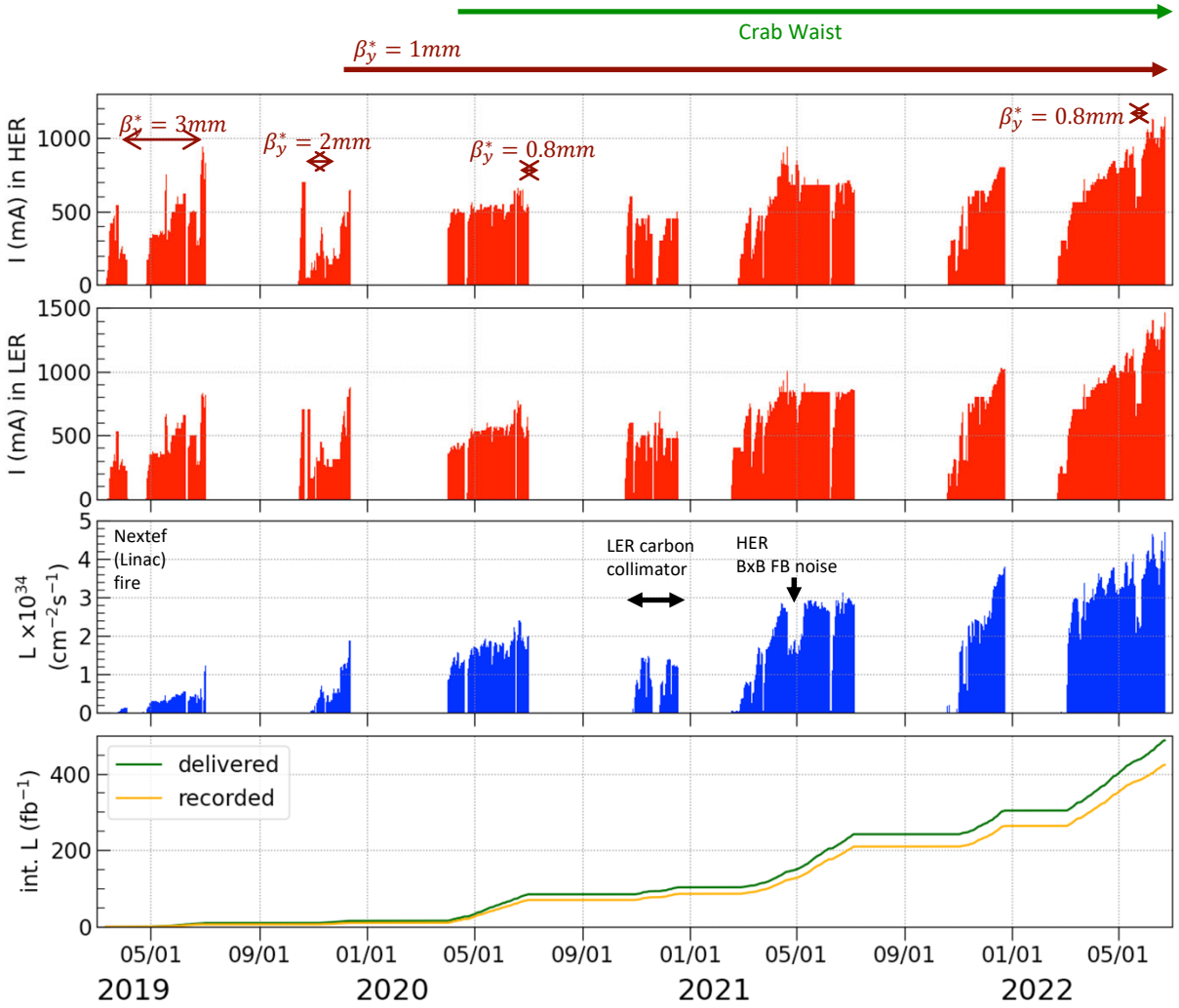
Status of SuperKEKB Accelerators

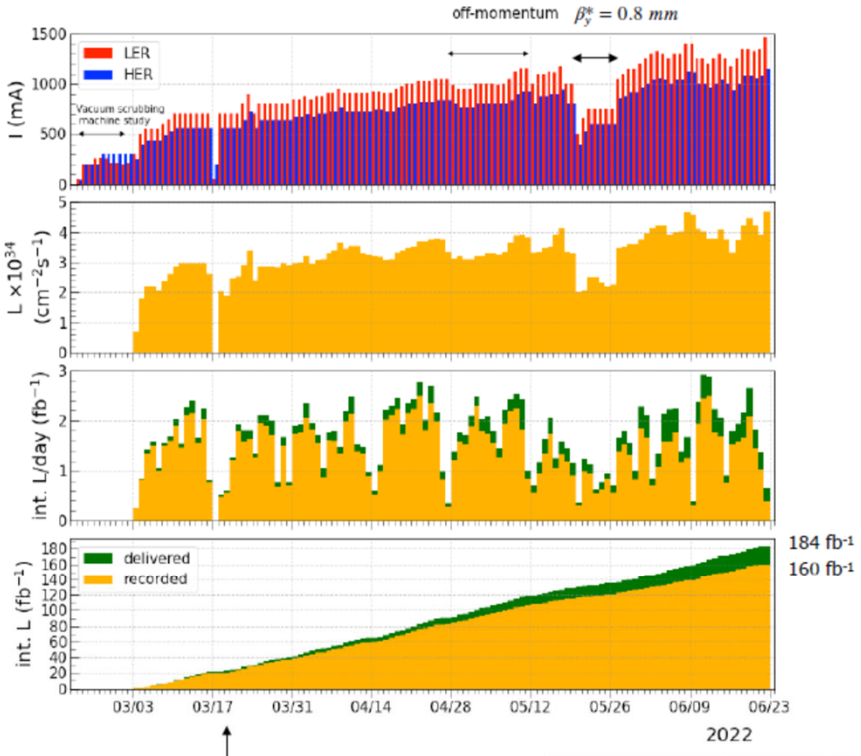
Makoto Tobiyama（KEK Accelerator Laboratory） for SuperKEKB Accelerator Team

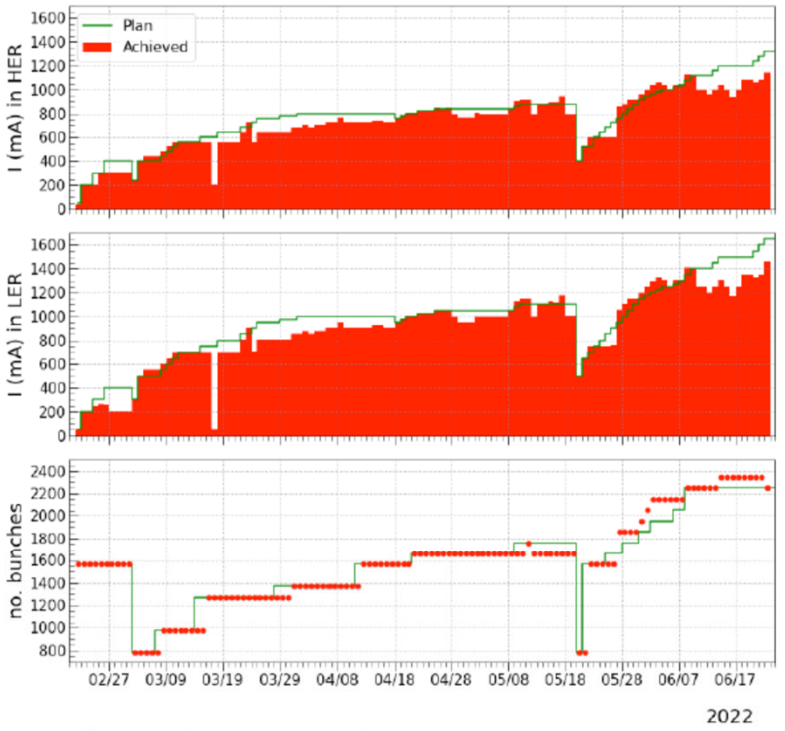
Recent Operation(JFY2022)

