SuperKEKB current status and prospects

K. Shibata

(on behalf of SuperKEKB Accelerator Group)

2020.12.03

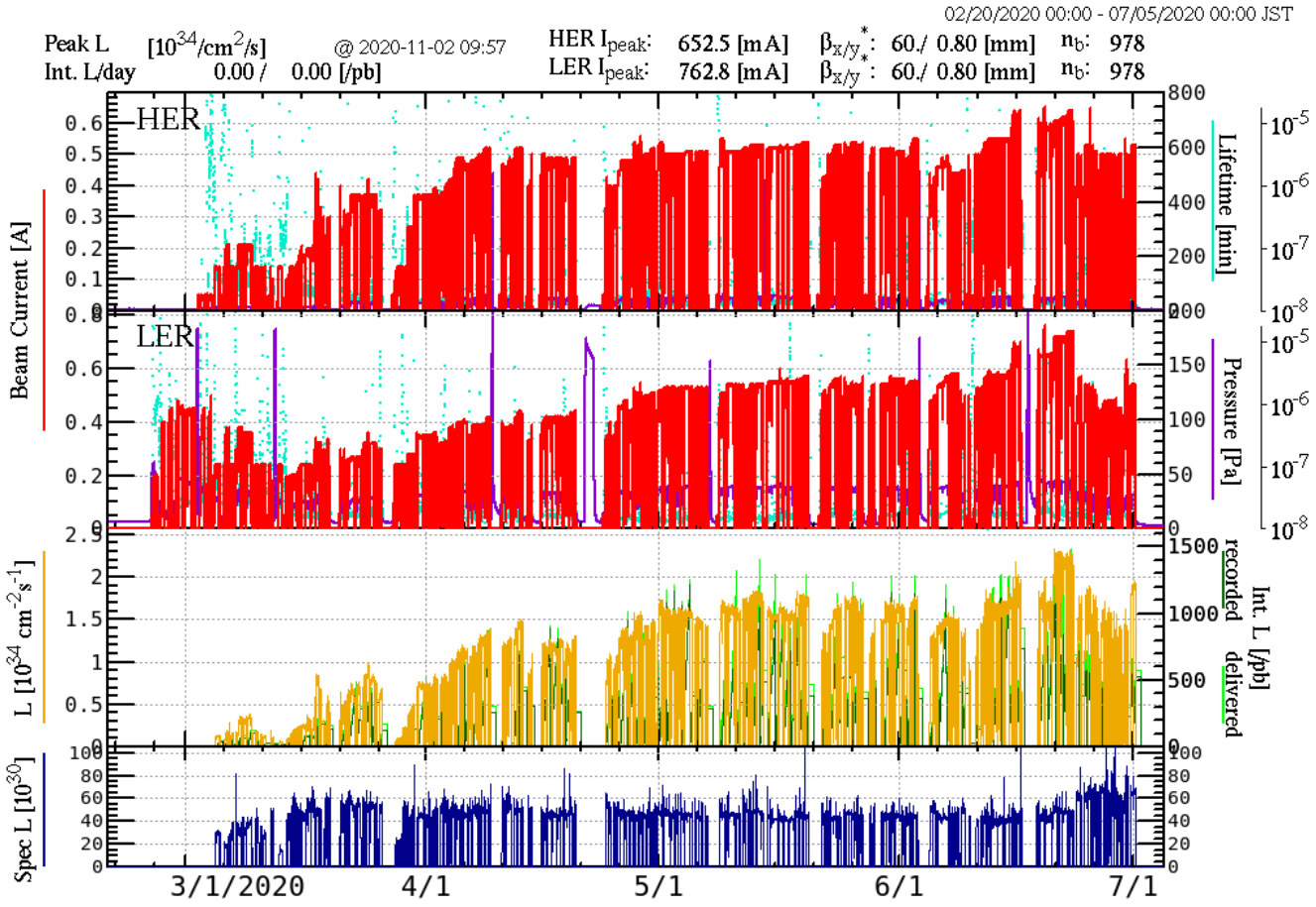
Belle II Physics Week

Highlight from 2020ab run

- Main missions of 2020ab run;
  - Physics run toward more than 100 fb^{-1}
  - Demonstration of crab-waist collision scheme
- Overview of 2020ab run;
  - From 25/Feb. to 1/July.
  - Beta squeezing:
    - Mainly β_y^* = 1 mm, β_x^* = 60(HER)/80(LER) mm
    - Finally β_y^* = 0.8 mm, β_x^* = 60 mm

      Smallest β_y^* in the world !!
  - Crab-waist:
    - Cabling work for HER crab-waist (20-23/April)
    - LER : 0 % → 40 % → 60 % → 80 %
    - HER : 0 % → 40 %
  - Luminosity:
    - Peak Lumi. : 2.4 × 10^{34} $cm^{-2}\cdot s^{-1}$ (NEW World Record!!)
      - $\beta_{x/y}^*$: 60/1mm (HER), 80/1 mm(LER)
      - Crab Waist : 40% (HER), 80% (LER)
      - Current : 610 mA (HER), 720 mA (LER)

        4.9 spacing (3-6 mix), 2 trains, 978 bunches
    - Delivered Integrated Lumi : ~74 fb^{-1}



Specific luminosity (2020ab)

- Luminosity

$$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma^*_{x,eff} \sqrt{\varepsilon_y \beta^*_y}}$$

- Specific luminosity

$$L_{sp} = \frac{L}{I_{b+} I_{b-} n_b} \propto \frac{1}{\sqrt{\varepsilon_y \beta^*_y}} \quad (\sigma^*_y)$$

  - L_{sp} depends on $1/\sigma_y^*$.
  - L_{sp} doesn't depend on $I_{b+}I_{b-}$.

  - However, it was observed that L_{sp} decreases as $I_{b+}I_{b-}$ increases.

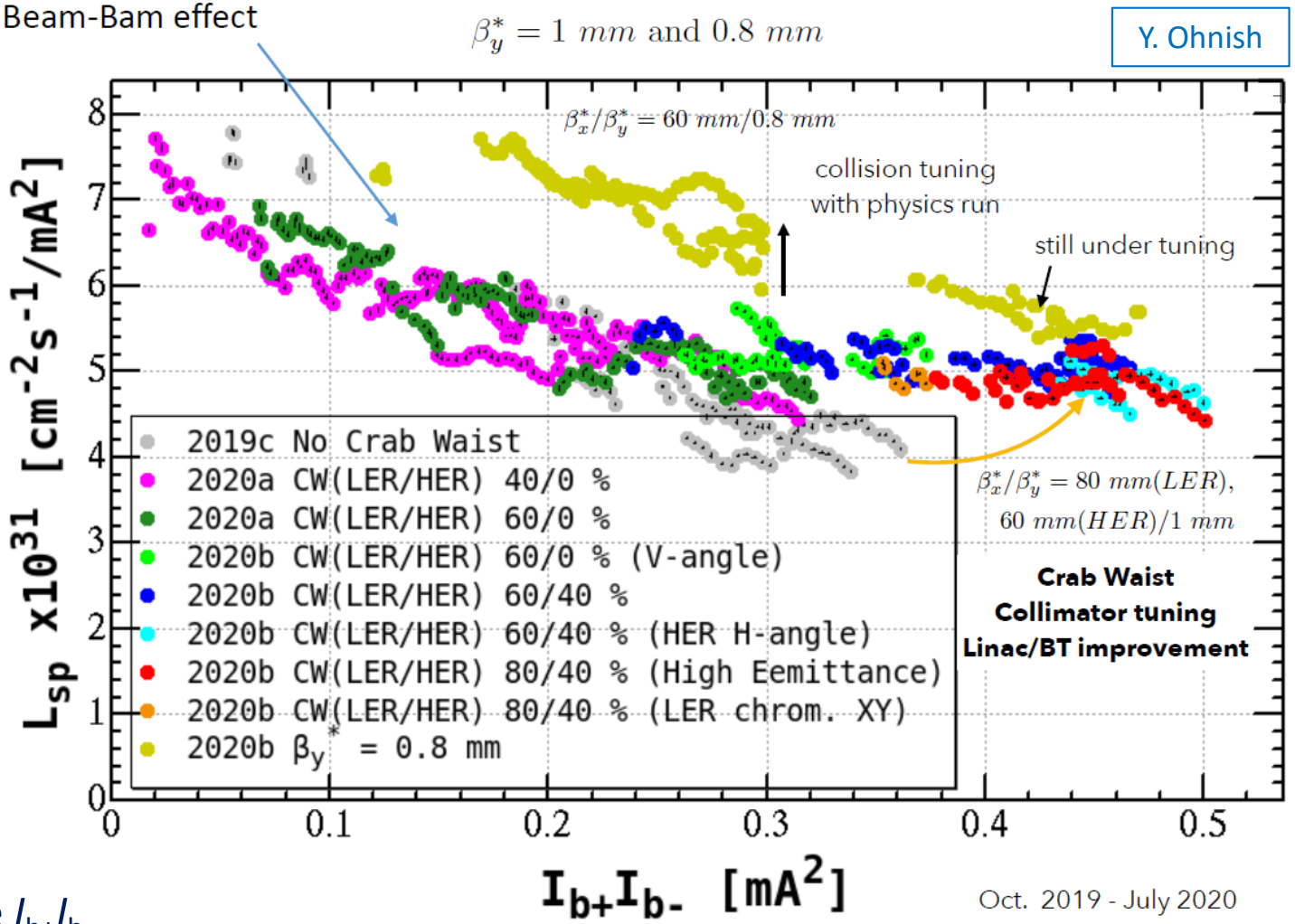
⇧

Beam blowup due to Beam-Beam effect at large $I_{b+}I_{b-}$.

