65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)

MITIGATION OF ELECTRON CLOUD EFFECT IN THE SUPERKEKB POSITRON RING

Contents

- Countermeasures for SuperKEKB positron ring
- ECE in Phase-1 commissioning (2016)
- ECE in Phase-2 commissioning (2018)
- Re-evaluation of effectiveness of antechambers, TiN-film coating, and groove structure in the ring
- ECE in Phase-3 commissioning (2019~)
- Summaries

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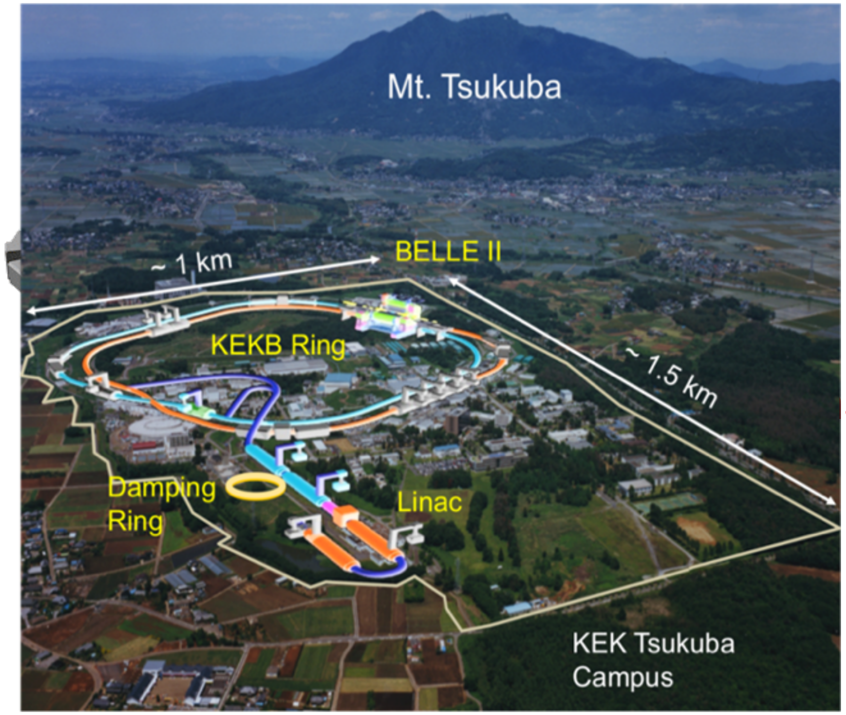
SuperKEKB

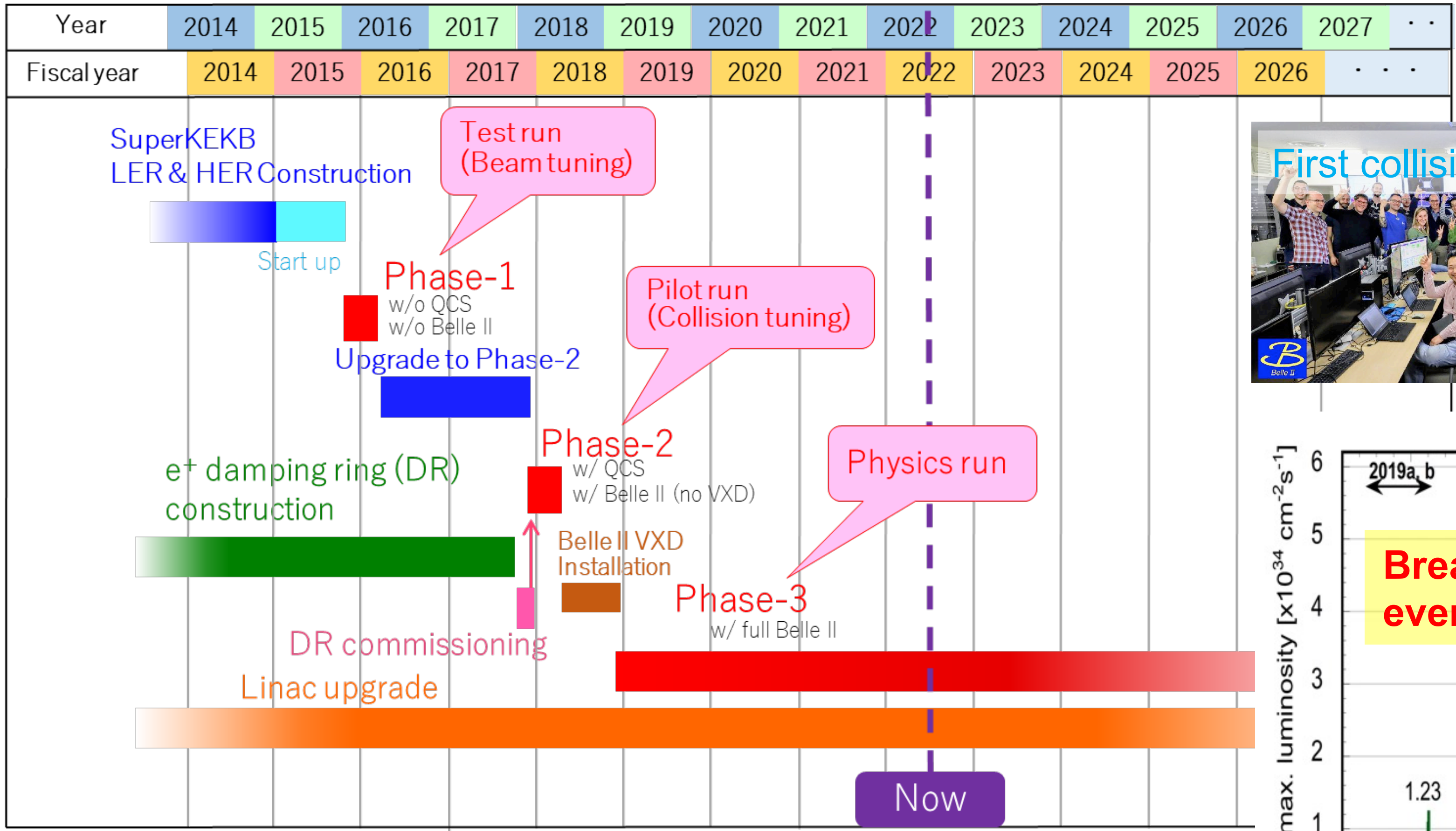
- Upgrade project of KEKB B-factory
  - Quest new theories beyond the standard model at B-meson regime.
  - Located at KEK Tsukuba campus.
- e^- - e^+ two-ring collider consisting of
  - BELLE-II detector
  - Injector (Linac): *L* ~600 m
  - Damping ring (DR) for e^+ : *C* ~135 m
    - 1.1 Gev e^+, 71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

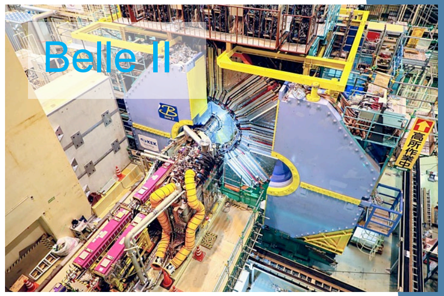


ac)

- The SuperKEKB has been operating since 2016, aiming an unprecedent high luminosity over 1×10^{35} cm^{-2}s^{-1} using "nano-beam collision scheme" with high beam currents, and an integrated luminosity of ~50 ab^{-1} in around ten years.
- Here reported are the summary of studies to mitigate the electron cloud effect (ECE) in the LER and the present status.

