Highlight from SuperKEKB Beam Commissioning

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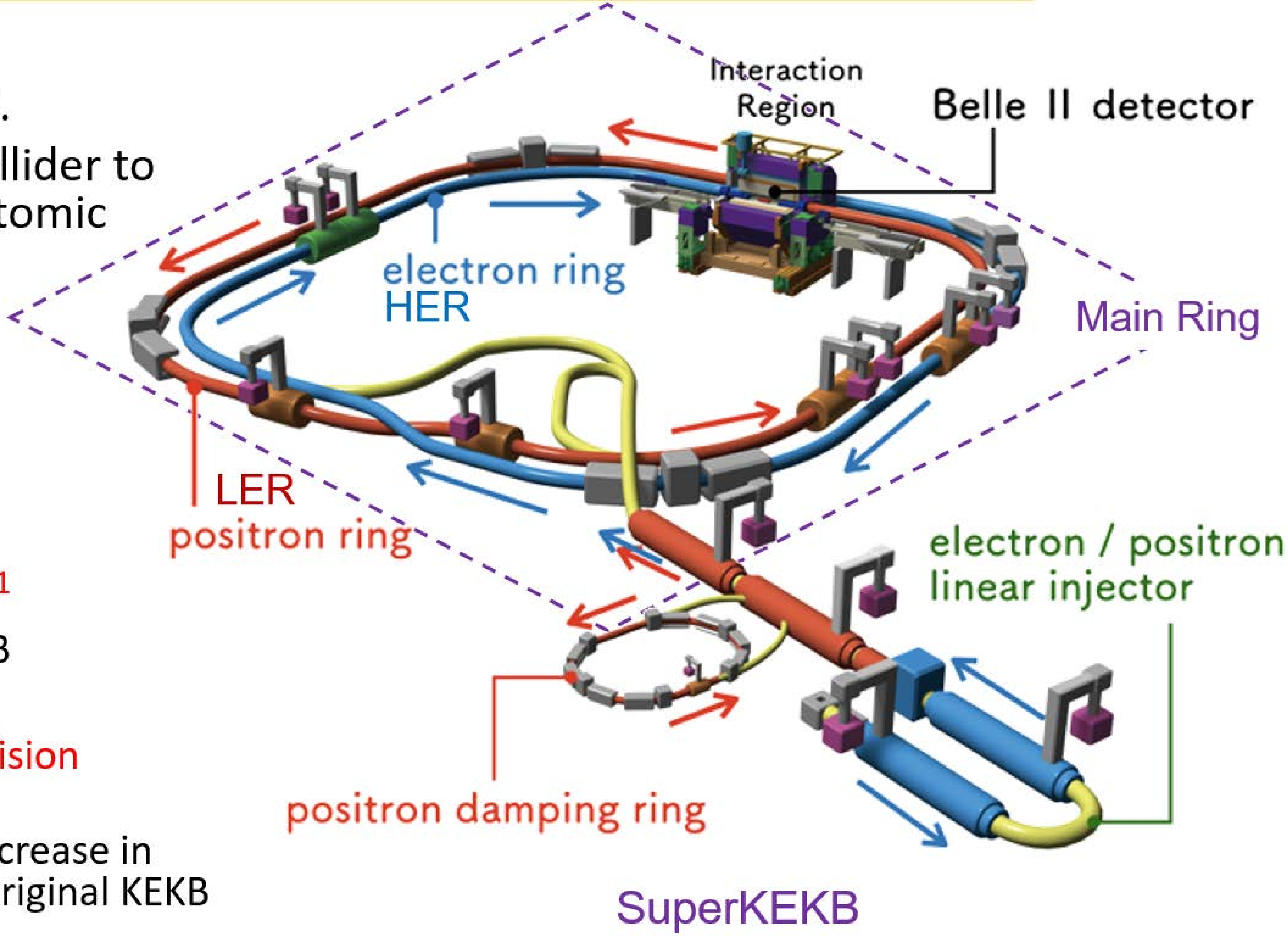
On behalf of SuperKEKB Commissioning Group

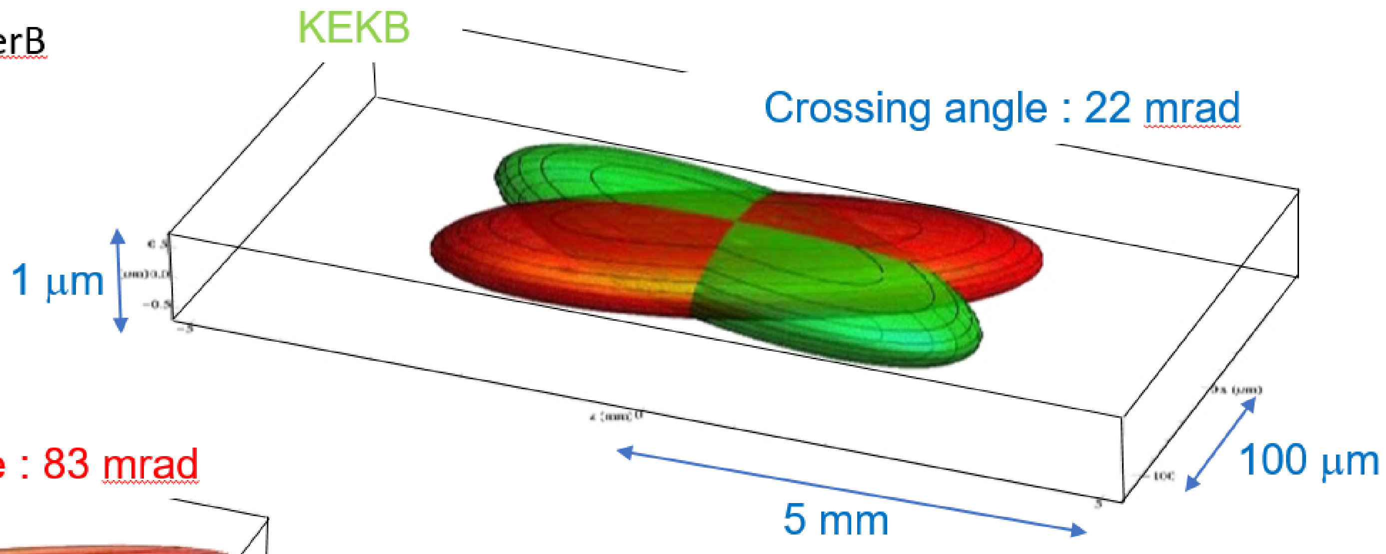
SuperKEKB

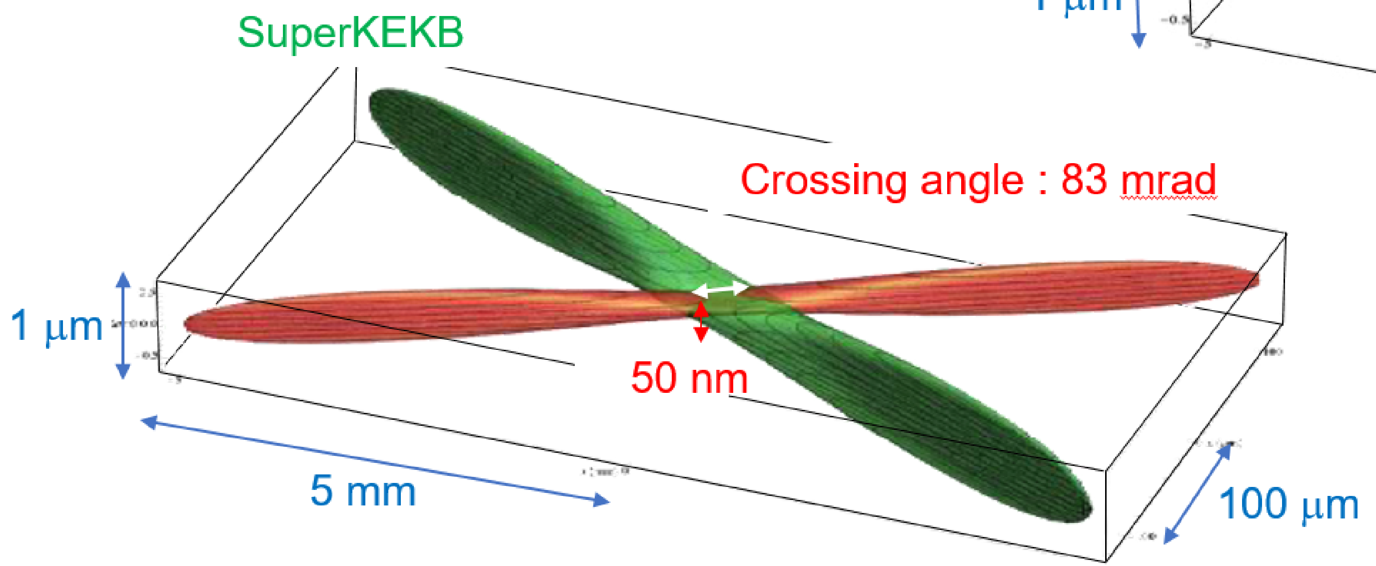
- SuperKEKB;
  - An upgrade of KEKB B-factory (KEKB).
  - High-luminosity electron-positron collider to seek out new physics hidden in subatomic particles.
  - Main ring (MR) is composed of
    - Low Energy Ring (LER);
      - 4.0 GeV Positron, 3.6 A
    - High Energy Ring (HER);
      - 7.0 GeV electron, 2.6 A
  - Design Luminosity : 8.0×10^{35} $cm^{-2}\cdot s^{-1}$
    - ✓ 40 times maximum luminosity of KEKB
    - ✓ Twice beam current of KEKB (×2)
    - ✓ Smaller emittance for nano-beam collision scheme (×20)
    - ✓ Over a period of 10 years, a 50-fold increase in integrated luminosity relative to the original KEKB is expected.



Nano-beam collision scheme

- Proposed by P. Raimondi at INFN-LNF for the Italian SuperB project around 2006 and tested successfully at DAΦNE.
- Implemented at SuperKEKB, for the first time, with low-emittance beams on a high-energy collider.





- To avoid Hourglass effect:
  - Beam bunces collide
    - ✓ With sufficiently small σ_x*.
    - ✓ At a large horizontal crossing angle.
  - The longitudinal size of the overlap between colliding bunches is much shorter than bunch length.
- It is possible to squeeze β_y* much smaller than bunch length.
  - Luminosity increases in proportion to $1/\beta_y^*$.

$$\begin{cases} L \approx \dfrac{\gamma_\pm}{2er_e}\left(\dfrac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right) \\ \xi_{y\pm} \approx \left(r_e N_\mp / 2\pi\gamma_\pm \sigma^*_{x,\mathrm{eff}}\right)\sqrt{\beta^*_y/\varepsilon_y} \end{cases}$$

constant

⇒

$$\begin{cases} L \propto \dfrac{I_\pm}{\beta^*_{y\pm}} \\ L_{sp} \equiv \dfrac{L}{n_b I_{b-} I_{b+}} \propto \dfrac{1}{\beta^*_{y\pm}} \end{cases}$$

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}		$cm^{-2}s^{-1}$	

SuperKEKB project history

- Phase1 operation (2016.Feb. ~ June);
  - Vacuum scrubbing, low emittance beam tuning, and background study for Belle II detector installation
  - w/o final focusing system (QCS) and Belle II detector
- Phase2 operation (2018.Mar. ~ July);
  - Pilot run of SuperKEKB and Belle II w/o pixel vertex detector (PXD)
  - Demonstration of nano-beam collision scheme
  - Study on background larger than at KEKB due to much lower beta functions at IP.
- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector.
  - Phase3 2019ab (2019.3~7)
    - "Status of Early SuperKEKB Phase-3 Commissioning" by A.Morita (WEYYPLM1) @ IPAC'19 (2019.5.22)
  - Phase3 2019c (2019.10~12)
  - Phase3 2020ab (2020.2~)

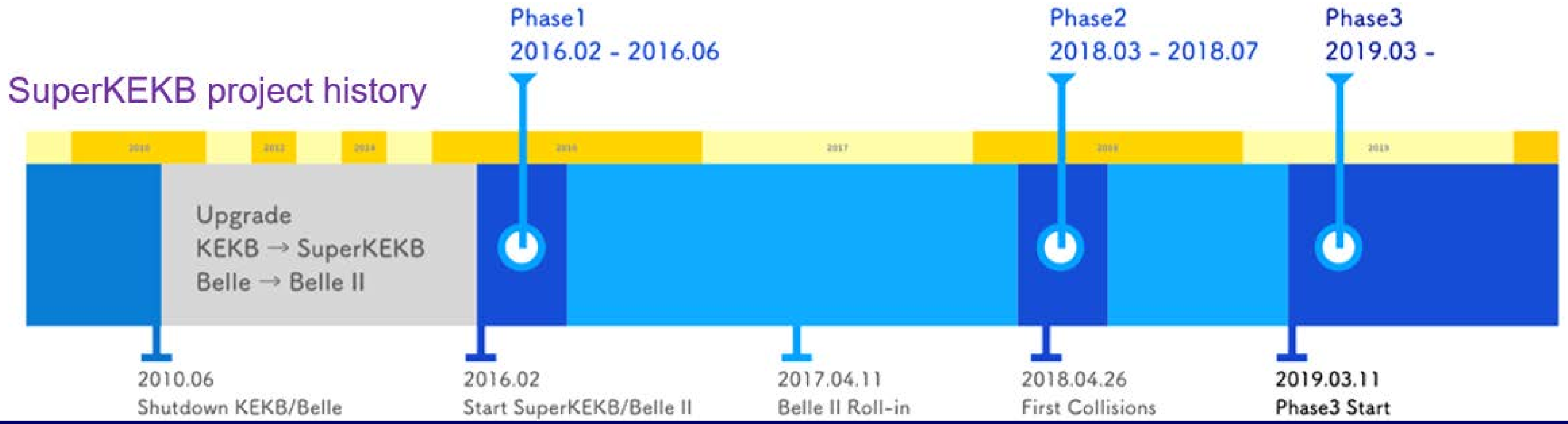
✓ New nomenclator of each run of Phase3

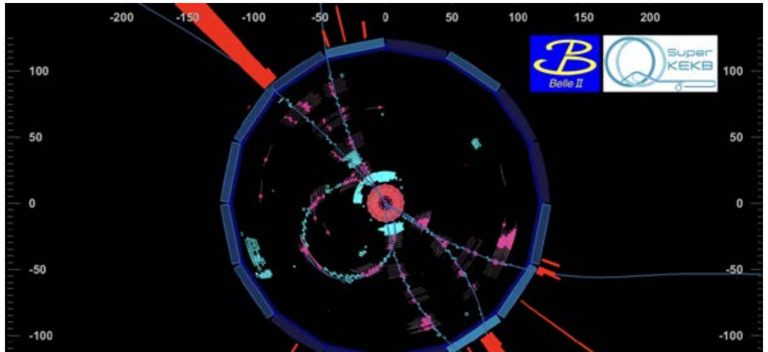
"Phase3 YYYYxx"

Calendar year

- a : Winter shutdown - March
- b : April - Summer shutdown
- ab : Winter shutdown – Summer shutdown
- c : Summer shutdown – Winter shutdown

April is beginning of Japanese fiscal year.



