Updates of SKEKB MR Vacuum System

Y. Suetsugu, KEK
on behalf of KEKB Vacuum Group

Contents

- Two major topics: Countermeasures against;
  - Electron cloud effect in LER
  - Pressure bursts accompanying beam loss in LER
- Other preparations for Phase-2 commissioning
  - Installation of new beam collimators
  - Replacement of beam pipes at LER injection region
  - Etc.
- Summary

Electron cloud effect

Brief review:

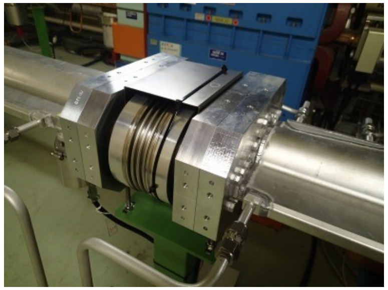
- The first ECE was observed at a beam current of ~600 mA (1/1576/3.06RF), which was caused by EC in the aluminum bellows chambers.
- This ECE was cured by permanent magnets around the bellows chambers.
- However, ECE was again observed at a beam current of ~900 mA (1/1576/3.06RF).
- As a source of EC, the TiN-coated beam pipe with antechambers at drift spaces was suspected.
  - Measured electron density is near to the threshold of the instability, ~3x10^{11} e^{-} m^{-3}
  - Permanent magnets around the beam pipes suppressed the non-linear pressure rise.

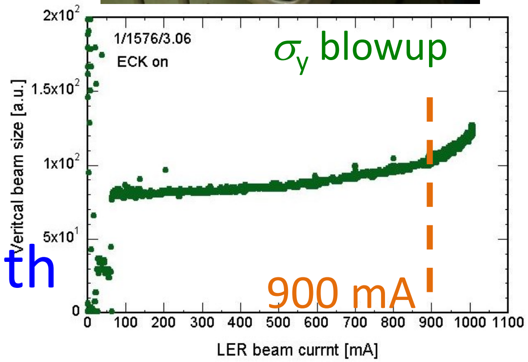
➡ Any countermeasures were required before Phase-2.

- The δ_{max} of TiN coating estimated from simulations was ~1.4, which is relatively higher than expected.

➡ Further analysis was necessary on this point.

Permanent magnet for bellows



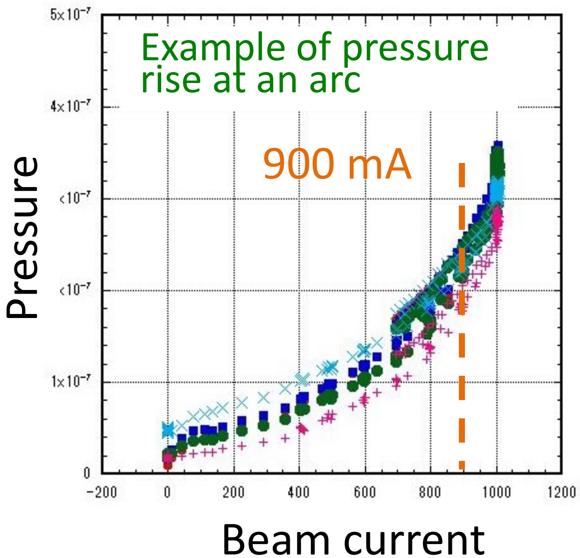


Electron cloud effect

Countermeasures

- We checked the behaviors of pressure against the beam current all over the ring. (2016/6/27, 1/1576/3.06RF)
  - EC → Electron multipactoring → Non-linear behavior of pressure

- Non-linear pressure rises were observed at
  - Al and Cu beam pipes with/without antechambers + TiN coating at Arc sections, IR (Interaction Region), Tsukuba straight section, Chicane sections, SRM (beam size monitor).
  - Al beam pipes reused from KEKB (without TiN coating) at Fuji straight section and injection section.
  - Not observed in wiggler section .



- We decided to apply magnetic fields in the beam direction by using solenoids or permanent magnets to these beam pipes, which was planned from the design stage.

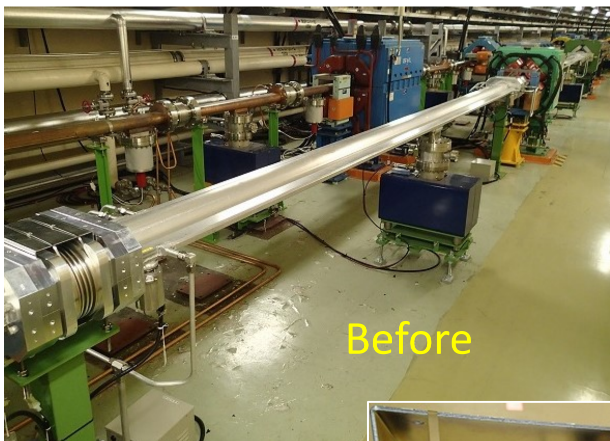
Electron cloud effect

Countermeasures

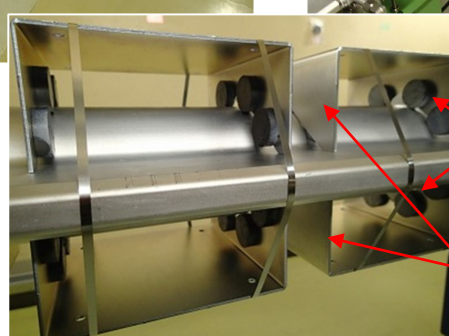
For drift spaces of Al or Cu pipes with antechambers + TiN coating

- Type-1 unit: Permanent magnets with iron yokes; 8 ferrite magnets (ϕ30) + iron plate (L160 mm), aligned with 40 mm pitch.
- This type was applied for the places more than 250 mm far from the ends of electromagnets (Q, SX, ST) to avoid the interference.

Application of Type-1 unit



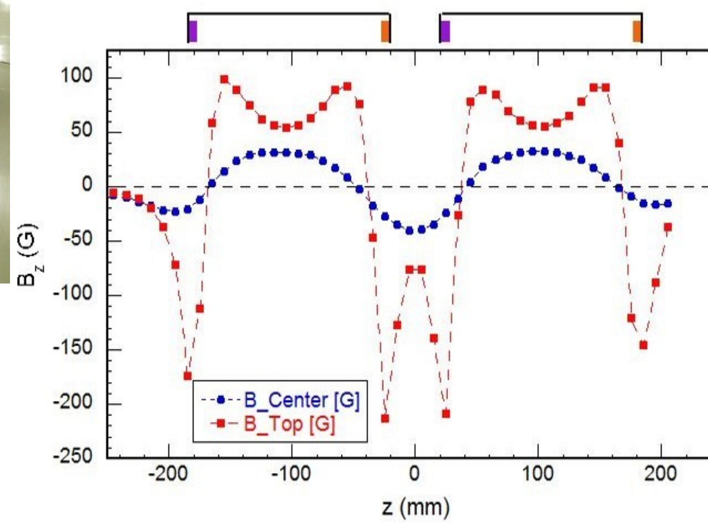
Type-1 unit



Permanent magnets

Iron yoke (plate)

Magnetic field of Type-1 unit
Typical strength ~ 60 G



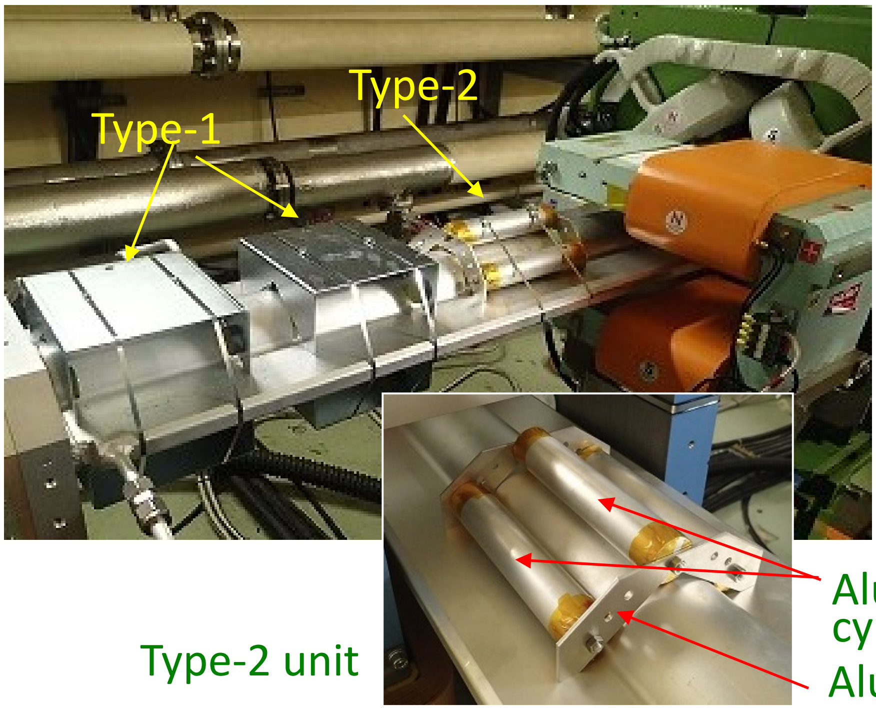
Electron cloud effect

Countermeasures

For drift spaces of Al or Cu pipes with antechambers + TiN coating

- Type-2 unit: Permanent magnets in Al cylinders; 21 ferrite magnets (ϕ30) in each Al cylinder (L180 mm).
- This type was applied for the places less than 250 mm from the ends of electromagnets (Q, SX, ST).

Type-1 and Type-2 units near Q magnet

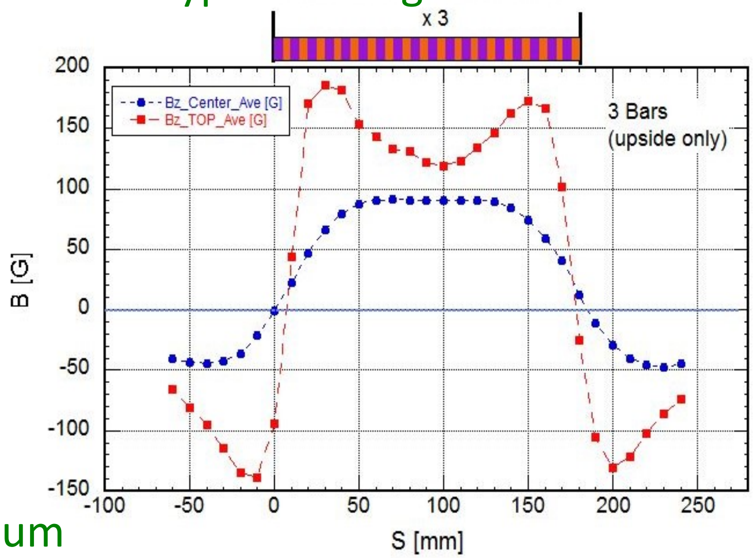


Type-2 unit

Aluminum cylinder

Aluminum support

Magnetic field of Type-2 unit
Typical strength ~ 100 G



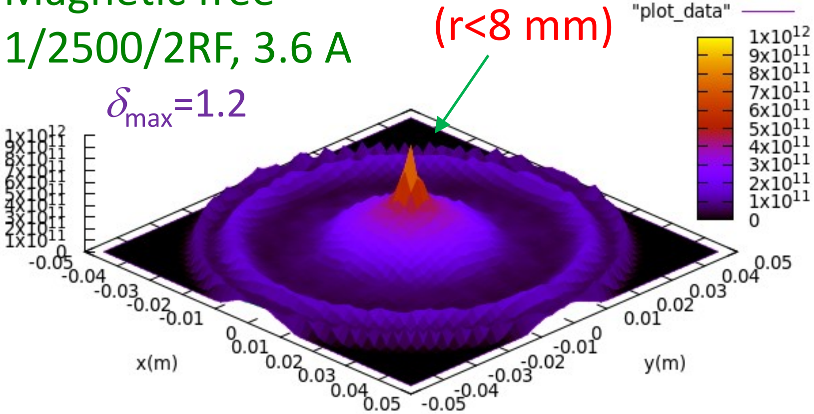
Electron cloud effect

Countermeasures

- Expected electron density in the Type-1 unit was calculated (modeled by Fukuma-san) for the beam current of 3.6 A with 1/2500/2RF by CLOUDLAND.
  - δ_{max} = 1.0~1.4, photoelectrons = 0.07~0.01x0.1x0.16 p.e./m/e^+/turn.
- The central electron density is on the order of 10^{10} m^{-3} for the design current.

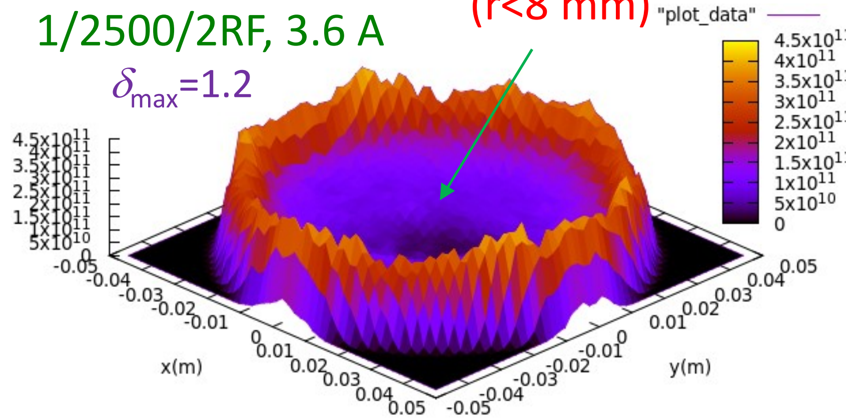
Magnetic free
1/2500/2RF, 3.6 A
δ_{max}=1.2

4.5x10^{11} m^{-3}
(r<8 mm)



Type-1 unit
1/2500/2RF, 3.6 A
δ_{max}=1.2

4x10^{10} m^{-3}
(r<8 mm)



- Note: the central electron density in Al bellows chamber with the permanent magnet is also estimated to be approximately 3.4x10^{10} m^{-3} for 3.6 A (δ_{max} = 2.0, photoelectrons = 0.01x0.1x0.16 p.e./m/e+/turn).