SuperKEKB Operation History



2022ab Run





Integrated luminosity	Recorded	Date	Delivered	Date
Shift (pb^{-1})	958.1	April 24, swing, 2022	1035.9	April 22, swing, 2022
1 days (fb^{-1})	2.503	April 22, 2022	2.912	June 11, 2022
7 days (fb^{-1})	15.001	April 18 - April 24, 2022	16.599	April 18 - April 24, 2022

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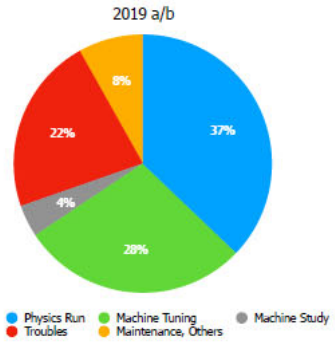
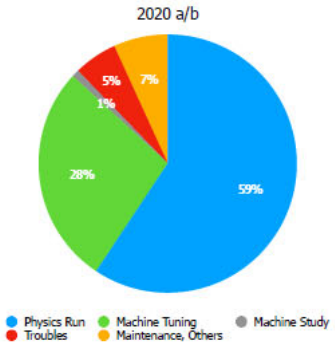
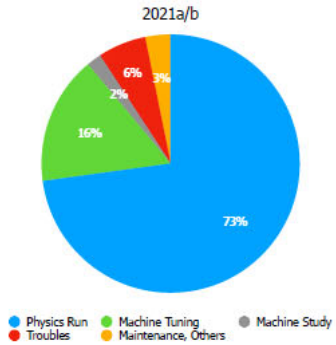
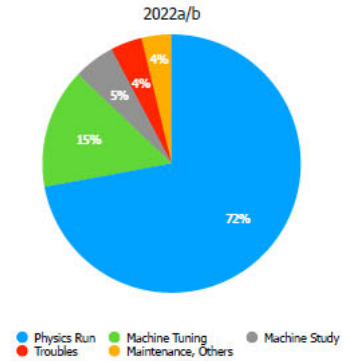
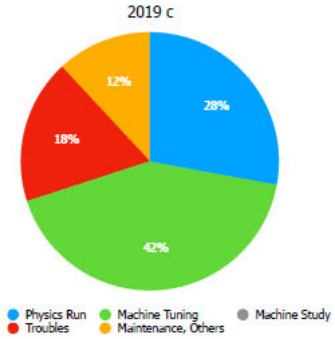
Operation Statistics

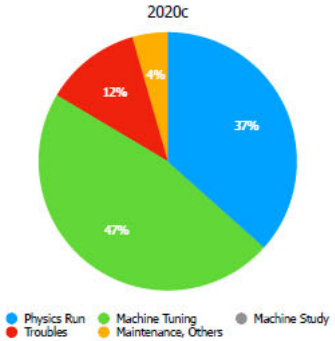


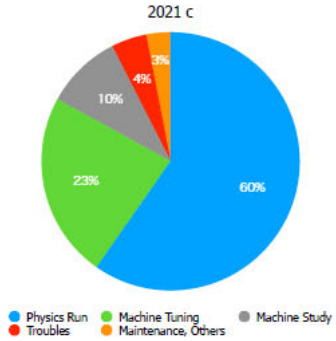










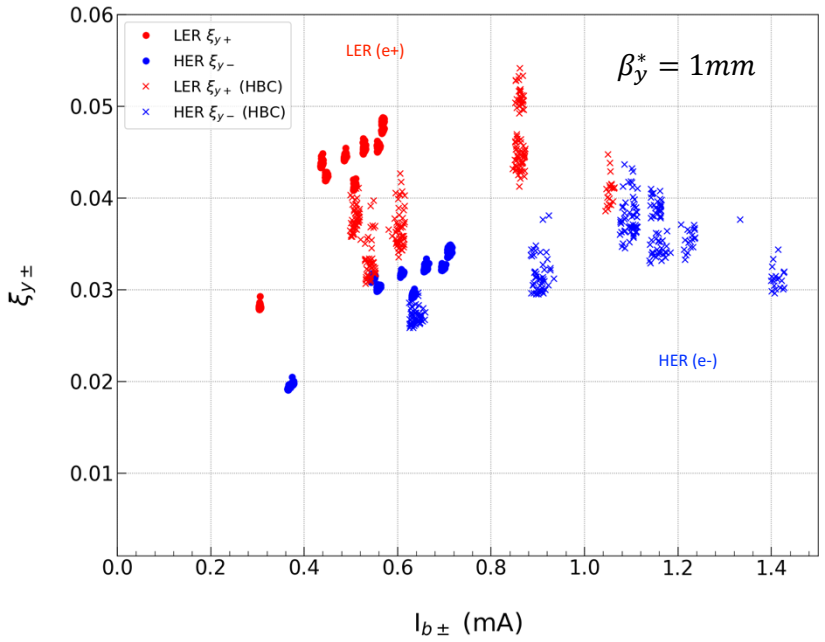


Operation statistics
2019 -2022

Beam-Beam Parameter and Specific Luminosity

● : physics run

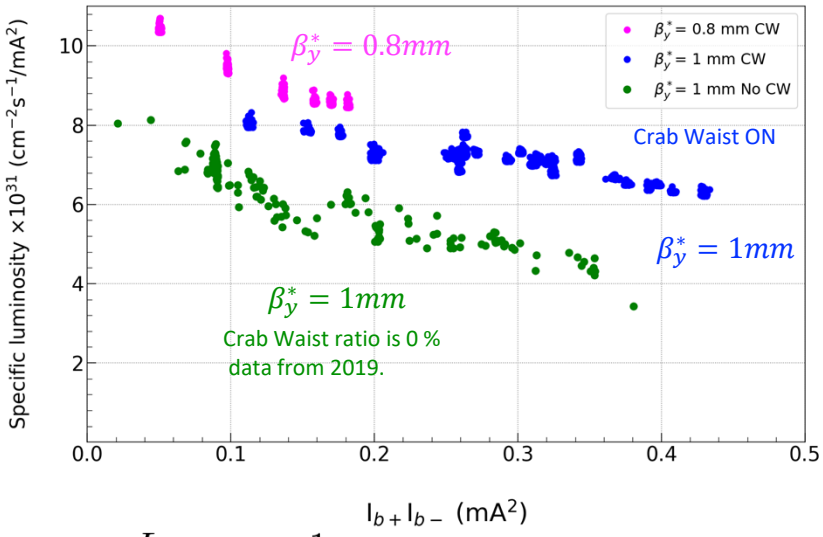
✕: HBC - High Bunch Current Study (393 bunches)



$$\xi_{y\pm} = 2er_e \frac{L\beta_y^*}{\gamma_\pm I\pm}$$

0.0565(LER) / 0.0434(HER)
at I_{b+} = 1.1 mA

Crab Waist ON



$$L_{sp} = \frac{L}{n_b I_{b+} I_{b-}} \propto \frac{1}{\Sigma_z \Sigma_y^*}$$

The CW improved luminosity.
Data without CW was not the same period as CW data.
We will confirm the luminosity gain in the next operation.
Also the CW ratio will be optimized by lifetime and luminosity gain.