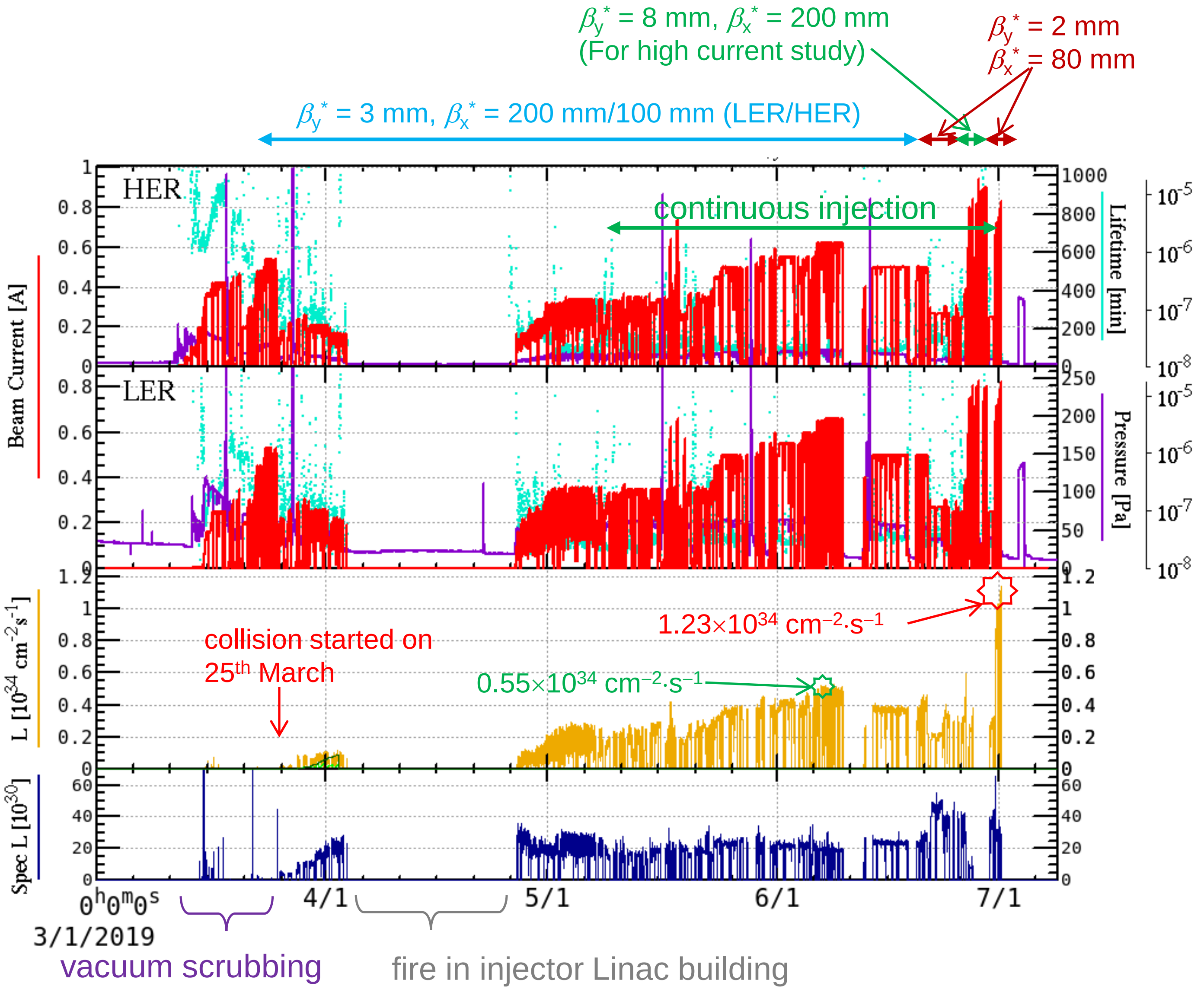


First hadronic event in the Phase3 2019ab

Phase3 2019ab (2019.3~7)

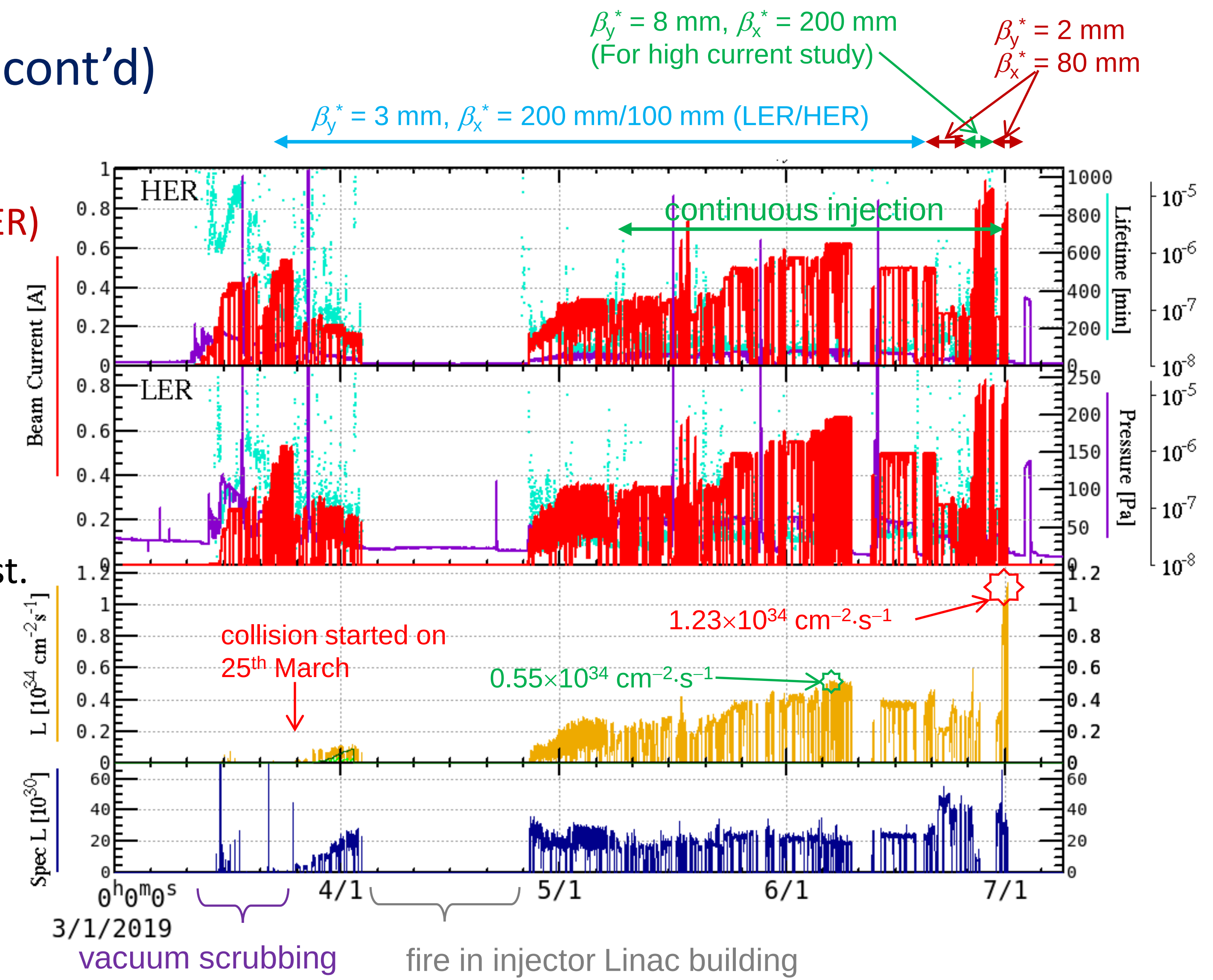
- Mission of Phase3 2019ab operation;
  - Starting full-scale physics run with fully instrumented Belle II detector.
  - Accelerator and collision tunings with lower β_y^* for higher luminosity.
    - ✓ β_y^* was already squeezed to 3 mm during Phase2.

- Overview of Phase3 2019ab
  - From 11/Mar. to 1/July.
  - Started with vacuum scrubbing.
  - Collision tuning started on 25/Mar.
  - 3-week interruption due to fire accident in Linac building (3/Apr. – 26/Apr.)
  - Commencement of continuous injection in both rings from May.
    - Increased the integrated luminosity.



Phase3 2019ab (2019.3~7)

- Overview of Phase3 2019ab (2019.3~7) (cont'd)
  - Beam current:
    - For physics run : ~660 mA(HER)&~620 mA(LER)
    - Maximum : 830 mA (HER) & 940 mA (LER)
  - Beta squeezing:
    - Physics run was mainly done with
      $\begin{cases} \beta_y^* = 3 \text{ mm} \\ \beta_x^* = 100 \text{ mm(HER) \& 200 mm(LER)} \end{cases}$
    - β_x^*/β_y^* were squeezed to 80 mm/2 mm at last.
  - Luminosity :
    - Peak Luminosity w/o Belle II detector taking data : 1.23×10^{34} cm$^{-2}\cdot$s^{-1}
    - Peak Luminosity w/ Belle II detector taking data : 0.55×10^{34} cm$^{-2}\cdot$s^{-1}
    - Total Integrated luminosity : 6.1 fb^{-1}

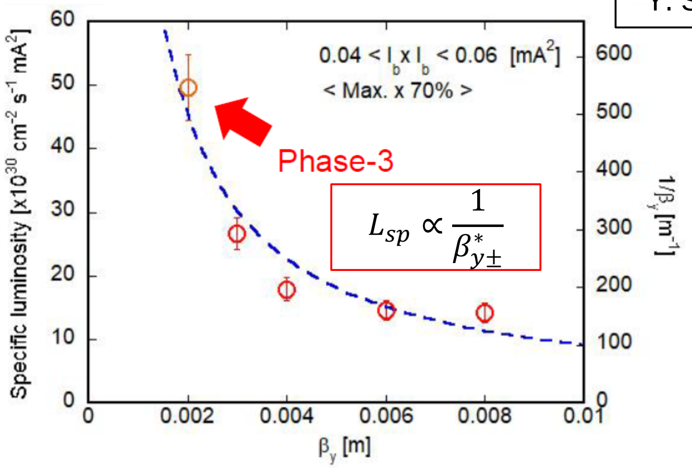


Luminosity in Phase3 2019ab

- Luminosity and beta squeezing;
  - Collision tuning was mainly done with
    β_y^* = 3 mm & β_x^* = 200 mm/100 mm (LER/HER)
    - Peak luminosity = 0.55×10^{34} cm$^{-2}\cdot$s^{-1}
      - at ~600 mA
      - with 3.06 RF bucket sp./1 train/1576 bunches
  - β_x^*/β_y^* were squeezed to 80 mm/2 mm on 21/June.
    - Peak Luminosity = 1.23×10^{34} cm$^{-2}\cdot$s^{-1}
      - at 830 mA (HER) & 820 mA (LER)
      - with 3.06 RF bucket sp./1 train/1576 bunches
    - Belle II could not take data due to high background noise.
    - Running time required to reach 1.0×10^{34} cm$^{-2}\cdot$s^{-1} was 200 days
      - 1/5 of the time taken by KEKB.
    - Specific Luminosity (L_{sp}) Increased in proportion to $1/\beta_y^*$
      - Nano-beam scheme collision worked well with β_y^* = 2 mm !!
      - Beam-beam parameter can be kept even though β_y^* was squeezed.
    - Slow degradation of specific luminosity with a increase of bunch currents.
      - Beam-beam effect increases the vertical emittance, reducing the specific luminosity.

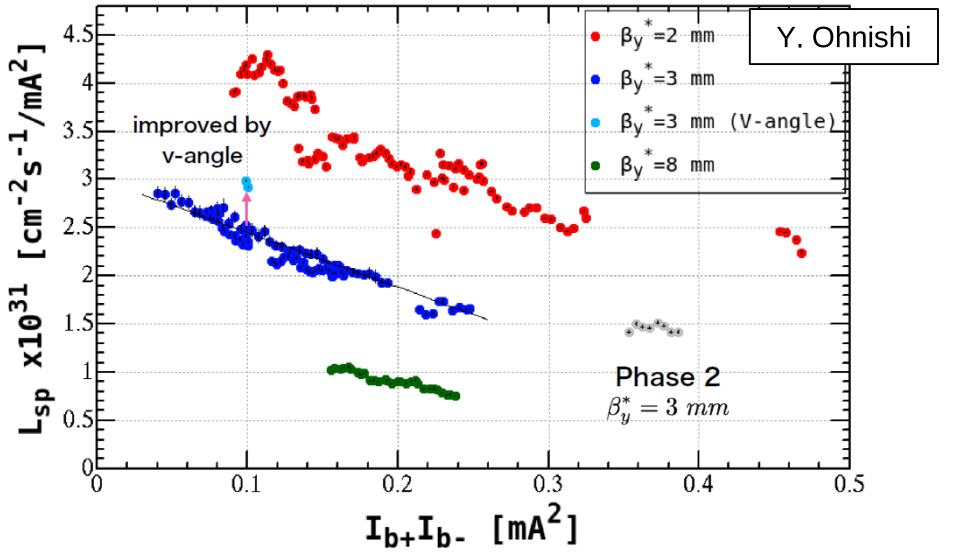
Specific luminosity as a function of β_y^*