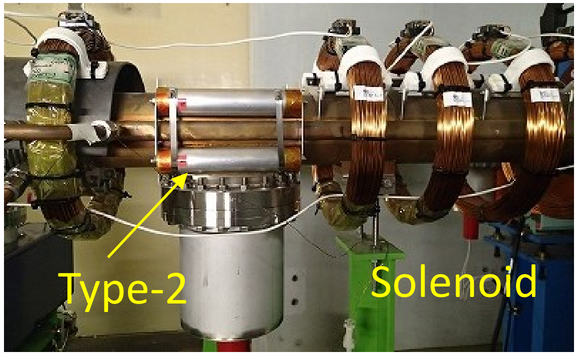
Electron cloud effect

Countermeasures

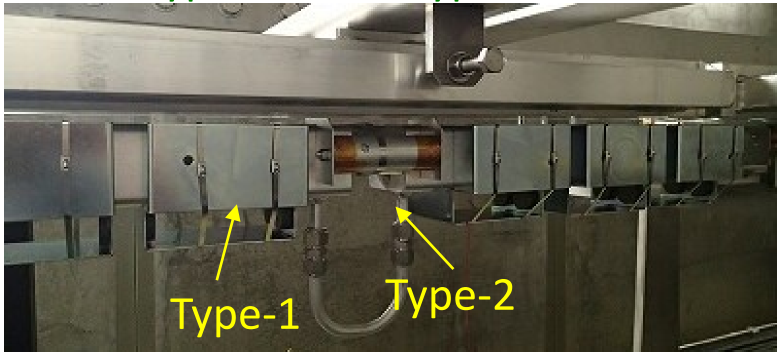
For Al pipes reused from KEKB (Fuji cross section)

- Retrieve solenoids at KEKB era + Type-1 and 2 permanent magnets

Solenoid + Type-2 unit



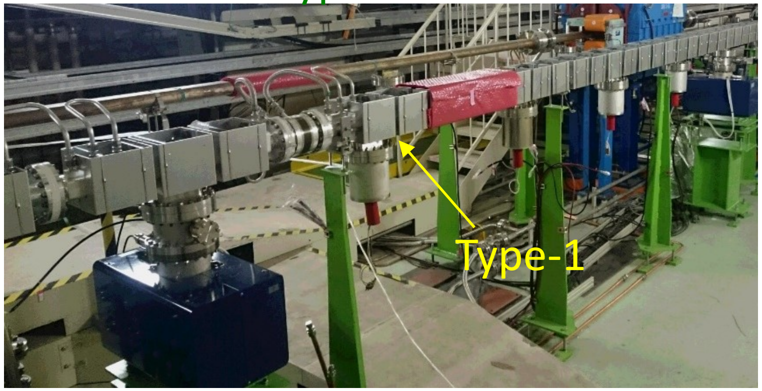
Type-1 unit + Type-2 unit



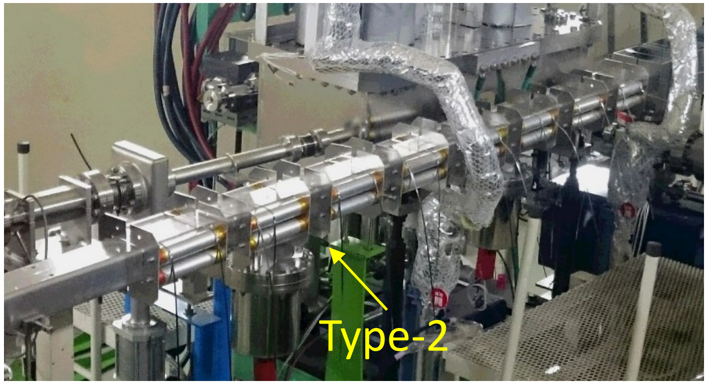
For new Al pipes with TiN coating for LER injection region

- Type-1 and 2 permanent magnets

Type-1 unit



Type-2 unit



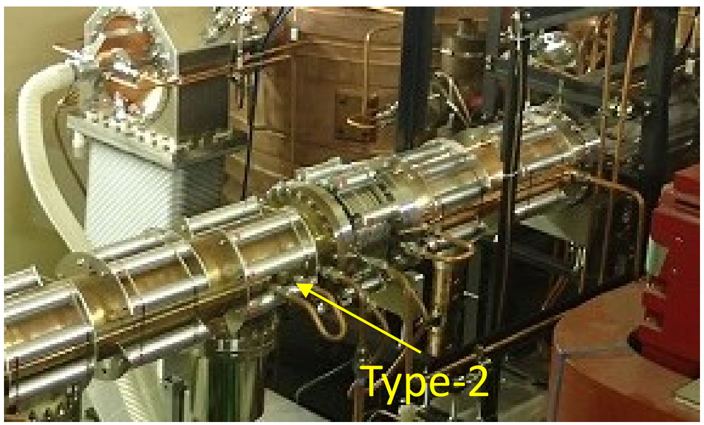
Electron cloud effect

Countermeasures

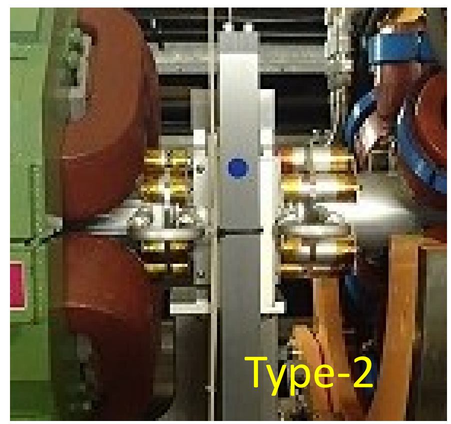
For places where ECE has not been observed, but will be important

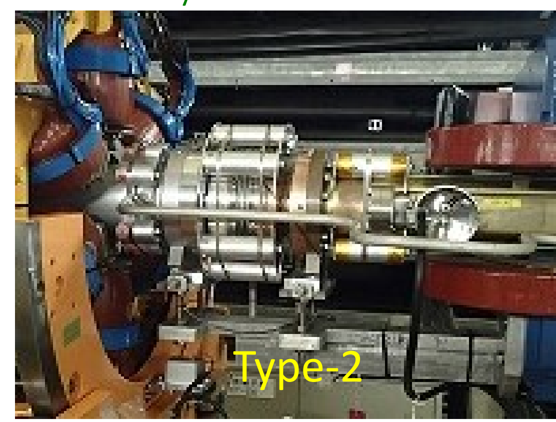
- Cu pipe at RF section without TiN coating: Retrieval of solenoids at KEKB era or Type-2 permanent magnets.
- High β_y region at Tsukuba LC section: Adding more Type-2 units.

Type-2 units for RF section (Cu pipe)



Type-2 units for high β_y region





- Now, approximately 86 % of the drift space of the ring (~2000 m) was covered by the magnetic fields with a strength higher than 20 G.
  - Remained parts are around BPM, wiggler sections, ends of bending magnets. Permanent magnets will be prepared until Phase-3.

Electron cloud effect

Estimated high value of δ_{max}

- Possible reasons of high δ_{max} ~1.4:
  - Aging is still insufficient.
  - No baking system, which usually shows high δ_{max}, etc.
- Other than these reasons, another possibility was recently pointed out: More photoelectrons than expected in the beam channel.
- The story is as follows:
  - The simulation starts from the premise that $n_e = 3\text{x}10^{11}\ \text{m}^{-3}$ (threshold of ECE at ~900 mA).
  - For n_e on these orders, n_e is not saturated. This means that the photoelectrons are important as well as the secondary electrons (δ_{max}). Actually, n_e is almost proportional to the number of photoelectrons in the beam channel.
  - If the number of photoelectron is different from that expected, the estimated value of δ_{max} should change.

Electron cloud effect

Estimated high value of δ_{max}

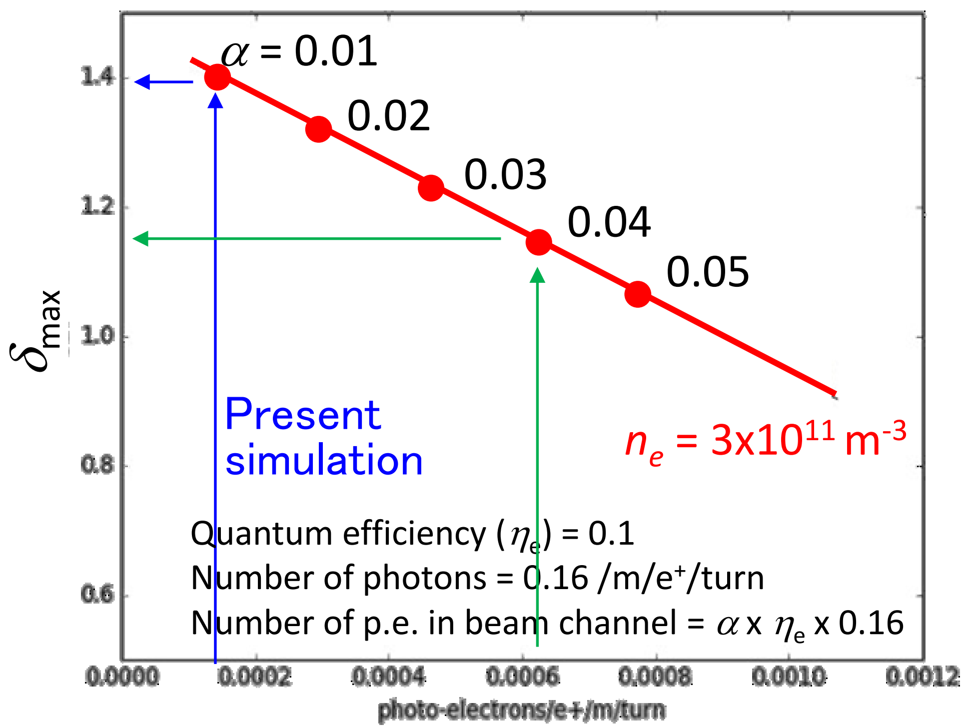
- Possible reasons of high δ_{max} ~1.4:
  - Aging is still insufficient.
  - No baking system, which usually shows high δ_{max}, etc.
- Other than these reasons, another possibility was recently pointed out: More photoelectrons than expected in the beam channel.
- The story is as follows (cont'd):
  - So far, in the simulation using a circular pipe, the effectiveness of antechamber (α = photoelectrons in beam channel/whole photoelectrons) has been assumed to be 0.01, on the base of the experiment in KEKB LER.
  - However, recent simulation studies showed that $\alpha > 0.01$ (0.03~0.1).
    - Calculation of photon distribution using Synrad-3D under the realistic SKEKB layout and conditions (Fukuma-san)
    - Calculation of photoelectrons going out from the antechamber part of actual beam pipe (Ohmi-san).

➡ δ_{max} might be smaller….

Electron cloud effect

Dependence of δ_{max} on α

δ_{max} vs α. Calculation by Fukuma-san



Number of photoelectrons in beam channel

- There are various combinations of δ_{max} and α to give the same density, n_e = 3x10^{11} m^{-3}.
- If α is 0.01, δ_{max} is ~1.4.
- But, if α is 0.04, for example, δ_{max} is ~1.2.
- Evaluation of actual numbers of photoelectrons (α) is very important for estimating δ_{max}!
- We will try the following two methods to estimate α in the Phase-2 commissioning.

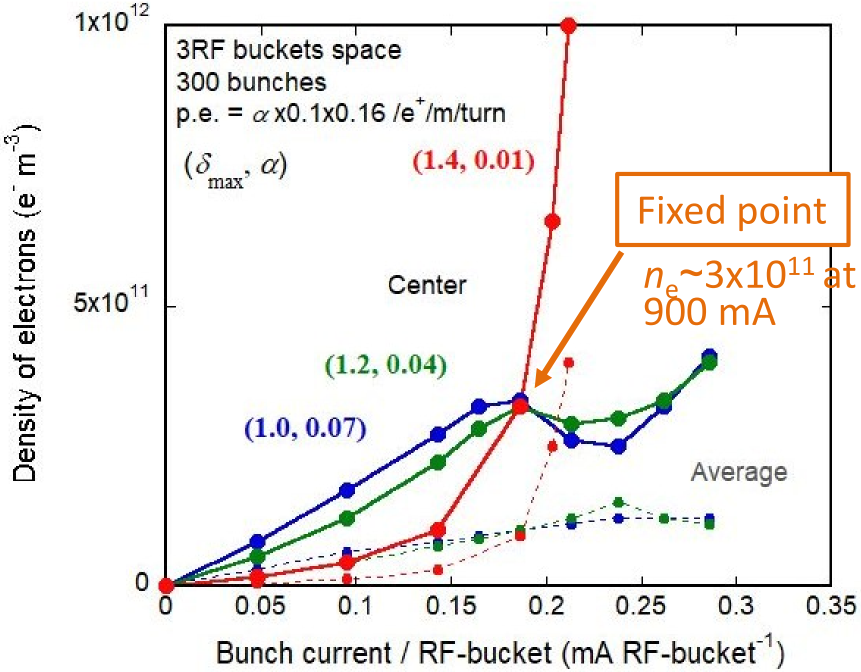
Electron cloud effect

Estimation of α : Method 1

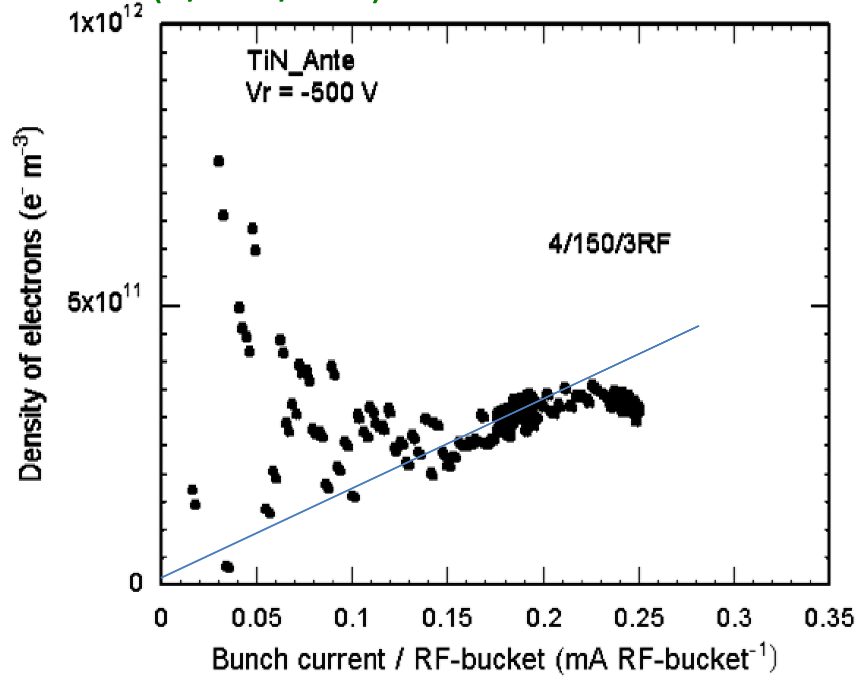
From the behavior of electron density against beam current.