Beam blowup due to Beam-Bam effect

σ_y^* = 0.19 μm →
σ_y^* = 0.22 μm →
σ_y^* = 0.26 μm →
σ_y^* = 0.31 μm →

Y. Ohnish



Luminosity performance

Y. Ohnish

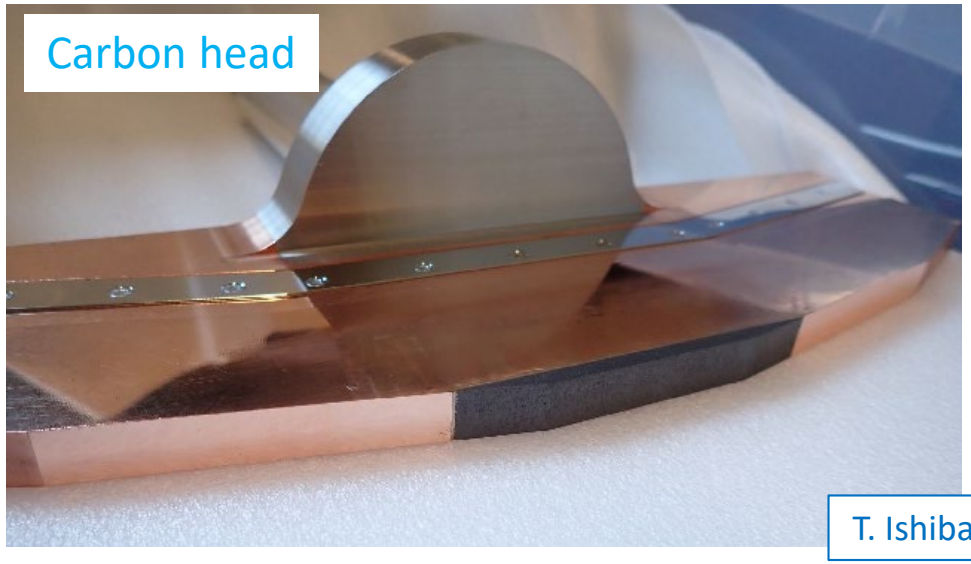
	Phase 2 2018a/b	Phase 3.1 2019a/b	Phase 3.2 2019c	Phase 3.3 2020a/b	
Date	**March 19 - July 17 2018**	**March 11 - July 1 2019**	**Oct. 15 - Dec. 12 2019**	**Feb. 25 - July 1 2020**	**Remarks**
Operation time (days)	120	91 (fire : 21)	57	127	~ 6 months per year
Beta Function at IP β_x^* / β_y^* (mm)	LER : 200 / 3 HER : 100 / 3	LER : 80 / 2 HER : 80 / 2	LER : 80 / 1 HER : 60 / 1	LER : 60 / 0.8 HER : 60 / 0.8	The minimum horizontal / vertical value
Beam Currents (mA)	LER : 860 HER : 800	LER : 940 HER : 840	LER : 880 HER : 700	LER : 770 HER : 660	The maximum values during the operatation
Peak Luminosity ($cm^{-2}s^{-1}$)	**2.62×10^{33}** → double	**5.50×10^{33}** → double	**1.14×10^{34}** → double	**2.40×10^{34}**	w Belle II
	5.55×10^{33}	1.23×10^{34}	1.88×10^{34}	-	w/o Belle II

Major works during summer shutdown

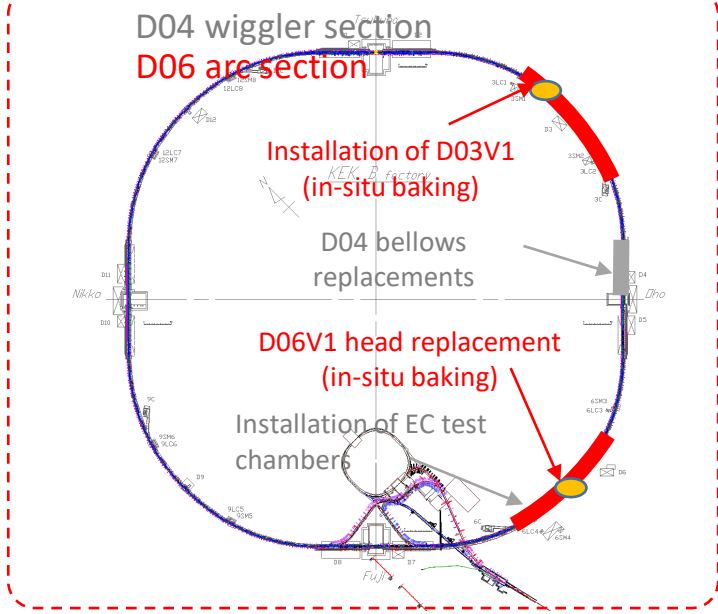
- Installation of new D03V1 collimator in LER
- Replacement of Tantalum jaws in D06V1 to Carbon jaws (Low-Z collimator)
- Installation of new skew-quadrupole (skew-Q) magnet in injection kicker section of LER
- Preparation and improvement of various beam tuning knobs to control rotatable sextupole magnets of LER
- Visual inspection of the inside of beam pipes of electron beam transport line.
- Others
  - Regular maintenance of various power supplies and components
  - Visual check of jaws in HER collimators
  - Removal of gate valves that may cause vacuum pressure spikes in HER
  - Installation of new bellows chambers with high SR-masks into Wiggler Sections in LER
  - Replacement of mirror of SR beam size monitor in HER
  - Etc.

Collimator works

- Installation of new D03V1 collimator in LER
  - In-situ baking was performed after installation to reduce the pressure.
  - Conventional Tantalum jaws are installed into D03V1 collimator.
- Replacement of Tantalum jaws in D06V1 to Carbon jaws (Low-Z collimator)
  - In-situ baking was performed after installation to reduce the pressure.
  - Removed Tantalum jaws were damaged during Phase-3 2020ab.
- Visual check of jaws in HER collimators (Reused KEKB collimators)
  - It was found that there are many damaged jaws, though it is unknown when they were damaged.



T. Ishibashi



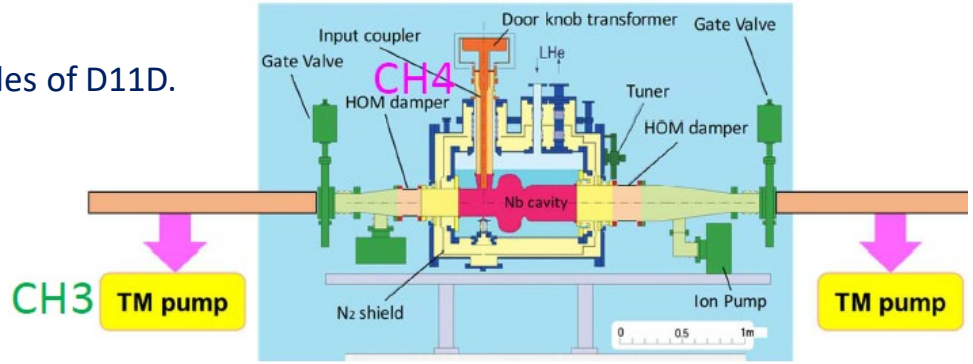
Installation of skew-Q magnet in LER

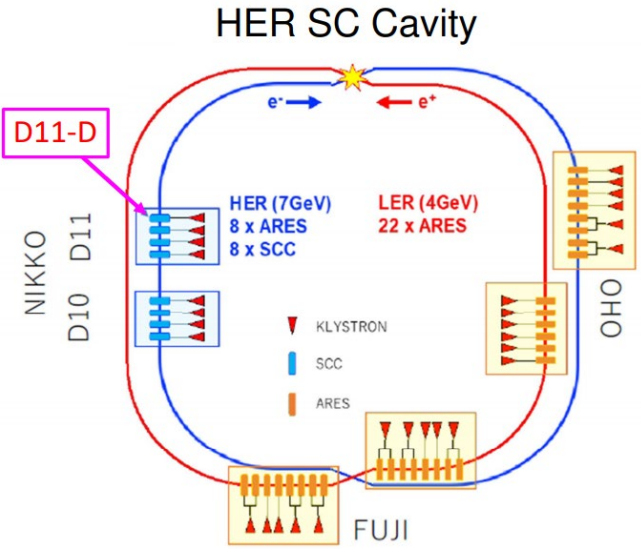
- Installation of new skew-quadrupole (skew-Q) magnet in injection kicker section of LER.
  - For correction of X-Y coupling due to Injections kickers.
  - Its effectiveness has been proven with permanent magnets during Phase-3 2020ab.
    - Improvement of injection efficiency
    - Reduction of injection BG duration
    - Suppression of luminosity drop during injection
    - etc.

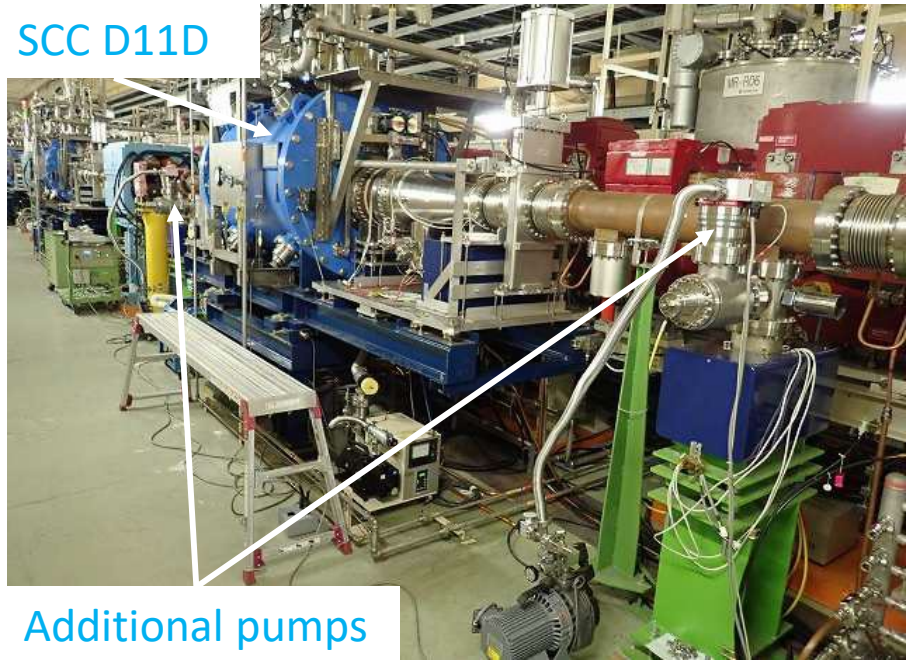
Skew-Q magnet
(trial model with permanent magnets)

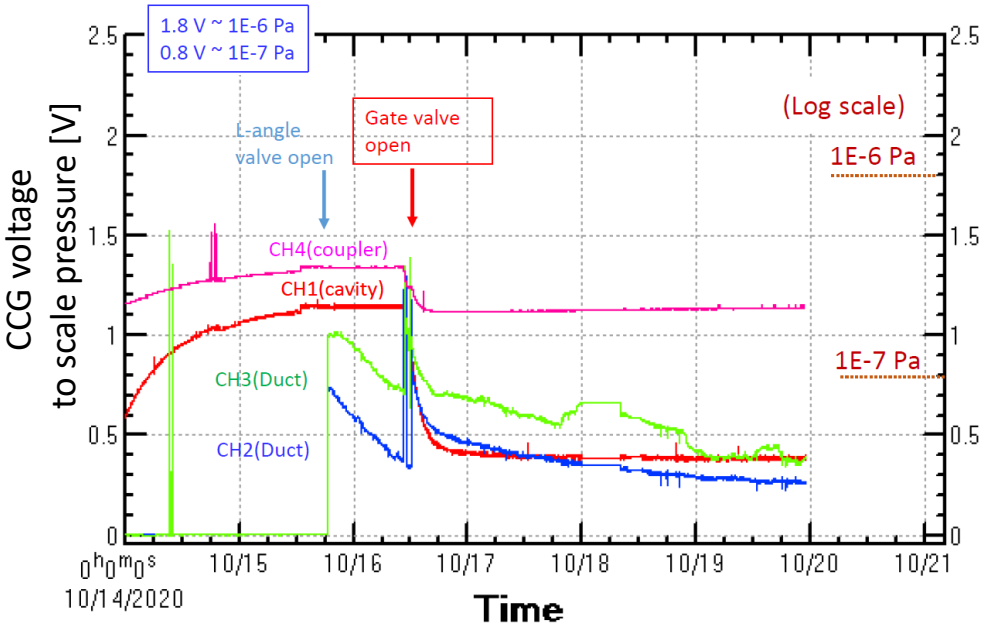
Superconducting cavity problem (HER)

- Abnormal high pressure was observed in Superconducting Cavity (SCC) D11D in HER immediately before 2020c run.
  - Small leakage was detected in D11D.
  - In order to reduce the pressure near D11D, two additional pumps were installed on both sides of D11D.
  - The pressure in D11D has been kept low enough to operate HER normally so far.
- It was decided not to use D11D for beam operation
  - D11D is detuned during 2020c operation.
  - Accelerating voltage is compensated by other SCCs.
  - D11D will be replaced with a spare cavity during this winter shutdown.



