Pressure bursts due to beam-dust interaction at SuperKEKB

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- Beam pipes
- Observation and possible causes
- Experiments
- Countermeasures and present tatus
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- Summaries

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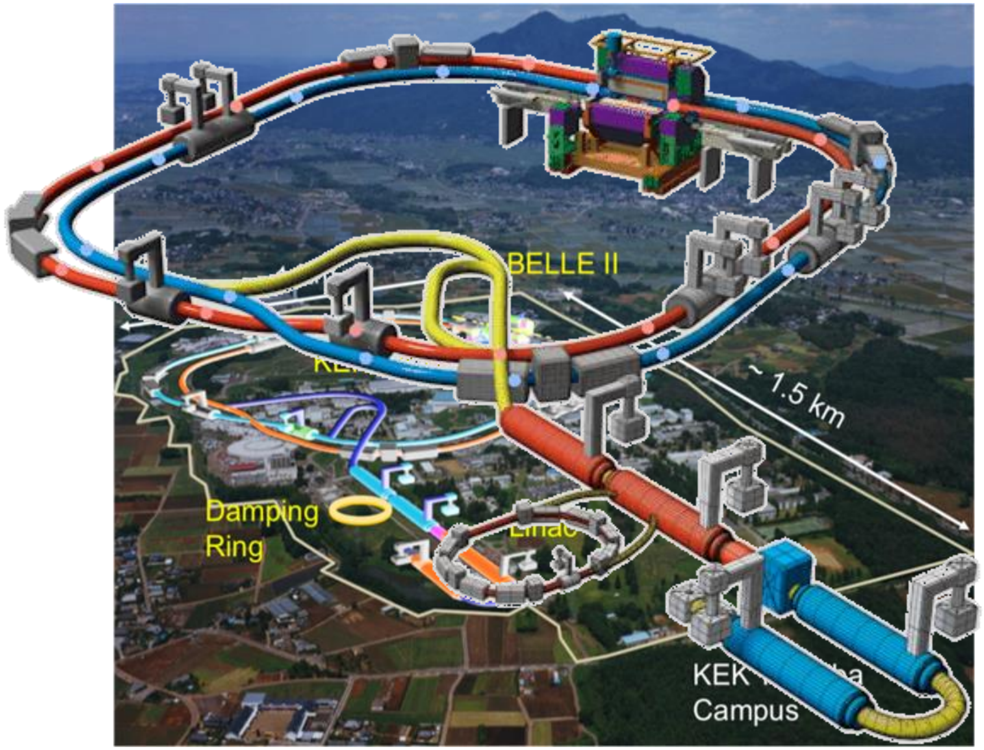
SuperKEKB

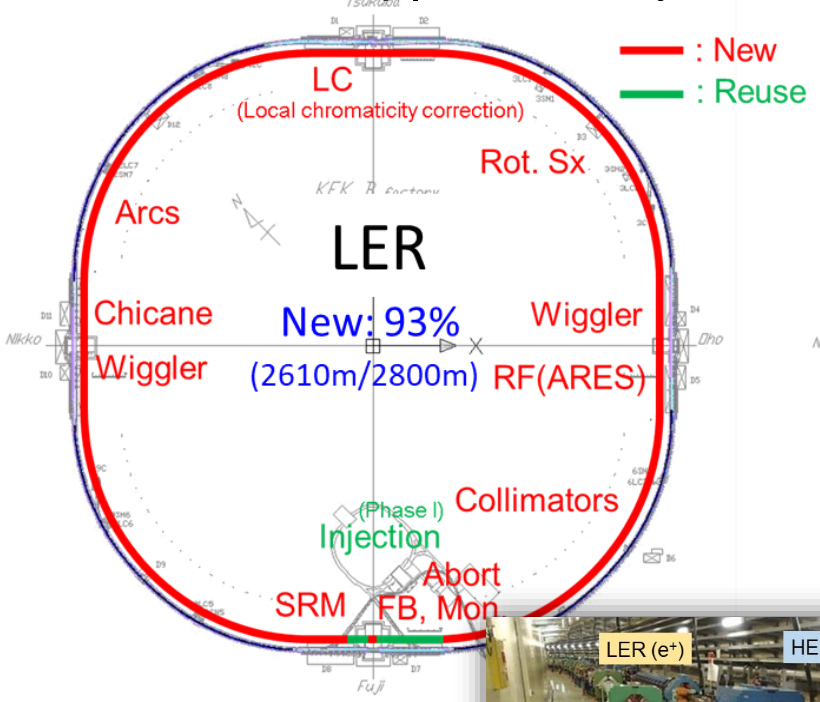
- Upgrade project of KEKB B-factory
  - Located at KEK Tsukuba campus.
- e^- - e^+ two-ring collider consisting of
  - BELLE-II detector
  - Injector (Linac): *L* ~600 m
  - Damping ring for e^+ : *C* ~135 m
    - 1.1 Gev e^+, 71 mA (Design)
  - Main ring (MR): *C* ~ 3016 m
    - HER: 7 GeV e^-, 2.6 A (Design)
    - LER: 4 GeV e^+, 3.6 A (Design)

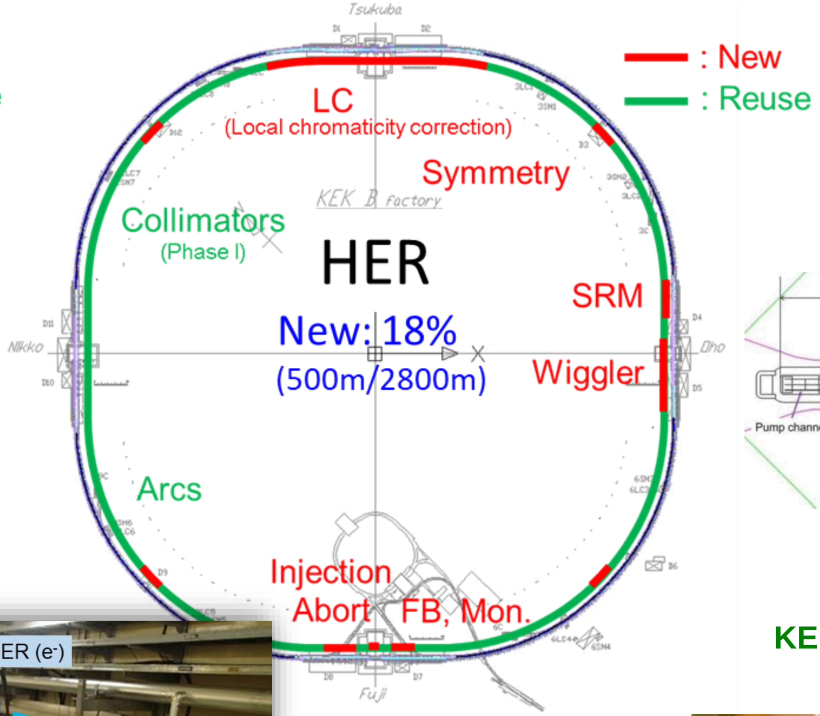


- The SuperKEKB has been operating since 2016 (Phase-1), aiming an unprecedent high luminosity over 1×10^{35} $cm^{-2}s^{-1}$ using "nano-beam collision scheme" with high beam currents.
- Achieved luminosity: $4.65 \times 10^{34}/cm^2/s$ (LER 1.32 A, HER 1.10 A, 2249 bunches)
  (~4 ns spacing)

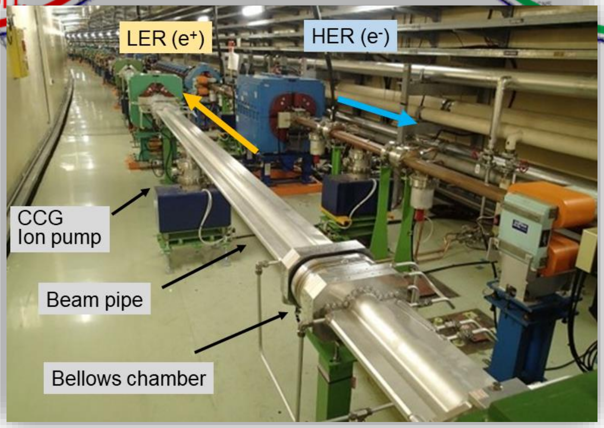
Beam pipes

- In the upgrade to SuperKEKB (2010~2016):
  - LER: Approximately 93% of beam pipes in length were renewed.
  - HER: Approximately 82 % were reused.

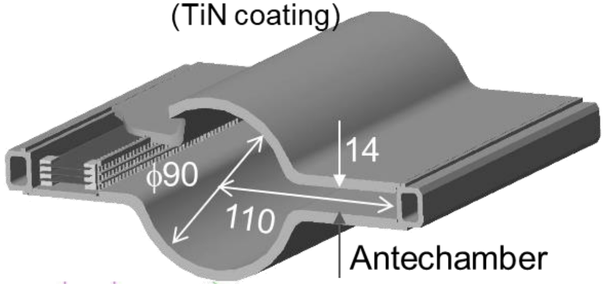


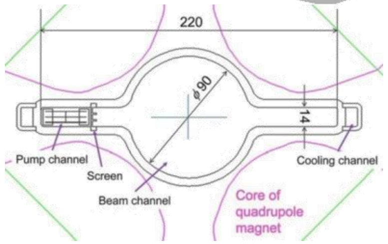


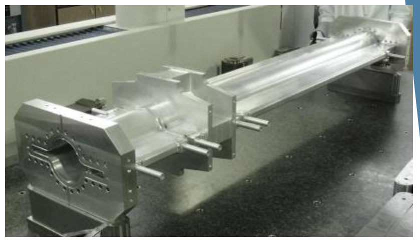
Layout in MR

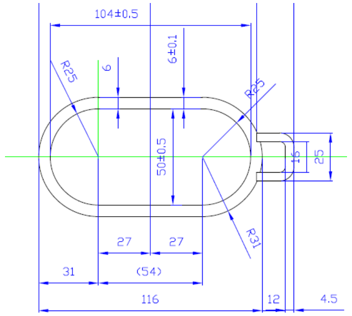


Typical beam pipe for LER (with antechambers)









