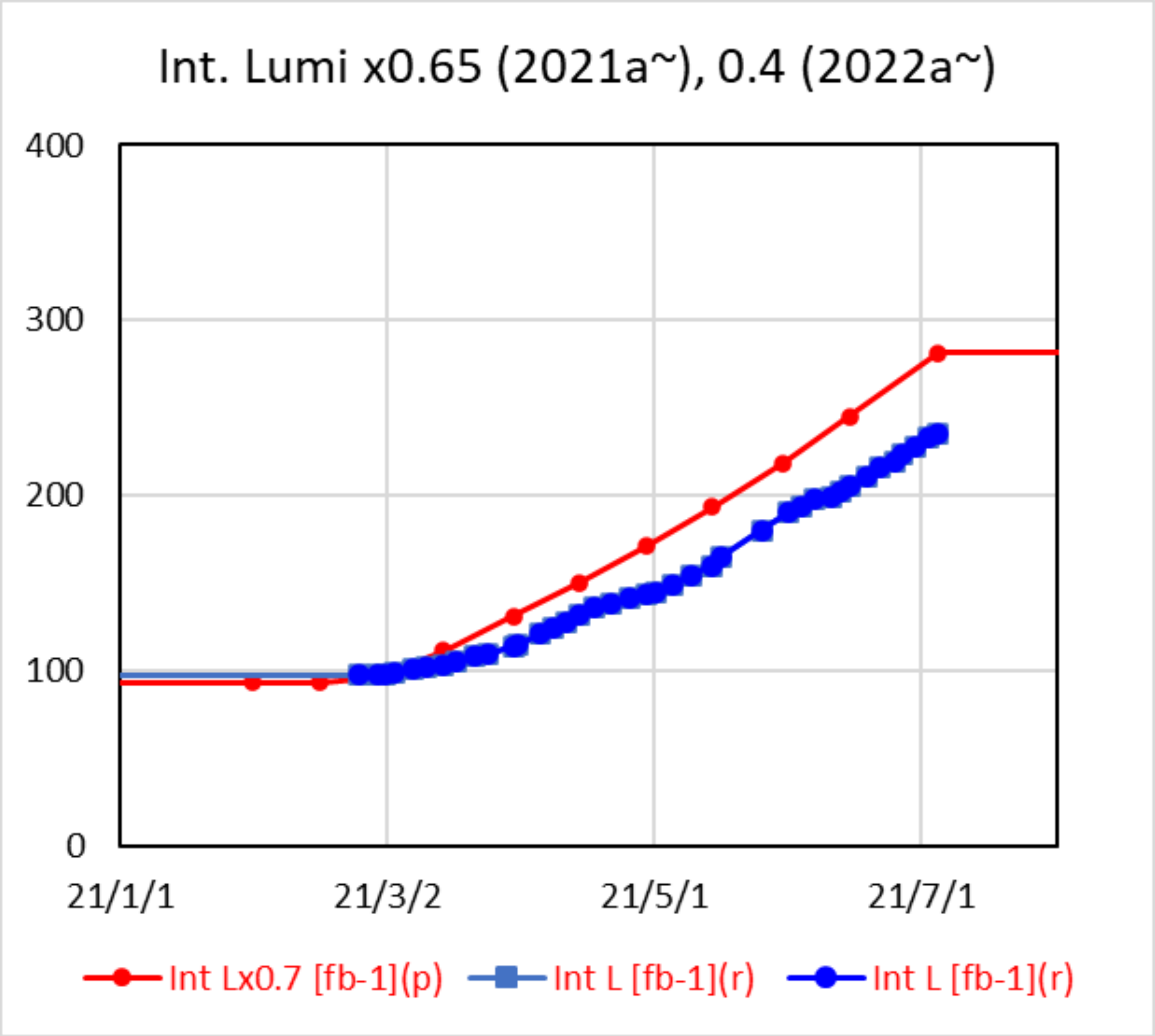


Summary of Machine Operation

Achievement of 2021ab







Summary of Machine Operation

1. Difficulties of increasing beam currents

- Abnormal beam abort with beam loss; no oscillation, very fast beam loss within a few turns. Damaged collimator head enhances the aborts (?).
- Narrow collimator aperture (physical aperture: PA) which is smaller than dynamic aperture (DA)
- Short lifetime in the LER; Crab waist reduces DA. However, the aperture in the LER is PA = DA.
- Lower "TMCI" threshold; 0.9 mA/bunch, large tune shift of single bunch ~0.013 > half of synchrotron tune in the LER
- Injection kicker leakage orbit in the LER; It becomes a source of instabilities. Beam loss is proportional to stored beam current. We measured the beam loss owing to orbit oscillation using BOR.
- BxB FB in the HER; noise effect (fixed) and feedback gain, feedback gain and luminosity.
- Synchro-beta resonance structure; good working area is small. Luminosity and DA is compatible ?
- Stabilities of linac injector; Many types of feedback system should work sufficiently. Stability of injection system; septum and kickers, especially HER septum behavior.

2. Beam-beam blowup

- Effect of chromatic X-Y couplings is still unclear or IP knob is not sufficient. Rotating sextupoles in LER is effective.
- Beam current ratio between LER and HER affects flip-flop of beam size.

3. Beta squeezing (not performed in 2021ab)

- Down to 0.8 - 0.6 mm is necessary to improve luminosity. Training process is needed. (It takes time; see $\beta_y^* = 1$ mm)