Y. Suetsugu



Specific luminosity as a function of bunch current products

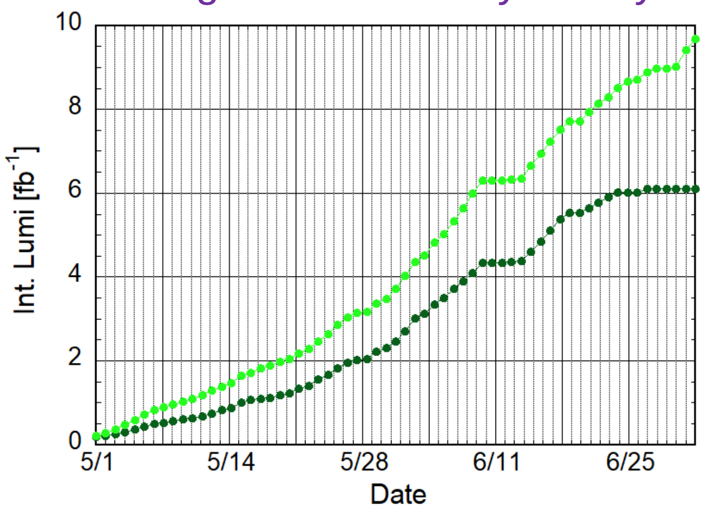
Y. Ohnishi



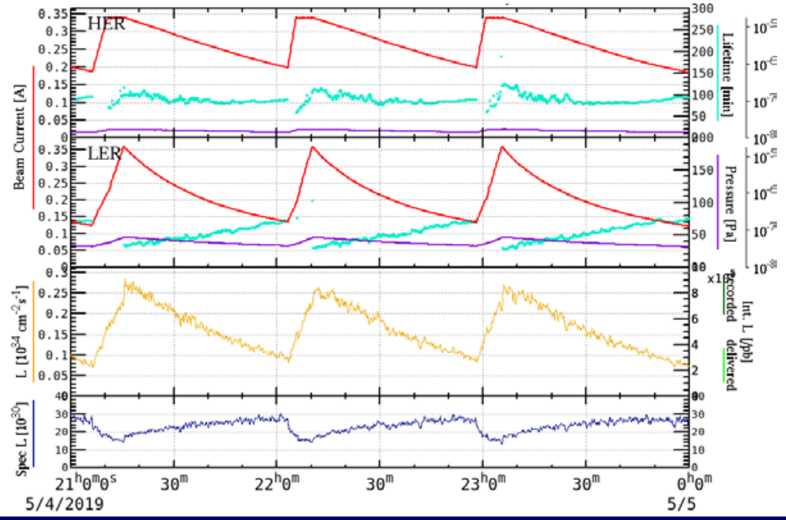
Integrated luminosity in Phase3 2019ab

- Integrated luminosity during Phase3 2019ab was 6.1 fb^{-1}
  - ~63 % of delivered luminosity was recorded.
- Continuous injection helped to increase integrated luminosity.
  - Continuous injection in both rings commenced from May.
  - Increased the integrated luminosity by 237 % compared with the normal injection.

Integrated luminosity history

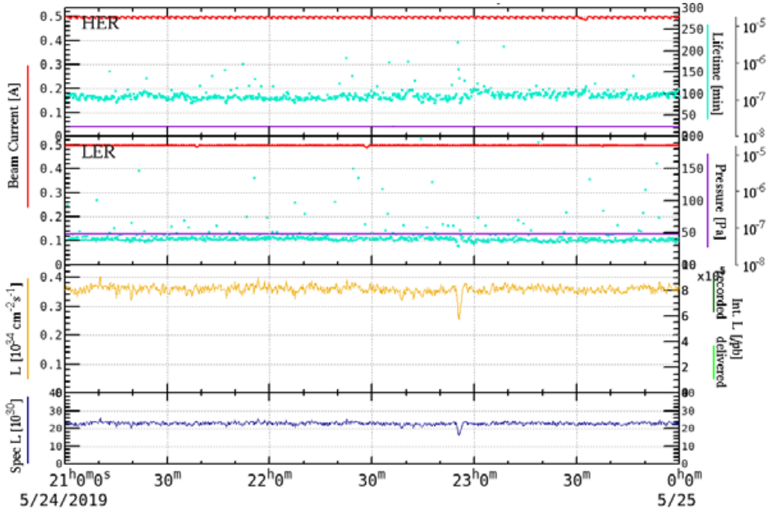


Normal injection mode



Integrated luminosity 237 % up !!

Continuous injection mode

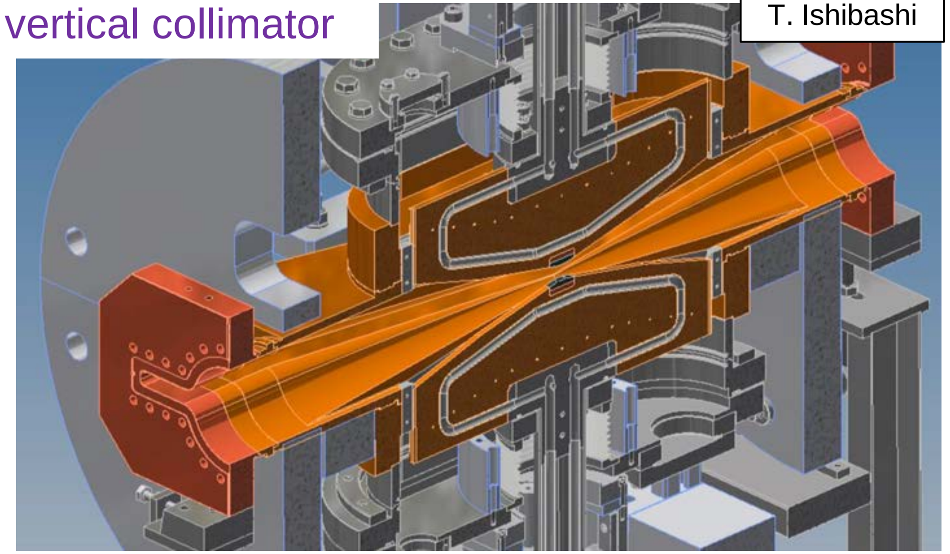


Major Issues of Phase3 2019ab

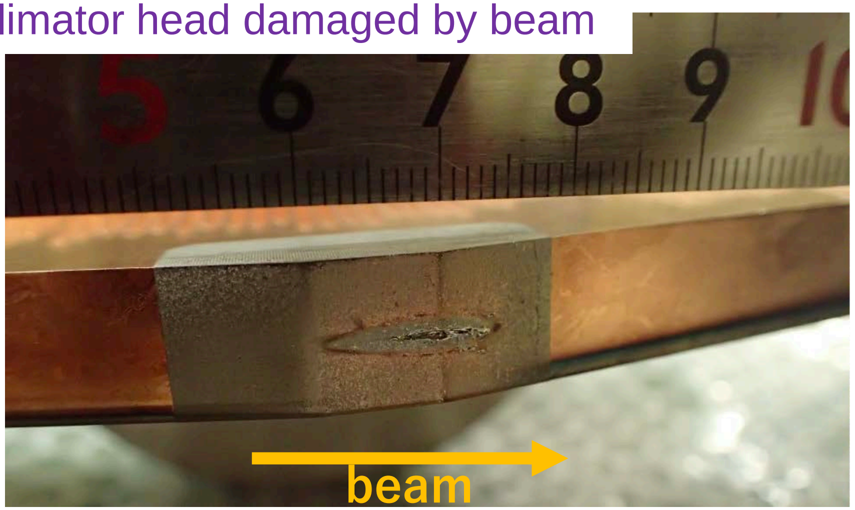
- Fast beam losses leading to collimator damage;
  - "High radiation dose to Belle II" and "QCS quench" due to subsequent beam showers hitting the Belle II and QCS.
  - The beam instabilities developed extremely fast, only in a few turns.
    - ✓ A possible cause of the beam instability is a falling dust particle in LER.
    - ✓ Detailed mechanism is not known.
  - ➢ Faster beam abort system and additional robust collimator with lower Z material are required.
- High detector background
  - Dominated by beam-gas scattering in the LER.
    - ✓ Limits the beam current and minimum β_y^*.
    - ✓ Jeopardizes the integrity of the detector.
  - Frequent injection background bursts
    - ✓ Seemed to be due to "rogue pulses" in the Linac/BT.
    - ✓ Limited the Belle II operation to a greater extent than the steady state (DC) backgrounds, which are mostly from LER beam gas scattering.
  - ➢ More vacuum scrubbing (LER), Linac tuning and injection tuning are required.

T. Ishibashi

vertical collimator

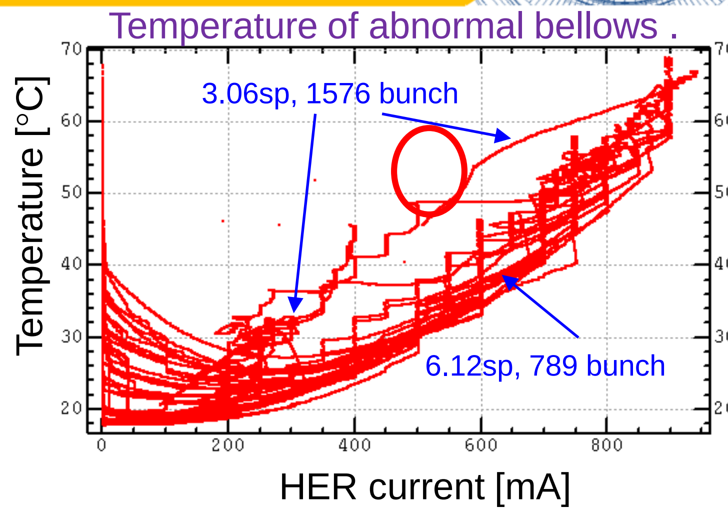


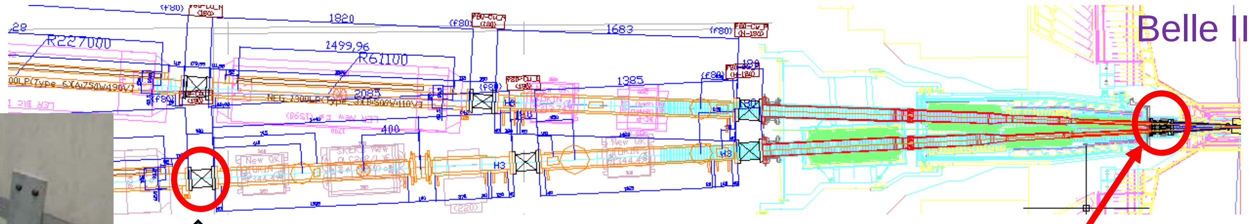
collimator head damaged by beam



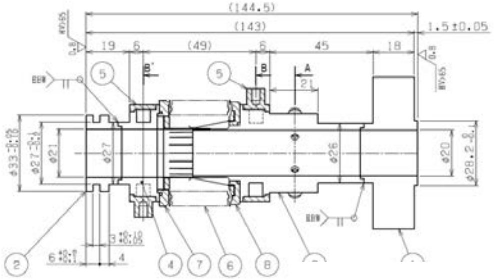
Major Issues of Phase3 2019ab

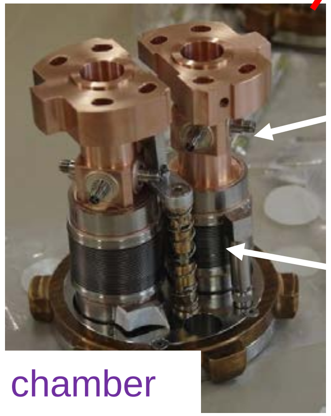
- Abnormal RF-shielded bellows of IP vacuum chamber;
  - External wall temperature of one of four IP-bellows rose up to more than 60 °C at high current.
  - As a result of internal check with a fiberscope after Phase3 2019ab operation, it was found that 3 RF fingers were out of normal positions.
  - During Phase3 2019ab operation, It was also known that one BPM cable was disconnected to BPM electrode.



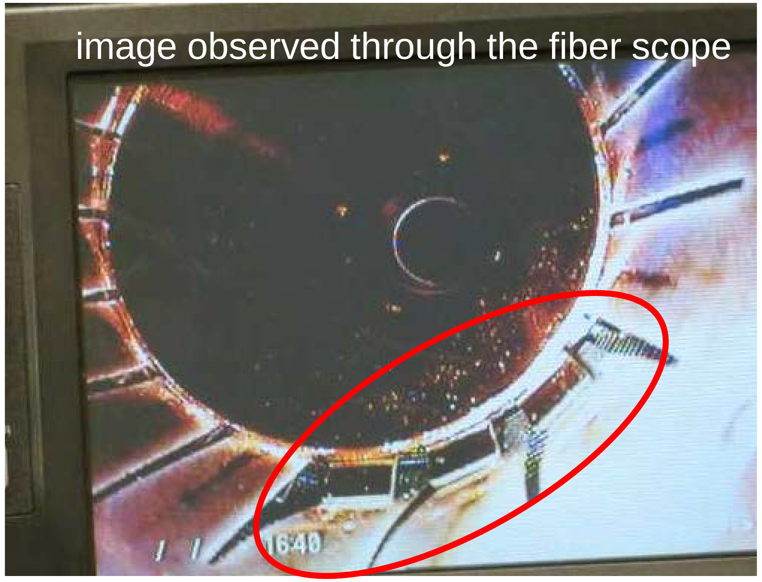


fiberscope was pushed from here.



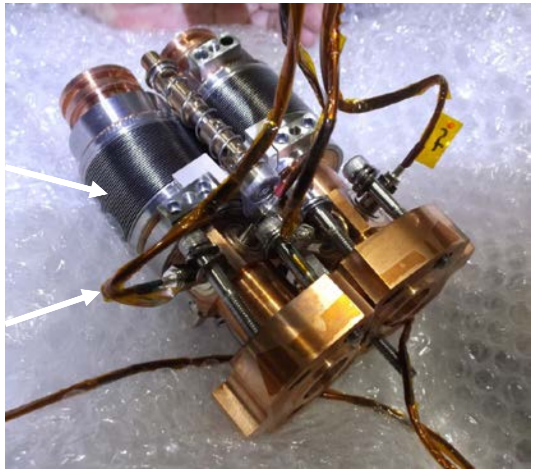


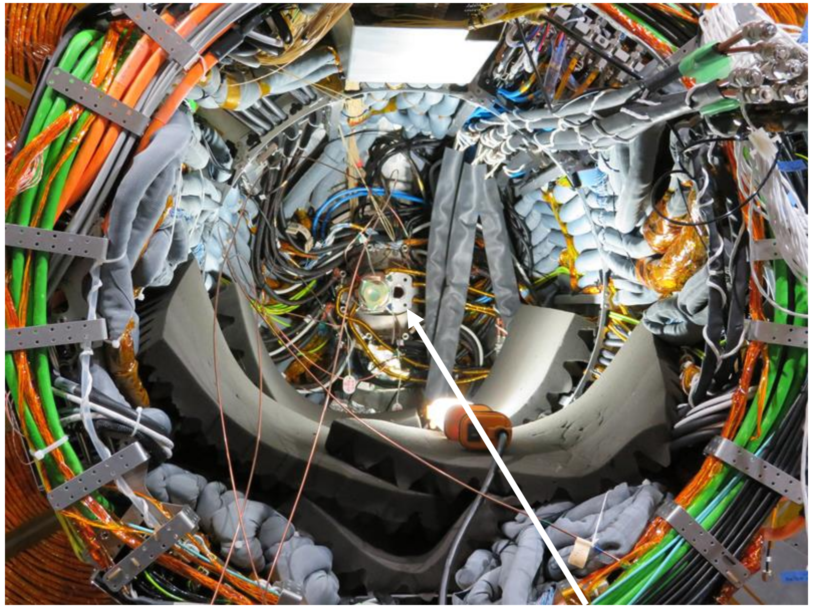
IP bellows chamber



Major works after Phase3 2019ab

- Replacement work of IP bellows and BPM cables;
  - QCS was pulled back from Belle II detector.
  - Bellows chamber and damaged BPM cables were replaced.
  - After replacement work, soundness checks of bellows and BPM cables were performed.
    - RF-fingers may have come out from their normal positions during installation work before Phase3 2019ab.
    - BPM cables may have been damaged during installation work before Phase3 2019ab.