Typical beam pipe for HER

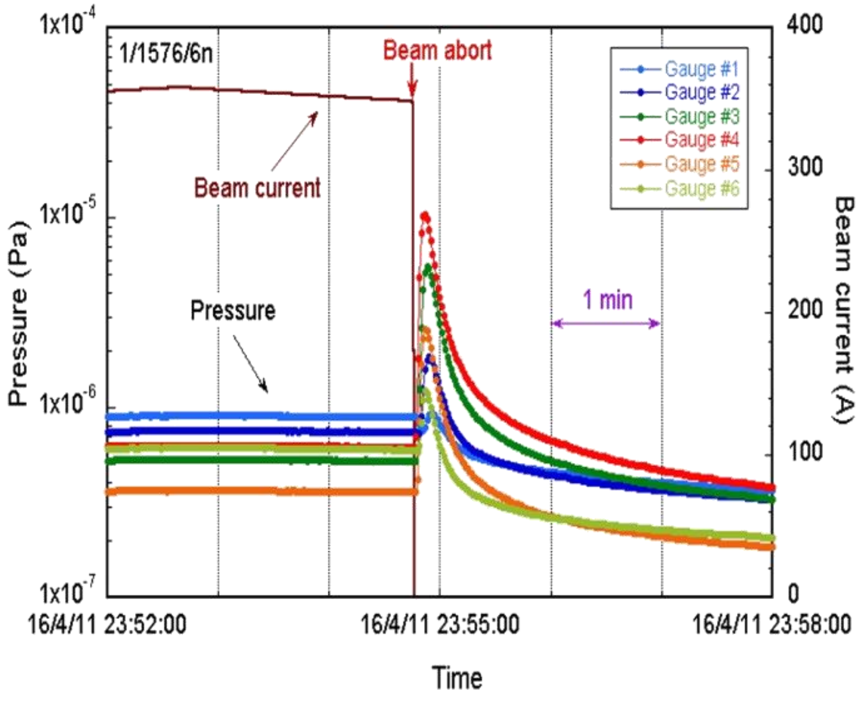
KEKB type (reuse) (racetrack)

Super KEKB type (new) (with antechambers)

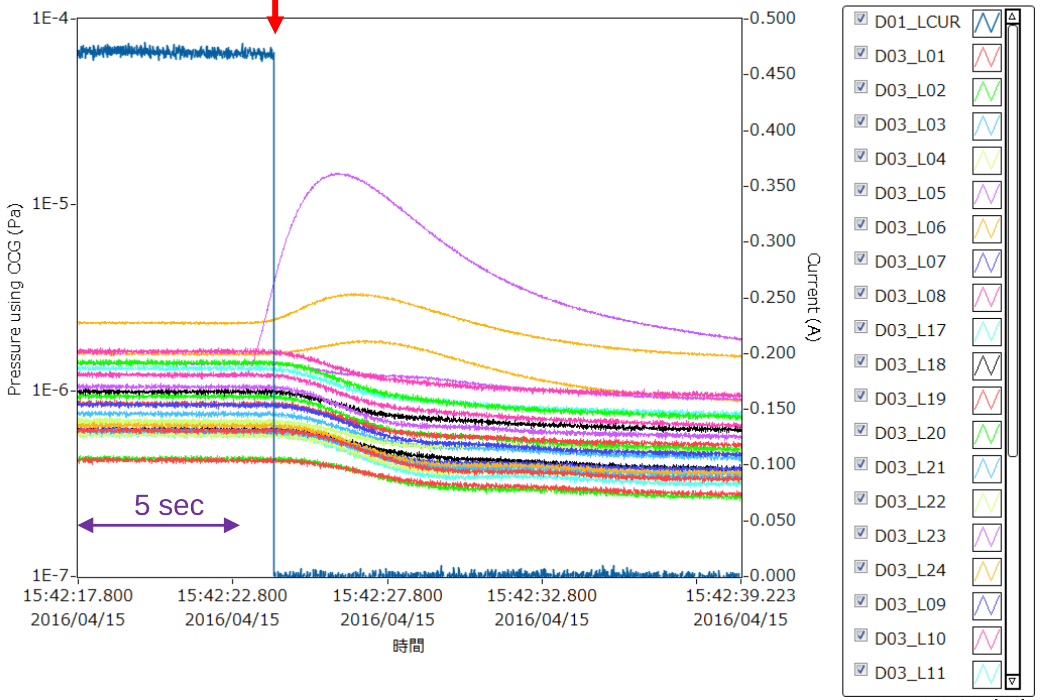
Observation

- Beam aborts accompanied by local pressure bursts were frequently observed in the Phase-1 operation (Feb. ~ Jun., 2016).
- Maximum pressure = $1x10^{-6}$ ~ $1x10^{-5}$ Pa.
- Observed at just after beam aborts: in a few seconds.
  - Vacuum gauges are located at approximately every 10 m in average along the ring.
- Sometimes the pressure rose "before" the beam abort, which was observed by a rapid monitoring system.

Typical pressure burst



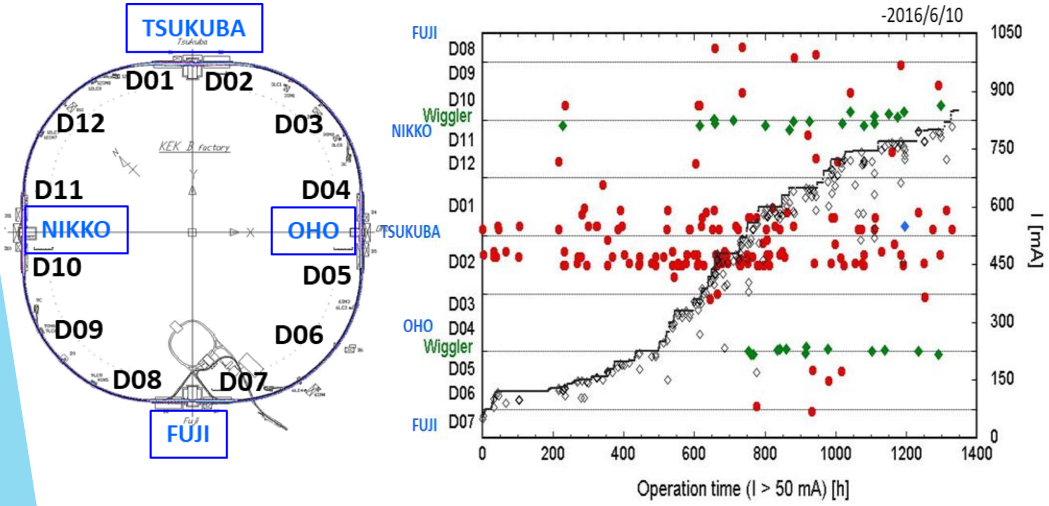
Beam abort



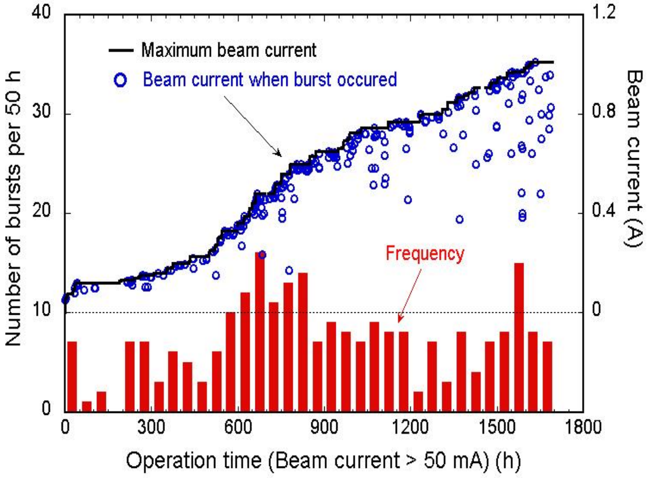
Observation

- The pressure bursts have been frequently observed in the LER, but also HER.
  - The locations of the pressure bursts have spread along the ring (LER).
  - However, more frequent in the Tsukuba straight section, wiggler sections, and beam injection sections. → New beam pipes.
  - The bursts seemed to happen at higher beam currents. → Aging effect?
    - Became more frequent when the maximum beam currents were increased.

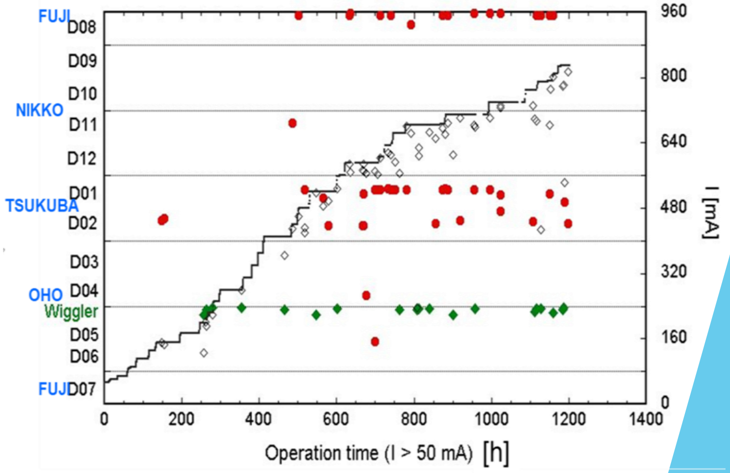
Location and beam currents when the bursts were observed for LER



Frequency of pressure bursts for LER



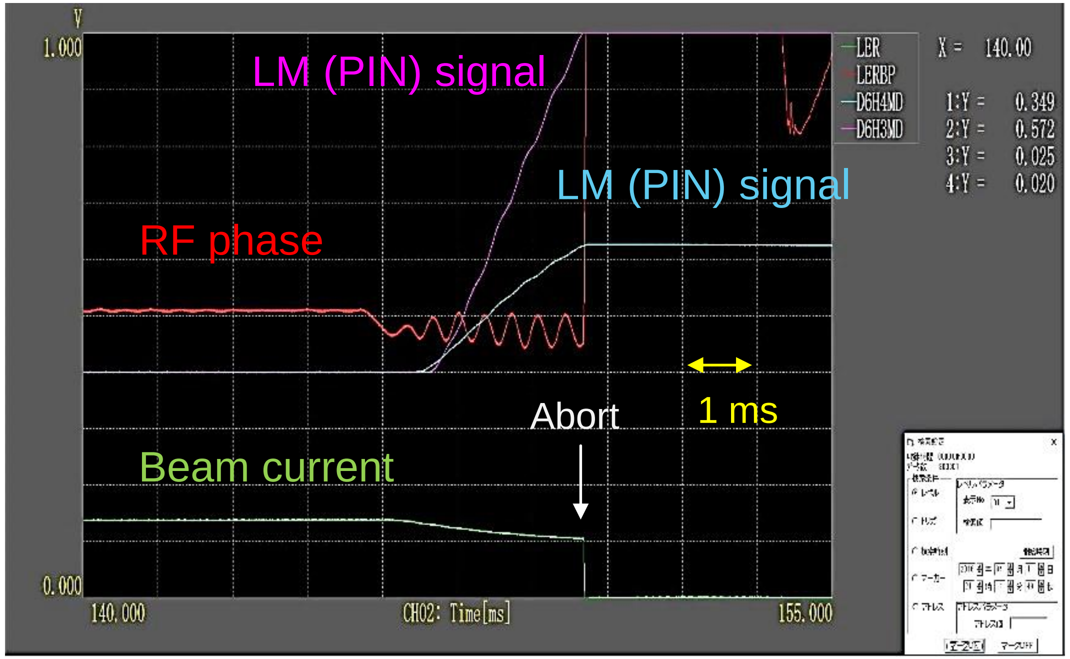
Location and beam currents when the bursts were observed for HER