Project timeline





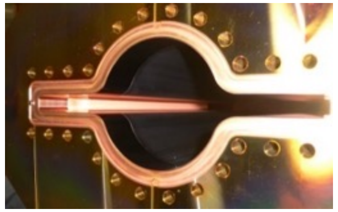
- 2010～2016 Construction (Upgrade work from KEKB)
- 2016/2～6 Phase-1: Test operation (Beam tuning)
- 2018/3～7 Phase-2 : Commissioning operation (Collision tuning) with final focusing SC magnets, Belle II Detector and DR.
- 2019/3～ Phase-3 : Physics operation

Countermeasures for SuperKEKB LER

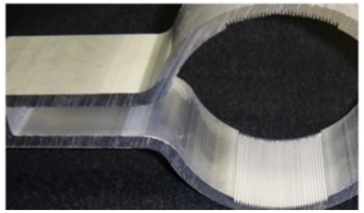
- Summary of countermeasures

Antechamber

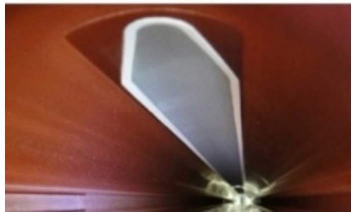
TiN coating



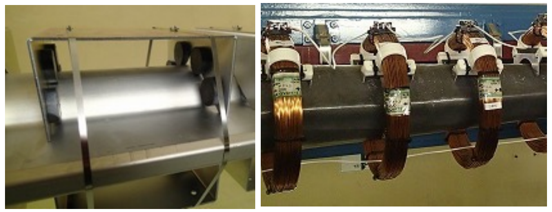
Groove



Clearing electrode



Magnetic field in the beam direction, B_z (Permanent Mag., Solenoid)



Countermeasures in SuperKEKB positron ring (Antechamber is default)

Sections	L [m]	L [%]	Countermeasure	Material
Drift space (arc)	1629	54	TiN coating + Solenoid (B_z)	Al (arc)
Steering mag.	316	10	TiN coating + Solenoid (B_z)	Al
Bending mag.	519	17	TiN coating + Groove	Al
Wiggler mag.	154	5	Clearing Electrode	Cu
Q & SX mag.	254	9	TiN coating	Al (arc)
RF section	124	4	(TiN coating +) Solenoid (B_z)	Cu
IR section	20	0.7	(TiN coating +) Solenoid (B_z)	Cu
Total	3016	100		

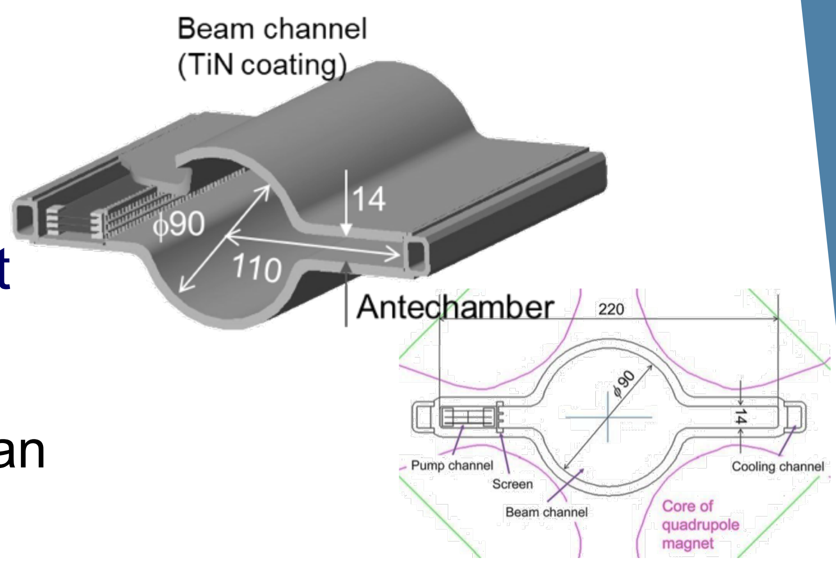
- No B_z at drift spaces when Phase-1 commissioning started.
- For DR (e^+ ring), antechambers, TiN-film coatings, and grooves in bending magnets were also adopted.

- Goal: electron density (n_e) around beam < $1\text{x}10^{11}$ m^{-3} (MR)
  - Predicted threshold of ECE ~ $3\text{x}10^{11}$ m^{-3} (Y. Suzaki *et al.*, IPAC'10)

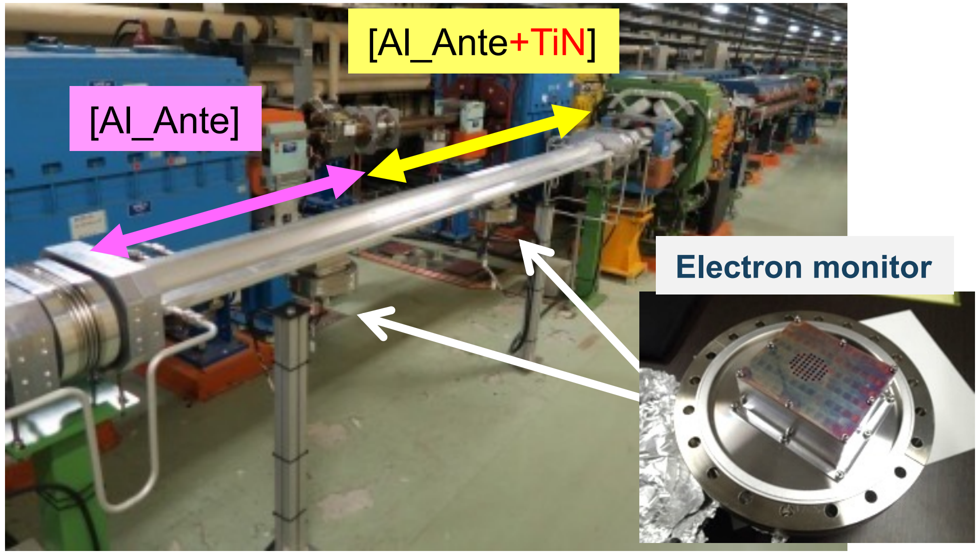
Measurement of electron density (n_e) around beam

- To measure n_e around the beam for test, two electron-current monitors were installed in a test beam pipe in the LER.
  - Equipped with a retarding grid and a collector.
- n_e was estimated from the measured electron current by a formula derived by K. Kanazawa (PAC’05)
  - n_e in the beam pipes with different surfaces, such as those with and without TiN-film coating, for example, can be measured at the same time.