Machine Parameters

Machine Parameters

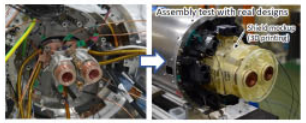
	May 22, 2022		June 8, 2022		June 22, 2022 *3		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	744	600	1321	1099	1363	1118	mA
Number of bunches	1565		2249		2249		
Bunch current	0.475	0.383	0.587	0.489	0.606	0.497	mA
Horizontal size σ_x^*	17.6	16.6	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y^*	0.250		0.303		0.315		μm *1
Vertical size σ_y^*	0.177		0.215		0.223		μm *2
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.574	44.525 / 46.589	45.532 / 43.573	44.524 / 46.594	45.532 / 43.574	
β_x^* / β_y^*	80 / 0.8	60 / 0.8	80 / 1.0	60 / 1.0	80 / 1.0	60 / 1.0	mm
Piwinski angle	10.7	12.7	10.7	12.7	10.7	12.7	
Crab waist ratio	80	40	80	40	80	40	%
Beam-Beam ξ_y	0.0309	0.0219	0.0407	0.0279	0.0398	0.0278	
Specific luminosity	8.74×10^{31}		7.21×10^{31}		6.95×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.49×10^{34}		4.65×10^{34}		4.71×10^{34}		$cm^{-2}s^{-1}$

$\sigma_y^* \simeq 2 \times$  virus

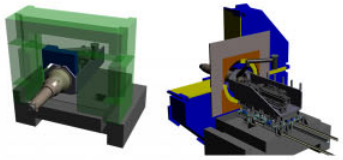
*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2
*3) Belle II HV off

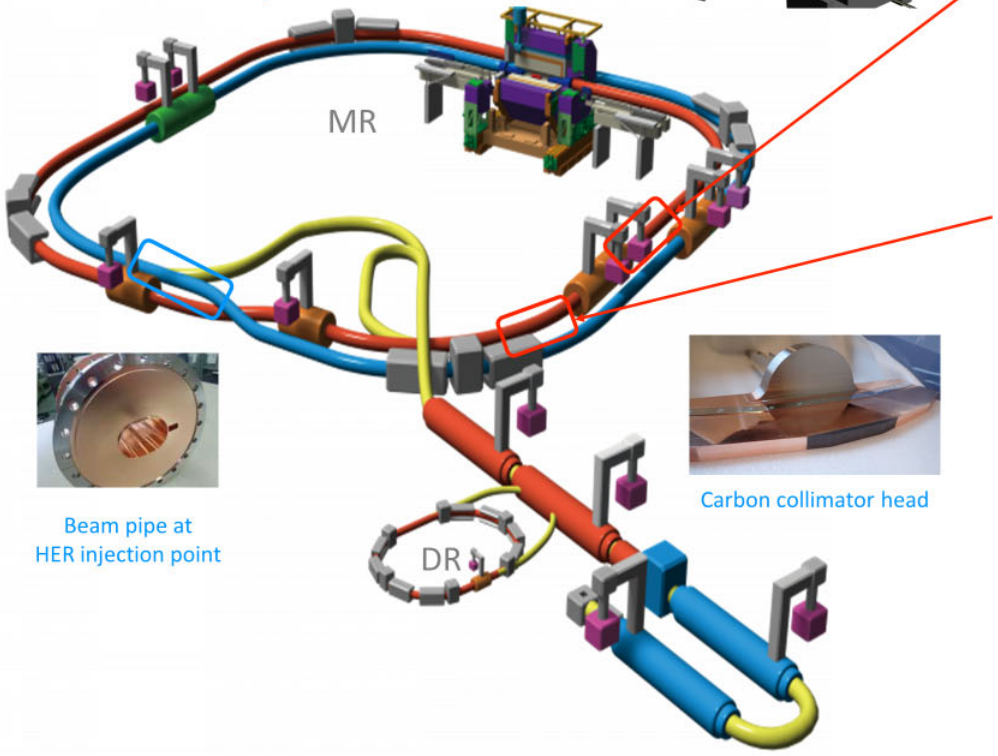
Long Shutdown 1

Modification during the 1st Long Shutdown (LS1)



New heavy metal shield on IP bellows





Beam pipe at
HER injection point

Carbon collimator head

- Nonlinear vertical collimator (LER)
  - reduction of impedance and backgrounds
- IR radiation shield modification
  - reduction of backgrounds
- Robust horizontal collimator head (LER)
  - replace with carbon-head for horizontal collimator.
- Copper-coated vertical collimator head
  - countermeasure for "fireball"
  - reduction of impedance
- New beam pipes with wider aperture a injection point (HER)
- RF cavity modification and replacement (LER)
  - stable operation and larger beam current

Ref. K. Shibata et al.

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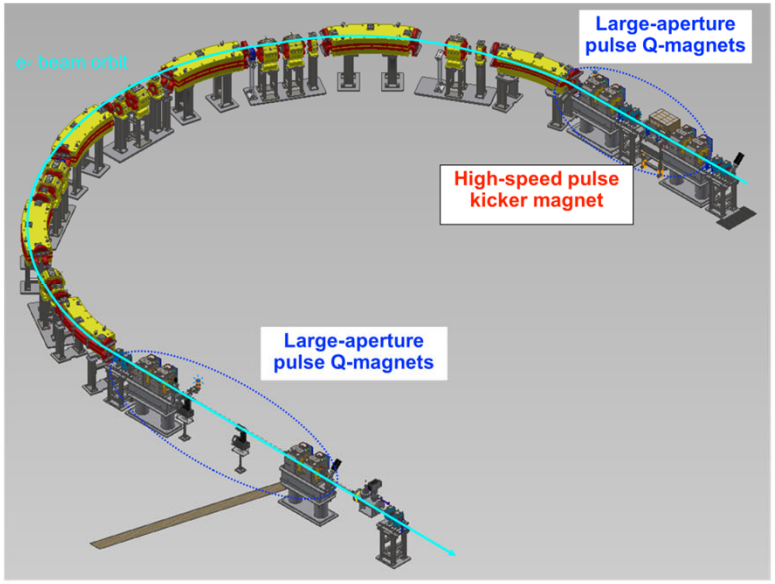
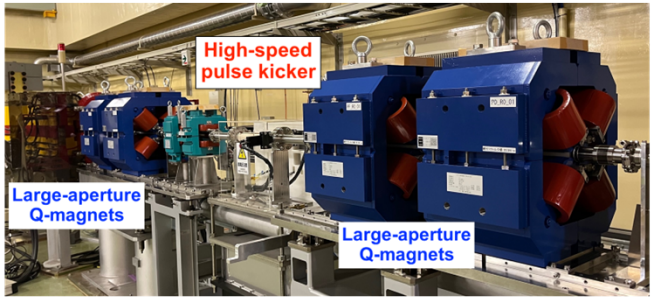
(LS1) upgrade for Injector

- High-speed pulse kicker magnets at the J-ARC and the sector 5 to control the orbit of two bunches independently.
- Large aperture pulse Q magnets at the entrance and exit of J-ARC to optically match the low-emittance e- and e+(primary high charge e-) beams independently.
- Four large aperture pulse Q magnets in the sectors 1-2 to make optical matching for both high energy e- and low-energy e+ beams and to reduce the emittance growth consequently.