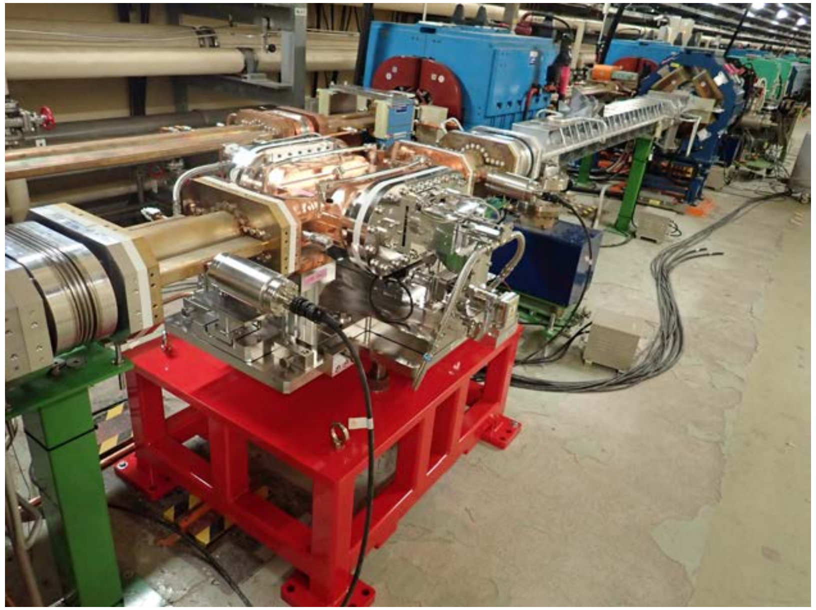


Major works after Phase3 2019ab

- Replacement of damaged collimator head (D2V1) and in-situ baking;
  - Detector background was dominated by beam-gas scattering in the LER.
  - In-situ baking was a countermeasure against high background noise.
- Installation of new BPM just before injection point (HER).
  - More precise injection tuning became possible.

T. Ishibashi

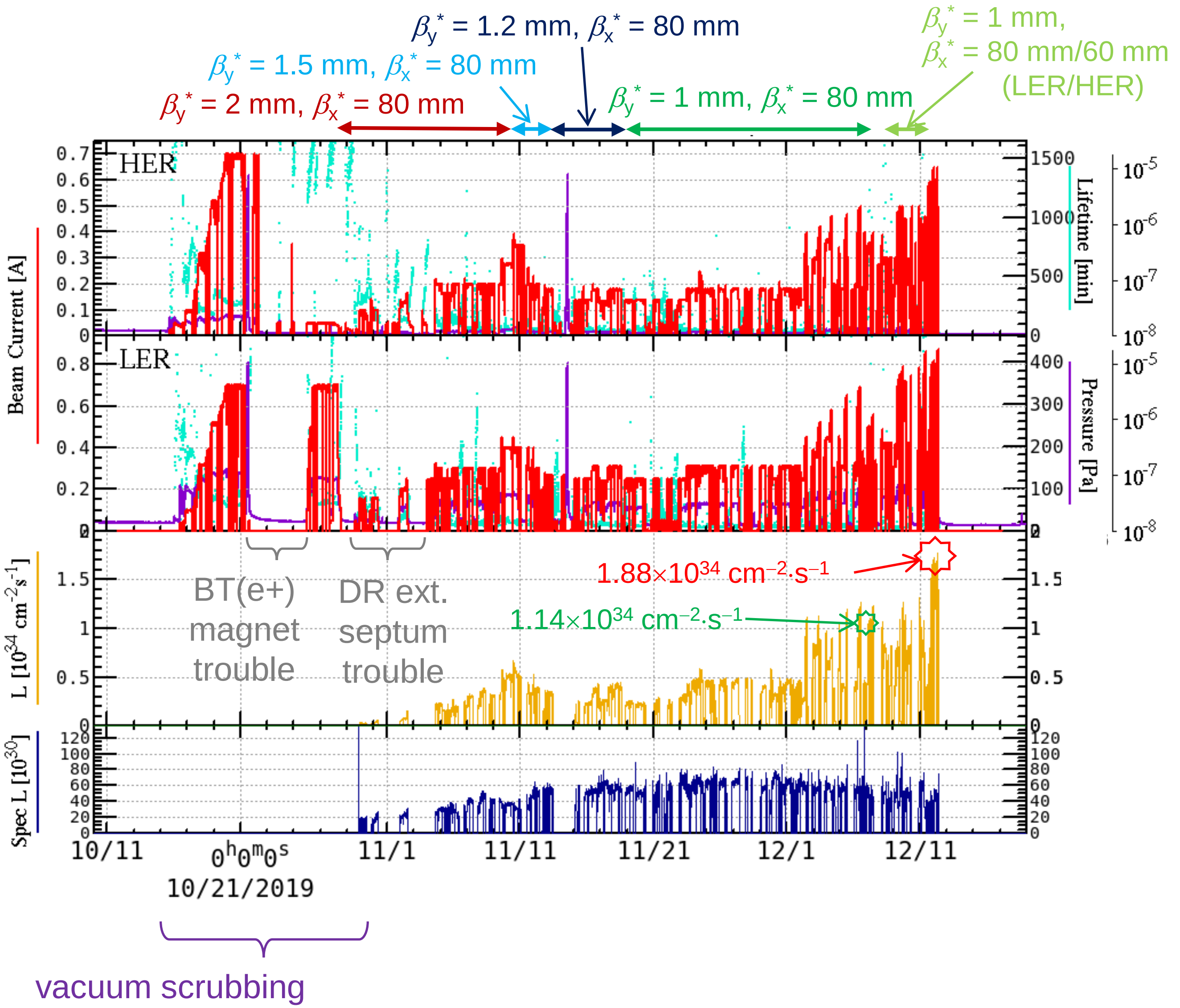
Collimators were baked by hot-air circular to reduce pressure.



Phase3 2019c (2019.10~12)

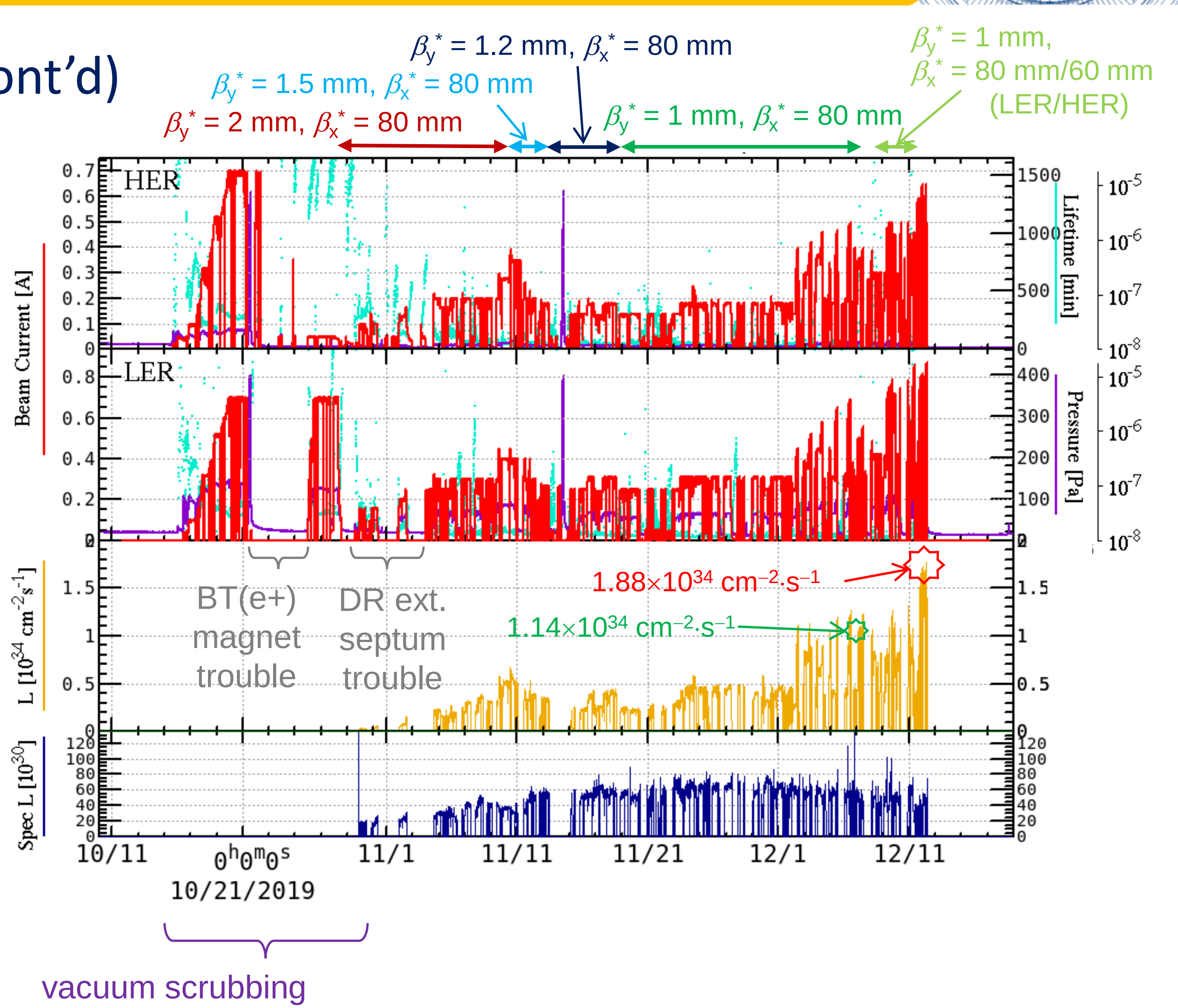
- Mission of Phase3 2019c operation;
  - Machine developments
    - ✓ β_y^* squeezing down to less than 1 mm.
    - ✓ Background studies
  - Physics run on weekends and 0:00-9:00 (owl shift).

- Overview of Phase3 2019c (2019.10~12)
  - From 15/Oct. to 12/Dec.
  - Started with vacuum scrubbing.
  - 1-week interruption due to BT(e+) magnet trouble and DR ext. septum trouble.
  - Collision tuning started on 29/Oct.



Phase3 2019c (2019.10~12)

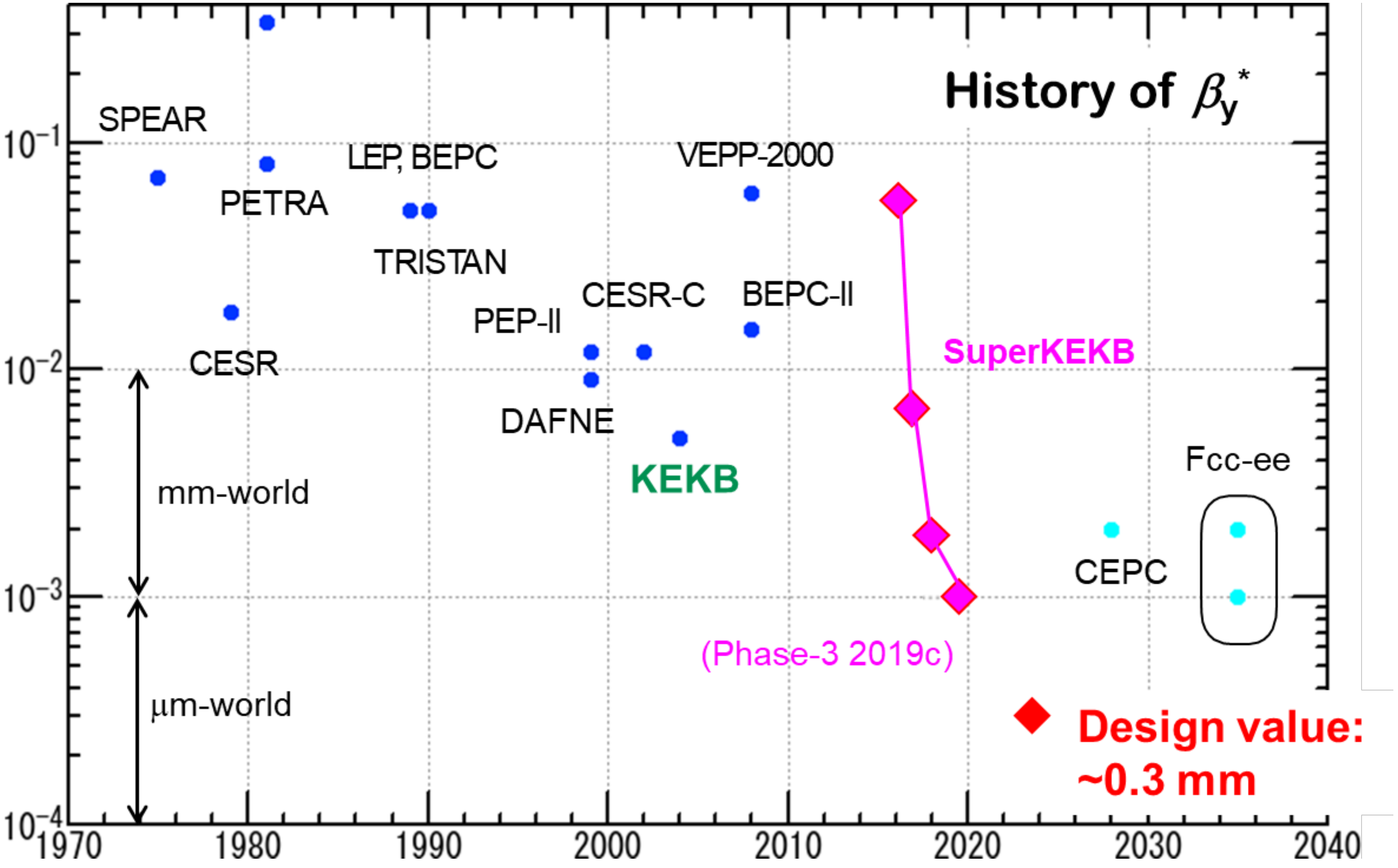
- Overview of Phase3 2019c (2019.10~12) (cont'd)
  - Beam current:
    - Maximum : 700 mA (HER) & 880 mA (LER)
    - Mostly low current (200~300 mA) for machine developments
  - Beta squeezing:
    - Started with $\beta_y^* = 2$ mm & $\beta_x^* = 80$ mm
    - β_y^* was squeezed down to 1 mm via 1.5 mm and 1.2 mm.
    - β_x^* of HER was reduced to 60 mm at last.
  - Luminosity :
    - Peak Luminosity w/o Belle II detector taking data : 1.88×10^{34} cm^{-2}·s^{-1}
    - Peak Luminosity w/ Belle II detector taking data : 1.14×10^{34} cm^{-2}·s^{-1}
    - Integrated luminosity (Phase3 2019c) : 4.0 fb^{-1}
    - Total integrated luminosity : 10.1 fb^{-1}



β_y* squeezing in Phase3 2019c

- β_y^* squeezing history;
  - Now we are operating with β_y^* = 1 mm.
    - ✓ Smallest value in the world!!
    - ✓ Lower than the bunch length of 6 mm.

