Status of SuperKEKB Main Ring

Till June 19th

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On Behalf of SuperKEKB Commissioning Group

B2GM June 2020

Topics

- Operation Summary

- Major Changes After the Last (2019c) Run

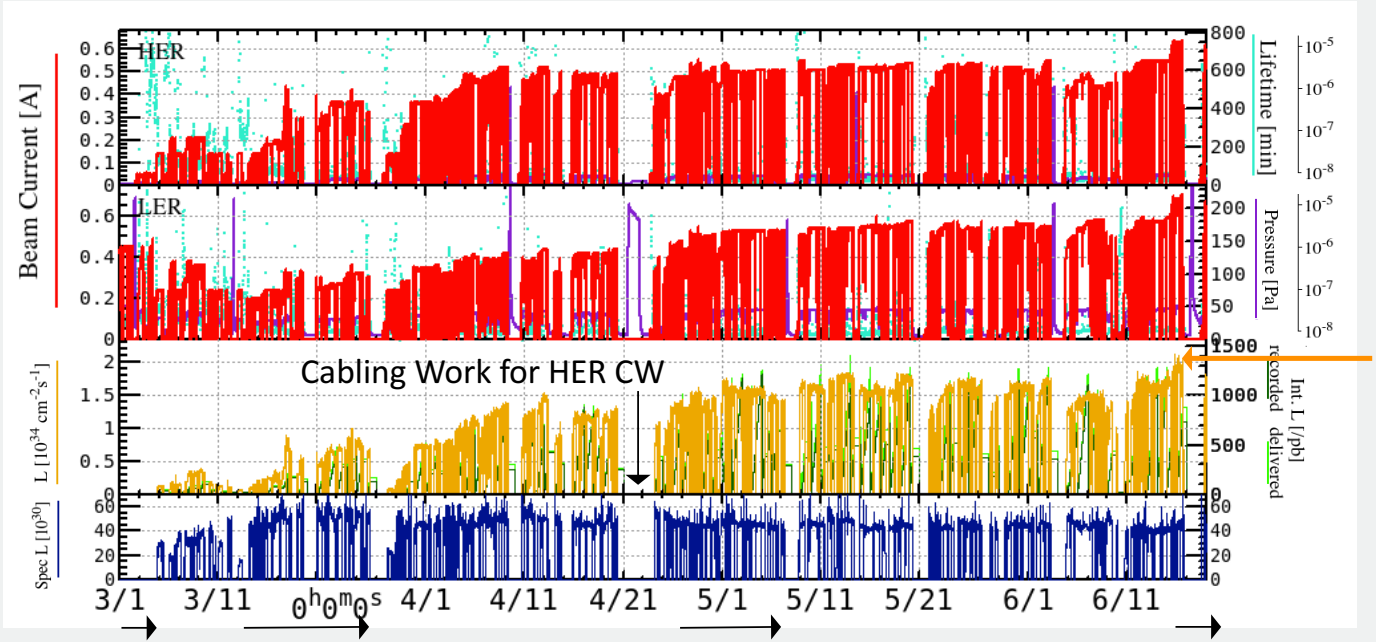
- Luminosity Tuning
  - Introduce Crab Waist(CW) scheme to both rings.
  - Horizontal angle orbit at IP and SR to PXD
  - Adjustment of the anti-solenoid field (ESL/ESR) of QCS.
  - Rotatable sextupole to control chromatic betatron coupling (XY-coupling).

- Other Topics

Status of Operation

- *We have broken the KEKB's record!* (2.108 x 10^{34} $cm^{-2}s^{-1}$)

- Peak luminosity = 2.23 × 10^{34} $cm^{-2}s^{-1}$ at 679(LER), 639(HER) mA, June 15th



Integrated Luminosity

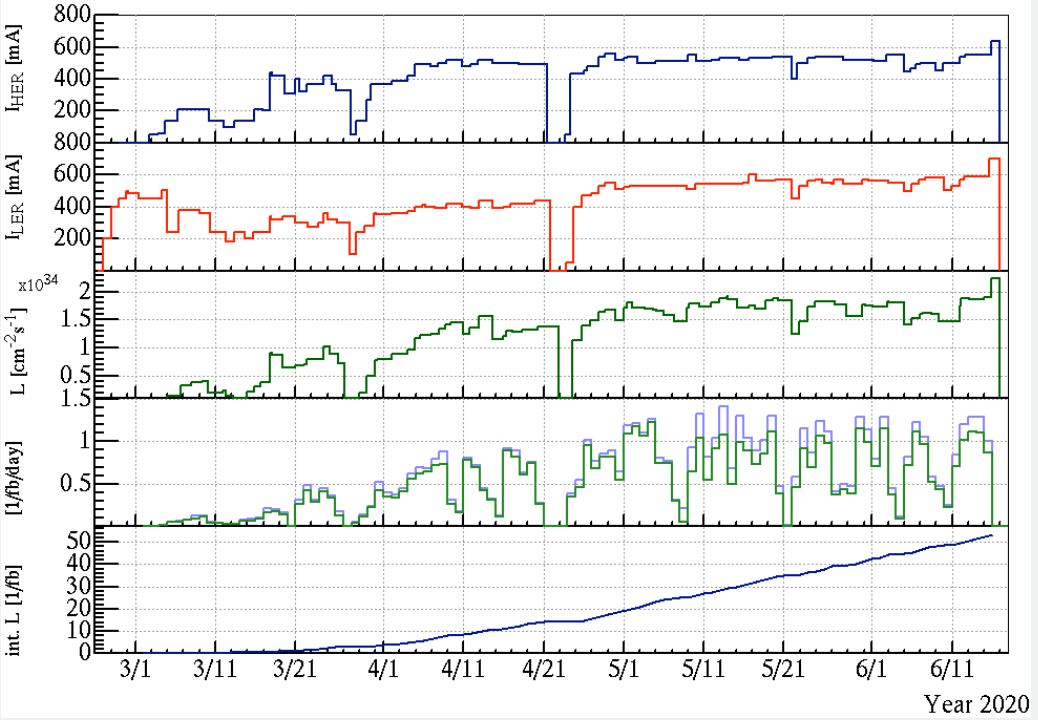
- Integrated luminosity: ~ 50 fb^{-1} (2020/03~2020/06/13)

Y. Ohnishi

- Integrated luminosity per day: 1 fb^{-1}

  It is depending on study time and machine troubles.

- We are struggle with machine troubles related to aging hardware not only in main rings but also hardware in the injector linac including beam transport line.



Machine Parameters

- Major changes from the last run:
  - LER high emittance lattice (To make beam lifetime longer)
  - Reduce # of bunches (To reduce BG to TOP detector and enable high-current operation.)

	SuperKEKB : June 15, 2020		SuperKEKB : Dec. 12, 2019		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	2.0	4.6	nm
Beam Current	679	639	819	640	mA
Number of bunches	978		1467		
Bunch current	0.694	0.654	0.558	0.436	mA
Horizontal size σ_x^*	17.9	16.6	12.6	16.6	μm
Vertical cap sigma Σ_y^*	0.308		0.416		μm*1
Vertical size σ_y^*	0.218		0.294		μm*2
Betatron tunes ν_x / ν_y	45.523 / 43.580	44.532 / 41.578	44.527 / 46.593	45.532 / 43.574	
β_x^* / β_y^*	80 / 1.0	60 / 1.0	80 / 1.0	60 / 1.0	mm
Piwinski angle	13	15	18	15	
Crab Waist Ratio	80	40	0	0	%
Beam-Beam parameter ξ_y	0.0378	0.0230	0.0265	0.0194	
Specific luminosity	5.02×10^{31}		5.26×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.23×10^{34}		1.88×10^{34}		$cm^{-2}s^{-1}$

Y. Ohnishi

*1) estimated by luminosity
*2) divide *1 by √2

1

Major Issues

- Luminosity and Beam Optics Tuning
  - Correction of beam optics parameters at IP
  - A reliable and robust strategy for low emittance tuning

- Injection
  - Stability of the injected beam, beam optics matching, etc.

- Stable and Safe Operation
  - Beam abort due to unknown issues
  - Aging hardware

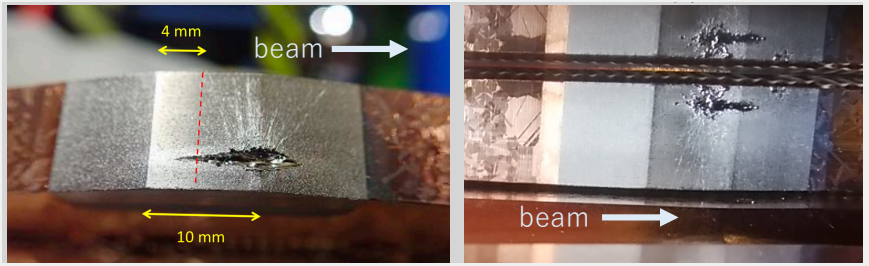
- Beam Background (BG) to Belle II
  - Currently, BG to TOP detector limits high current operation.

Major Changes After the Last (2019c) Run

Major Changes after the Last (2019c) Run

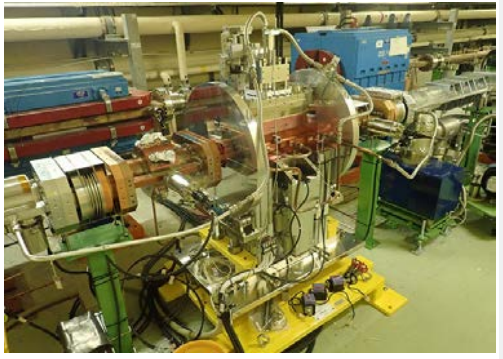
T. Ishibashi

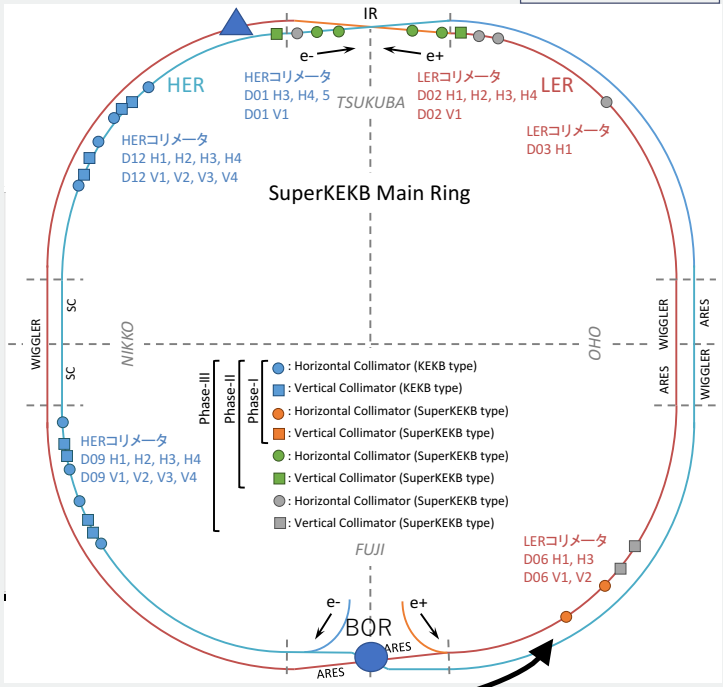
- Replacement of damaged collimator head



- Installation of a new vertical collimator (D06V1) in LER.