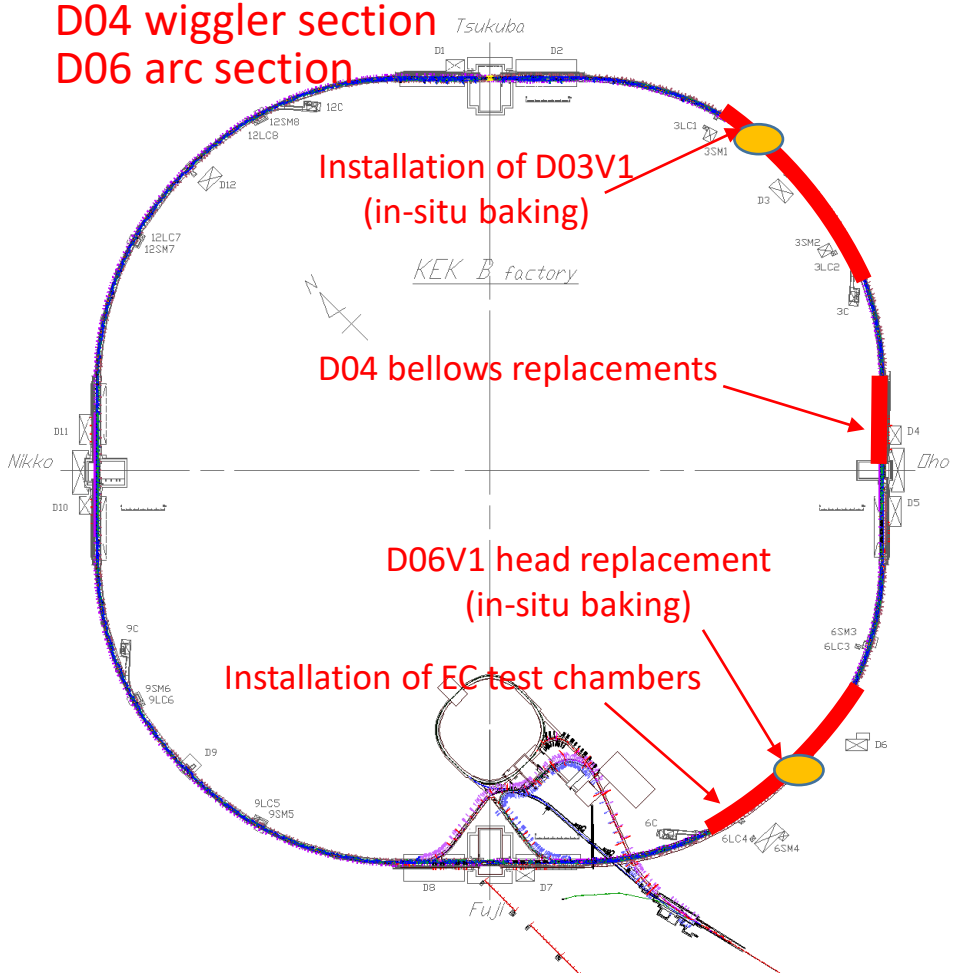




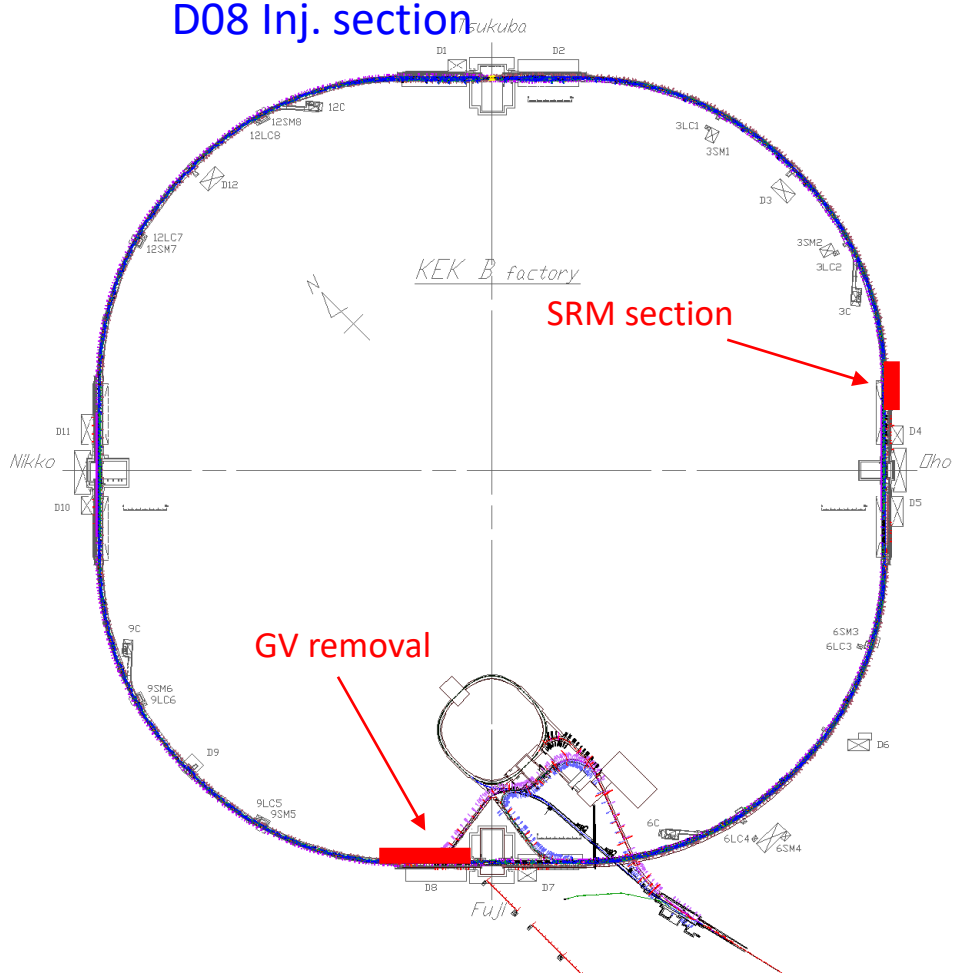


Vacuum work locations during summer shutdown

LER: D03 arc section
D04 wiggler section
D06 arc section

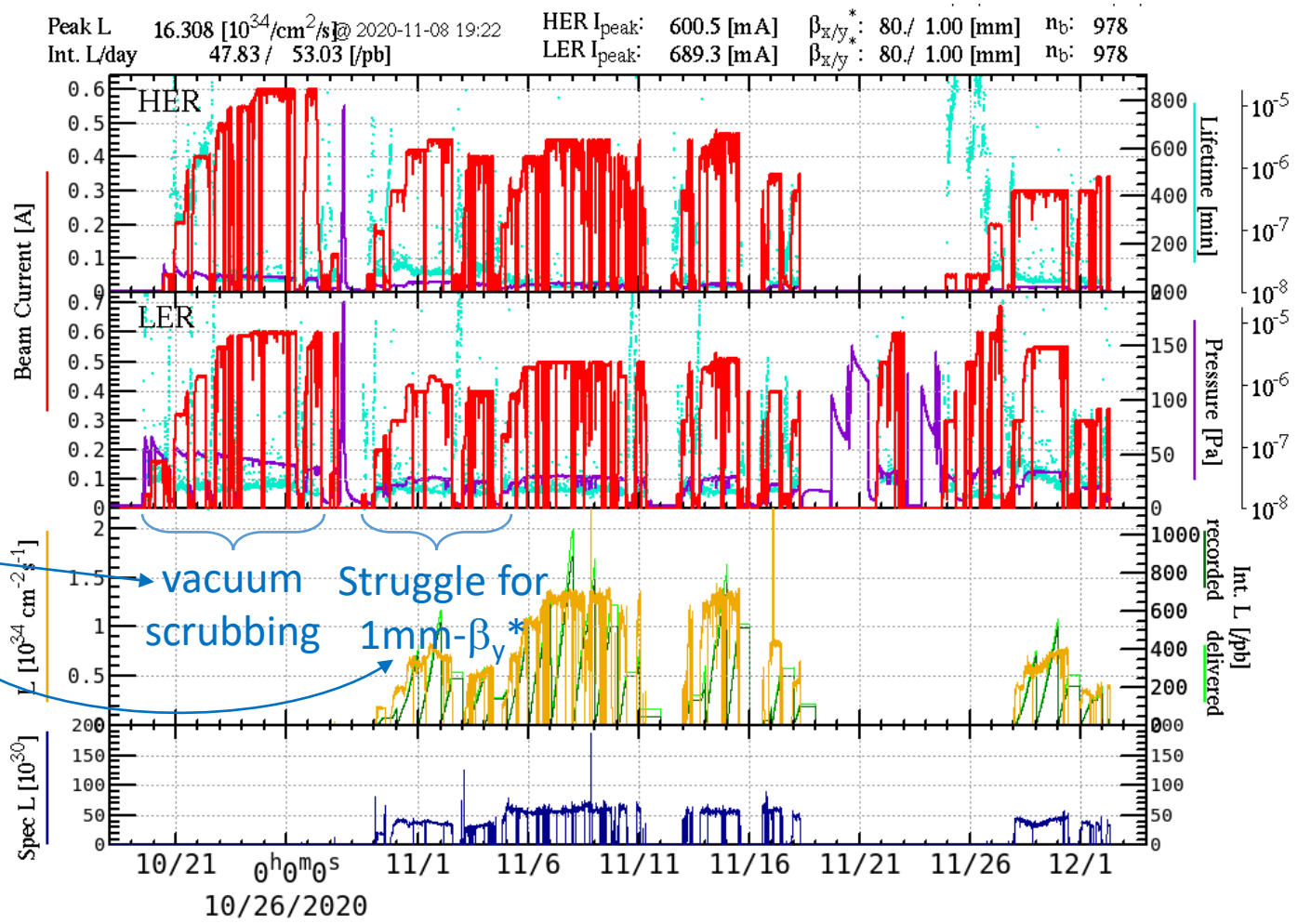


HER: D04 SRM section
D08 Inj. section



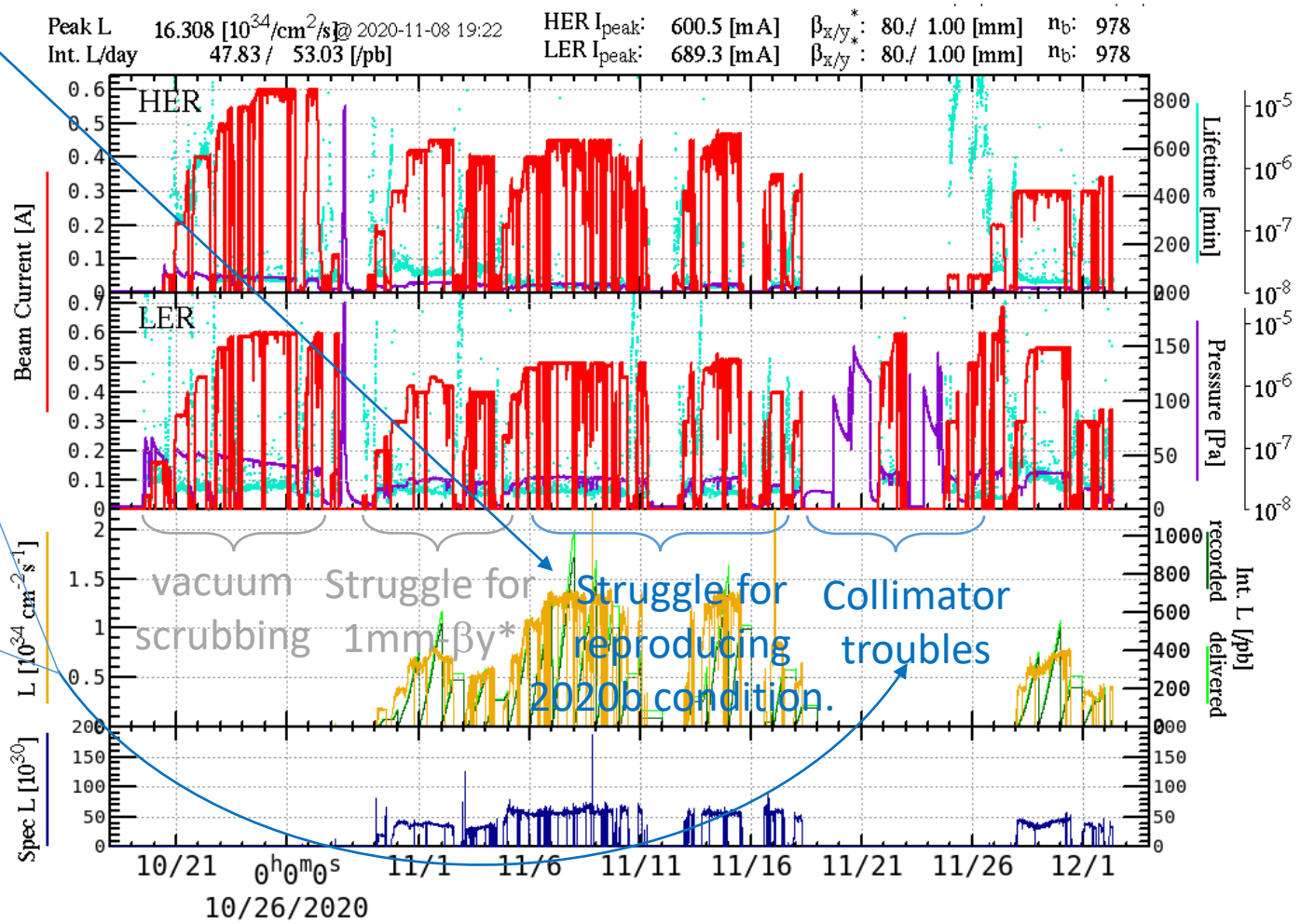
Phase-3 2020c run

- Main missions of Phase-3 2020c run;
  - Physics run toward more than 40 fb^{-1} (only in 2020c)
  - Challenge to Peak Lumi. of ~4×10^{34} $cm^{-2} \cdot s^{-1}$
    - Doubling luminosity world record
    - With beam currents of 0.75 – 1 A
    - Beta squeezing : $\beta_{x/y}^{*}$ = 60/0.6 mm
- Overview of 2020c run (until 3/Dec.);
  - Operation time : 60 days (19/Oct. - 18/Dec.)
  - Vacuum scrubbing : 19/Oct. - 27/Oct.
  - Struggle to squeeze β_y^* to 1 mm
    - It took approximately two weeks until we could squeeze HER β_y^* back to 1 mm.
    - Finally we succeeded in resuming the best optics of 2020b…
      - HER β_y^* = 1 mm, β_x^* = 80 mm, Crab-waist 40 %
      - LER β_y^* = 1 mm, β_x^* = 60 mm , Crab-waist 60 %



Phase-3 2020c run (cont'd)

- Overview of 2020c run (until 3/Dec.);
  - Struggle to reproduce the machine condition of 2020b
    - Unstable electron beam from Linac and BT made injection&collision tunings very difficult.
  - Damage of collimator jaws (LER D02V1)
    - Jaws of LER collimator D02V1 were heavily damaged on 15th Nov.
    - Replacement work of damaged jaws (2days)
    - Vacuum scrubbing
  - Vacuum leakage at D02V1
    - Replacement work of leaking flange
    - Vacuum scrubbing (2 days)
  - Re-start of Physics Run from 27th Nov.