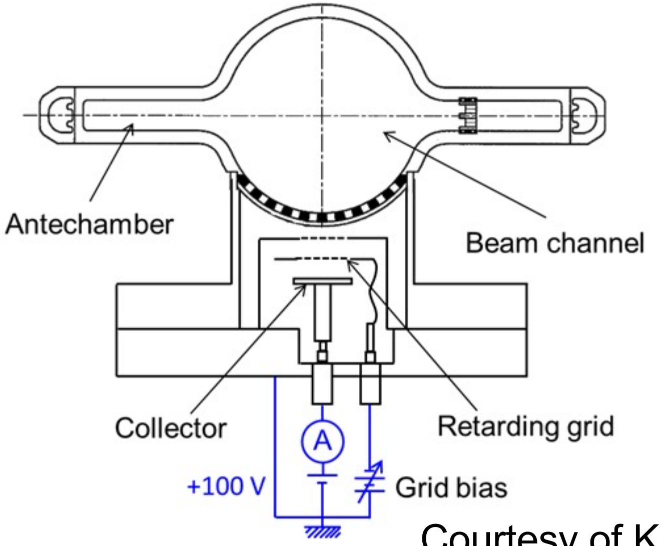
Typical beam pipe at arc



Test chamber in LER arc section



Cross section of electron monitor

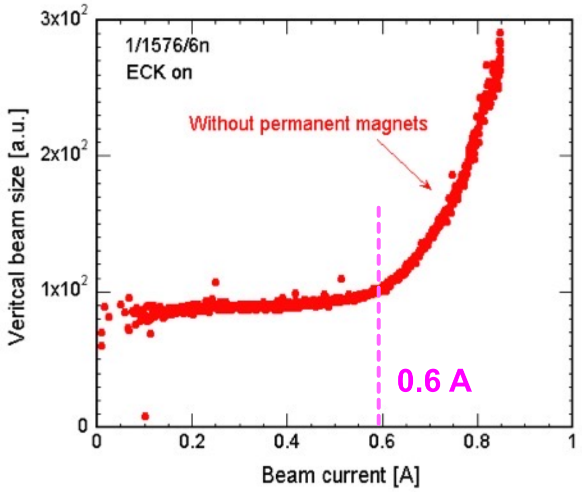


Courtesy of K. Kanazawa

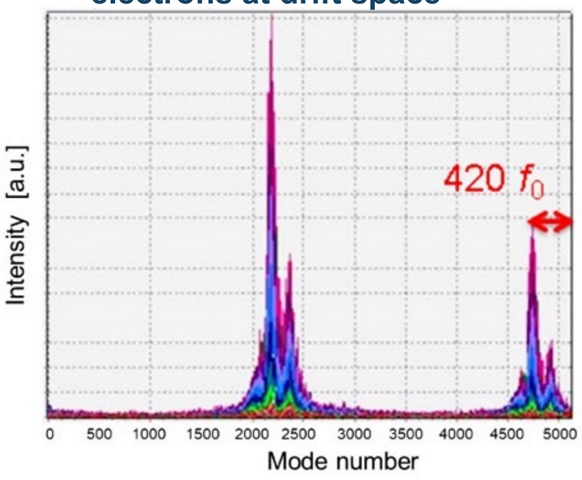
ECE in Phase-1 commissioning (2016) -1

- ECE was first observed in Phase-1 at a beam current ~0.6 A for ~3 RF-buckets (6 ns) spacing, 1576 bunches (1/1576/3.06RF), a beam current lower than expected.
  - Non-linear increase in pressure
  - Blow-up of vertical beam size
  - Coupled bunch instabilities (CBI) at typical modes for ECE
- The ECE (beam-size blow-up) began at almost the same "current linear density (I_d)" of ~0.12 mA/bunch/RF-bucket even for different bunch spacings.
  - The current linear density (I_d) : the bunch current divided by the bunch spacing.
  - One of characteristics of ECE.

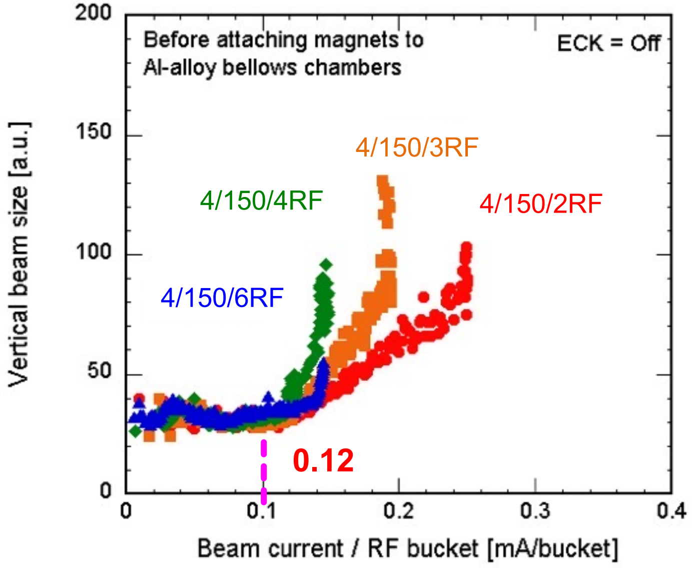
Non-linear pressure rise



Typical CBI modes caused by electrons at drift space



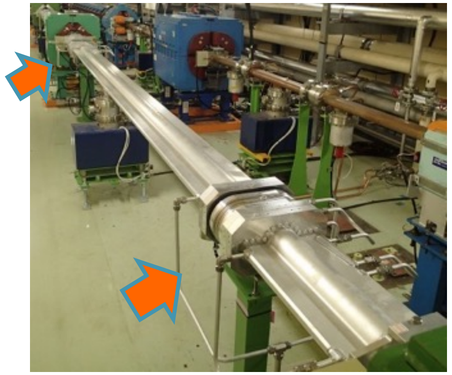
Vertical beam size blowup



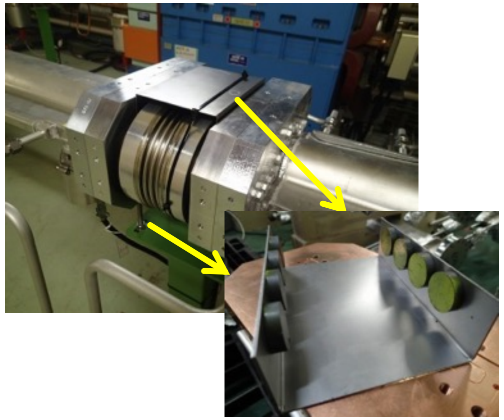
ECE in Phase-1 commissioning (2016) -2

- The cause of ECE was found to be the electron cloud in aluminum (Al) bellows chambers without TiN-film coating.
  - Although the total length is ~160 m, i.e. ~1/20 of the ring circumference, the measured n_e at aluminum region without TiN coating was high ~6x10^{12} m^{-3}, ~20 times of the threshold.
- As a countermeasure, permanent magnet (PM) units generating B_z of ~100 G (Max.) were attached to all the Al bellows chambers.
  - A C-shape iron-plate yoke + 8 permanent magnets (ϕ30 ferrite magnet)
  - The same effect with a solenoid of B_z ~ 50 G.
- The threshold of I_d where ECE began to appear went up from 0.12 to 0.2 mA/bunch/RF-bucket.
  - The ECE was relaxed to an extent.