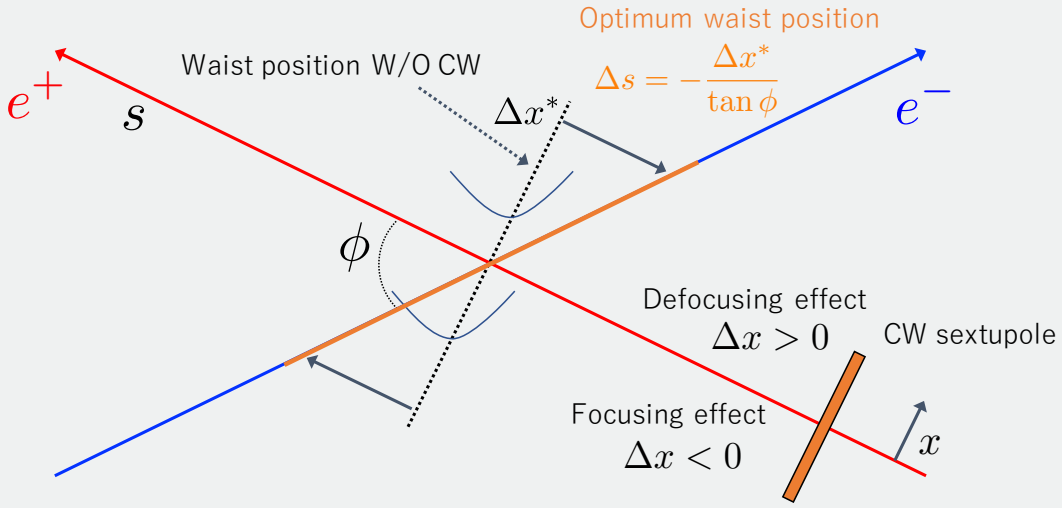
  This will protects the D02V1 collimator which is the most crucial vertical collimator for QCS and Belle II detector protection





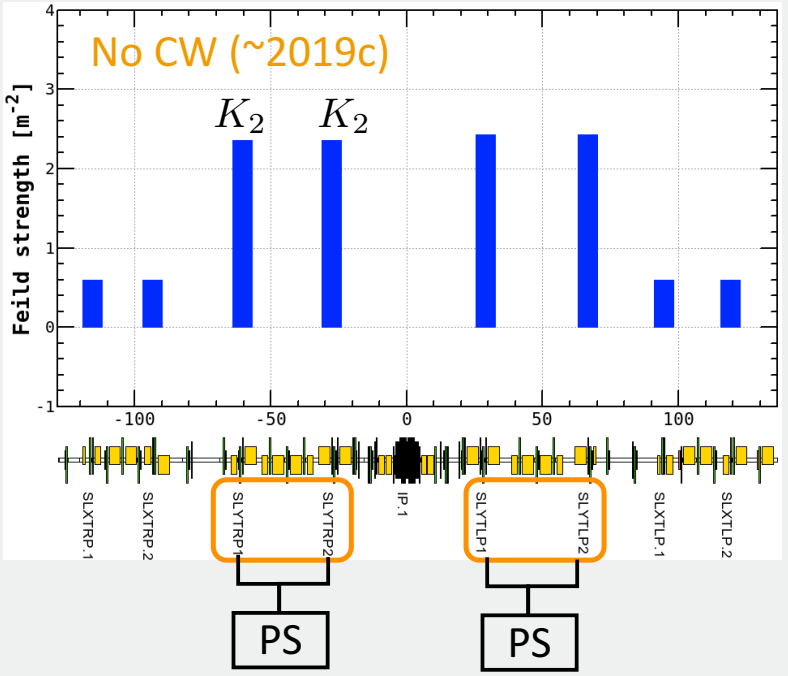
Major Changes after the Last (2019c) Run

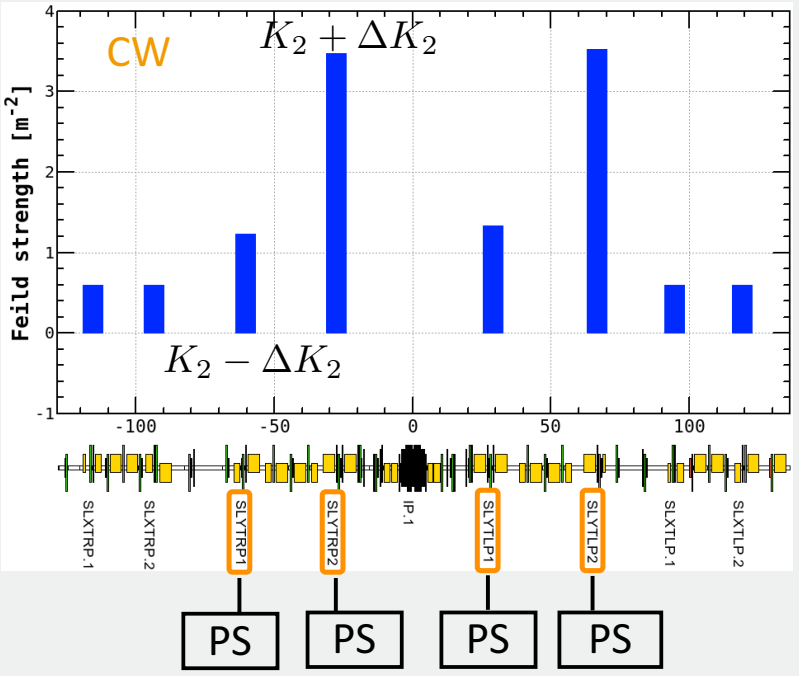
- Introduce Crab Waist (CW) scheme
  - A scheme to mitigate a sort of hourglass effect.
  - Optimum waist position of a particle depends on its horizontal orbit offset Δx^* at IP.
  - A particle at sextupole feels focusing/defocusing force depending on horizontal offset.
  - An appropriate set of sextupoles can align the waist position along the central trajectory of the other one while minimizes unwanted forces from sextupoles.



Major Changes after the Last (2019c) Run

- Individual power supply is needed for sextupole magnets near IP.
- Cabling work has been successfully completed.
- We tried LER first , then introduce it to HER during 2020a,b run.

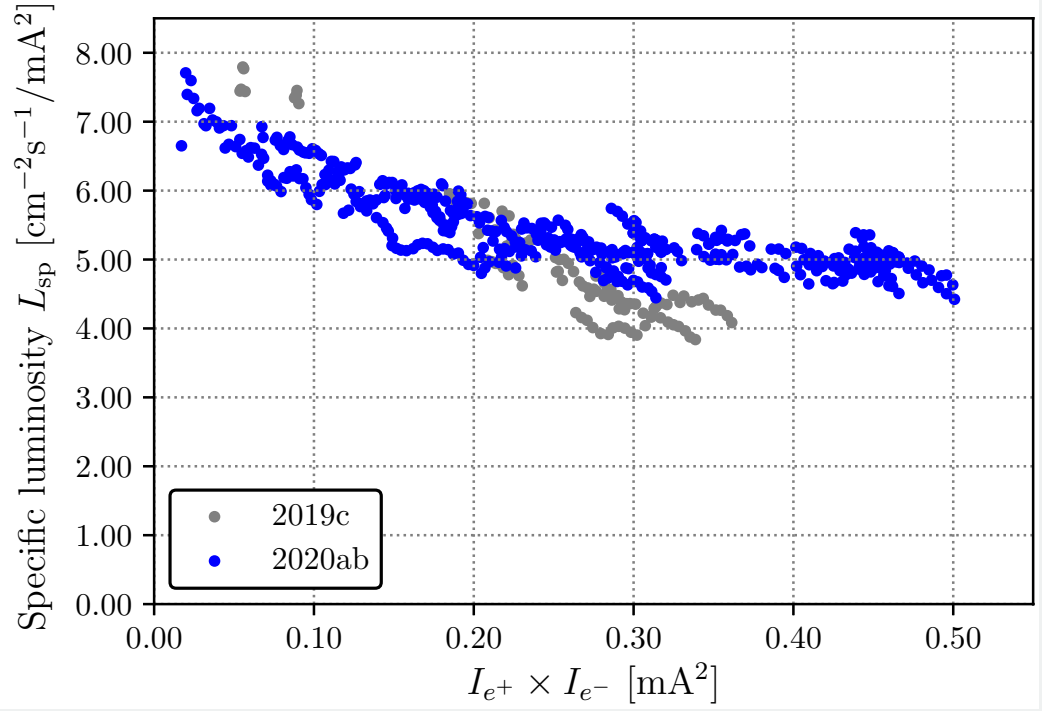




Luminosity Tuning

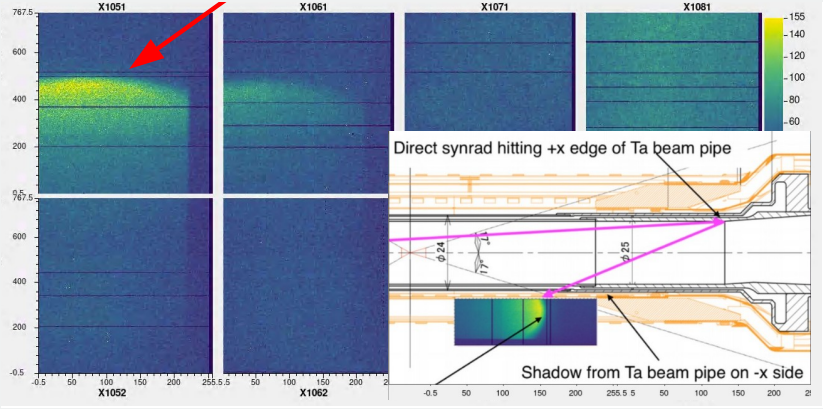
Specific Luminosity

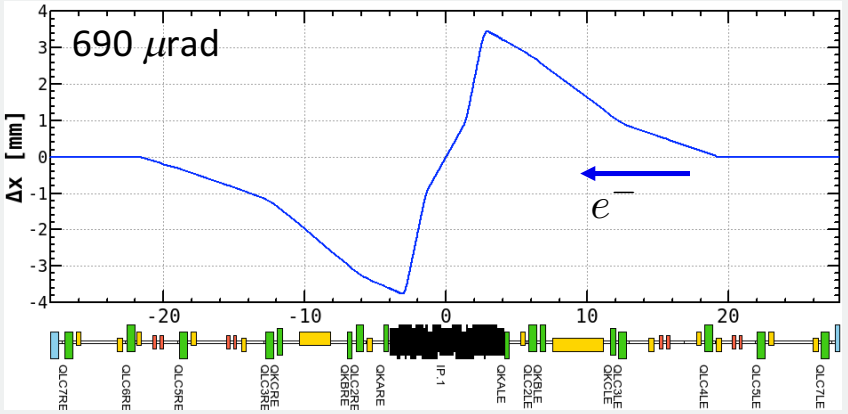
- Owing to CW, collision operation at high-bunch-current region is possible 2020a,b.
- Many trials to keep specific luminosity at higher-bunch-current region.



