SuperKEKB main-ring status

Gaku Mitsuka (KEK, Accelerator Laboratory)
on behalf of the SuperKEKB commissioning group

B2GM, 8 Feb. 2021

Outline

- Target luminosity and operation schedule
- Strategy for 2021a
- Challenges for high-current beam operation
- Readiness for the other major challenges
- Summary

Target luminosity and operation period

- **2021 runs will be dedicated for luminosity production.**
  - Towards integrated luminosity higher than BaBar's 433 fb^{-1} (integrated luminosity at the end of 2020c is 90 fb^{-1}.)
- **Expected operation period through 2021 runs is ~6.4 months.**

Present plan

[Y. Suetsugu, M. Tobiyama]

FY2020	2020									2021			
	4	5	6	7	8	9	10	11	12	1	2	3	
Present plan (20th Oct.)		2020b ~3M						2020c ~2M				2021a ~1.5M	**Total ~6.5M/y**
FY2021	2021									2022			
	4	5	6	7	8	9	10	11	12	1	2	3	
Plan (not fixed) [MEXT Road Map]	4/1	2021b ~3.1M		7/5			10/7	2021c ~2.6M	12/23	**PXD exchange**			**Total ~5.7M/y**

- **2021a run will start on 16 Feb.**
  - The first week will be dedicated to vacuum scrubbing at only LER.
  - HER operation is supposed to start on 24 Feb, upon how we get the SCC safety certificate on time.

Strategy for 2021 run

First target is to achieve the peak luminosity ~2.4 x 10^{34} $cm^{-2}s^{-1}$.

- It was realized in 2020b run:
  - β_y^* = 1 mm, β_x^* = 80 mm(LER)/60 mm(HER)
  - Crab waist 80%(LER)/40%(HER)
  - 978 bunches in total of 700 mA
- Start off 2021a with such a well-understood optics, i.e. same as 2020b
- Important to establish stable beam-injection

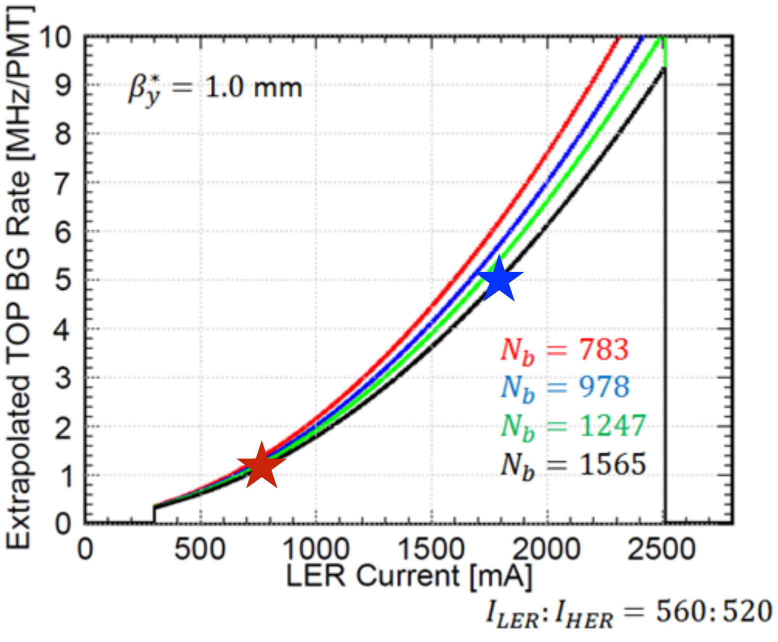
Increase beam currents gradually at β_y^* = 1 mm with 1565 bunches

- Relaxing the TOP BG threshold from 1.2 MHz to 5 MHz allows higher beam currents, i.e. putting a priority on getting luminosity > reducing BGs.
- Accordingly, the LER maximum beam current can be extended to 1.6-1.8 A.

Other options

- Squeeze β_y^* further than 0.8 mm upon positive indication

[K. Kojima]

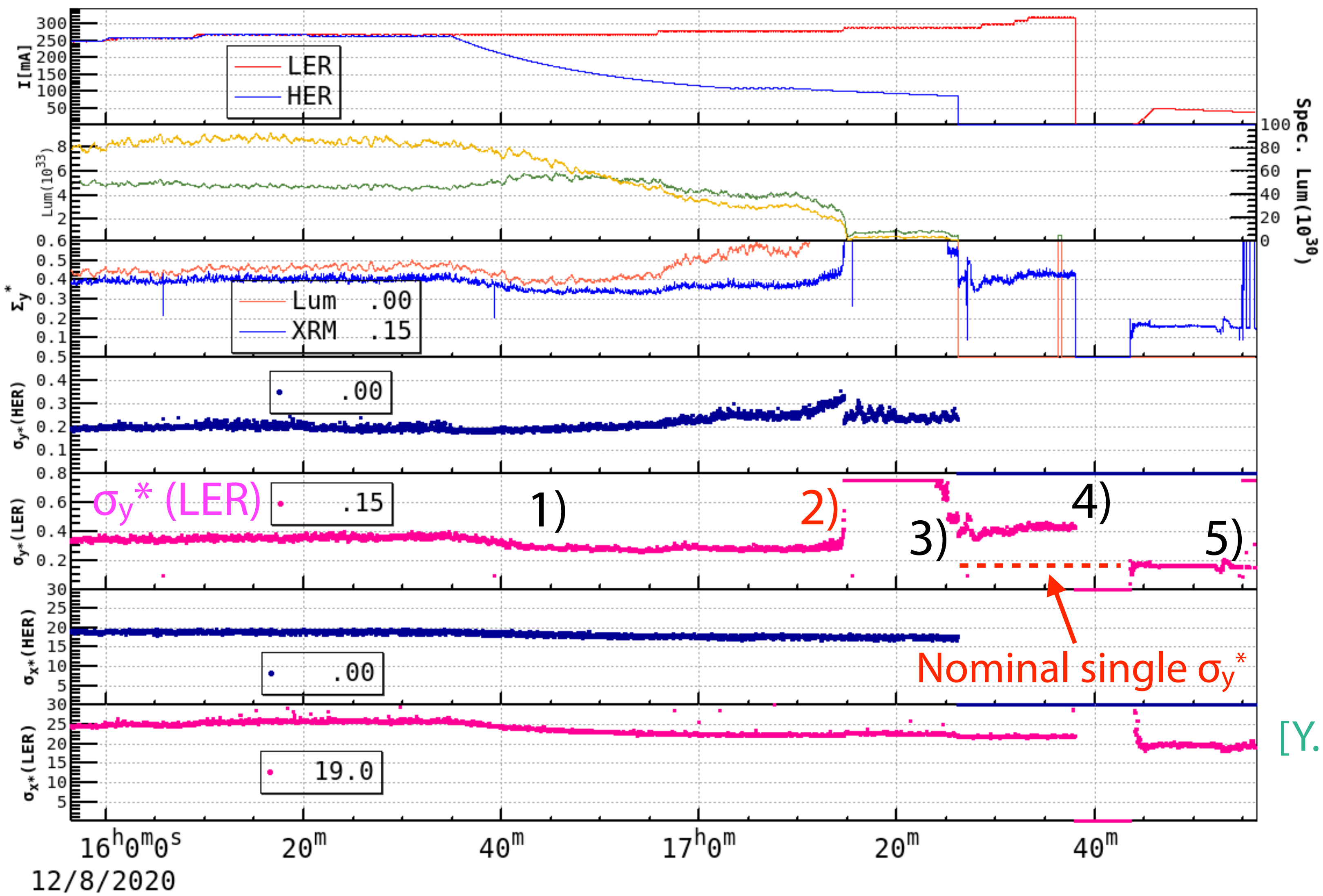


Challenges

High beam currents

- Transverse-mode-coupling-instability (a.k.a. TMCI), occurred in 2020c, resulted in the rather tight I_{bunch} threshold ~0.7 mA/bunch.

Beam size σy* blowup due to dipole motion (8 Dec. 2020)



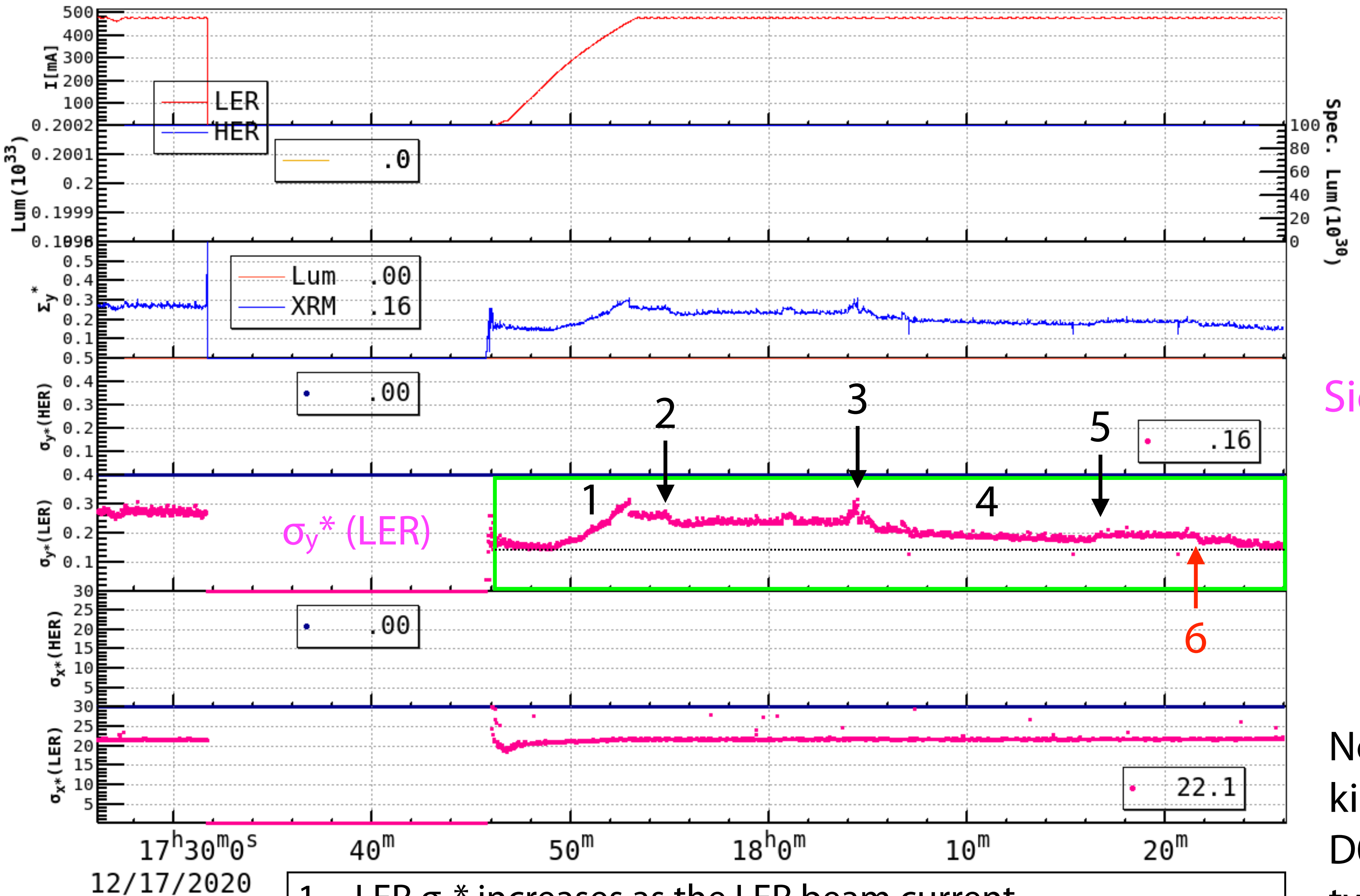
1) LER beam-beam blowup got tamed by decreasing the HER current.
2) Beam size suddenly blowed up due to dipole motion at ~0.73 mA/bunch.
3) BxB FB gain +12 dBm
4) The dipole motion was suppressed by increasing BxB FB gain (0.81 mA/bunch). Nevertheless visible beam size (dominantly dipole motion) was still large.
5) σ_y^* for single LER back to normal (<0.2 μm)

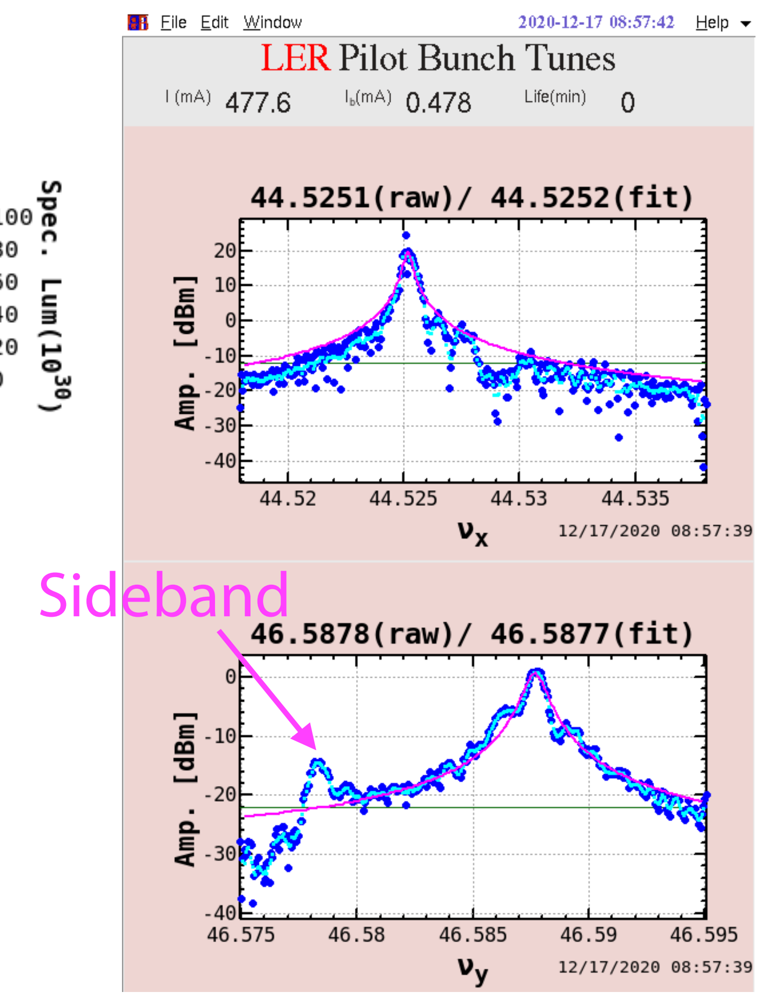
[Y. Ohnishi, M. Tobiyama, T. Ishibashi, S. Terui, H. Koiso and many…]

- Most likely TMCI was caused by high-frequency wake fields owing to the carbon-head D06V1 and additional D03V1 collimators.