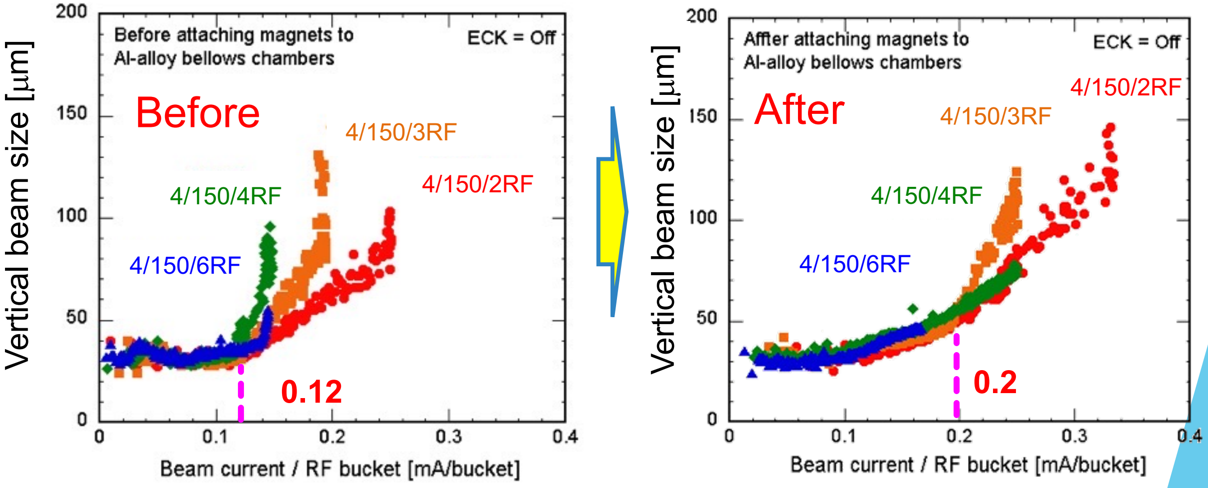
Al bellows chambers along the ring



Permanent magnets (PMs) attached to bellows chamber



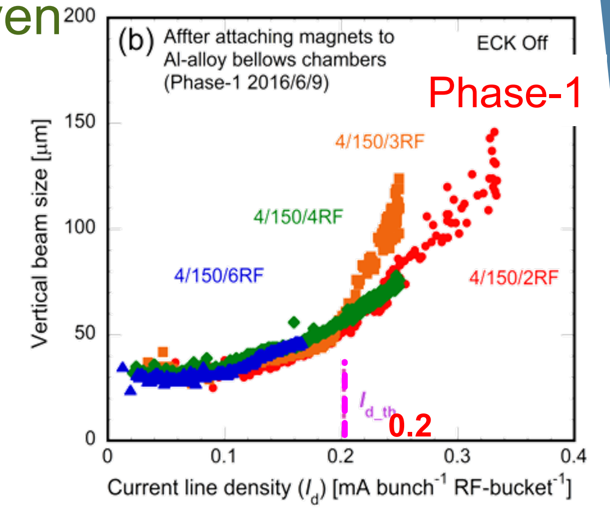
Vertical beam size blowup vs. current linear density
Before and after attaching PMs to Al bellows chambers

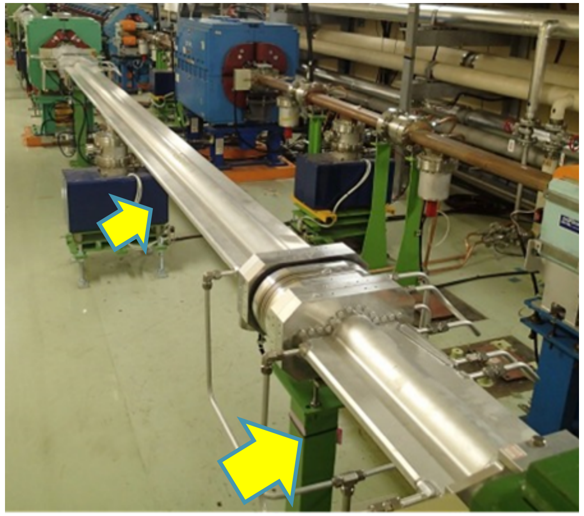


ECE in Phase-1 commissioning (2016) -3

- But, ECE still remained over I_d ~0.2 mA/bunch/RF-bucket.
  - Blow-up of beam size and non-linear increase in pressure.
  - Coupled bunch instabilities caused by electrons in drift spaces.
  - n_e increased near to the threshold (~3x10^{11} m^{-3}) at the region even with TiN-film coating for 2 and 3 RF-bucket spacings.
- These indicated the electron cloud was formed in the beam pipes with antechambers + TiN-film coating at drift spaces.

Vertical beam size blowup vs. current linear density





ECE in Phase-1 commissioning (2016) -3

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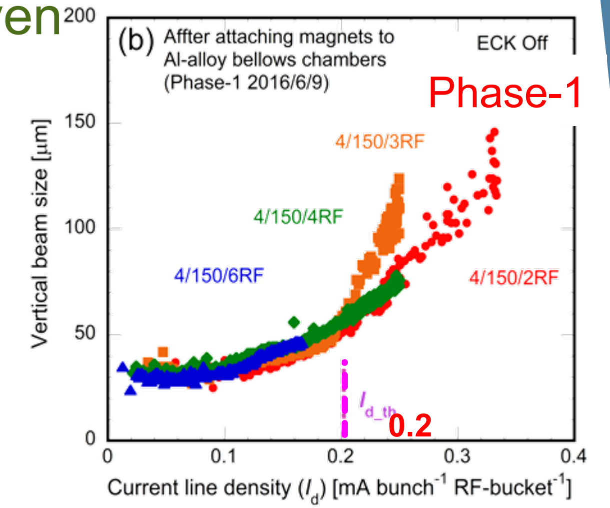
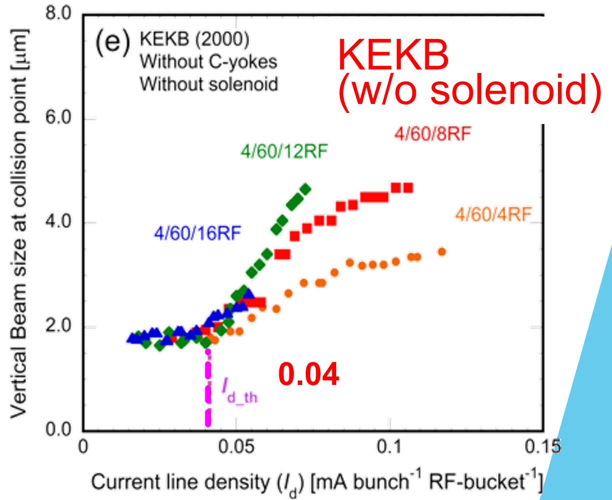
- These indicated the electron cloud was formed in the beam pipes with antechambers + TiN-film coating at drift spaces.
- The excitation of ECE in Phase-1 pointed out;
  - The countermeasures in Phase-1 are insufficient, and additional countermeasures are required before starting the next Phase-2 commissioning.
  - The re-evaluation of the effectiveness of antechambers and TiN-film coating in the real ring is necessary to check whether they are working as expected.
    - For reference, the threshold of I_d is higher than that of KEKB beam pipe where circular copper beam pipes without any coating were used. The antechamber and TiN coating are working to an extent.