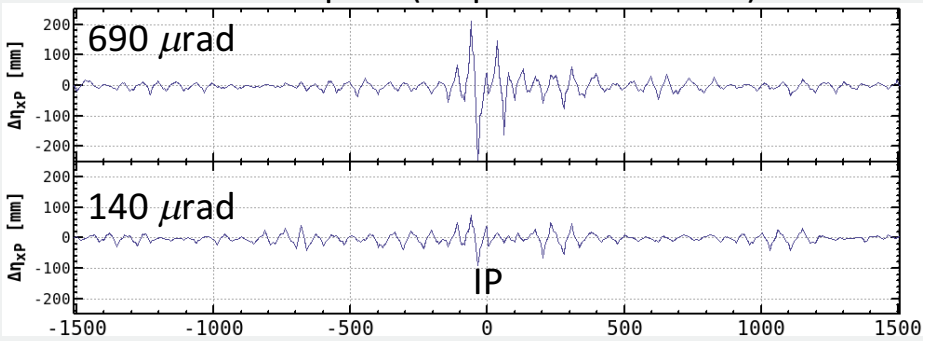
Horizontal Angle of Beam Orbit at IP and SR on PXD

- Localized horizontal angle of 690 μrad is applied at IP to minimize SR on PXD.
- While this angle causes beam-optics distortion.
- We tried different angle (140 μrad)
  which minimizes the optics distortion.





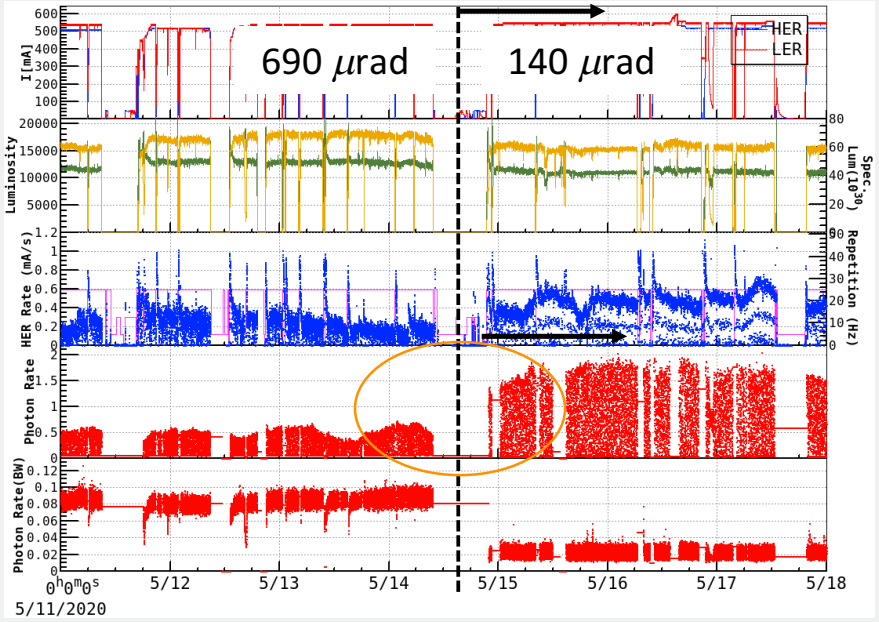
Beam Optics (Dispersion Function)

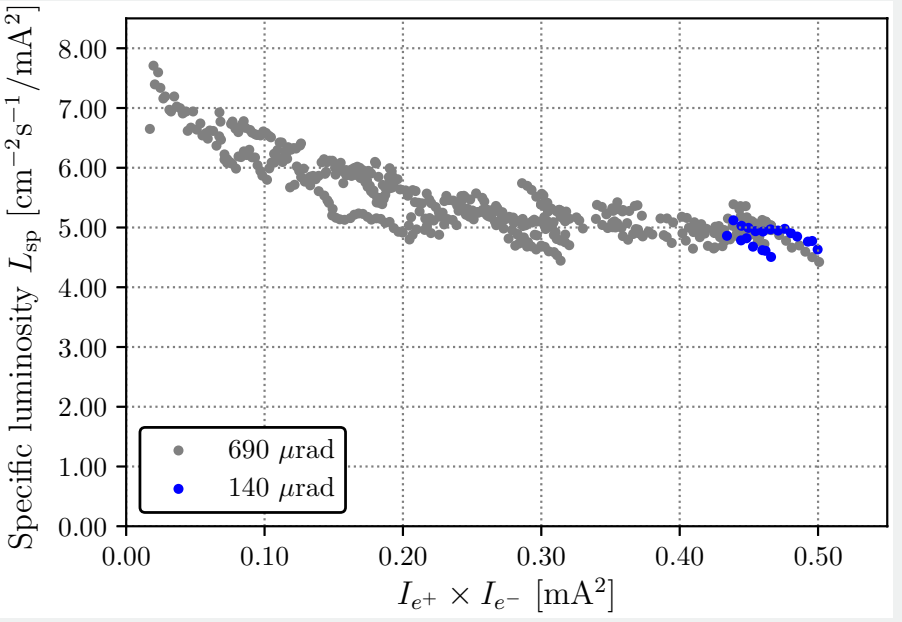


Horizontal Angle of Beam Orbit at IP and Luminosity

- No improvement in luminosity,(or rather worse?), and SR level is indeed higher.
- We decided to back to the original angle value 690 μrad

H-angle adjustment





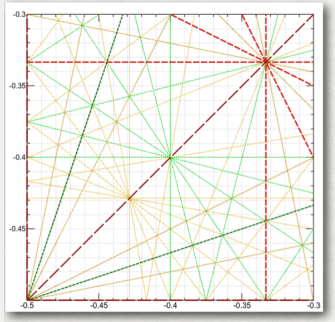
Chromatic XY-Coupling (Ch-XYC) Correction - Simulation -

- Ch-XYC correction will effectively suppress beam blow up.

K. Oide

LER tune survey

$\varepsilon_{y0}/\varepsilon_y$

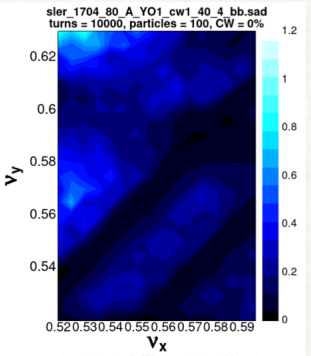


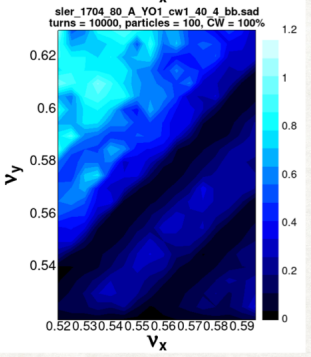
CW = 0%

CW = 100%

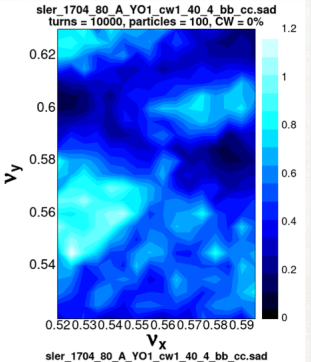
- Sextupoles are not re-optimized at each point.

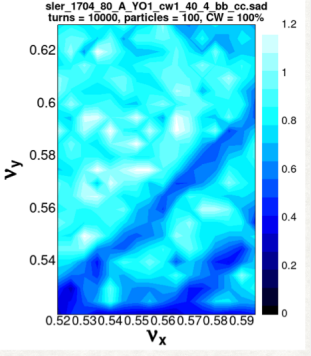
Original (SK2=0)





Chromatic coupling corr.



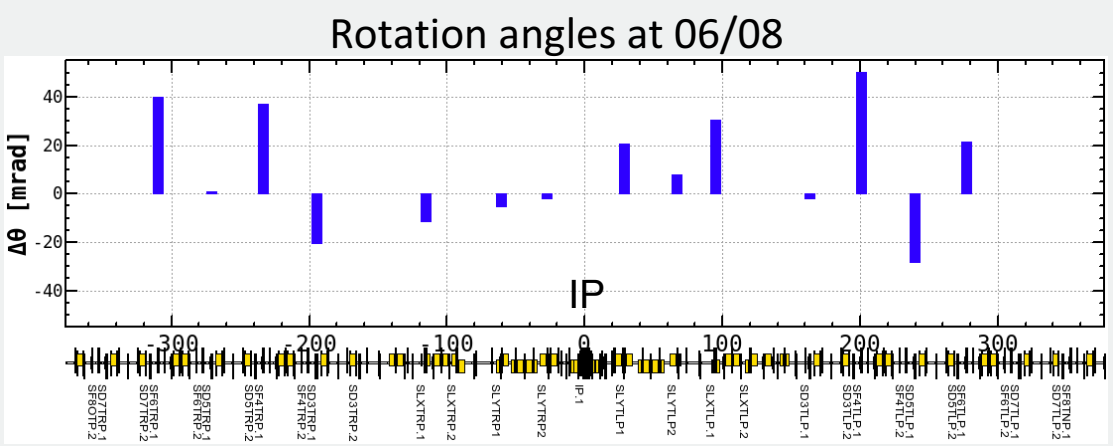


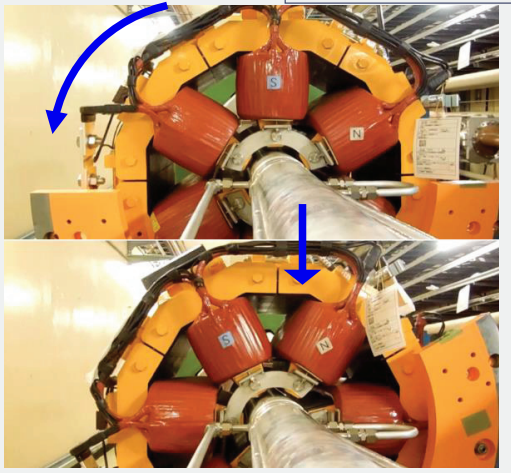
Ch-XYC Correction - First Trial -

- Correction with changing rotation of sextupole magnets.
- Rotation angle is determined by measured Ch-XYC and the model accelerator.
- Two sets of rotation angles are tried.
  - 06/05: Only 4 sextupole magnets near IP are tilted as the first test.
  - 06/08: Use 14 rotatable sextupole magnets