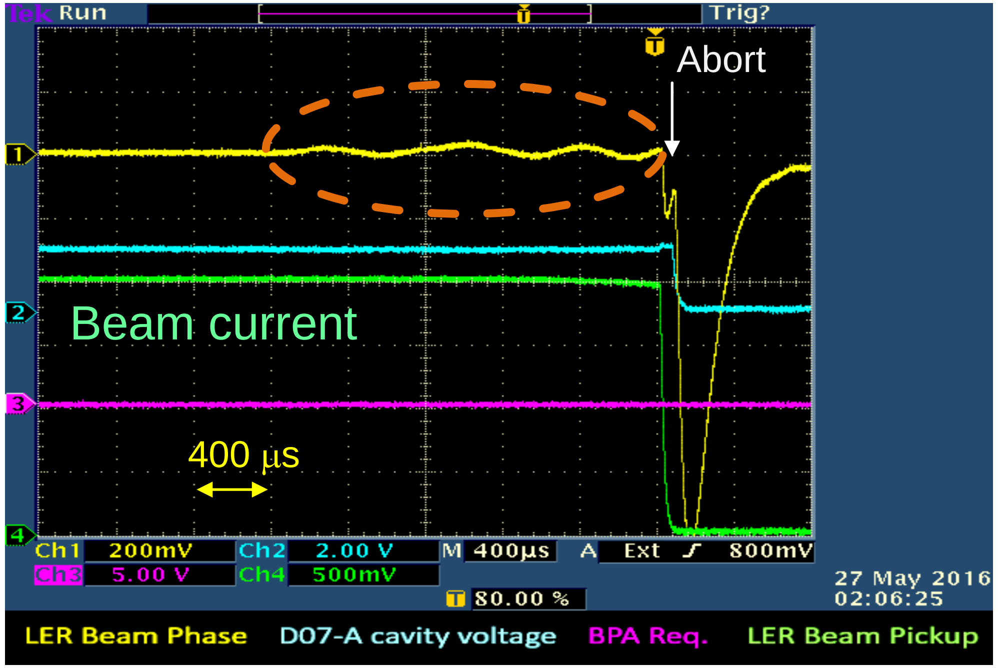


Observation

- Beam loss
  - Beam-loss monitors at collimators triggered the beam aborts.
  - The beam loss lasted for 1 ~ a few ms before the beam abort.
  - Synchrotron oscillation was observed before beam loss. → Any energy loss.

Typical abort log for the case pressure burst was observed. (H. Ikeda)

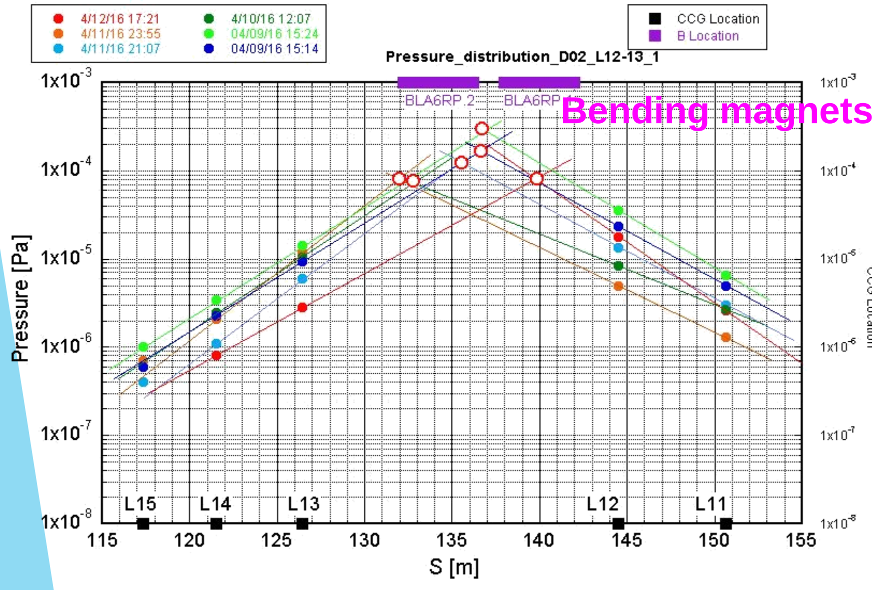


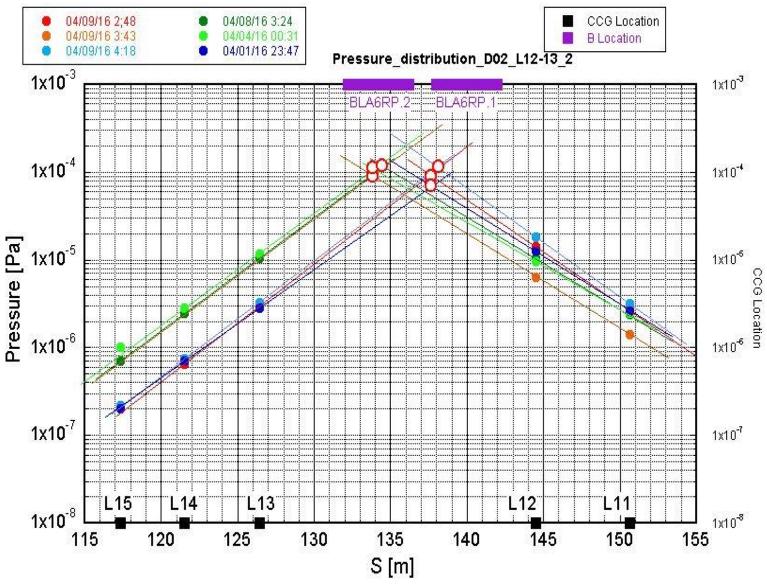


Observation

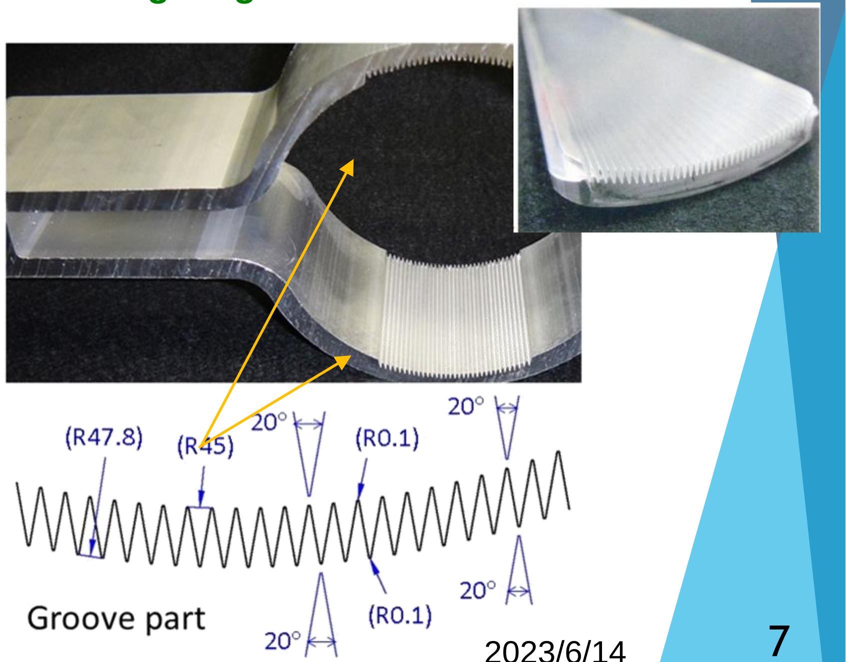
- Locations of pressure bursts.
  - Deduced from the distribution of pressure heights along the ring.
  - In most cases, the bursts were observed near the beam pipes in dipole magnets, which have a groove structure as a countermeasure for the electron cloud effect (ECE).
    - The surface at the top and the bottom of beam channel was grooved.
  - Groove structure → easy to trap "dusts".
  - Note that the beam pipes with groove structure are also used in arc sections. But the manufacture is different from that of the beam pipes at Tsukuba straight section.

Estimated detailed locations of pressure bursts



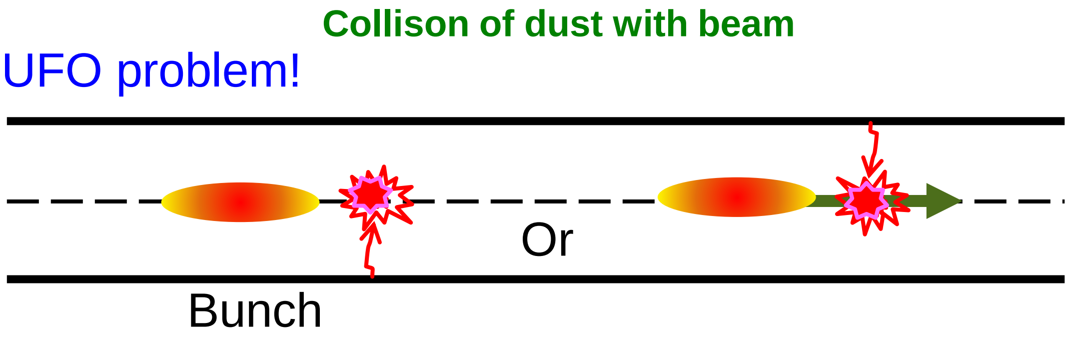


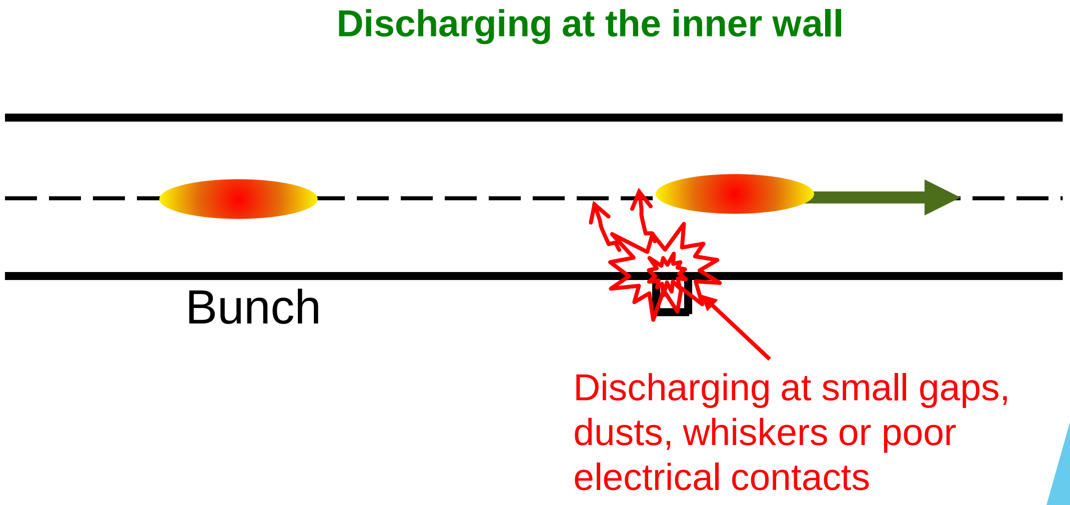
Groove structure in beam pipes for bending magnets



Possible causes

- Most possible cause: Collision of “dusts” with circulating beams.
  - Groove structure is likely to catch dusts.
  - Aluminum groove were formed by cold extrusion at the first stage of beam pipe fabrication. The cutting and machining were processed after that. →The cleaning after the machining seemed insufficient.
- Another possible cause: Discharges by wall current (or HOM) at the inner wall
  - Discharges sometimes emit heavy (melted) materials leading to the beam loss toward beam orbit direction.
  - But, no extra heating around these points was observed.
  - Small pressure bursts, which are likely observed in discharging phenomena as a precursory, were not also observed.