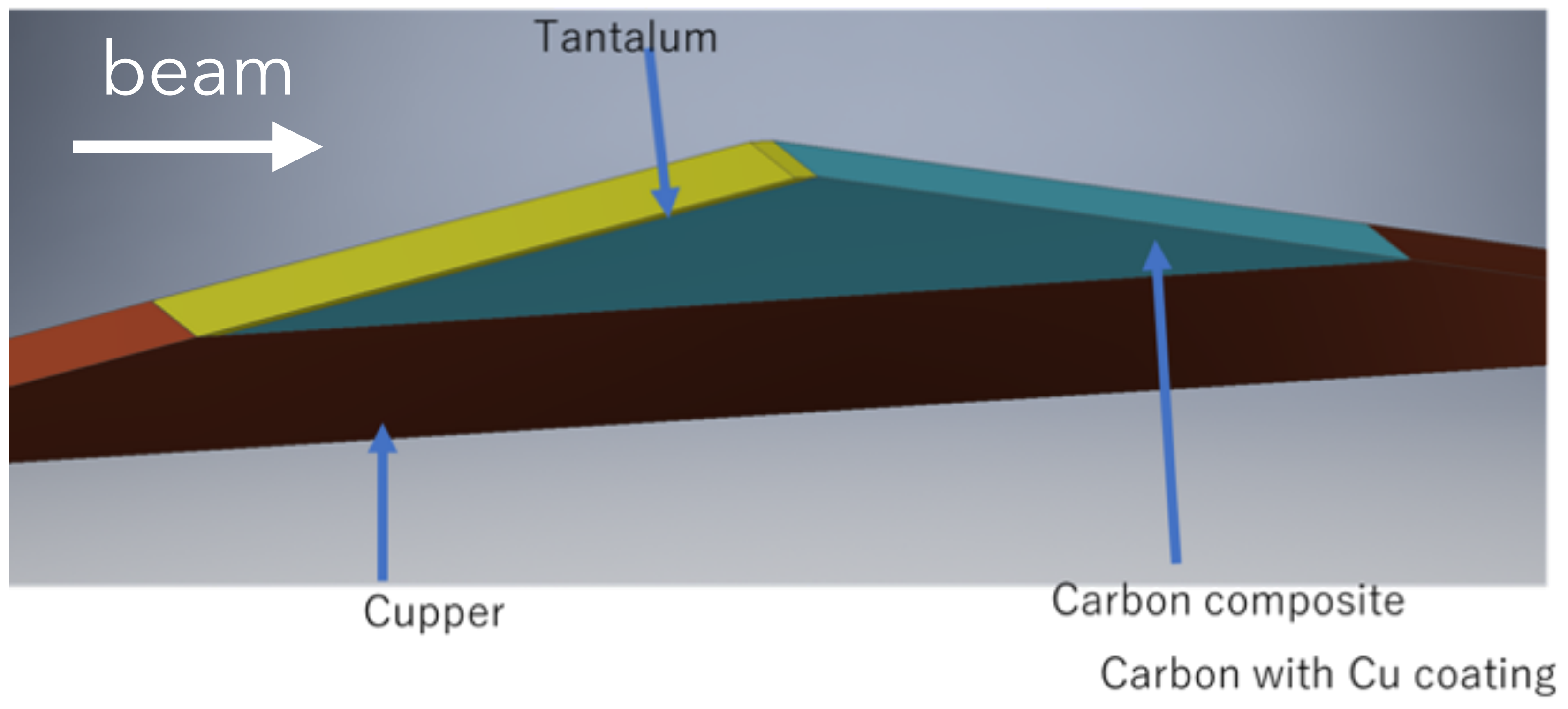
Near-Term Plan

	2021b		2021c	2022b
	Target	Achieved	Target	Target
L_p ($cm^{-2}s^{-1}$)	3.8 x10^{34}	3.12 x10^{34}	4.8 x10^{34}	8 x10^{34}
int. L (fb^{-1})	280	213.5	410	730
I_{max} (A)	1.1	1.0 (0.85)	1.2	1.6

Y. Suetsugu

Works Planed in This Summer Shutdown

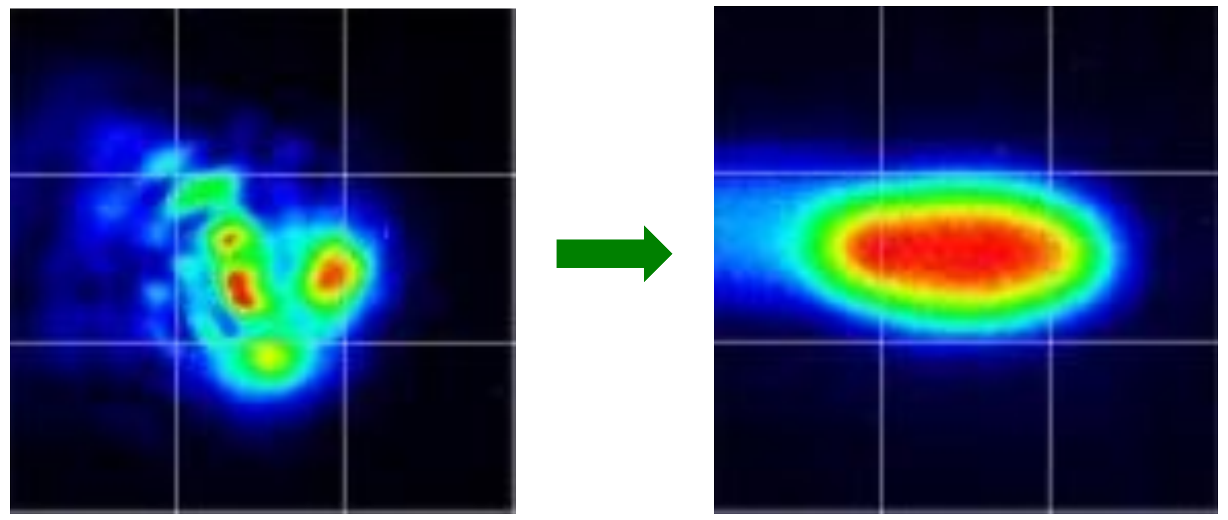
- Regular maintenance
- Movable Collimator
  - Replacement of 2 collimator heads in HER
  - Upgrade of driving device of 2 collimators in HER
  - Replacement of collimator head (D06V2) with hybrid-type (tantalum and Cu coated carbon) in LER
  - Relocation of D02V1 in LER (not decided)
- Exchange of the mirror of SR beam size monitor in LER
- Installation of HOM absorber at RF section (Nikko) in HER
- Beam transport line (BT)
  - beam profile monitors with OTR screen
  - beam shutter at the injection in LER
- Installation of strip-line kicker in RTL line (DR)
- Infrastructures; measures against aging
  - Replacement of HV (66 kV and 6.6 kV) power cables
  - Repair of roof at power stations to avoid leakage rain drops
  - Replacement of old cooling water pumps

