EC R&Ds at KEKB and Plans for the future Super KEKB

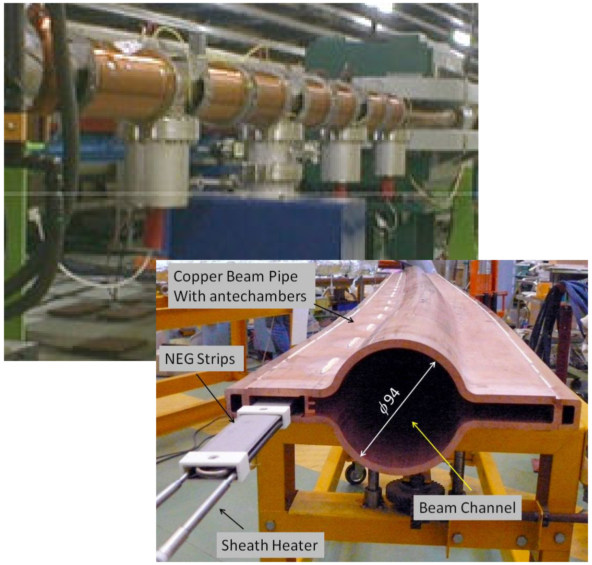
Y. Suetsugu, KEK
on behalf of KEKB Vacuum Group

Contents

1. EC R&Ds at KEK

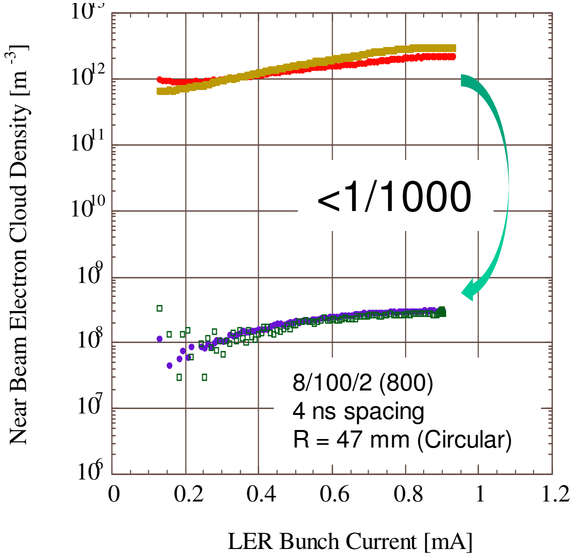
- A pressing issue for the upgrade of KEKB (Super KEKB): To establish effective and applicable EC mitigation techniques for the e^+ ring, especially in a magnetic field.
  - At drift space: "Solenoid field + Beam pipes with antechamber" is a basic and a very effective remedy.← Experience at KEKB
  - In magnets, the antechamber-scheme together with some coatings will be also effective. But more definitive techniques are required.

Solenoid

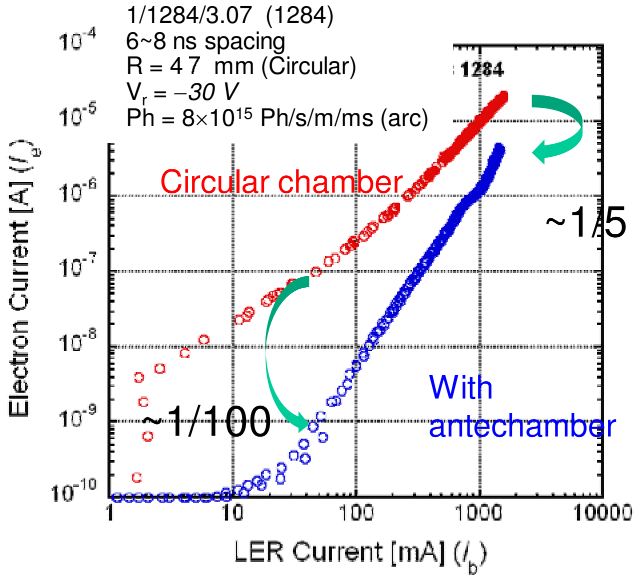


Beam pipe with antechambers

Effect of solenoid [by K. Kanazawa]



Effect of antechamber



1. EC R&Ds at KEK

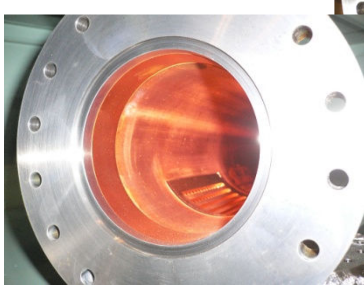
- Focused R&D items in these years are;
  - Experiments of coatings
    - TiN, NEG materials, Graphite, DLC
  - Experiments of clearing electrodes and grooved surfaces
  - Measurements of electron densities around beam orbit by using electron monitors with RFA.
    - In wiggler magnets, in quadrupole magnets, in solenoids
  - Measurement of SEY
    - At laboratory, in situ., surface analysis
- Using the KEKB positron ring:
  - Energy = 3.5 GeV
  - Beam current ~1600 mA with 1585 bunches (~1 mA [10 nC] /bunch)
  - Typical bunch spacing ~ 6 ns (4 ~ 16 ns in study)
  - Bunch length ~ 6 mm

- Reported here are about the recent progress on coatings, clearing electrodes and grooved surfaces.

2.1 Coating

- Some coatings on inner surface are effective to reduce SEY.
  - TiN, NEG materials, Graphite, DLC
  - Mainly focused on TiN coating here [K. Shibata, AEC'09, CERN, 2009]
    - The technique was well established.
- Test chambers with/without coatings have been installed into the KEKB e^+ ring, and the electron densities in the chambers were compared each other.
  - Chamber materials: copper (Cu, OFC), aluminum alloy (Al)
  - Measured at the same location, using the same monitor with RFA, and evacuated by the same pumps.

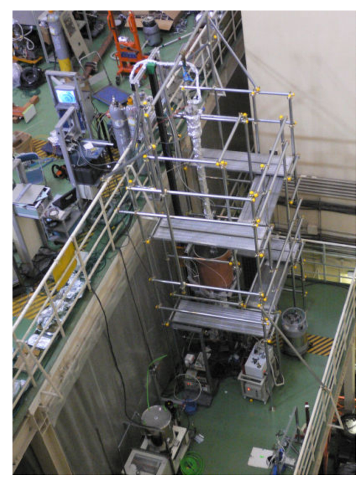
Cu

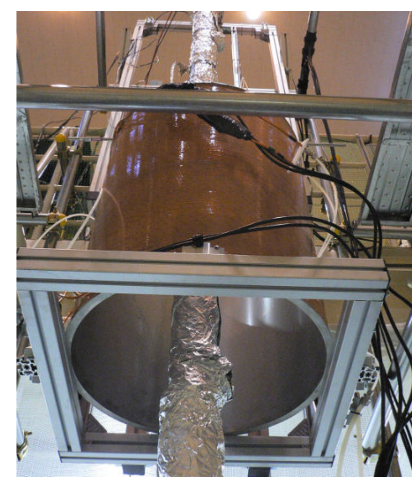


Cu+TiN

Cu+NEG

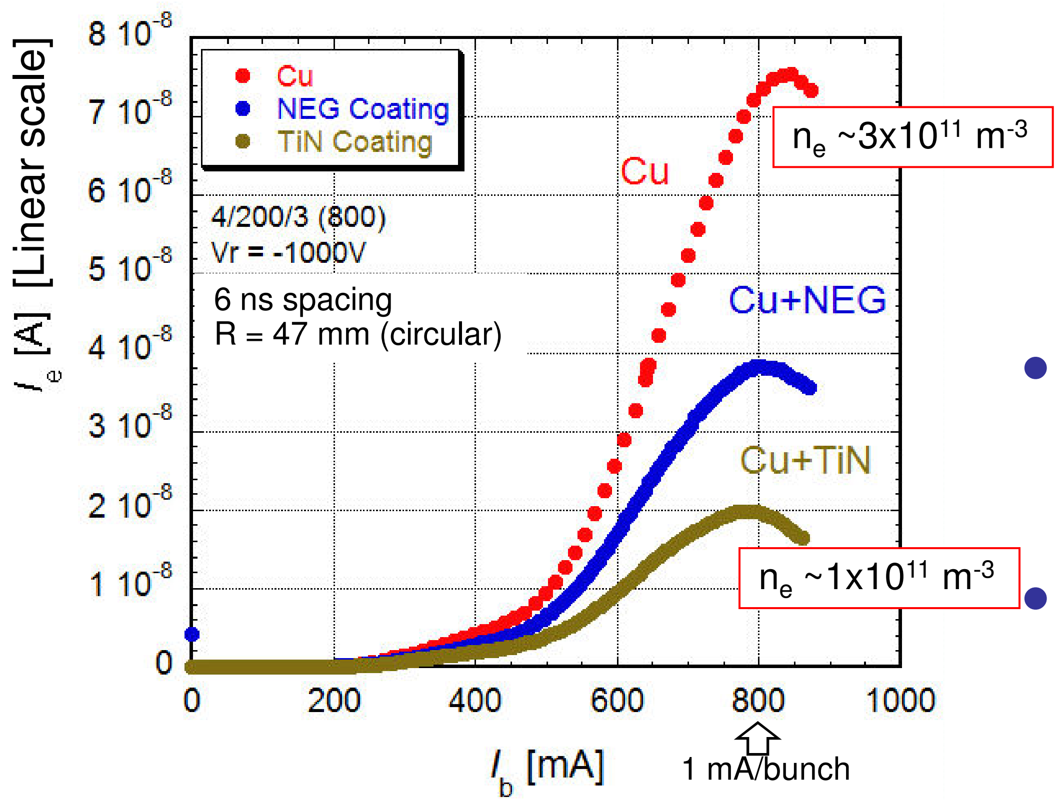
TiN coating system at KEK



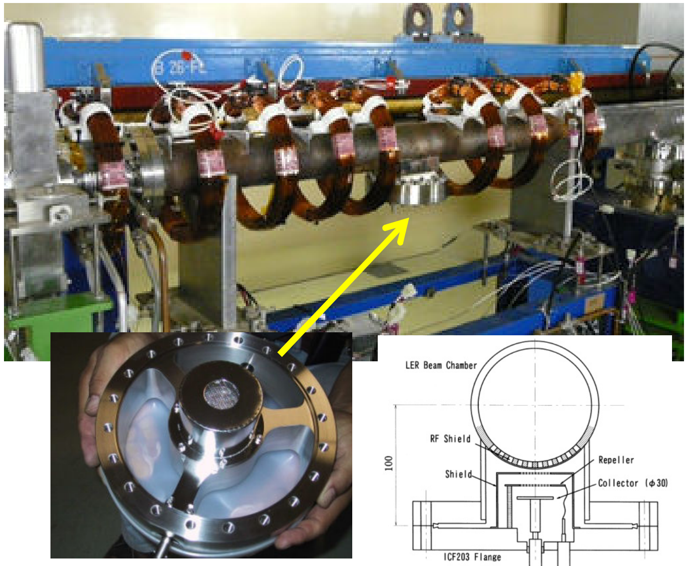


2.1 Coating

- Straight section [2006~]
  - Photons= 3x10[12] photons/s/m/mA
  - Drift space
- Cu, Cu+TiN, Cu+NEG
  - Circular pipe (ϕ 94)



Installed test chamber



Electron monitor with RFA

- These coatings can decrease the electron density compared to the bare copper by a factor of 2~3.
- Estimated δ_{max}
  - Cu: 1.1 ~ 1.3
  - TiN 0.8 ~ 1.0

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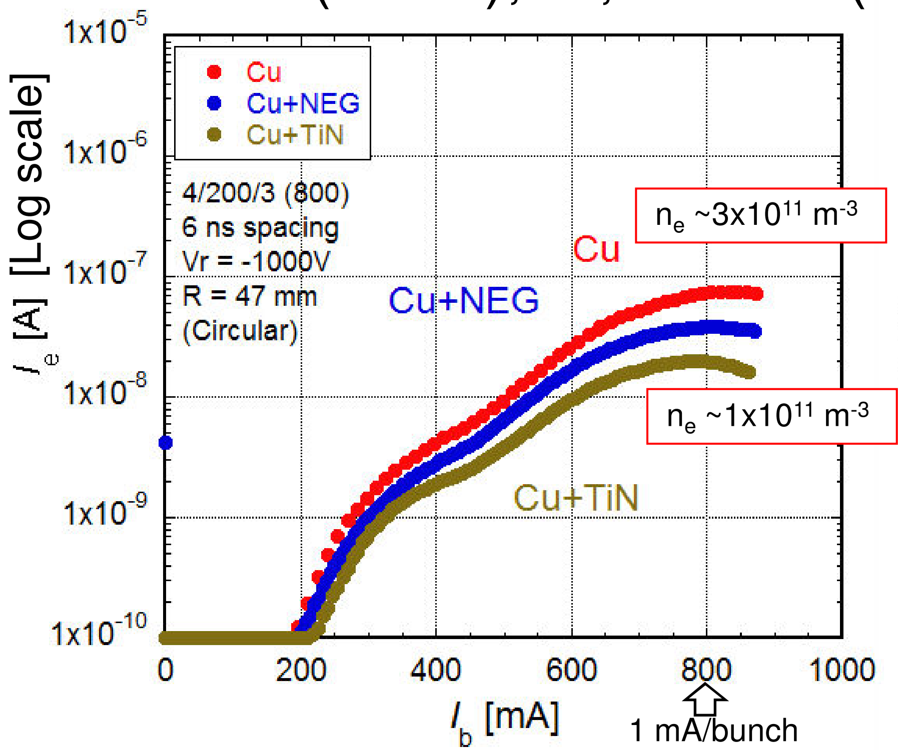
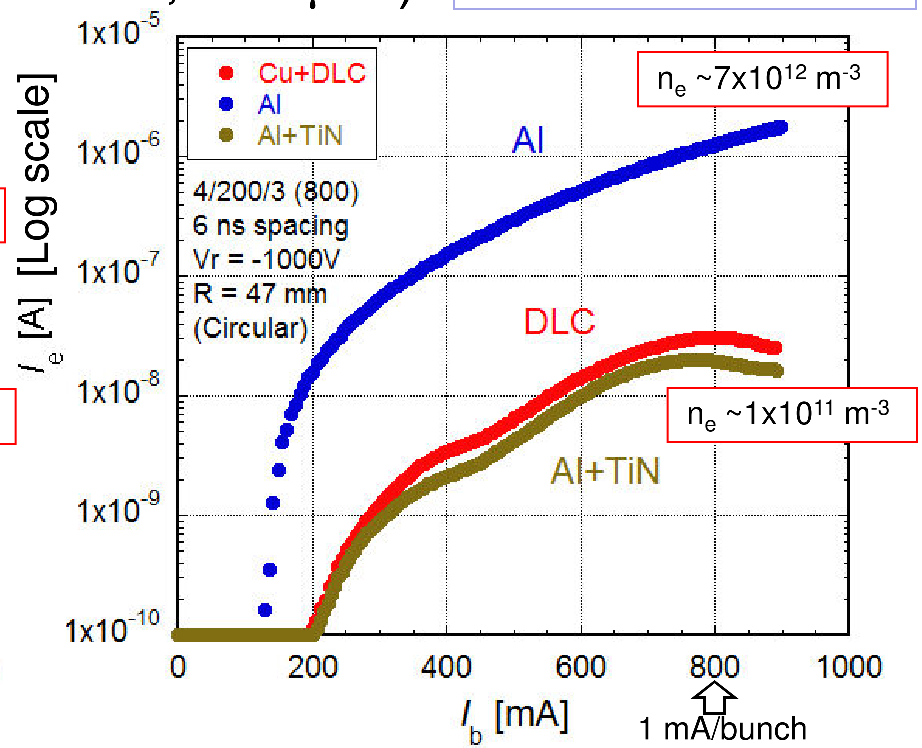
2.1 Coating