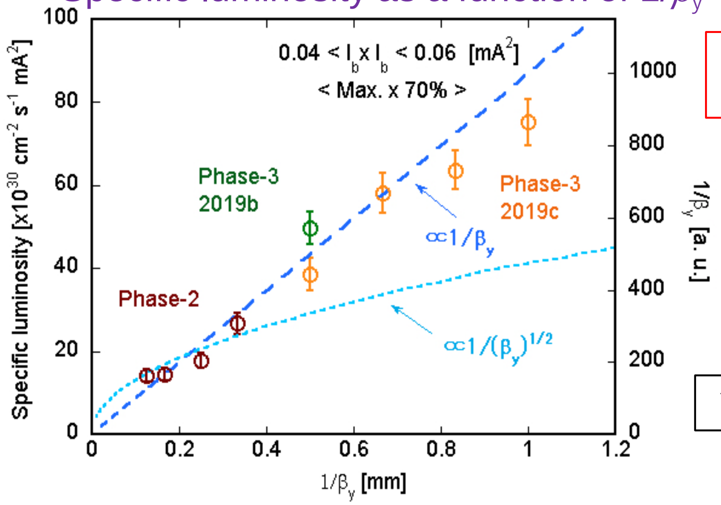
Y. Suetsugu



Luminosity in Phase3 2019c

- Luminosity;
  - Peak Luminosity w/o DAQ = 1.88×10^{34} cm$^{-2}\cdot$s^{-1}
    - at 650 mA (HER) & 850 mA (LER)
    - with 3.27 RF bucket sp./2 train (2 abort gaps)/1476 bunches
    - β_y^* = 1 mm & β_x^* = 80(LER)/60(HER) mm
    - Belle II could not take data due to high background noise.
  - Peak Luminosity w/ DAQ = 1.14×10^{34} cm$^{-2}\cdot$s^{-1}
    - at 360 mA (HER) & 500 mA (LER)
    - with 6.12 RF bucket sp./2 train (2 abort gaps)/783 bunches
    - β_y^* = 2 mm & β_x^* = 80 mm
  - Integrated luminosity : 4.0 fb^{-1}
- Specific luminosity;
  - Specific Luminosity (L_{sp}) Increased almost in proportion to $1/\beta_y^*$
    - Nano-beam scheme collision worked well with β_y^* = 1 mm !!
  - Slow degradation of specific luminosity with a increase of bunch currents.
    - Beam-beam effect increases the vertical emittance, reducing the specific luminosity.
    - Key issue in the future commissioning.

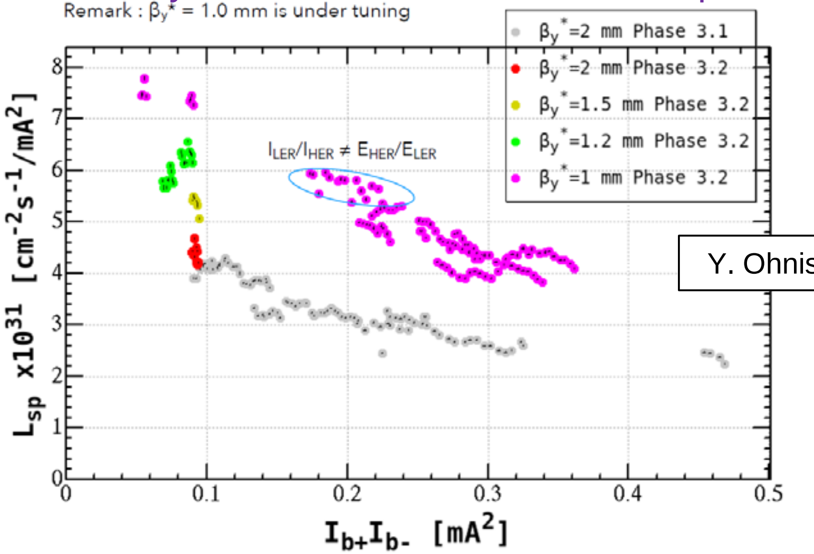
Specific luminosity as a function of $1/\beta_y^*$



$$L_{sp} \propto \frac{1}{\beta_{y\pm}^*}$$

Y. Suetsugu

Specific luminosity as a function of bunch current products



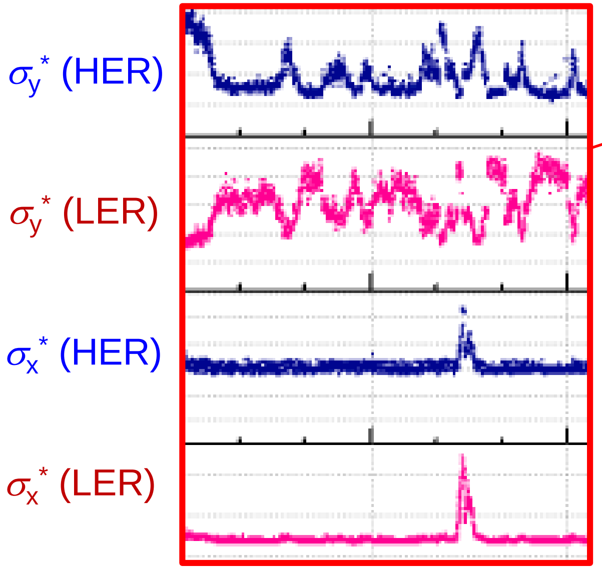
Y. Ohnishi

Major issues of Phase3 2019c

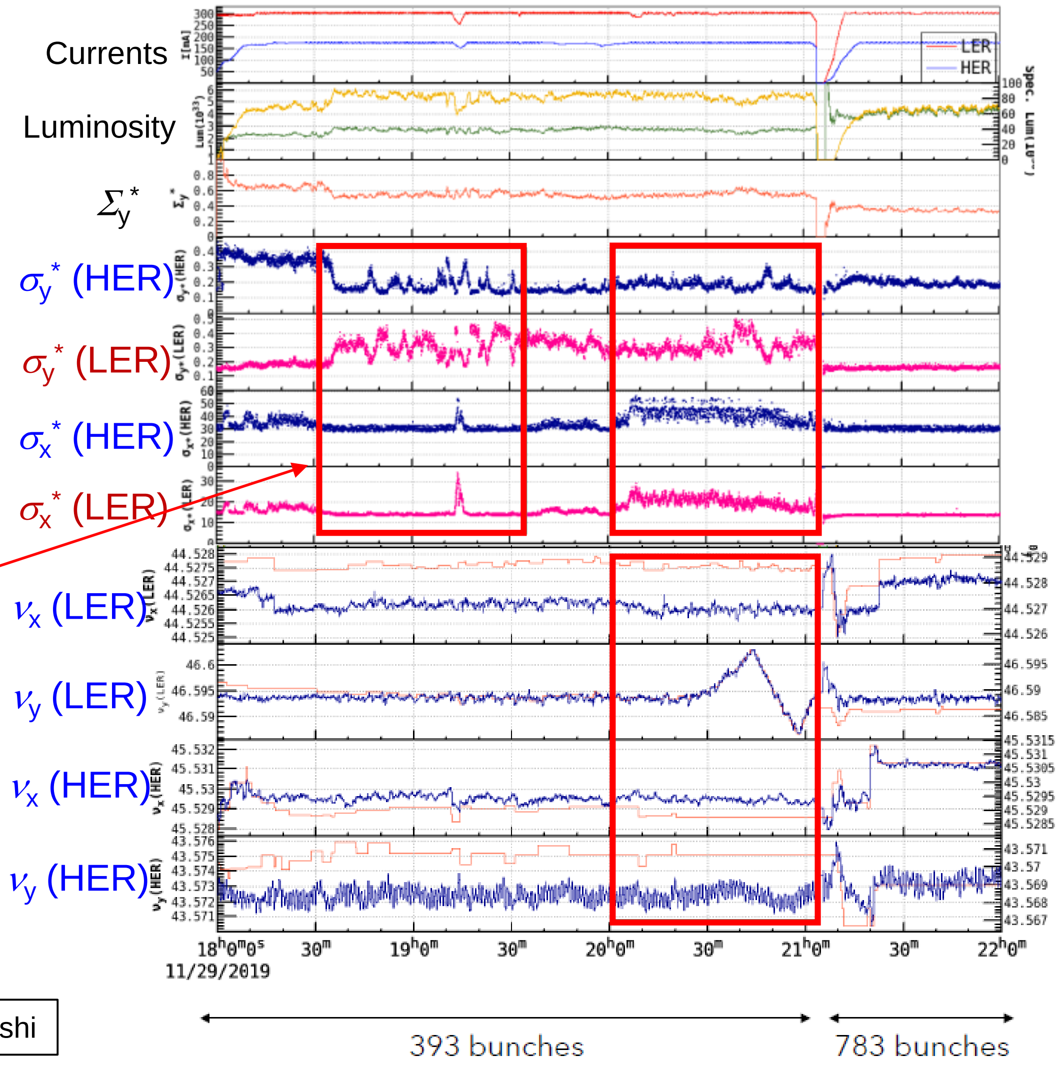
- Unstable modes at high bunch current;
  - Flip-flop phenomena between HER and LER beam sizes were observed at high bunch currents.
    - ✓ Seems to be sensitive to betatron tune.
    - ✓ Coherent beam-beam head-tail instability?
  - ➢ Understanding the mechanism is required.

β_x^*		80 mm
β_y^*		1 mm
Current	HER	180 mA
	LER	310 mA
Bunch current	HER	0.458 mA/bunch
	LER	0.788 mA/bunch
Current products		0.36 mA^2

Flip-flop phenomena



Trend of beam parameters



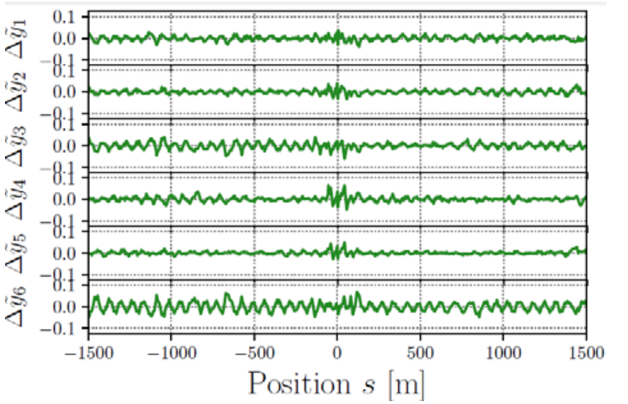
Y. Ohnishi

Major issues of Phase3 2019c

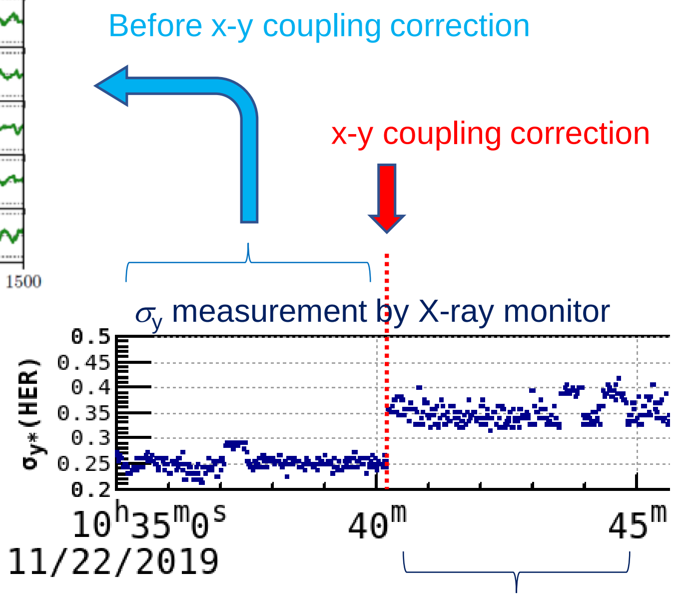
- Optics issues;
  - Some difficulties were gradually revealed as decreasing β_y^*.

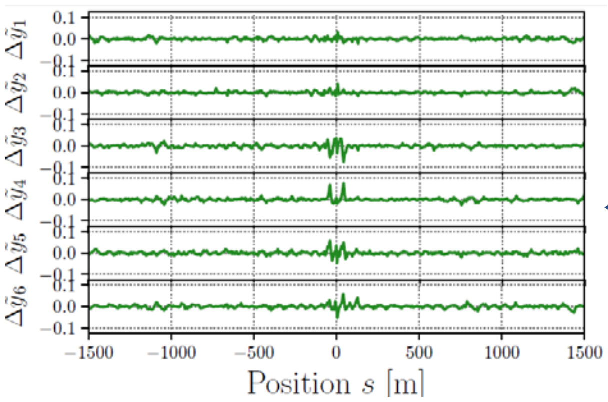
1. Difficulty in x-y coupling correction;
   - ✓ σ_y increased even though the coupling correction seemed to work well.
   - ✓ x-y coupling correction with skew Q coils of sextupole magnets in Local Chromaticity Correction section may cause this issue.
   - ➢ Not yet understood well.
2. Difficulty in more precise measurement of optics;
   - We have to deal with 10 μm or less beam position change to evaluate optics parameters, and then the residual of the orbit correction is 20~30 μm in RMS.
   - Estimated beam position changes in this orders at sextupoles have non-negligible impact on emittance.
   - ➢ Method for more precise measurement of optics should be established.

x-y coupling measurement



x-y coupling correction seems to work well.

