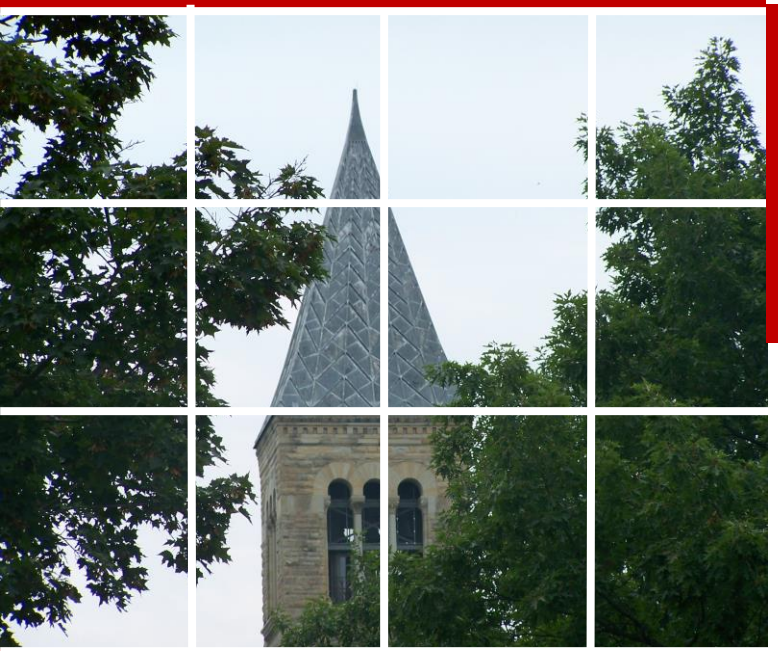

Vacuum Science and Technology for Particle Accelerators

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Albuquerque, New Mexico
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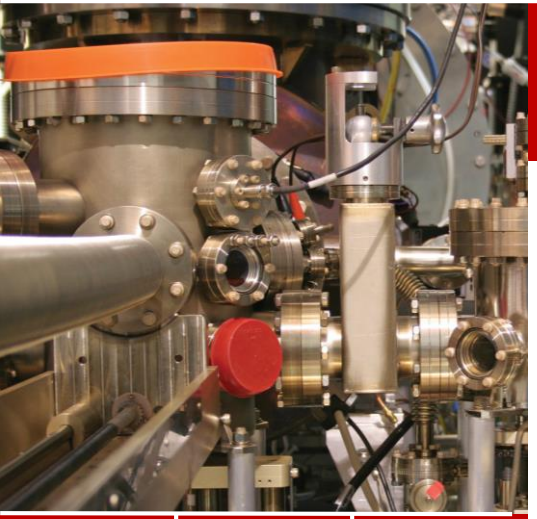
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

SLAC NATIONAL ACCELERATOR LABORATORY



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SESSION 7: **Accelerator Vacuum Considerations**

1. Electron Beam Gas Scattering and beam lifetime
2. Ion and "dust" trapping
3. Electron Cloud and suppression
4. Vacuum chamber impedances

Electron Beam Loss due to Residual Gas Scattering

Beam Lifetime in a Storage Ring

- Number of particle lost is proportional to the number of beam particles,

$$dN = -\sigma N(t)dt \qquad \text{where } \sigma = \text{constant}$$

- Define the beam lifetime as $\tau = 1/\sigma$; then beam current decays as:

$$I = I_0\, e^{-t/\tau}$$

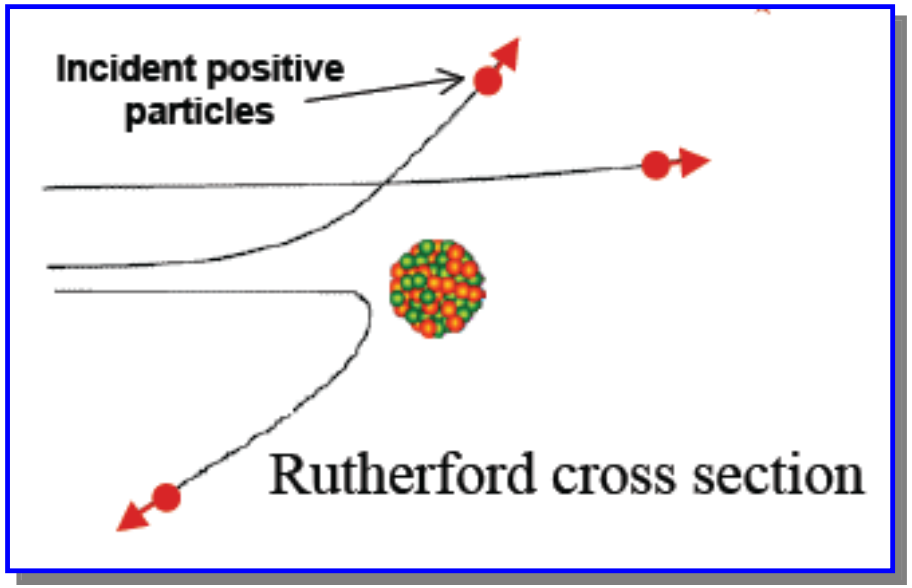
- There are three beam-loss processes: the quantum excitation (radiation dumping), intra-beam scattering (Touschek effect), and scattering off residual gas molecules (elastic and inelastic). The individual loss mechanisms contribute the total lifetime as:

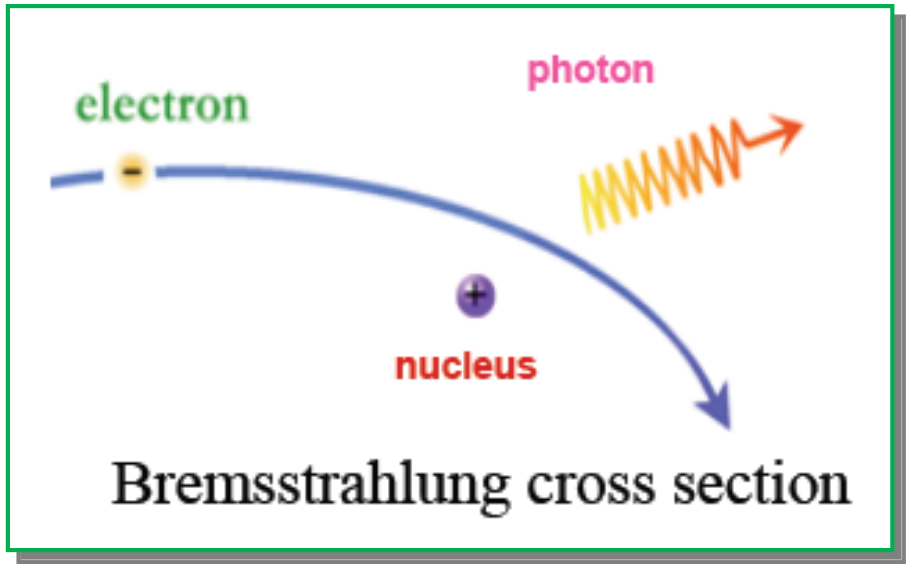
$$\frac{1}{\tau} = \frac{1}{\tau_{quantum}} + \frac{1}{\tau_{Touchek}} + \frac{1}{\tau_{elastic}} + \frac{1}{\tau_{inelastic}}$$

- In most cases, the quantum lifetime is significantly longer than all others. For high intensity electron beam with small sizes (transverse and/or bunch length), the Touschek lifetime may dominate. The goal of vacuum design is to achieve a pressure level as such that beam lifetime due to residual gas scattering is significantly below the Touschek lifetime.

Beam Loss by Residual Gas Scattering

- Elastic (Coulomb scattering) from residual background gas
  - → Scattered beam particle alters transverse motion, and undergoes betatron oscillations.
  - → The particle will be lost when the oscillation amplitude exceeds physical acceptance aperture.
- Inelastic scattering (Bremsstrahlung) causes particles to loss energy. The particle will be lost if the energy loss exceeds the momentum acceptance of the ring.
- Inelastic scattering via atomic excitation has much smaller cross section, as compare to Bremsstrahlung.





Elastic Scattering Lifetime

$$\frac{1}{\tau_{el}} = \frac{4\pi r_e^2 c N_A}{R\gamma^2} \cdot \frac{\langle \beta_y \rangle}{A_y^{\min}} \cdot \frac{P}{T} \sum_i^n Z_i^2 N_i f_i$$

Where N_A is Avogadro's number, R=8.314 J/(K·mol) is the universal gas constant, T (K) is the residual gas temperature, P(Pa) is pressure, $\langle \beta_y \rangle$ is the average vertical beta function, A^{min}_y is the limiting (vertical) aperture, n is the residual gas (**atomic**) components number, f_i is partial fraction of gas atomic components i, Z_i the atomic number, N_i the number of atoms per molecule i.