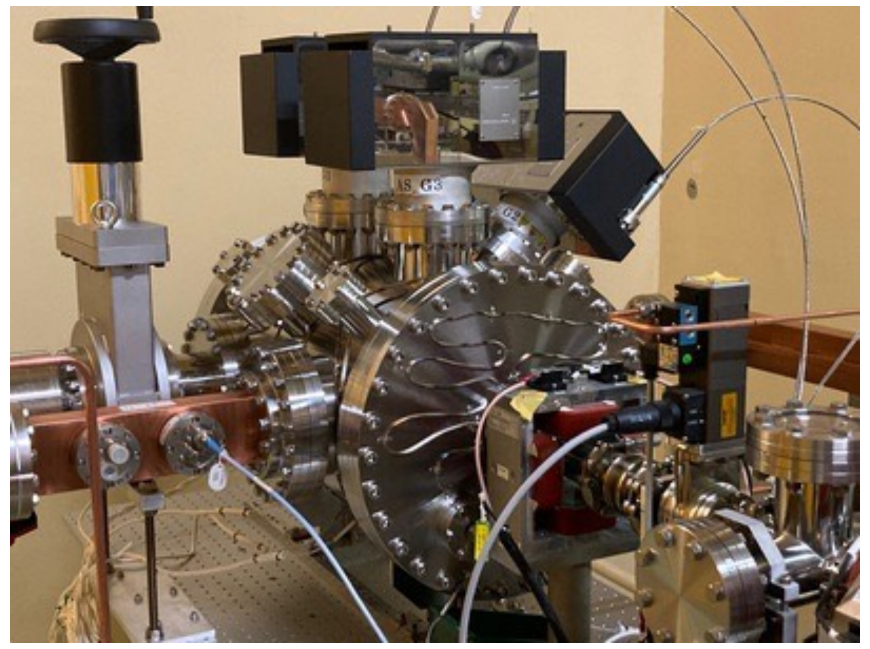


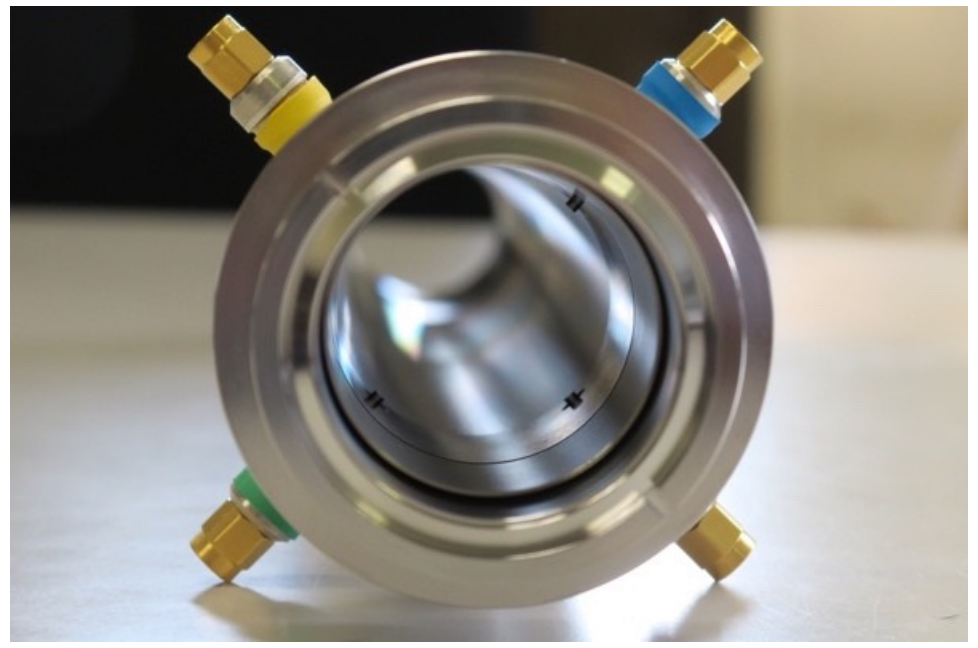
Near-Term Plans at Injector Linac

K. Furukawa

- Summer 2021
  - Amplifier and optical elements to 2nd laser for rf-gun
  - Cathode and window replacement for rf-gun
  - Core switch upgrade for the computer network
  - Seven pulsed steering magnets in upstream linac
  - Solid state amplifiers to replace a mid-power klystron
  - Degraded rf waveguide replacements
  - Fast beam position monitor to separate e-/e+
  - 2nd rf-gun as a backup/development, … and more
- Upgrade before 2026
  - Pulsed magnets/fast kickers
  - Girder movers
  - Energy compression system
  - RF gun
  - Positron capturing
  - Accelerating structures
  - New capacitors to eliminate PCB