    - Struggle to reproduce the machine condition of 2020b.



Luminosity performance

Y. Ohnish

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Peak Luminosity ($cm^{-2}s^{-1}$)	**2.62×10^{33}** → **5.50×10^{33}** → **1.14×10^{34}** → **2.40×10^{34}** double double double				**4×10^{34}**	w Belle II
	5.55×10^{33}	1.23×10^{34}	1.88×10^{34}	-	-	w/o Belle II

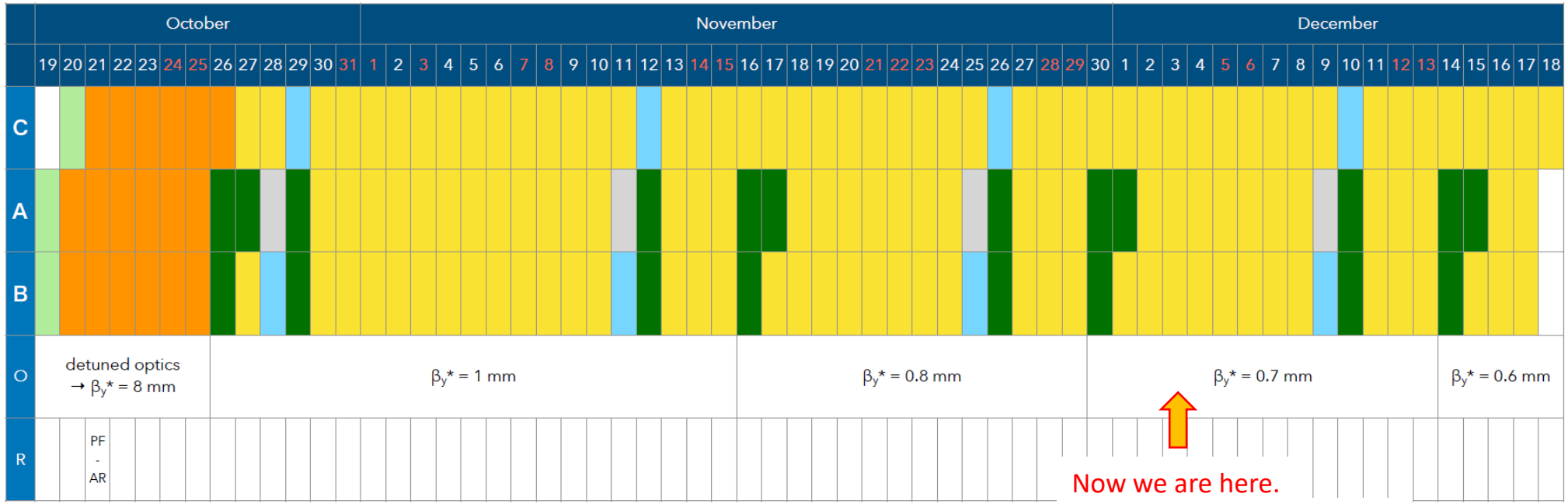
- Target stability of machine performance : 1.5 fb^{-1}/day

Operation plan of Phase3 2020c

Y. Ohnish

Tentative Plan for 2020c

total: 60 days, 120 shifts



Now we are here.
(β_y^* is still 1 mm...)

- maintenance
- Linac/BT study
- Start up MR
- Vacuum scrubbing, Machine tuning etc.
- Machine tuning, Machine study.
- Physics run

Physics run can be changed to machine tuning or machine study.

Linac/BT operation: 9/28 - 12/22

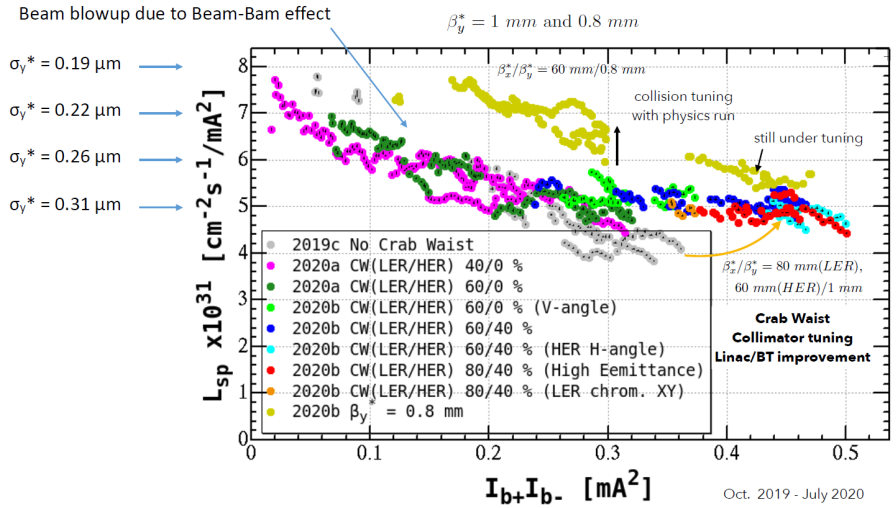
Don't stop DR/BT hardwares just after MR operation !

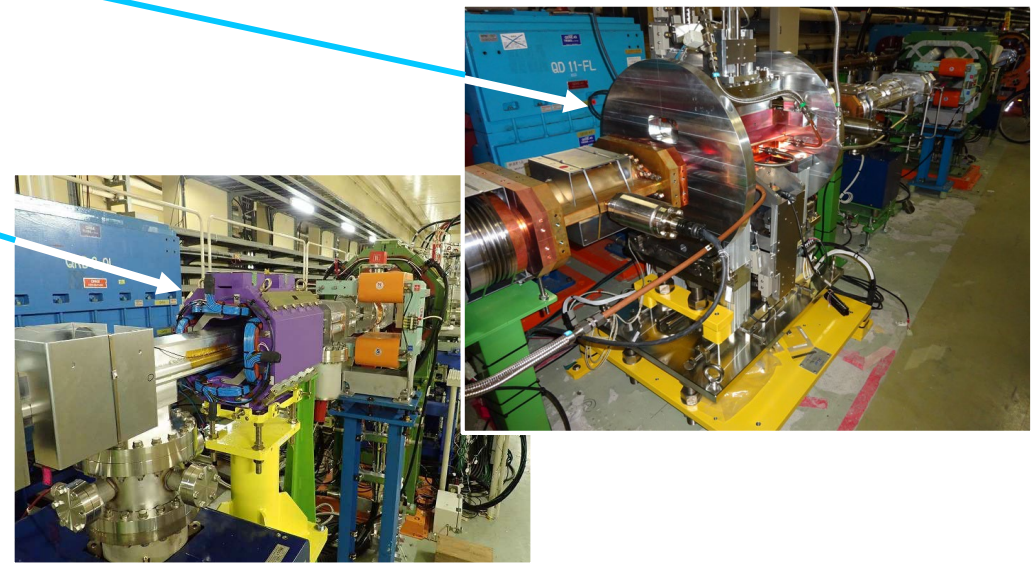
Y. Ohnishi, Oct. 16, 2020

4

Challenges in 2020c

- Raising peak luminosity
  - Further β_y^* squeezing down to 0.6 mm
  - Collision tuning to suppress beam-beam blow-up at high bunch current products
  - Raising beam current
- Reduction of background noise to Belle II detector
  - New vertical collimator D03V1 in LER
  - New carbon jaws of D06V1 (low-Z collimator) in LER
- Suppression of X-Y coupling at injection kicker section of LER
  - New skew-Q magnet at injection kicker section
- Extension of very short beam lifetime
- Overcoming difficulties in correction of beam optics
- Maintaining aged hardware including buildings
- Etc.