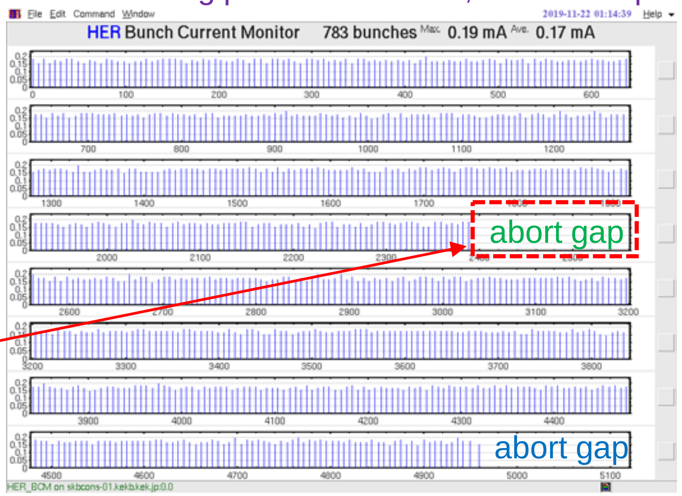




Improvement in beam abort system

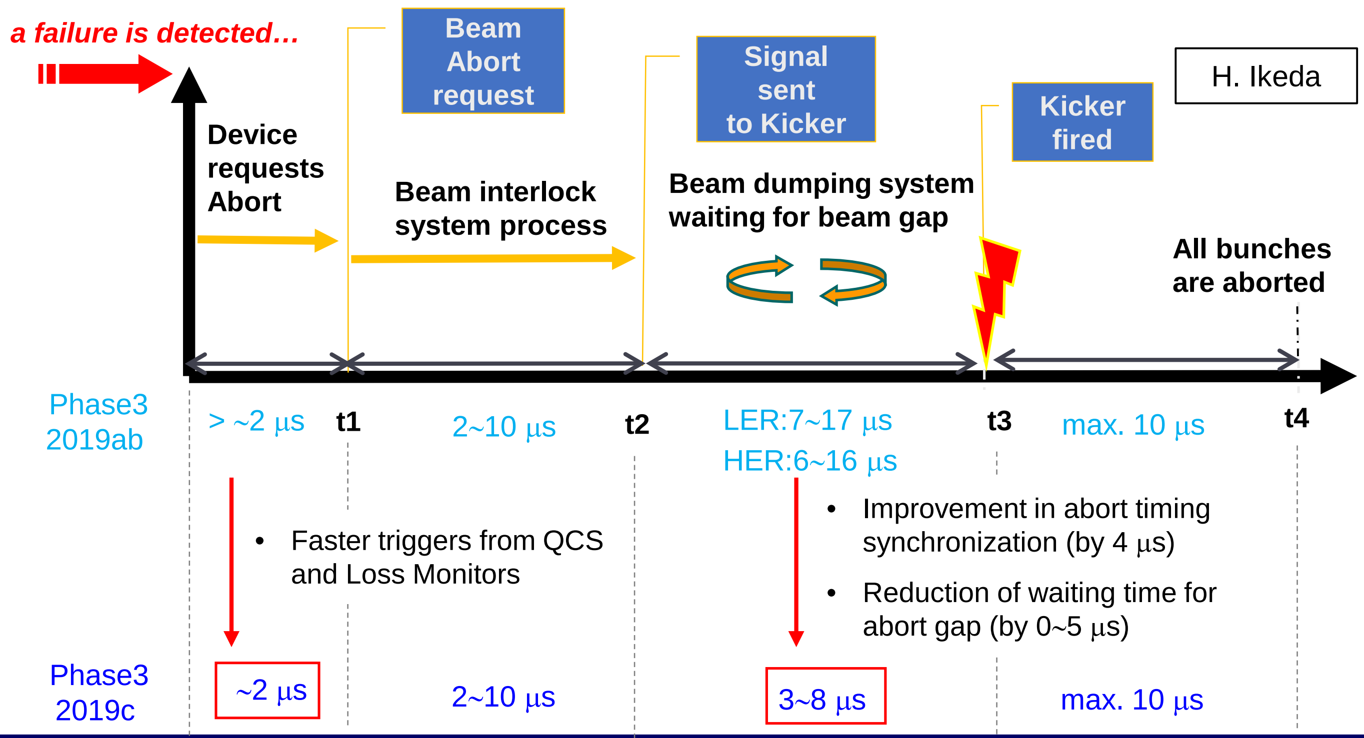
- For faster beam abort to avoid damages to collimators and Belle II detector;
  - Improvement in abort trigger delivery time on accelerator side.
    - ✓ 21 ~ 39 μs (2019b) → 17~30 μs (2019c) (reduced by –0~9 μs !!)
  - More to come from detector side. (by ~7.5 μs)

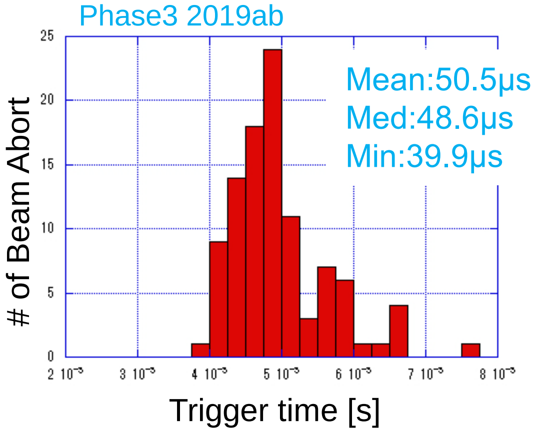
New bunch filling pattern : 2 Trains, 2 Abort Gaps

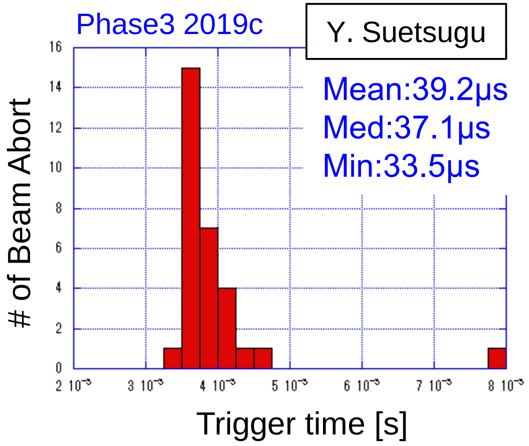


New abort gap to reduce waiting time for kicker firing.

Time chart of beam abort trigger delivery







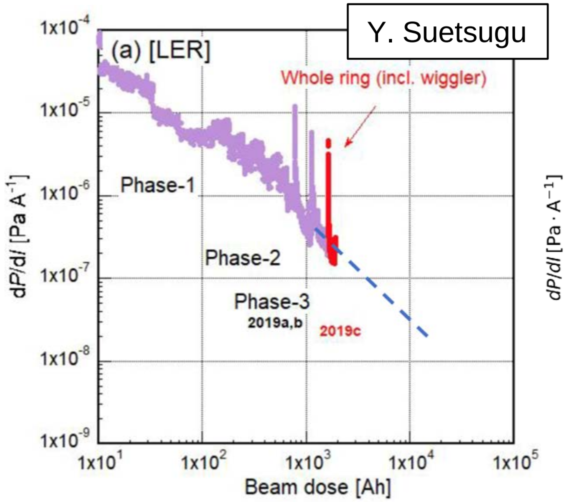
- Beam abort trigger issued faster by ~10 μs.
- ➢ However, one collimator was damaged again.

Detector background of Phase3 2019c

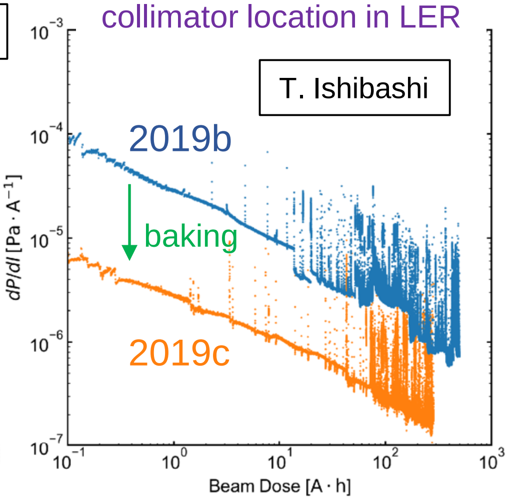
- Storage beam BG
  - Major source was still beam-gas scattering in LER.
  - Even though β_y^* squeezing (3 mm $\rightarrow$ 1mm) should increase the loss rate, BG was improved by a factor of 2~3 compared to 2019ab.
    - ✓ Tighter collimator settings, which can be available thanks to more stable injection with smaller emittance growth in beam transport line.
    - ✓ Progress of vacuum scrubbing, which was helped by in-situ baking of collimators.
- Injection BG;
  - LER injection BG on detector leak current
    - ✓ Large leak current caused DAQ deadtime and limited maximum beam currents for physics run.
  - Long duration of LER injection BG
    - ✓ ~13 % dead time @ 12.5 Hz injection.
    - ✓ Injection BG duration should be suppressed to increase integrated luminosity.
  - Synchrotron radiation BG on PXD
    - ✓ PXD started to see significant SR increase after HER β_x^* squeezing (80 mm $\rightarrow$ 60 mm).
    - ✓ Rotation of HER horizontal orbit reduced SR by ½.
    - ✓ SR hit was correlated with injections. Why?

➢ Stable injection with low emittance is a key challenge in the next run.

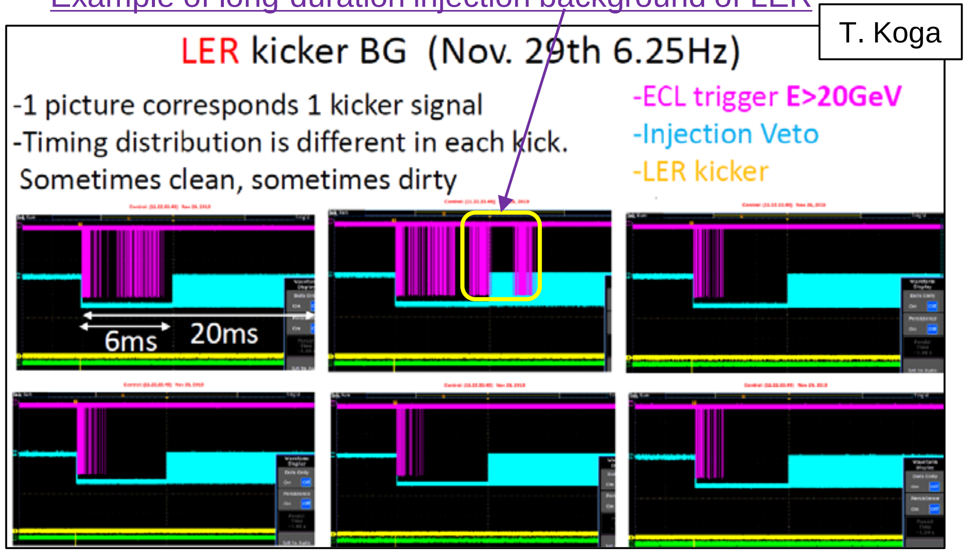
Vacuum scrubbing in LER



Vacuum scrubbing at collimator location in LER



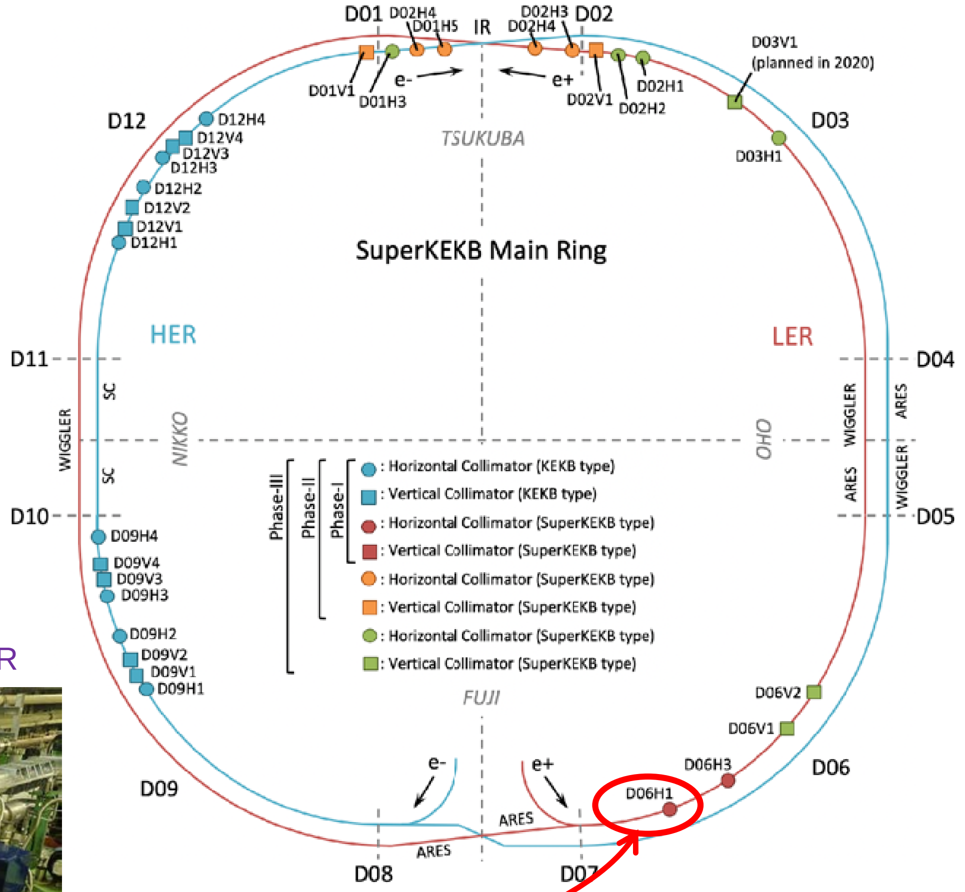
Example of long-duration injection background of LER



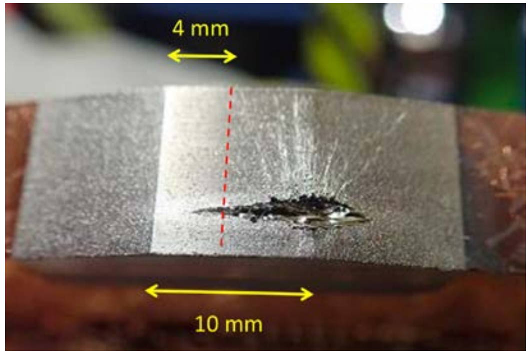
Major works after Phase3 2019c

- Replacement of damaged collimator head;
  - One of LER collimator head was damaged during Phase3 2019c.
  - 4 collimator heads were damaged in total so far.
    - ✓ LER : D06V2 (Phase3 2019c), D02V1 (Phase3 2019ab), D02V1 (Phase2)
    - ✓ HER : D01V1 (Phase2)
  - ➢ Robust collimator is required in order to increase beam current.
    - R&D of Low-Z collimator is undergoing.
    - Short Ta head was set to D06V2 in a chain of low-Z collimator R&D.
- Installation of new vertical collimator (D06V1) in LER.
  - ➢ Reduction in BG by a factor of 2.5 is expected by a simulation.