M. Masuzawa

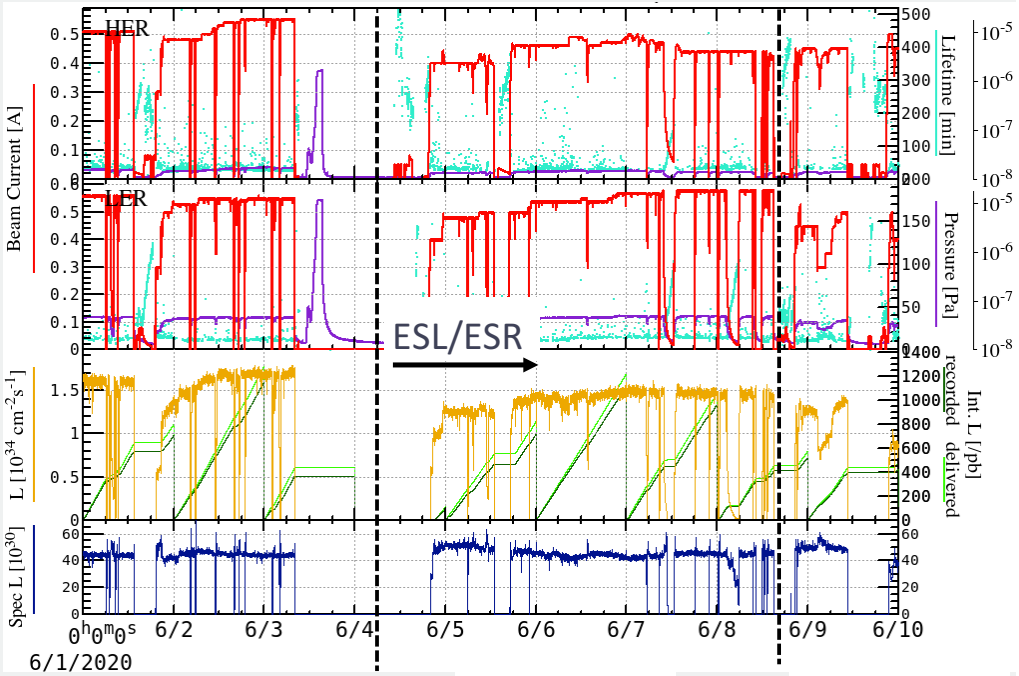
Rotation angles at 06/08





Ch-XYC Correction - Result -

- No improvement was obtained by Ch-CYC correction so far.
- The study was done concurrently with field adjustment of QCS(ESL/ESR), and we found that the ESL/ESR adjustment has strong impact on the machine condition.
- In addition, Ch-XYC measurement itself is a very challenging issue, thus it's not so surprising that the rotation angles we set did not give better luminosity performance.
- We finally needs a tool which enables us Ch-XYC scan during beam collision.



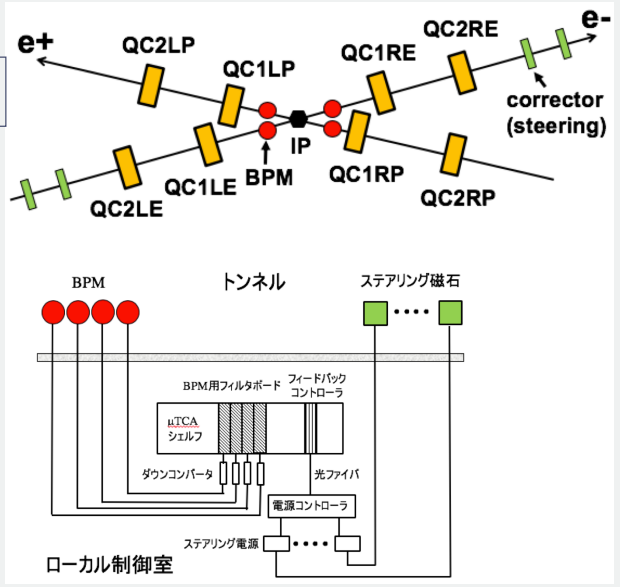
Ch-XYCC (1) Ch-XYCC (2)

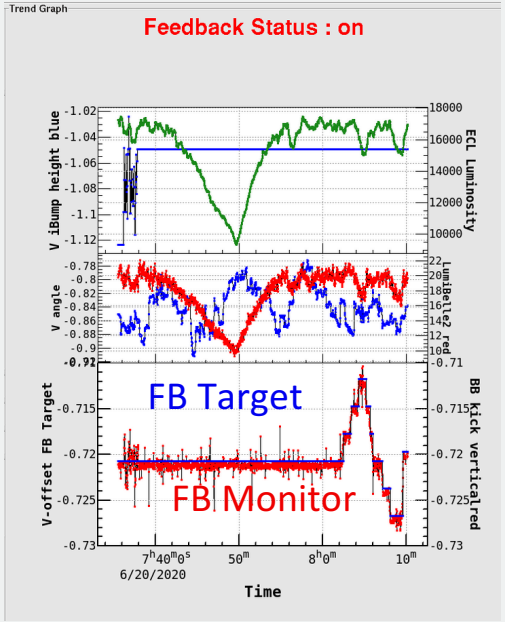
Other Topics

Fast (33kHz) IP Orbit Feedback

- Some test runs were performed. The FB system basically works.
- However, the FB system caused beam aborts or QCS quench in some conditions.
- These unexpected events are analyzed, and we applied countermeasures to the system.
- Test run of the revised system is ongoing.

H. Fukuma



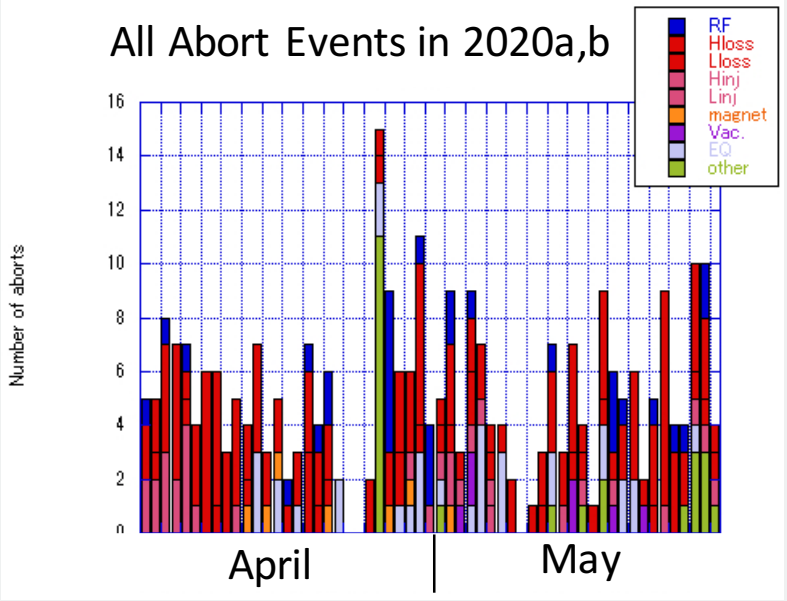


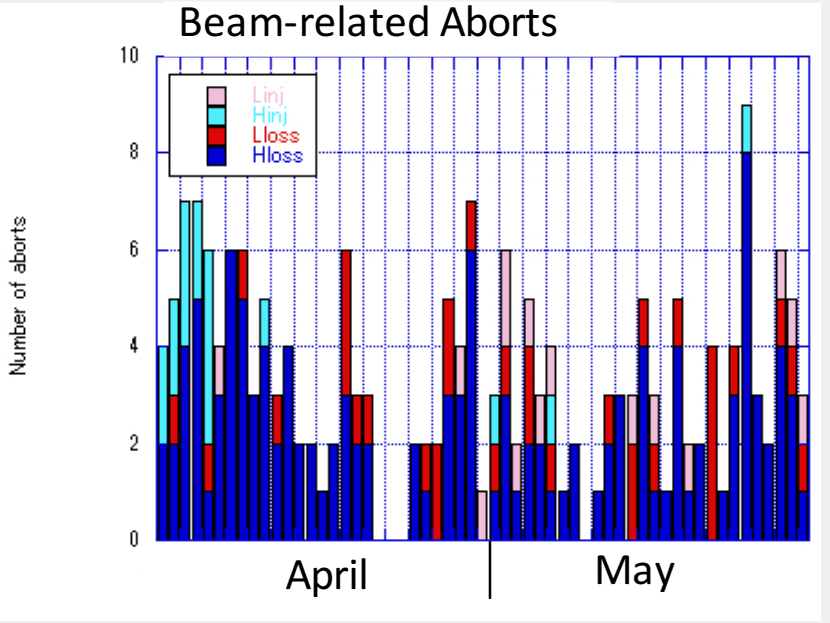
Beam Abort Events

H. Ikeda

- Currently, HER beam loss abort due to unknown reason is the most frequent event.
- We also have abort events due to misfiring of pulsed magnets in the injector linac.
- Detailed investigation to reduce beam aborts has started.