Observation of TMCI with σ_y* and ν_y

Beam size σy* blowup for each collimator setting (17 Dec. 2020)





[Y. Ohnishi]

1. LER σ_y* increases as the LER beam current.
2. Changing ν_y reduces σ_y*.
3. BxB FB gain adjusted.
4. D03V1 collimator opens (18:09-18:14, ±1 mm → ± 2 mm).
5. D03V1 collimator closes (18:16, ±2 mm → ±1 mm).
6. D06V1 collimator opens (18:22, ±1.95 mm → ±2.25 mm).

Note:
kick factor of the carbon-head D06V1 collimator is about twice that of D03V1 (GdfidL by Ishibashi).

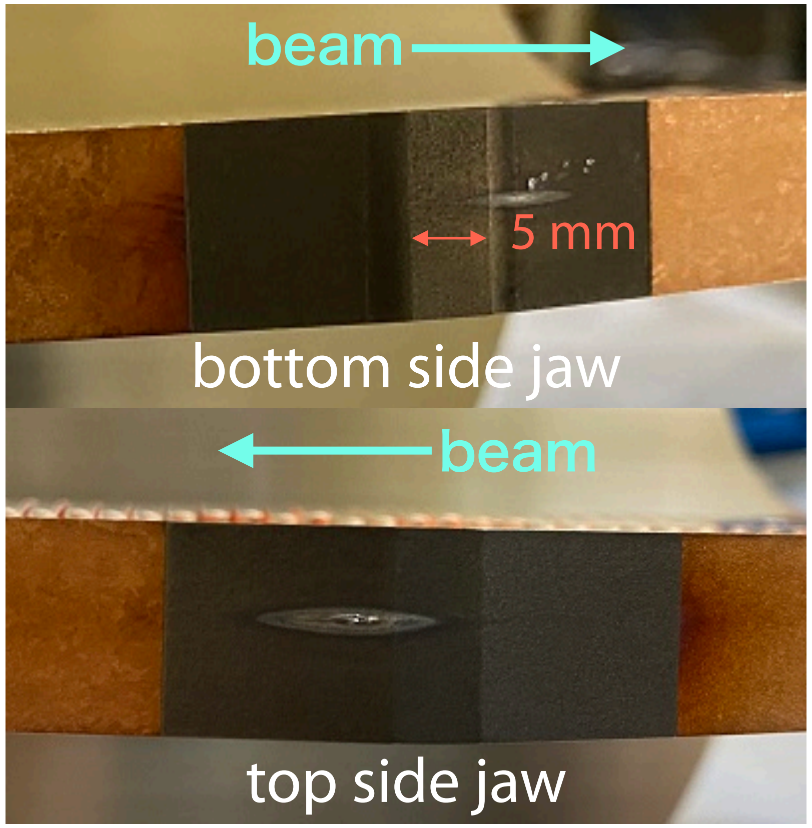
$$I_{th} = \frac{2\pi Q_s E/e f_0}{\sum \beta_T k_T(\sigma_s)}$$

[J. Gareyte, CERN-SL-2000-075]

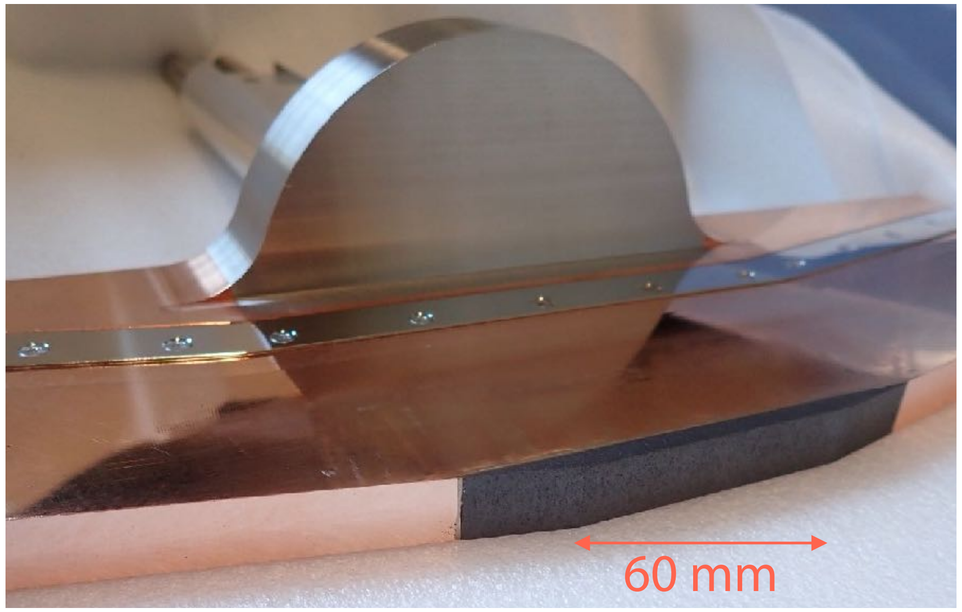
The D06V1 collimator replacement(s)

2020a	2020b	2020c	2021a
tantalum (→damage)		carbon→TMCI	tantalum (re-used)

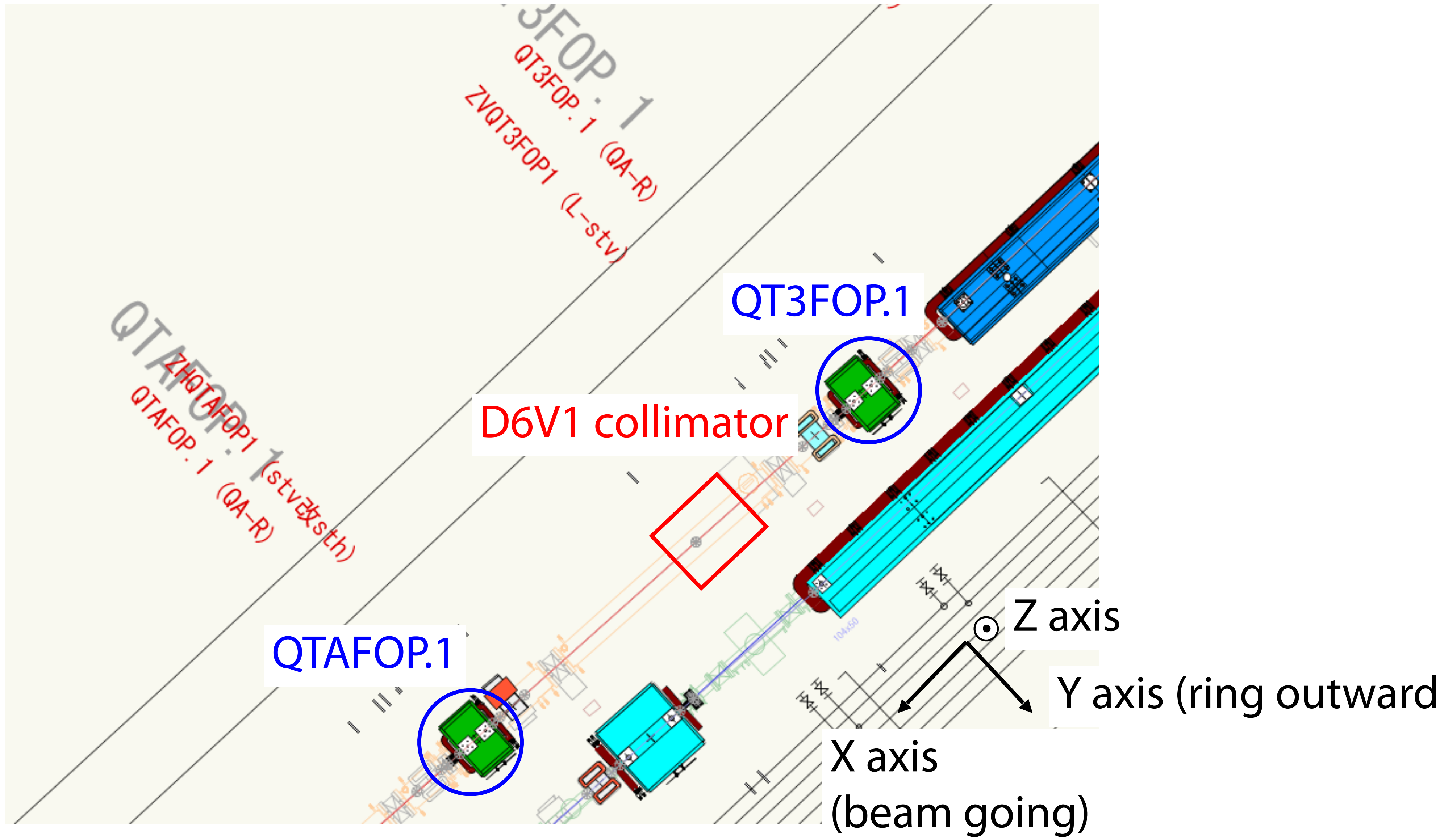
- In 2020c we observed no unexpected pressure increase nor heating.
- But, as a counter effect, the carbon-head collimator having large impedance caused the beam instability and resulted in the 0.7 mA/bunch threshold.
- Replaced the carbon head again in Jan 2021 with the tantalum head (re-used), allowing higher beam current in 2021a



[T. Ishibashi, S. Terui]



D06V1 collimator alignment in Jan 2021

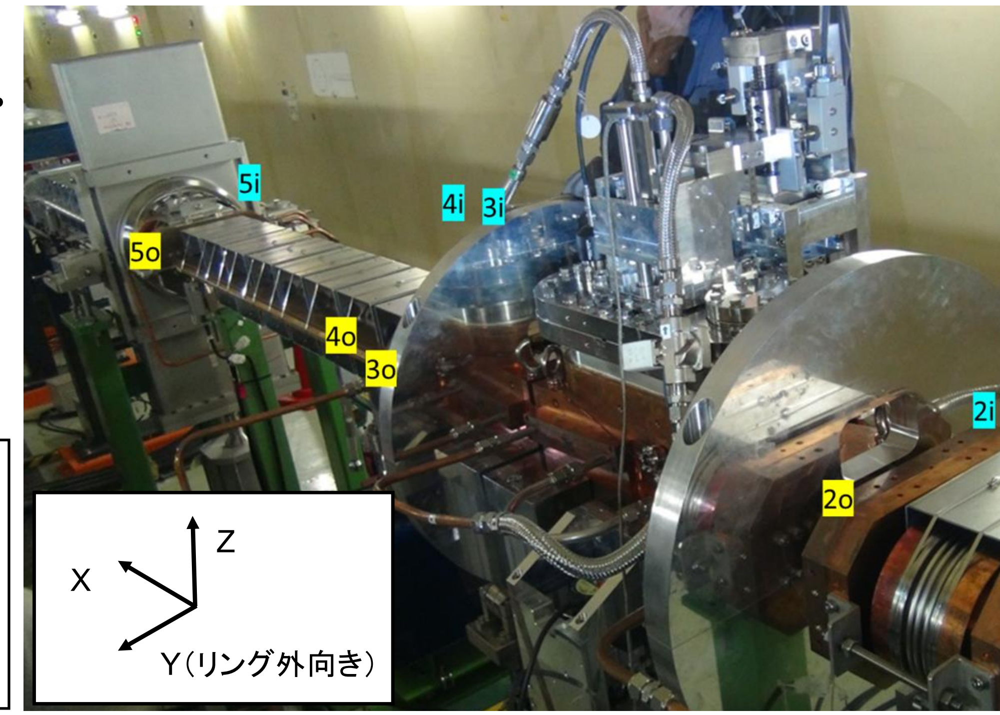


- Align the center of flanges on each side of the D06V1 collimator to lie along a line connecting two Q-magnets

D06V1 collimator alignment in Jan 2021

- Note that these results do not assure the alignment of the collimator head w.r.t. Q-mag.
- Both horizontal and vertical residuals are well below 100 um.