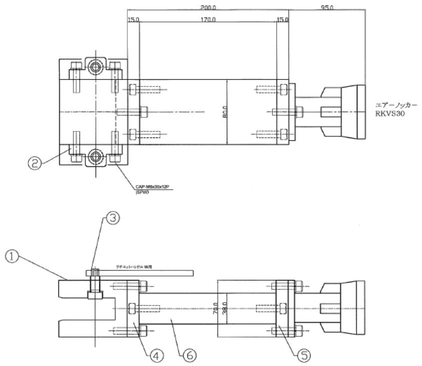


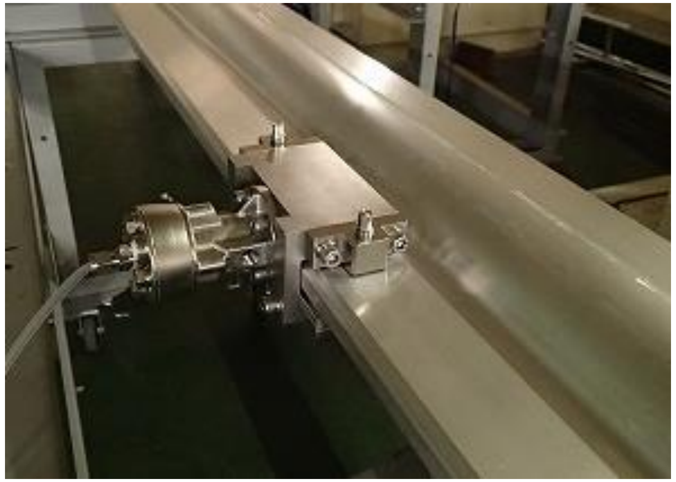


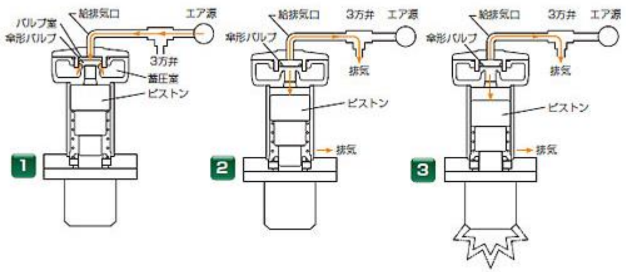
Experiments

- Knocking test
  - A “knocker” was developed to knock the beam pipe during beam operation.
    - Driven by a high pressure of 0.65 MPa.
    - Remote control.
    - Available even in magnets (non-magnetic).

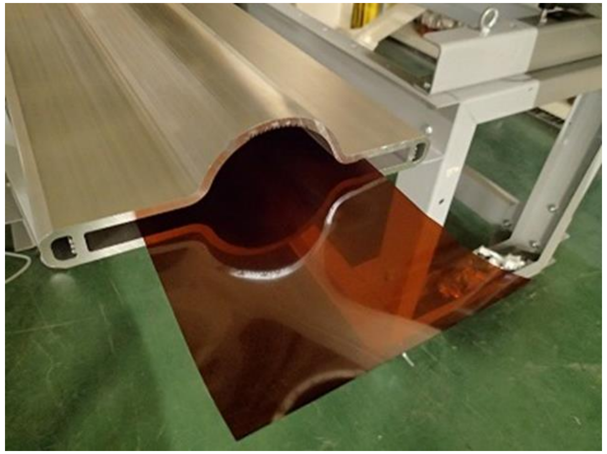
Knocker







- A bench test using a reserved pipe (raw pipe) demonstrated the falling of dusts by knocking.
  - Dusts with a diameter of several hundreds micrometers were included.

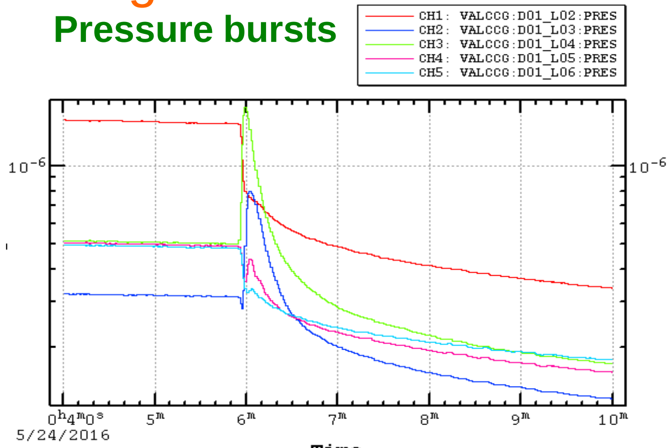


Kapton film to gather dusts dropped from the top surface

Experiments

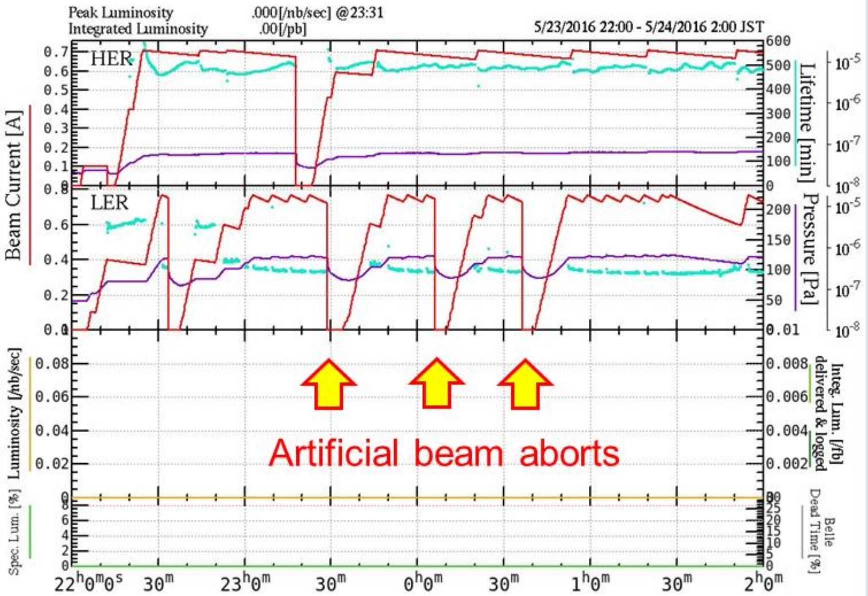
- Knocking test
  - The “knocker” was set at a beam pipe in a bending magnet in the LER, where the bursts had been observed frequently.
  - Succeeded in reproducing the phenomena three times by the knocking!
    - Beam losses were detected by loss monitors located at the front of the beam pipe.
  - We observed the phenomena by knocking beam pipes with the groove structure for both aluminum and copper beam pipes.
  - We also tried for beam pipes without the groove structure, but could not observe the phenomena.

Pressure bursts

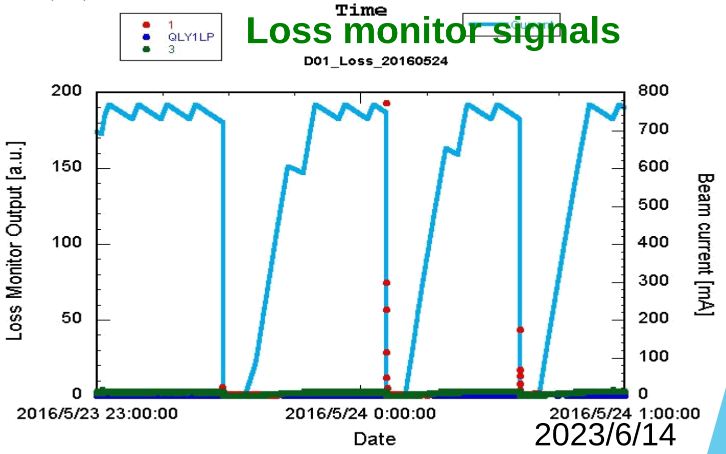


Knocker set to a beam pipe in a magnet

Beam abort induced by knocking

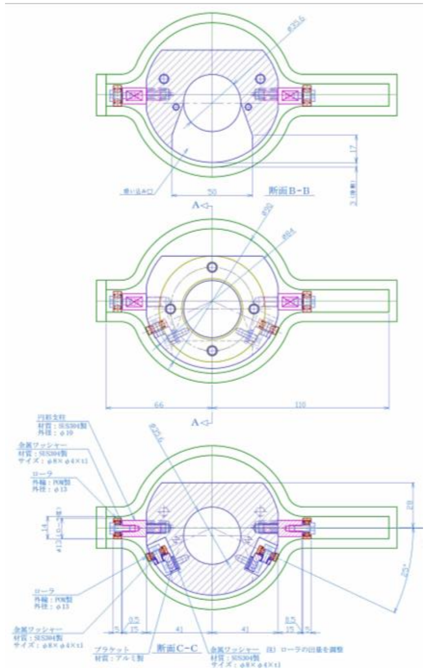


Loss monitor signals

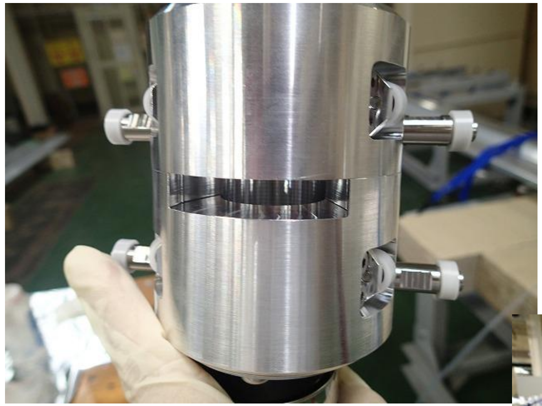


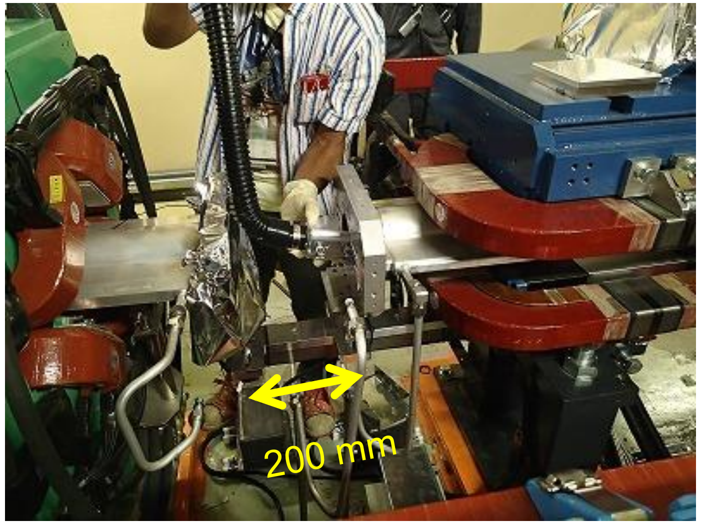
Experiments

- Gathering of dusts from actual beam pipes in the ring.
  - A special tool to cleanup the inside of beam pipes with antechambers was developed.
  - The beam pipes where the pressure bursts had been frequently observed were used.
    - The beam pipes have the grooved structure.
  - After knocking the beam pipe in vacuum, the beam pipe was slowly filled with N_2 and the bellows were removed. Then the dusts at the bottom of beam channel was gathered by a powerful vacuum cleaner.