M. Satoh-san's talk



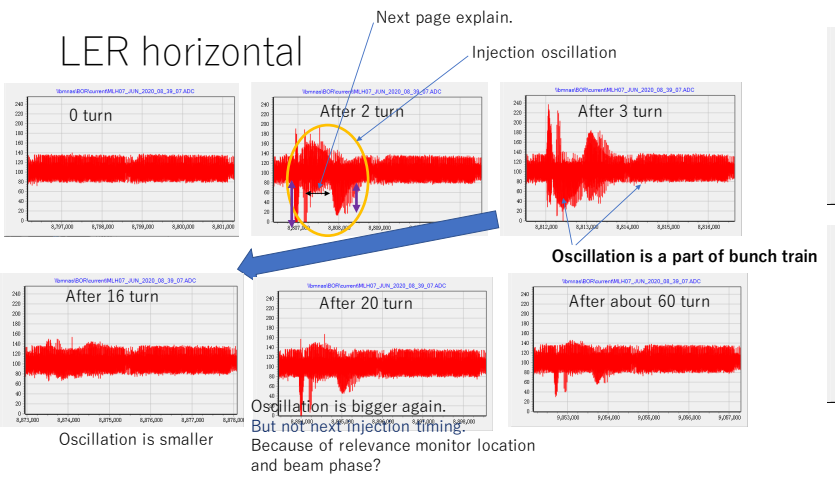


Transverse Injection Oscillation

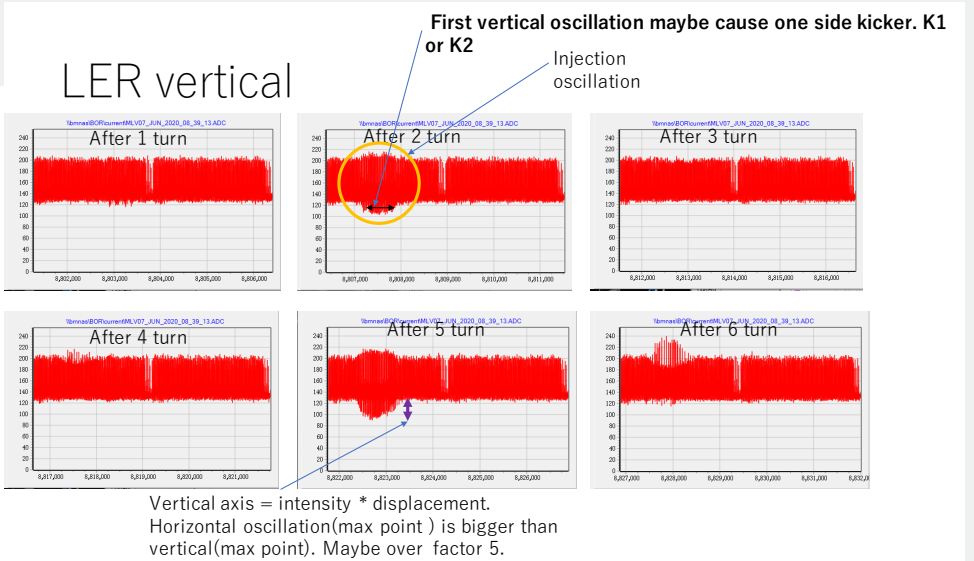
S. Terui

- Bunch oscillation monitor shows that a part of bunch train oscillates due to remaining field of (horizontal) pulsed injection kickers.
- Vertical oscillation is also observed. <- kicker rotation and/or XY-coupling?
- We are trying to identify the source of the oscillation and cure this issues to reduce background to Belle II.

LER horizontal



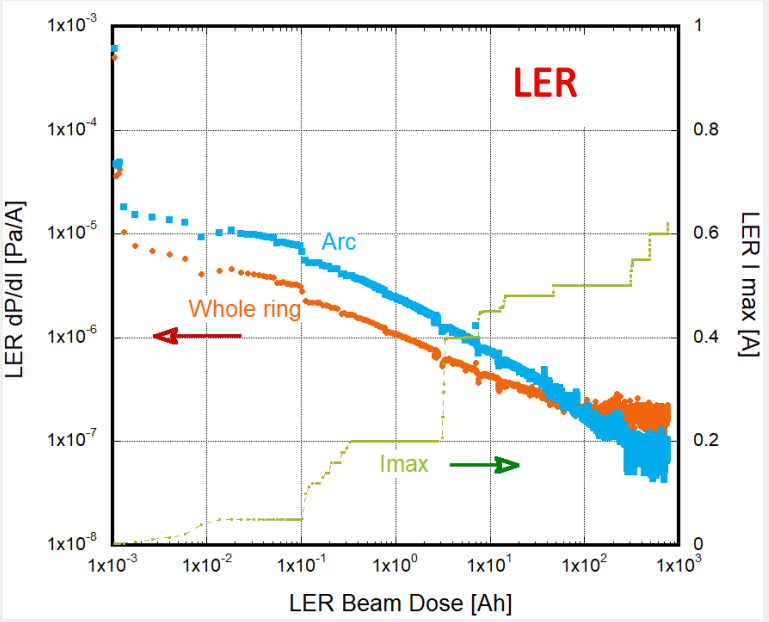
LER vertical

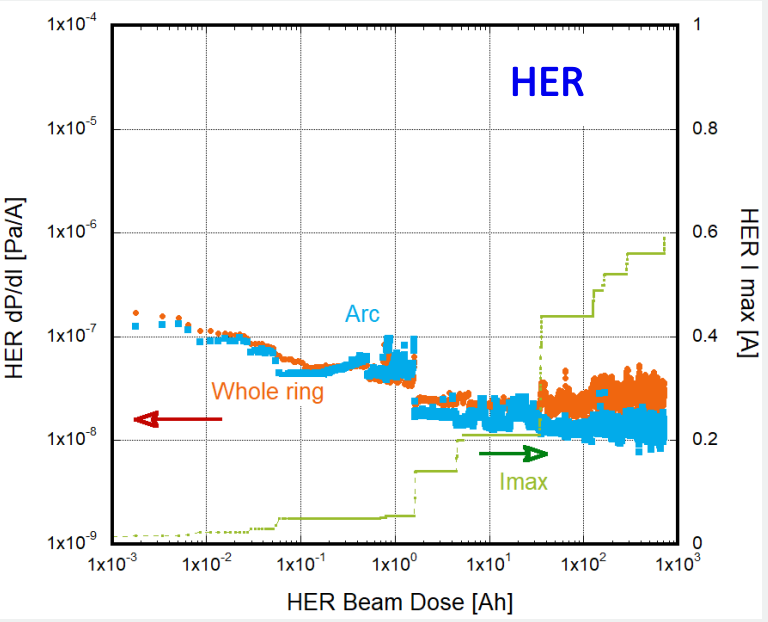


Vacuum Scrubbing

Y. Suetsugu

- The most dominant component of storage BG is beam-gas scattering in LER.
- We hope the BG component will be reduced as dP/dI decreases.



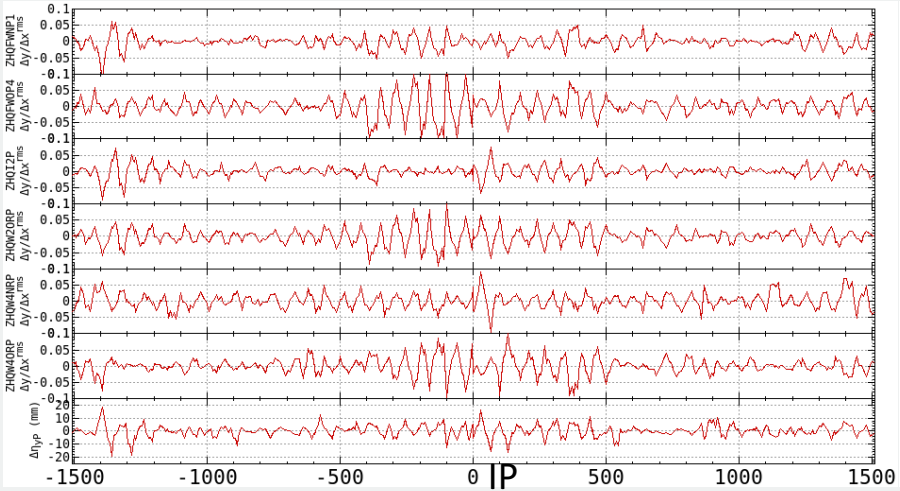


Difficulty in Beam Optics Correction

- We found that global correction does not always reduce vertical beam size.
- This implies that beam size is sensitive to local beam optics parameters.
- We guess detailed optics in interaction region is a key, but still don't know a robust strategy to get small beam size.

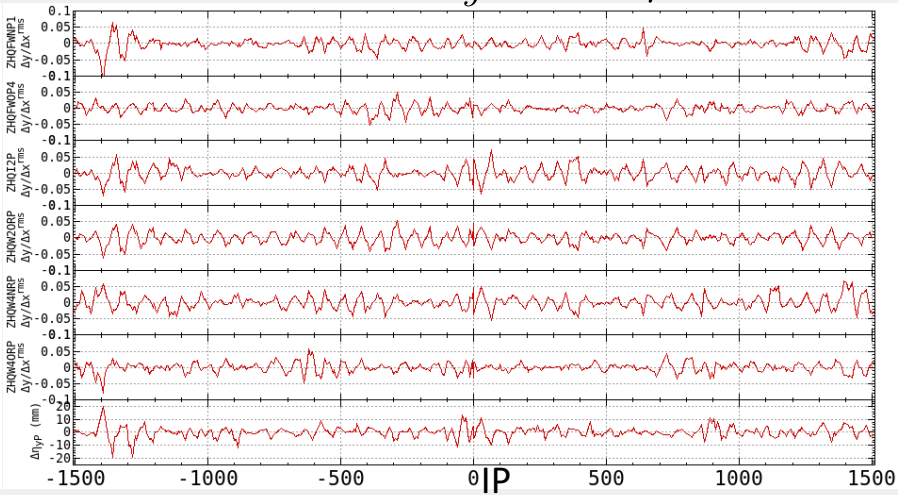
Beam Optics Distortion (a)

Beam size $\sigma_y = 24\ \mu\mathrm{m}$



Beam Optics Distortion (b)

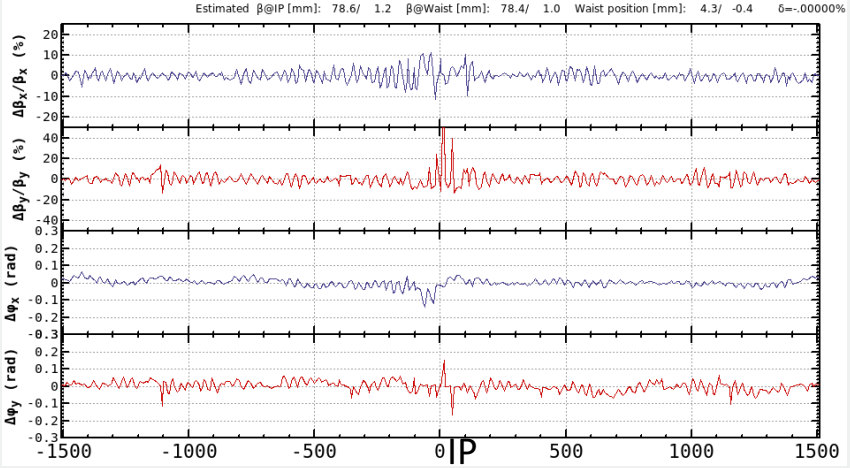
Beam size $\sigma_y = 30\ \mu\mathrm{m}$



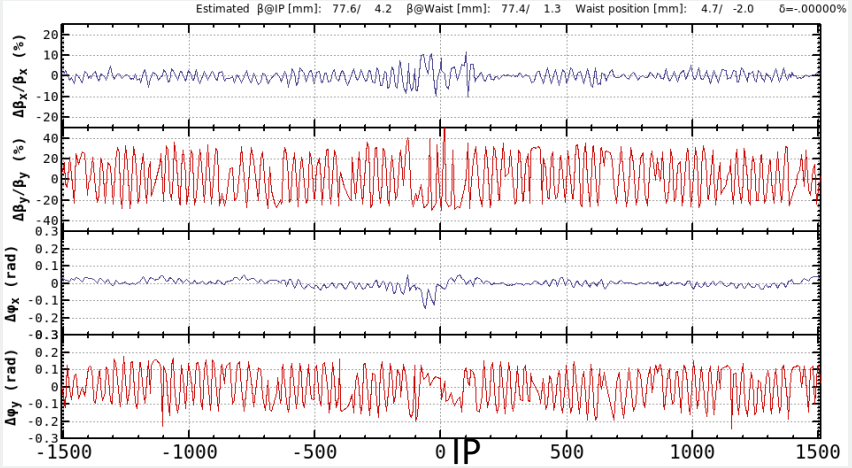
Machine Stability

- We sometime observe unexpected behavior of machine after maintenance day or a series of physics runs.
- Example: Residual optics error in LER

Just after optics tuning (2020/05/14)



Right: After physics run (2020/05/18)



- Possible sources are orbit drift, hysteresis of magnets, etc.
  Not so easy to identify the source and compensate it.
- The machine will becomes more sensitive by squeezing β_y^* furthermore.