This is D02V1, NOT D06V1!



[R. Ueki, M. Masuzawa, T. Kawamoto]

D6V1_U_OUT : Collimator flange's outer position directed to QT3FOP.1
D6V1_U_IN : Collimator flange's inner position directed to QT3FOP.1
D6V1_D_OUT : Collimator flange's outer position directed to QTAFOP.1
D6V1_D_IN : Collimator flange's inner position directed to QTAFOP.1

Alignment results and residuals from target values (14 Jan. 2021)

Location	Δy [mm]	Average [mm] (IN+OUT)/2	Δz [mm]	Average [mm] (IN+OUT)/2
D6V1_U_OUT	0.05	0.054	-0.077	0.012
D6V1_U_IN	0.057		0.1	
D6V1_D_OUT	0.044	0.048	0.095	0.021
D6V1_D_IN	0.051		-0.053	

Other collimator work in shutdown

In situ baking of D02V1 and D06V1 collimators (LER)

- Reduction in the base pressure may suppress beam-gas scattering BGs.

Replacement of damaged D09V3 collimator jaws (HER)

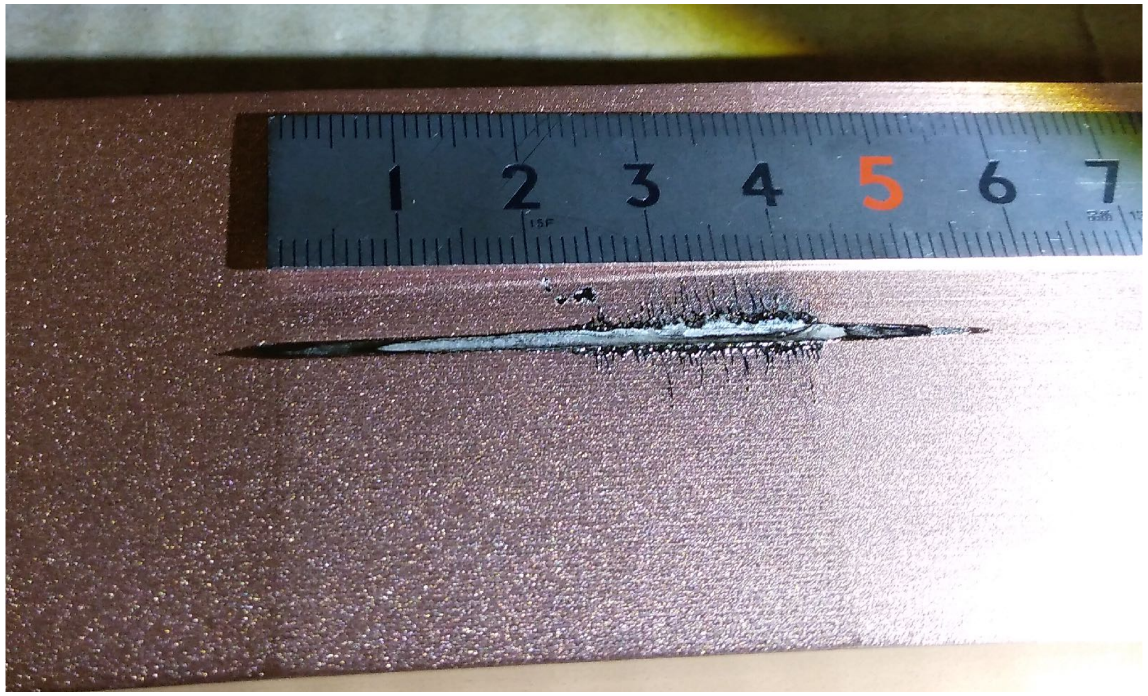
- KEKB type titanium jaw (Ti + Cu-coat, 40 mm long), possibly reduces BGs

Replacement of D12V1 collimator drive mechanism (HER)

- Allows precise positioning

[K. Shibata]

D09V3 head after removal (19 Jan. 2021)



Challenges

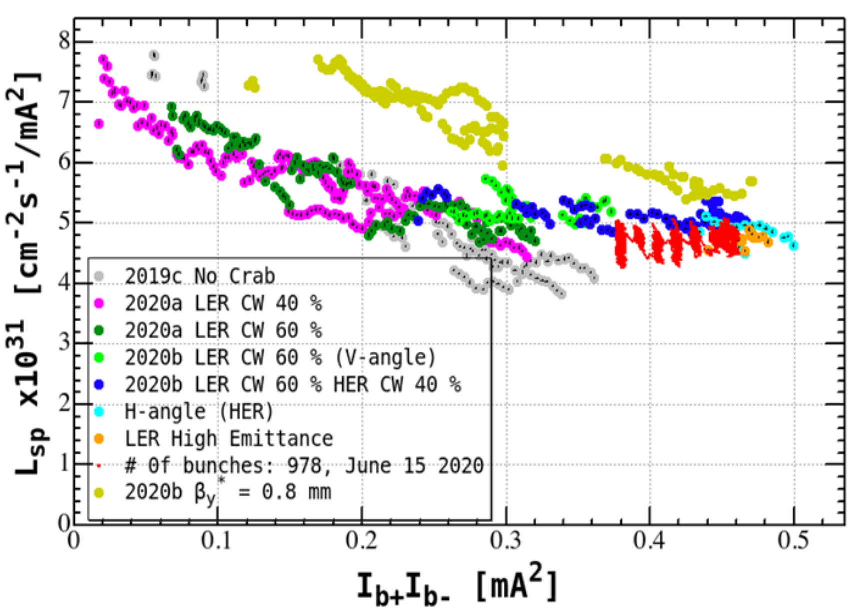
High beam currents (cont'd)

- Beam collimators will be stayed open in 2021 to enlarge the physical aperture and reduce impedance.
- Such a collimator setting will increase BGs and injection-induced beam aborts (Belle aborts and CDC trips), furthermore bring a risk of collimators' damage and QCS quench.

Beam injection (see also linac reports)

- Establish stable and two-bunch injection at 25 Hz repetition rate
- Based on the experience so far, the maximum beam current with 1565 bunches will be ~1.2 A (~0.7 mA/bunch) for 2021a+b.

[Y. Funakoshi]



β_y^*	N_b	TOP Limit (LER,HER)	TMCI(C)	TMCI(Ta)	Expected Luminosity (Carbon)	Expected Luminosity (Ta)	Injection LER 2-bunch (22Hz)	Injection HER 2-bunch (25Hz)
1mm	978	1.13A, 1.05A	0.685A	0.978A	2.1 x 10^{34}	3.4 x 10^{34}	1.35A	1.14A
1mm	1174	1.16A, 1.08A	0.821A	1.17A	2.6 x 10^{34}	4.5 x 10^{34}	1.42A	1.25A
1mm	1565	1.22A, 1.13A	1.10A	1.57A	3.4 x 10^{34}	4.1 x 10^{34}	1.54A	1.44A
1mm	1663	1.23A, 1.14A	1.16A	1.66A	3.6 x 10^{34}	4.0 x 10^{34}	1.57A	1.49A
1mm	1761	1.24A, 1.15A	1.23A	1.76A	3.8 x 10^{34}	3.9 x 10^{34}	1.60A	1.52A
0.8mm	978	1.00A, 0.929A	0.685A	0.978A	2.7 x 10^{34}	4.7 x 10^{34}	0.991A	0.799A
0.8mm	1174	1.06A, 0.984A	0.821A	1.17A	3.2 x 10^{34}	4.8 x 10^{34}	1.04A	0.875A
0.8mm	1565	1.13A, 1.05A	1.10A	1.57A	4.3 x 10^{34}	4.5 x 10^{34}	1.13A	1.01A
0.8mm	1663	1.15A, 1.07A	1.16A	1.66A	4.4 x 10^{34}	4.4 x 10^{34}	1.15A	1.04A

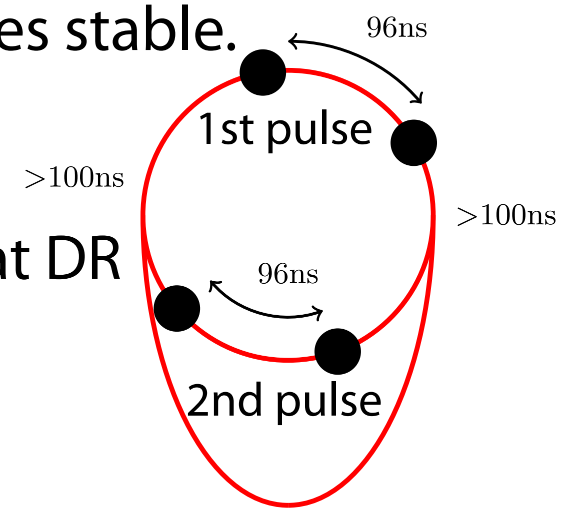
Even with 2-bunch injection, stored currents are below requirements with β_y^*=0.8mm.

Upgrade of Bucket Selection

The upgraded bucket selection system offers a degree of freedom in a choice of injection buckets owing to the RF-phase pulse-by-pulse modulation in the LINAC 3-5 sectors;

- Enables two-pulses operation at DR
- Enables injections with unequal intervals
- Injection rate can be changed without closing Beam Gate.
- Trigger system becomes stable.

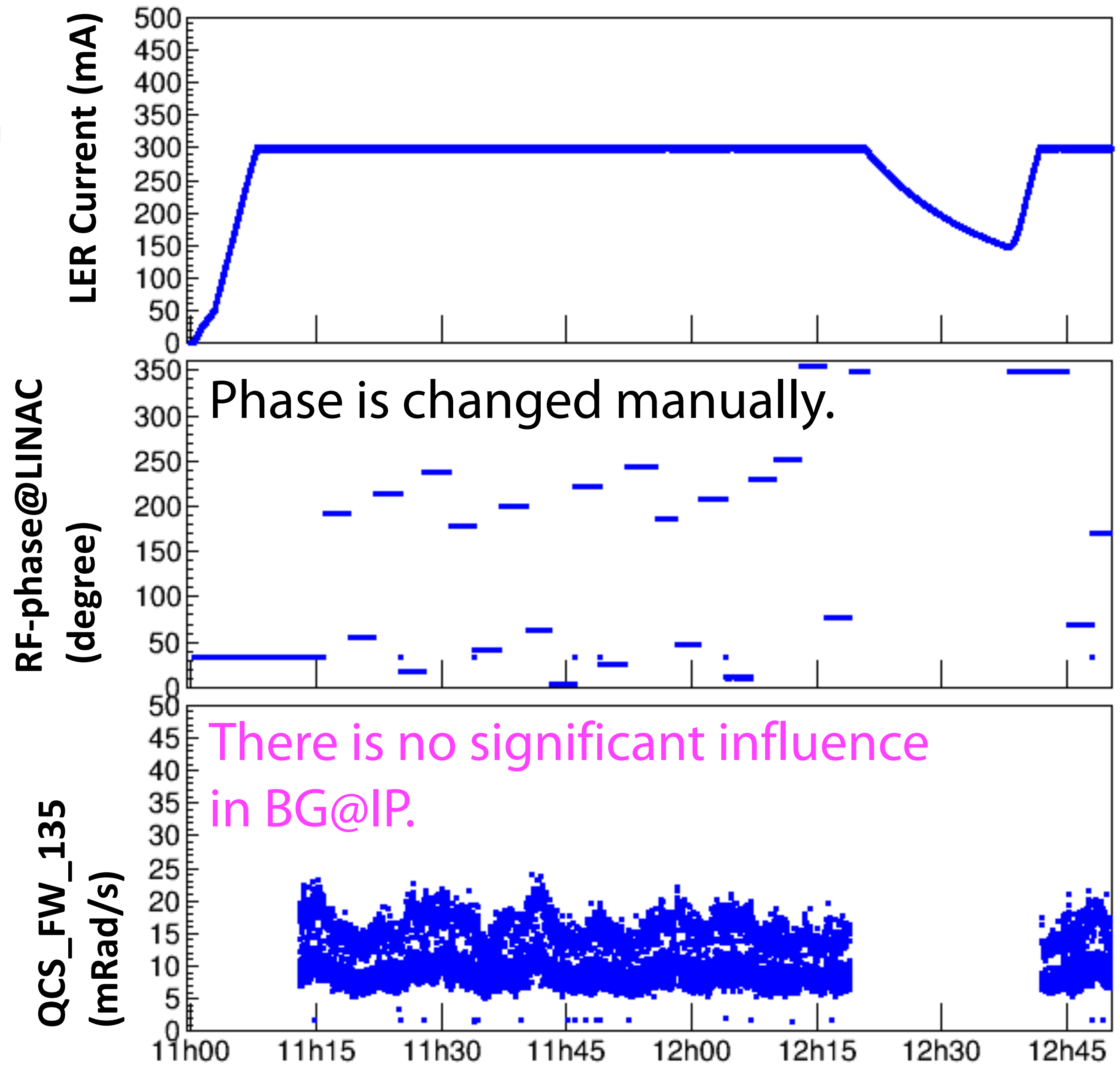
Storage configuration at DR



The fruitful tests are carried out in 2020ab and 2020c runs.