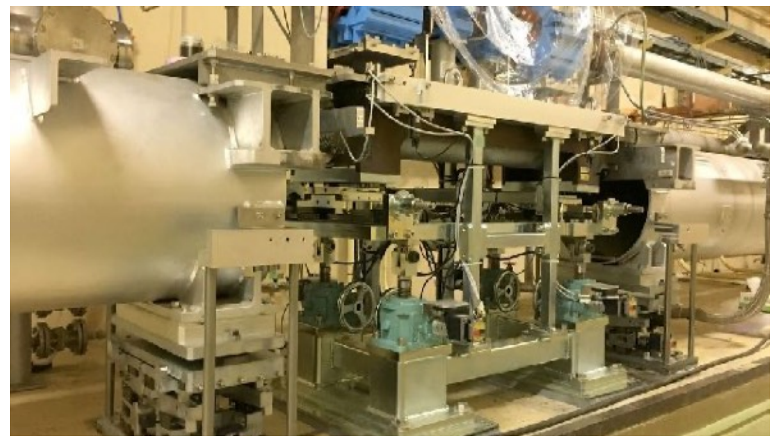

Laser shaping with DOE


Secondary RF gun


New beam position monitor

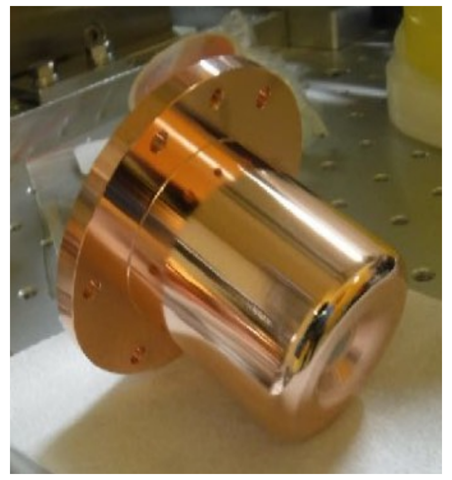

Core network switches

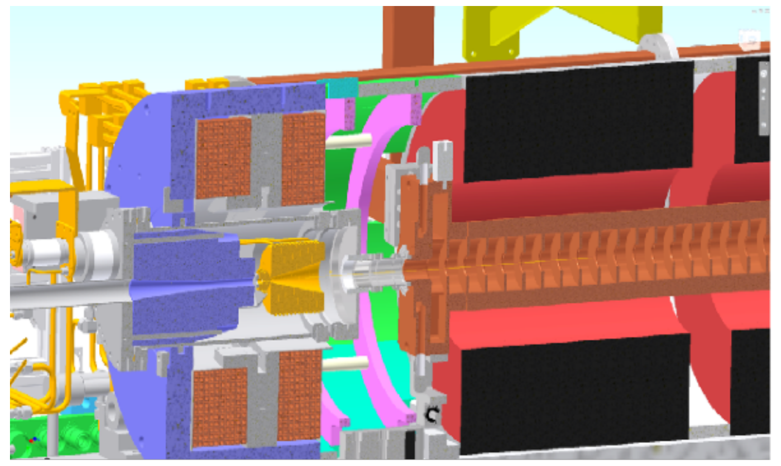

Pulsed magnets/kickers

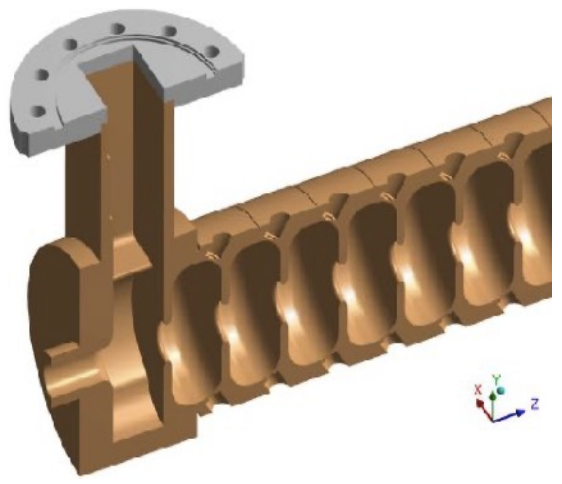

High precision movers


PCB capacitor renewal


New energy compressor


RF gun


Positron capture section


Accelerating structure

Positron beam

M. Satoh

emittance

$\varepsilon_{nx,ny}$ (2.3 nC)

∼99.7/3.2 μm (BT1)