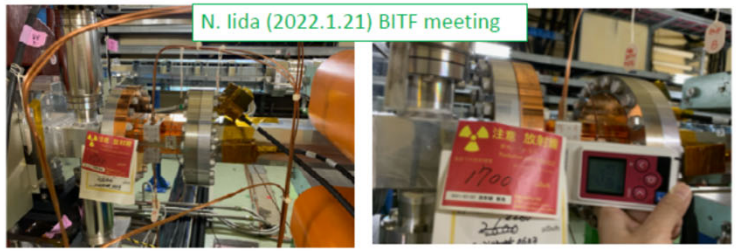
Pulse magnets at the entrance of J-ARC

Large-aperture pulse Q magnet in 1-Sector

HER injection line physical aperture

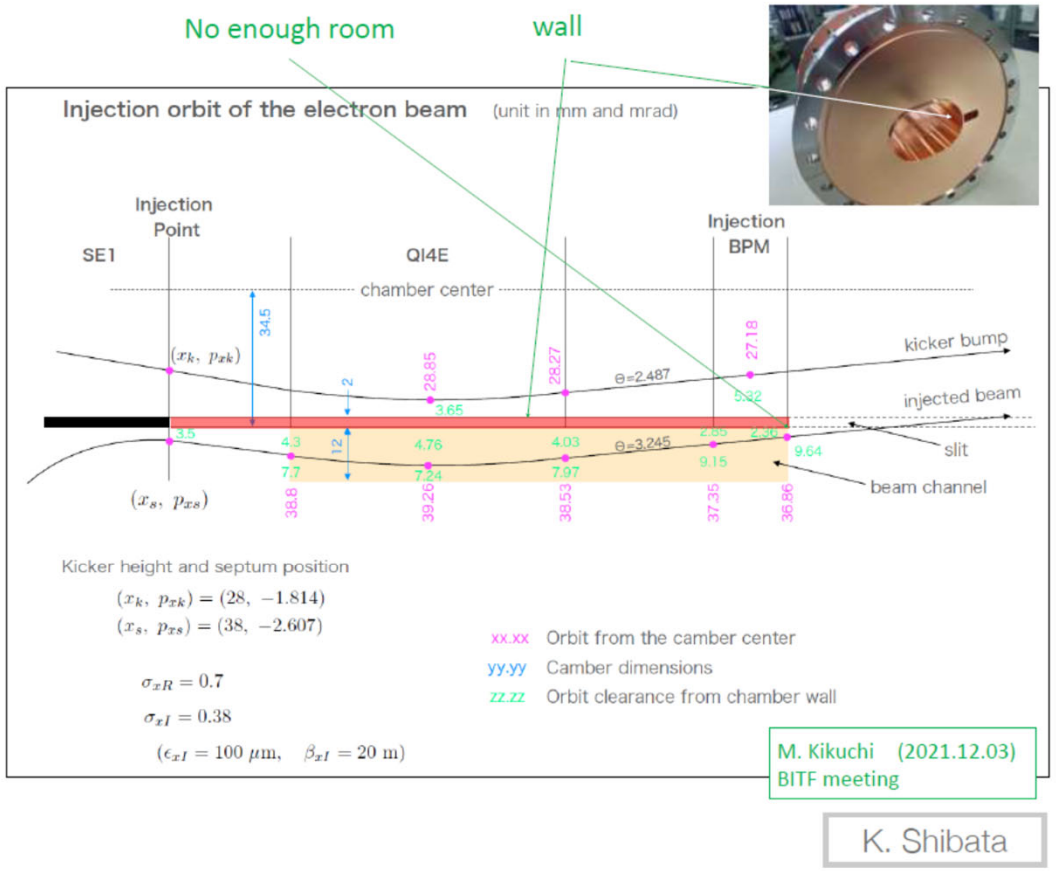
- Problem of HER injection
  - Wall can be an obstacle to injection.
    - A wall should be placed between beam channels for stored beam and injected beam.
    - Injected beam orbit is too close to the wall.
    - High levels of radiation detected at the injection BPM chamber indicates that the injected beam hits the wall.
    - It is hard to modify the injection beam orbit.

    ⇒ it is necessary to enlarge the horizontal aperture of the injection channel.



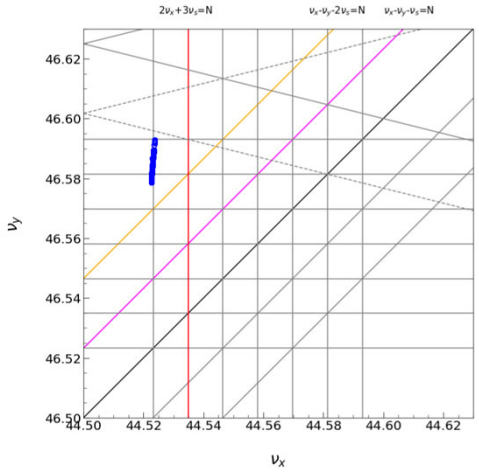
  - What is planned during LS1
    - Replacement of three beam chambers with new ones.
    - Update of injection BPM

    ⇒ More precise injection tuning

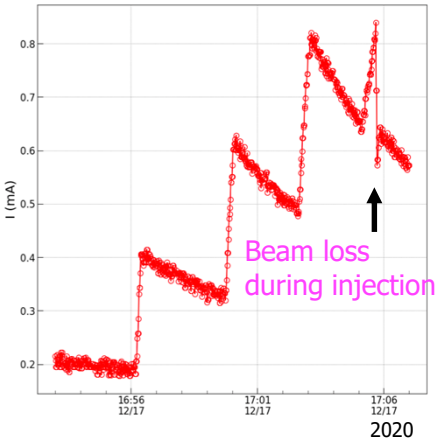


K. Shibata

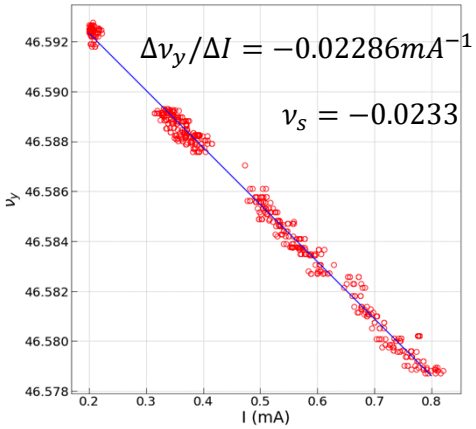
TMCI Observation at SuperKEKB

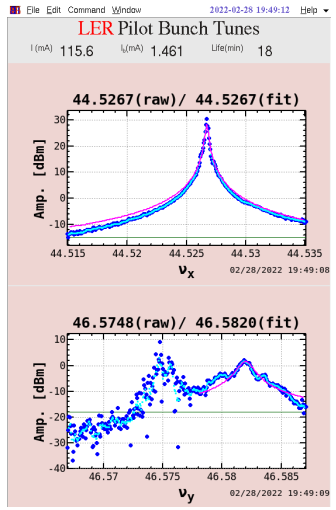


LER



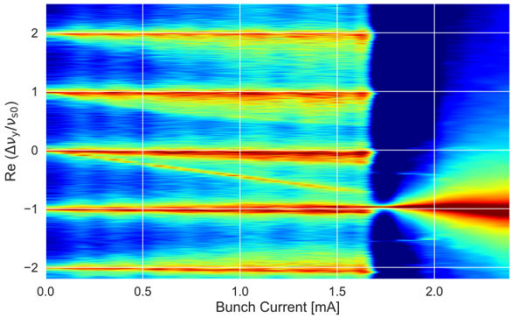
single bunch operation



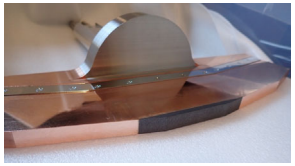


Tune measurement:
side band was observed
at high bunch current.

Simulation: PyHEADTAIL ($\Delta\nu_y/\Delta I \sim \nu_s/2$)



T. Ishibashi



We observed TMCI at SuperKEKB when we used a carbon head for one of the vertical collimators.
The tune shift was similar to the synchrotron tune and the threshold was 0.85 mA/bunch. (2020)

We control the vertical collimator aperture to keep the tune shift less than half of ν_s.
The TMCT threshold becomes 1.7 mA/bunch in the LER for the normal operation.

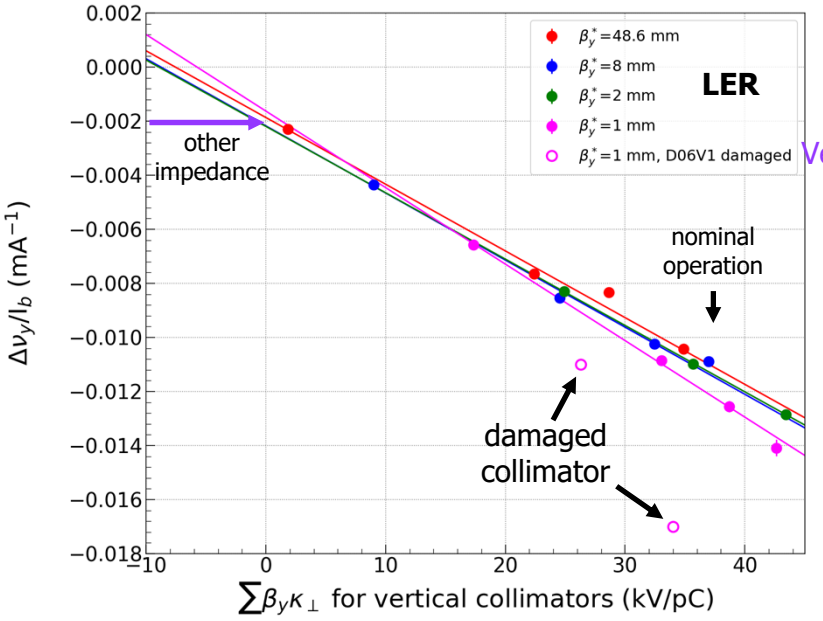
* We replaced the carbon head with tantalum after this experiment.