→ **Feasibility is confirmed.**

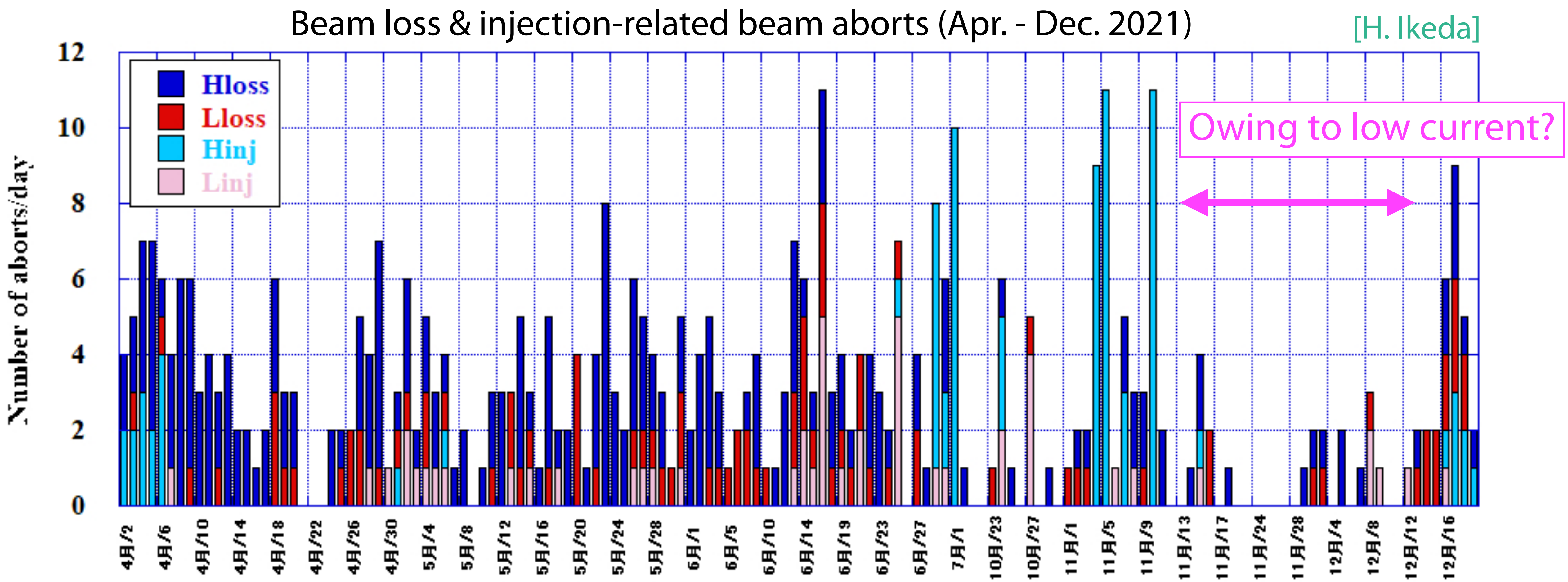
Test run taken on Dec 16, 2020



[H. Kaji, H. Sugimura]

- 2021ab starts with the existing (no modulation) Bucket Selection system.
- Will be switched to the new system once the MR operation goes stable.

Beam abort diagnostics

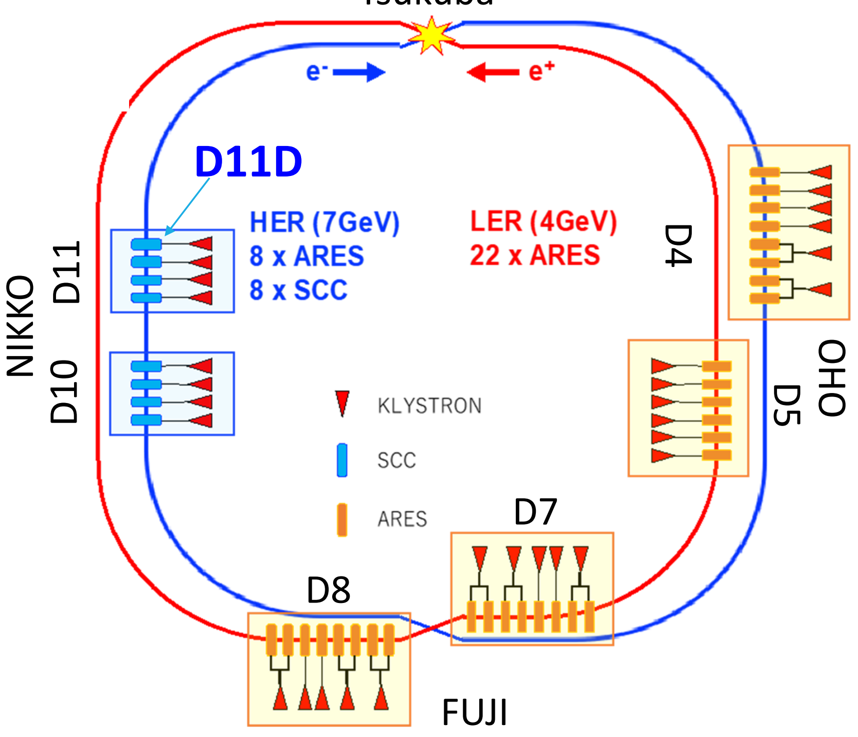


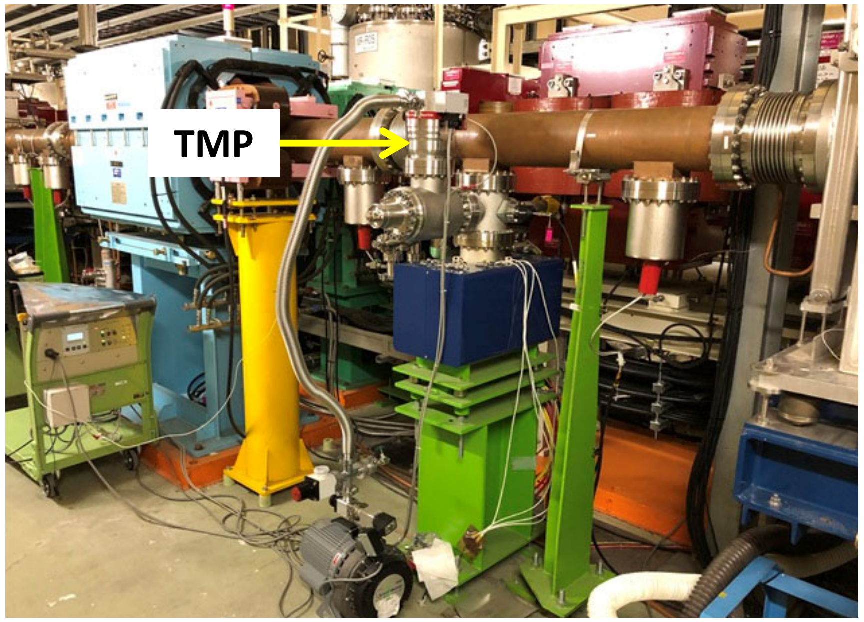
- Many *injection-related aborts* (H/Linj) especially on Nov at HER, investigation on-going by the injector group.
- *Non-injection aborts* (H/Lloss) need another preparation, since it has caused QCS quenches and collimator damages. Understanding beam-dust scatterings is ongoing (simulation, LM timing measurements, etc.)
- Injection-veto module will be applied to LM signals near collimators not to stop collimator and/or injection tunings.

RF system

- Completed the replacement of the D11D SCC with a spare cavity in Jan 2021
  - D11D SCC showed the cavity pressure increase on Oct. 2020 and has been detuned through 2020c.
  - No significant effects of the D11D detuning on beam operation
- Once the safety certificate is issued (expected on 22 Feb), HER operation will start on 24 Feb.
- Other systems are overall stable (some upgrades are ongoing/planned.)

[M. Nishiwaki, Y. Morita]