- Straight section (contd.) [~2009]
  - Drift space, Photons= 3×10^{12} ph/s/m/mA
- Cu+DLC (KEK*), Al, Al+TiN (KEK**, 0.2 μm)

*S.Kato, AEC'09, CERN, 2009
**K. Shibata, AEC'09, CERN, 2009

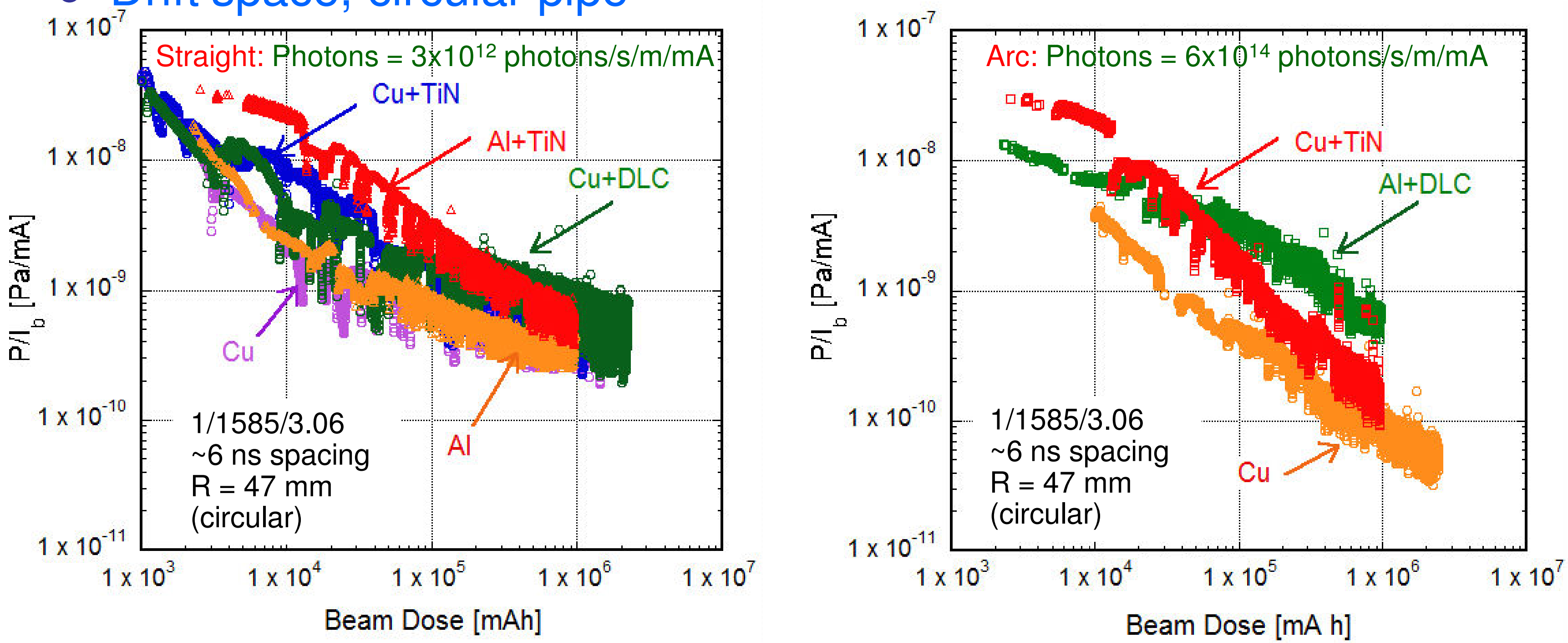




- Bare aluminum is nightmare. These coatings is very effective compared to bare aluminum.
- The effect of TiN coating is independent on the substrate.

2.1 Coating

- Gas desorption (Photon Stimulated Desorption)
  - Cu, Cu+TiN, Cu+DLC (KEK*), Al, Al+TiN (KEK**)
- Measured at straight section and arc section
  - Drift space, circular pipe



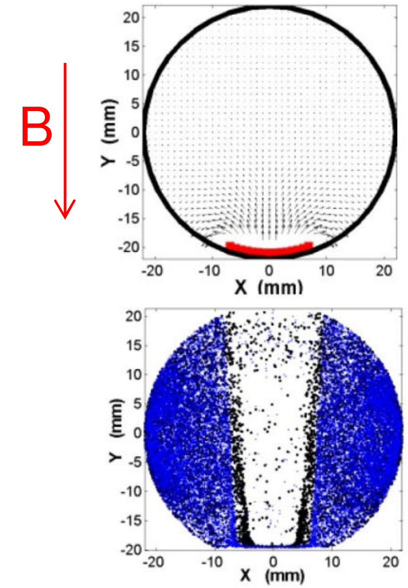
- TiN coating has a large gas desorption rate at initial stage. But the gas desorption decreases by scrubbing, and becomes comparable to copper or aluminum. (~ by a factor of 2)
- Main gas desorbed from DLC was H_2 (by M. Nishiwaki)

2.1 Summary of coating

- If aluminum alloy is used as a beam pipe, the coating is indispensable.
  - The electron densities are much smaller than that for the case of bare aluminum, but comparable to the case of bare copper.
- If copper is used as a beam pipe, the merit of coating should be considered together with cost, labor, construction period, reliability (QC), and also the possibility of electrodes and grooves (see next section)
- TiN coating seems most suitable for Super KEKB at present, if used.
  - Technique is well established, applicable to both Cu and Al-alloy.
  - Long term experience at PEPII (high current e^+ machine)
  - Pumping effect is not so important for us.
  - Baking up to 180°C in situ is actually hardly is difficult to activate NEG.
  - Relatively high gas desorption: High current → Quick vacuum scrubbing?

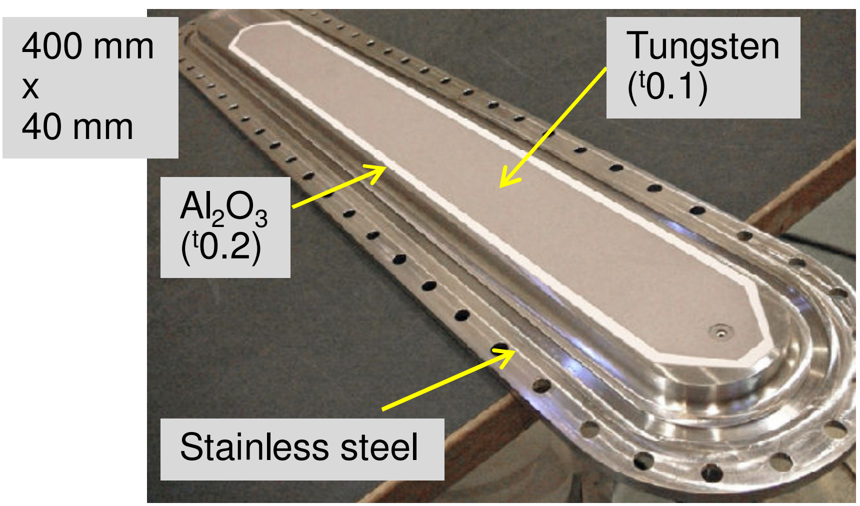
2.2 Clearing electrode

- Clearing electrode has been said to be very effective to reduce EC in magnetic field.
  - Impedance and heating of electrode have been serious problems for intense e^+ beam.
- Very thin electrode structure was developed.
  - 0.2 mm Al_2O_3 insulator and 0.1 mm tungsten (W) electrode formed by a thermal spray method.
    - Good heat transfer and low beam impedance
  - Flat connection between feed-through and electrode

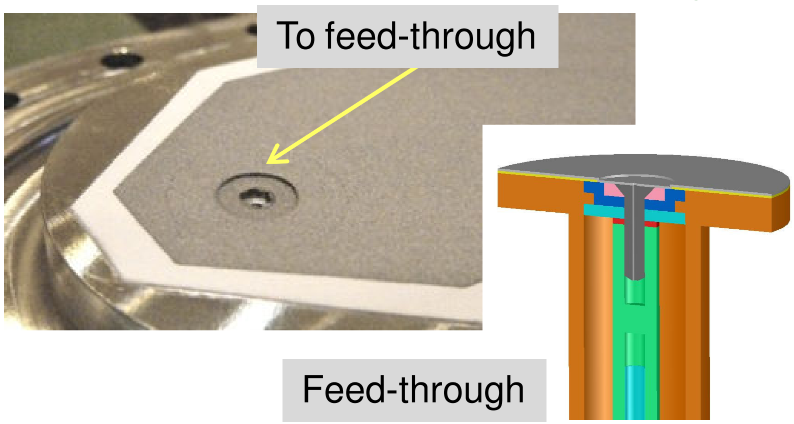


Simulation by L. Wang

An insertion for test with a thin electrode



Connection to feed through



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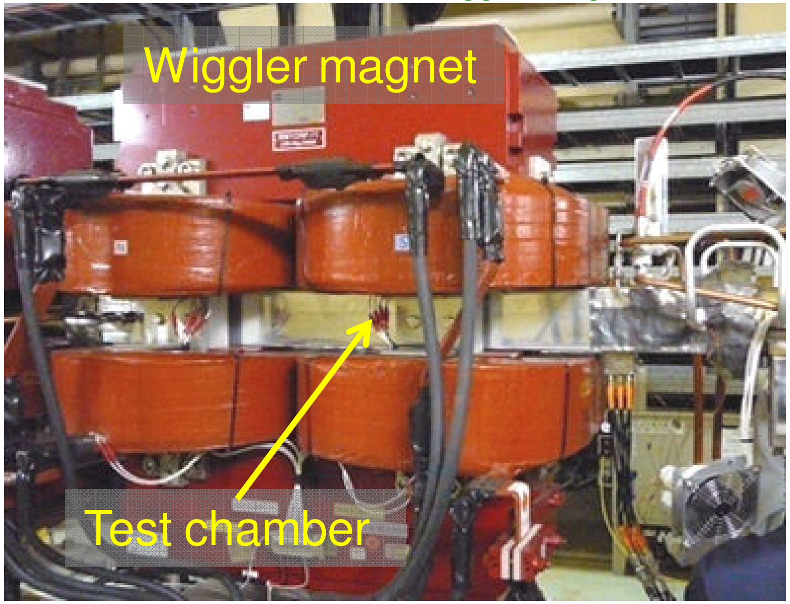
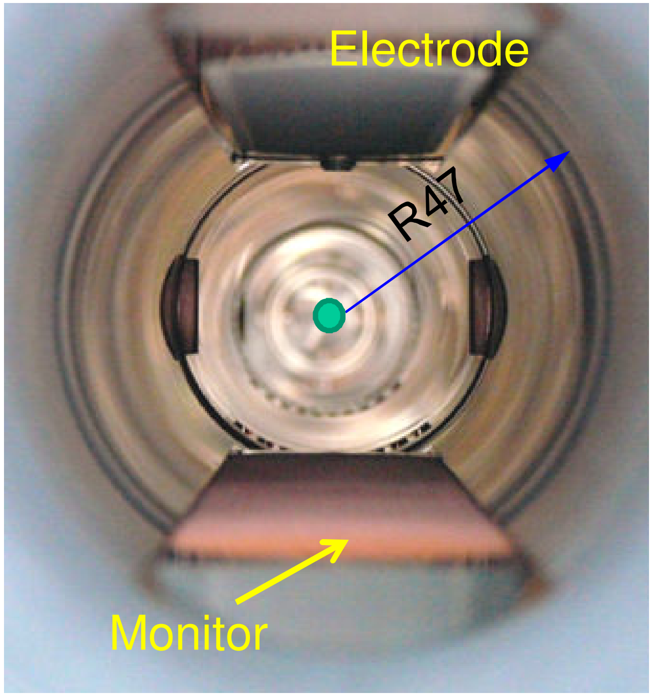
2.2 Clearing electrode

- A test chamber was installed in a wiggler magnet. [2008]
  - Magnetic field: 0.78 T
  - Effective length: 346 mm
  - Aperture (height): 110 mm
  - Photons: 1×10^{14} photons/s/m/mA

Test chamber in a wiggler magnet



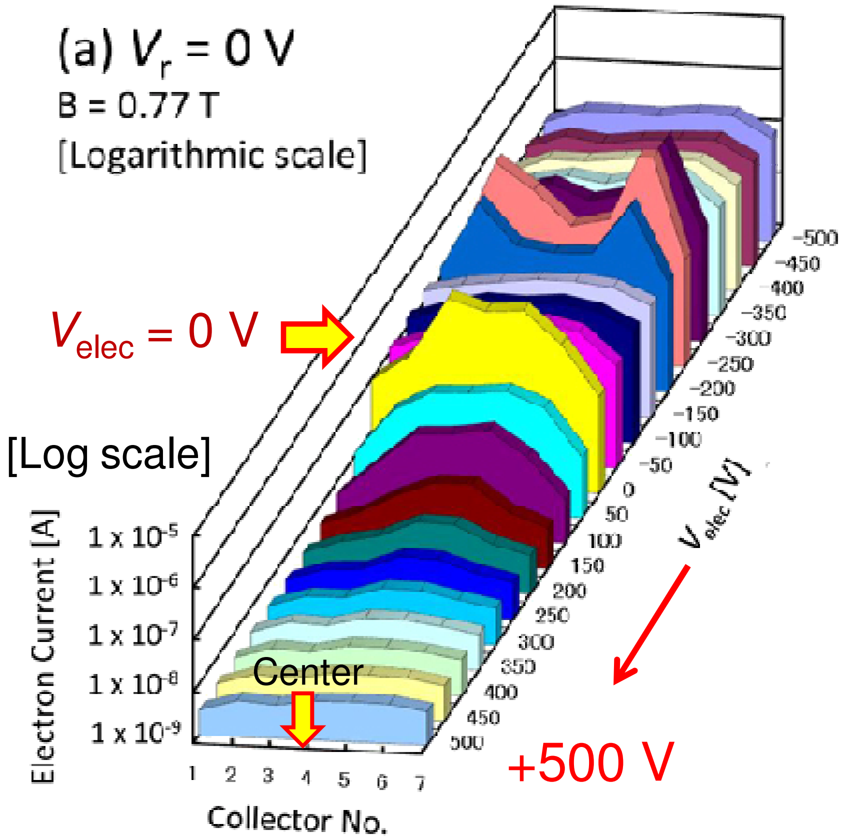
Inside view



- An electron monitor and an insertion with an electrode are placed at the center of a pole, face to face.
- Electron monitor has an RFA and 7 strips to measure spatial electron distribution (~40 mm width in total).