- The behavior changes for the combinations of δ_{max} and α.

Calculated n_e for several combinations of δ_{max} vs α. Here n_e = 3E11 m^{-3} at 0.18 mA/RF-bucket is fixed (1/300/3RF).



Preliminary data:
Measured n_e in Phase-1 [2016/6/20] (4/150/3RF).

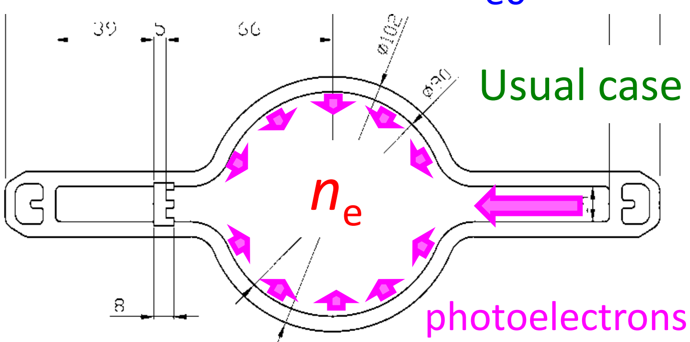


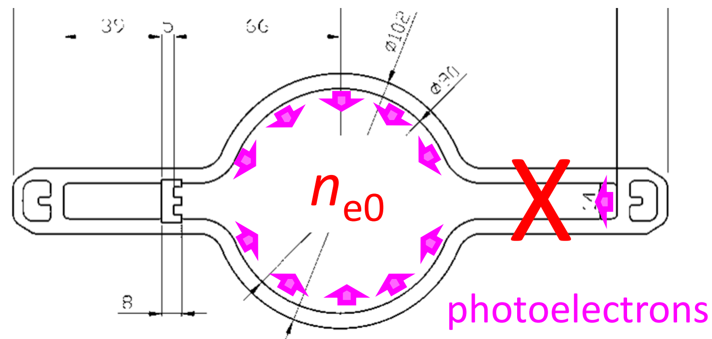
- The behaviors are similar to the cases of (δ_{max}, α) = (1.2, 0.04) ~ (1.0,0.07). But, more data are required.

Electron cloud effect

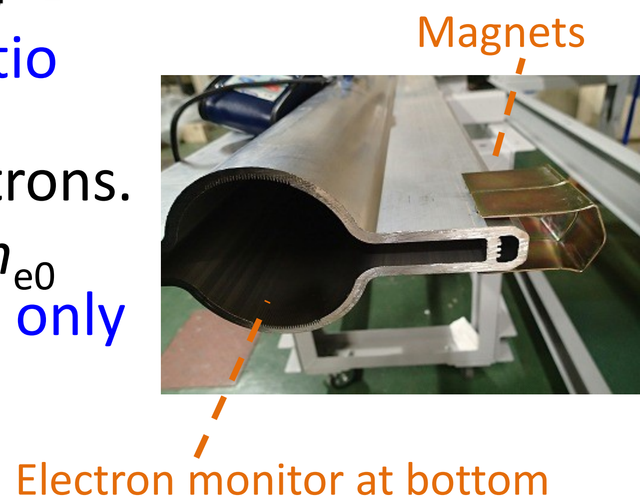
Estimation of α : Method 2

From the difference of measured electron densities between the usual case (n_e) and the case where the effect of photoelectrons from antechamber is little (n_{e0})





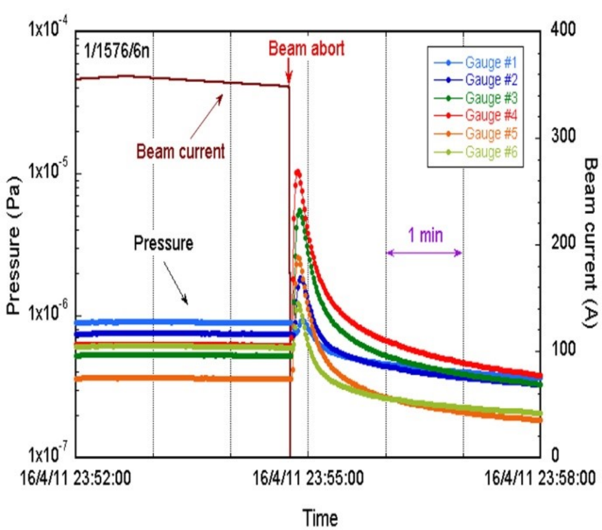
- We will be able to estimate α from the ratio of n_{e0} and n_e, assuming that the density is proportional to the number of photoelectrons.
- For example, we will be able to measure n_{e0} when weak magnetic fields are applied to only the antechamber.
- We will continue the evaluation of properties of our TiN coating.



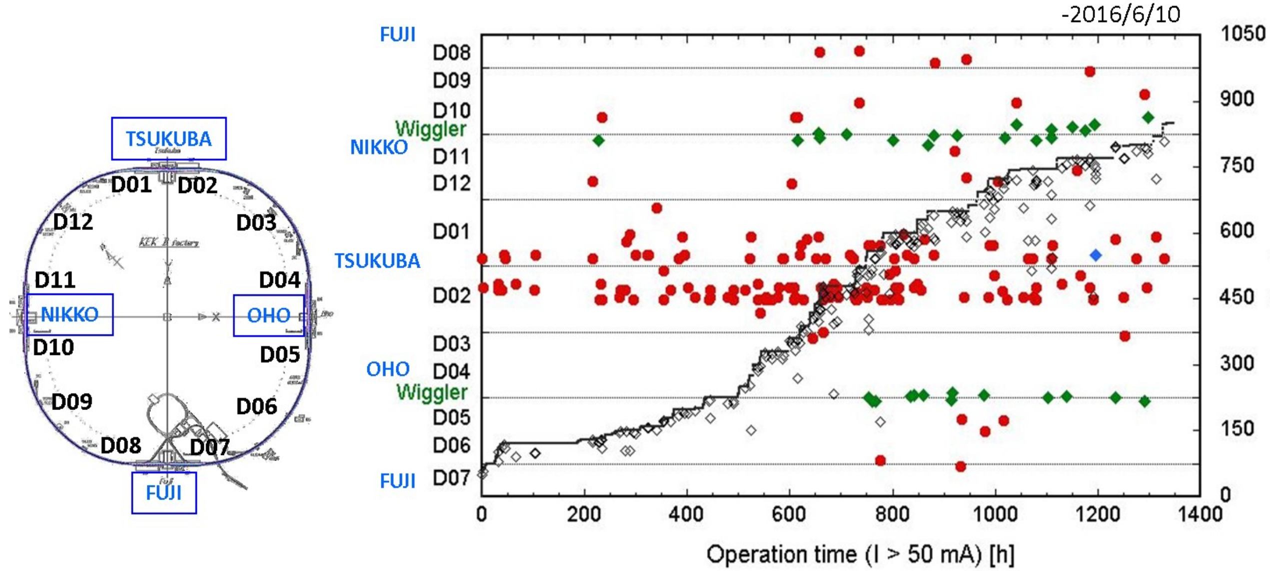
Brief review

- Beam aborts accompanied by local pressure bursts have been frequently observed in the LER.
  - The locations of the pressure bursts have spread to more than 20 points along the ring. More frequent in the Tsukuba straight section.

Typical pressure burst



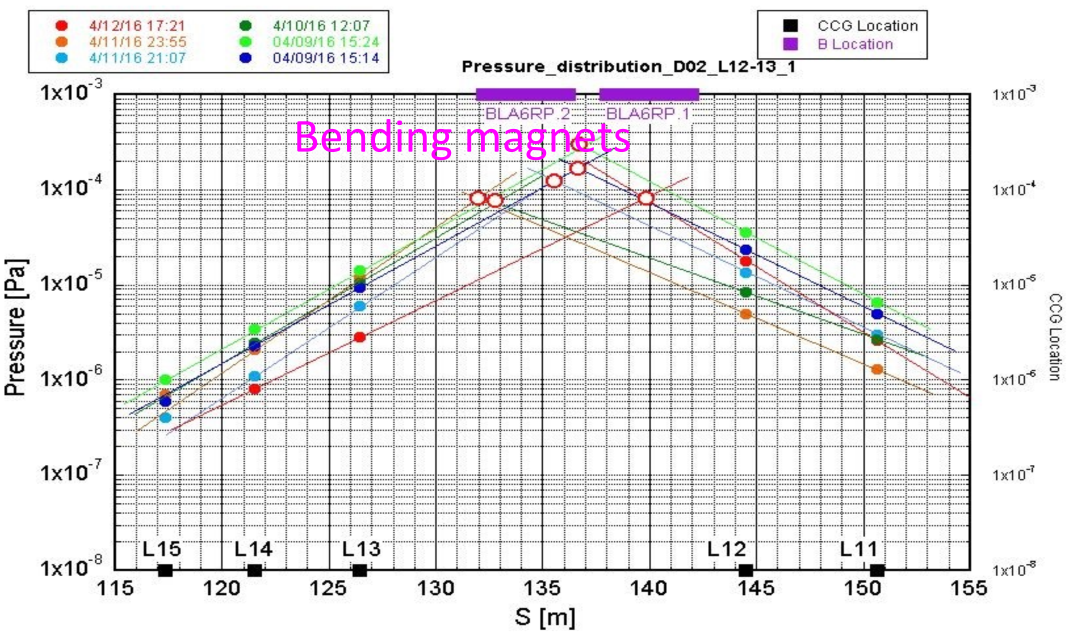
Locations of pressure bursts and the history



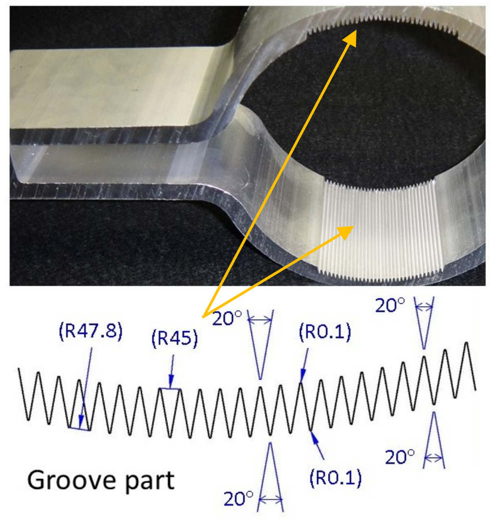
Brief review

- Beam aborts accompanied by local pressure bursts have been frequently observed in the LER.
  - The locations of the pressure bursts have spread to more than 20 points along the ring. More frequent in the Tsukuba straight section.
  - In most cases, the bursts were observed near aluminum beam pipes in dipole magnets, with groove structure.

Estimated detailed locations of pressure bursts



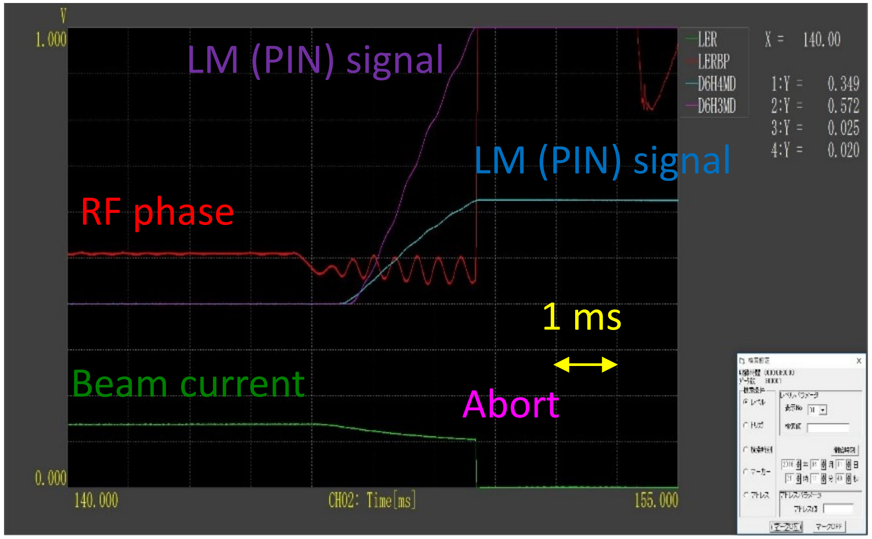
Groove in the beam pipe



Brief review

- Beam aborts accompanied by local pressure bursts have been frequently observed in the LER.
  - The locations of the pressure bursts have spread to more than 20 points along the ring. More frequent in the Tsukuba straight section.
  - In most cases, the bursts were observed near aluminum beam pipes in dipole magnets, with groove structure.
  - The beam-loss monitors at collimators triggered the beam aborts.
  - Beam loss lasted a few ms before the beam abort.