Vertical beam size blowup vs. current linear density

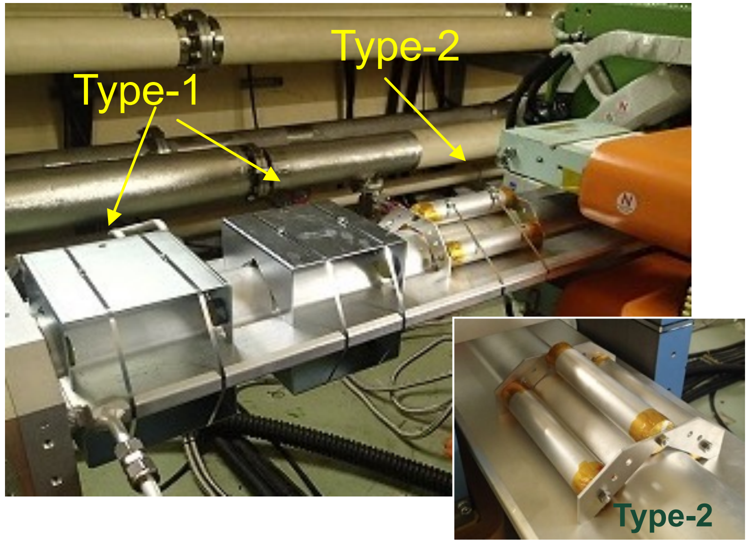




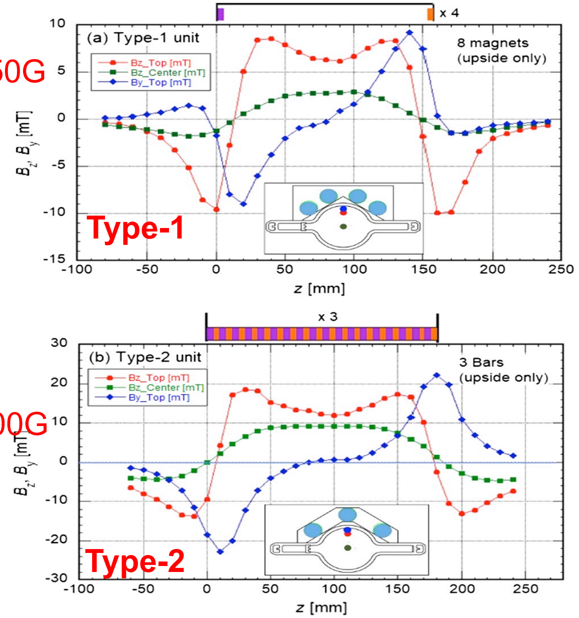
Additional countermeasures for Phase-2 commissioning

- Permanent magnets were attached to beam pipes at drift spaces.
  - Type-1 unit: PM units with iron yokes; eight ferrite magnets ($\phi 30$) + one iron plate (L160 mm), aligned with 40 mm gap.
  - Type-2 unit: PM units in Al cylinders; 21 ferrite magnets ($\phi 30$) in each Al cylinder (L180 mm). No ferromagnetic materials. -> placed close to electromagnets
- Approximately 86 %of the drift space of the ring (~2 km) was covered by B_z with a strength higher than 20 G before starting the Phase-2 commissioning.
- A simulation by CLOUDLAND indicated a sufficient reduction of n_e even for the designed beam parameters.

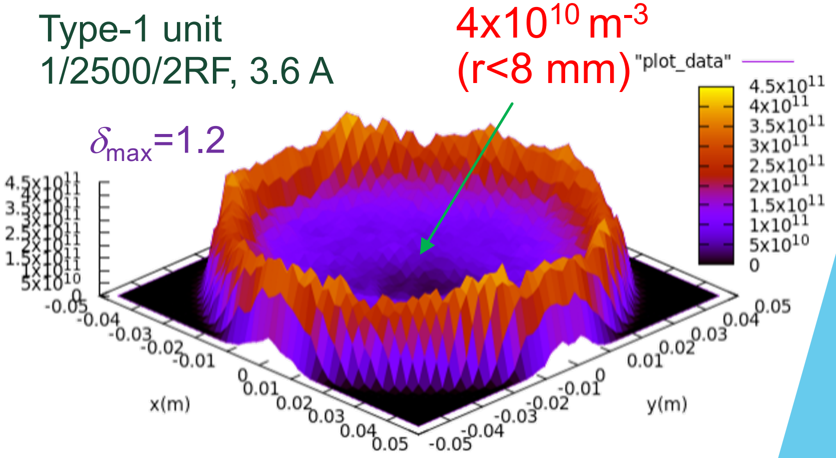
Type-1 and Type-2 units near Q magnet



Measured B in PM units



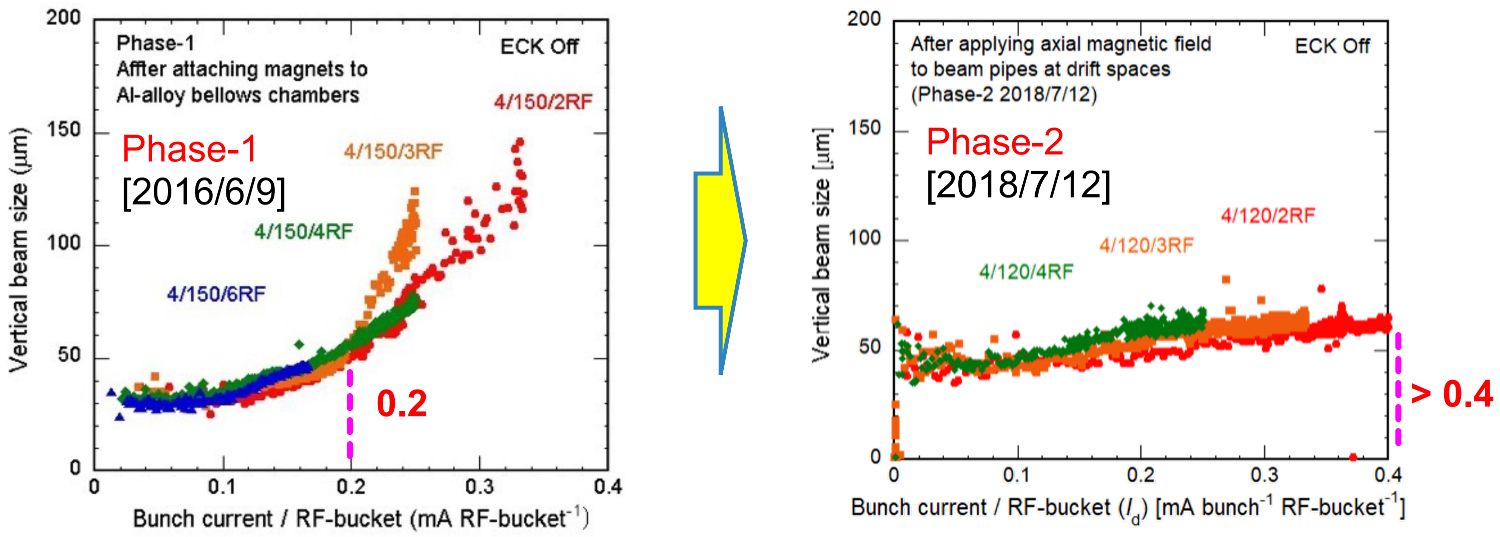
Calculated n_e in Type-1 units for the designed beam parameters



ECE in Phase-2 commissioning (2018)

- The excitation of ECE was checked in June, 2018.
- ECE was not observed until I_d ~ 0.4 mA/bunch/RF-bucket (the max. I_d in the Phase-2 commissioning).
  - No beam size blow-up
  - No non-linear increase in pressure
  - The modes of the CBI excited by the electrons at the drift space were not observed, but those excited by electrons near the inner wall trapped by B_z were detected instead.
    - Note that the CBI was well suppressed by the bunch by bunch feedback system.
- ECE was well suppressed by applying B_z in drift spaces.
  - Any harm on the optics by these PM were not observed, such as an increase in x-y coupling.