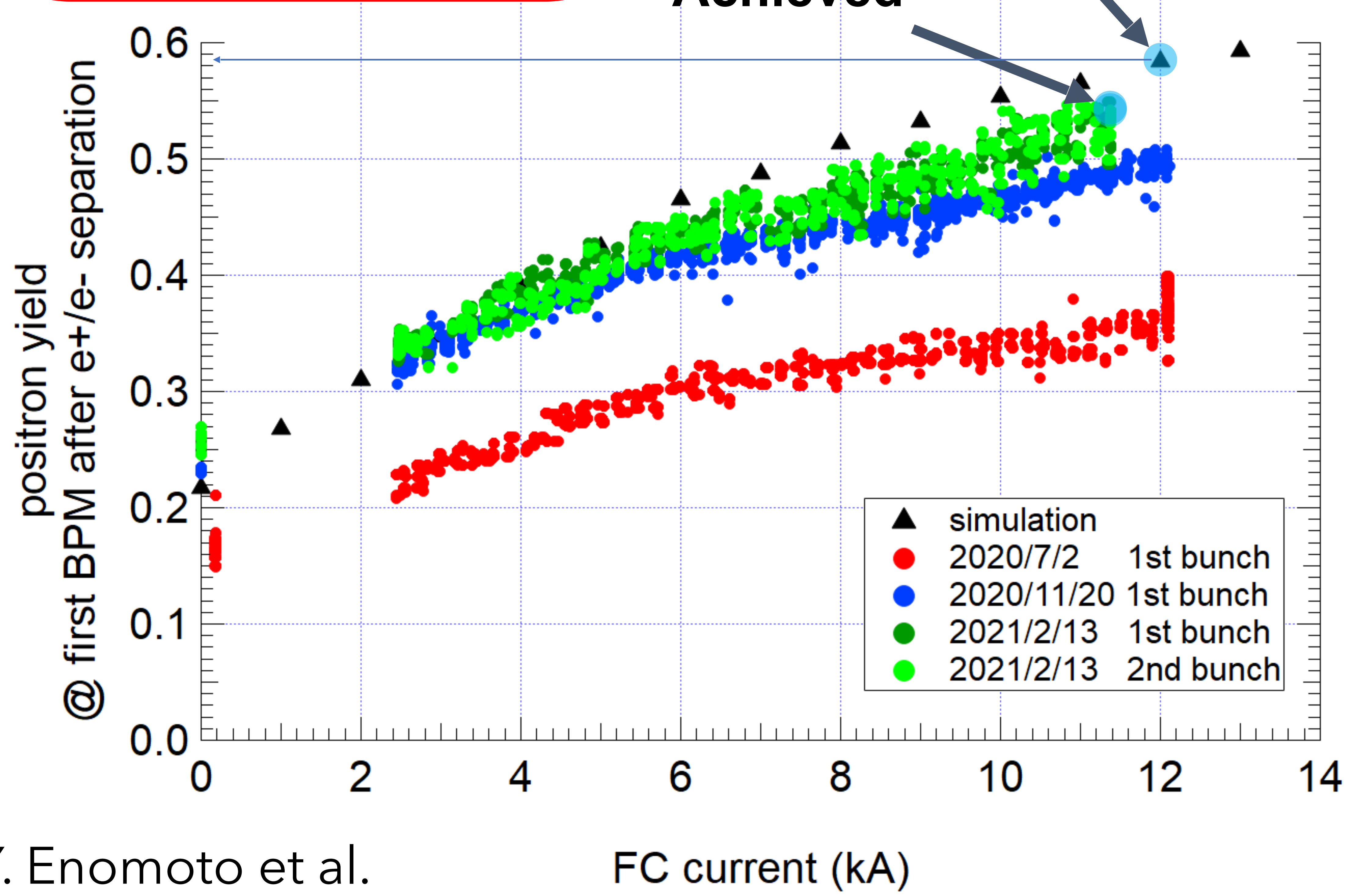
Results of measurement

β_x @MWP.1 [m] :	9.504	β_y @MWP.1 [m] :	20.183
α_x @MWP.1 :	-.251	α_y @MWP.1 :	1.737
ε_x [m] :	1.3258E-8	ε_y [m] :	4.193E-10
$\Delta\varepsilon_x$ [m] :	3.5336E-9	$\Delta\varepsilon_y$ [m] :	1.498E-10
$\gamma\varepsilon_x$ [μm] :	99.667	$\gamma\varepsilon_y$ [μm] :	3.152
$\Delta\gamma\varepsilon_x$ [μm] :	26.563	$\Delta\gamma\varepsilon_y$ [μm] :	1.126
Goodness x :	.827	Goodness y :	.982
Bmag x :	1.089	Bmag y :	1.458
ε Bmag x :	1.4436E-8	ε Bmag y :	6.112E-10
γε Bmag x :	108.522	γε Bmag y :	4.594