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



Pressure bursts accompanying beam loss

Brief review

- Beam aborts accompanied by local pressure bursts have been frequently observed in the LER.
  - The locations of the pressure bursts have spread to more than 20 points along the ring. More frequent in the Tsukuba straight section.
  - In most cases, the bursts were observed near aluminum beam pipes in dipole magnets, with groove structure.
  - The beam-loss monitors at collimators triggered the beam aborts.
  - Beam loss lasted a few ms before beam abort.
- A possible cause: Collision of “dusts” with circulating beams.
  - Manufacturer of beam pipes in Tsukuba section is different from others.
  - Groove structure is likely to catch the dusts.
  - Aluminum grooves were formed at the first stage of beam pipe fabrication.
  - A “knocker” was set at a beam pipe in a bending magnet, where the burst had been observed frequently, and we could reproduce the phenomena by knocking the beam pipe.

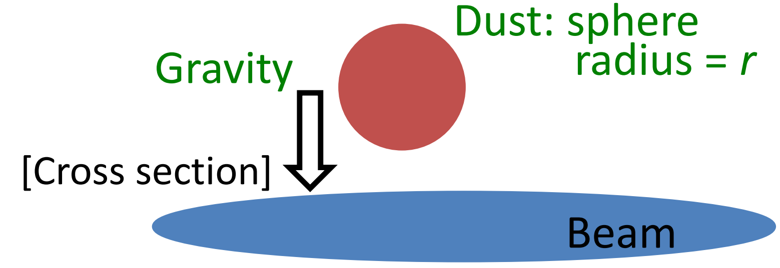
➡ How to deal with it?

Pressure bursts accompanying beam loss

Estimation of dust size

- Hints:
  - Beam loss lasts for long time, ~ ms.
  - Short beam lifetime, < 10 ms.

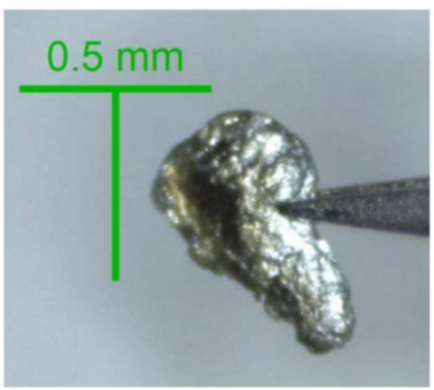
➡ Large dusts, over 100 μm~1 mm?.

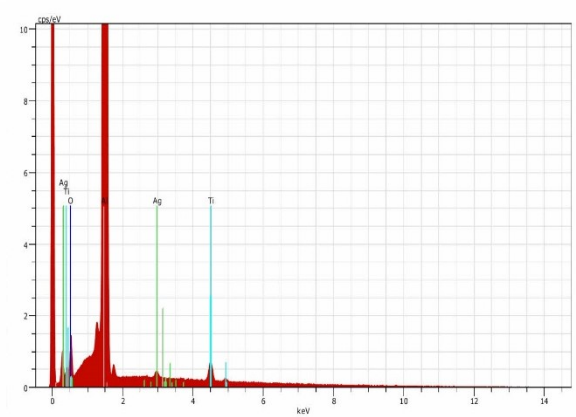


Crossing time ~3 ms for r = 500 μm, σ_y = 1 mm.

- Dusts in reserved beam pipes were checked.
  - Dusts larger than 100 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

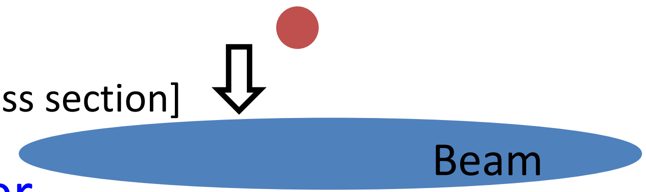
Pressure bursts accompanying beam loss

Estimation of dust size

- Hints:
  - Beam loss lasts for long time, ~ ms.
  - Short beam lifetime, < 10 ms.

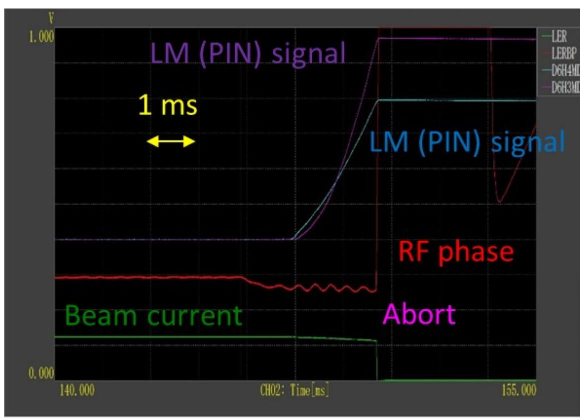
Small dust < 10 μm

[Cross section]



- Note: there is another possible story:
  - Dust is small, < 10 μm, such as NEG powder.
  - The collision induces the synchrotron oscillation, and it grows to the large betatron oscillation. That leads to the beam loss.
  - Reason: the loss signal is observed behind the synchrotron oscillation, ~ ms.
  - We have to know the dinamic aperture.
  - Further investigation is required, and some studies are planed in Phase-2.

Typical abort log

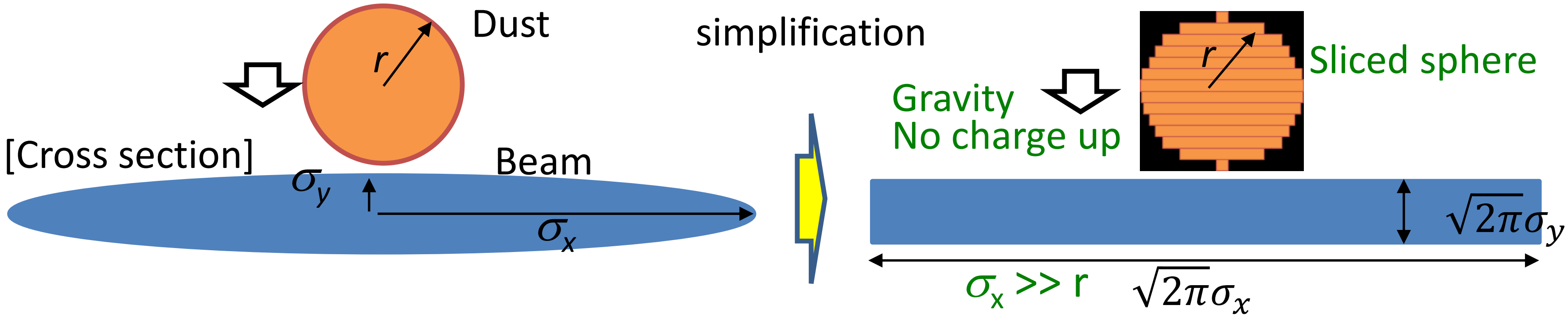


- Here, we tried to explain the phenomena assuming that the dust is large.

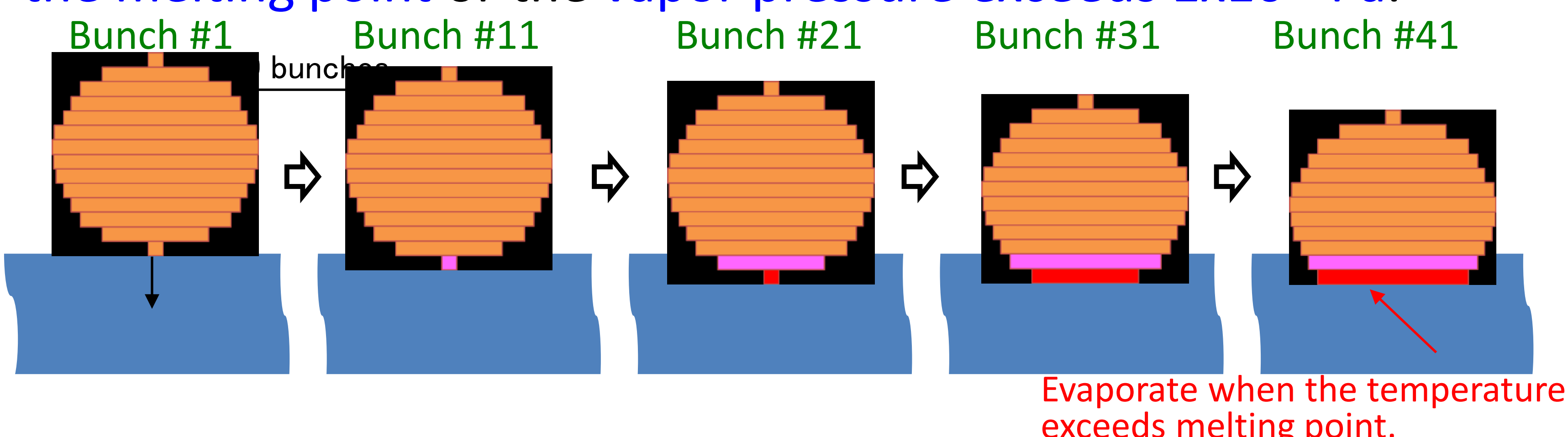
Pressure bursts accompanying beam loss

A simple model

Drop from above surface



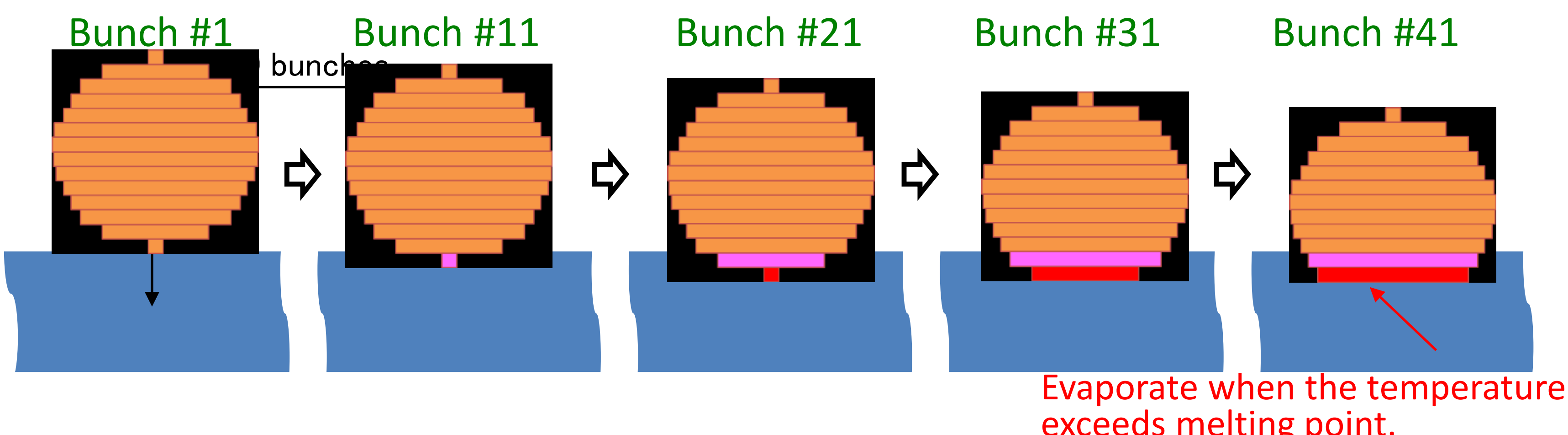
- Calculate temperature of each slice every 10 bunches while the dust is interacting with beam. Height of one slice is ~ 55 nm.
- Assume that the slice evaporates when the temperature exceeds the melting point or the vapor pressure exceeds 1×10^{-2} Pa.



Pressure bursts accompanying beam loss

Calculation using the model

- 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.
  - These calculations followed the method used in the dust trapping analysis by F. Zimmermann. But, not trapped here.