Major Challenges found in 2020c

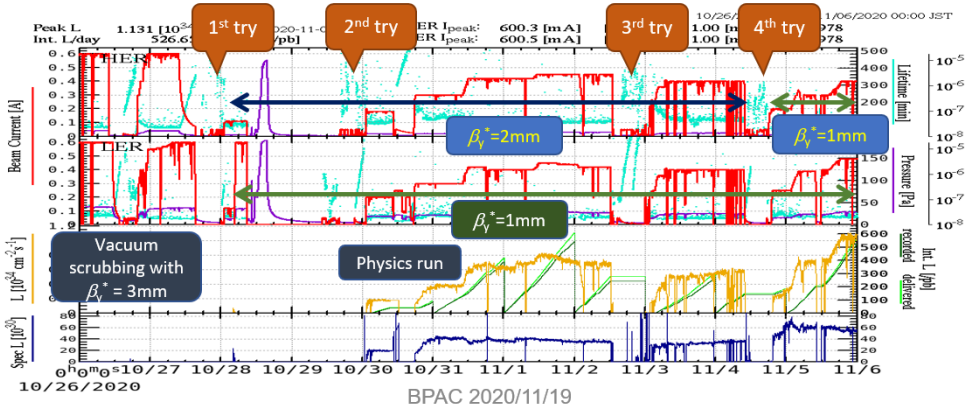
- Difficulty in reproducing the machine condition of 2020b run
- Poor injection rate of electron beam

Y. Suetsugu

Major challenges in 2020c (MR)

(1) Difficulty in resuming the machine condition to that of 2020b.

- It took approximately two weeks until we could squeeze HER β_y^* to 1 mm, at the fourth try.
  - Physics run with β_y^* = 2 mm for HER until then.
- Heavy beam losses during optics correction were observed.
  - Narrow physical or/and dynamic apertures?
- Finally succeeded by elaborate optics corrections, by opening a horizontal collimator, and so on. But the reason of this difficulty is not so clear, and should be clarified.
  - The problem might be related to the next one.



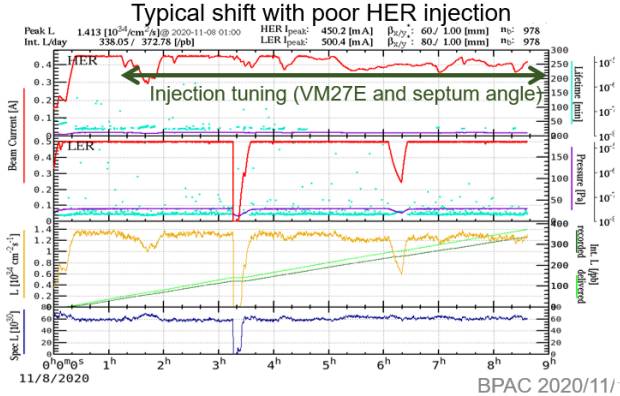
Y. Suetsugu

Major challenges in 2020c (MR)

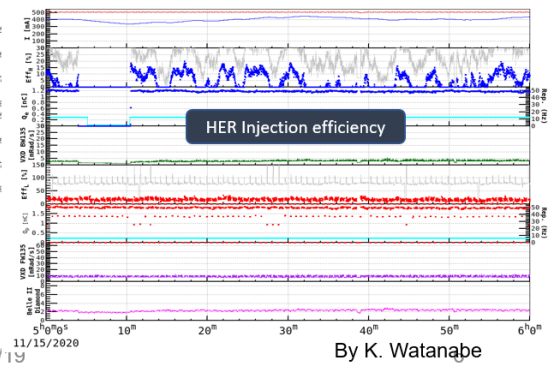
(2) Poor injection rate of electron beam

- Unstable electron beam from Linac and BT makes difficult the injection tuning and also machine tuning.
  - For example, periodical horizontal/vertical orbit changes (approximately 7 min. interval), and time variation of energy spread.
- Small physical or/and dynamic aperture in the ring?
  - Narrow parameter ranges for good injection rate.
  - Short beam lifetime
- HER beam current was limited by the injection rate.
- High bunch-current study was also hardly possible.

Typical shift with poor HER injection



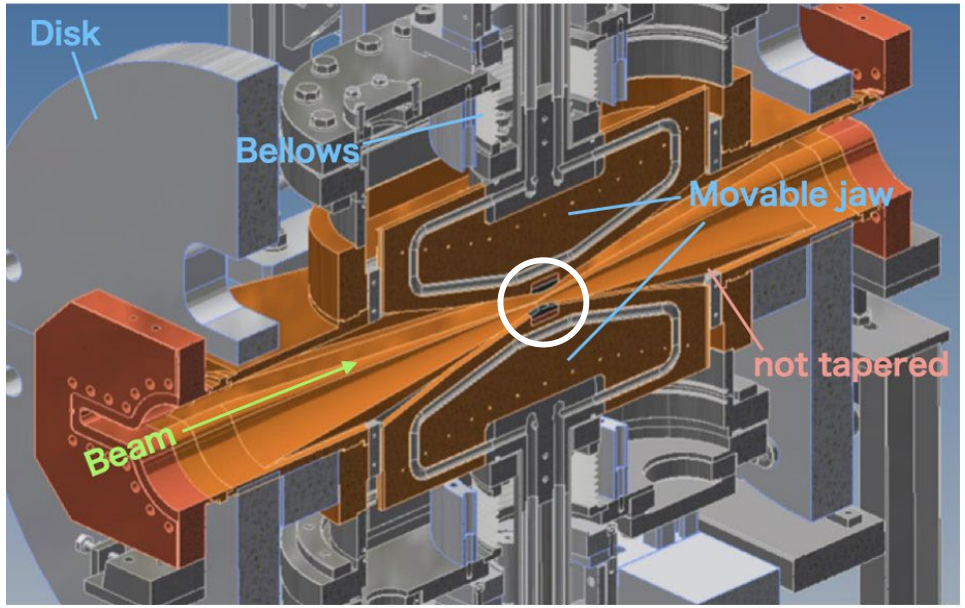
Typical trend of HER injection rate (one hour)



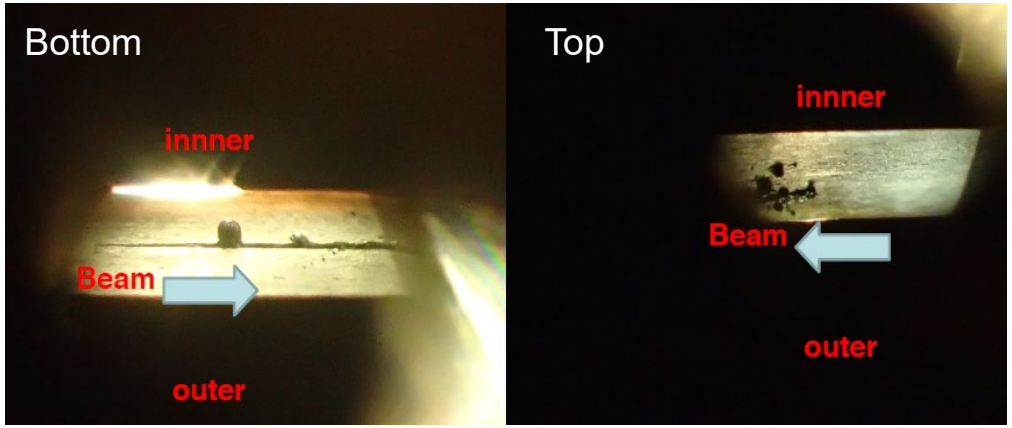
By K. Watanabe

LER collimator trouble

- Damage and vacuum leakage of LER collimator (D02V1)
  - D02V1 jaws were heavily damaged on 15th Nov.
    - At the same timing, final focusing superconducting magnet QC1RP was quenched due to strayed beams.
    - Cause of this trouble is unknown.
      - So-called “dust problem”?
  - New D06V1 collimator (Low-Z collimator) could not protect D02V1.
    - D06V1 was installed at the place where the betatron phase is aligned to that at D02V1 to protect it from crazy beams.
    - Reason why D06V1 did not work as expected is unknown.
      - D06V1 center position may have been off BPM center?
      - Dust event may have occurred between D06V1 and D02V1?



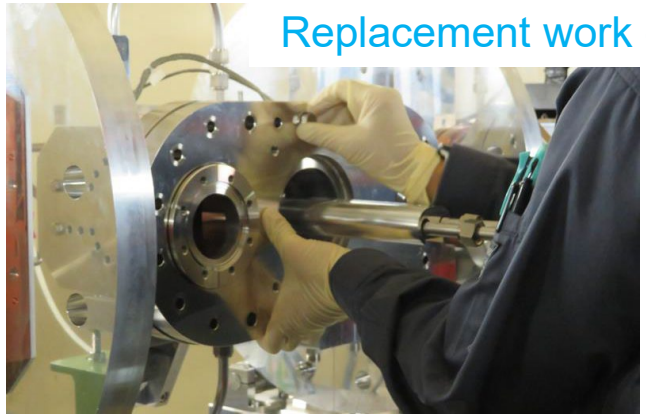
T. Ishibashi and S. Terui

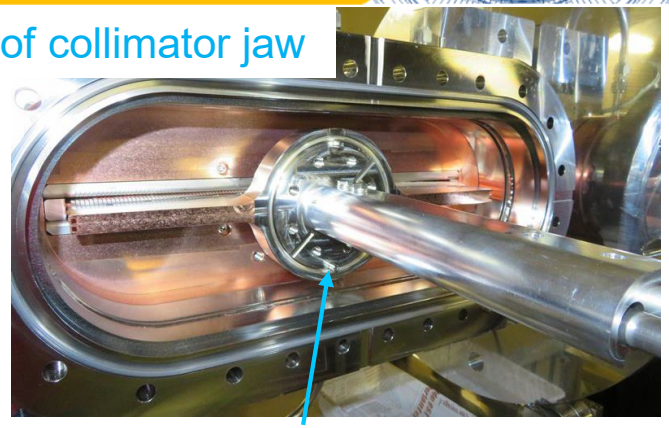


LER collimator trouble (cont'd)