Special tool to cleanup the bottom of beam channel

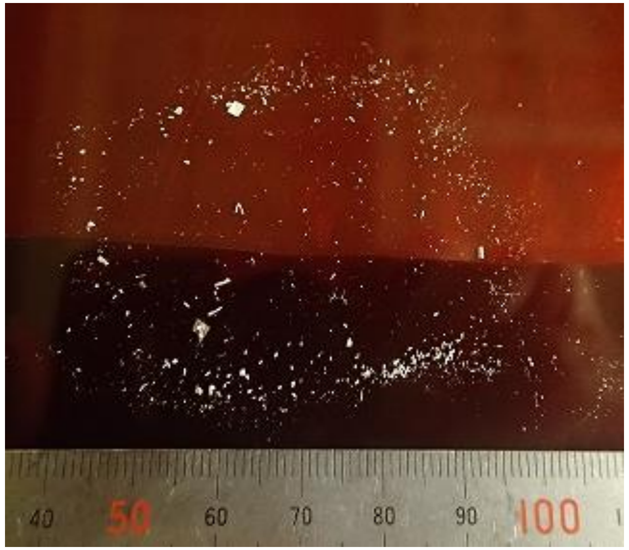




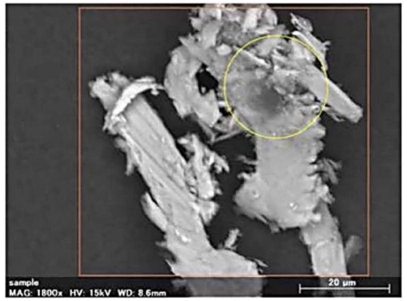
Experiments

- Gathering of dusts from actual beam pipes in the ring.
  - Lots of large (in the order of one hundreds microns) dusts were found from one of the two beam pipes.
    - Small dusts could pass through the filter of the cleaner?
    - We did not check the inside of beam pipes at places where the bursts were not observed.
  - Most typical dust component were Al_2O_3 (chips left after machining aluminum?).
    - Others: Zr, V, Fe, C, O → NEG material, Si, O, C → SiO_2 (sand?)

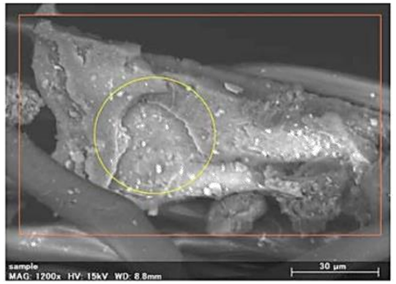
Dust obtained from the beam pipe in question



Typical components of dusts



Element	AN	Series	norm. C [wt.%]	Atom. C [at.%]
Aluminium	13	K-series	41.82	26.09
Carbon	6	K-series	38.51	53.98
Oxygen	8	K-series	17.52	18.43
Magnesium	12	K-series	2.15	1.49
		Total:	100.00	100.00

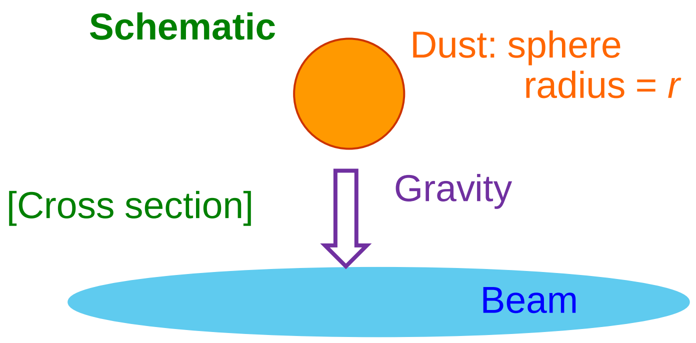


Element	AN	Series	norm. C [wt.%]	Atom. C [at.%]
Carbon	6	K-series	38.53	50.65
Oxygen	8	K-series	34.70	34.24
Silicon	14	K-series	24.53	13.79
Aluminium	13	K-series	2.25	1.31
		Total:	100.00	100.00

Dust size estimation

- Hints:
  - Beam loss lasts for long time, ~ ms.
  - Short beam lifetime, ~ several tens ms.
- Passing time (only gravity, no charge up)
  - ~240 μs for r = 100 μm
  - ~50 μs for r = 10 μm

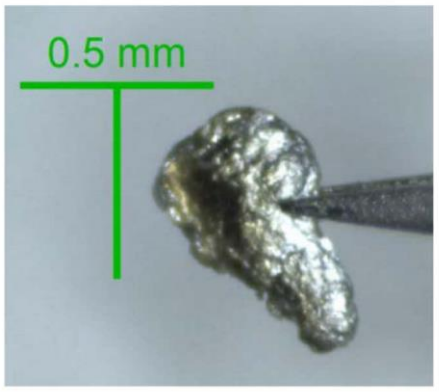
→ Large dusts, over 100 μm~1 mm?

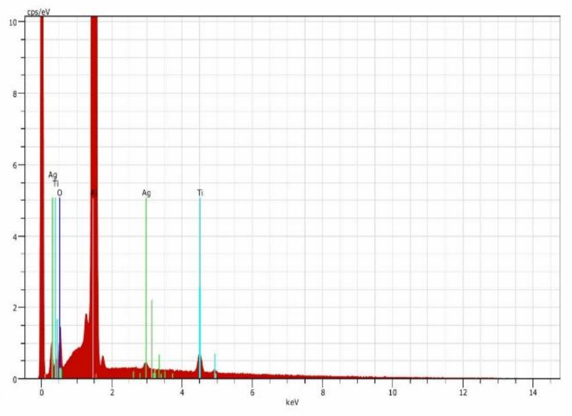


σ_y = 14 μm, pipe radius = 45 mm

- Simple simulation indicated that the dusts with sizes of larger than 100 μm for Al_2O_3 can explain the observed beam loss phenomena.
- Actually, dusts in the order of several hundreds μm were actually found, although smaller dusts were dominant.

Example of a large dust (Al_2O_3) found in the reserved beam pipe.



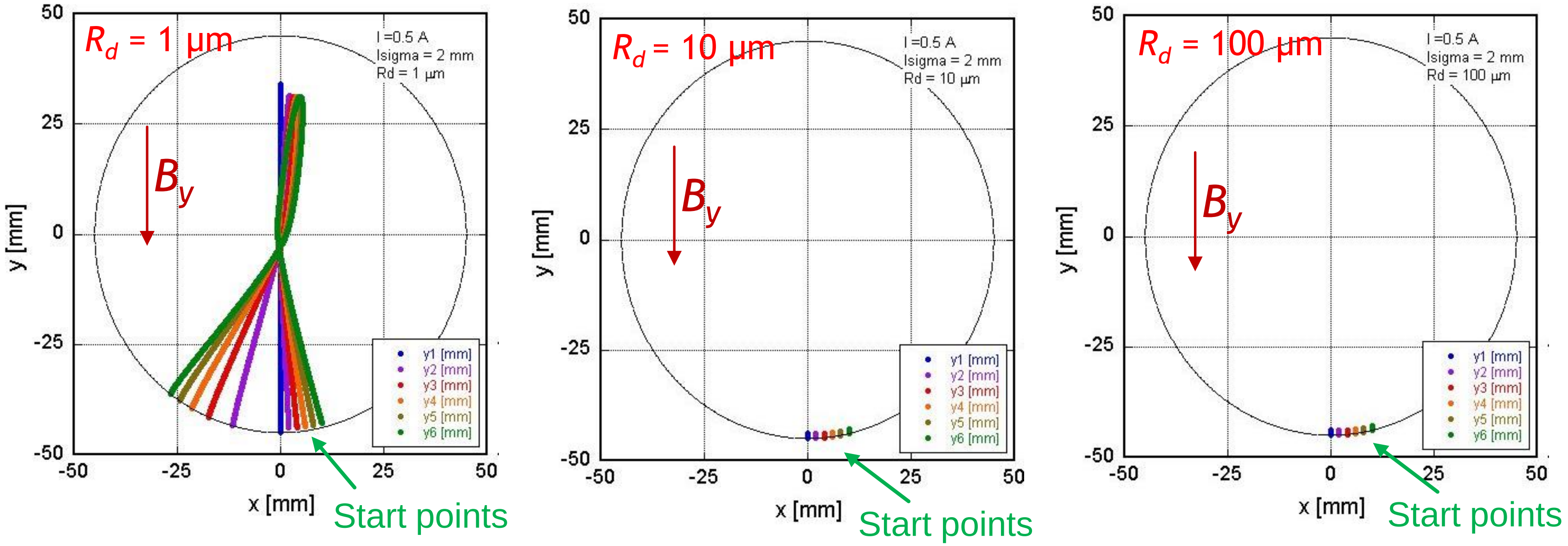


Element	AN	Series	norm. C [wt.%]	Atom. C [at.%]
Aluminium	13	K-series	91.93	90.25
Oxygen	8	K-series	5.00	8.27
Titanium	22	K-series	2.33	1.29
Silver	47	L-series	0.74	0.18
		Total:	100.00	100.00

Counter measures

- It is hardly possible practically to cleanup the all dusts by the cleaner during the commissioning.
- But if the sizes of dusts are large, it is quite unlikely that the dusts are picked up from the bottom of beam channel, which might be charged up by electrons(?).
  - Simple calculation showed that a circular dust with a diameter larger than 10 μm cannot be lift up by the beam. (Dust potential = 10 V, beam current = 500 mA, Initial dust location = 1 mm from the surface to remove mirror charge effect, magnetic field = 2 kG in bending magnet, smooth surface (without groove)).