Summary

- We applied the CW scheme to both LER and HER.
- We have broken the KEKB's record.

  Peak luminosity = 2.23 $\times 10^{34}$ $cm^{-2}s^{-1}$ at 679(LER), 639(HER) mA
- Major issues
  - Stability of the beam injection
  - Stable and safe operation
  - Beam abort due to unknown issues
  - Beam Background to Belle II
- As for further improvement of specific luminosity

  Correction of chromatic XY-coupling is an urgent issue.
- We plan to try further beta-squeezing (1mm->0.8mm) in this run.

Thank you for your kind attention.

Design Machine Parameters

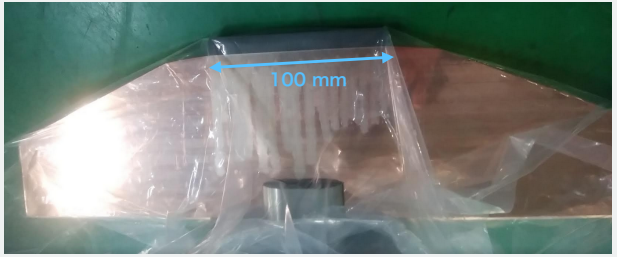
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

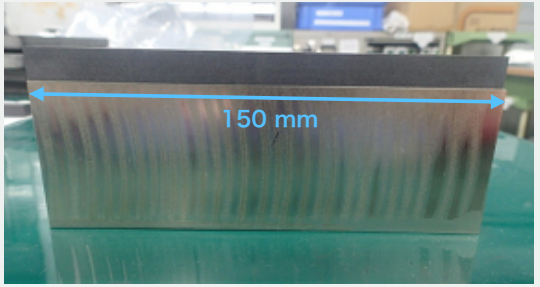
Low-Z Collimator Development

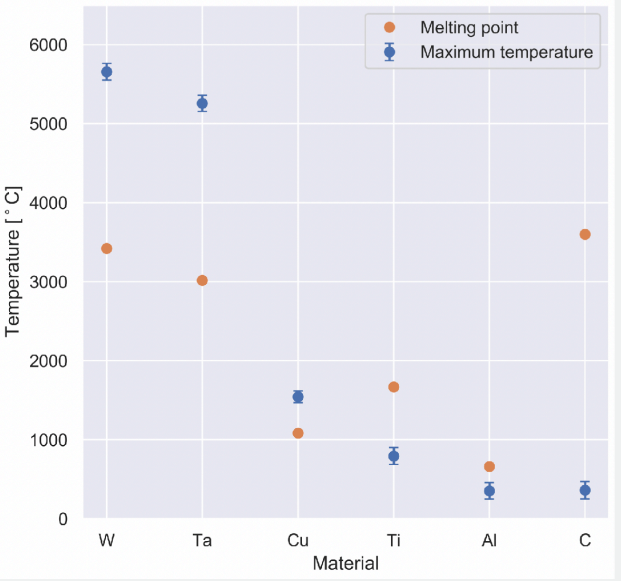
T. Ishibashi

- Four collimator heads were damaged in total so far.
- We have used tungsten or tantalum for materials of the tip.
- Low-Z (Low atomic number materials) collimator is under development to reduce damage by abnormal beam hit.
- Tip of Carbon will be applied to one of vertical collimator (D06V1) in the next run.

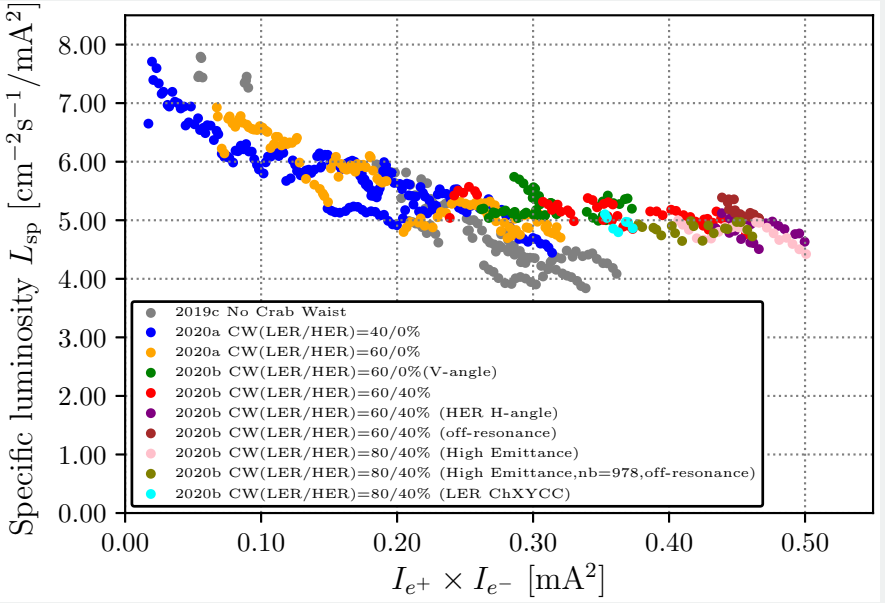
Bonding test







Specific Luminosity

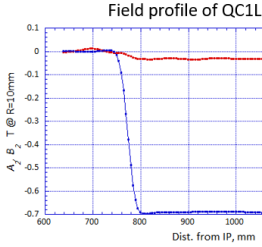


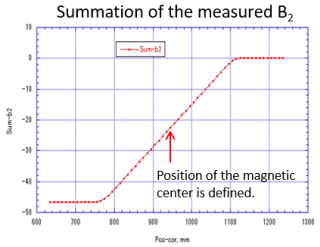
- The colors and labels show our many trials to improve the machine performance.
- My personal impression is that it's not so easy to judge whether a trial is effective or not, because as I mentioned, the machine status seems to be depending on other unknown parameters also.

Adjustment of anti-solenoid field of QCS (ESL/ESR)

- Tried to correct to ESL/ESR field strength based on field measurement results.
- No improvement in luminosity performance, and the machine seems to be unstable.
- It seems that impact on beam optics is considerably large.
- Need more systematic study after preparing a remote control system for ESL/SER.

- The magnetic center was measured by the quadrupole field profile





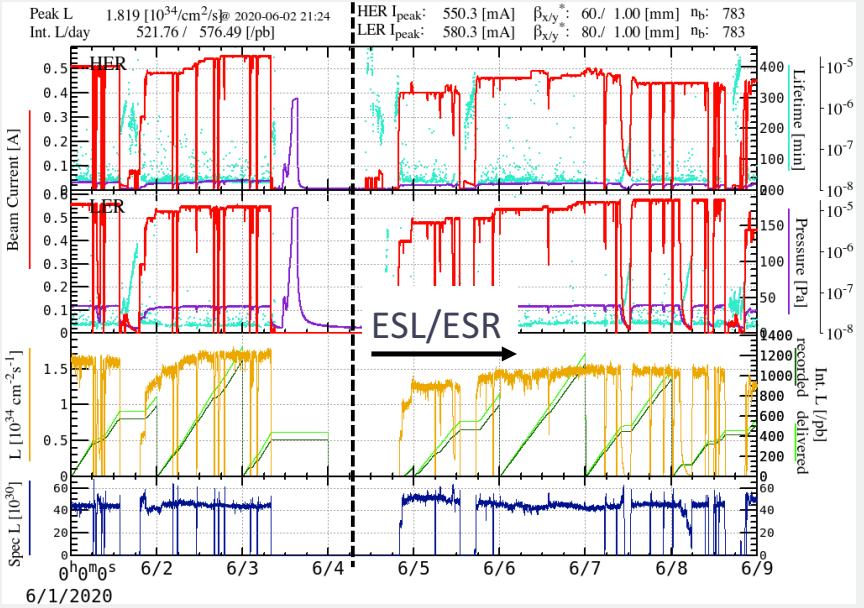
Distance of the quadrupole center from IP, mm

	QC1LP	QC1LE	QC2LE	QC1RP	QC1RE
With excitation of solenoids	939.50	1416.10	2695.10	938.46	1413.28
Without excitation of solenoids	937.02	1414.36	2695.18	937.52	1412.41
Δ (with-without)	2.48	1.74	0.08*	0.94	0.87

Movement of Support table by EMF **+0.34 mm**

* EMF on QC2LE is small. **+0.25 mm**

N. Ouchi



Injection Tuning

- Injection tuning is one of the most difficult part.
- The performance is very sensitive to many parameters including the injector condition.
- Reproducibility is not so good, we need frequent tuning to keep injection performance.
- Example:

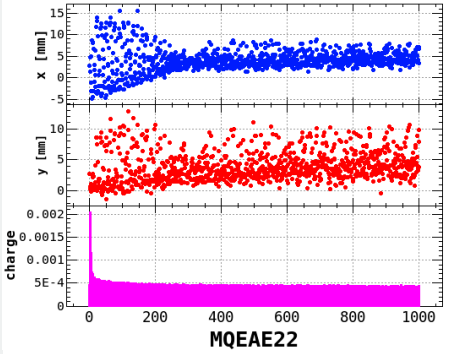
  Transverse injection oscillation observed in 06/08 and 06/10

Shift report by Y. Funakoshi

Even the machine setting is almost same (we believe), the behavior of injected beam is quite different and the injection efficient is poor at 06/08.

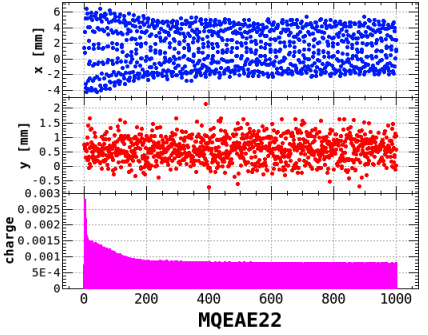
Injection tuning HER

Smearing of horizontal oscillation is very fast. This is quite unusual. There were unusually large nonlinear components?



2020/6/8 swing

Today's smearing speed is usual.