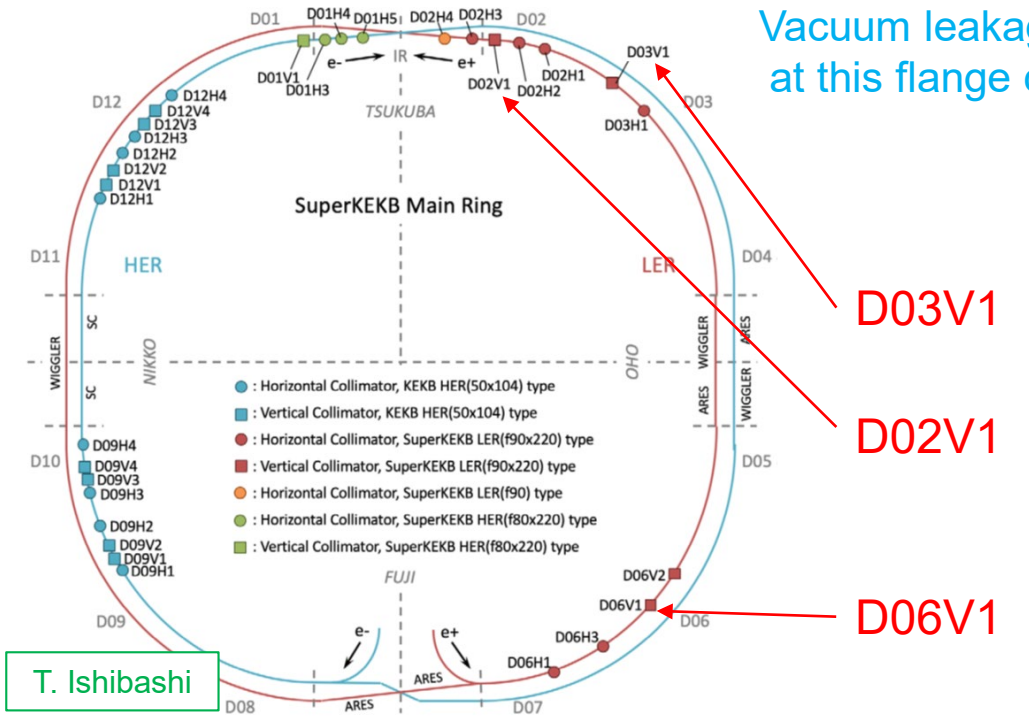
- Damage and vacuum leakage of LER collimator (D02V1)
  - Damaged jaws was replaced with spears.
    - Vacuum leakage occurred at the connection flange of bottom jaw after replacement work.
    - It took more than 1 week to complete all works.
    - Work period was effectively utilized to investigate various urgent issues of electron beam in Linac and BT lines.
  - Physics run re-stared on 27th Nov.
    - We will try new optics where the betatron phases at D03V1 and D06V1 are aligned to that at D02V1 to protect D02V1 jaws.
    - Offset of vertical collimator centers with respect to BPM centers will be checked by beam.

Replacement work of collimator jaw





Vacuum leakage occurred at this flange connection.



D03V1

D02V1

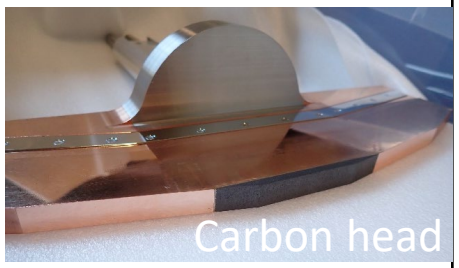
D06V1

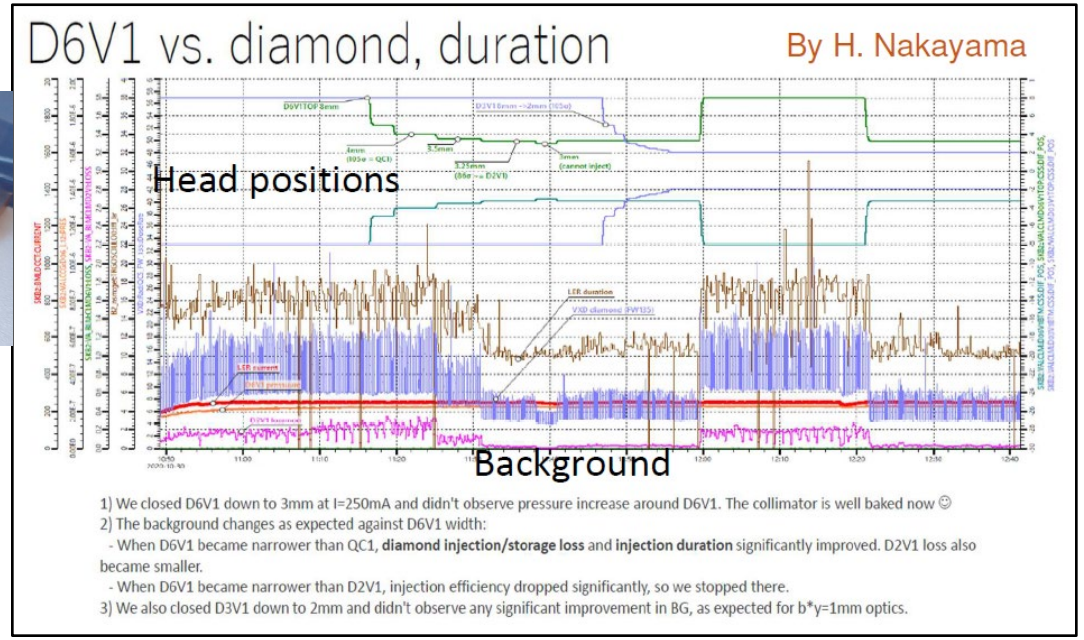
T. Ishibashi

Machine studies

News flash of recent machine studies

1. Carbon-head (Low-Z) collimator D06V1 in LER
   - It was confirmed that low-Z collimator worked well to suppress BG.

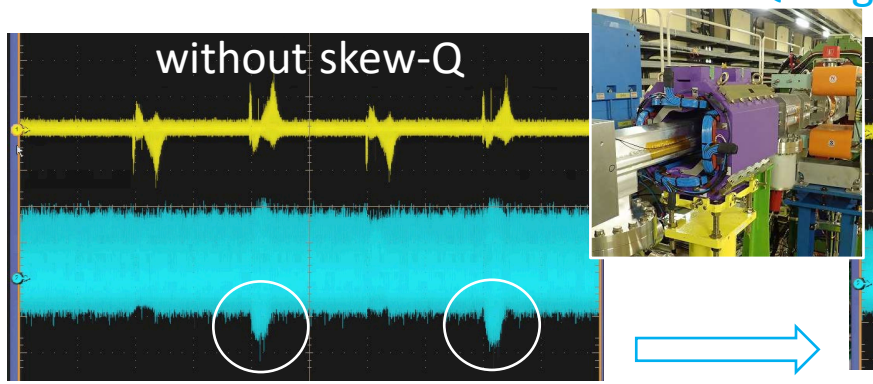




2. Skew-Q magnet at injection section in LER
   - It was confirmed that new skew-Q magnet installed at injection section of LER worked well to suppress X-Y coupling of injected beam.
   - BG due to injected beams were reduced.
   - BG duration was also reduced.

New skew-Q magnet

S. Terui



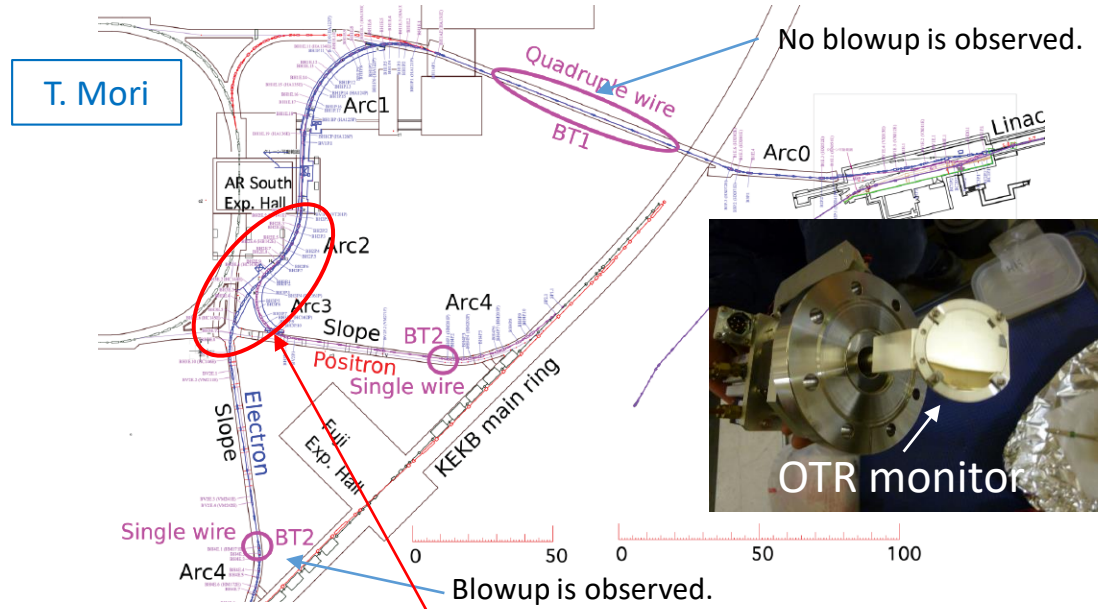
Vertical oscillation of injected beam was well suppressed.

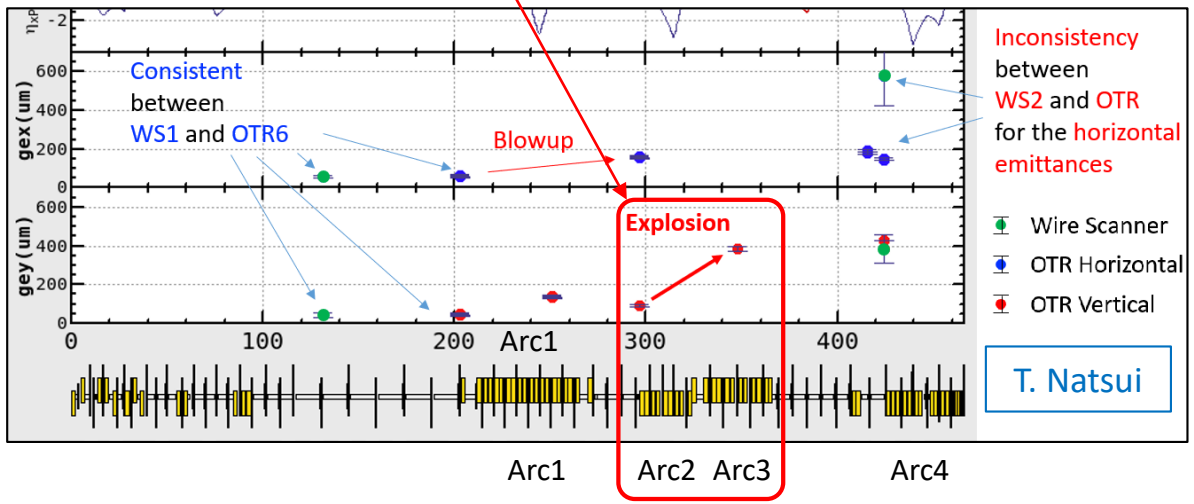
Machine studies (cont'd)

Emittance blowup (explosion) in electron beam transport line (BTe)

- Emittance blowup has been observed at exit of BTe.
  - Cause and precise location of emittance blowup are unknown.
  - Only wire scanners at entrance and exit of BTe could measure emittance.
- Emittance blowup is one of top-priority issues that must be solved.
  - Low emittance injection beam can increase injection efficiency and luminosity.
- There has been some progress in emittance blowup investigation.
  - Visual inspection of the inside of beam pipes was done during last summer shutdown.
    - We found nothing that can be the cause of emittance blowup.
  - Some fluorescent (Al_2O_3) screen monitors were replaced with OTR monitors during last summer shutdown.
    - OTR : Optical Transition Radiation
    - Conventional fluorescent screen monitor do not allow precise emittance measurement, but OTR monitor do.
  - Collimator-work period was effectively utilized to investigate emittance blowup.
    - Blowup location was narrowed down to around Arc2 and Arc3.