Calculated orbits of dusts picked up by beam from the bottom of beam pipe

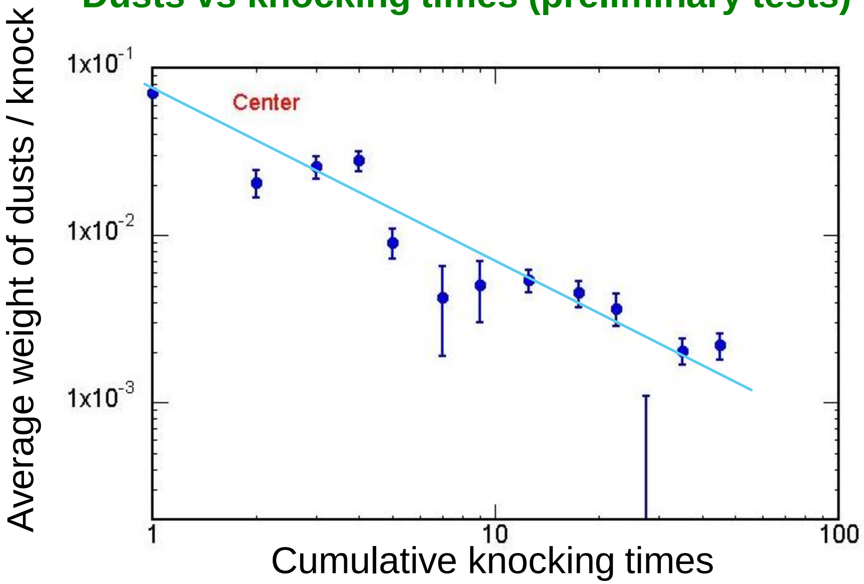


Counter measures

- Under these considerations, we had knocked 24 beam pipes for bending magnets (with groove) around LER Tsukuba straight section for test, where the pressure bursts were frequently observed, and dropped dusts from the top.
- We knocked 150 times for each beam pipe (50 times x 3 locations in a beam pipe), based on the result of preliminary tests using reserved pipes.
  - The amount of dropped dust decreased by orders of magnitude in the experiment at a test bench.

Knocking of beam pipes for bending magnets

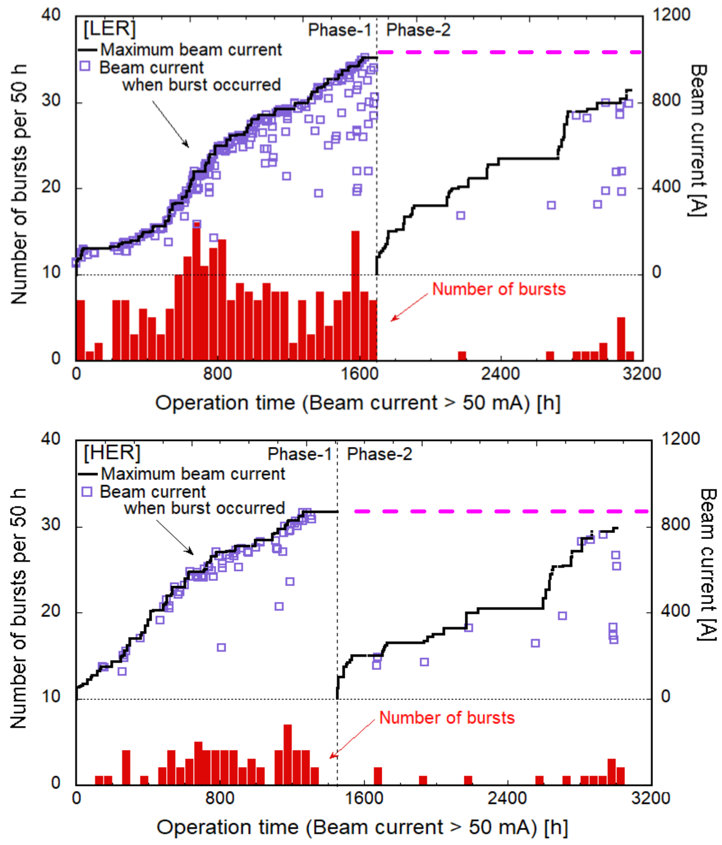
Dusts vs knocking times (preliminary tests)



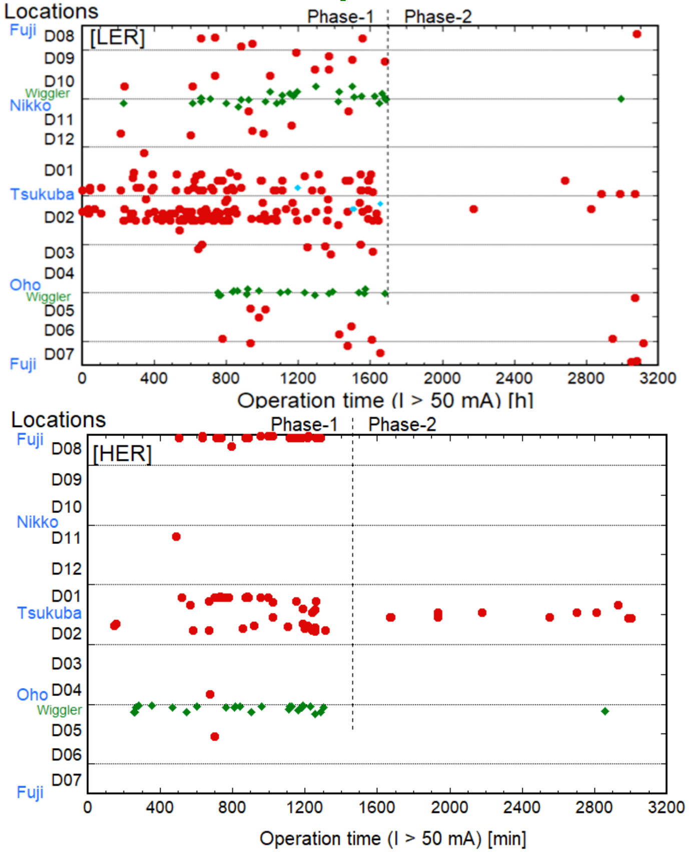
Status in Phase-2

- Frequencies of pressure bursts during Phase-2 operation (Mar. ~ Jul., 2018)
  - The frequency decreased drastically.
  - However, that at sections other than Tsukuba straight section also decreased.
  - Pressure busts were observed at IR (Interaction Region), where new beam pipes were installed.
- Possible reasons
  - Beam currents were lower than that in Phase-1
    →Aging (conditioning) effect?
  - Lower threshold for beam aborts to protect Belle II.?
- Need continued observation.
- All beam pipes in bending magnets of LER were knocked after Phase-2 anyway.

Frequency of pressure bursts



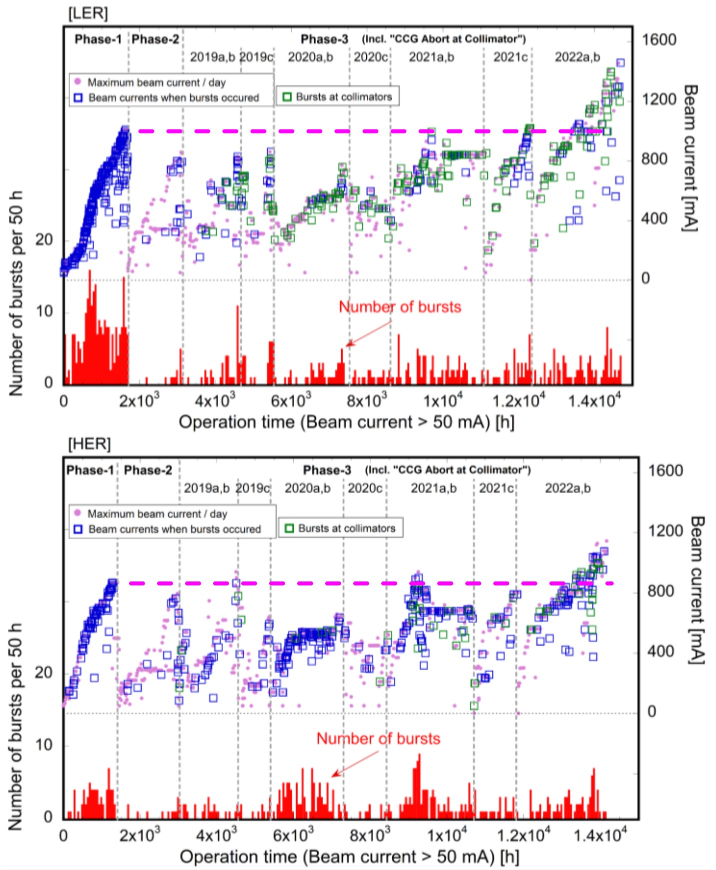
Location of pressure bursts



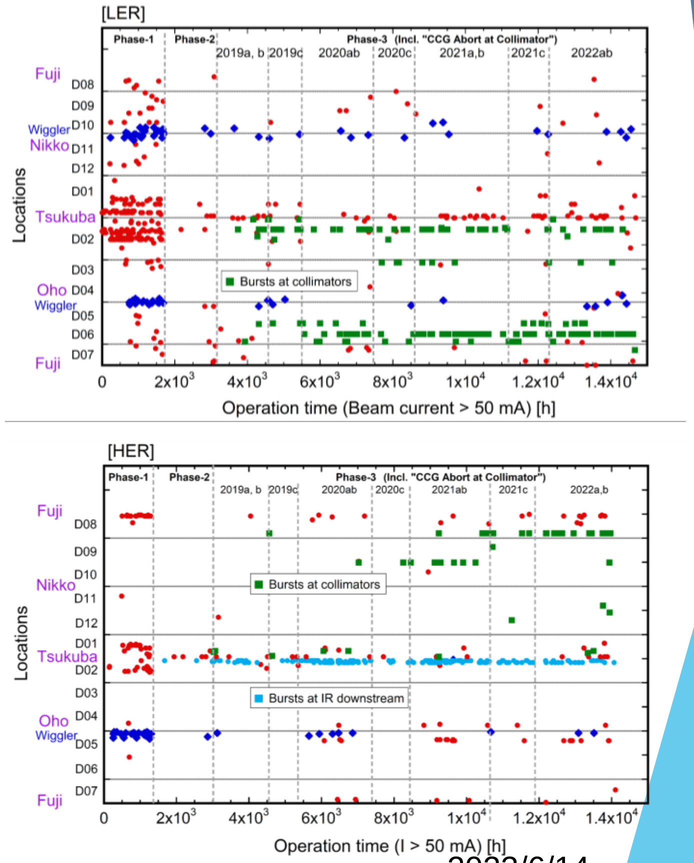
Present status

- Frequencies of pressure bursts up to June, 2022 (Mar., 2019 ~ [Phase-3])
  - Most of pressure bursts were observed at beam collimators and around IR.
    - Pressure bursts at beam collimators sometime indicated the damage of them.
    - The aperture of vertical-type collimators were very small (~ a few mm).
  - For locations other than above, the frequency is still lower than that in Phase-1 even at higher beam currents.
- The knocking seems to be effective in reducing the pressure bursts observed in Phase-1.
- But further careful observation should be continued in the future operation.
  - Conditions such as optics and location of beam collimators are different from Phase-1.
- The relevance to the SBL (Sudden Beam Loss) should be also investigated further.