Single Bunch Tune Shift and Impedance

Tune shift is equivalent to impedance.

Larger circumference (larger T_0) makes larger tune shift.

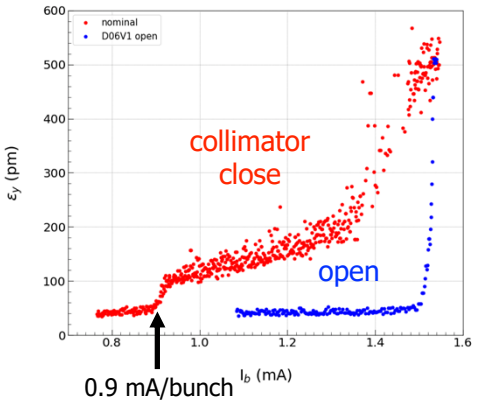
$$\frac{\Delta\nu_y}{I_b} = -\frac{T_0}{4\pi(E/e)}\sum_i \beta_{yi}\kappa_i(d) \qquad \rightarrow \frac{T_0}{4\pi(E/e)} = 0.2(ps/kV) \quad \text{for SuperKEKB}$$

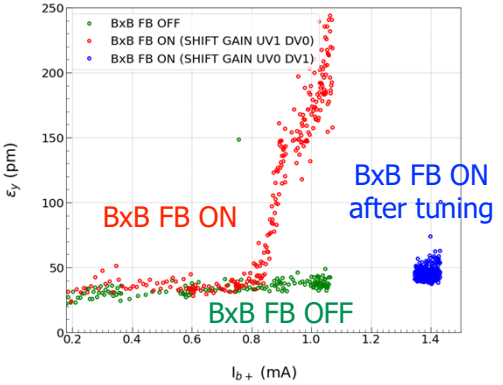


Kick factors of vertical collimators are calculated by GdfidL (and ECHO3D).

The vertical collimators contribute approximately 70 % of the total impedance.

Vetical beam size blowup was observed at much smaller than the TMCI threshold
"-1 mode instability" ← impedance and BxB FB tuning

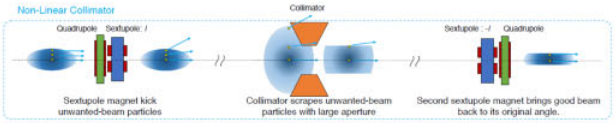




$\sum\beta_y\kappa = 33.3(kV/pC)$

Reduction of Impedance: Nonlinear Collimator

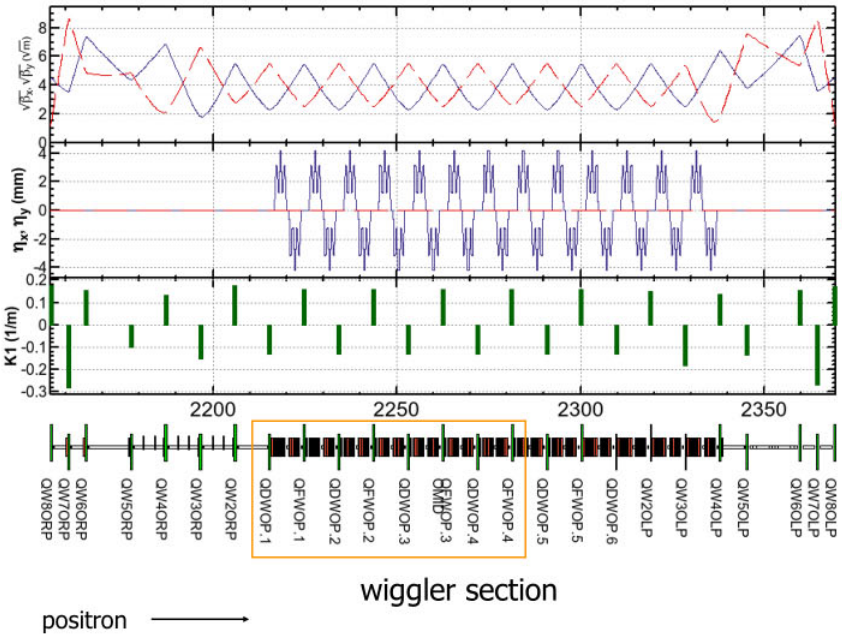
We install a nonlinear collimator (D05V1) to reduce impedance in the vertical direction.



$$\Delta p_y = \frac{SK_2}{2}\Delta y^2$$

OHO section

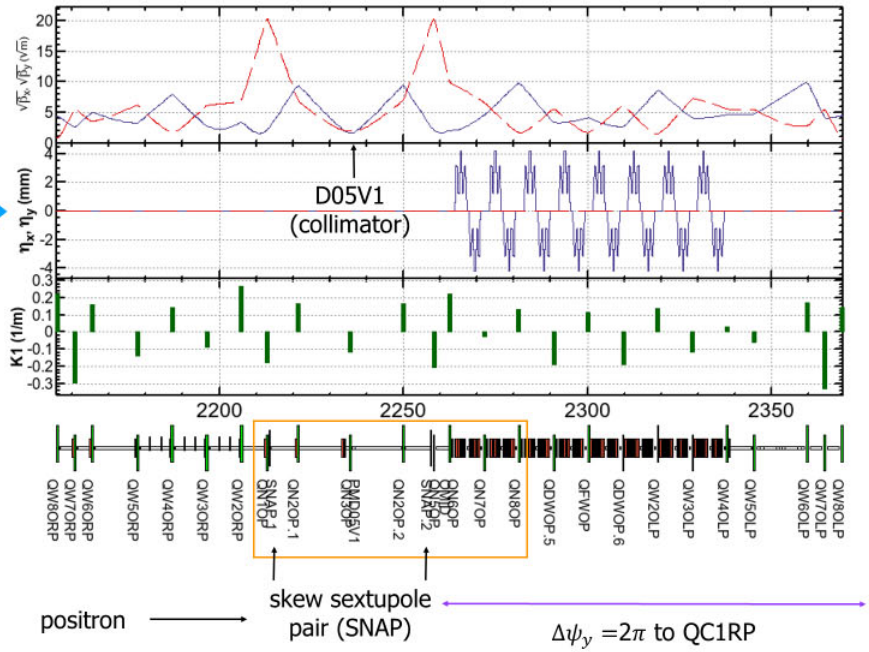
before LS1



wiggler section

positron ⟶

after LS1



positron ⟶

skew sextupole pair (SNAP)

$\Delta\psi_y = 2\pi$ to QC1RP

M = -I'

Damping time (msec):
X : 45.67757 Y : 45.68328 Z : 22.84954

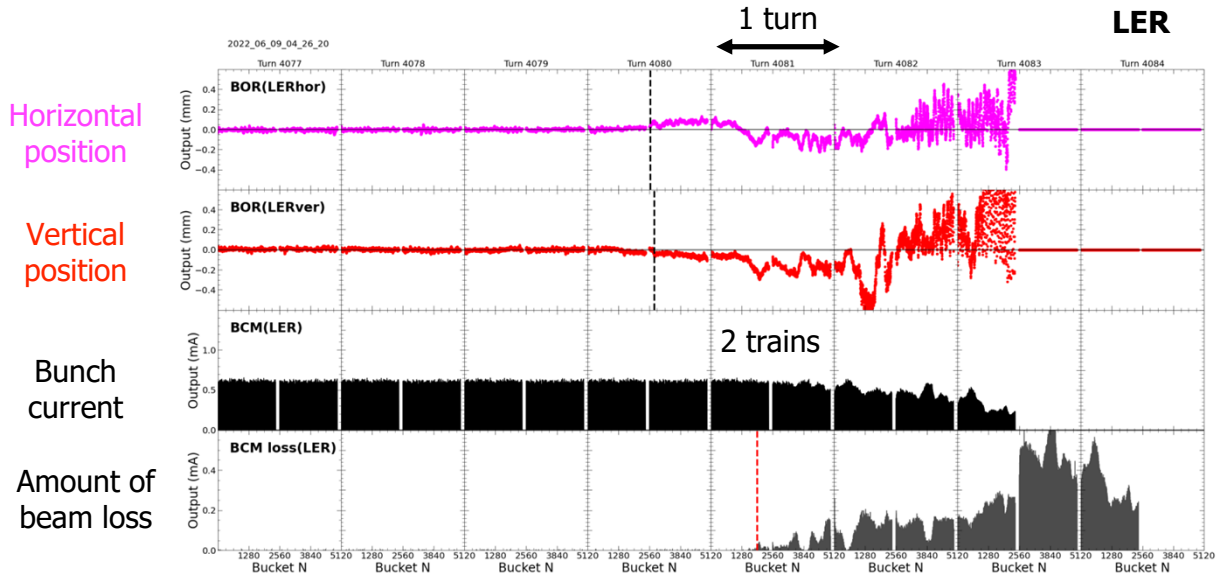
Damping time (msec):
X : 52.99557 Y : 53.00312 Z : 26.50934