Oct. 2020

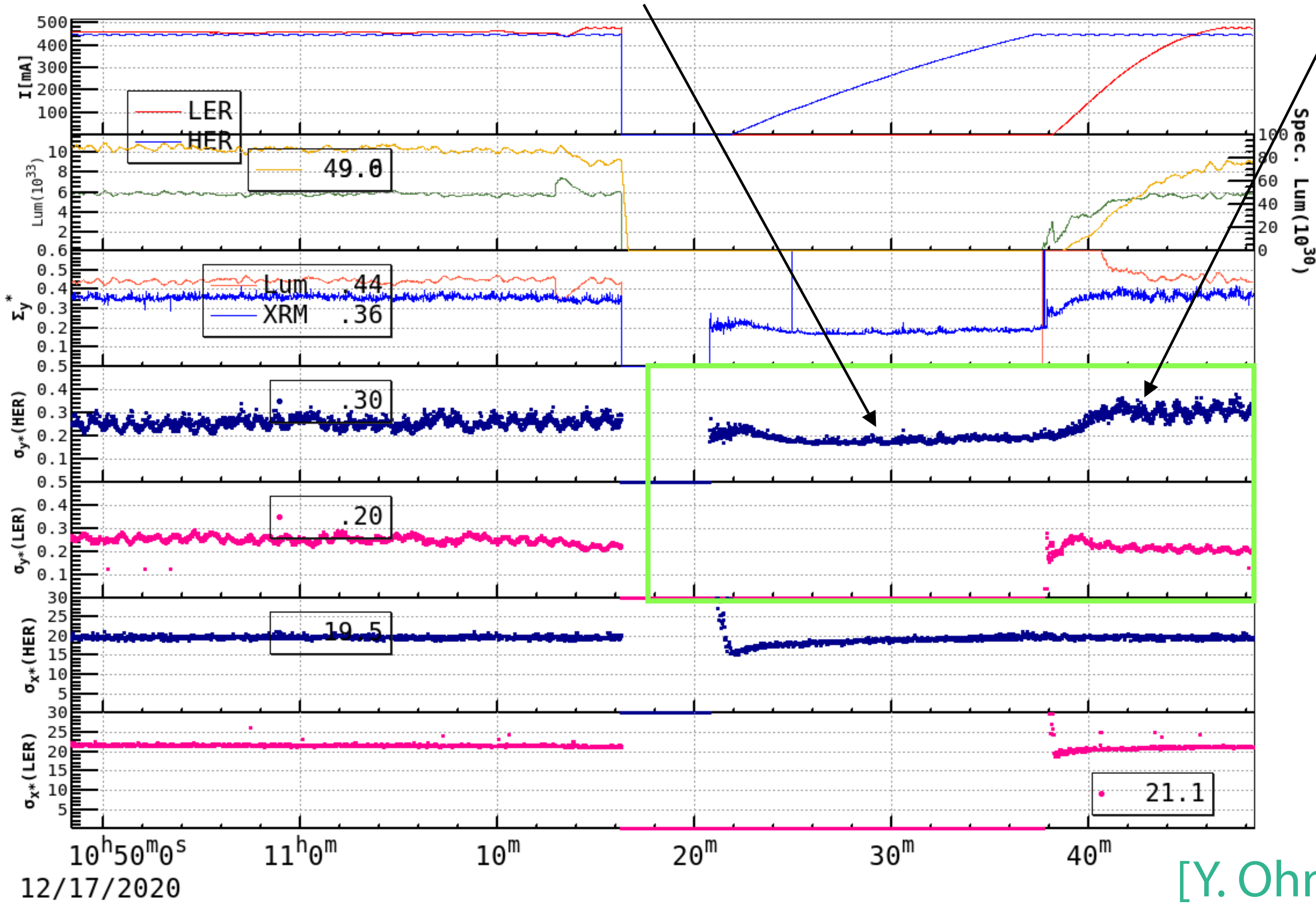

Jan. 2021

Optics tuning

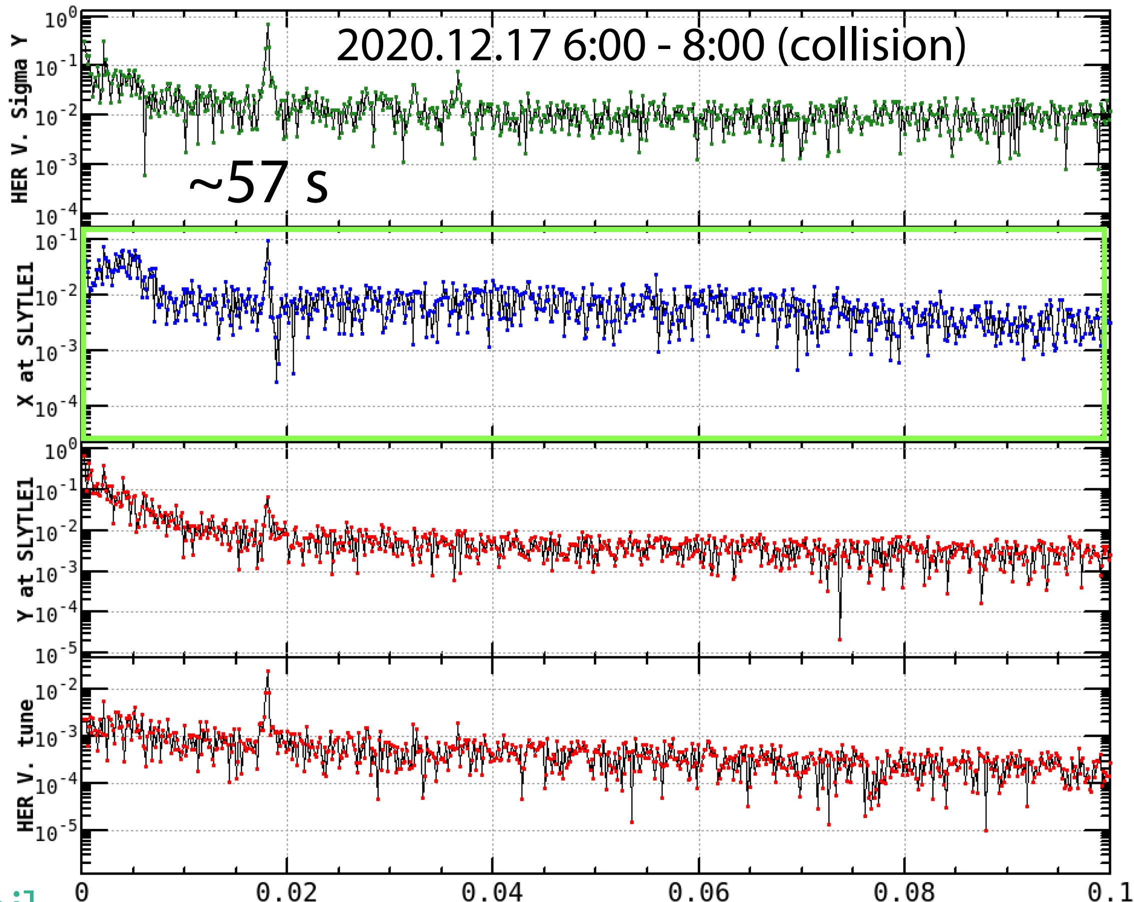
- Stable injection and ring operation at high beam currents
- Chromatic X-Y couplings, octupole, etc.
- Rotatable sextuple controllable remotely can be used for lumi. tuning (under development).

- Investigation of orbit and beam size fluctuations (1/f ~ 57 s, 200 s…)

Beam size oscillation disappears for single beam.



Oscillation appears with collision depending on I_{LER}.



[Y. Ohnishi]

Summary

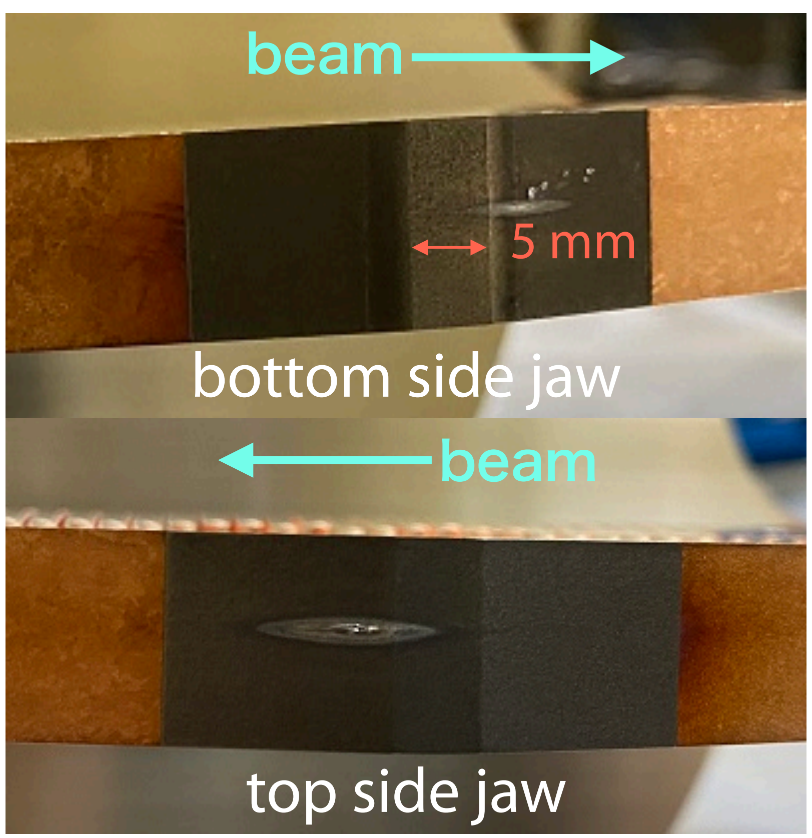
- One of the big issues found in 2020c was a limit of the bunch current due to high impedance of the carbon-head collimator at D06V1.
    - Tantalum-head collimator will be re-used at D06V1 since 2021a.
- Continuous efforts to establish stable injection, and two-bunch at 25 Hz
    - Upgraded bucket selection offers a greater degree of flexibly in injection.
- Beam size and orbit oscillations with 1/f ~57 sec. still remain as homework.
    - Would systematic and comprehensive measurements offer hints?

- All hardware and software are maintained by experts and ready for 2021a.

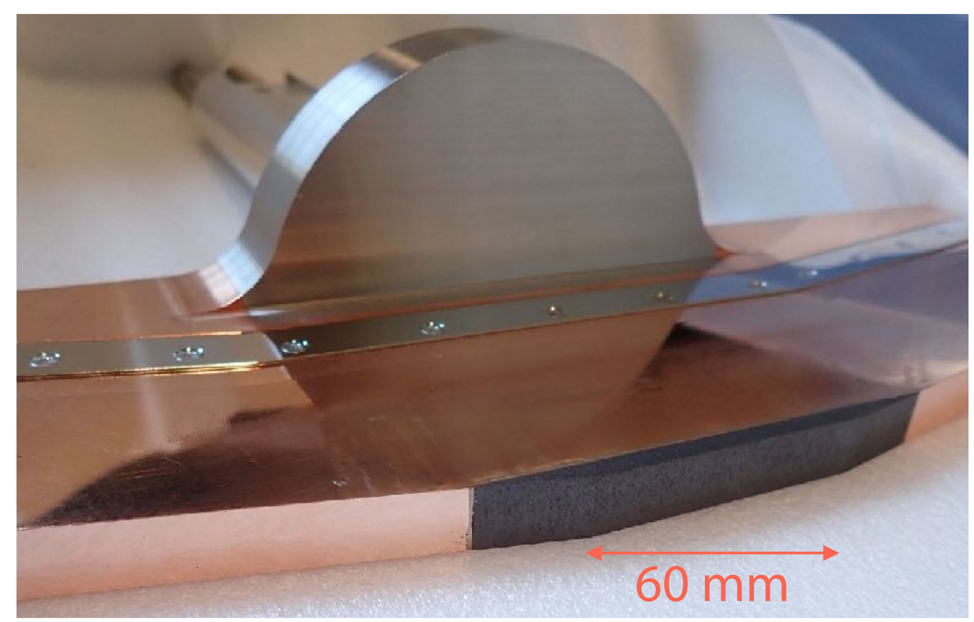
Backup

Why we used C-head collimator at D06V1?

- Unstable beams sometimes directly collided with collimators utilized for BG suppression, e.g. D02V1. Such collisions heavily damaged the collimators.
- D06V1 collimator is expected to guard the collimators for BG suppression from abnormal beams.
- High-z materials is good for a beam-tail shield though, the beam loss is localized followed by high temperature exceeding the melting point.
- During the 2020 summer shutdown, the tantalum-head of the D06V1 collimator used in 2020a+b were replaced with a newly-developed ***carbon head (low-z)***.

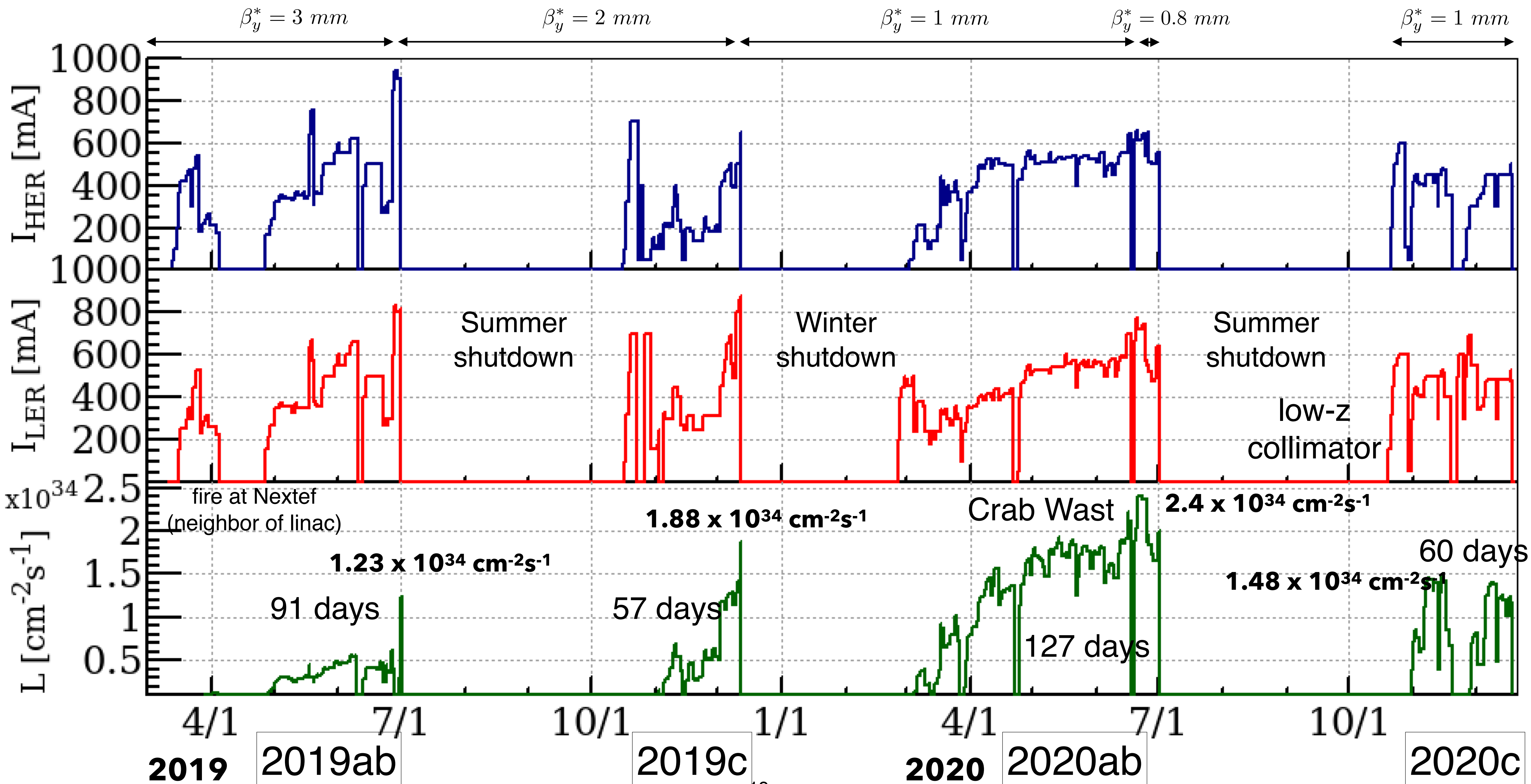


[T. Ishibashi, S. Terui]



[Y. Ohnishi, 2020c Summary Meeting]