T. Mori





T. Natsui

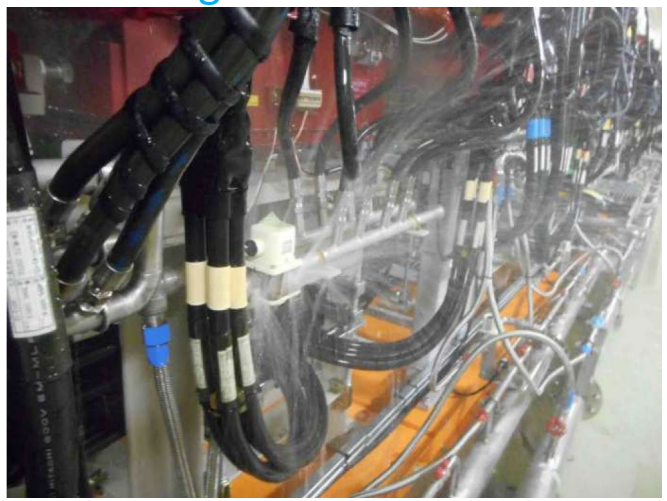
Maintaining aged hardware

- Anti-aging measures for old components and facilities are indispensable for stable operation of SuperKEKB.
  - Potential risk of long-term failure increases rapidly.
  - Budget for beam operation will have to be allocated to maintenance costs.
  - This is not a problem just for this term, but a long-term problem.

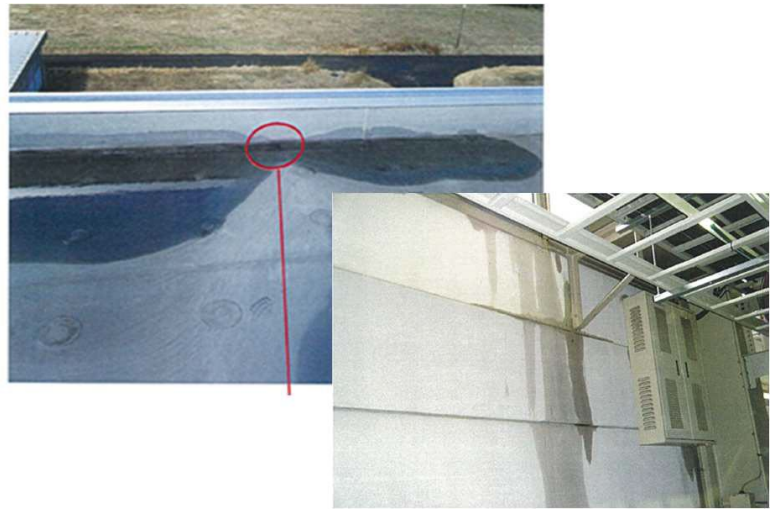
Examples of aging:

Erosion of Klystron cooling towers

Water leakage from old flow sensors



Leakage of roof of power supply buildings



Others: Frequent failures of old power supplies for magnets
Heat up of power supply building due to poor thermal barrier
etc.

Long-term plan

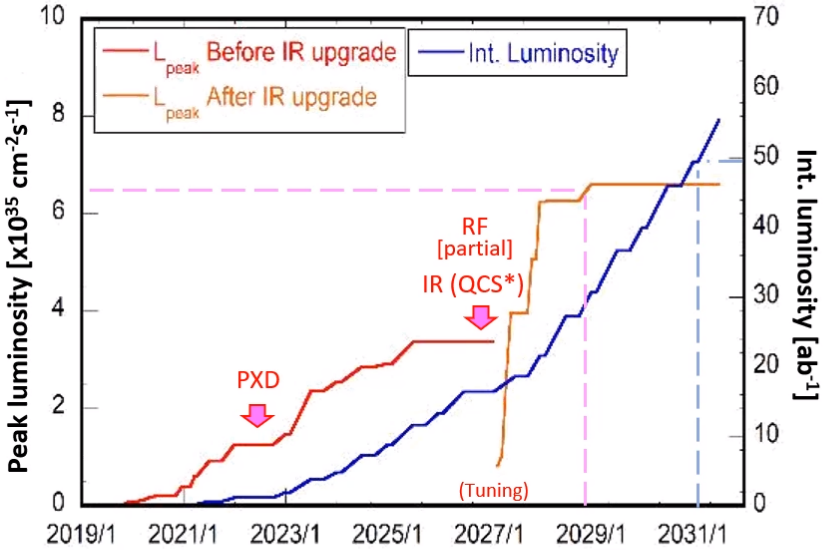
- Plan proposed for MEXT Roadmap2020

  MEXT : Ministry of Education, Culture, Sports, Science and Technology
  - Based on results obtained so far and expected budged.
  - QCS upgrade is newly proposed.
- New goals:
  - Integrated luminosity : 50 ab^{-1} around 2030
  - Peak luminosity : ~6×10^{35} $cm^{-2} \cdot s^{-1}$
  - β_y^* squeezing: 0.5 mm before IR upgrade, 0.3 mm after that
  - Beam currents (LER/HER): ~2.5A/~1.8A before RF upgrade ~2.9A/~2.1A after that
- Required investment in equipment
  - IR upgrade(QCS, its beam pipes, etc.)
  - Partial RF-power upgrade (2 stations)
  - Beam collimator upgrade
  - Linac upgrade
  - Belle II upgrade

Y. Suetsugu

Update of operation plan and its reasons

- Updated plan
  - Proposed in Roadmap 2020



*QCS:
Superconducting final focusing quadrupole magnet

- Peak luminosity ~6E35 $cm^{-2}s^{-1}$ in ~2028
- Integrated luminosity 50 ab^{-1} in ~2030 (40 ab^{-1} in ~2029)
- PXD exchange in 2021~2022
- Partial RF-power upgrade (2 stations) in 2026
- IR (QCS and its beam pipes etc.) upgrade in 2026
- β_y^*=0.3 mm in 2026 after IR upgrade, and ~0.5 mm before that
- Max. beam currents: LER 2.8 A, HER 2.0 A (1761 bunches) in 2027
- Basically, 8 months operation per year.

[Investment in equipment]
- IR (QCS and its beam pipes etc.)
- Partial RF-power upgrade (2 stations)
- Beam collimator upgrade
- Linac upgrade
- Belle II upgrade

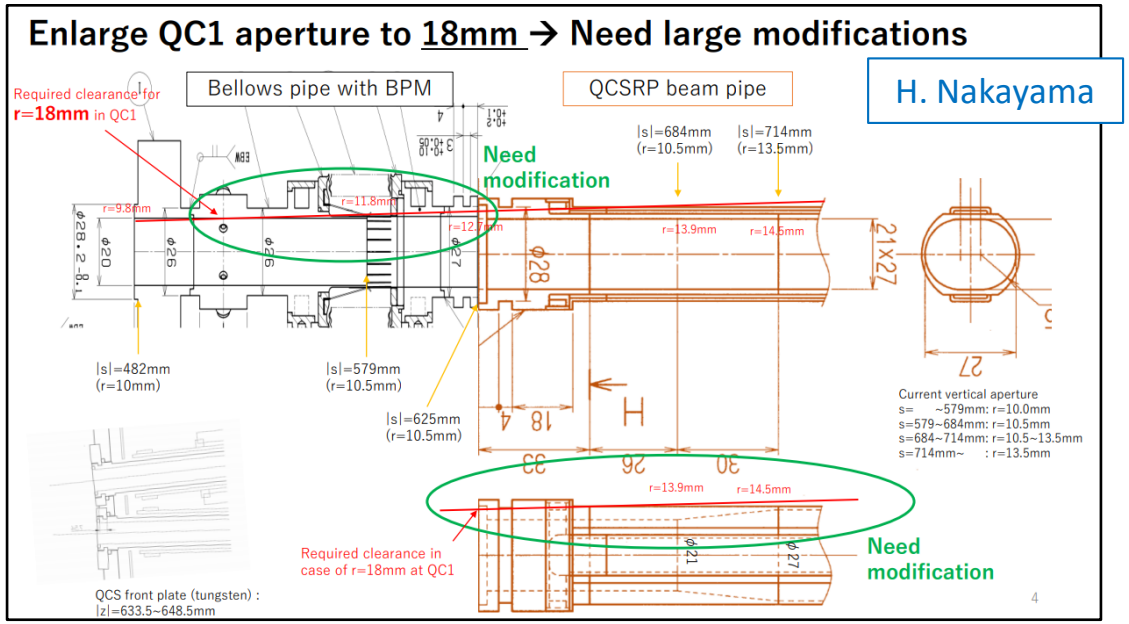
2020/6/29 BPAC 2020 0629 21

IR upgrade plan

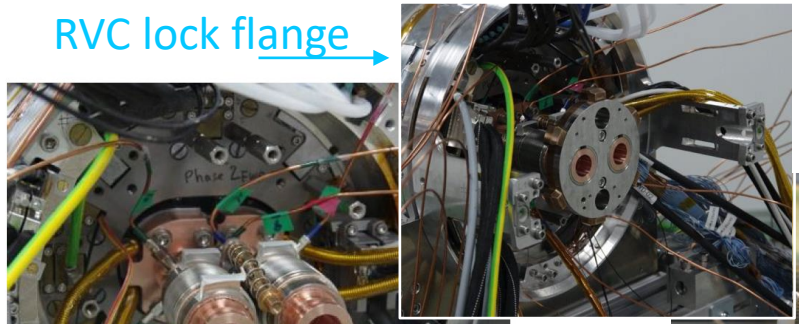
- Motivation
  - Strong beam-beam effects in high bunch current region
    - Resent studies indicate that one promising countermeasure is modification of QCS to avoid interference between its magnetic field and Belle II solenoid field for LER.
  - Narrow physical aperture in QCS beam pipes
    - QCS quenches caused by unstable beam hits have been observed.
    - If we squeeze βy^* to less than 0.5 mm, it will be difficult to protect QCS by using collimators.
  - Large background noise from QCS beam pipes
    - At present, background in Belle II is larger than expected.
    - One of main background sources is hit of beam halo on the QCS beam pipes.
    - Background will become larger as βy^* is further squeezed.

→ Modification of QCS magnets and QCS beam pipes with large aperture are required.