Vertical beam size vs. current linear density

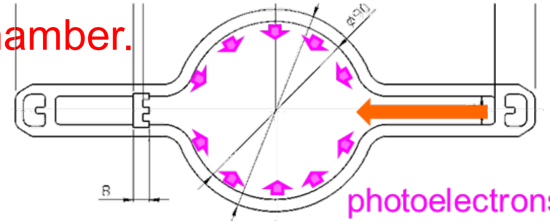


Re-evaluation of antechamber and TiN coating -1

- Figure of merit of antechambers : α

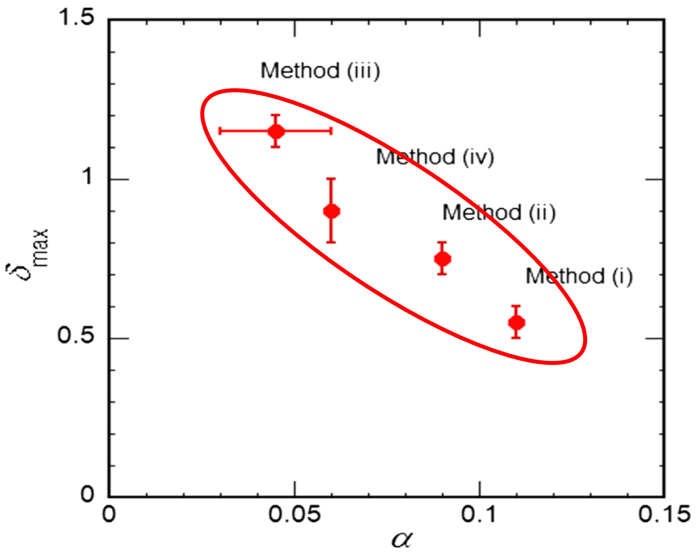
$$\alpha \equiv \frac{\text{Photoelectrons in the baem channel}}{\text{Total numbers of photoelectrons}}$$

- For a circular beam pipe, α = 1.
- Lower α means higher effectiveness of antechamber.

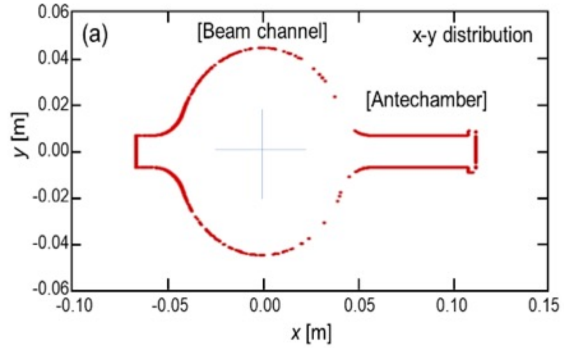


- Figure of merit of TiN-film coating: δ_{max}
- Re-evaluation methods; Y. Suetsugu et al., PRST-AB, 22, 023201 (2019)
  i. From the measured n_e with/without photoelectrons from antechambers,
  ii. From photon distribution calculation using Synrad3D codes,
  iii. From the behavior of the measured n_e against the beam current,
  iv. From the dependence of the measured n_e on the bunch train lengths comparing the results calculated by PyECLOUD codes

- Summary of results
  - α = 0.05 ~ 0.11
  - δ_{max} = 1.1~0.5



Photon distribution (Synrad3D)

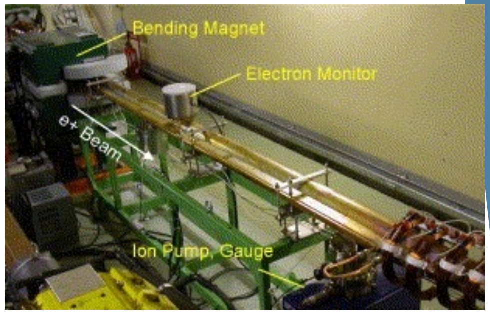


- 5~11% of total photons are hitting beam channel.

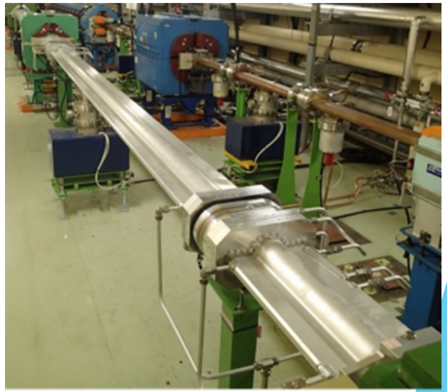
Re-evaluation of antechamber and TiN coating -2

- In conclusion, the estimated values of α were less than 0.11, but larger than that obtained in the experiments of KEKB, i.e. 0.01.
- As for δ_{max} of TiN coating, the values are close to or somewhat lower than those obtained in the laboratory (~1.0).
- This large α in the SuperKEKB will be explained by:
  - (1) Location in the ring : Just downstream (< 1 m) of bend magnet [KEKB], or ~7 m downstream of it [SuperKEKB]
  - (2) Height of antechamber: 18 mm [KEKB] or 14 mm [SuperKEKB]
  - (3) Material: Cu [KEKB] or Al-alloy (TiN coating) [SuperKEKB]
  - (4) Treatment of side surface of antechamber, etc.
  - Among these, reasons (a) and (b) seem the most plausible; Some photons from upstream should hit the beam channel far downstream of the bending magnets because of the vertical spread and scattering of SR in the real machine.
- Importance of suppressing the photoelectrons were recognized.