Sudden Beam Loss (SBL)

Beam becomes unstable suddenly at high beam current.
Beam loss can lead to severe damage on collimators or final focus magnet (QCS) quench.

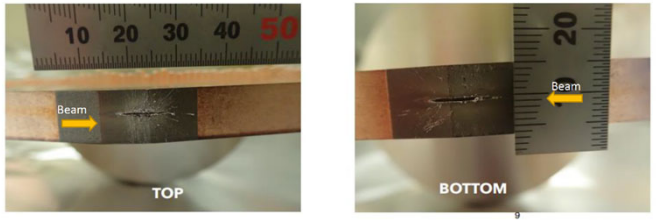
LER beam current : 1.4 A
number of bunches : 2249
luminosity : 4.58 x 10^{34} $cm^{-2}s^{-1}$

Beam loss within a few turns
without large oscillation before the loss.

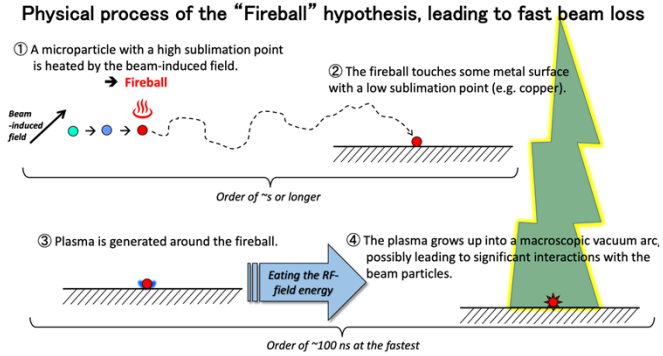


M. Aversano

Damage of collimator head



Fireball hypothesis



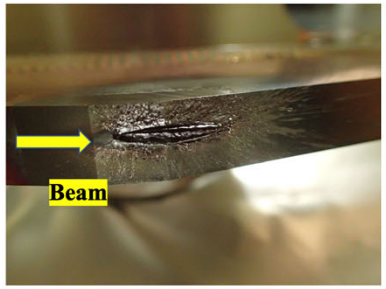
T. Abe at al., RF breakdown trigger, PR-AB 21, 122002, 2018.

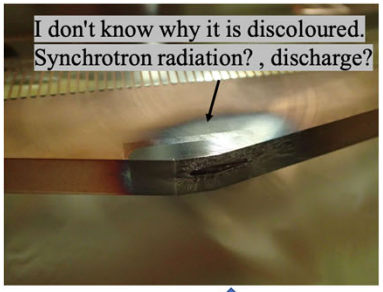
Trigger source can be collimator head.

Copper coating of collimator head will be effective if different sublimation point is problem.

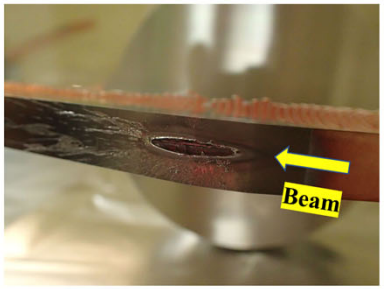
Vertical Collimator

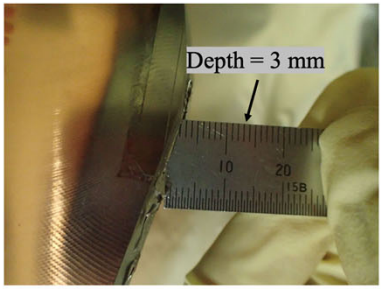
TOP side





BOTTOM side





I think the colours are similar.

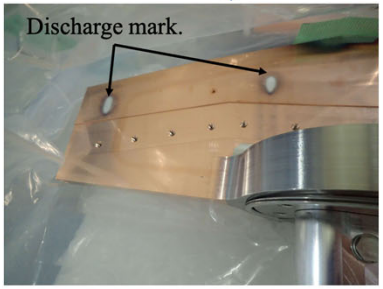
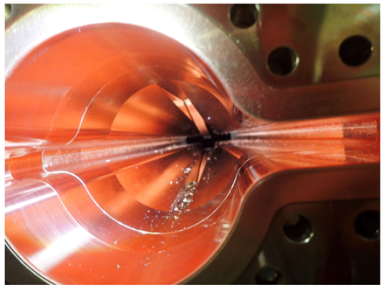
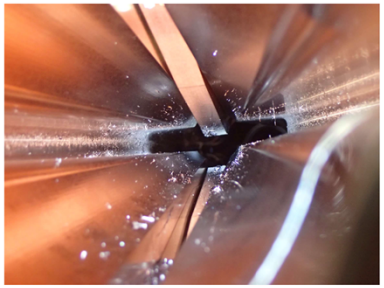


Photo from downstream.



top

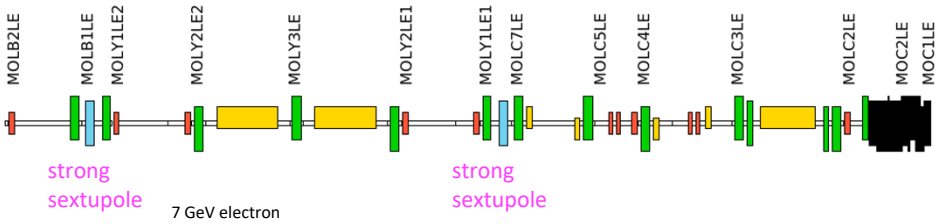


bottom

We never expected the collimator damage before the commissioning.

There are many dusts.

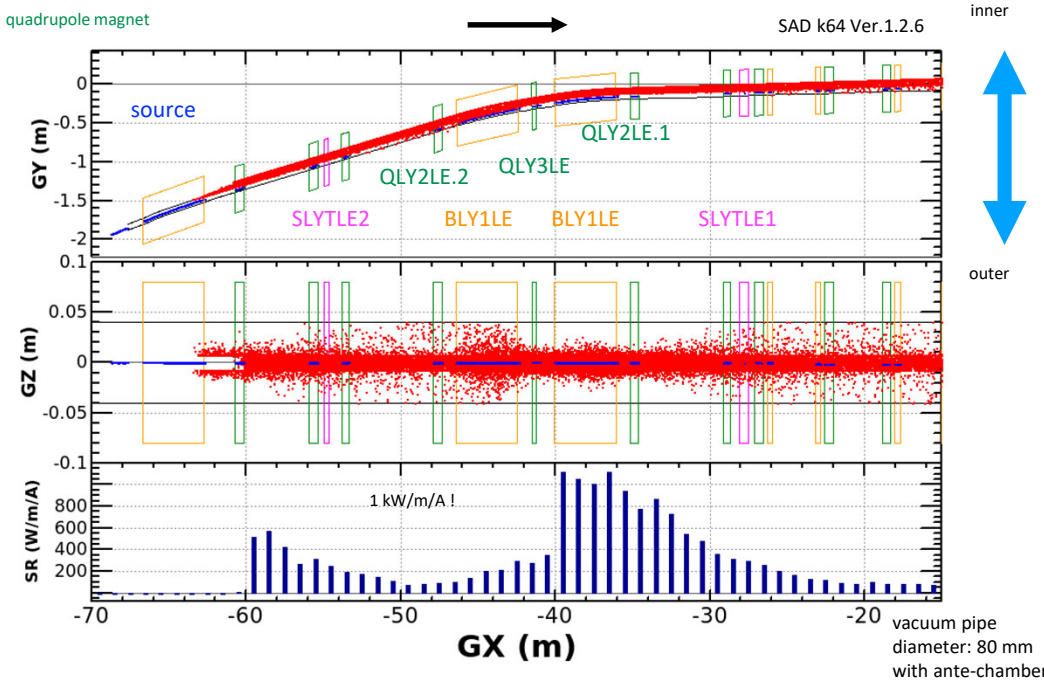
Synchrotron Radiation at Strong Sextupole Region in HER