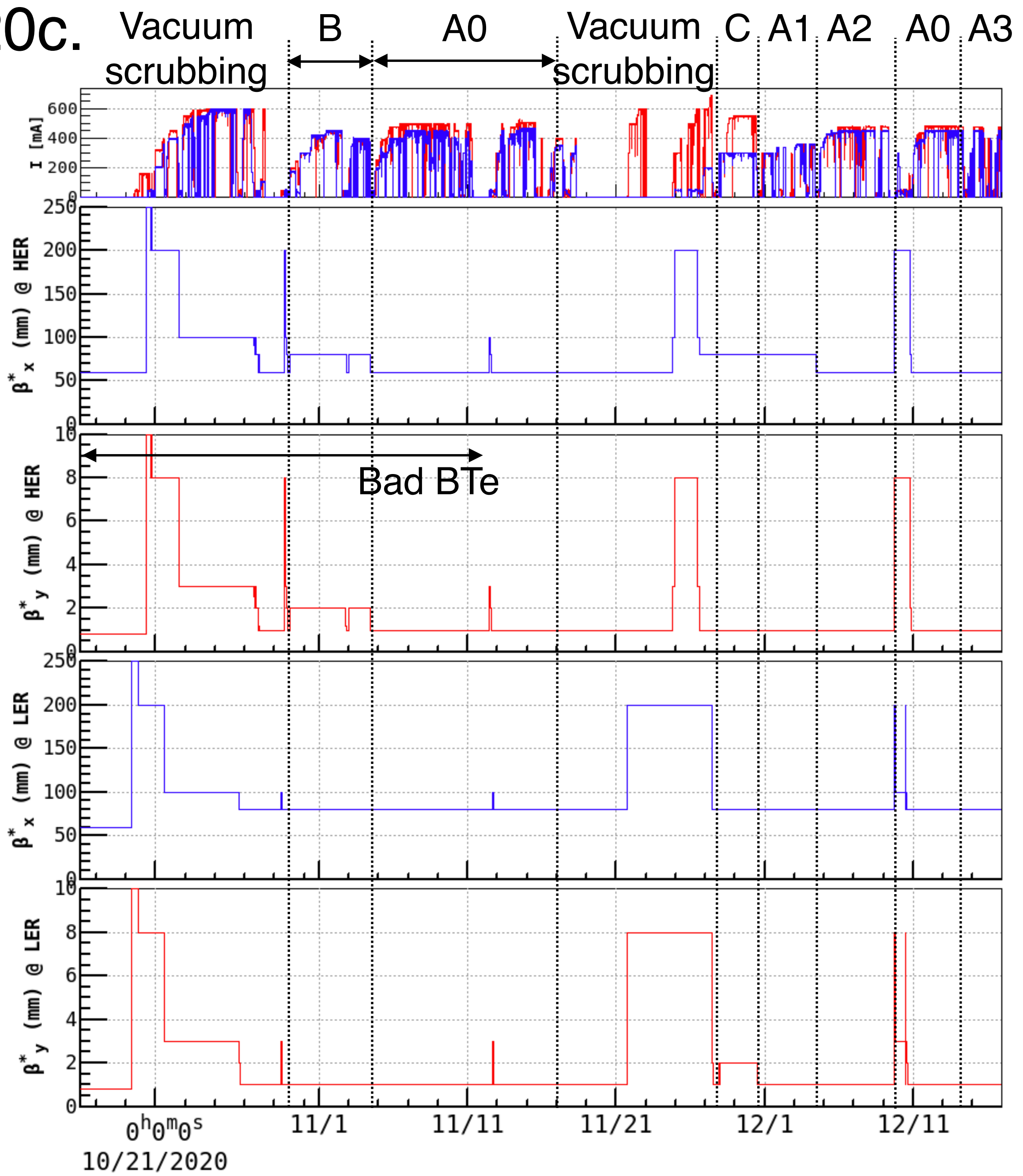
History of Phase 3



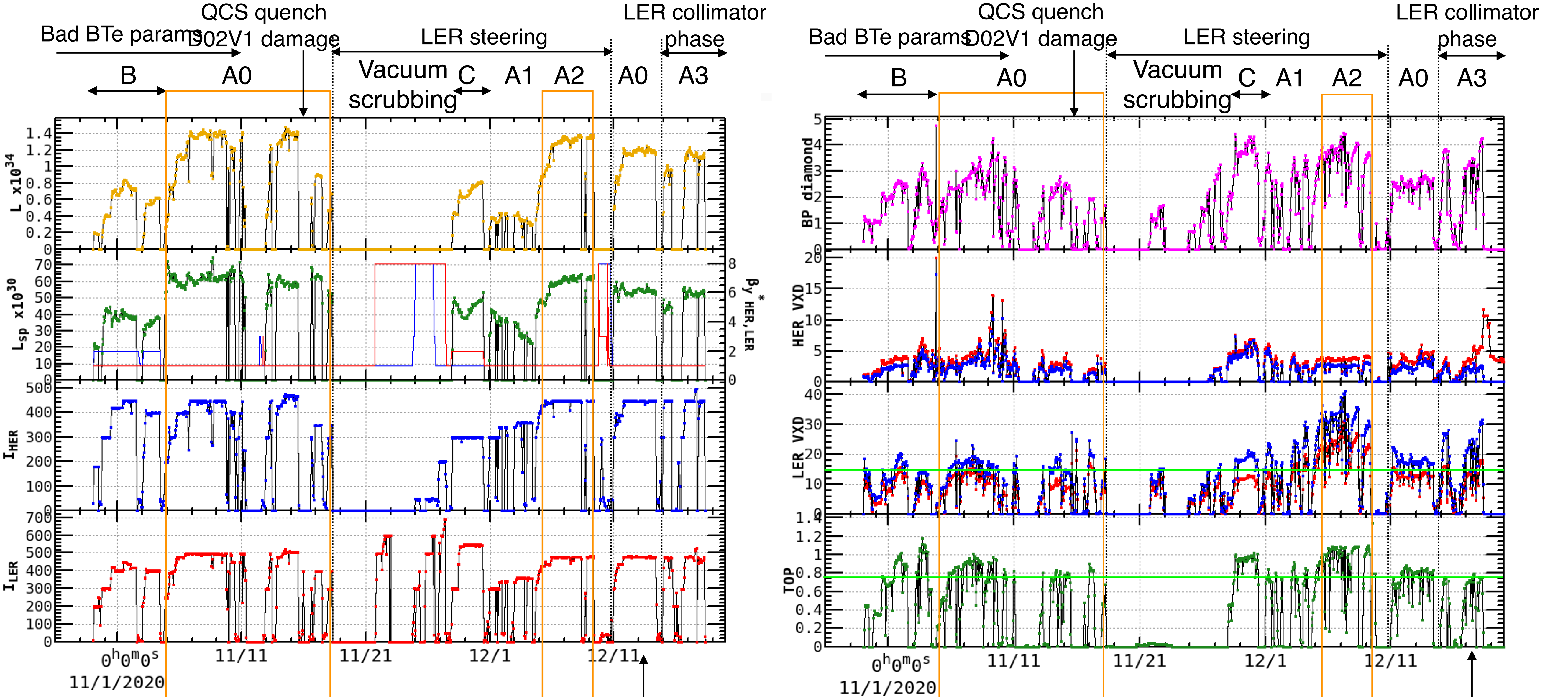
Optics Variations

We tested 6 optics variations during 2020c.

Optics ID	LER β_x^* / β_y^* CW	HER β_x^* / β_y^* CW	Remarks
A0	80 / 1 80 %	60 / 1 40 %	Reference Same as 2020ab
B	80 / 1 80 %	80 / 2 0 %	BTe abnormal orbit (different backleg
C	80 / 2 0 %	80 / 1 0 %	LER steering HER β_x^* = 80 > 60 mm
A1	80 / 1 80 %	80 / 1 0 %	LER steering LER QCS correctors
A2	80 / 1 80 %	60 / 1 40 %	LER steering LER QCS correctors
A3	80 / 1 80 %	60 / 1 40 %	LER collimator phase Based on A0



Operation in 2020c



The second A0 could not reproduce the first A0 for L_{sp}.
BG level became almost same as November 13.

HER BG GOOD
LER BG GOOD

HER BG GOOD
LER BG BAD

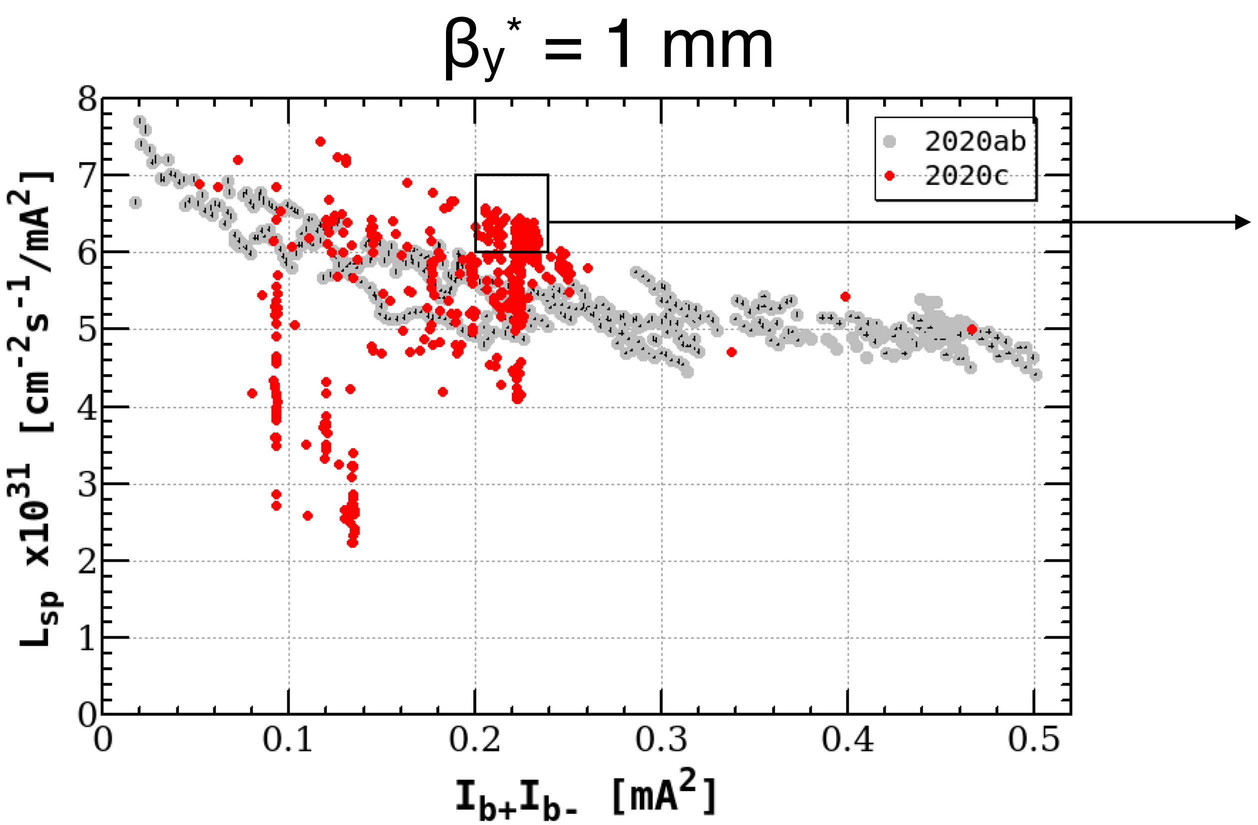
LER VXD BG BAD
TOP is GOOD

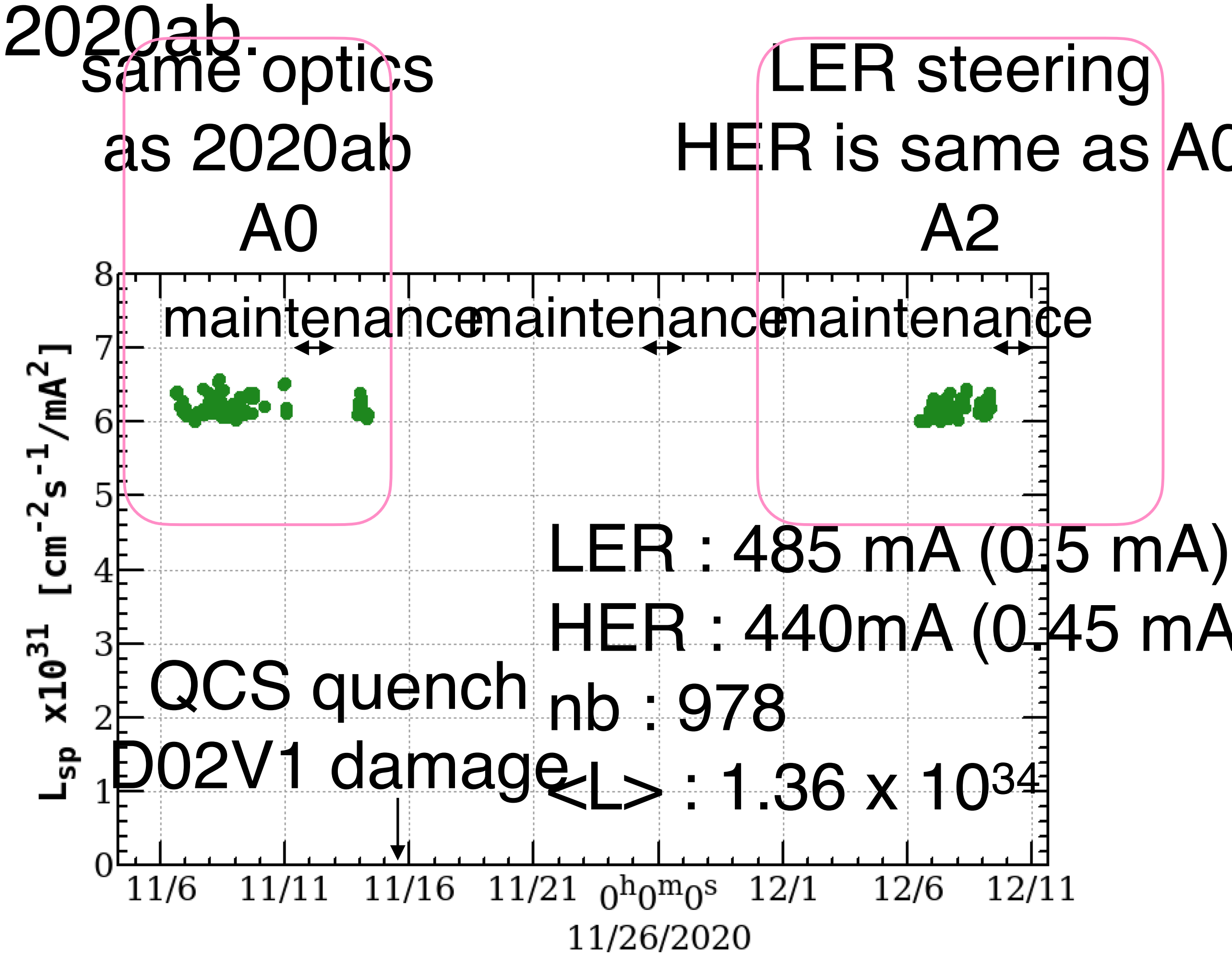
* The plots are peak value for 1 hour

* The plots are average for 1 hour.