Frequency of pressure bursts



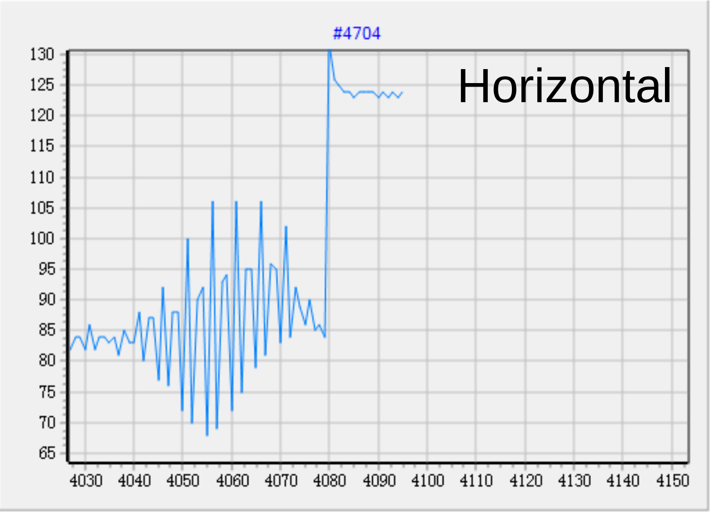
Location of pressure bursts

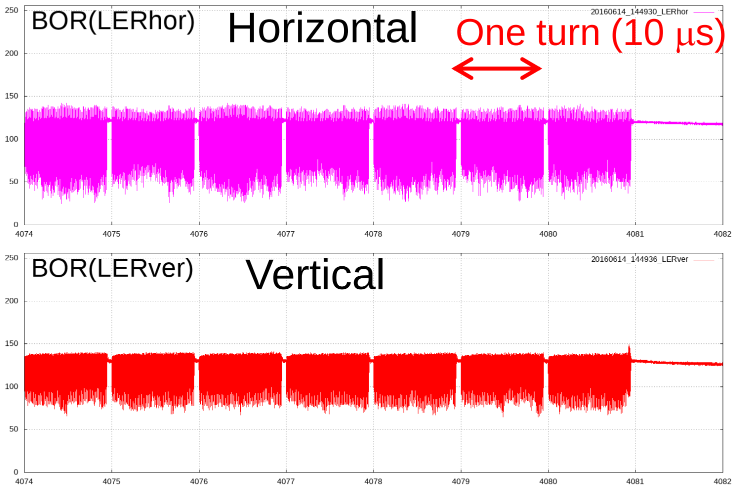


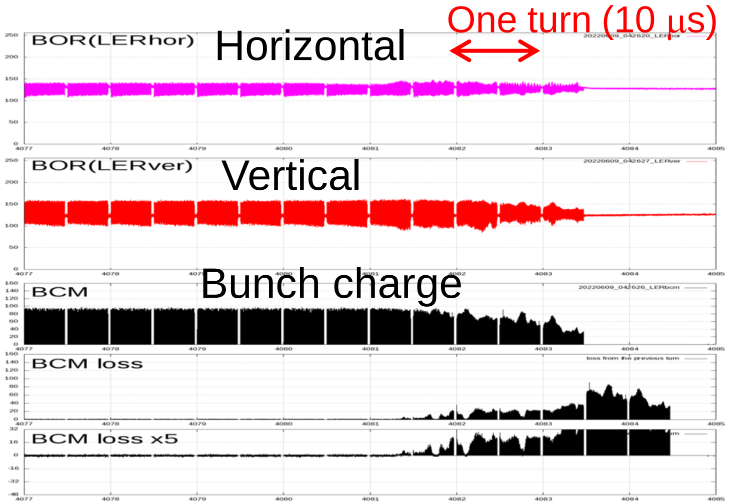
Relevance to SBL (Sudden Beam Loss) at SuperKEKB

- Horizontal oscillation just before the beam abort (M. Tobiyama, S. Terui)
  - Horizontal oscillation was measured by BOR (Bunch Oscillation Recorder).
  - Horizontal oscillation seems to start ~40 turns (~ 400 μs) before abort.

BOR data at a beam abort triggered by a knocking of beam pipe (2016)







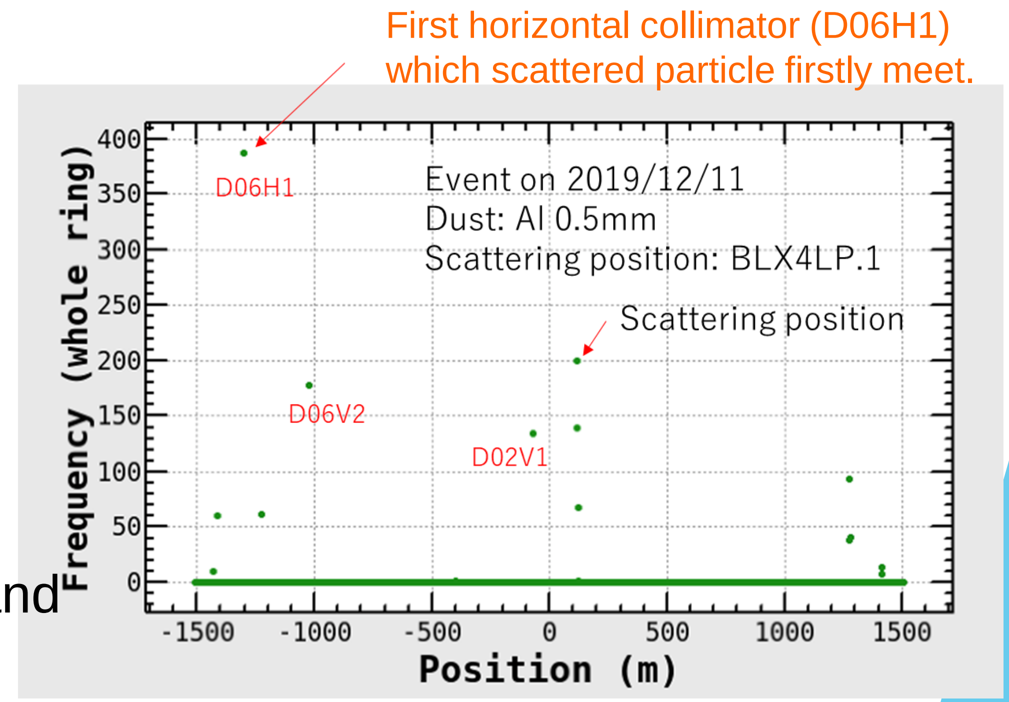
BOR data at a typical SBL

- The behaviors are different from SBL, where the beam loss starts several turns before abort.

Relevance to SBL (Sudden Beam Loss) at SuperKEKB

- Simulation by Y. Funakoshi
  - Presented in the SuperKEKB international task force meeting, 2022/8/31) [https://kds.kek.jp/event/43499/]
  - A dust particle suddenly appeared at the beam orbit and collided with the beam.
    - Dust : Aluminum with a thickness of 0.1 mm to 1 mm. Not at collimator location.
  - All bunch particles collide with the dust particle.
  - The energy loss and the change in the horizontal and vertical angular divergence were calculated by using the PHITS code (S. Terui).
  - Sextupole mis-alignments are included.
  - Beam-beam effect is not included.
- Results
  - About 10% of the beam is lost within 2 turns.
  - In all cases, the number of lost particles is maximum at D06H1 collimator which is the first horizontal collimator after the collision with dust (energy lost particles).
  - In the SBL, such beam loss at the horizontal collimator were not observed.
  - This is a discrepancy between the simulations and the real SBL events.

Simulation result



Summaries

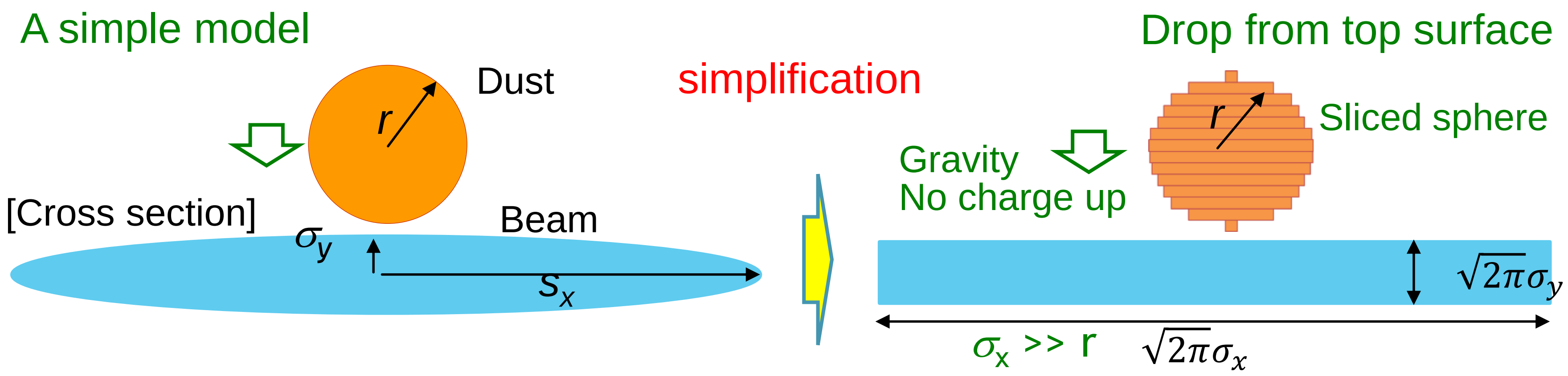
- Pressure bursts accompanied with beam loss had been observed frequently in Phase-1 operation.
- The most possible cause was the collision of “dusts” with circulating beam.
  - Experiments using a knocker reproduced the phenomena.
  - Lots of dusts were actually found in beam pipes.
- As a countermeasure, the beam pipes in bending magnets were knocked.
  - Estimated dust sizes are large, ~several hundreds μm, and the pickup from the bottom will be hardly possible.
  - The frequencies of pressure bursts decreased after the knocking. But, the frequency decreased at locations without knocking…
  - The aging (conditioning) also seems effective.
- Pressure bursts are still observed in Phase-3, but most of them are at beam collimators and IR.
  - The frequency at other than these locations is still low even at high beam currents.
- The relevance to SBL in SuperKEKB is not clear and further investigation is required.
  - There are some discrepancies between them. But it should be noted that the beam optics is quite different from that in Phase-1 operation.
  - Pressure bursts at other than beam collimators were sometimes observed at the same timing.

Thank you for your attention.