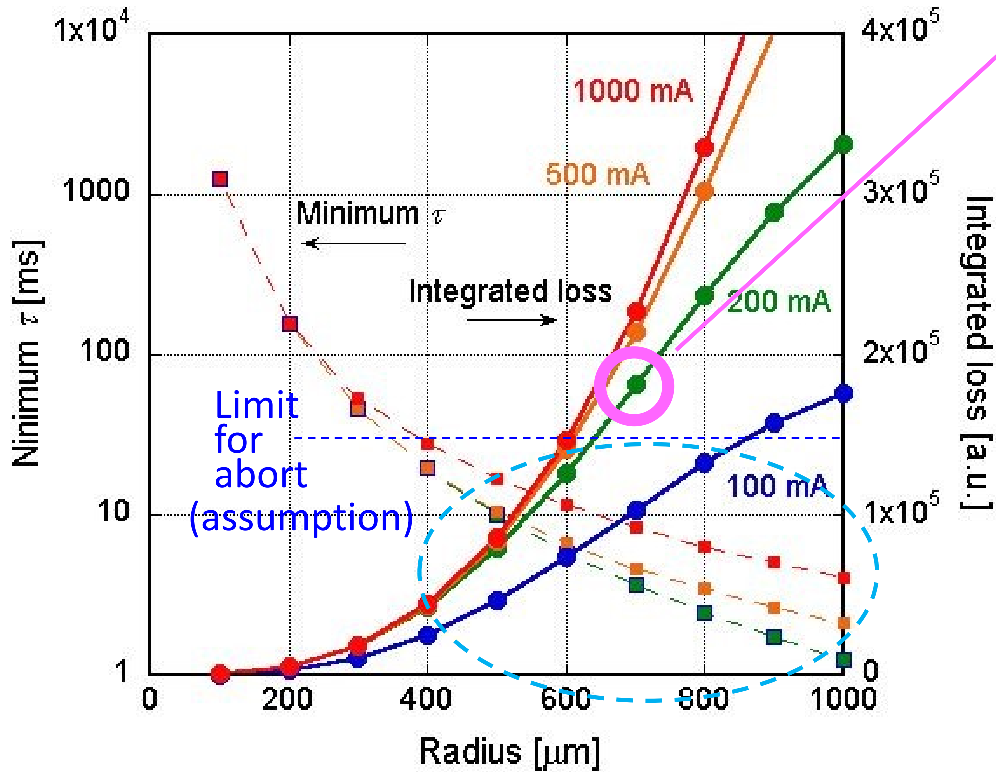


Pressure bursts accompanying beam loss

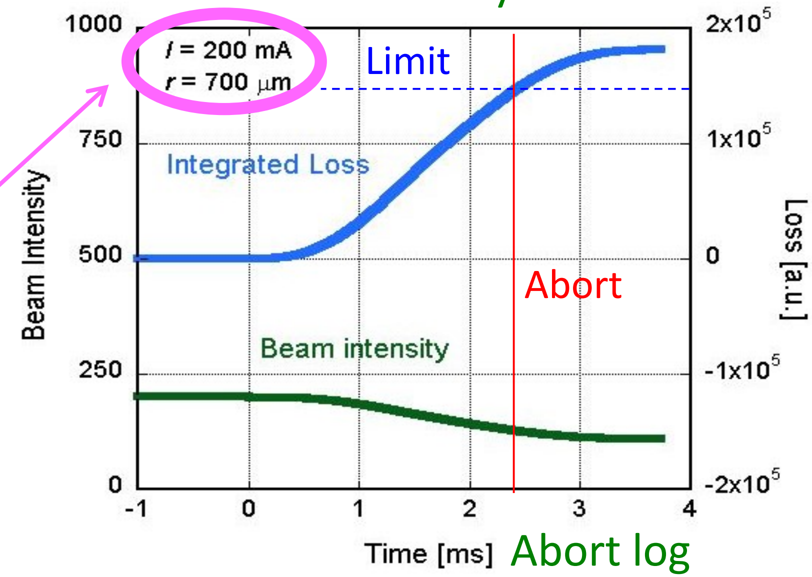
Typical result

For Al_2O_3, which is the most probable dust in Al beam pipe

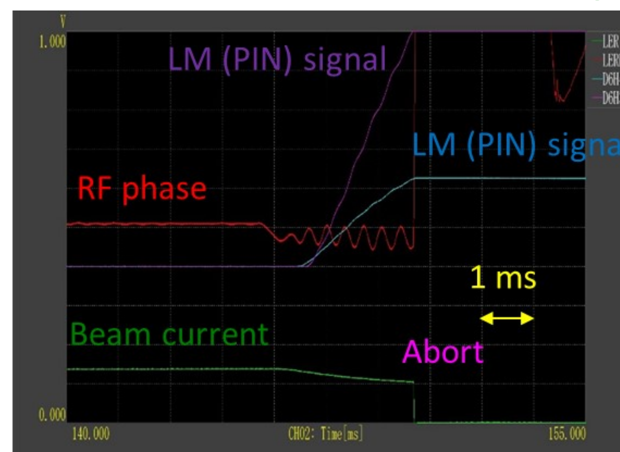
Min. lifetime and integrated loss against dust radius for several beam currents.



Time change of integrated loss and beam intensity



Abort log

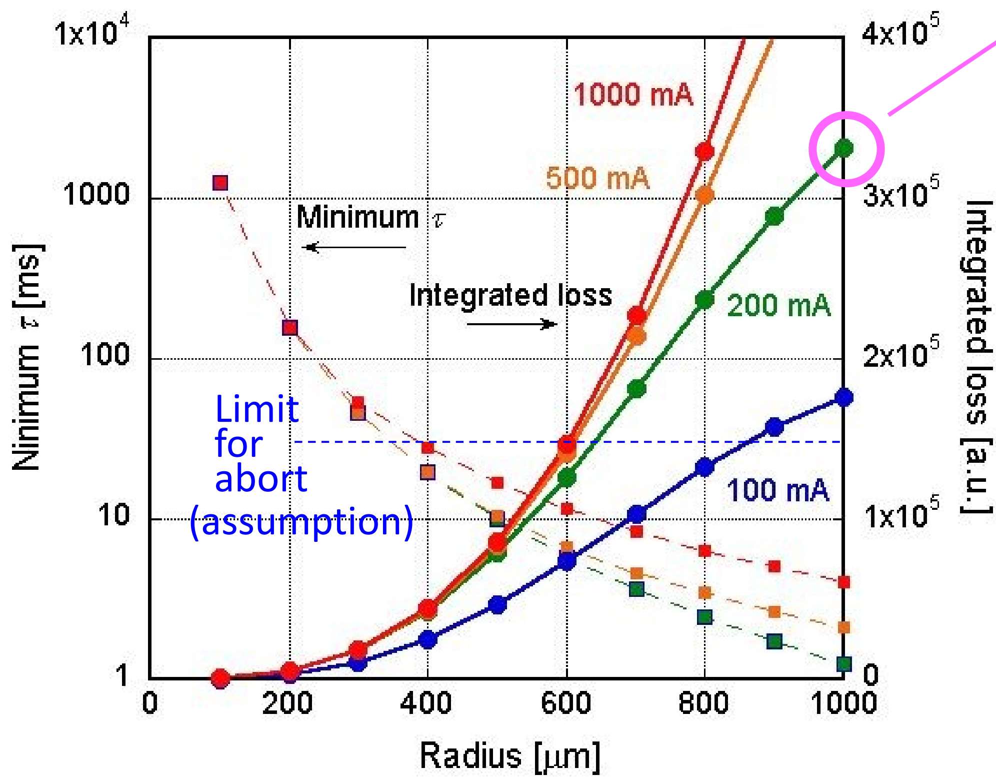


Pressure bursts accompanying beam loss

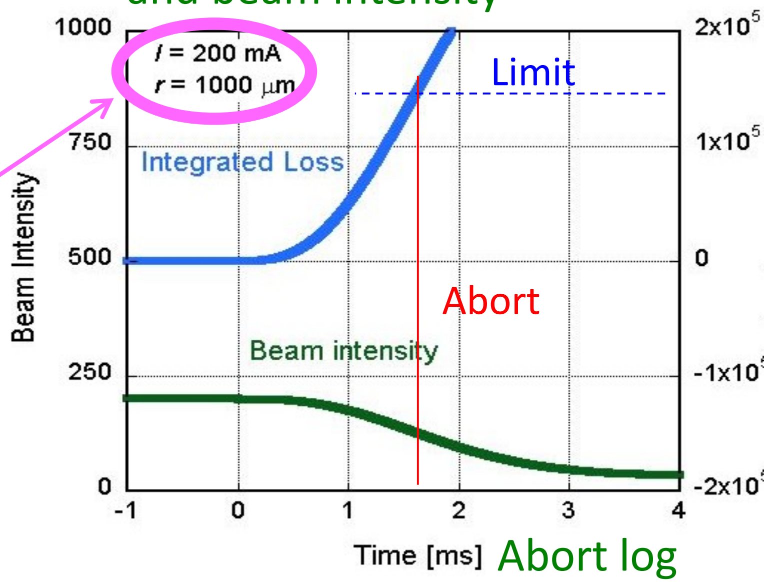
Typical result

For Al_2O_3, which is the most probable dust in Al beam pipe

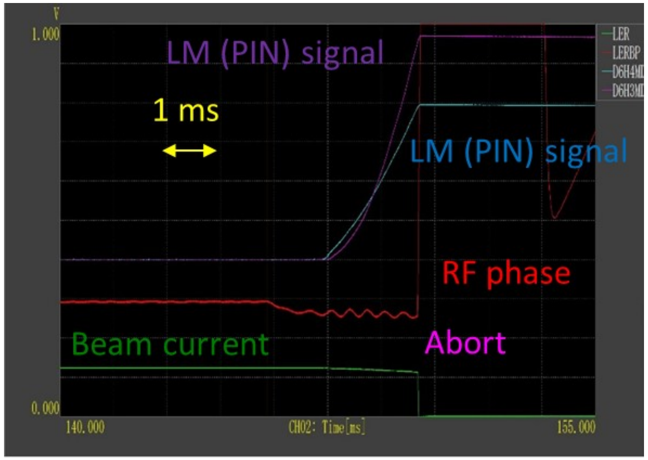
Min. lifetime and integrated loss against dust radius for several beam currents.



Time change of integrated loss and beam intensity



Abort log

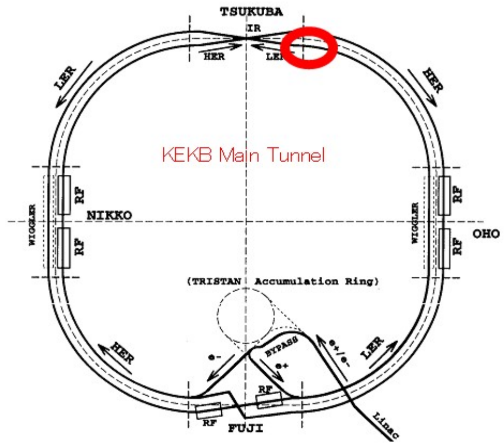


- We can reproduce the log qualitatively.

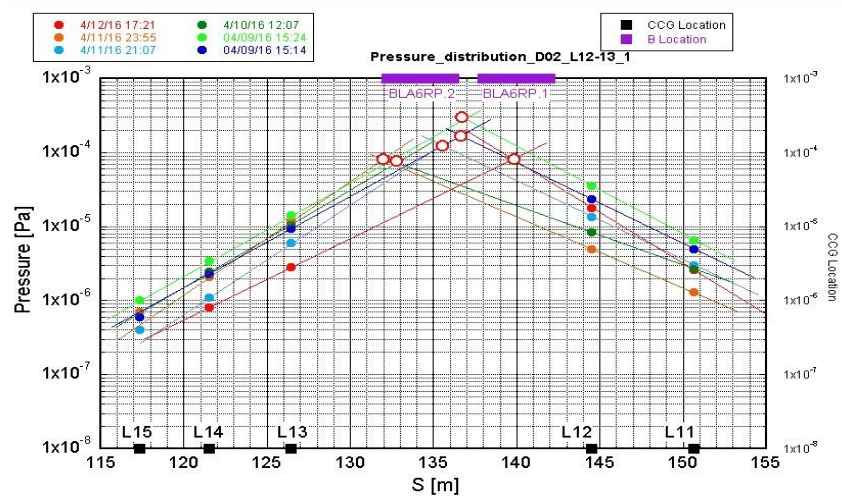
Pressure bursts accompanying beam loss

Gathering of dusts from actual beam pipes in the ring

- The beam pipes where the bursts were frequently observed.



Location of beam pipe

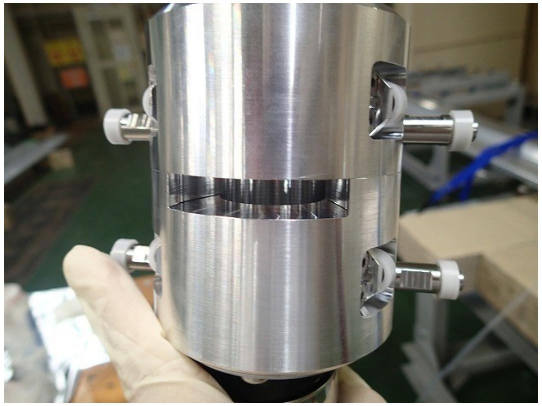


Pressure bursts accompanying beam loss

Gathering of dusts from actual beam pipes in the ring

- The beam pipes where the bursts were frequently observed.
- A special tool to cleanup the inside of beam pipes with antechambers was developed.
- The dusts was gathered by a powerful vacuum cleaner.
  - After knocking the beam pipe, the beam pipe was slowly filled with N_2. Then the dusts at the bottom of beam channel was vacuumed.

Special tool to cleanup the bottom of beam channel

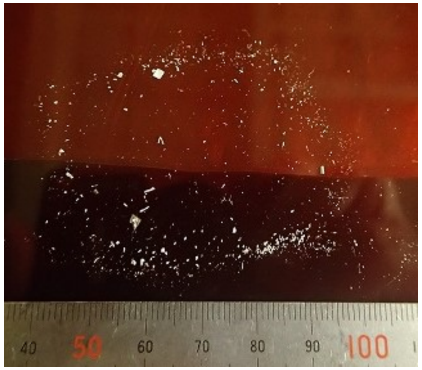


Pressure bursts accompanying beam loss

Gathering of dusts from actual beam pipes in the ring

- The beam pipes where the bursts were frequently observed.
- A special tool to cleanup the inside of beam pipes with antechambers was developed.
- The dusts was gathered by a powerful vacuum cleaner.
  - After knocking the beam pipe, the beam pipe was slowly filled with N_2. Then the dusts at the bottom of beam channel was vacuumed.
- Lots of large dusts were found from one of the two beam pipes!
  - We did not check the inside of other beam pipes in which the bursts were not observed.
  - But, this is one strong evidence for the assumption of large dusts.

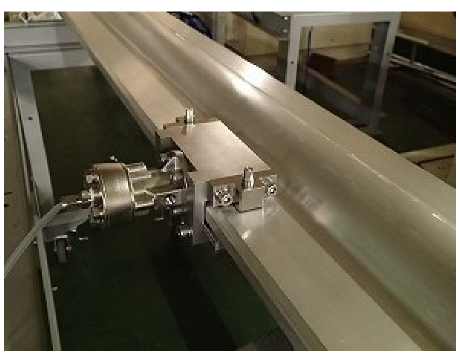
Dust obtained from the beam pipe in question

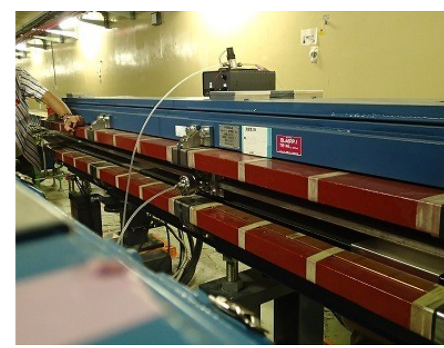


Pressure bursts accompanying beam loss

Countermeasures

- It is hardly possible to cleanup the all dusts.
- But if the sizes of dusts are large, it is quite unlikely to imagine that the dusts are picked up from the bottom of beam channel, which might be charged up by electrons(?).
- We knocked 24 beam pipes for bending magnets (with groove) around Tsukuba straight section, where the pressure bursts were frequently observed, and dropped dusts from the top.
    - Knocked 150 times for each beam pipe.
- We expect the reduction of the bursts in Phase-2 commissioning.
    - The study will be continued.