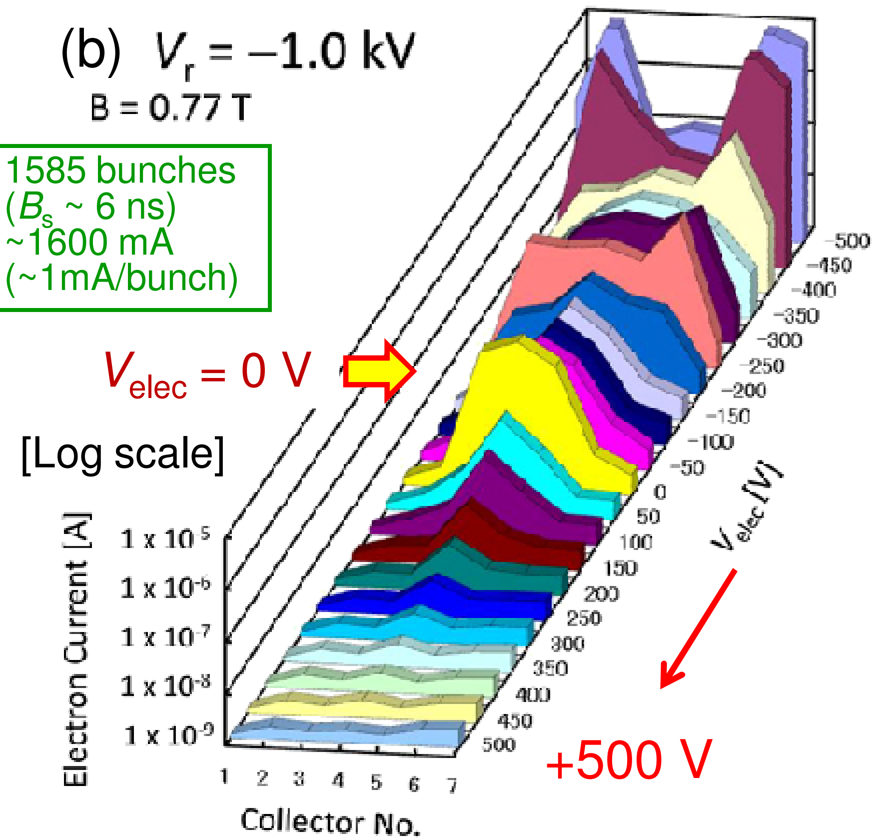
2.2 Clearing electrode

- Results: Effect of electrode potential (V_{elec})
  - Drastic decrease in the electron density by applying V_{elec} was observed. (For negative large V_{elec}, electrons flows into the monitor)
  - Similar effect was observed for 2 ~ 16 ns spacings.



[Spatial distribution]

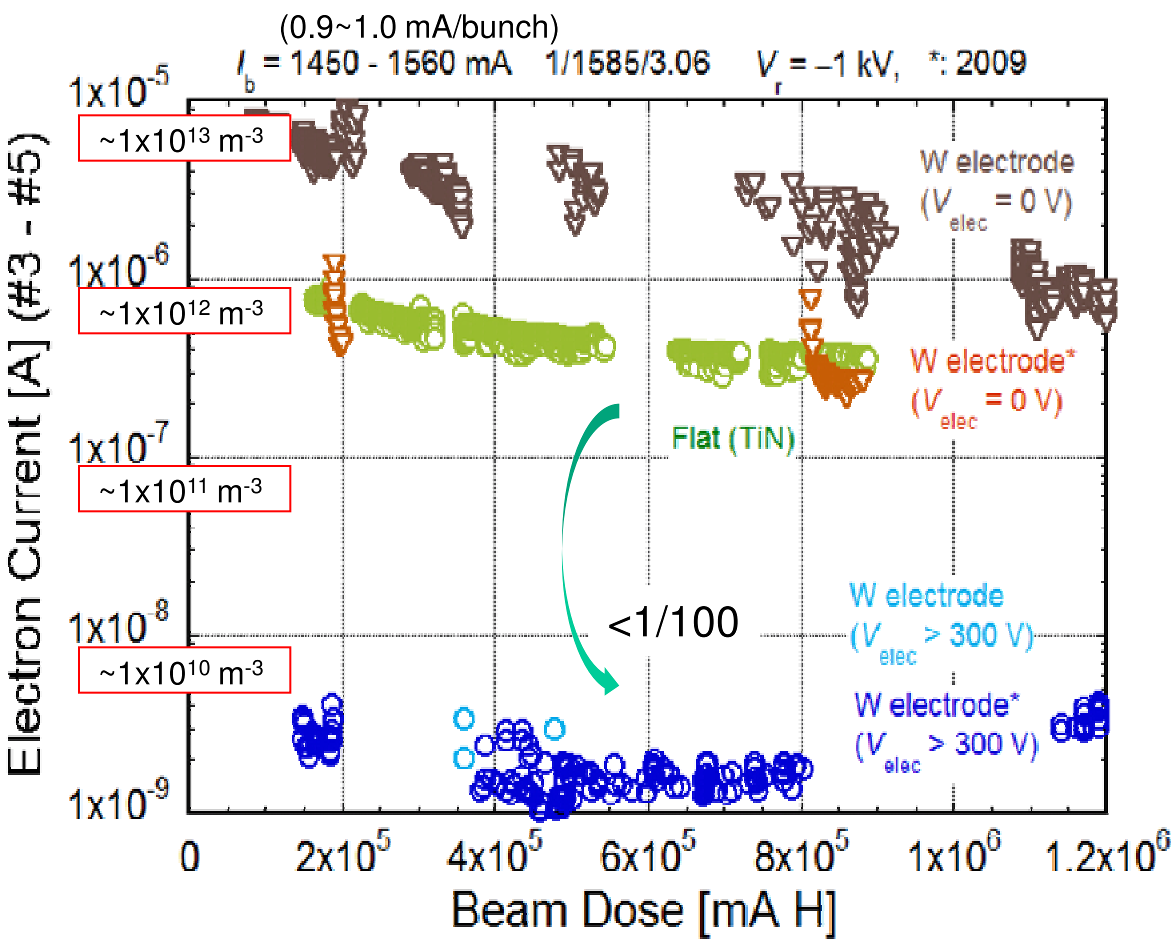
1585 bunches
(B_s ~ 6 ns)
~1600 mA
(~1mA/bunch)



[Spatial distribution]

2.2 Clearing electrode

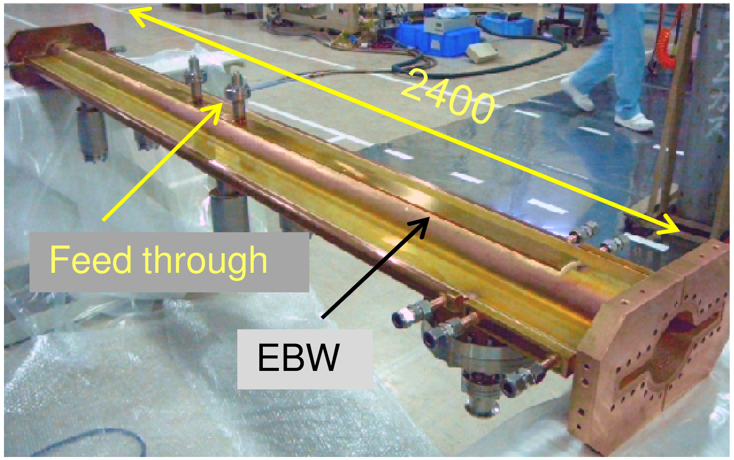
- Results: Change with beam dose (integrated beam current)
  - The electron density decreased to less than ~1/100 at V_{elec} > ~+300 V compared to the values at V_{elec} = 0 V (W) and a TiN-coated flat surface.

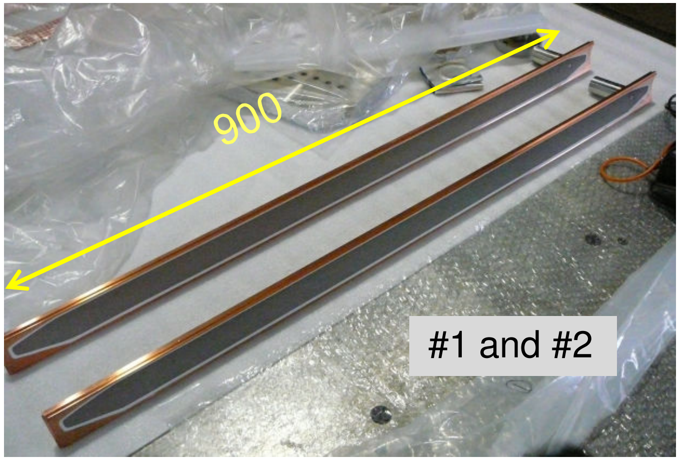


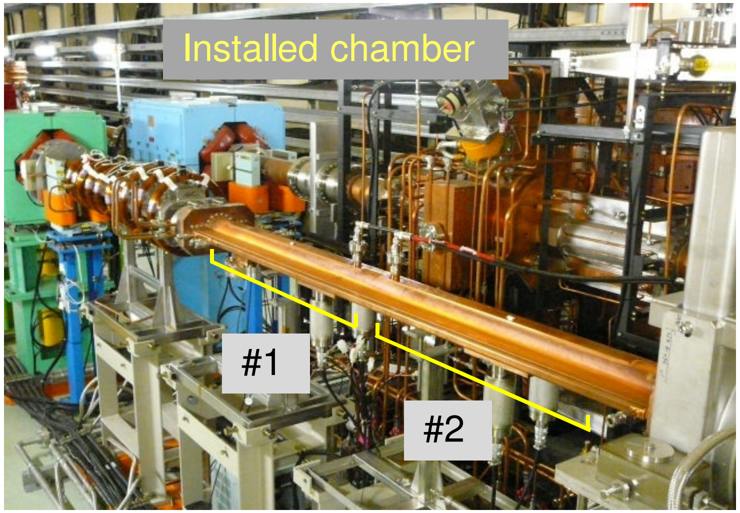
- Two-time experiments.
- Electron currents for the thermal-sprayed tungsten (V_{elec} = 0V) is similar to the case of flat TiN-coated surface.
  ←Rough surface?
- No extra heating of electrode and feed-through was observed.
- Basic design was established.

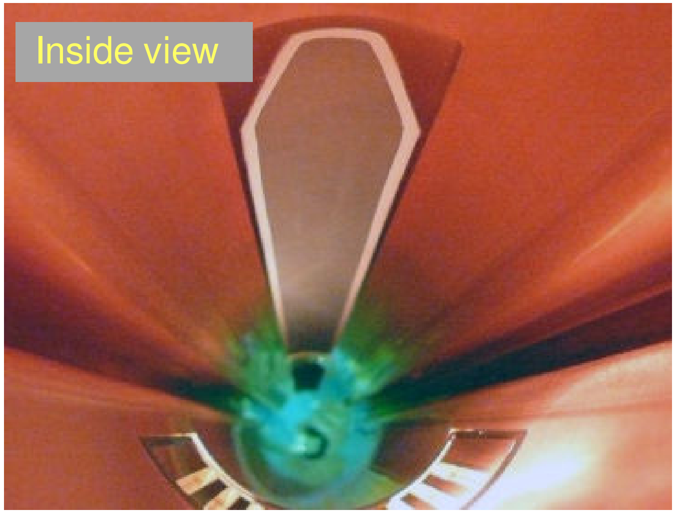
2.2 Clearing electrode

- Application to a real beam pipe with antechambers. [2009]
  - Final check of feed through and heating of electrode → No problem



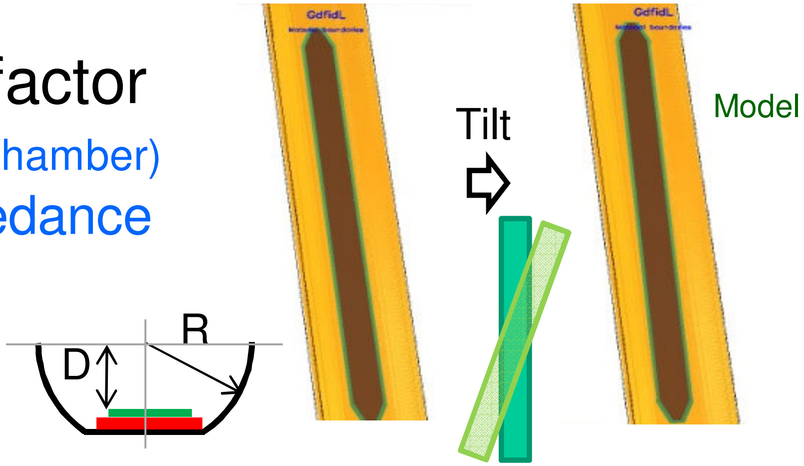


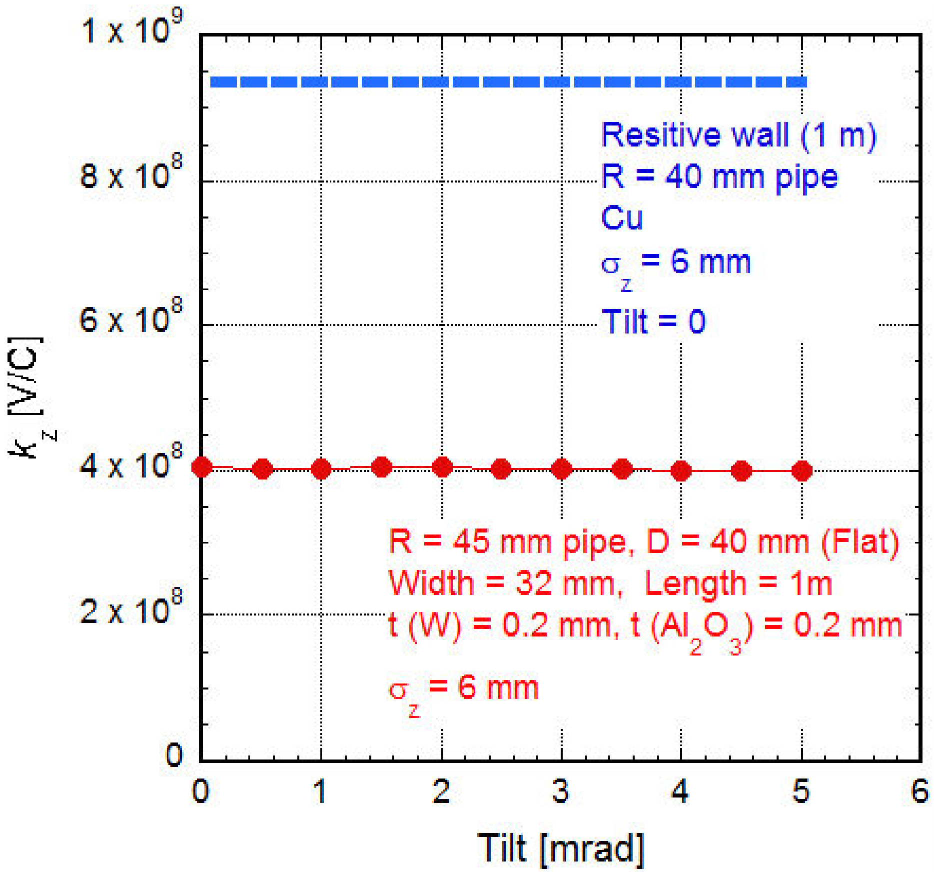




2.2 Clearing electrode

- Impedance: Effect of tilt on loss factor
  - Calculated by GdfidL (1m model, half chamber)
  - Comparison with resistive wall impedance
  - Up to 5 mrad