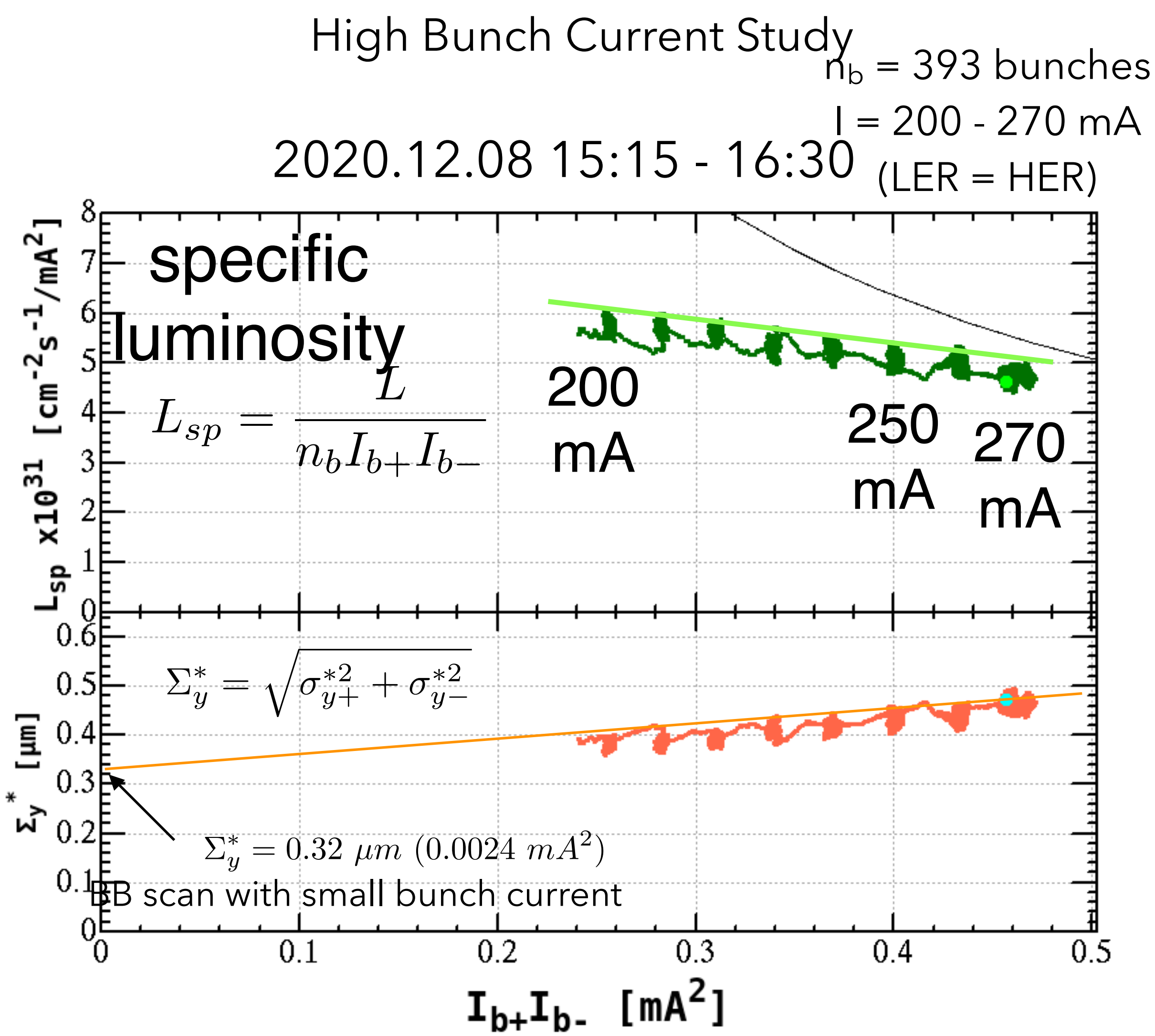
Comparison of Specific Luminosity

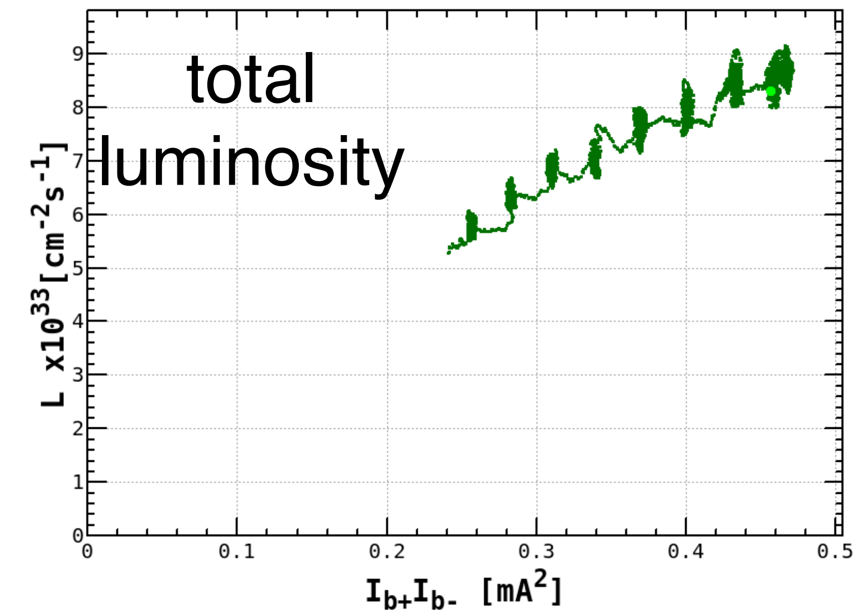
cific luminosity in 2020c was improved from 2020ab.

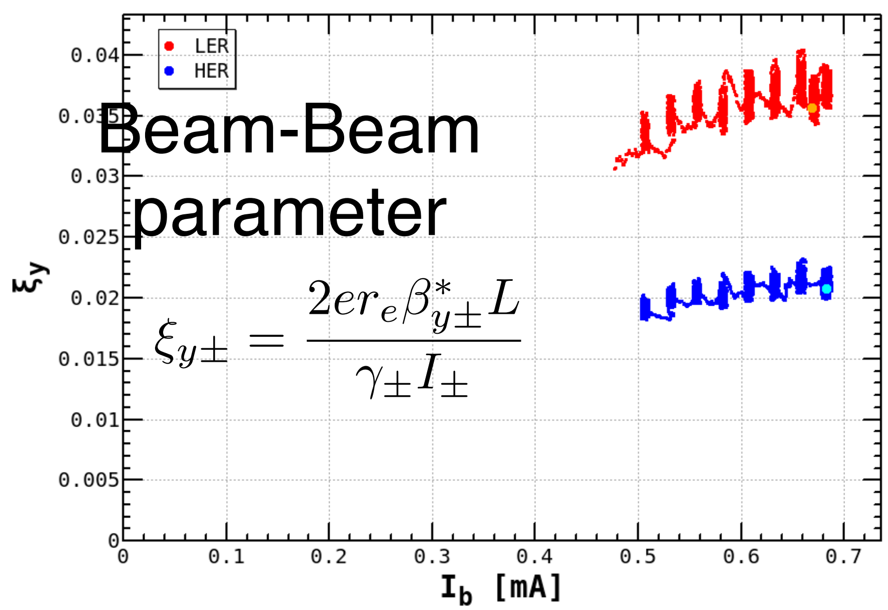




High Bunch Current Study: Specific Luminosity





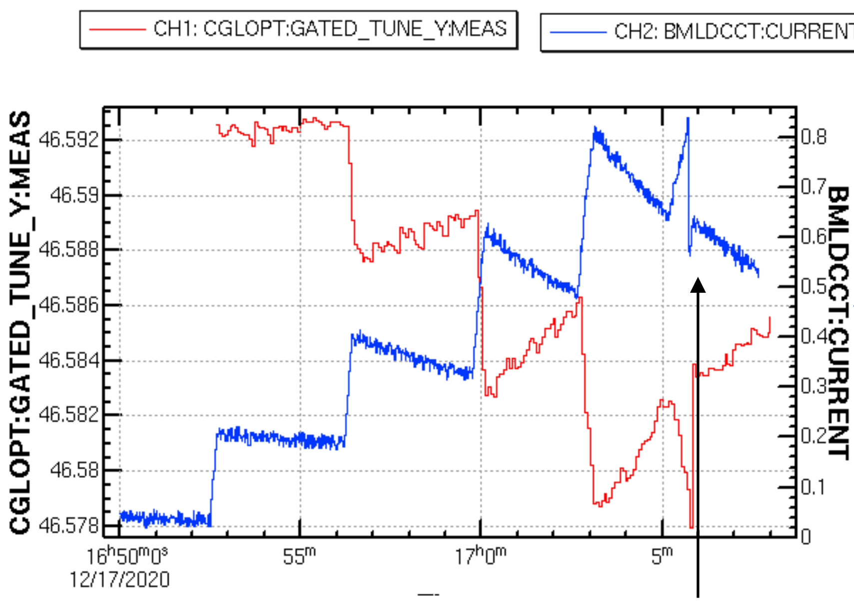


$L_{sp} = 6 \times 10^{31}$ at 0.3 mA^2 (I_b = 0.55 mA, n_b=393)

[Y. Ohnishi, 2020c Summary Meeting]