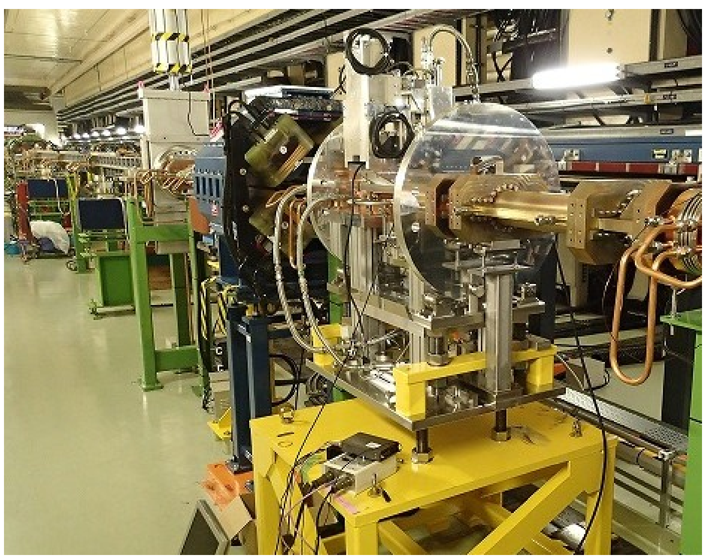



Other preparations for Phase-2

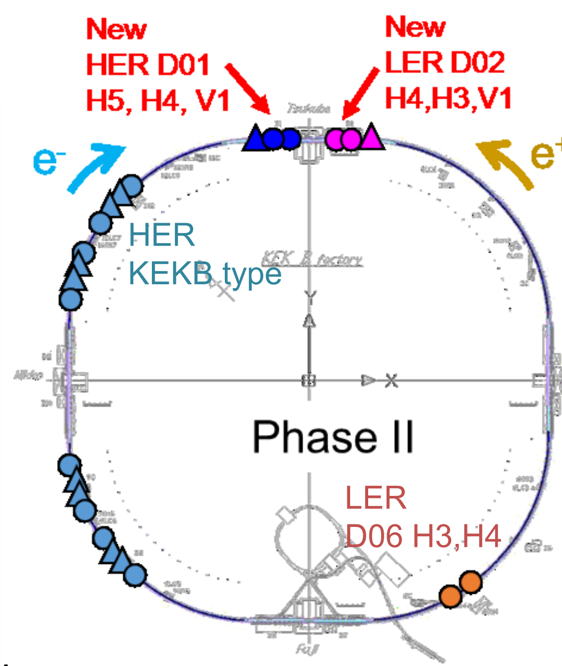
Installation of new 6 beam collimators

- Two collimators, installed in the SuperKEKB positron ring for test in Phase-1 commissioning, worked well as expected.
  - Designed on the base of SLAC-type Low-impedance collimators.
- Taking these promising results, six new collimators were manufactured and installed in the positron ring (LER) and the electron ring (HER) for Phase-2 commissioning.

A new vertical type collimator installed in the ring



Collimator system in Phase-II



Other preparations for Phase-2

Replacement of beam pipes for LER injection region

- In order to accommodate the injection of low-emittance positron beam, the septum magnet was renewed.
- LER abort system including kicker magnets is also upgraded to tolerate the higher beam current with a smaller beam size.
- The beam pipes were replaced to new ones accordingly, including the beam pipe inside the septum chamber.

septum and beam pipes for injection region

Other preparations for Phase-2

Countermeasures against problems found in Phase-1

- Air leak from a flange of a tapered beam pipe at Fuji straight section.
  ➡ Replace to a new beam pipe with a "beam mask" as well as SR mask.

- Heating of flanges in wiggler sections
  ➡ Re-alignment of beam pipes, and install new bellows chambers with SR masks at the entrance of antechambers.

- Heating of beam pipes at the downstream of wiggler sections.
  ➡ Cooling–water paths are optimized to increase the flow rate.

- Others
  - Installation of bellows chambers with SR baffles to reduce photon scattering to the mirror of SR beam size monitor.
  - Installation of new test beam pipe for EC studies.
  - Inside check of some bellows chambers
  - Replacement of several vacuum gauges and ion pumps.

Summary

- The MR vacuum system is now ready for the Phase-2.
- Various countermeasures were taken for problems found in Phase−1.
  - Electron cloud effect
    - Approximately 86 % of the drift spaces of the ring were covered by magnetic fields using permanent magnets or solenoids.
    - The analysis of the properties of countermeasures are on going.
  - Pressure bursts
    - The beam pipes in questions were knocked to drop the dusts from the top of beam channel.
    - The investigation on this phenomena is continuing.
- Other preparations
  - Installation of new beam collimators
  - Replacement of beam pies at LER injection region
  - Etc.

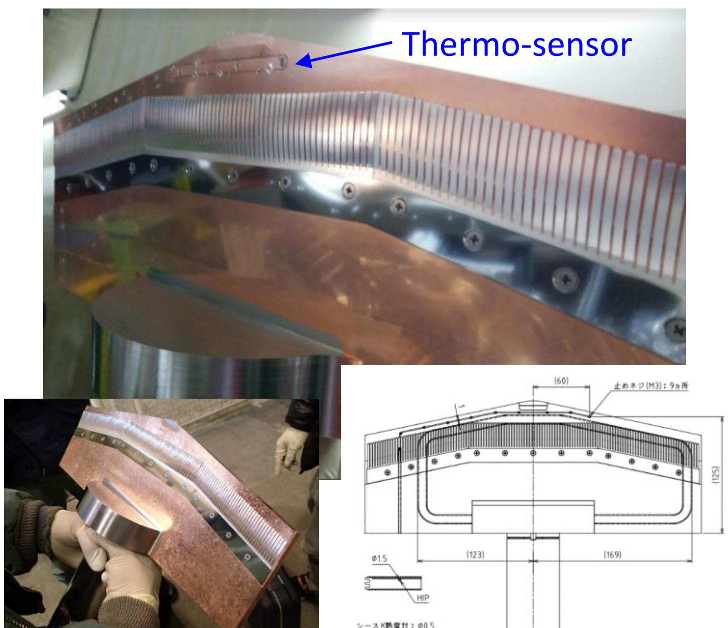
Thank you for your attention.

Other preparations for Phase-2

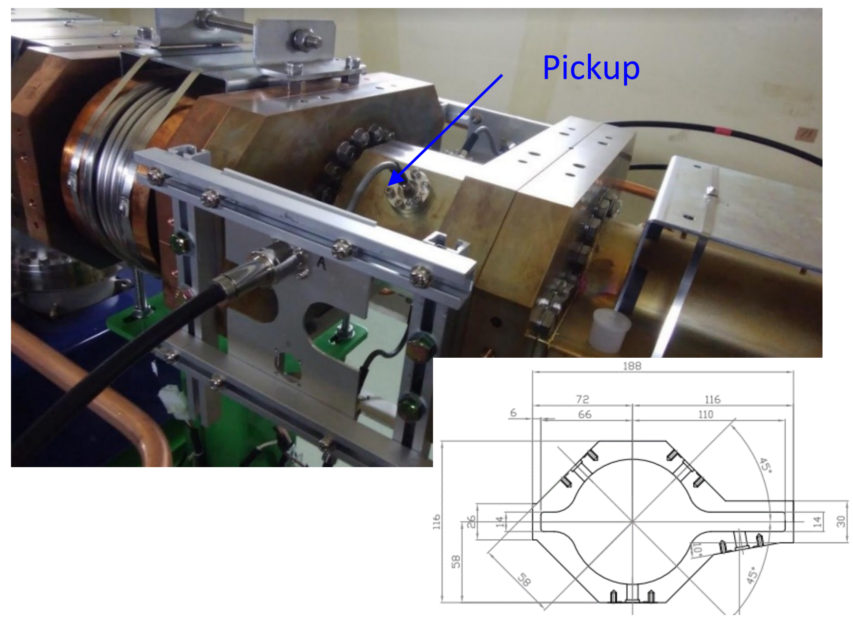
Installation of new 6 beam collimators

- One of the new collimators was equipped with a thermo-sensor to measure the temperature at the tip of the head.
- A special beam pipe with four pickup electrodes was installed just near a collimator for measuring the characteristics of HOM (Higher Order Mode) generated by the collimator.
- Installation of lead shielding is also on going.

Collimator head equipped with thermo-sensor



Beam pipe with HOM pickups



Design of key components_8

- **Countermeasures against electron cloud (EC) effect [LER]**
  - Serious issues for recent positron and proton storage rings.

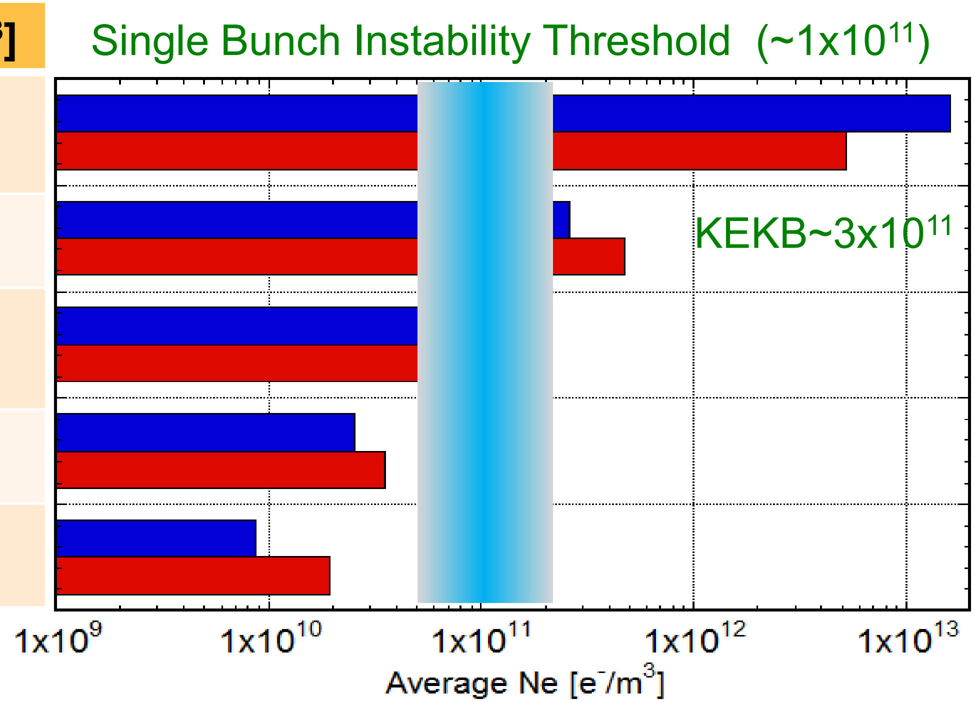
Sections	L [m]	L [%]	Countermeasure	Material
Total	3016	100		
Drift space (arc)	1629 m	54	TiN coating + Solenoid	Al (arc)
Steering mag.	316 m	10	TiN coating + Solenoid	Al
Bending mag.	519 m	17	TiN coating + Grooved surface	Al
Wiggler mag.	154 m	5	Clearing Electrode	Cu
Q & SX mag.	254 m	9	TiN coating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

  - By using these countermeasures, the average electron density on the order of 10^{10} e^-/m^3 will be obtained.
    - Threshold of head-tail instability: ~1.6×10^{11} e^-/m^3

Expected electron density

- n_e after applying measures described so far (Red)
- **n_e of approx. 1/5 of the threshold one is expected.**
- Compared with results of CLOUDLAND (Blue)
  - δ_{max}=1.2, Solenoid field=50G (→n_e=0), Antechamber; photoelectron yield =0.01 (1/10)

Condition	ne [m^{-3}]
Circular Cu chamber [KEKB beam pipe]	5.2E12
+Solenoid at Drift (1/50)	4.7E11
+Antechamber (1/5)+TiN (3/5)	5.7e10
+Electrode in Wiggler (1/100)	3.5e10
+Groove in Bend (1/4)	2.0E10

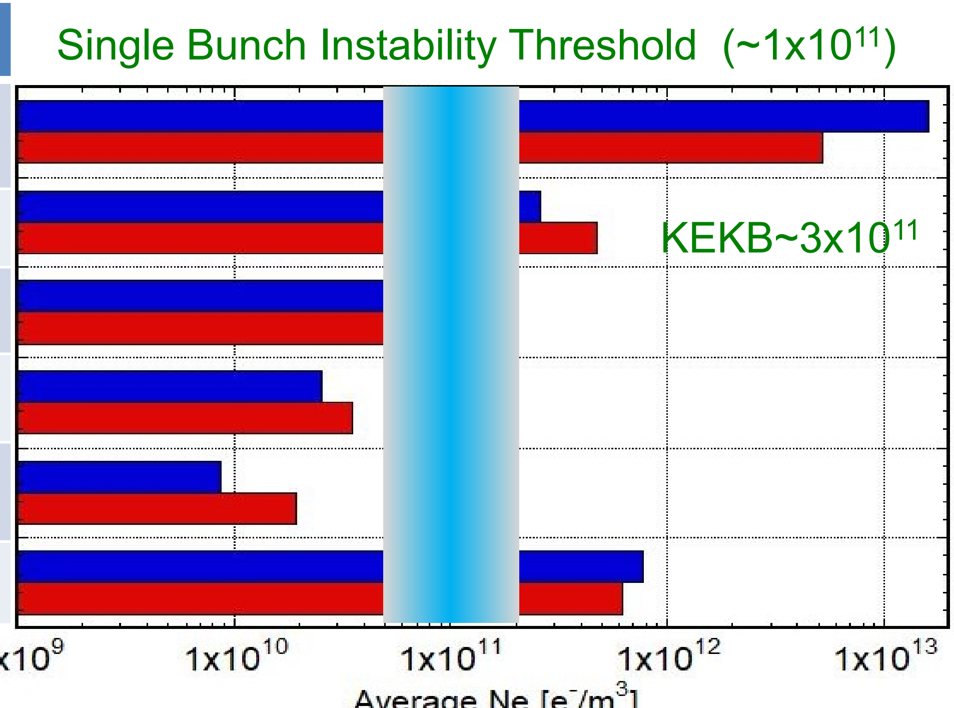


Low density in the simulation ← ne=0 by solenoid. Careful solenoid winding is important.