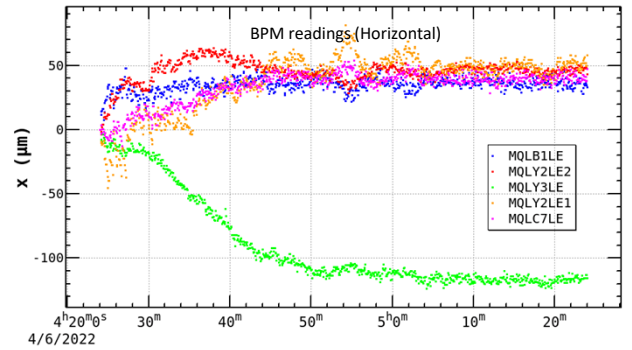
The sextupole magnet does not touch the beam pipe.

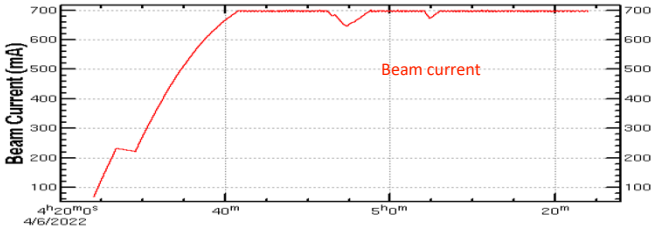
So, the sextupole does not move due to the beam pipe deformation.

Beam pipe pushes quadrupoles with BPM, they move due to intense SR heating.



vacuum pipe
diameter: 80 mm
with ante-chamber: 110 mm
height: 14 mm (±7 mm)



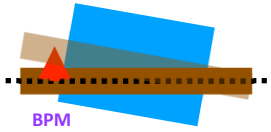


BPMs, Quadrupoles, and Sextupoles

BPM is fixed at quadrupole magnet and displacement monitor measures relative deviation (horizontal and vertical) between the BPM and the sextupole magnet.

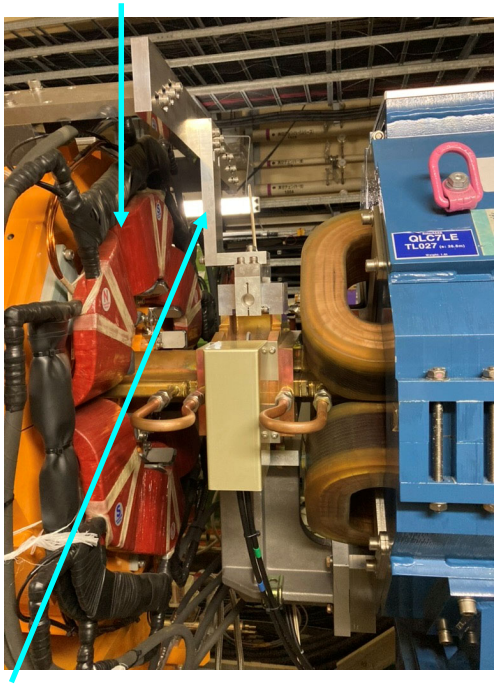
BPM and Quadrupole Magnet

The beam pipe (BPM) is fixed to the quadrupole magnet.



Quad. moves like yaw
and horizontal shift
if BPM pushes quad.

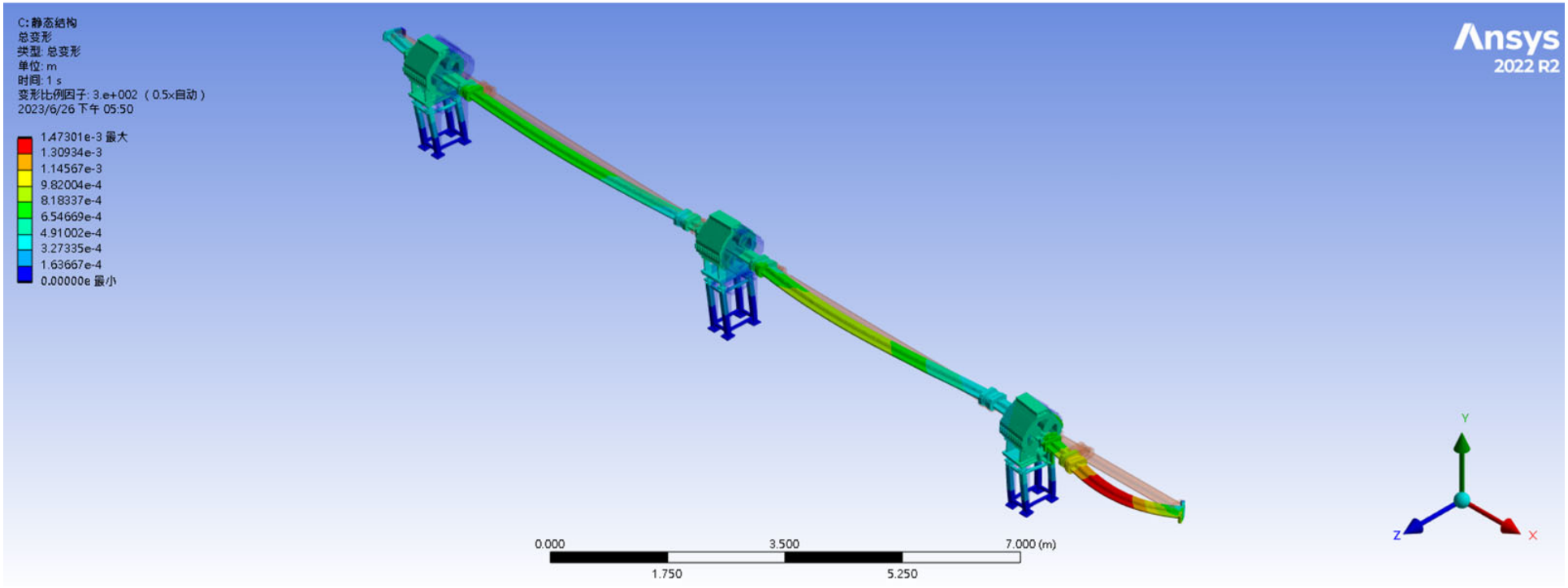
Crab Sextupole in the HER



Gap sensor measures $(\Delta x, \Delta y)$ between BPM and sextupole.
Relation between BPM and quad. does not change. (see left fig.)