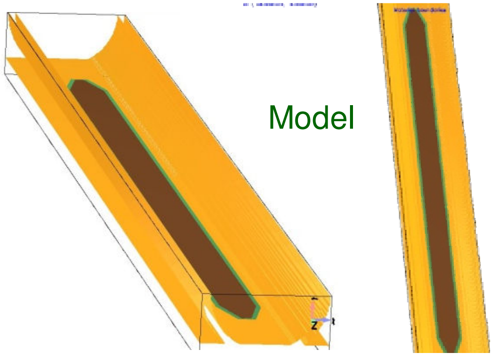


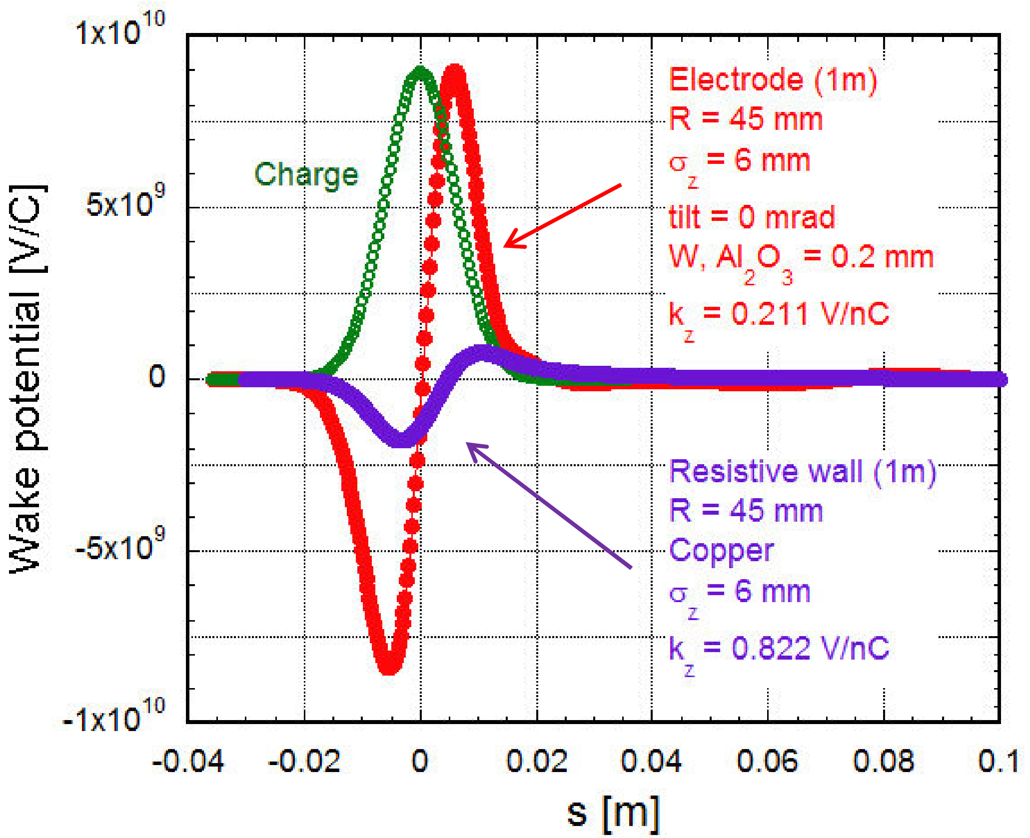


- Loss factor is smaller (~1/2) compared to that of the resistive wall (Cu, for 1 m). That is, the increase in total loss factor is ~ 50%.
- Loss factor is constant against tilt.

2.2 Clearing electrode

- Impedance: Comparison with resistive wall
  - Calculated by GdfidL (1m model, half chamber)
  - Comparison with resistive wall

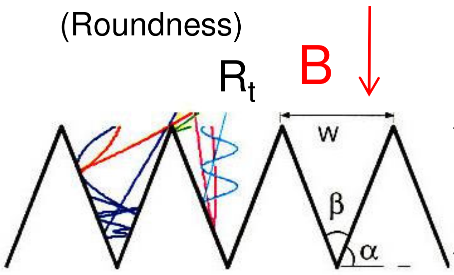




- The wake potential is inductive.
- The peak value of the wake potential is higher by a factor of 5, though the loss factor is small.
- Should be carful in using the electrode for long section, in relation to single bunch instability

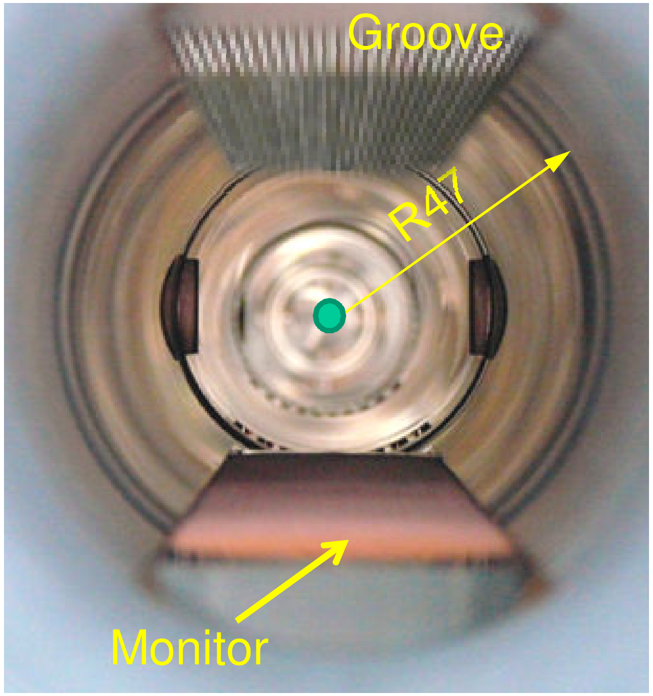
2.3 Grooved surface

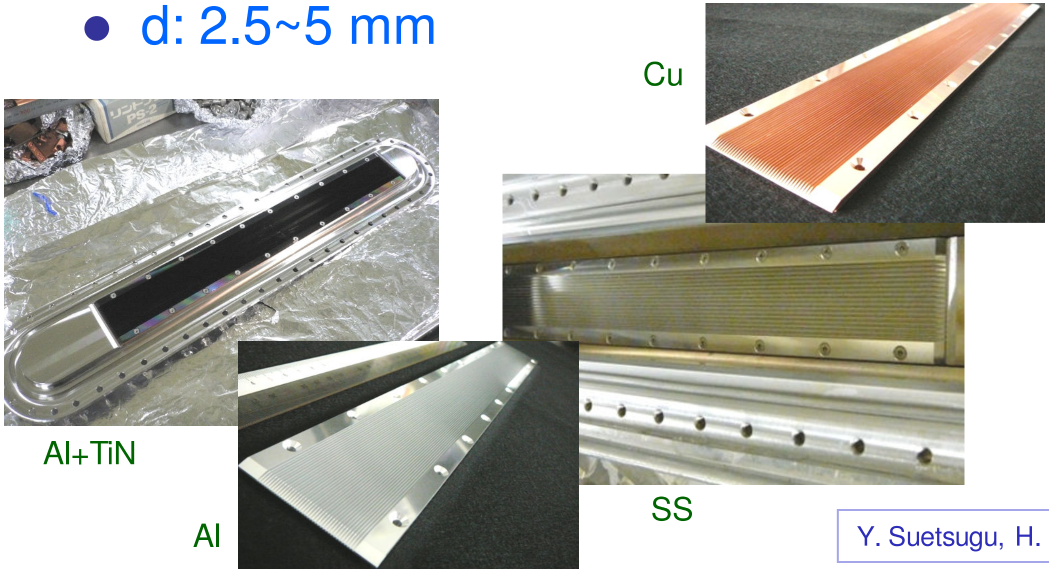
- Grooves geometrically reduces the effective SEY.
  - The properties were studied in a wiggler magnet using the same experimental setup to that of the previous clearing electrode.
  - B = 0.78 T
- Parameters of grooves
  - Material: Cu, Al-alloy, SS
  - β : 20~30°, R_t:0.1~0.2 mm (rectangular)
  - d: 2.5~5 mm



by L. Wang et al.

Inside view





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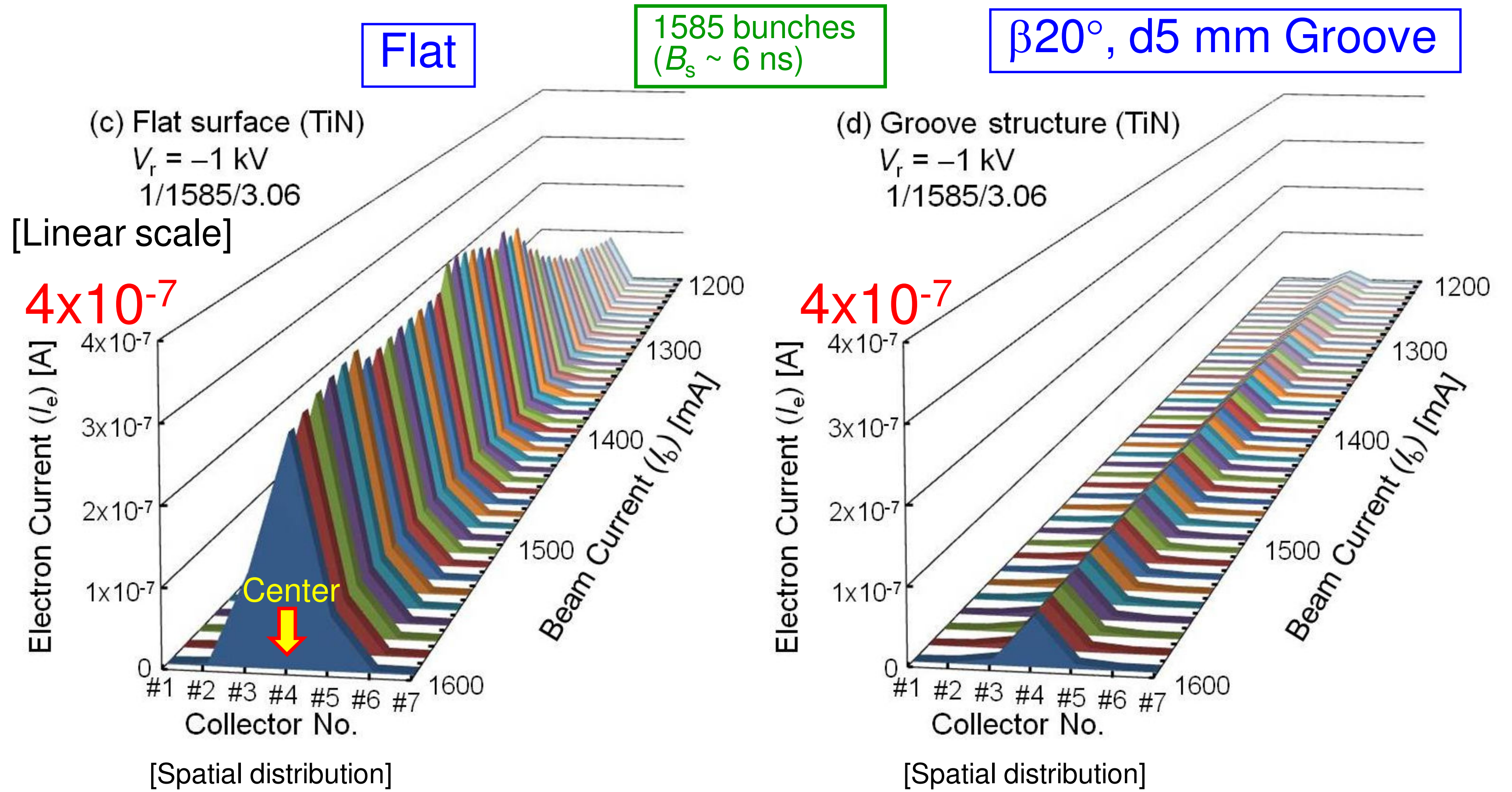
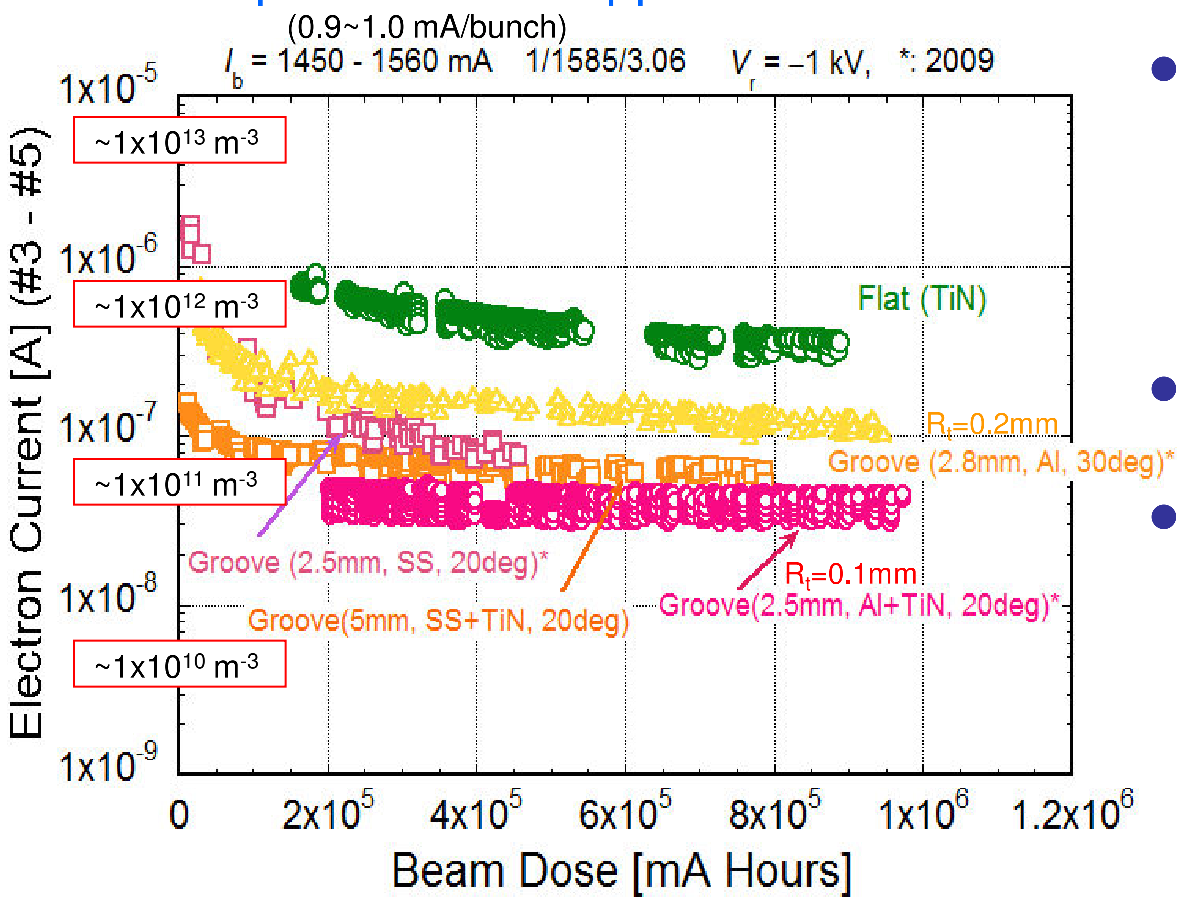
2.3 Grooved surface