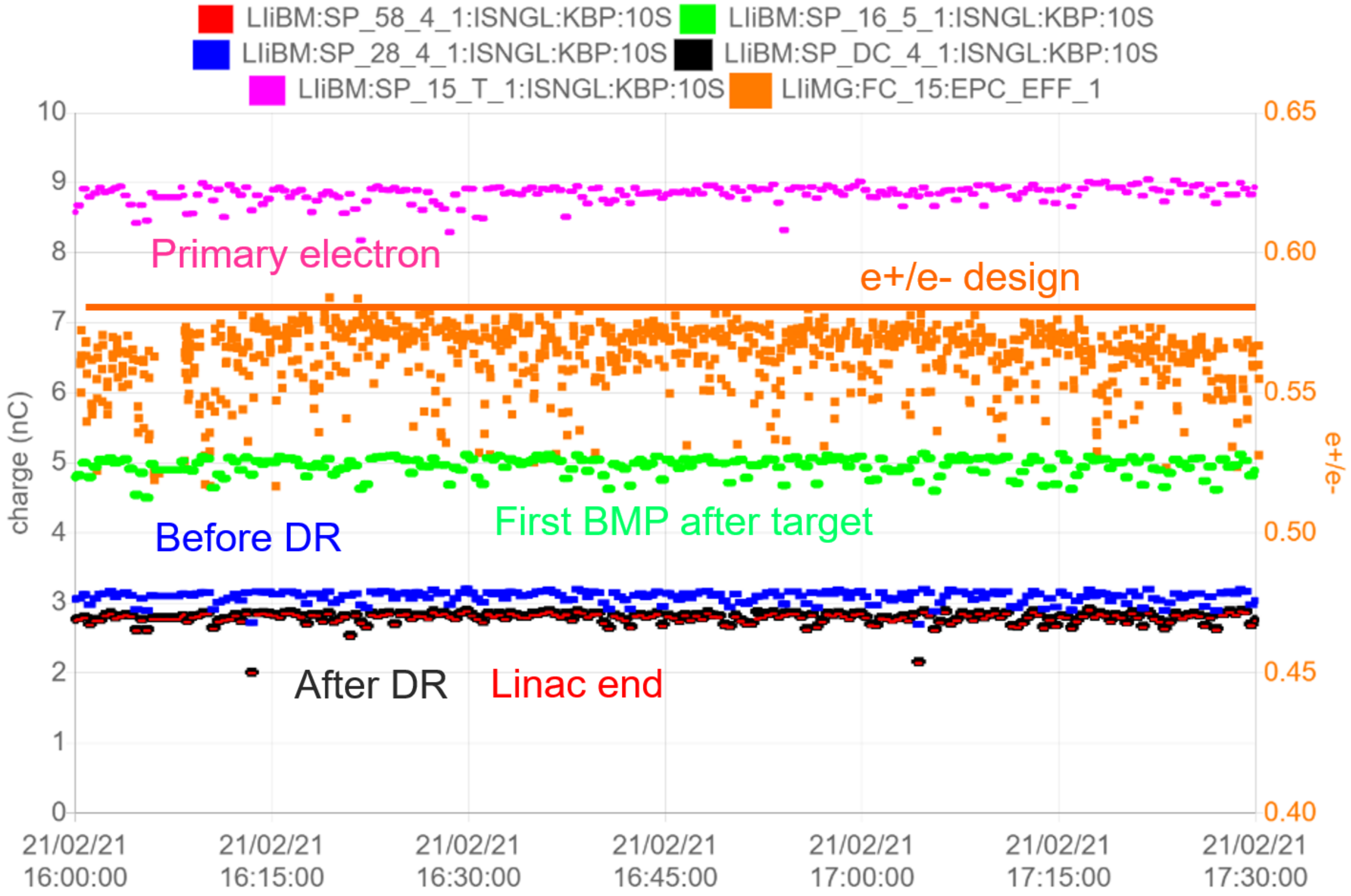
Goal: $\varepsilon_{nx,nxy}$ (4 nC)

∼100/15 (H/V) μm)

- 5 nC at BPM<SP_16_5> (1st BPM after e+ target)
- ∼ 3 nC LTR (Linac To damping Ring) and downstream
- For obtaining 4 nC at BT:
  - Some more steering/Q magnets will be installed after target in 2021 (this summer).
  - Increase gradient: 7.3 MV/m to 14.0 MV/m (design) for two structures (AC_15_1[2] situated at downstream e+ target)
  - Increase FC field and DC solenoid field. (power supply should be improved)



Y. Enomoto et al.



Luminosity Projection