In more practical units:

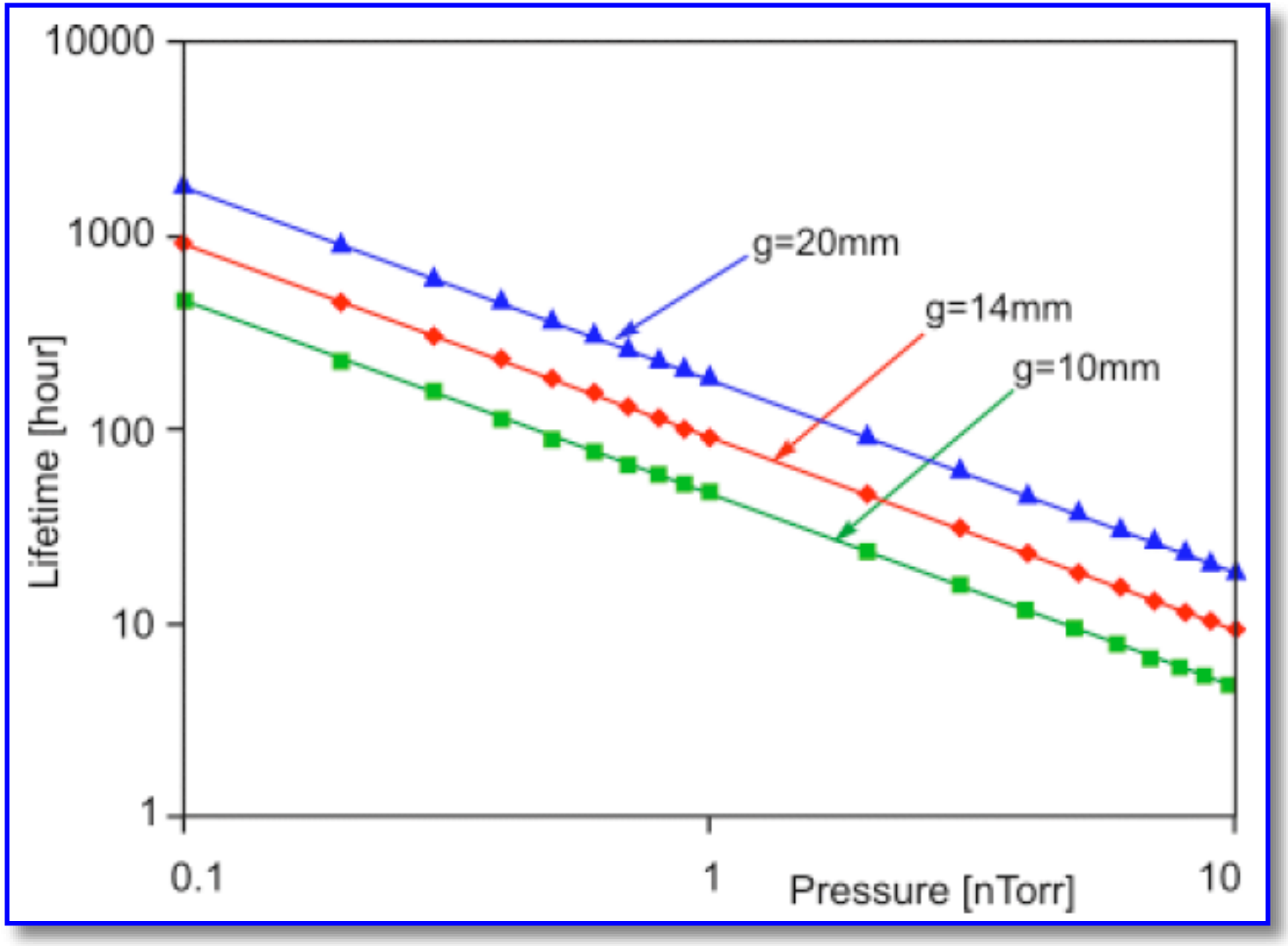
$$\frac{1}{\tau_{el}[h]} = 0.272 \frac{1}{E^2[GeV^2]} \frac{\langle \beta_y \rangle [m]}{A_y^{\min}[mm]} \cdot \frac{P[nTorr]}{T[K]} \sum_i^n Z_i^2 N_i f_i$$

Elastic Scattering Lifetime Cont.

Machine example:

Beam energy=3 GeV, $\langle\beta_y\rangle$=10m, smallest gap in the ring, g=10, 14 and 20 mm ($A_y=(g/2)^2/\beta_y$).

The calculated lifetimes from elastic scattering of N_2 ($n=1$, $f_1=1$, $Z_1=7$, $N_1=2$) :



Elastic Scattering Lifetime Cont.