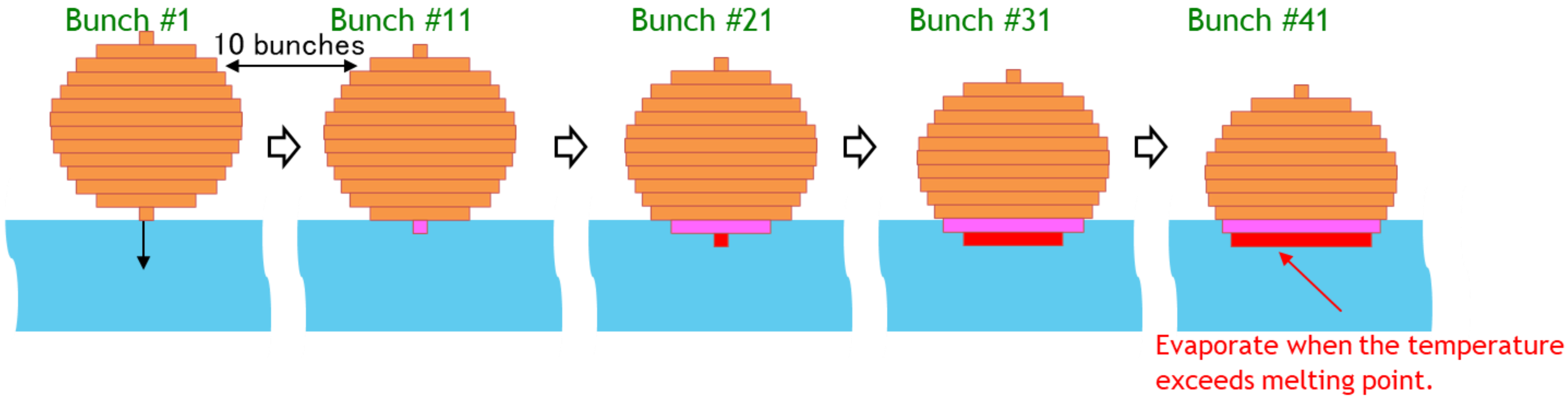
Back up

Dust size estimation

- Model

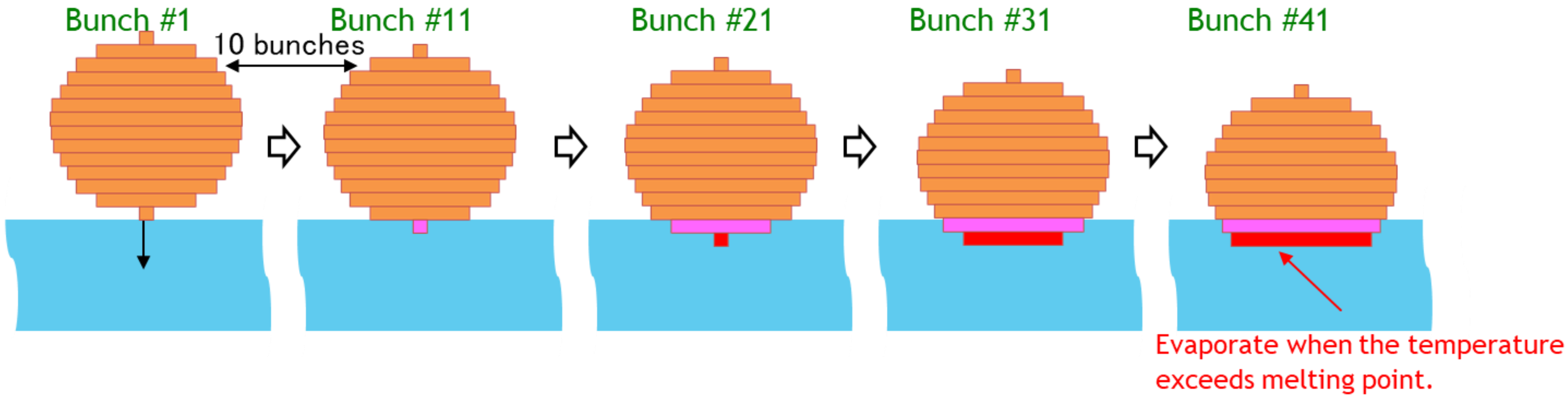


- Calculate temperature of each slice every 10 bunches while the dust is interacting with beam. Height of one slice is ~ 55 nm.
- Assume that the slice evaporates when the temperature exceeds the melting point or the vapor pressure exceeds $1x10^{-2}$ Pa.



Dust size estimation

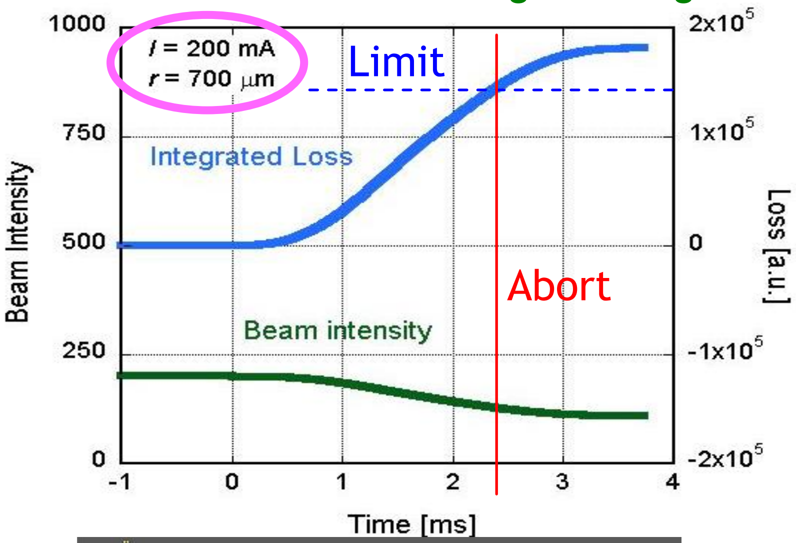
- Calculation methods
  - Following the method used in the dust trapping analysis by F. Zimmermann.
    - For ex., 'Trapped Dust in HERA and Prospects for PEP-II', PEP-II-AP-Note No. 8-94.
    - But, not trapped.
  - Increase in the temperature is calculated from the energy absorption at the overlapped region. (thermally insulated)
  - Decrease in the temperature is calculated from the black body radiation. (much smaller than the increase rate)
  - The beam lifetime is determined from the Bremsstrahlung, the Rutherford scattering and the Möllar scattering.
  - The beam intensity and the beam loss rate are calculated every 10 bunches.

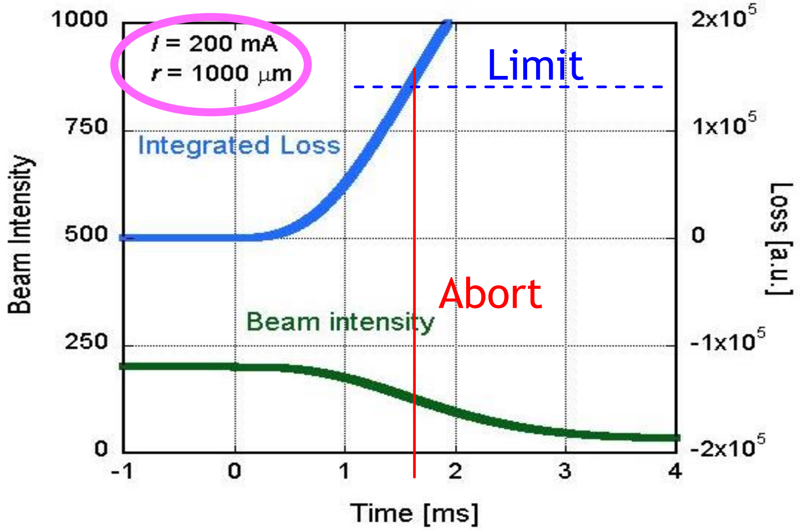


Dust size estimation

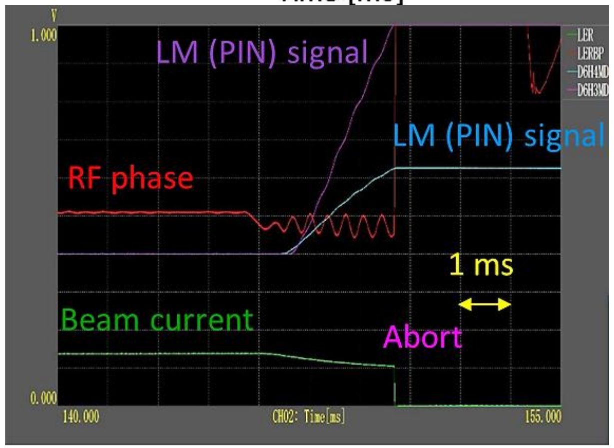
- Typical results
  - Calculated for Al_2O_3, which is the most probable dust in Al beam pipe.
  - We could reproduce the logged data qualitatively for large dusts.

Time change of integrated loss and beam intensity (calculated)

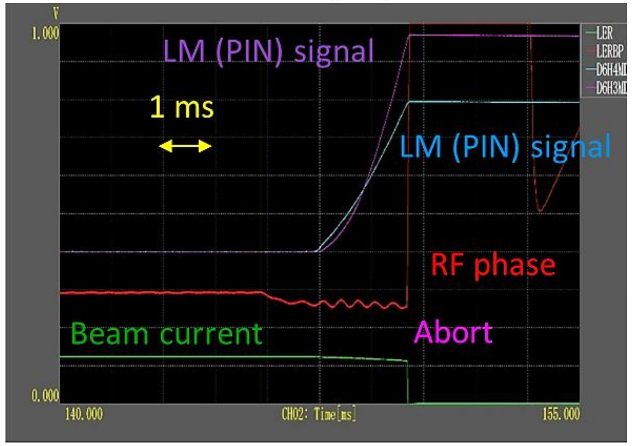




For detail, please check Y. Suetsugu, "Updates of SKEKB MR Vacuum System", 22nd KEKB Review Committee Meeting, 2018. https://www-kekb.kek.jp/MAC/2018/Report/Suetsugu.pdf



Abort log (Measured)



Reference: SBL and X-aborts in KEKB era

- Report by T. Ishibashi
  - Presented in the SuperKEKB international task force meeting, 2022/8/31) [https://kds.kek.jp/event/43499/]
- X-aborts: Beam loss due to RF-fingers damages in KEKB era. Similar beam losses had been observed in PEP-II.
- In the X-aborts in KEKB,
  - Phase changes (beam energy losses) had been observed hundreds of μs before aborts.
  - RF-fingers in bellows chambers were seriously damaged, and this was involved in these beam losses. → collision with melted metal dusts.
  - Abnormal temperature rises at bellows chambers had been observed and the catastrophic damages in the RF-finger had been confirmed.
- In the SBL in SuperKEKB,
  - Beam losses with BCM (Bunch Current Monitor) etc. had been observed dozens of μs before aborts.
  - No apparent energy loss was observed.
  - Abnormal temperature risings at bellows chambers had not been observed so far.

[KEKB review 2006, Y. Funakoshi]