Sinale Bunch Tune Shift in LER

vert. tune

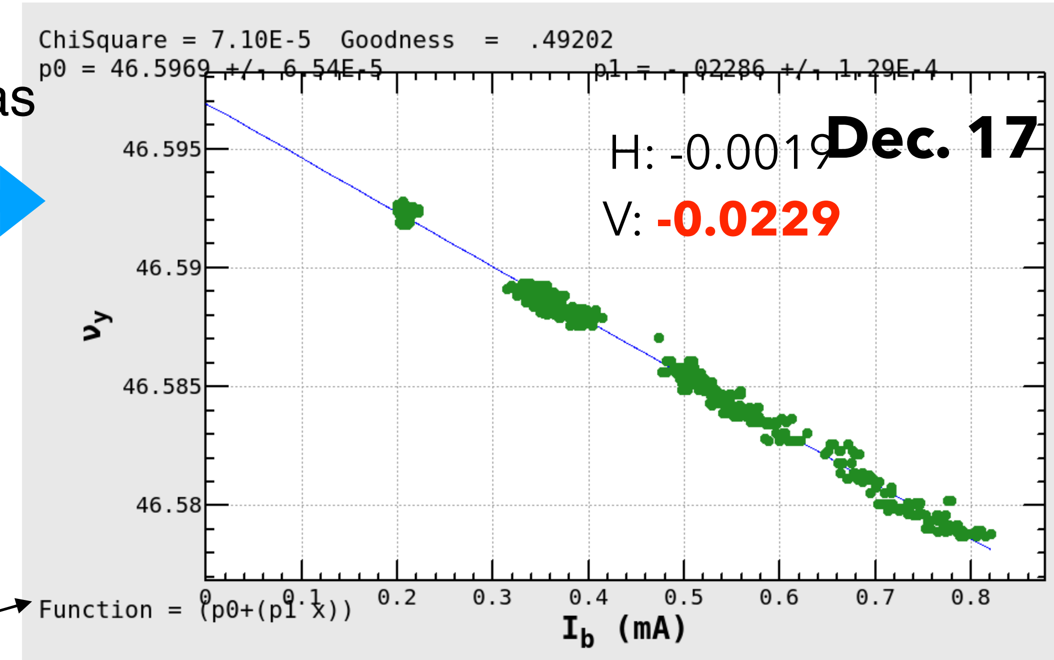


Tune shift is same as synchrotron tune

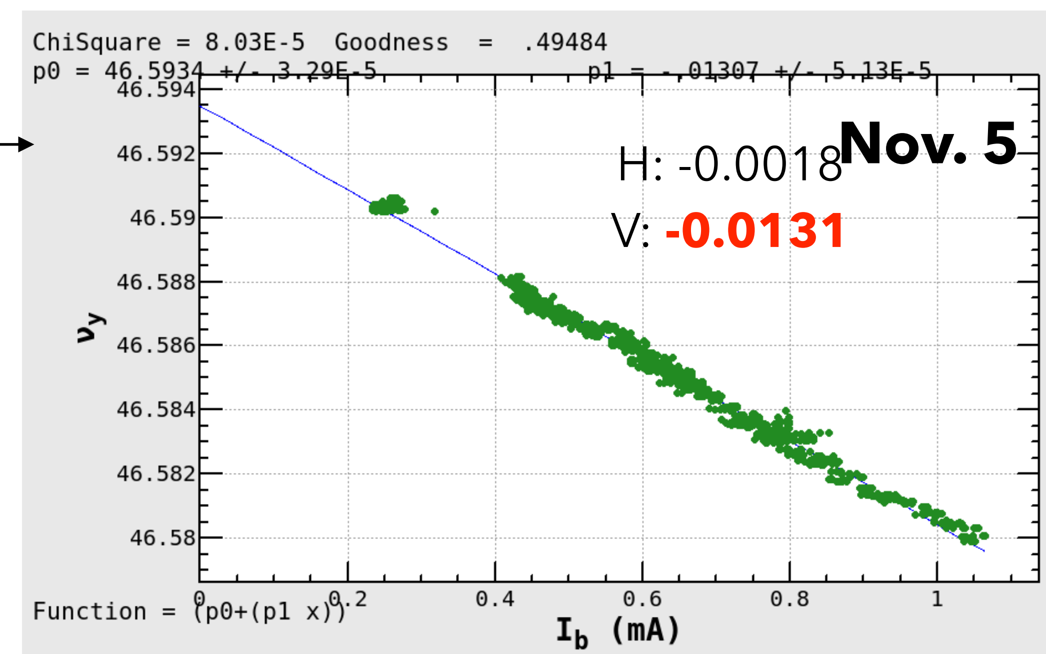
$\nu_s = -0.0235$

single bunch current

eam current can not be stored larger than 0.8 mA/bunch.



	Dec. 17 (A3)	Nov. 5 (A0)
D02V1 (mm)	1.68 / 1.2 (1.44)	1.52 / 1.2 (1.36)
D03V1 (mm)	**0.68 / 1.38**	2.0 / 1.98 (1.99)
D06V1 (mm)	**2.7 / 1.2 (1.95)**	3.2 / 3.2 (3.2)
D06V2 (mm)	2.28 / 1.85 (2.07)	2.2 / 1.9 (2.05)



Operation Statistics

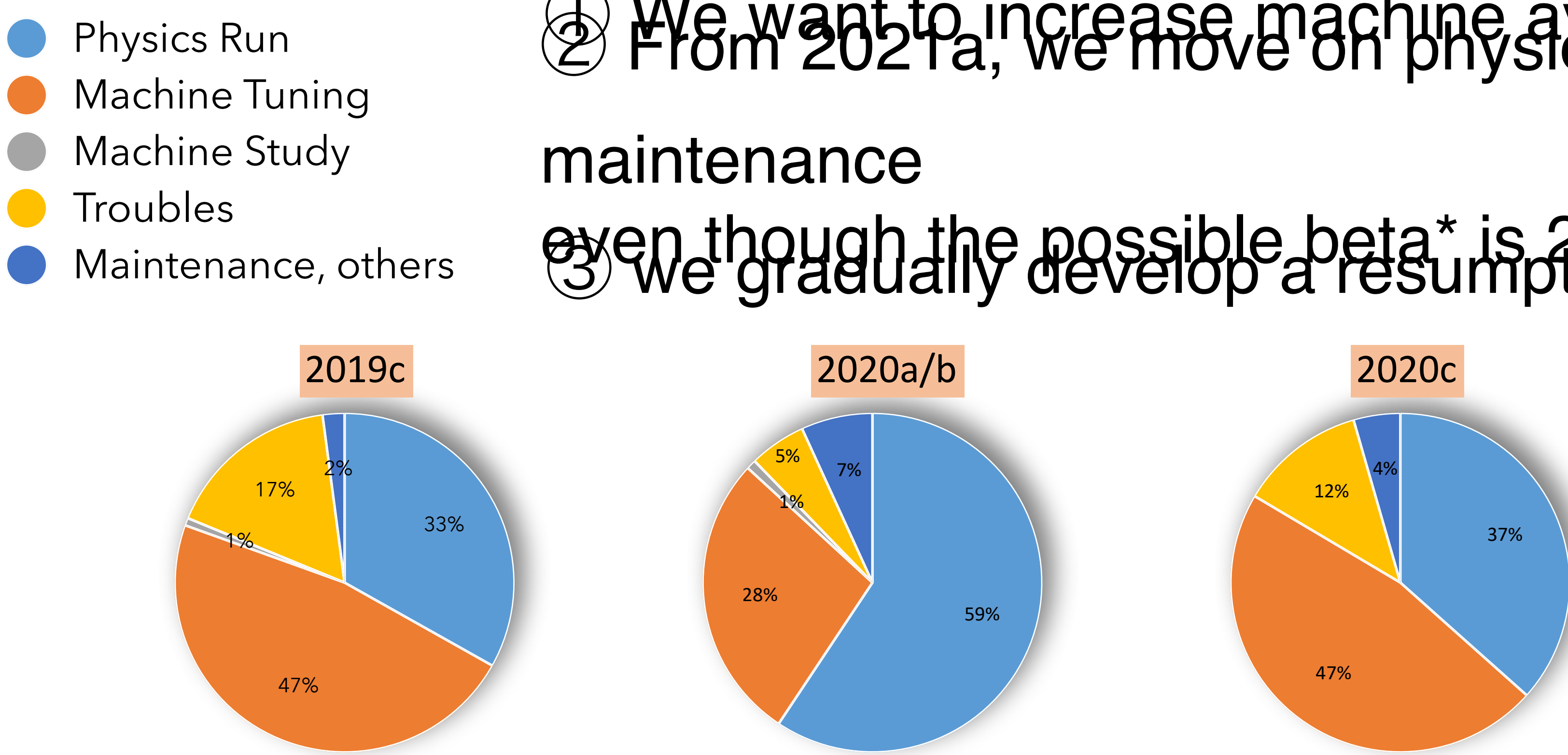
① We want to increase machine availability for physics run as mu

② From 2021a, we move on physics run as soon as possible after maintenance even though the possible beta* is 2 mm in the day.

③ We gradually develop a resumption strategy and try to reduce n

④ Maintenance is usually injection tuning for PF and PF-AR then SuperKEKB injection tuning starts. Startup with stable operation of linac injector is a key point to resume SuperKEKB as quick as possible.

⑤ Linac injector tuning should be as needed. (Wednesday is advant a disturbance for PF and PF-AR is



Physics run: 33 %
Machine tuning: 47 %

Physics run: 59 %
Machine tuning: 28 %

Physics run: 37 %
Machine tuning: 47 %

2019c was dedicated to the machine tuning.

similar statistics coincidentally ?

Troubles

Group	Device	Content	hour:mi	#
LINAC	safety	Linac Ready	0:17	1
	charge limit	1S abort	0:57	1
MG	QCS	QC1RP quench	1:17	1
	QEAP 44	PS tracking error	0:59	1
RF	D11AB KPS	crowbar work, solenoid PS	14:09	1
	air fin cooler (AFC)	frozen (human error)	3:16	1
	D11A HOM chiller	compressor abnormal	2:51	2
VAC	D02V1	damage, replace head	174:26	1
Infrastructure	water cooling pump (NIKKO)	malfunction → vacuum leakage at LER	1:28	1
DR	DR ext. septum	cooling water abnormal	1:43	2
	BL1S 1 2	magnet water stop	0:32	1
	DR Inj. kicker	PS fault	2:19	1
	DR inj. kicker	reserver PS communication error	0:37	1
	QRF	magnet water low rate	0:47	1
BTp	BV2P 1 2	magnet water stop	2:18	1
	BH1BP	abnormal water flow rate	0:46	1
	B2P 2	magnet water stop	1:58	3
	QAD9P	PS Tracking I/L	1:19	
BTe	BV2E 4	PS OV	1:16	1

DR inj./ext. kicker communication fault: no. incident is 51 (< 15 min for e

Operation Statistics

2020	Physics run	Machine tuning	Machine study	Troubles	Maintenance and others	total (hours)
February	0.0	102.0	0.0	0.0	10.0	112.0
March	344.0	314.5	0.0	17.5	68.0	744.0
April	468.0	135.0	0.0	71.5	45.5	720.0
May	525.0	133.5	0.0	26.0	59.5	744.0
June	463.0	153.5	28.0	50.5	25.0	720.0
July	9.0	0.0	0.0	0.0	0.0	9.0
total (hours)	1809.0 59.3 %	838.5 27.5 %	28.0 0.9 %	165.5 5.4 %	208.0 6.8 %	3049.0
October	37.2	536.6	0.0	8.3	45.1	627.2
November	324.7	180.6	0.0	197.2	17.7	630.2
December	283.8	111.0	0.0	6.5	15.8	417.1
total (hours)	645.7 36.6 %	828.2 46.9 %	0.0 0.0 %	212.0 12.0 %	78.6 4.5 %	1764.5

[Y. Ohnishi, 2020c Summary Meeting]

Comparison between 2020b(June) and 2020c(November)

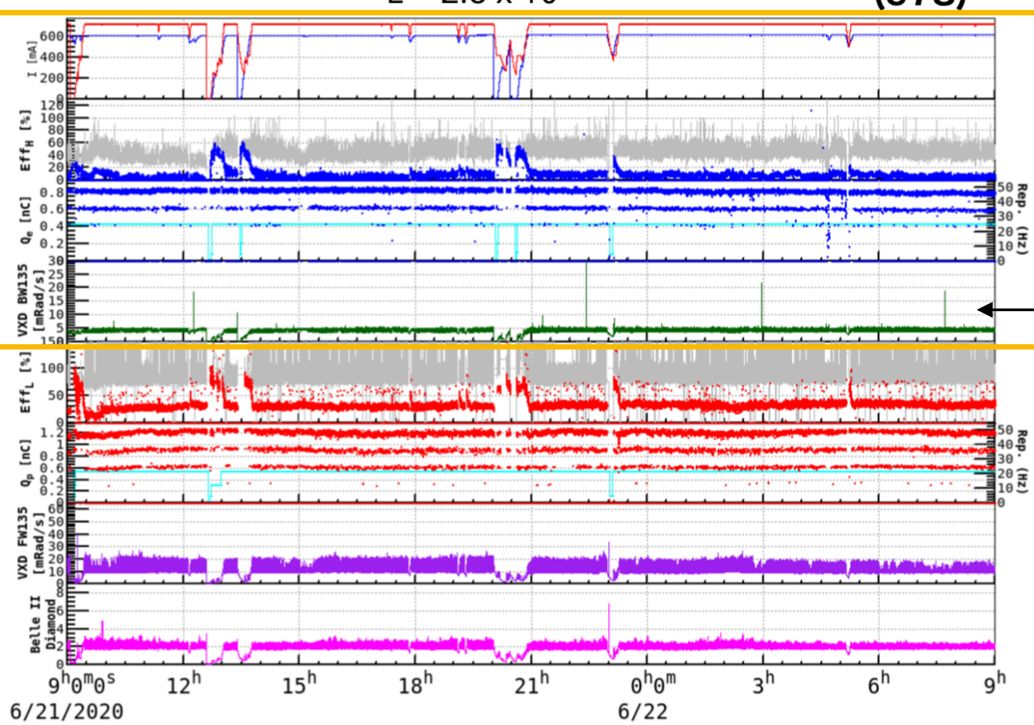
2020b

HER injection was good.

$\beta_x^* = 60\ mm\ \beta_y^* = 1\ mm$

L ~ 2.3×10^{34}

HER
600 mA
(978)



←BCM efficiency ~ 30 %

0.8 nC/bunch 25 Hz

VXD BG was very small.

2020c (~Nov.12)

HER injection was terrible.

e-: 1.3 nC/bunch 12.5 Hz