Test in KEKB



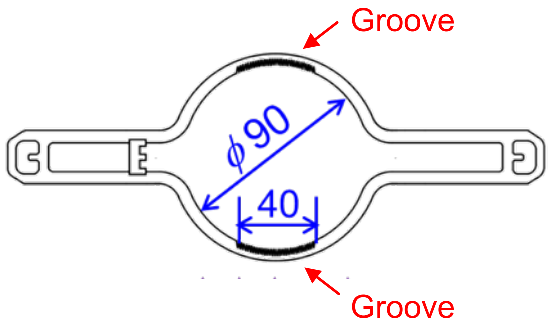
SuperKEKB



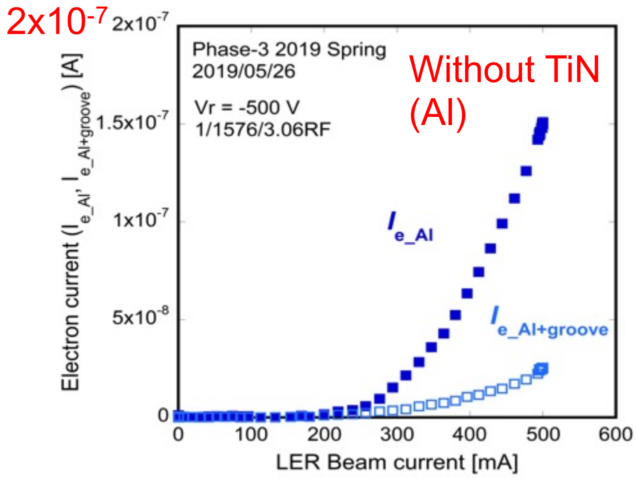
Re-evaluation of groove structure -1

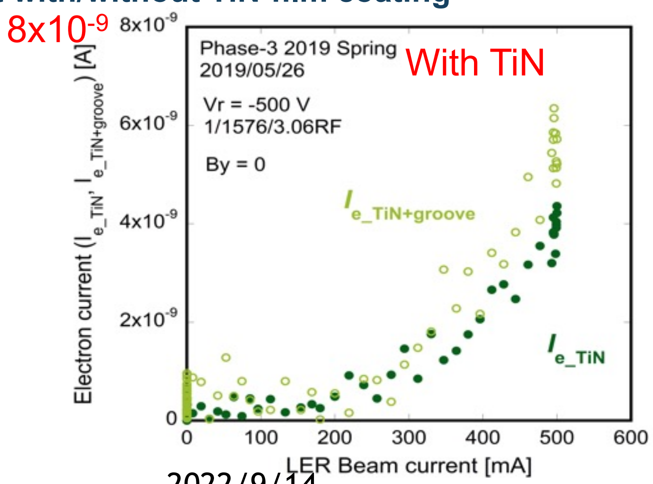
- The effectiveness of the groove structure of the real beam pipe was re-evaluated.
  - The groove structure was formed at the top and bottom of the beam channel in dipole magnets to reduce the SEY.
- Without TiN: The values of electron currents I_{e_Al} (without groove) is much higher than that of $I_{e\_Al+groove}$ (with groove), and the effectiveness is clear.
- With TiN: the values of I_{e_TiN} (without groove) and $I_{e\_TiN+groove}$ (with groove) are almost the same.
- The reasons are:
  - For the case without TiN-film coating, since the SEY (Al) is high, the n_e is in the order of 10^{12} m^{-3}. Then the SEY plays a large role and the effect of groove is observed clearly.
  - On the other hand, for the case with TiN-film coating, since the SEY (TiN-film) is low, the photoelectron plays a large role. Then the effect of groove is small.

Cross section of beam pipe with groove



Measured electron current with/without TiN-film coating

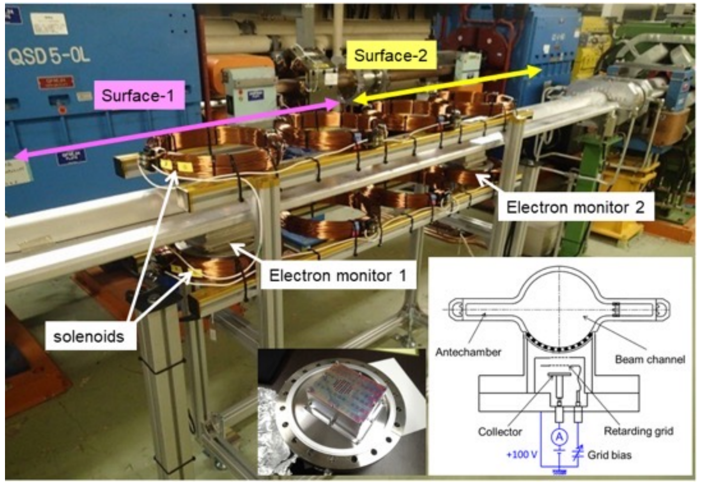


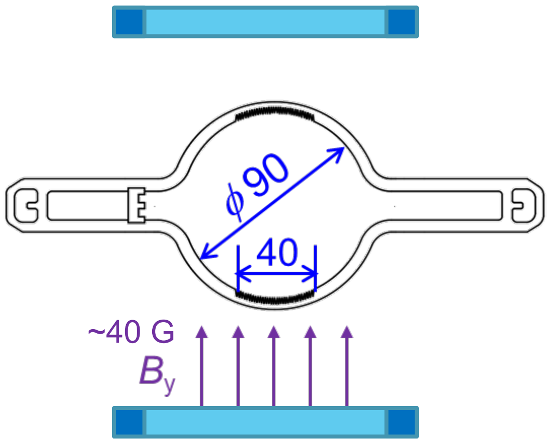


Re-evaluation of groove structure -2

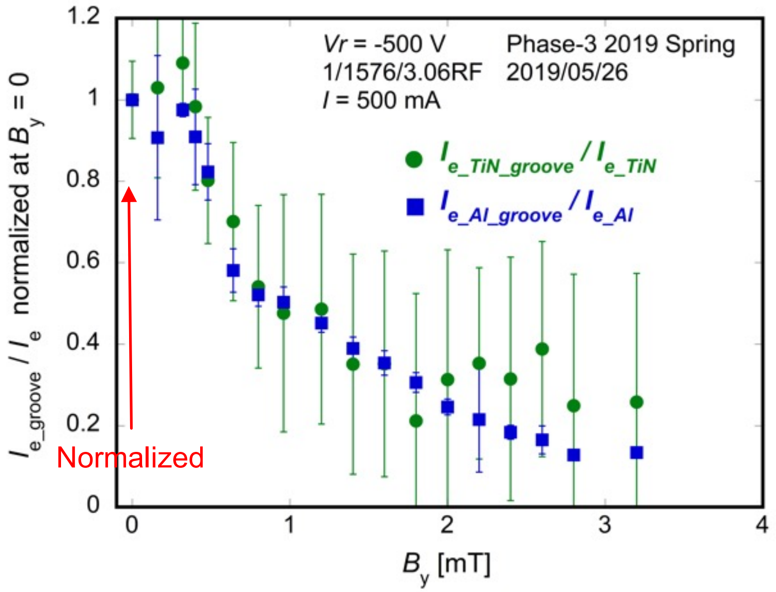
- Expecting that the effect of the groove structure became prominent, the electron currens were measured applying a weak B_y at the location of the electron monitors.
  - The groove structures are at the top and bottom of the beam channel.
  - The movement of electrons are restricted in vertical direction by applying B_y.
  - The photoelectrons from the side of the beam pipes are suppressed.
- The ratio of I_e with groove (I_{e_groove}) to that without groove (I_e) decreased with B_y regardless of with and without TiN film coating.
- This means qualitatively that the SEY of the groove structure is smaller than that of the smooth surfaces.

Test beam pipe with solenoids





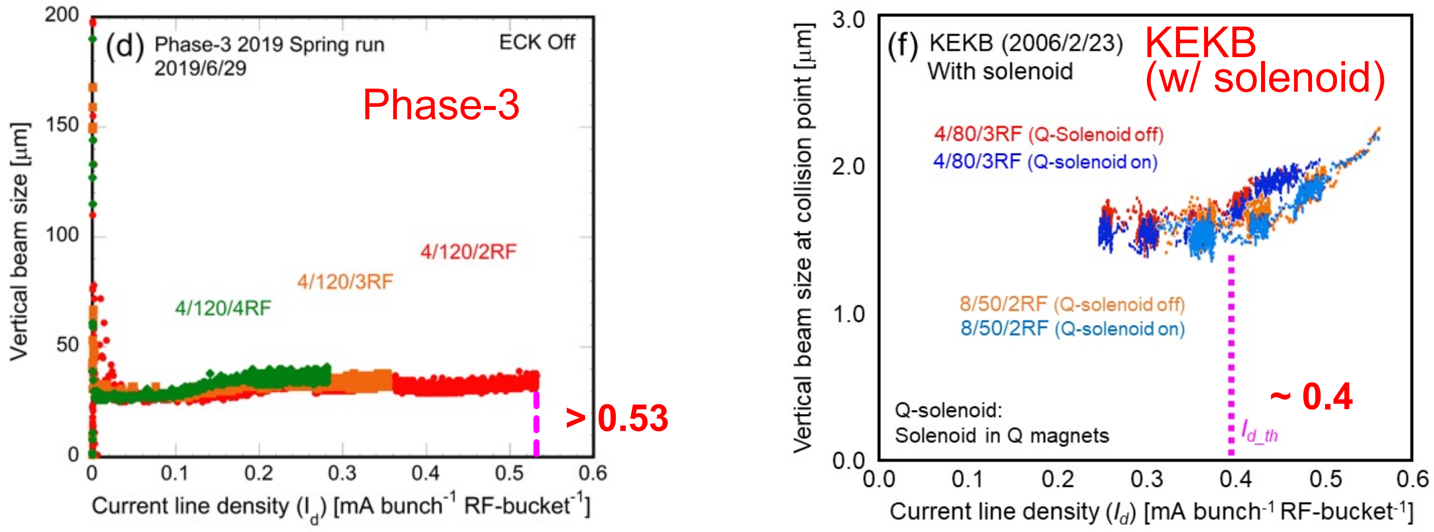
Ratio of I_e with groove to that without groove