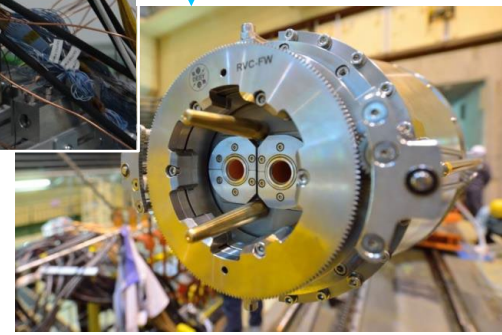
- Accelerator Review Committee requested an investigation into the feasibility and effectiveness of IR upgrade plan before making final decision. (within ~2 years)
- Design works of new QCS and its beams pipes started, and they are ongoing now.
- IP bellows, RVC lock flanges and QCSR front plate should be modified too.



RVC lock flange



QCS beam pipes (front end)



Beam energy

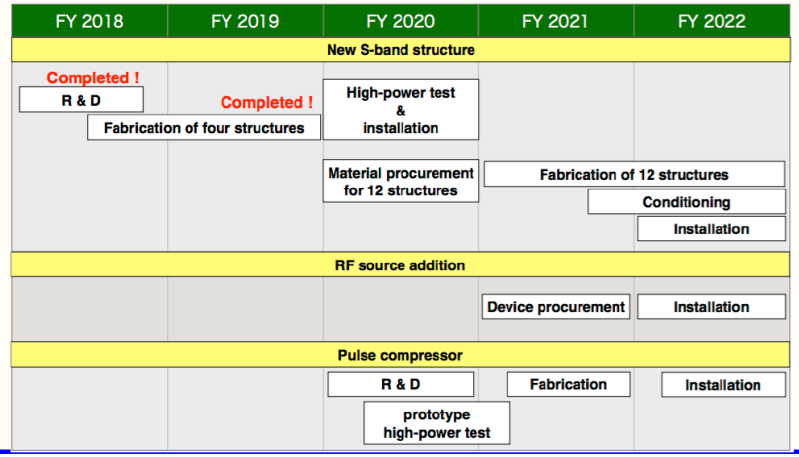
- Linac upgrade toward $\Upsilon(6S)$ is ongoing now.
  - Physics run at $\Upsilon(6S)$ will be possible after 2023 winter shutdown.

New accelerator structure

Higher energy injection and collision

K. Furukawa

- Mitigation of accelerator structure failures
  - Originally designed for 8 MeV/m, but used at 20 MeV/m
  - Degradation that lead to high field emission rate and discharges
  - Water leaks
  - Not only Y(6S) but even Y(4S) could be suffered
- 4-year plan to fabricate and install new accelerator structures



Energy

K. Furukawa

- Recent effort to optimize parameters
  - 10.753 + 0.023/2 GeV could be possible with backups
    - e+ : 4.071 GeV, e- : 7.124 GeV
    - with 2 nC/bunch
- After structure upgrade in 2023 winter
  - 6S : 11.020 GeV could be reached with backups
    - e+ : 4.165 GeV, e- : 7.289 GeV
    - with 2-3 nC/bunch
- BT limit
  - e+ : 4.290 GeV, e- : 8.465 GeV (both coil heating limit)
- MR
  - No discussion yet, while included in the design
  - Easier with Belle II solenoid scaled
  - Otherwise, …

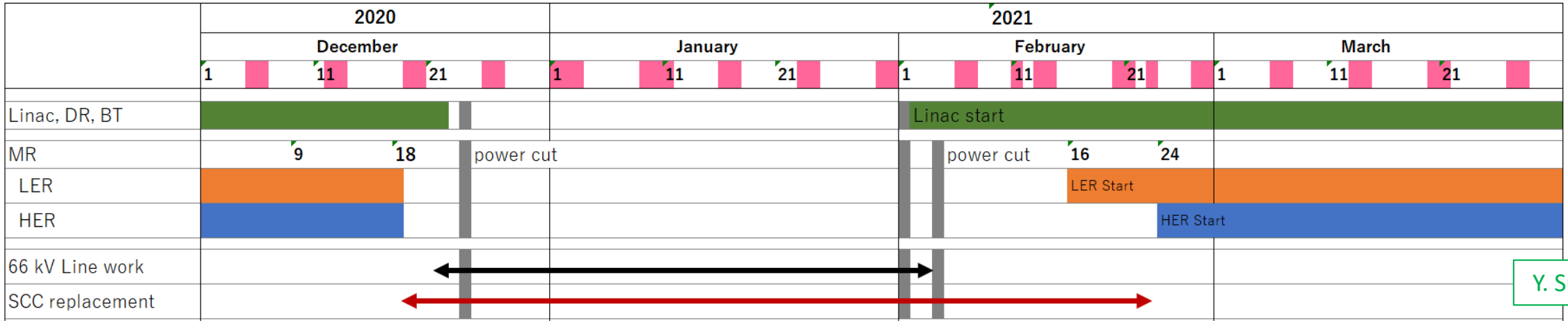
2021a operation plan

- Winter shutdown
  - From 18/Dec./2020 to 16/Feb./2021
  - Replacement of SCC D11D
  - Replacement of 66 kV high-voltage power supply lines
- 2021a run
  - From 16/Feb. to 31/Mar.
    - Operation cost will be covered with an extra budget from Director.
  - LER operation will start on 16/Feb.
  - HER operation will start on ~24/Feb.
    - It depends on D11D replacement work.

- By the end of March 2021
  - Operation time of this JFY (Apr. 2020 –Mar. 2021) will be ~6.5 months.
  - Toward more than 240 fb^{-1} in total
  - Target peak lumi. : ~6.5 × 10^{34} $cm^{-2}·s^{-1}$
    - Beam currents : ~ 0.9 A
    - Beta squeezing : $\beta_{x/y}^{*}$ = 60/0.6 mm

	Parameters			
	Int. L [fb^{-1}]	L_p [E34]	I_{max} [A] (ave.)	β_y^* [mm]
Base plan until 2020c	~110	~4	0.74	0.6
Base plan until 2021a (Depend on operation time)	240~140	6.5~4.5	0.9~0.75	0.6

SuperKEKB 2020c&2021a Operation Plan



Y. Suetsugu

JFY2021 run plan

- JFY2021 budget request process is ongoing.
- MEXT has asked to align JFY2021 budget request to the plan submitted for the MEXT Roadmap2020.
  - 5.7 months of operation in JFY2021
  - Taking account of long shutdown for PXD replacement from Jan. 2022.

JFY: Japanese Fiscal Year, from April to March of next year.
MEXT : Ministry of Education, Culture, Sports, Science and Technology

	2020									2021			
FY2020	4	5	6	7	8	9	10	11	12	1	2	3	Y. Suetsugu
Present plan (20th Oct.)		2020b						2020c				2021a	Total ~6.5M/y
		~3M						~2M				~1.5M	
	2021									2022			
FY2021 preliminary	4	5	6	7	8	9	10	11	12	1	2	3	
Original plan (not fixed) [MEXT Road Map]	4/1	2021b		7/1			10/4	2021c	12/24		PXD exchange		Total ~5.7M/y
		~3M						~2.7M					

Summary

- 2020c run
  - From 19/Oct. to 18/Dec.
  - We are having a very hard time to reproduce the machine condition of 2020b.
  - LER collimator jaws (D02V1) were damaged and replaced with spears.
  - Physics run with β_y^* = 1 mm has been resumed.
- 2020 winter shutdown
  - SCC D11D will be replaced with a spare cavity.
- 2021a run
  - From 16/Feb. to 31/Mar.
  - Target peak luminosity : ~6.5×10^{34} $cm^{-2} \cdot s^{-1}$
    - Beam currents : ~ 0.9 A
    - Beta squeezing : $\beta_{x/y}^*$ = 60/0.6 mm
- Long-term plan proposed for MEXT Roadmap2020
  - New luminosity targets :
    - Integrated luminosity : 50 ab^{-1} around 2030
    - Peak luminosity : ~6×10^{35} $cm^{-2} \cdot s^{-1}$
  - IR upgrade & Partial RF-power upgrade are required.
  - JFY2021 budget request process is ongoing.

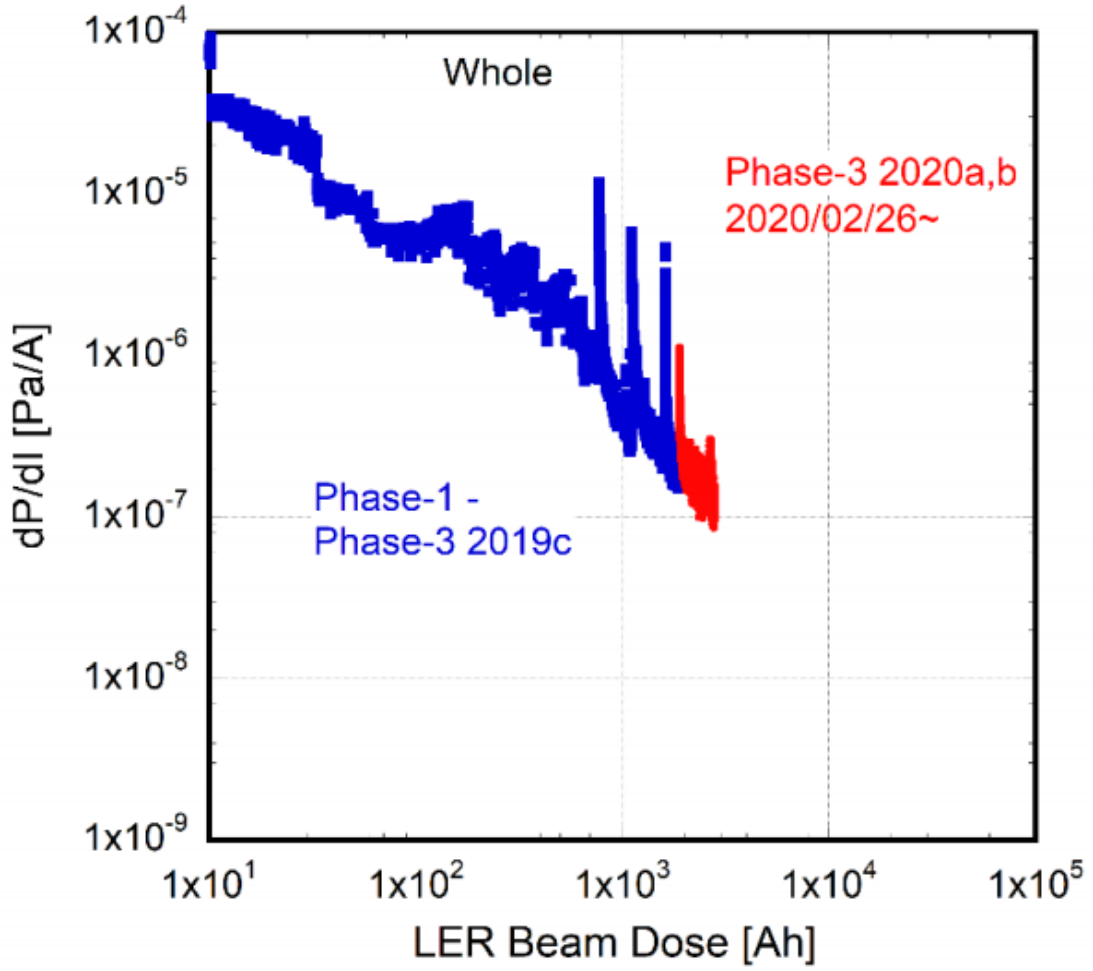
Fin.

Thank you for your attention.

Backup

Vacuum scrubbing since Phase1

LER



HER

Y. Suetsugu