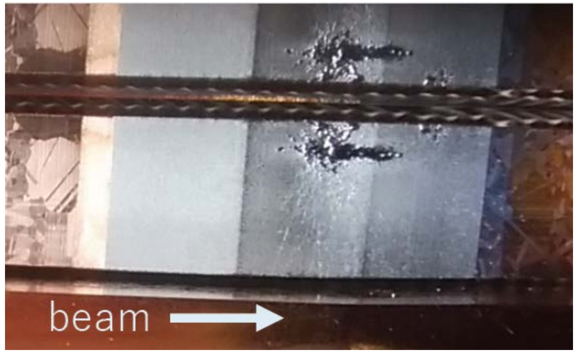
T. Ishibashi



Damaged head



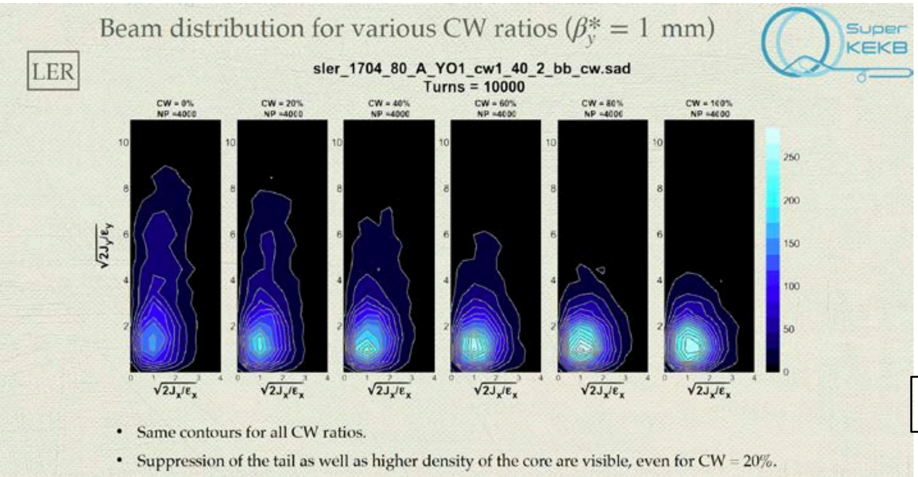
Head opposite the damaged head



New vertical collimator in LER

Major works after Phase3 2019c

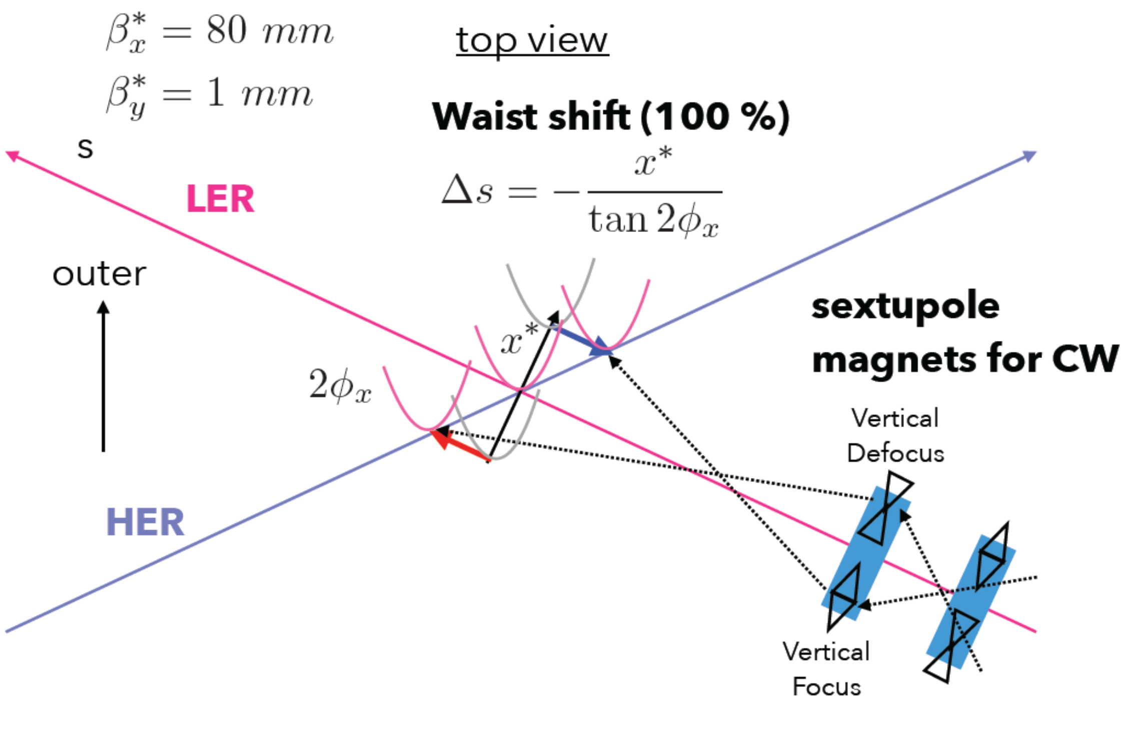
- Cabling work for crab-waist scheme for LER
  - Beta function waist of one beam is oriented along the central trajectory of the other one.
    - The vertical beta-function rotation is provided by sextupole magnets placed on both sides of the IP.
  - Simulation indicated the improvement of luminosity.
    - Reduction of beam-beam blowup, beam-tail, then beam background.
    - Effective down to $\beta_y^* \sim 0.5$ mm.
  - ➢ We decided to try crab-waist scheme in SuperKEKB last December.
    - Try to LER first, then try to HER.
    - Cabling work for crab-waist for LER was completed during winter shutdown.



K. Oide

Crab Waist Scheme (CW)

Y. Ohnishi

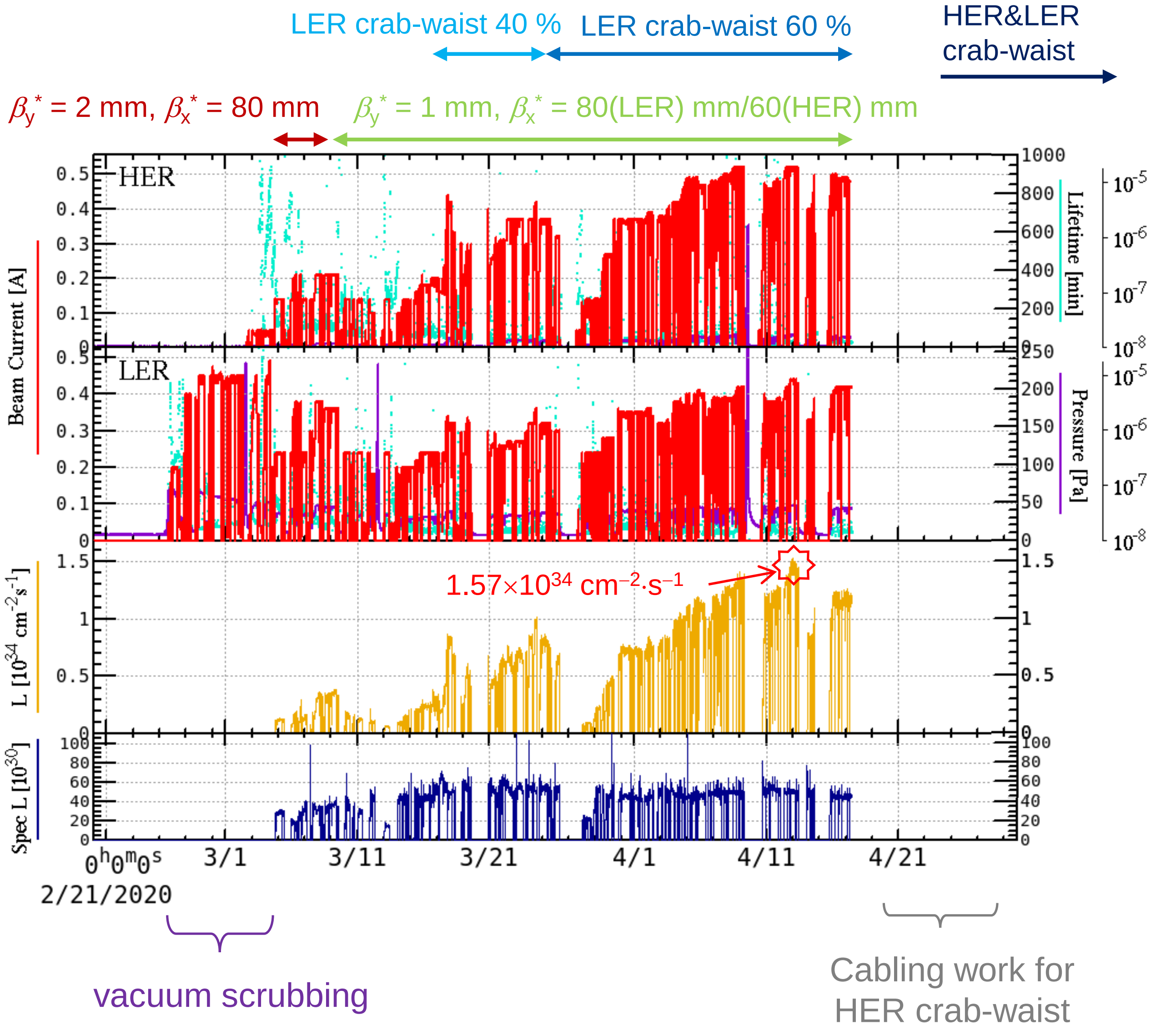


The LER waist (the minimum beam size) can be shifted proportional to the horizontal orbit offset at the IP and aligned on the HER beam line.

Phase3 2020ab (2020.02~07)

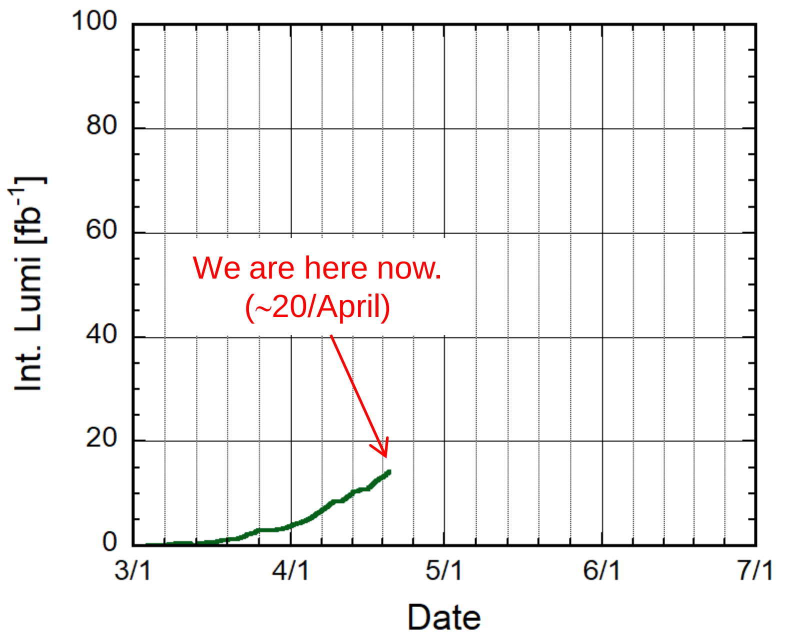
- Mission of Phase3 2020ab operation;
  - Physics run toward more than 100 fb^{-1} by the end of June.
  - Demonstration of crab-waist scheme