ECE in Phase-3 commissioning (2019)

- The excitation of ECE was checked in June, 2019.
  - PM units were further added in the drift spaces, up to approximately 91% of the drift spaces before starting Phase-3 commissioning.
- ECE was not observed until I_d ~ 0.53 mA/bunch/RF-bucket (the max. I_d at that time).
  - The pressure increased almost in proportion to the beam current.
  - No beam size bow-up was observed.
  - The CBI modes related to the electron cloud at the drift spaces were not observed.
- B_z produced by the PMs is working effectively to suppress ECE so far.
  - The I_d of 0.53 mA bunch^{-1} RF-bucket^{-1} corresponds to approximately 2.5 A for the bunch fill pattern of 1/2400/2RF.

Vertical beam size vs. current linear density



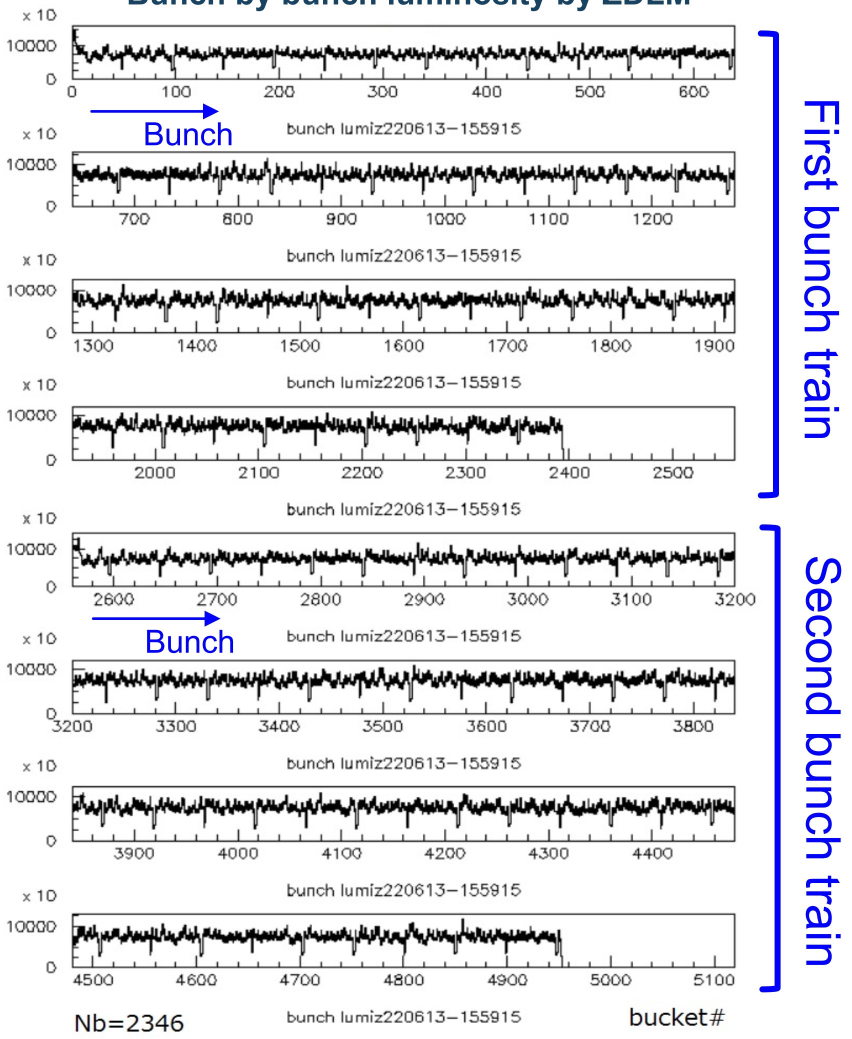
- Note that the threshold of I_d in Phase-3 is higher than that of KEKB beam pipe after winding the solenoids for most of drift spaces.

ECE in Phase-3 commissioning (2022)

- The luminosity of each bunch was measured by ZDLM (Zero Degree Luminosity Monitor).
  - The electromagnetic calorimeters which aim to measure the bunch-by-bunch luminosity.
  - The calorimeters detect electromagnetic showers induced by photons or positrons from the radiative Bhabha scattering.

ZDLM

Bunch by bunch luminosity by ZDLM



- As seen in the figure, the bunch luminosity seems to be flat along the train, and there is no apparent "long-term" change for each train, which would be resulted in due to the beam-size blow-up caused by the ECE. (2/1173/2.04RF)
  - A piece of supporting evidence that there is no beam size blow-up caused by the ECE during the physics run.

Courtesy of S. Uehara, Belle II

Summaries

- Countermeasures for SuperKEKB
  - Various countermeasures were adopted on the basis of R&D results obtained in various machines.
- ECE in Phase-1 commissioning (2016)
  - The ECE due to Al bellows was suppressed by permanent magnets.
  - The ECE due to beam pipes with antechambers and TiN coating was remained.
- ECE in Phase-2 commissioning (2018)
  - Permanent magnets or solenoids were attached to beam pipes at drift spaces for ~ 86 % in length before starting Phase-2 commissioning.
  - As a result, the ECE was not observed until 0.4 mA bunch^{-1} RF-bucket^{-1}.
- Re-evaluation of antechambers and TiN coating in the ring
  - Number of photoelectrons in the beam channel is larger than expected.
  - The maximum SEY, δ_{max}, is close to that expected in laboratory.
- Re-evaluation of groove structure in the real beam pipe
  - The reduction of SEY was qualitatively confirmed.

Summaries

- ECE in Phase-3 commissioning (2019~)
  - Permanent magnets or solenoids were attached to beam pipes at drift spaces for ~ 91 % in length before Phase-3 commissioning.
  - The ECE has not been observed until 0.53 mA bunch^{-1} RF-bucket^{-1}.
  - No indication of ECE was observed in usual collision experiments so far.

- Countermeasures for SuperKEKB have been working well up to now.
- However, the examined maximum threshold of I_d (0.53 mA bunch^{-1} RF-bucket^{-1}) is lower than the designed I_d (0.7 mA bunch^{-1} RF-bucket^{-1}). Careful observations of ECE should be continued in the future.

Thank you for your attention.

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