Yao, Mu-Lee

Deformation



International Task Force (ITF) for SuperKEKB

61 researchers are joined to the ITF.
(26 researchers from foreign institutes ~43 %)

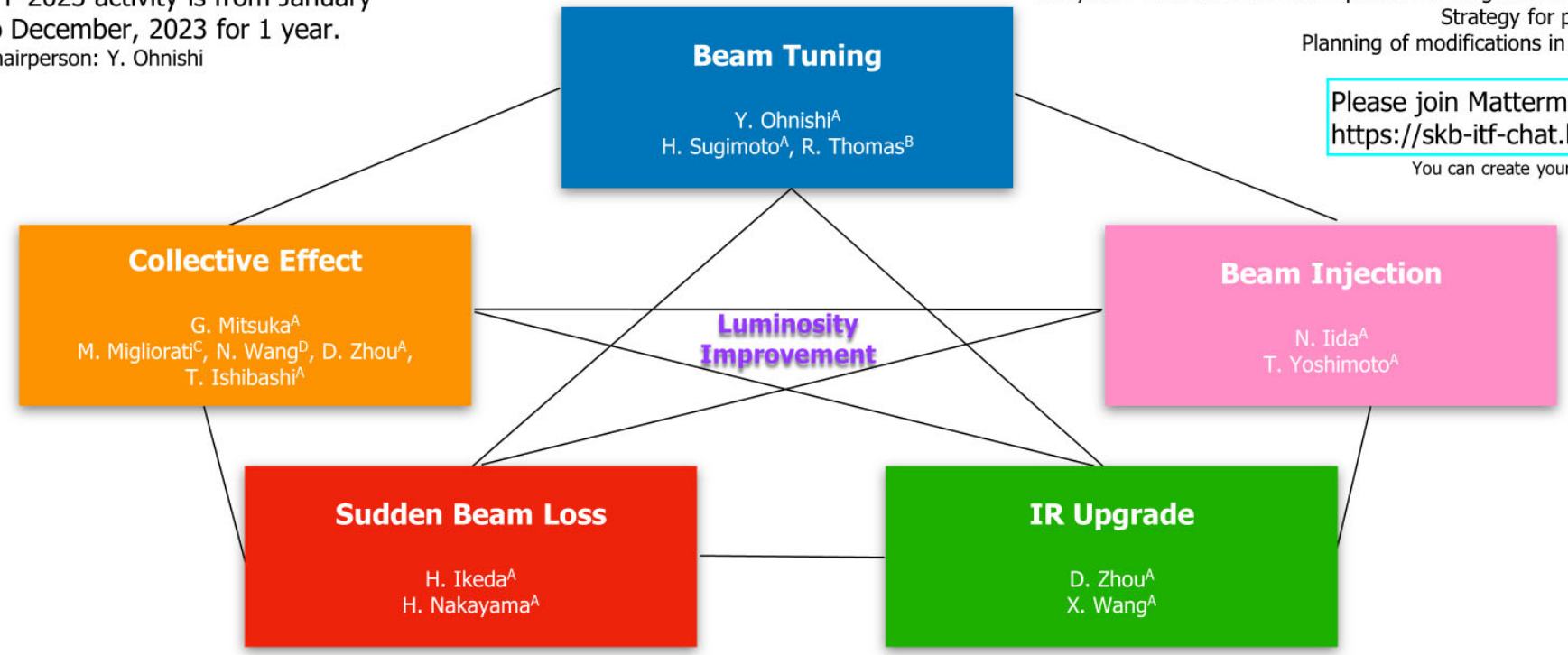
Find a realistic path to achieve 10^{35} $cm^{-2}s^{-1}$ in the post LS1 (1st long shutdown since mid. of 2022).
Find ideas to achieve $6x10^{35}$ $cm^{-2}s^{-1}$ after LS2 with a view to major modifications.

FCC-ee, CEPC, EIC, Super-Tau-Charm

Investigation of factors inhibiting machine performance improvement
Analysis of data obtained from operation through summer 2022
Strategy for post-LS1
Planning of modifications in the LS2

ITF 2023 activity is from January to December, 2023 for 1 year.
Chairperson: Y. Ohnishi

Please join Mattermost:
https://skb-itf-chat.kek.jp
You can create your account.

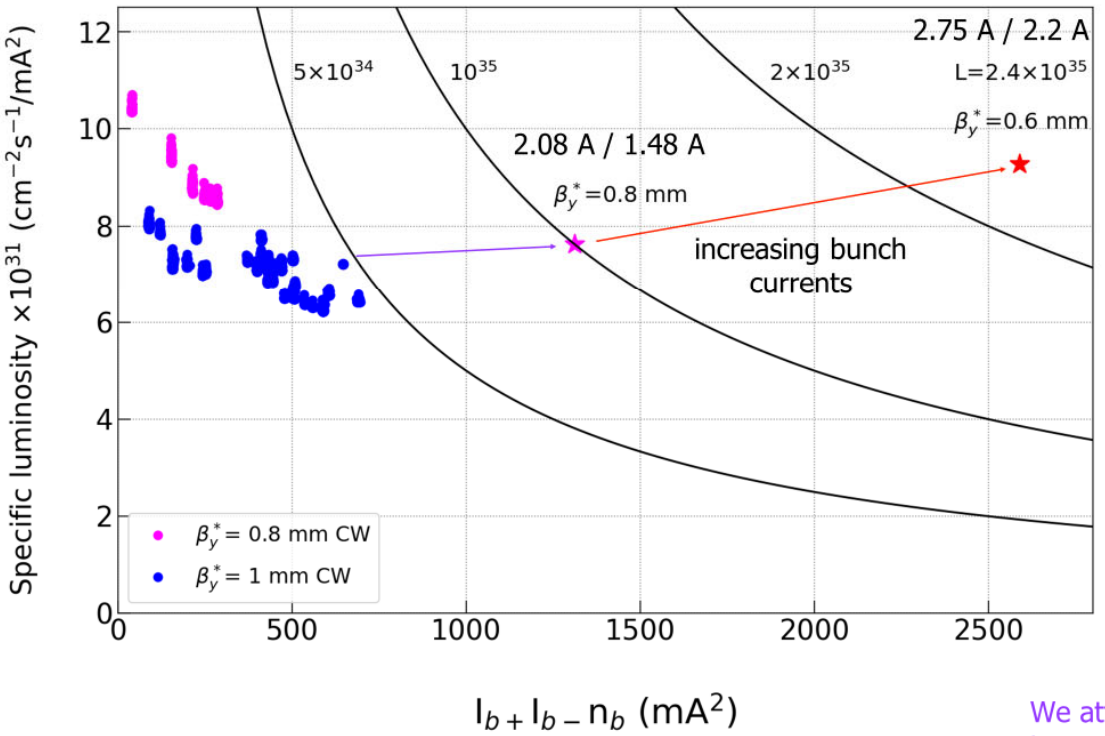


ITF is organized under the B-Factory promotion office at KEK.

[A] KEK, [B] CERN, [C] UNIROME1, [D] IHEP

Toward 2.4 x 10^{35} $cm^{-2}s^{-1}$

The first milestone after LS1 is 10^{35} $cm^{-2}s^{-1}$.



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

Unit of luminosity:

10^{34} $cm^{-2}s^{-1}$ = 1 KEKB

10^{35} $cm^{-2}s^{-1}$ = 1 SuperKEKB

We attempt to improve luminosity toward a new luminosity unit.

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Recent status

- HER new injection chamber has been installed successfully.
- OHO NLC elements, such as skew sextupoles, new vacuum chambers, lead radiation shield after vertical collimator have been installed successfully. OHO concrete radiation shield have been restored. Additional concreate shield will be installed soon.
- QCS-L (backward) has been restored. L-side magnets, vacuum chambers are also restored.
- First trial of QCS-R (forward) insertion failed.
  - Found (not negligible) interference between RVC and cable support of VXD. Also seems to damage RVC structure.
  - DESY group has quickly prepared modified RVC gear not to interfere cable support.
  - Up to now, operating ring in December will not be easy (almost impossible).

Summary

- Peak luminosity of $4.7 \times 10^{34} cm^{-2} s^{-1}$ has been achieved
- Demonstrated stable operation over 1A in the LER (with smaller bunch current less than 0.7mA/bunch)
- Sudden beam loss is serious challenge to increase luminosity and beam current, up to now.
- Many other challenges:
  - Vertical beam size blowup in LER
  - Beam line deformation with HER beam current
  - Shorter beam lifetime; both dynamic aperture and physical aperture (beam collimators), need to clarify the effect of crab waist.
  - Injection efficiency, long-term stability of the injector.
- Several upgrade items during long shutdown 1.
- International Task Force for SuperKEKB upgrade
  - Beam Tuning, Collective Effect, Beam Injection, Sudden Beam Loss, IR Upgrade subgroups are actively on-going.