- Results: EC growth
  - A significant reduction in the electron density was observed by using grooved surfaces.
  - Similar effect was observed for 2 ~ 16 ns spacings.



2.3 Grooved surface

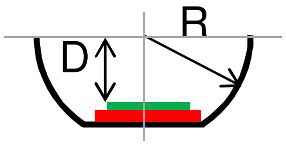
- Results: Change with beam dose (integrated beam current)
  - The electron density decreased to 1/6~1/10 compared to the case of a flat TiN-coated surface (for $\beta = 20$). That is, less than ~1/10 compared to flat copper.

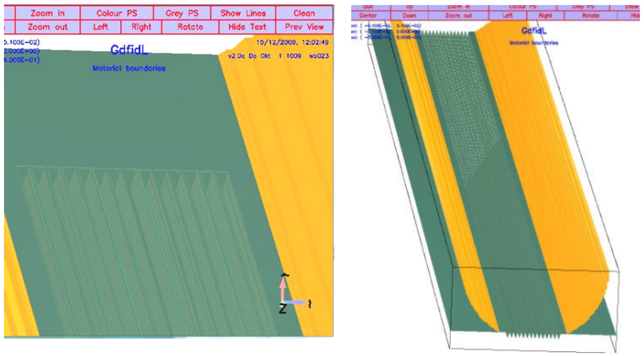


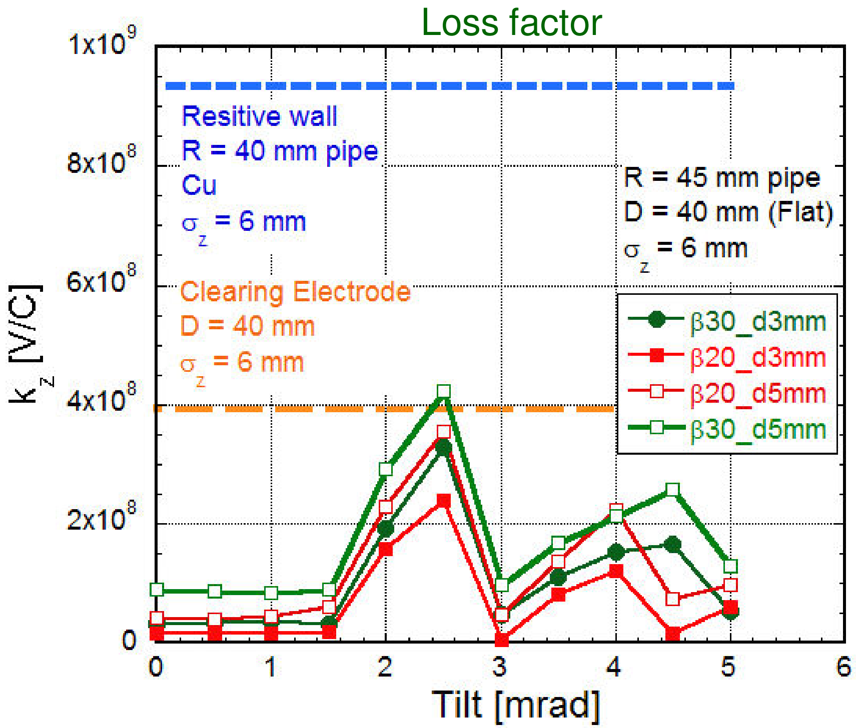
- Electron densities for grooves surfaces in these parameters were lower than the case of a flat TiN-coated surface.
- Less density for smaller β and R_t.
- TiN coating improves the effect, but the groove structure seems much effective to reduce SEY.

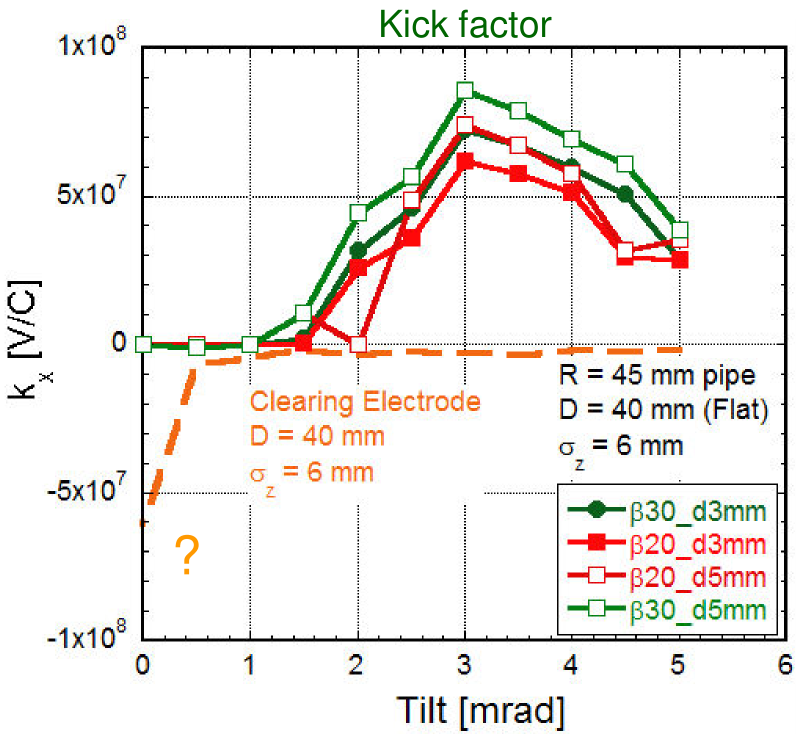
2.3 Grooved surface

- Impedance: Effect of tilt on loss factor
  - Calculated by using GdfidL
    (1m model, Half chamber)
  - Up to 5 mrad







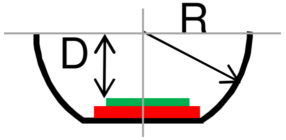


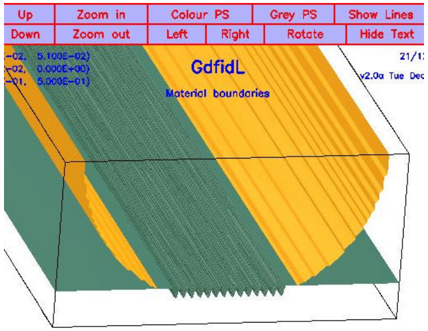
- The loss factor is very small for tilt angle = 0 ~ 1mrad. (~10 % of resistive wall)
- It increases up to a comparable level with (still lower than) a clearing electrode for tilt > 2mrad.

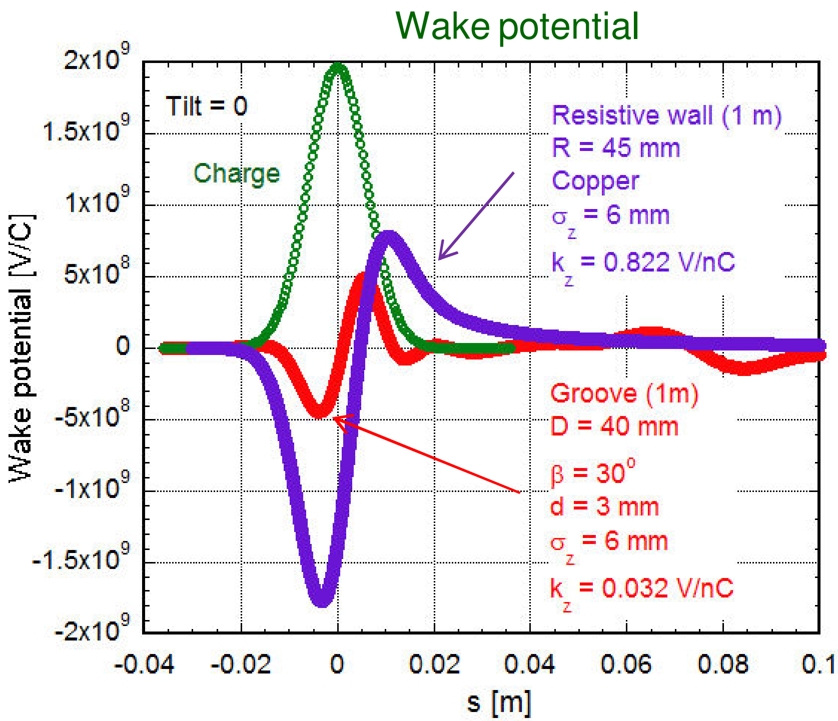
2.3 Grooved surface

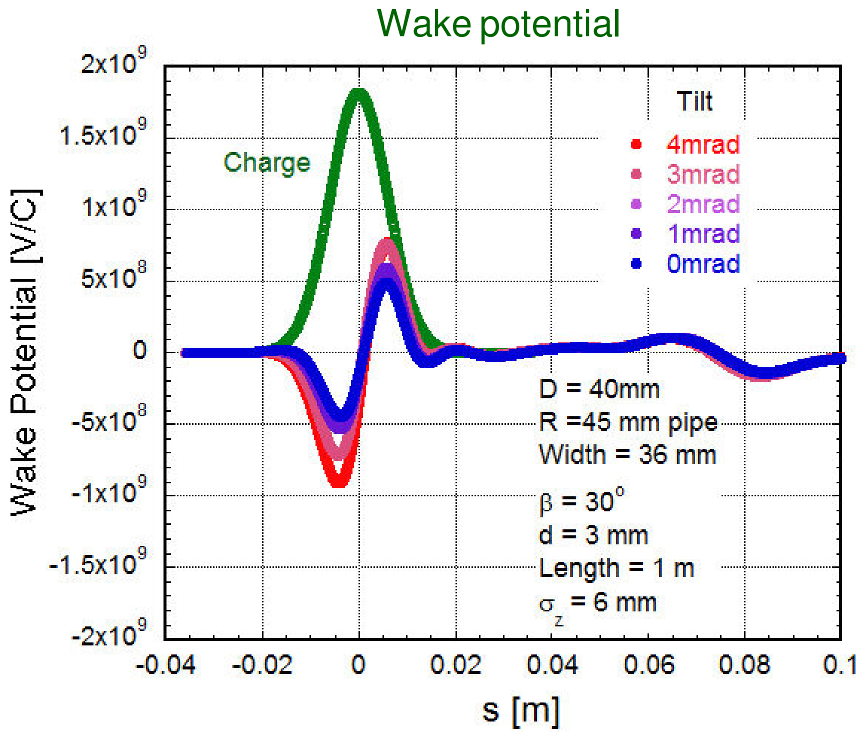
- Impedance: Comparison with resistive wall
  - Calculated by using GdfidL

    (1m model, Half chamber)





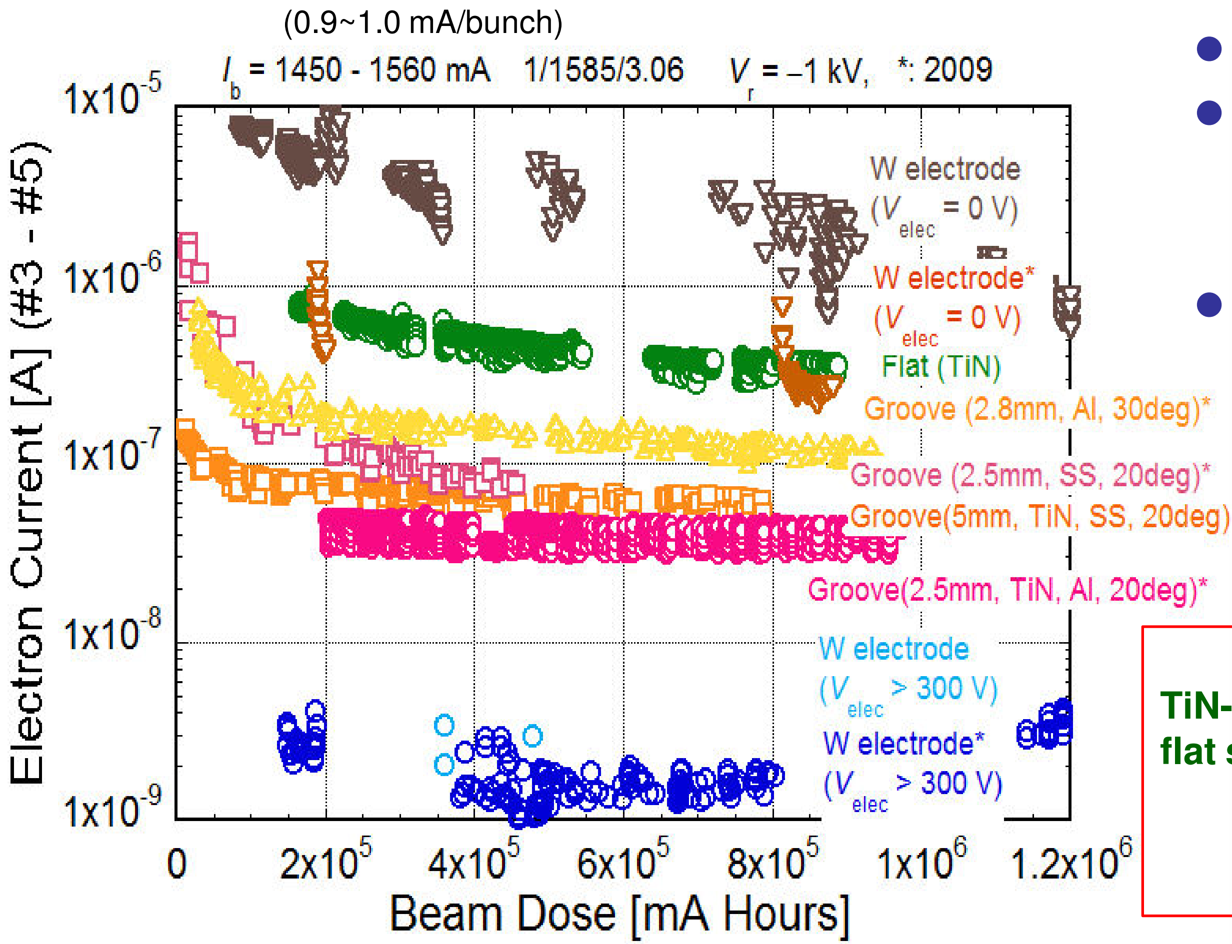




- Wake potential is inductive, and smaller than that for resistive wall.
- The peak height of wake is 1/2~1/3 of that of the resistive wall. The shape does not so change against the tilt angle.