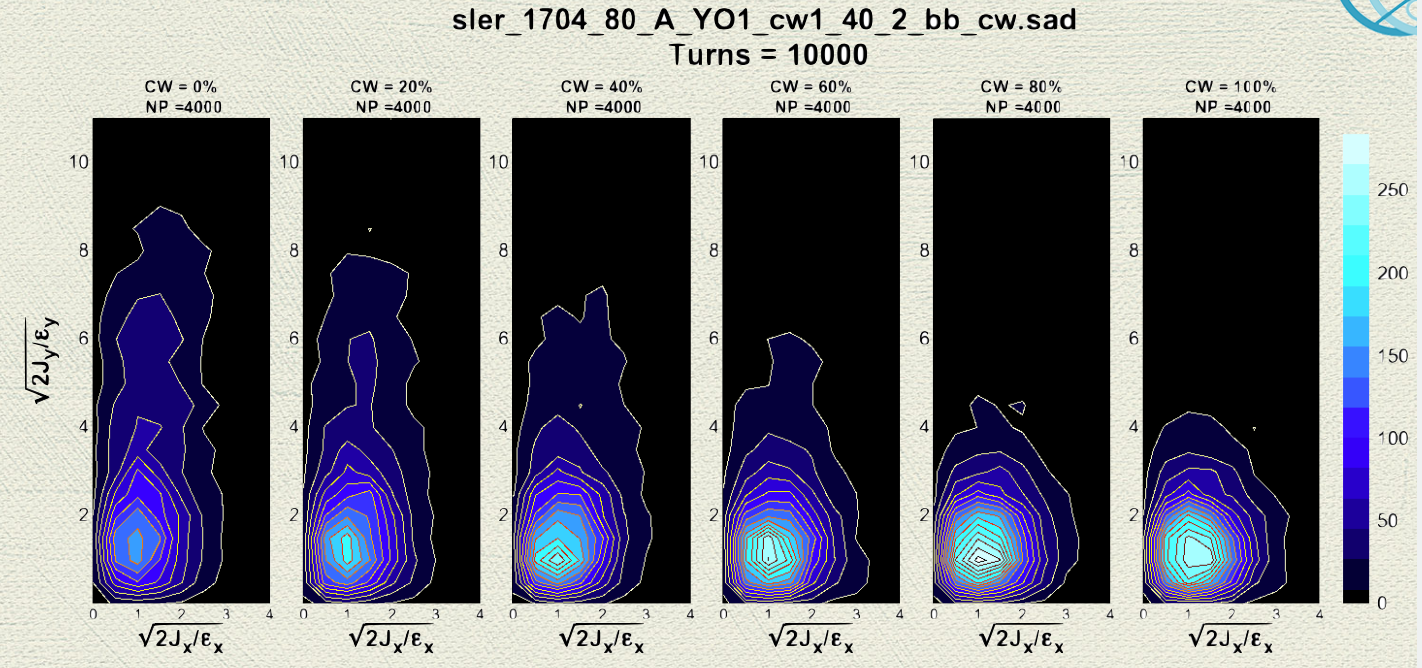
2020/6/10 swing

Simulation on CW

K. Oide

Beam distribution for various CW ratios ($\beta_y^* = 1$ mm)

LER

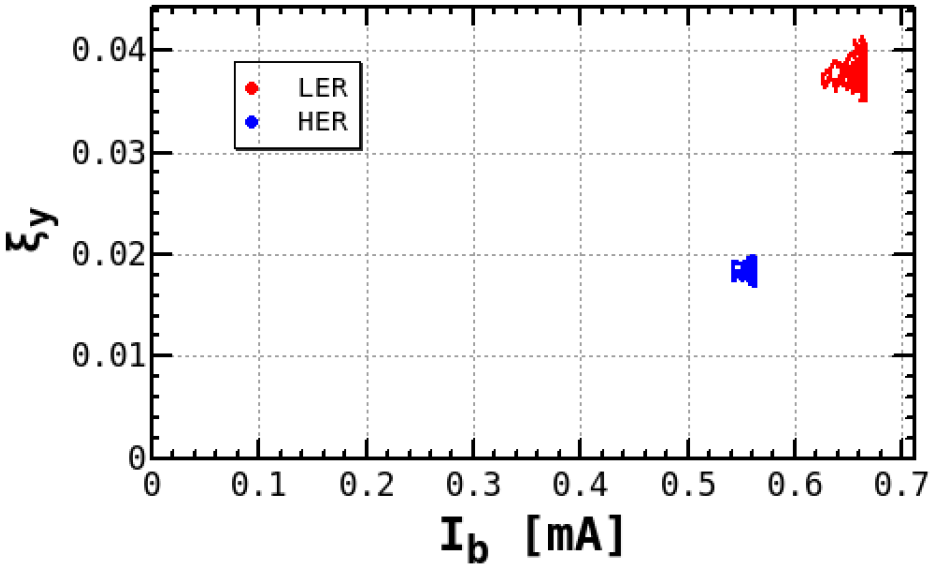


Beam Aborts

- Local XY-coupling correction
- Abort dye to abnormal orbit
- Troubles
- XY-coupling correction and beam size
- Fill pattern
- difficuluty in optics tuning after shutdown
- Tuevey on radiation activayion
- H angle and SR
- High Emittance
- Injection BG and #of Bunch
- Fast Ibump FB and Quench
- ESL/ESR adjustment
- Off resonance
- Difficukuty in Beta-Squeezing
- Injection Tuning
- Injection Kicker rotation
- Beam Aborts task force.
- Rotable sextupole and synchro beta emittance

Items

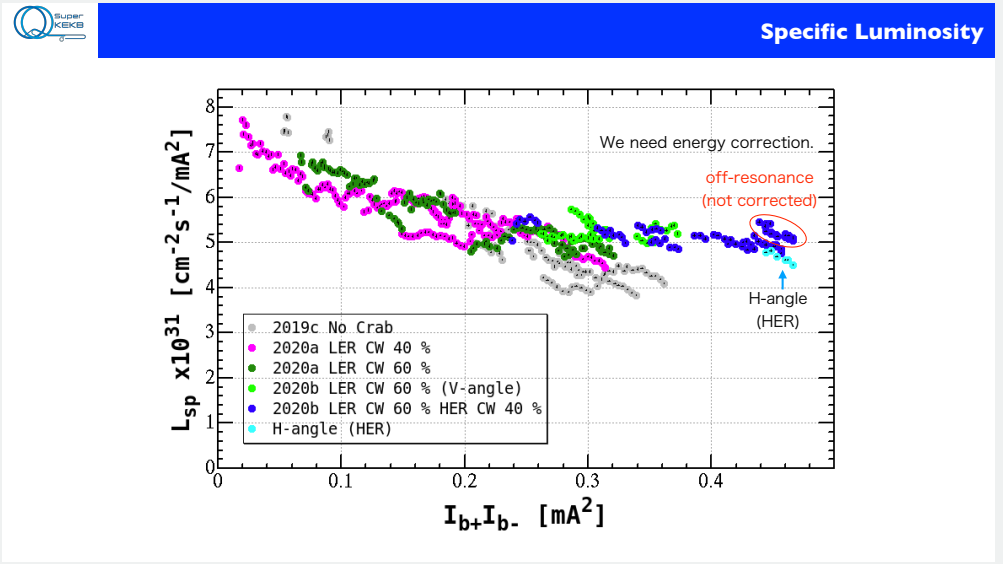
- 02/27 Start operation -> Vacuum scrubinng
- 03/04 Start collision with by*=2mm
- 03/09 beta squeezing -> by*=1mm
- 03/16 LER CW 0->40%
- 03/24 LER CW 40->60%
- 04/20-23 Cabling work for HER CW
- 04/24 HER CW 0 -> 40%
- 05/11-14 Off-momentum
- 05/15 back to on-momentum and H-angle correction
- 05/25 QCS quench due to Fast iBump FB
- 06/01 LER CW 60% -> 80%, Restore H-angle
- 06/02 ESL/ESR adjustment
- 06/05 Rotatable sextupole



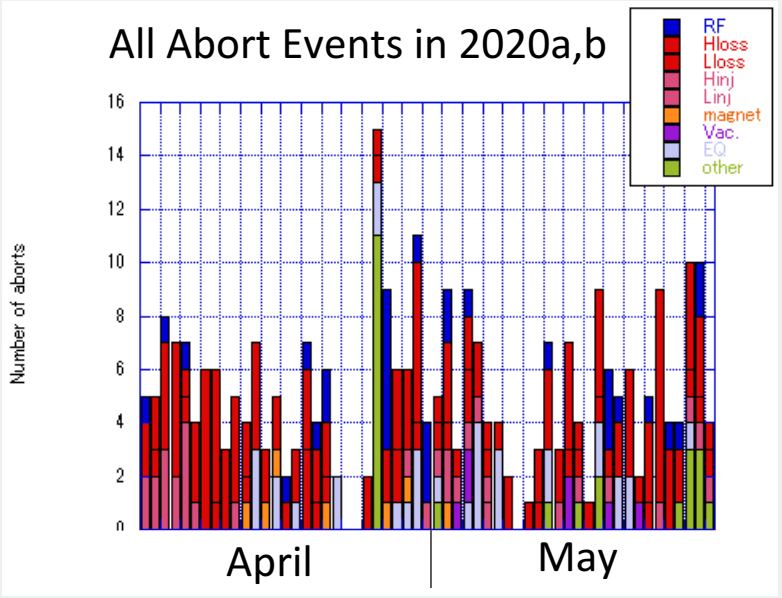
Definition of beam-beam parameter (here)

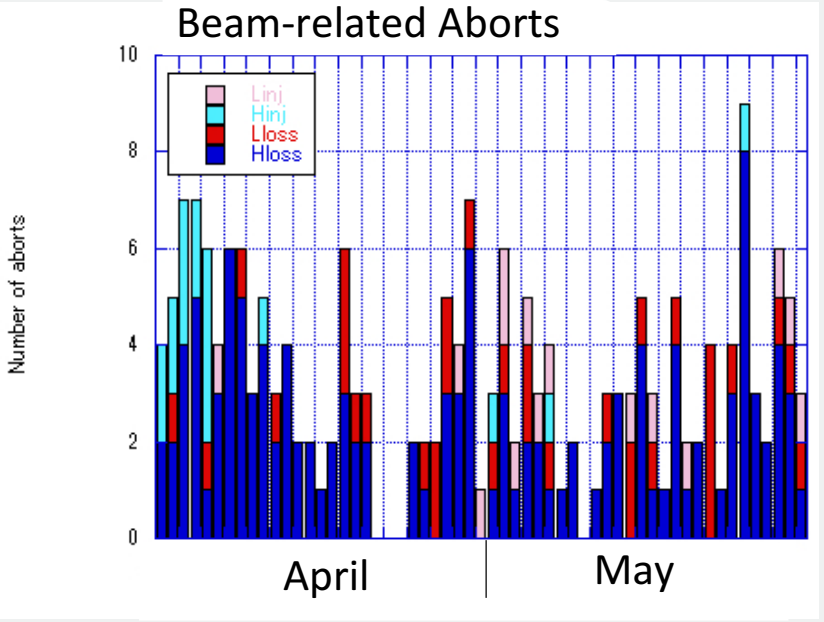
$$\xi_{y\pm}(I_{b\mp}) = \frac{2er_e\beta^*_{y\pm}}{\gamma_\pm I_\pm}L$$

$$\frac{\xi_{y+}+\xi_{y-}}{2} \geq \sqrt{\xi_{y+}\xi_{y-}}$$



• 2020abのcrab waistありではバンチ電流が高くてもspecific luminosityは横ばいで推移している。2020b crab waistなしでのspecific luminosityか2019cと比べて低いので、crab waistありでのspecific luminosityは調整により今後もっと高くなる可能性あり。
• Phase-3 2020abのビームドーズはLER: 238 Ah、HER:199 Ah。D06アーク部のdp/dIが高い。今のところメンテナンス日に実施したNEG活性化の効果は見られない。