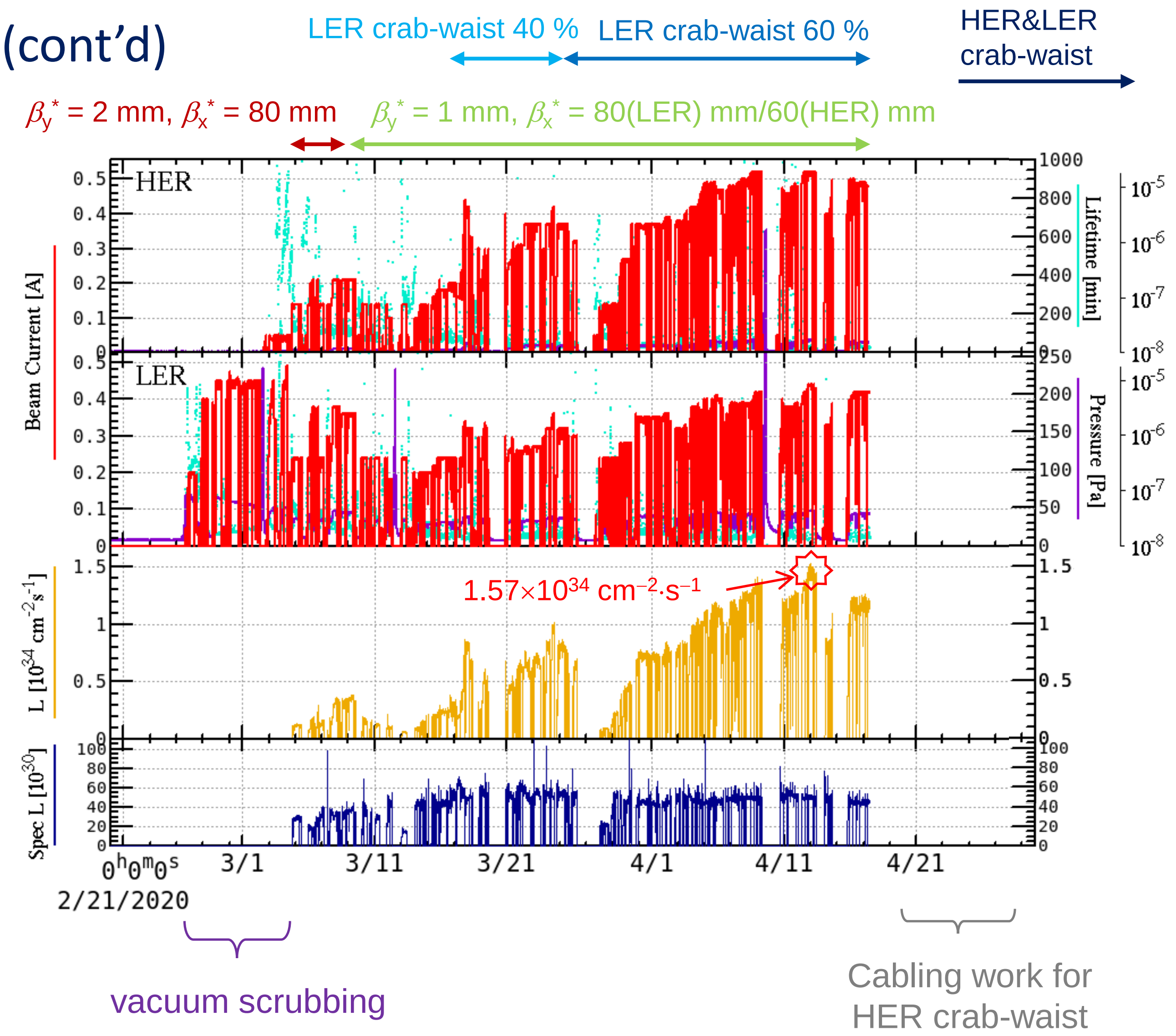
- Overview of Phase3 2020ab (2020.Feb.~20/April)
  - From 25/Feb. to 1/July.
    - This talk covers things only up to 20/April (before HER crab-waist).
  - Started only with LER for vacuum scrubbing.
  - HER beam on 2/March
  - Beta squeezing:
    - Keeping $\beta_y^* = 1$ mm & $\beta_x^* = 60$(HER)/80(LER) mm
    - More time is required for Linac tuning and Inj. tuning.
  - Crab-waist:
    - LER : 0 % → 40 % on 16/March
    - LER : 40 % → 60 % on 24/March
    - Cabling work for HER crab-waist (20-23/April)
    - Machine operation was resumed on 23/April.



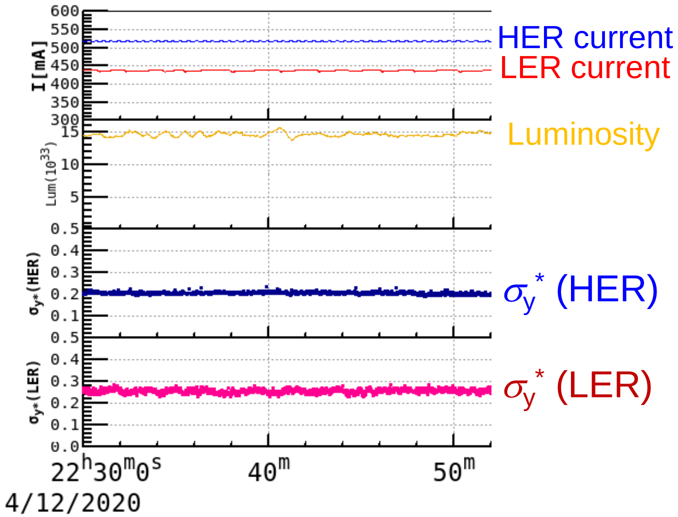
Phase3 2020ab (2020.02~07)

- Overview of Phase3 2020ab (2020.Feb.~20/April) (cont'd)
  - Beam current:
    - Maximum : 520 mA (HER) & 500 mA (LER)
  - Luminosity (up to 20/April):
    - Peak Luminosity w/ Belle II detector taking data : 1.57×10^{34} $cm^{-2}\cdot s^{-1}$
    - Integrated luminosity : 13.9 fb^{-1} (up to 20/April)

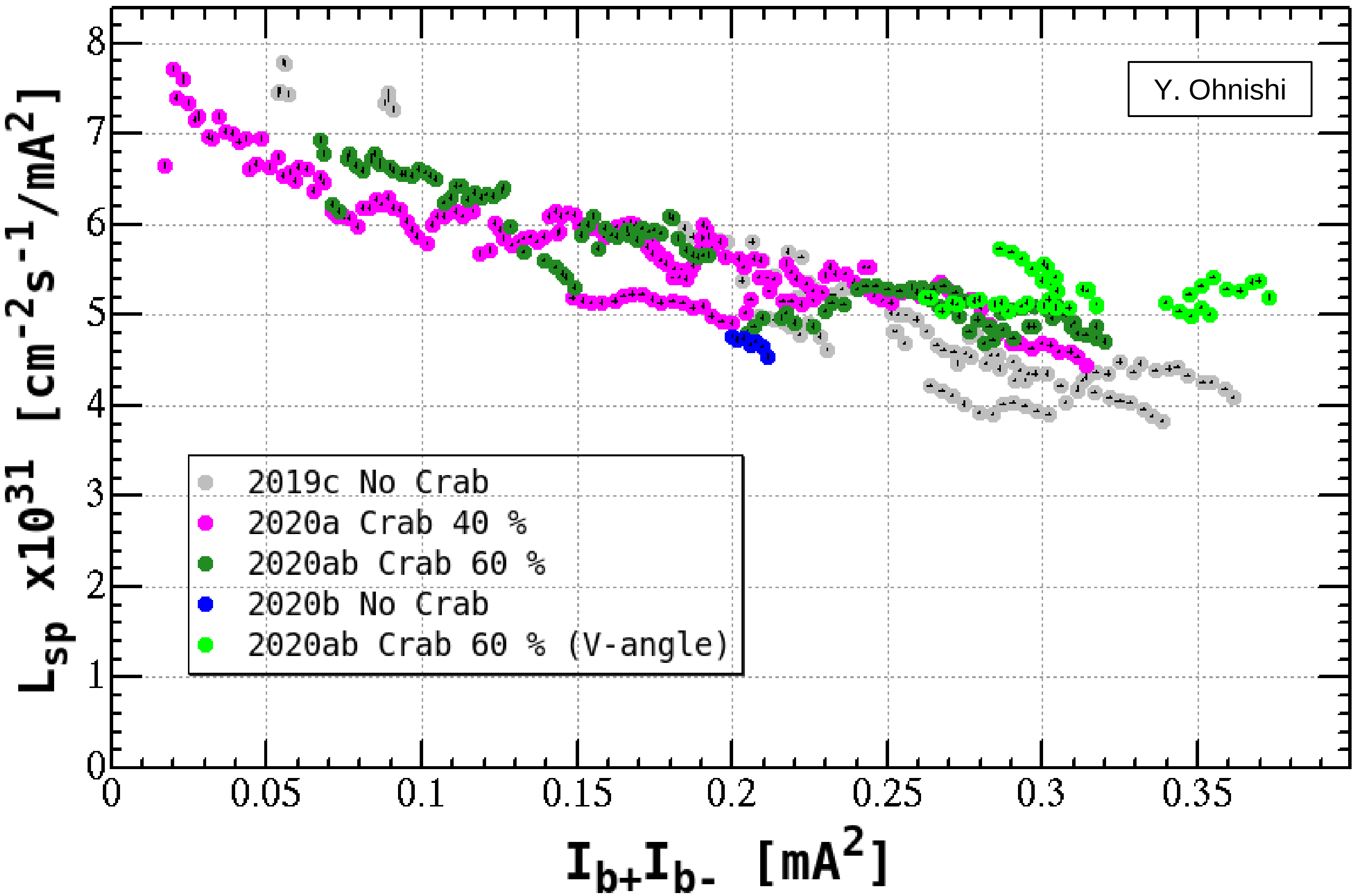




- Specific luminosity;
  - Specific luminosity was kept high at high bunch current products.
    - LER Beam-beam blowup at high bunch currents was suppressed by LER crab-waist.
    - Contrary to the energy transparency condition, HER current can be increased more than LER current to push up luminosity .
      - I_{HER} (520 mA) > I_{LER} (440 mA)
      - E_{HER} (7 GeV) > E_{LER} (4 GeV)



Specific luminosity as a function of bunch current products



Luminosity performance with LER crab waist

K. Oide

Luminosity performance

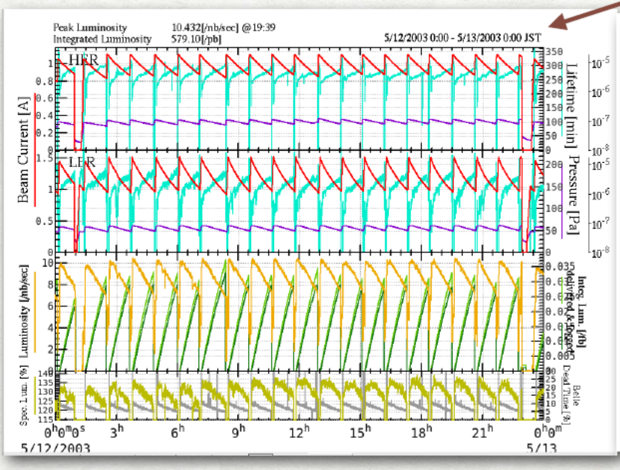
Date		May 13, 2003 LER	May 13, 2003 HER	Dec. 9, 2019 LER	Dec. 9, 2019 HER	Mar. 24, 2020 LER	Mar. 24, 2020 HER
Beam energy	GeV	3.5	8	4	7	4	7
Current/beam	A	1.38	1.05	0.70	0.44	0.36	0.42
Particles/bunch	10^{10}	6.84	5.21	2.81	1.77	2.89	3.37
β_x^*	mm	590	580	80	60	80	60
β_y^*	mm	5.8	7	1			
σ_x^*	μm	103	118	13.0	16.6	13.0	16.6
σ_y^*	μm	2.2	2.2	0.20	0.24	0.20	0.22
ξ_x		0.093	0.068	0.0018	0.0014	0.0034	0.0014
$\xi_y{}^a$		0.065	0.051	0.020	0.019	0.042	0.022
Bunches/ring		1265		1565		783	
Half crossing angle	mrad	11		41.5			
Crab waist	%	0				40	
Luminosity	nb/s	10.5		10.4		10.0	

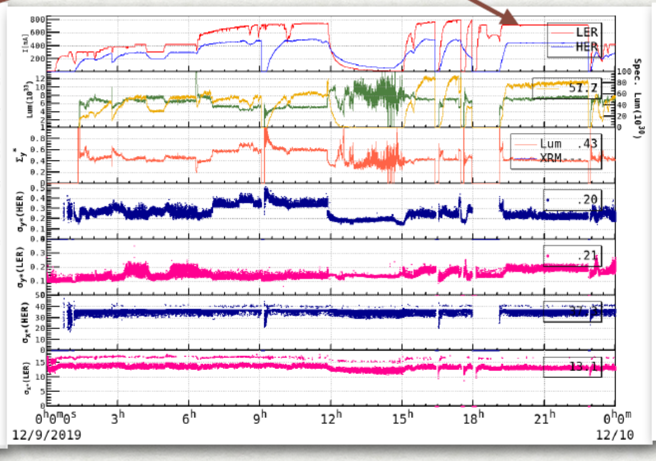
^{a}incl. hour glass

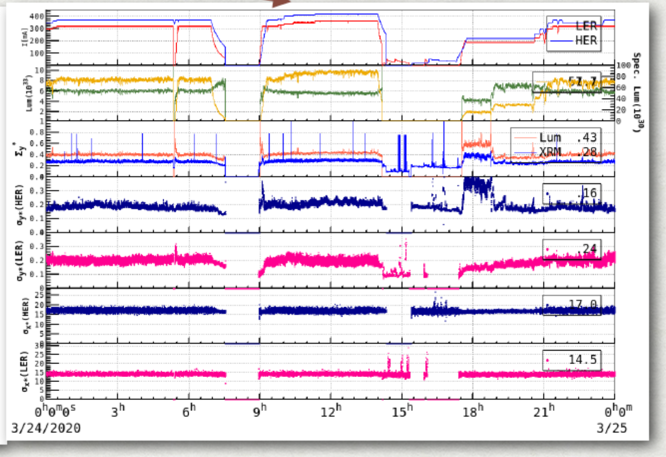
- The 40% crab waist of the LER has made the same luminosity (1e34) possible with **1/2 stored current** in the LER!!
- ξ_y in the LER has been **doubled** by 40% CW.

Thanks to
T. Nakamura, Y. Ohnishi

Apr. 2, K. Oide







Summary

- Phase3 2019ab (2019.3~7) & 2019c (2019.10~12);
  - Physics run with fully instrumented detector has finally started.
  - "Nano-beam scheme" collision was demonstrated up to $\beta_y^* =$ 1mm.
    - β_y^*/β_x^* have been squeezed to 1 mm/60 mm.
  - Peak Luminosity w/o Belle II detector taking data : 1.88×10^{34} $cm^{-2}\cdot s^{-1}$
    - Peak Luminosity w/ Belle II detector taking data : 1.14×10^{34} $cm^{-2}\cdot s^{-1}$
  - Integrated luminosity up to end of Phase3 2019c : 10. 1 fb^{-1}
    - Continuous injections increased integrated luminosity by 237 % compared with the normal injection.
  - Key challenges were;
    - Slow degradation of specific luminosity with a increase of bunch currents.
    - Optics difficulties revealed as squeezing β_y^*.
    - Fast beam losses leading to collimator damage, QCS quench, and detector damage.
    - Large detector background
    - And so on.
- Phase3 2020ab (2020.2~);
  - Started on 25/Feb. and will end on 1/July.
    - This talk covered things only up to 20/April (before HER crab-waist).
  - LER crab-waist (60%) pushed up peak Luminosity w/ Belle II detector taking data to 1.57×10^{34} $cm^{-2}\cdot s^{-1}$.
  - Cabling work for HER crab waist has just finished on 23/April.
    - Effect of HER crab-waist will be reported at IPAC'21!!

Fin.

Thank you for your attention.