2.3 Electrode and grooved surface

- Comparison of effects on EC
  - All data so far are plotted in one figure



- B = 0.78 T
- Measured with the same monitor at the same location.
- Clearing electrode is much effective in reducing electron density compared to other methods.

TiN-coated flat surface	》	Grooved surface (β~20°)	》	Clearing electrode
	1/6~1/10		~1/20	

2.2 Electrode and clearing electrode

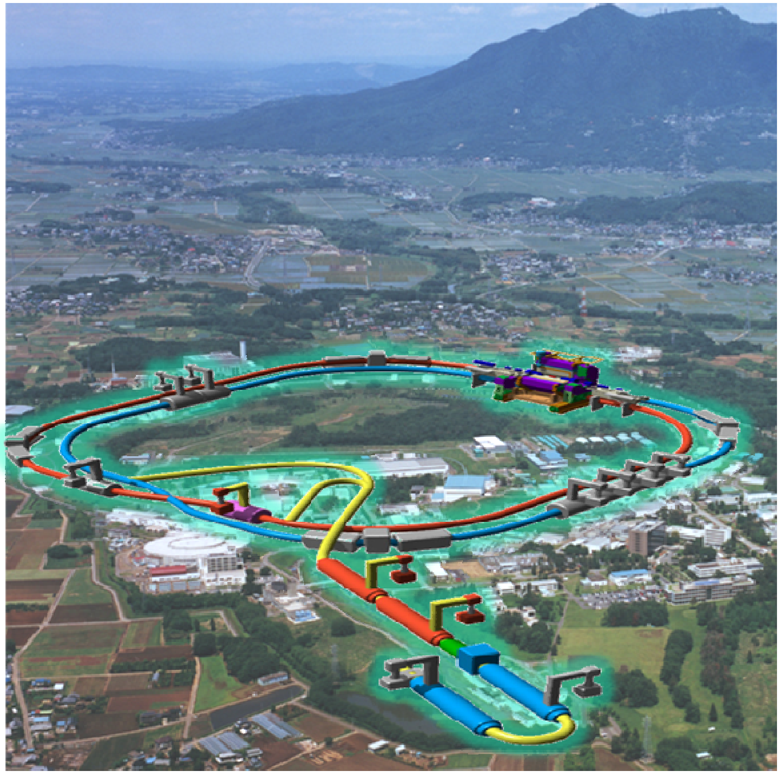
- Comparison of Impedance issues
  - For electrode;
  - Loss factor is smaller than that of resistive wall [Cu] (~1/2)
  - No change in loss factors against tilt (~5 mrad).
    - Suitable for wiggler section.
  - Wake potential is larger than that of resistive wall by a factor of 5.
    - Be careful in using for long section.
  - Also be careful for periodic impedance due to the strip-line structure.

  - For grooved surface;
  - The loss factor is very small without tilt.
  - For the tilt angle > 2 mrad, however, the loss factor increases up to comparable level to a clearing electrode.
    - Suitable for bending magnets, rather than wiggler magnets
    - The effect of tilt will be small if the groove is formed (dug) along the bent beam pipe.
  - Wake potential is smaller than that of resistive wall.

3. Plans for Super KEKB

- Recent design of Super KEKB
  - Low emittance option for L = 8E35 $cm^{-2}s^{-1}$
  - ε_x = 1.7(e^-) ~ 3.2(e^+) nm

Super KEKB site (Tsukuba)



- Main parameters of e^+ ring
  - Circumference = 3016 m
  - Energy = 4.0 GeV
  - Beam current ~ 3.6 A
  - Bunch numbers = 2500
  - Bunch current = 1.4 mA
  - Bunch charge= 14 nC
  - Bunch spacing = 4 ns
  - Bunch length = 6 mm
  - Bending radius = 71 m

3. Plans for Super KEKB

- Required electron density to avoid single bunch instability

K. Ohmi , KEK Preprint 2005-100 (2006)

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_{e,y}\sigma_z/c}{\sqrt{3}KQr_e\beta L}.$$

Here,

$$\omega_{e,y} = \sqrt{\frac{\lambda_+ r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

E [GeV] = 4.0				
γ = 7828	N_b	= 6.25E+10		
ν_s = 0.0185	Q_b[C]	= 1.4E-08	(1.4 mA/bunch)	
	S_b [m]	= 1.2	(4ns)	
σ_z [m] = 6.E-03	λ [C/m]	= 5.2E+12	($Q_b/2/\sigma_z$)	
c [m/s] = 3.E+08	σ_y [m]	= 2.E-05		
K = 11	σ_x [m]	= 2.E-04		
Q = 7				
r_e [m] = 2.80E-15	ω_e	= 5.46E+11	$K = \omega_e\ \sigma_z/c$	
β_y [m] = 25	$\omega_e\ \sigma_z/c$	= 10.9	$Q = \mathrm{Min}(Q_{nl},\ \omega_e\ \sigma_z/c)$	
L [m] = 3016			Q_{nl} ~7	

ρ [m^{-3}] =1.13E11 → Our target =1E11 m^{-3}

3. Plans for Super KEKB

- Lengths of main sections of Super KEKB e^+ ring

Sections	L [m]	L [%]	n_e [e^-/m^3]	n_ex L [%]
Total	3016	100	Ave.5E12	100
Drift space (arc)	1629 m	54	8E12	78
Steering mag.	316 m	10	8E12	15
Bending mag.	519 m	17	1E12	3.1
Wiggler mag.	154 m	5	4E12	3.6
Quadrupole mag.	216 m	7	4E10	0.05
Sextupole mag.	38 m	1	4E10	0.007
RF section	124 m	4	1E11	0.07
IR section	20 m	0.7	5E11	0.06

Main part (Drift space (arc), Steering mag.)

- Electron densities were estimated for the present beam pipe.
  - A circular Cu pipe (ϕ 94mm), 4 ns spacing, 1 mA(10nC)/bunch, No solenoid
- n_e ~ 5E12 e^-/m^{-3}

  → Any cures are required to reduce n_e down to 2%!

3. Plans for Super KEKB

- Comparison of mitigation techniques
  - Based on the experiments so far. Standard = Cu (circular pipe)

Materials, methods	Relative EC density	Relative (k_z) Impedance	Notes
Al	~20	1.4	Coatings are indispensable.
Cu (Circular pipe)	1	1 (Resistive wall)	Low gas desorption
Solenoid [Drift space]	~1/50	1	~50 G, considering gaps (<1/1000 if uniform)
Antechamber	~1/5	1	<1/100 for photoelectrons
Cu+TiN coating (Al+TiN coating)	~6/10	~1 (if thin)	Relatively high gas desorption (TiN)
Groove (β~20°) [in B]	~1/10	~1 (small tilt) ~1.5 (~5mrad)	Large tilt brings large impedance (~ electrode)
Electrode [in B]	~1/200	~1.5 (~5 for wake)	Most effective in EC, but large impedance. Expensive

3. Plans for Super KEKB

- Strategy for EC mitigation: Drift space

Sections	n_e [e^-/m^3]	n_exL [%]
Total	5E12	100
Drift space	8E12	78
Steering mag.	8E12	15
Bending mag.	7E11	3.1
Wiggler mag.	2E12	3.6
Quadrupole mag.	4E10	0.05
Sextupole mag.	4E10	0.007

Drift space, Steering mag. ⇨ Antechamber (Cu or Al+coating) [Straight] ×1/5 + Solenoid ×1/50

Quadrupole mag., Sextupole mag. ⇨ Antechamber (Cu or Al+coating) [Straight] ×1/5

- Basically
  - Beam pipe with antechamber for arc section
  - Coating is indispensable for Al chamber
  - Solenoid field at drift space and steering mag. space
  - Q and Sx: small fraction

3. Plans for Super KEKB

- Strategy for EC mitigation: Wiggler section

Sections	n_e [e^-/m^3]	n_exL [%]
Total	5E12	100
Drift space	8E12	78
Steering mag.	8E12	15
Bending mag.	7E11	3.1
Wiggler mag.	2E12	3.6
Quadrupole mag.	4E10	0.05
Sextupole mag.	4E10	0.007

⇨ Antechamber (Cu) + Electrode
[Straight]
×1/5 ×1/200

- Wiggler magnets
  - Beam pipe with antechamber
  - Copper is required due to high SR power.
  - Electrode is possible (straight beam pipe).
  - Length is small (1/20 of total length). →Small contribution to the total impedance

3. Plans for Super KEKB

- Strategy for EC mitigation: Bending magnets

Sections	n_e [e^-/m^3]	n_exL [%]
Total	5E12	100
Drift space	8E12	78
Steering mag.	8E12	15
Bending mag.	7E11	3.1
Wiggler mag.	2E12	3.6
Quadrupole mag.	4E10	0.05
Sextupole mag.	4E10	0.007

⇨ Antechamber (Cu or Al+coating) [Bent, ρ = 70m] + Groove(?)

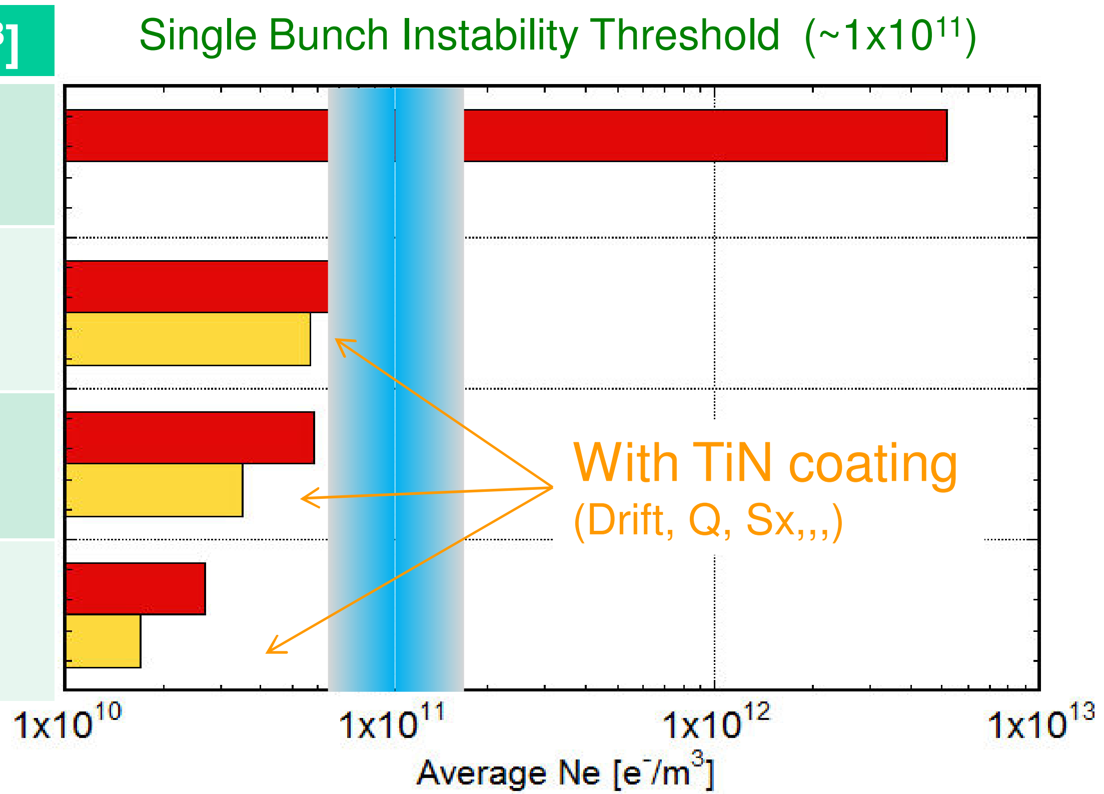
$\times$1/5 ($\times$1/10)

- Bending magnets
  - Beam pipe with antechamber
  - Grooved surface should be effective.
    - Need further discussions;
      how to make grooved bent chamber?
      Are any coatings are required?

3. Plans for Super KEKB

- Summary
  - Major electron cloud will be reduced by antechamber scheme and solenoid field at arc section. But it seems still insufficient.
  - Electrodes in wiggler and grooves in bending magnets will decrease EC further and increase the safety margin.
  - The groove in B is still under consideration → further R&D.