Expected electron density

- Expected electron density without solenoid (from KEKB)
  - 赤 : n_e expected from experiments in KEKB
  - 青 : n_e calculated using CLOUDLAND
    - Conditions : ϕ94 mm Cu pipe、δ_{max}=1.2, Solenoid field=50G (n_e=0), Antechamber (photoelectron yield =0.01:1/10 of circular pipe)、4ns spacing (2RF)、1 mA/bunch = 600 mA/600 bunch

Condition	ne [m^{-3}]
Circular Cu chamber [KEKB beam pipe]	5.2E12
+Solenoid at Drift (1/50)	4.7E11
+Antechamber (1/5)+TiN (3/5)	5.7e10
+Electrode in Wiggler (1/100)	3.5e10
+Groove in Bend (1/4)	2.0E10
No solenoid	6.2E11



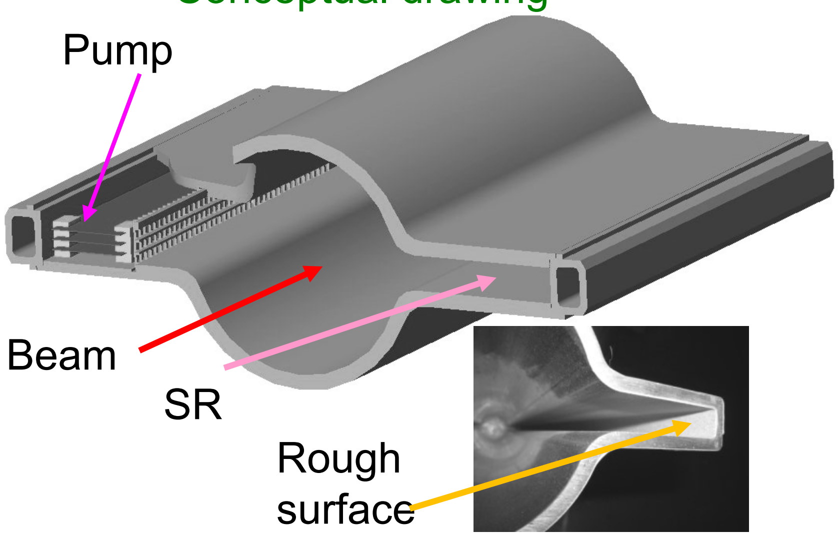
- Without solenoid, n_e is on the order of 10^{11} m^{-3}, near to the measured value.

Drift section_1

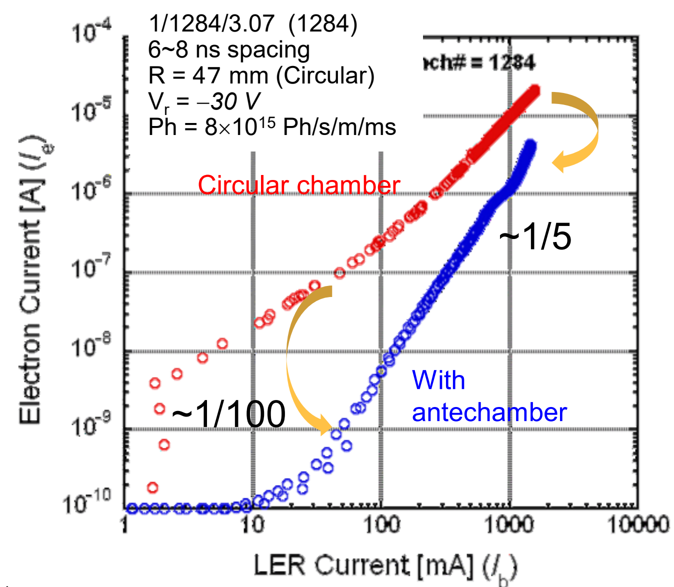
- **Beam pipe with antechambers**
  - Effective to reduce photoelectrons
    - Adopted in PEP-II LER
  - Also effective to reduce photon scattering (with rough surface)
  - Contribute to decrease impedance
  - Reduction rate: ~ 1/5 at high current region

Depth: 65 mm
Height:14 mm
Arc

Conceptual drawing



Effect of antechamber



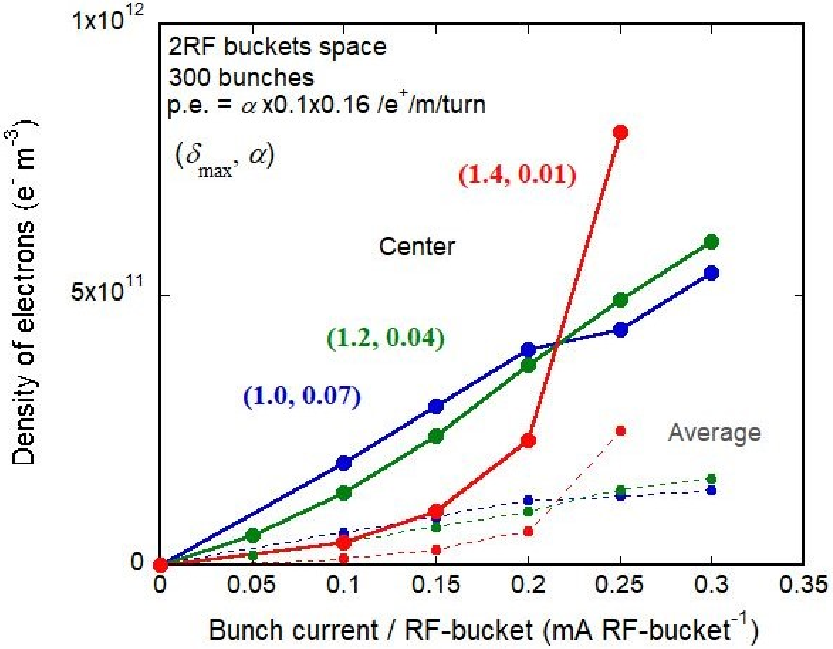
Electron cloud effect

Estimation of α : Method 1

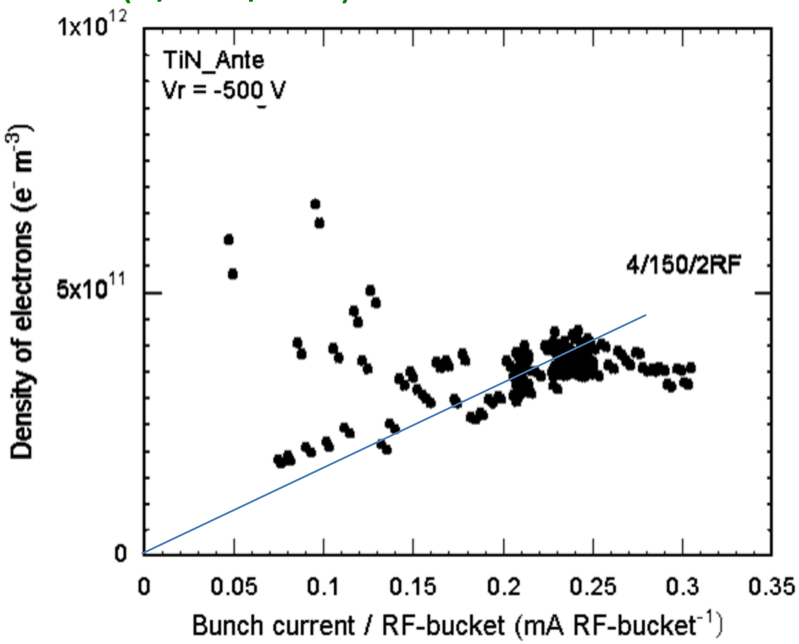
From the behavior of electron density against beam current.

- The behavior changes for the combinations of δ_{max} and α.

Calculated n_e for several combinations of δ_{max} vs α. (1/300/2RF).



Preliminary data:
Measured n_e in Phase-1 [2016/6/20] (4/150/2RF).



- The behaviors are similar to the cases of (δ_{max}, α) = (1.2, 0.04) ~ (1.0,0.07). But, more data are required.

Electron cloud effect

Estimation of α : Method 2

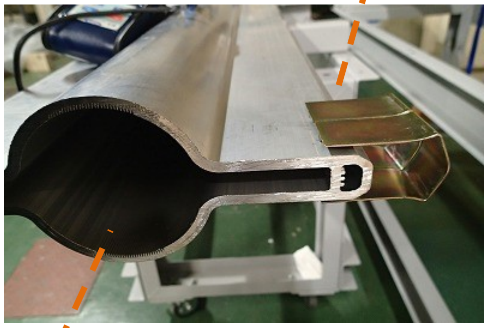
From the difference of measured electron densities between the case where the effect of photoelectrons from antechamber is small (n_{e0}) and the usual case (n_e).

- For example, we will measure the electron density when weak magnetic field is applied to only the antechamber.
  - Assuming that n_e is proportional to the number of photoelectrons in the beam channel, and also that the quantum efficiency is constant,

$$\frac{n_{e0}}{n_e} = \frac{PE_b}{PE_b + \beta \times PE_a}$$

  - PE_b and PE_a: number of photoelectrons in the beam channel and in the antechamber. β: probability that photoelectrons in the antechamber go out to the beam channel.

Apply weak magnets at ante-chamber near electron monitor

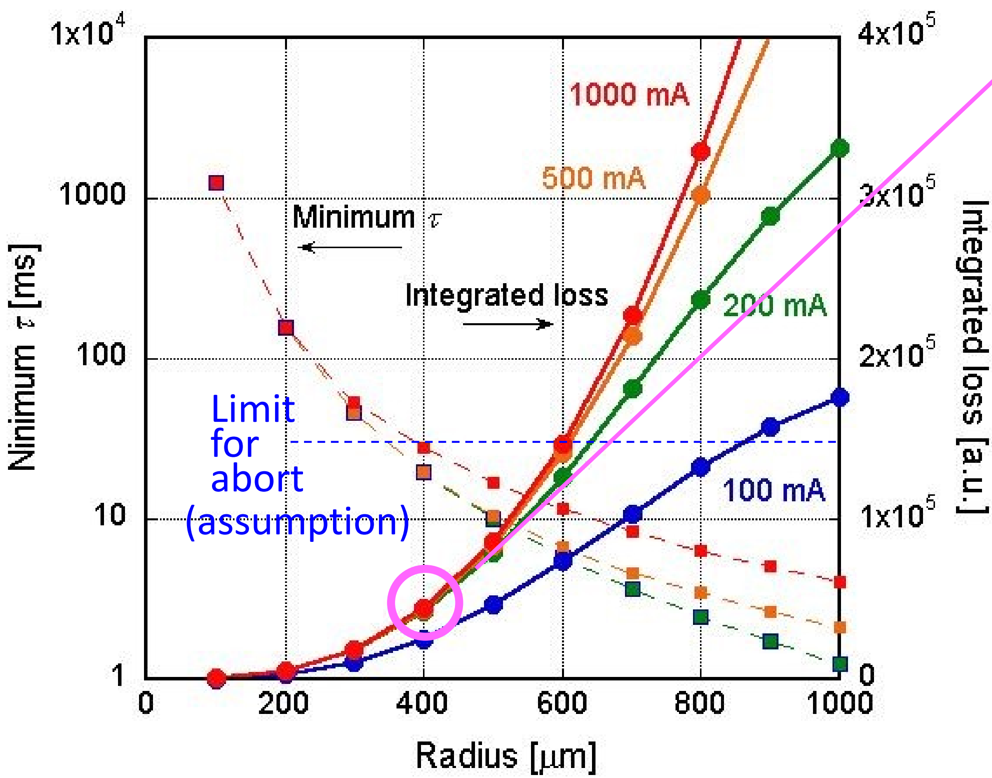


Pressure bursts accompanying beam loss

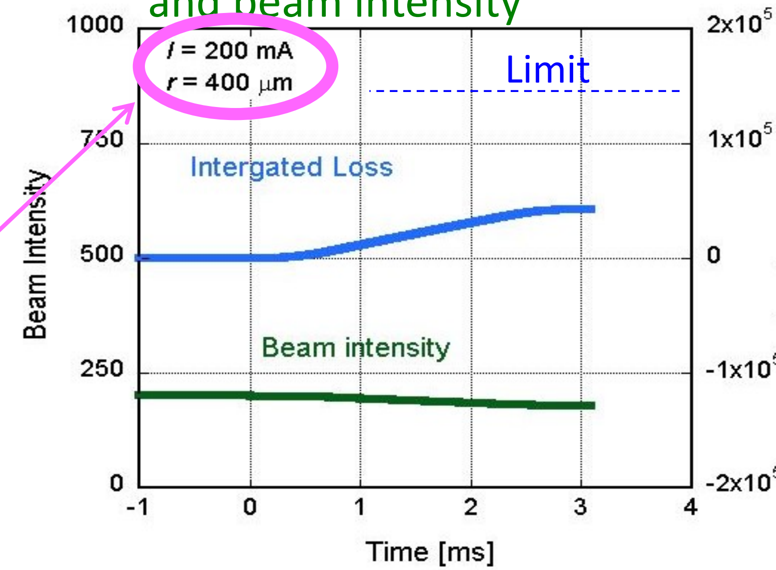
Typical results

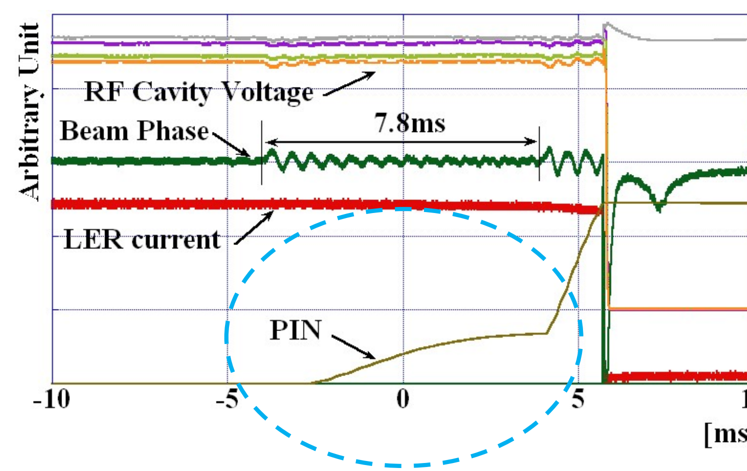
- For Al_2O_3, which is the most probable dust in Al beam pipe

Integrated loss and min. lifetime against dust radius for seal beam currents.