All Abort Events in 2020a,b
RF
Hloss
Lloss
Hinj
Linj
magnet
Vac.
EQ
other
Number of aborts
0
2
4
6
8
10
12
14
16
April
May


Beam-related Aborts
Linj
Hinj
Lloss
Hloss
Number of aborts
0
2
4
6
8
10
April
May

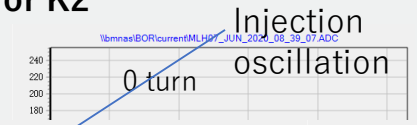
ical

LER horizontal

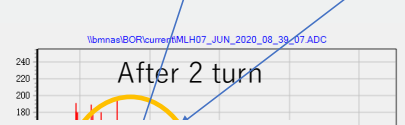
First vertical oscillation maybe cause one side kicker, K1 or K2

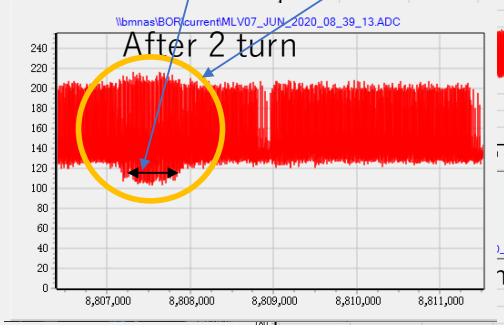
Next page explain.

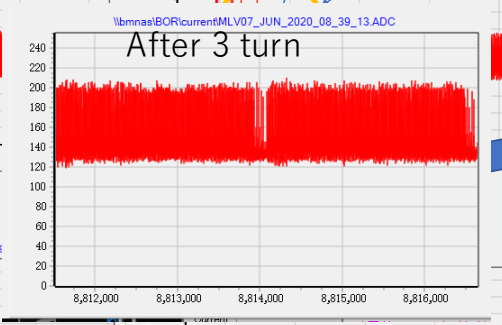
Injection oscillation



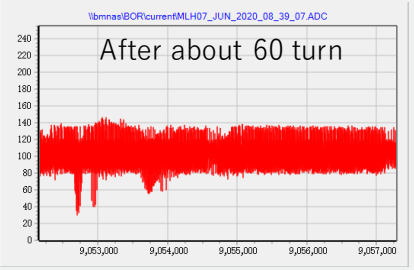
Injection oscillation

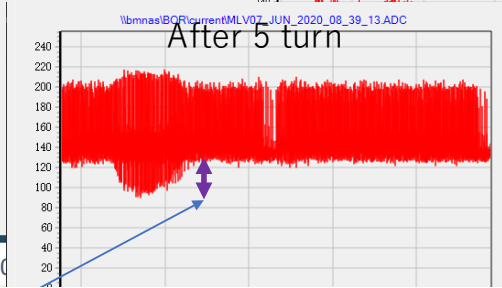


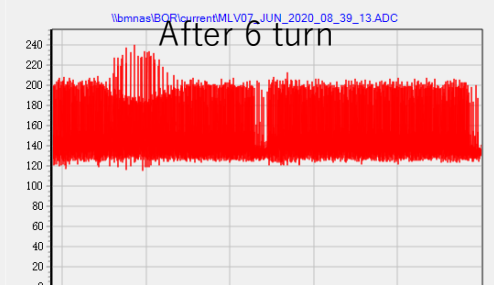




Oscillation is a part of bunch train





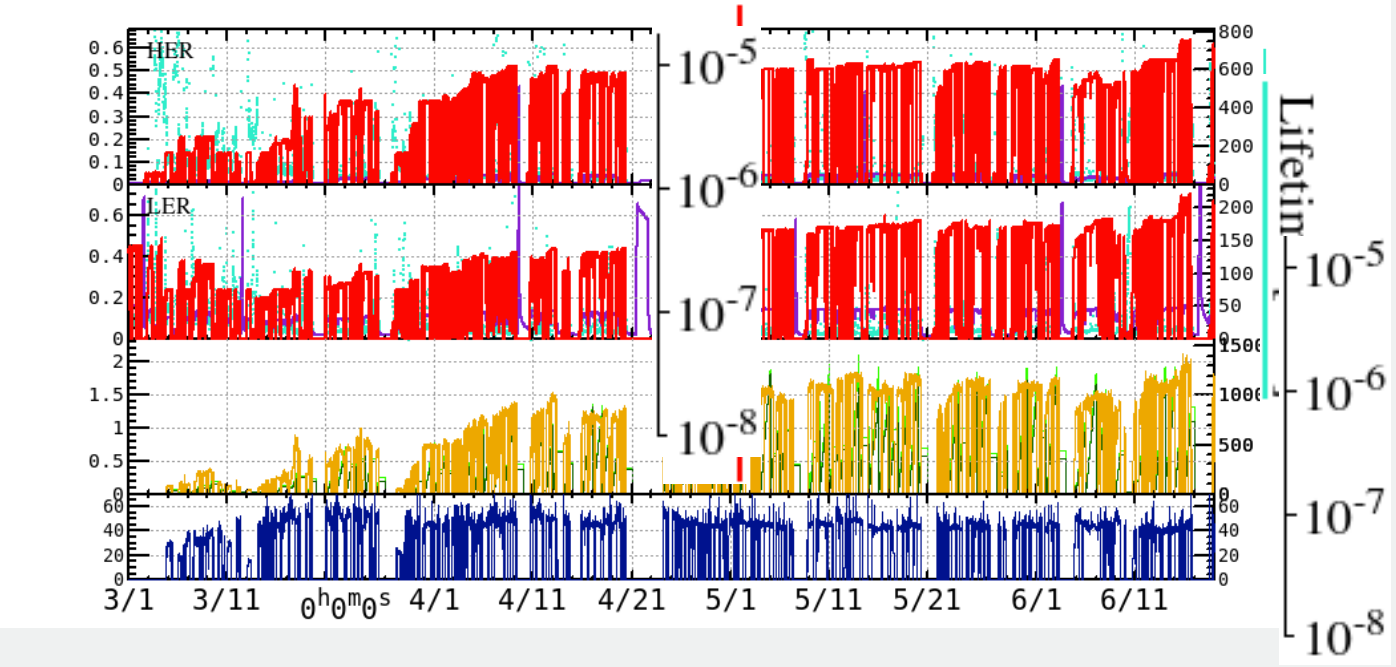


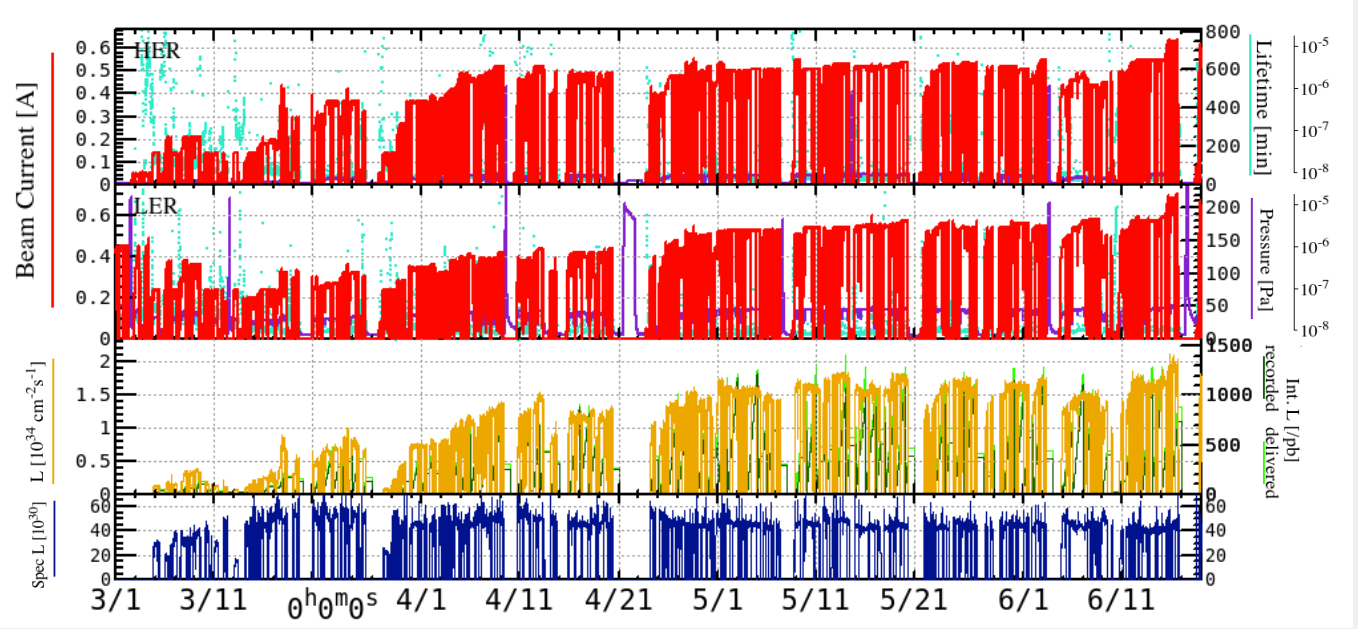
or location

Status of Operation

- *We have broken the KEKB's record!* (2.108 x 10^{34} $cm^{-2}s^{-1}$)

- Peak luminosity = 2.23 × 10^{34} $cm^{-2}s^{-1}$ at 679(LER), 639(HER) mA




HER
LER
Beam Current [A]
Lifetime [min]
Pressure [Pa]
L [10^34 cm^-2 s^-1]
Spec L [10^30]
Int. L [/pb]
recorded
delivered
3/1
3/11
0h0m0s
4/1
4/11
4/21
5/1
5/11
5/21
6/1
6/11