Condition	ne [m^{-3}]
Circular Cu chamber [KEKB beam pipe]	5.2E12
Solenoid at Drift (1/50) +Cu Antechamber (1/4)	9.4E10 5.7e10
+Electrode in Wiggler (1/200)	5.8E10 3.5E10
+Groove in B (1/10)	2.7E10 1.7e10



Backup slides

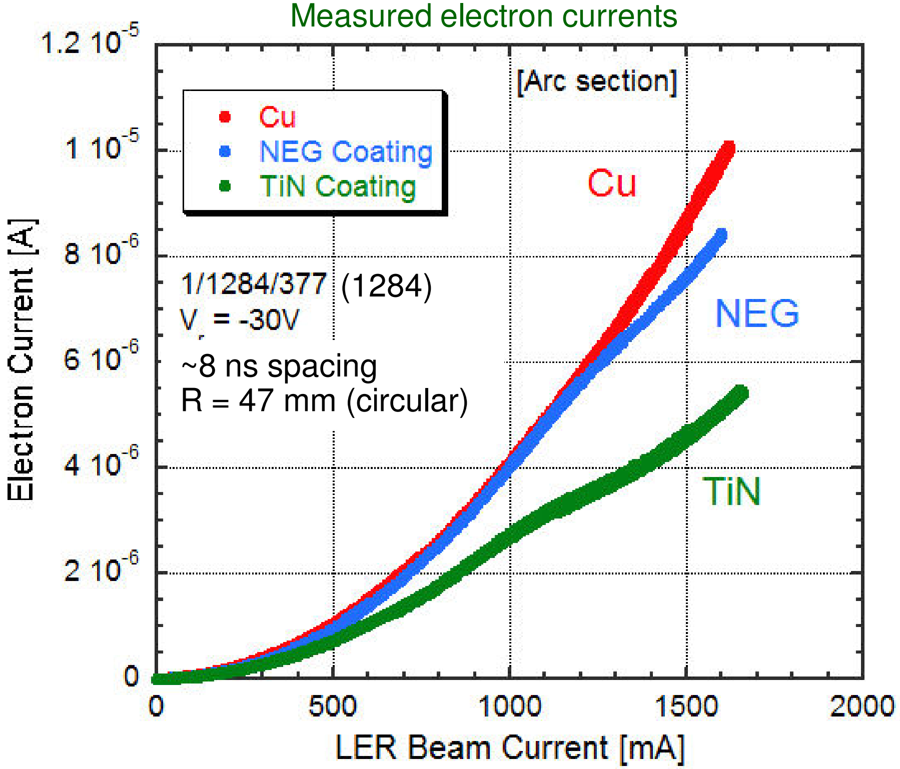
Machine Parameters

		LER	HER	
Emittance	ε_x	3.2	1.7	nm
Coupling	$\varepsilon_y/\varepsilon_x$	0.40	0.48	%
Beta Function at IP	β_x^* / β_y^*	32 / 0.27	25 / 0.42	mm
Beam Size	σ_x^* / σ_y^*	10.1 / 0.059	6.5 / 0.059	μm
Bunch Length	σ_z	6	5	mm
Half Crossing Angle	ϕ	41.3		mrad
Beam Energy	E	4	7	GeV
Beam Current	I	3.6	2.6	A
Number of Bunches	n_b	2500		
Energy Loss / turn	U_0	2.28	2.15	MeV
Total Cavity Voltage	V_c	6.3	6.3	MV
Energy Spread	σ_δ	7.92×10^{-4}	5.91×10^{-4}	
Synchrotron Tune	ν_s	-0.0185	-0.0114	
Momentum Compaction	α_p	2.85×10^{-4}	1.90×10^{-4}	
Beam-Beam Parameter	ξ_y	0.09	0.09	
Luminosity	L	8×10^{35}		$cm^{-2}s^{-1}$

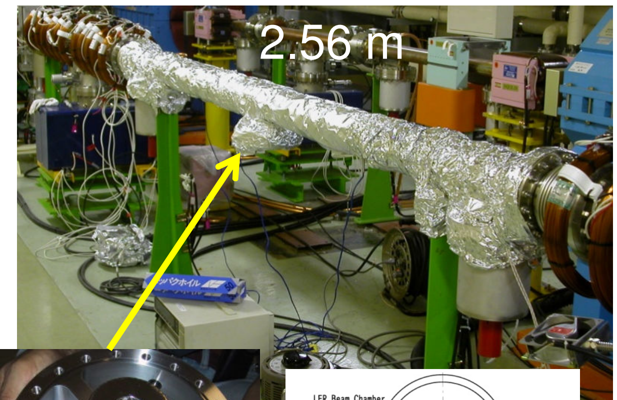
2.1 Coating

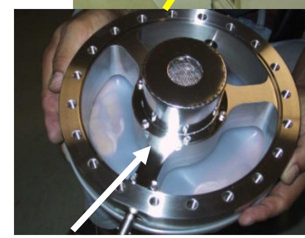
- Arc section [2004~]
  - Photon density= 6×10^{14} photons/s/mA/m
  - Drift space
- Cu, Cu+TiN(~1μm), Cu+NEG(0.3~1μm)
  - Circular pipe (φ94) [Ti, Zr, V]

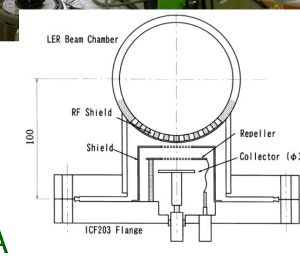
Measured electron currents



Installed test chamber





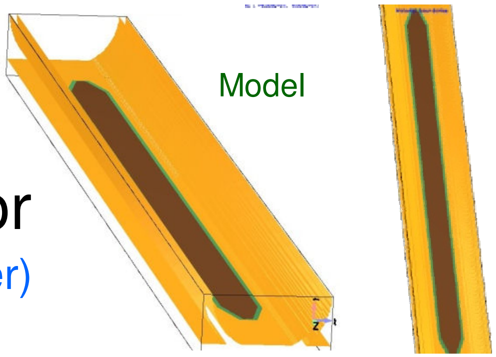


Electron monitor with RFA

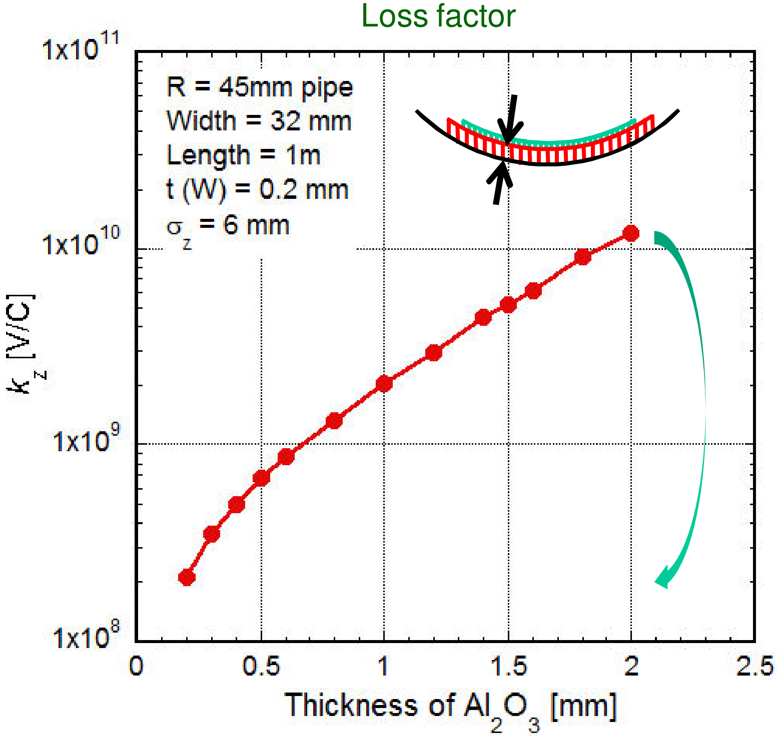
- Photoelectron is dominant at arc sections. → Photoelectrons should be suppressed first of all.
- TiN coating has a relatively low photoelectron emission yield.

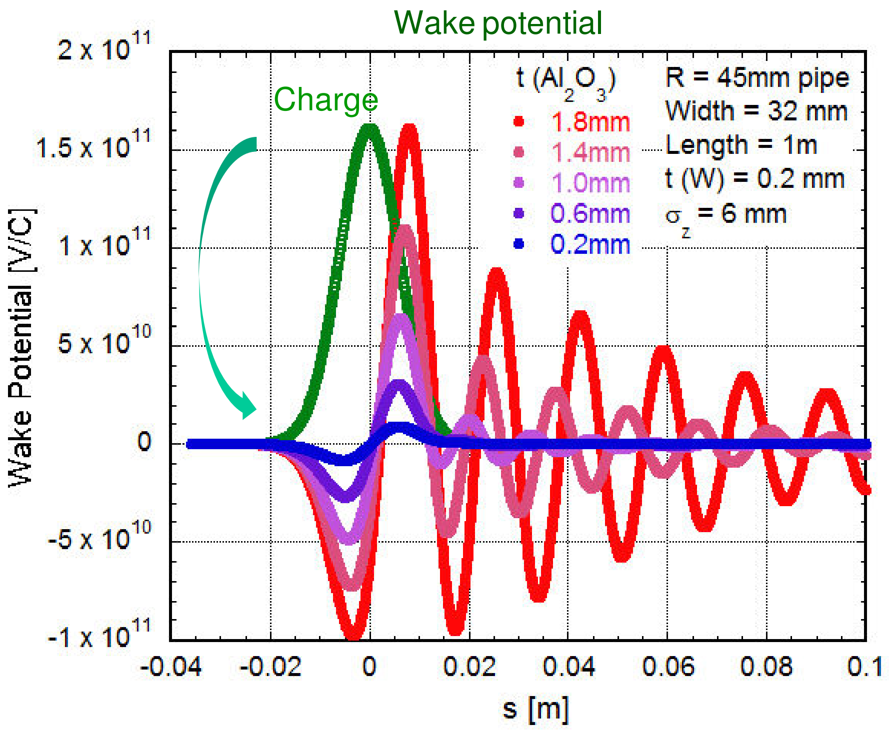
Y. Suetsugu et al., NIM-PR-A, 554 (2005) 92

2.2 Clearing electrode



- Dependence of loss factor and wake potential on the thickness of Al_2O_3 insulator
  - Calculated by using GdfidL (1m model, half chamber)
  - ^{t}0.2 mm ~ 2.0 mm

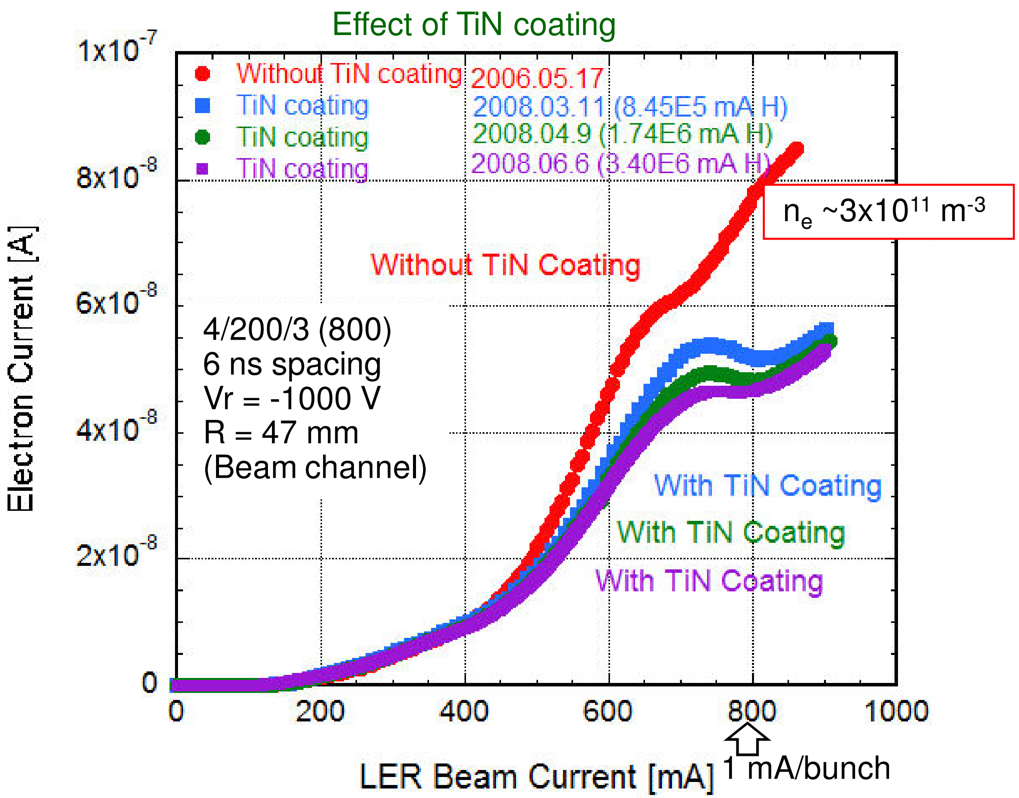


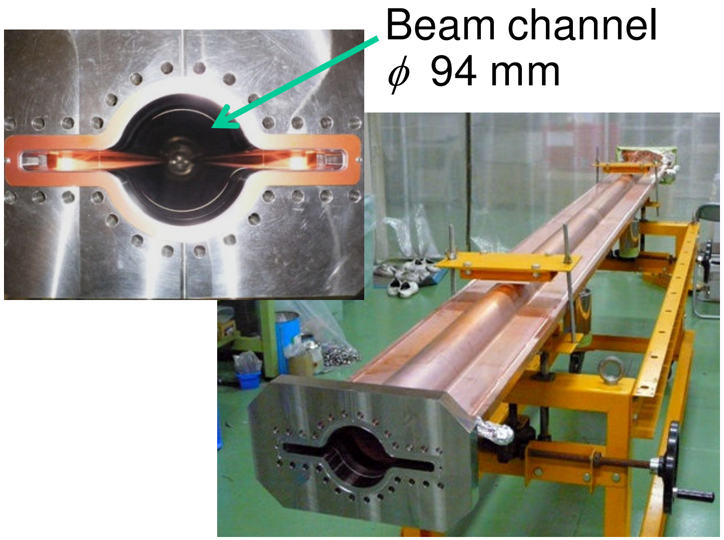


- With a decrease in the thickness of insulator, the loss factor decrease.
- The wake potential also decreases, and is inductive for thin insulator.