Time change of integrated loss and beam intensity



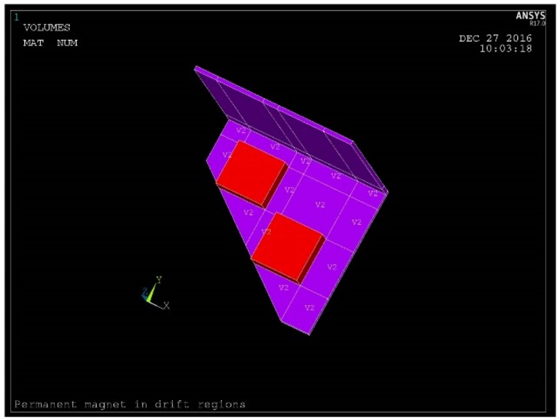


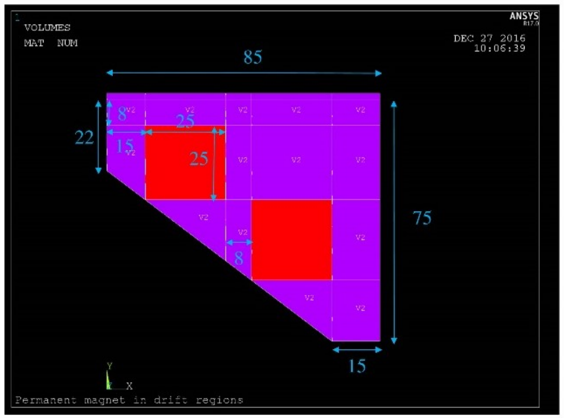
- We can reproduce the log qualitatively.

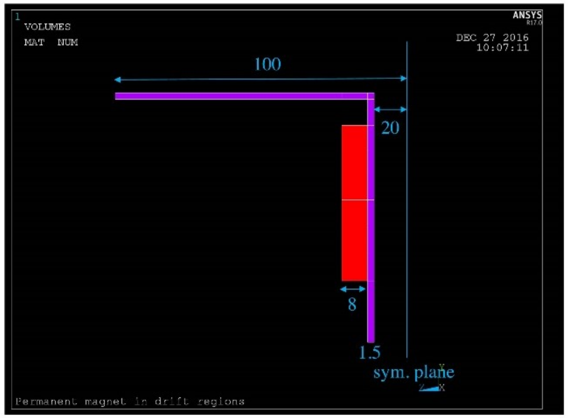
Electron cloud effect

Model of permanent magnet Type-1 (Fukuma san)

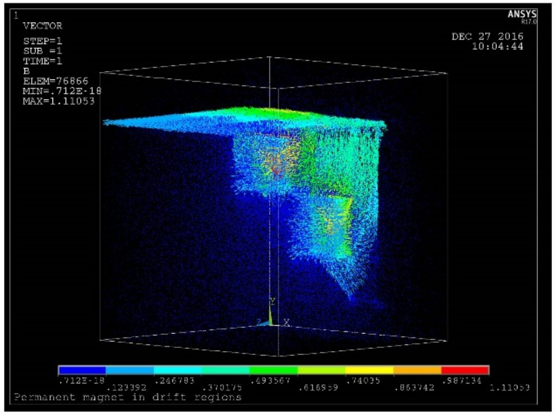
1/8 model

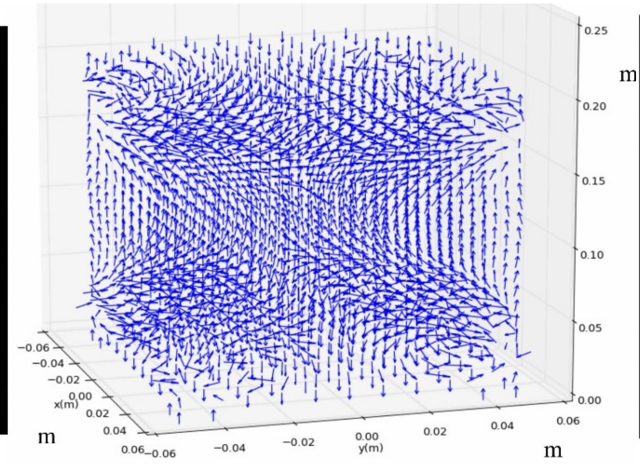


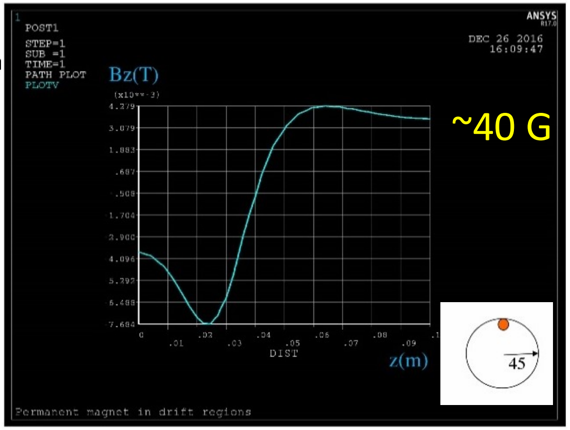




Magnetic field





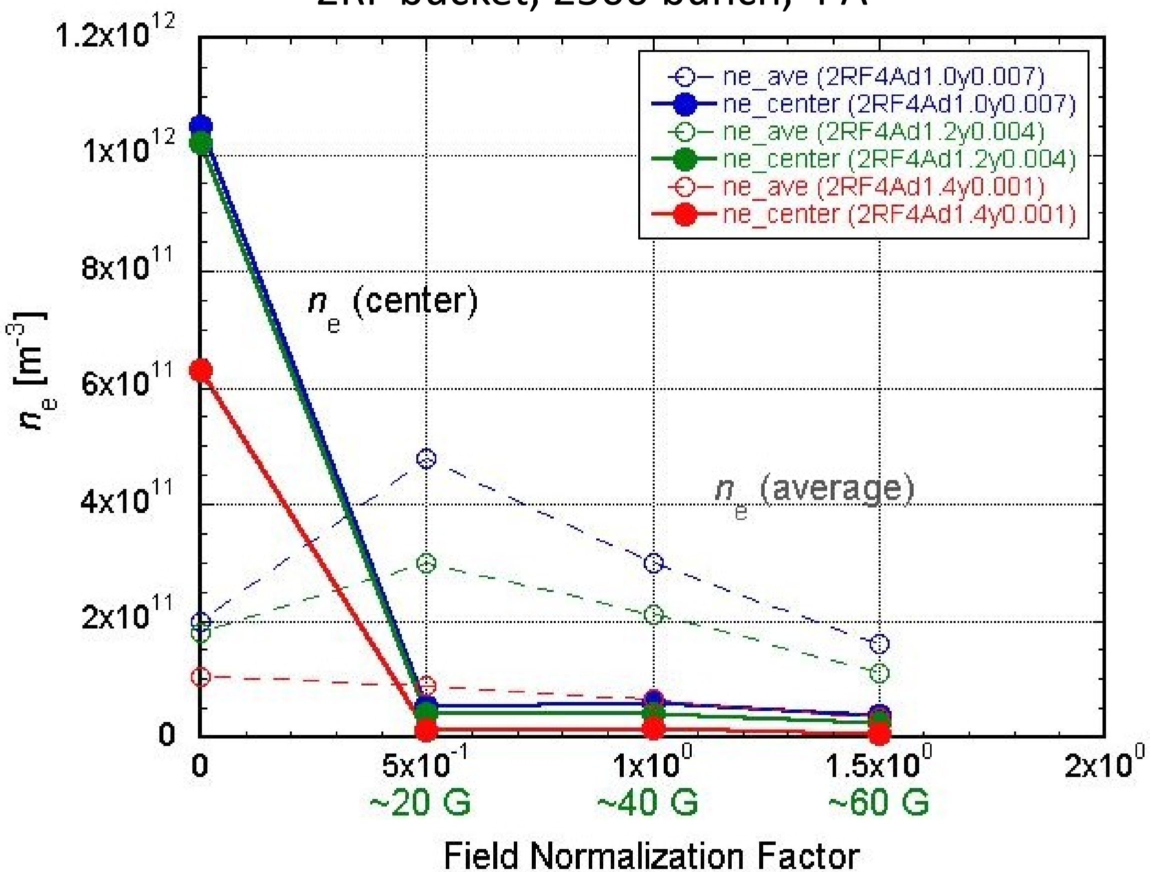


Electron cloud effect

Density of electrons in the Type-1 unit

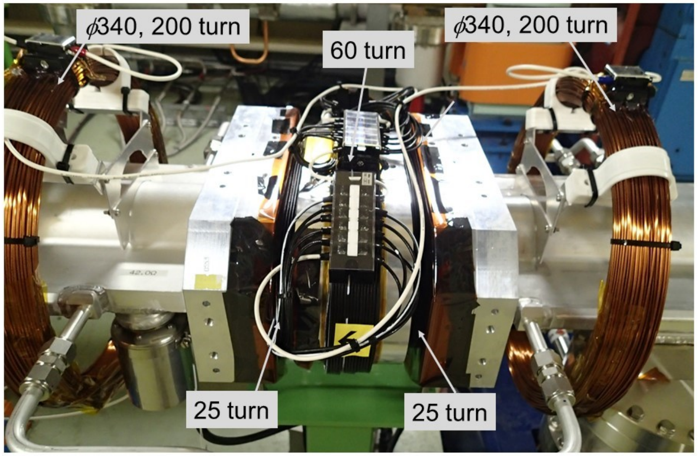
Central density of electrons inside of the Type-1 unit for δ_{max} = 1.0~1.4 and α =0.007~0.001.

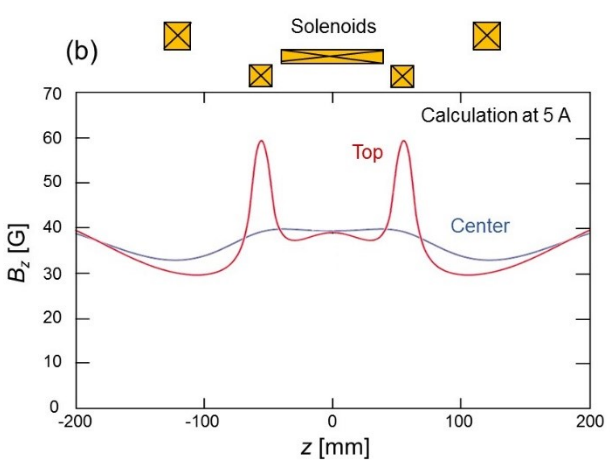
2RF bucket, 2500 bunch, 4 A

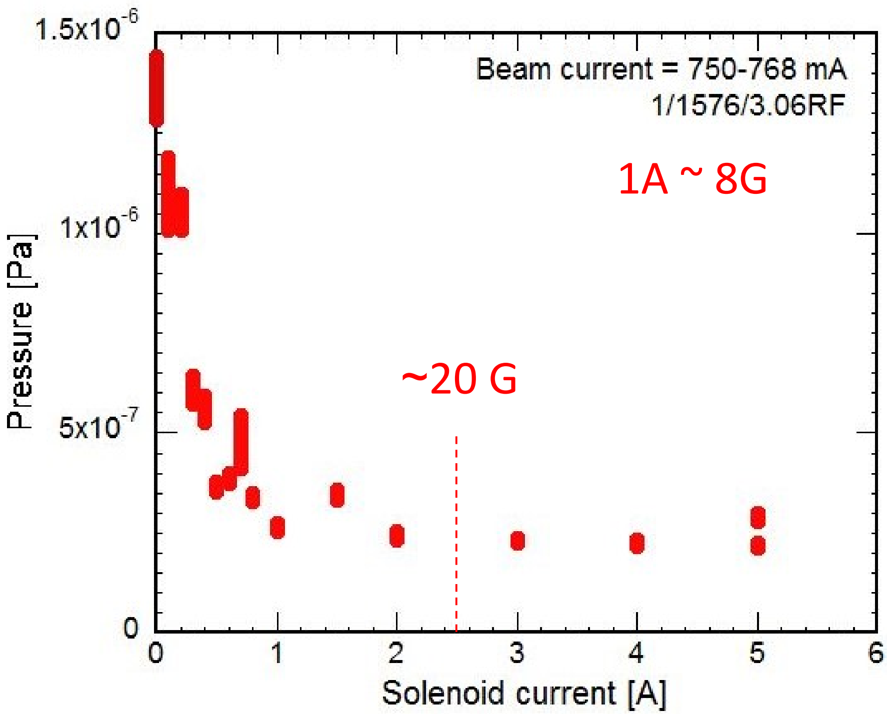


Electron cloud effect

Effect of magnetic field







Effect of Baking on δ_{max} of TiN coating (in laboratory)