2.1 Coating

- Straight section (wiggler)
  - Photons = 8x10^{14} photons/s/m/mA (~ arc)
  - Drift space
- Cu, Cu +TiN (0.2 μm) (beam channel)
  - Antechamber



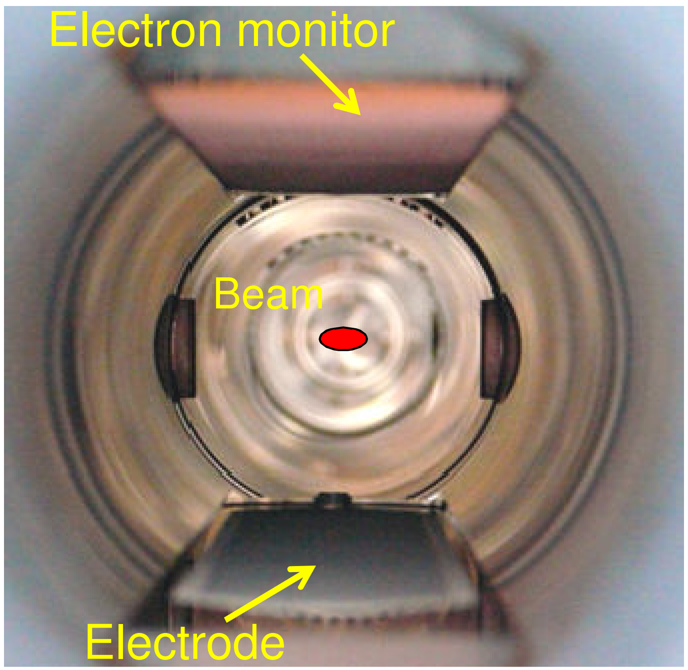


- TiN was coated only in the beam channel. Photoelectrons are almost the same.
- The electron currents are the same order to those in straight section, although the photon density is large (~x100)
- TiN coating reduces the electron density by a factor of 2 at high current region.

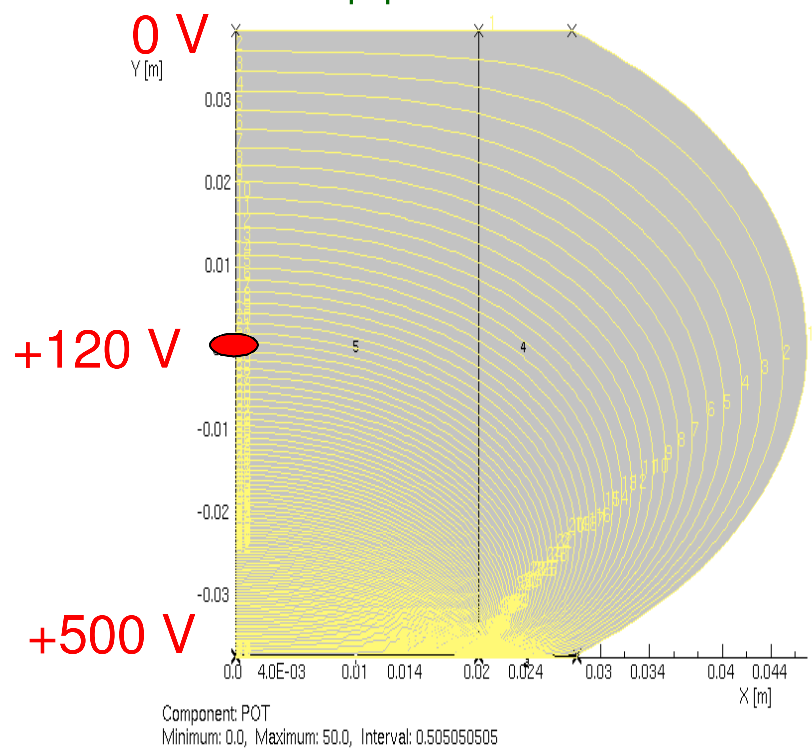
2.2 Clearing electrode

- Electric potential in the test chamber
  - ~6 kV/m at the beam orbit, when 500 V is applied to the electrode.

Inside view

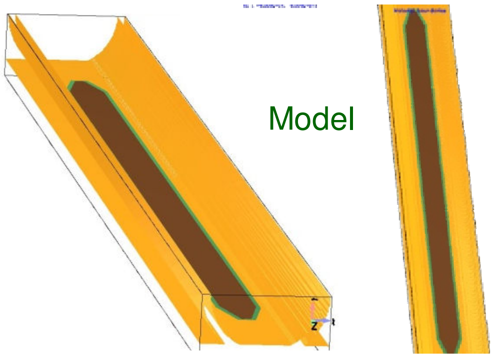


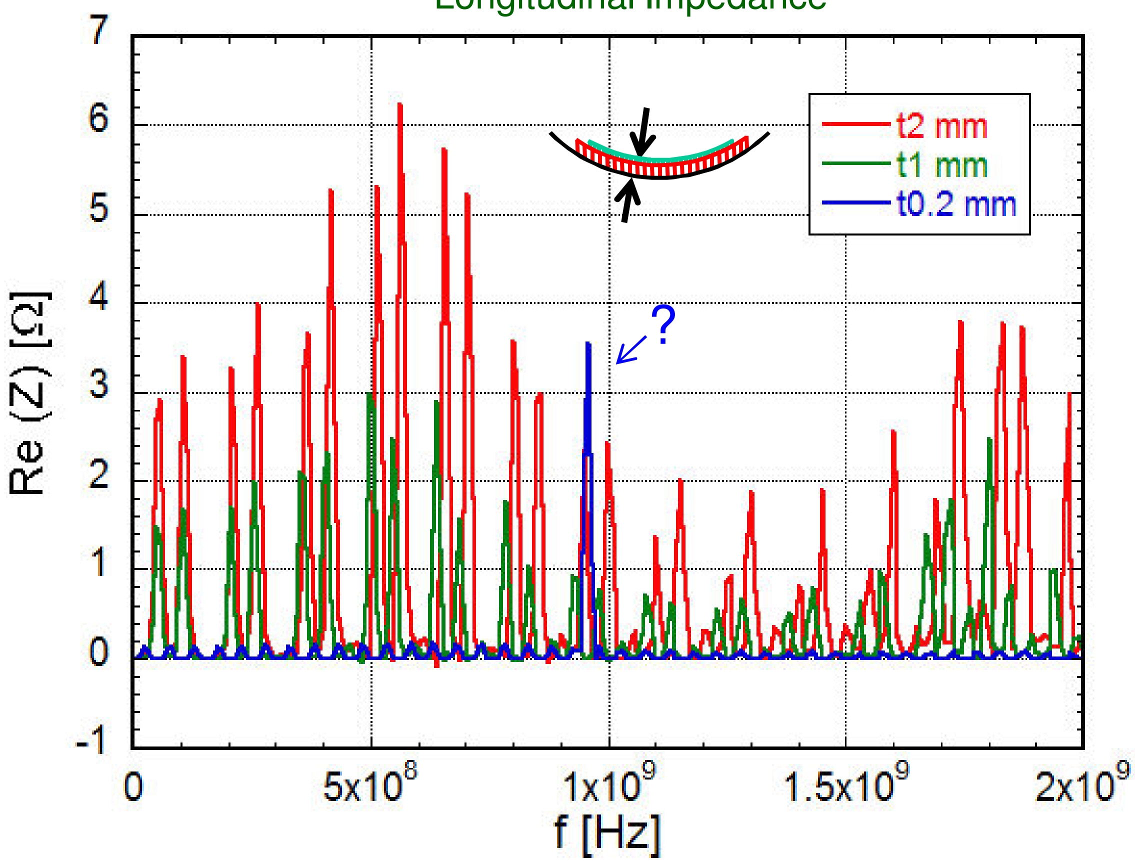
Equipotential lines



2.2 Clearing electrode

- Dependence of impedance on the thickness of Al_2O_3 insulator
  - Calculated by using GdfidL (1m model, half chamber)
  - ^{t}0.2 mm ~ 2.0 mm

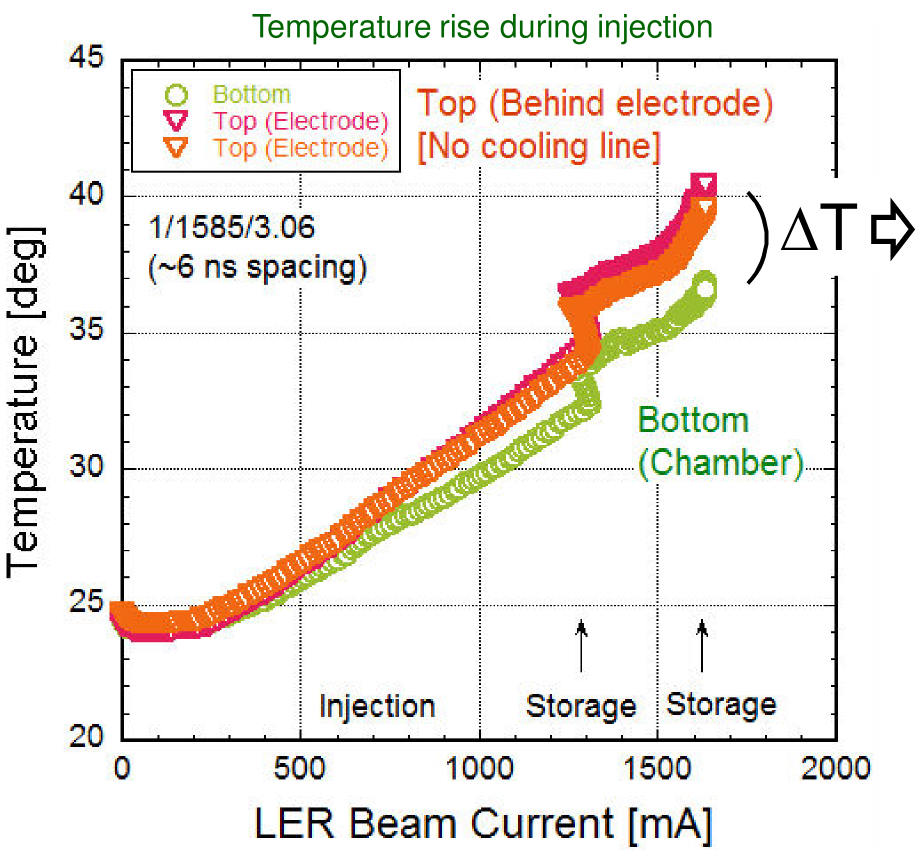


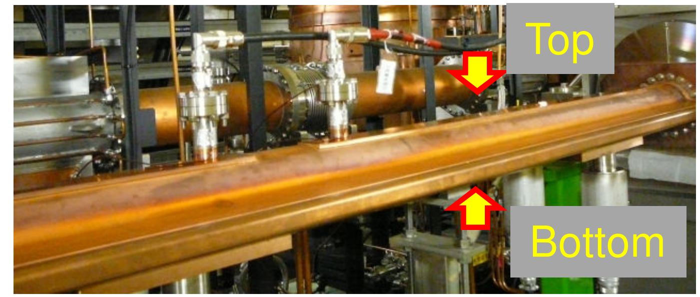


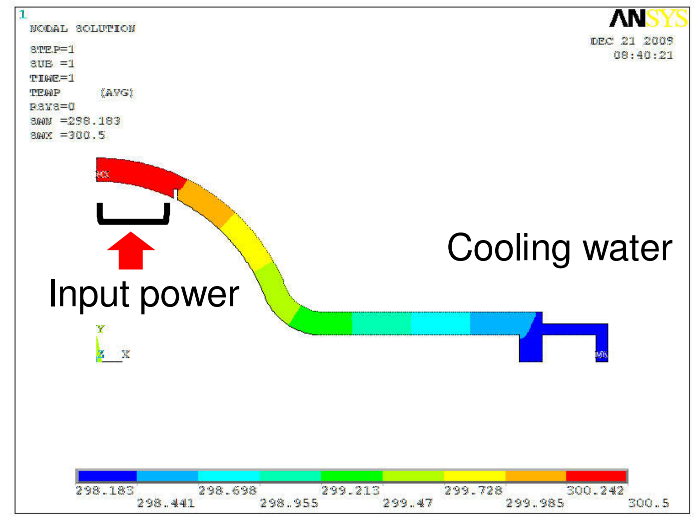
- Calculated for 20 m (for σ_z = 20 mm).
- A periodic impedance is found as in the case of a usual strip line.
- The peak values beccme small with decreasing the thickness of insulator.
- The values are less than 1 Ω. Q ~ 20.
- Experiments here were performed for 0.2 mm insulator and 0.1 mm electrode

2.2 Clearing electrode

- Results: Heating
  - Temperature behind the electrode was measured.
  - No cooling channels in the back





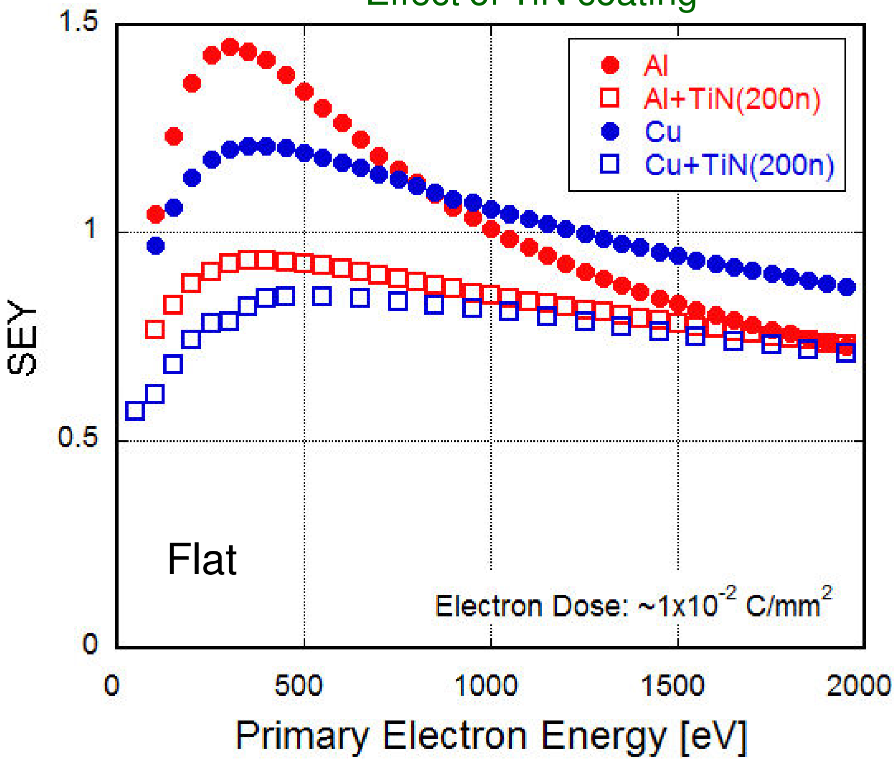


- Estimated input power was ~40 W/m: reasonable value.
- No heating at feed through.

2.3 Grooved surface

- SEY Measurement at Laboratory (B = 0): Effect of structure
  - The TiN coating decrease Max. SEY to 0.9~0.8.(Al, Cu)
  - Groove structures decrease it to ~0.7 even without TiN (Al); the effect of groove structure seems larger even for aluminum (if β = 20°).
  - Grooved surface seems effective even without B field.

Effect of TiN coating



Effect of groove structure