For the same machine parameters, but with 80% H_2 and 20% CO :

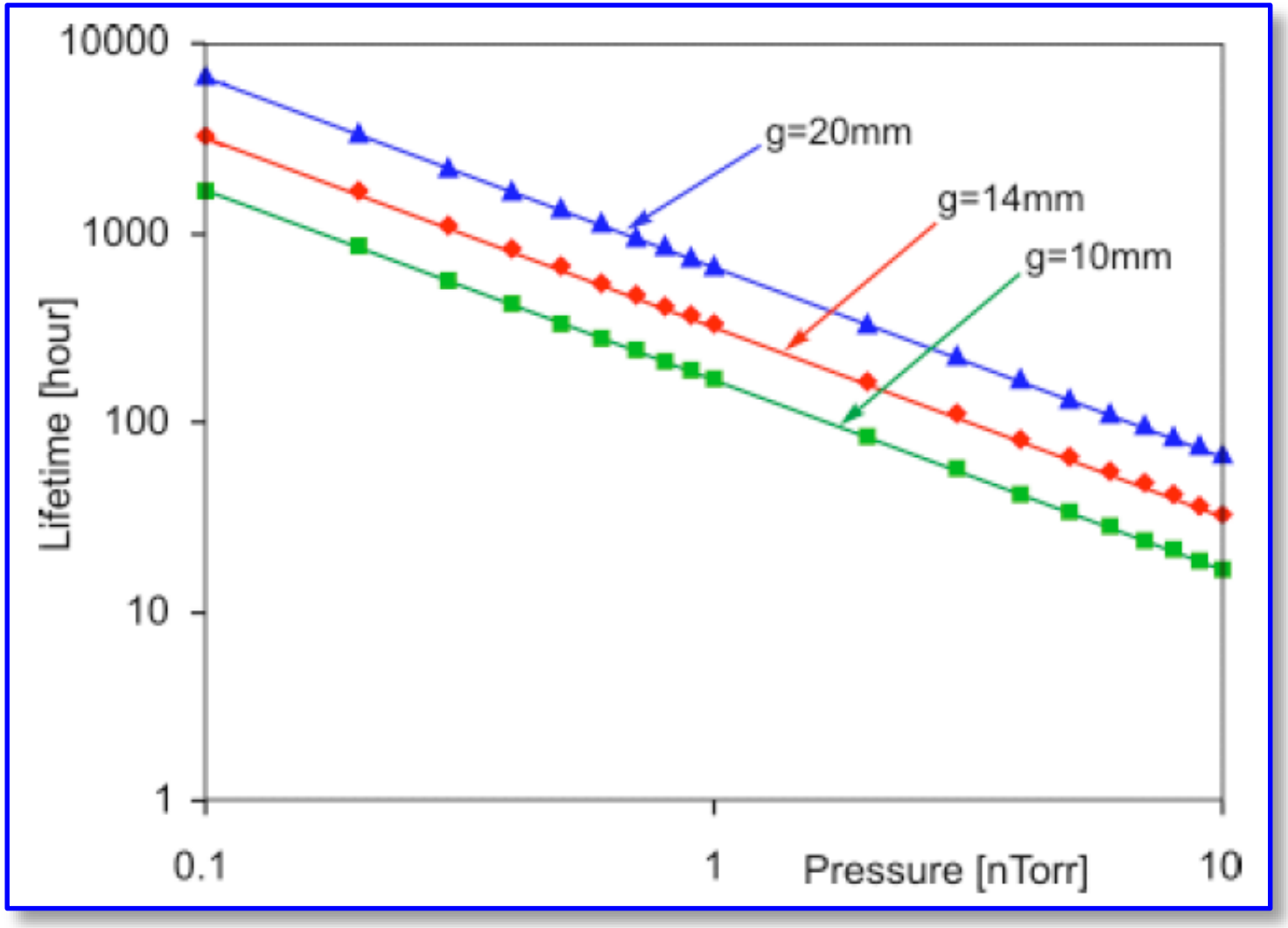
$n = 3$,

$f_1=0.8, Z_1=1, N_1=2$

$f_2=0.2, Z_2=6, N_2=1$

$f_3=0.2, Z_3=8, N_3=1$

the elastic scattering lifetime:



Inelastic (Bremsstrahlung) Scattering Lifetime

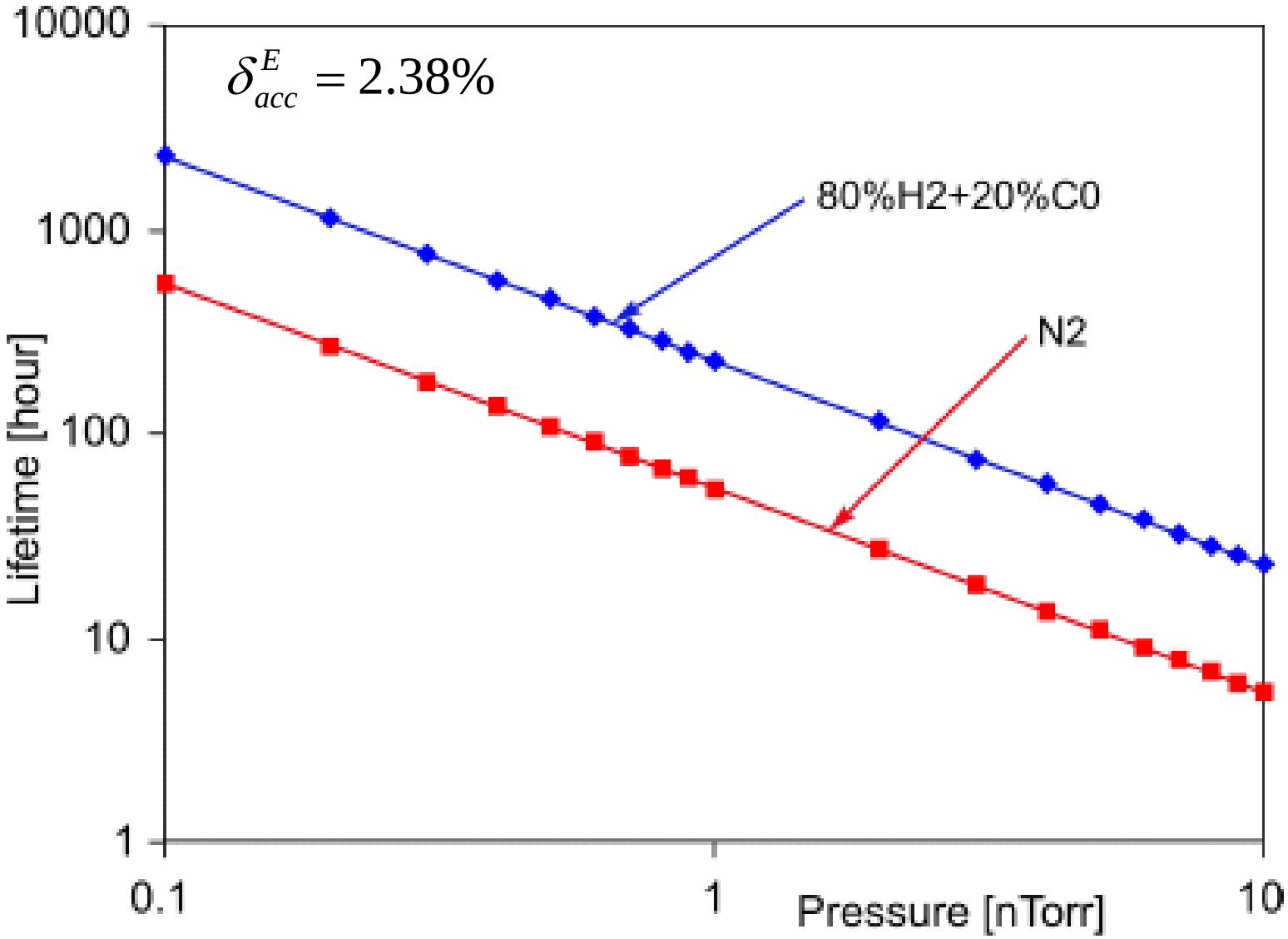
$$\frac{1}{\tau_{brem}(h)} = 2.42\times10^{-3} L\left(\delta_{acc}^{E}\right)\frac{P[nTorr]}{T[K]}\sum_{i}^{n}\ln\left(\frac{183}{\sqrt[3]{Z_i}}\right)Z_i^2 N_i f_i$$

Where, $L\left(\delta_{acc}^{E}\right)=\frac{4}{3}\left(\ln\frac{1}{\delta_{acc}^{E}}-\frac{5}{8}\right)$

and δ_{acc}^{E} is energy acceptance (%) of the ring. The Bremsstrahlung lifetime has similar dependence on residual gas properties (Z and N), but a weak dependence on relative energy acceptance.

$\delta_{acc}^{E}(\%)$	2	3	4	5
$L\left(\delta_{acc}^{E}\right)$	4.37	3.84	3.45	3.16

Bremsstrahlung Scattering Lifetime Cont.

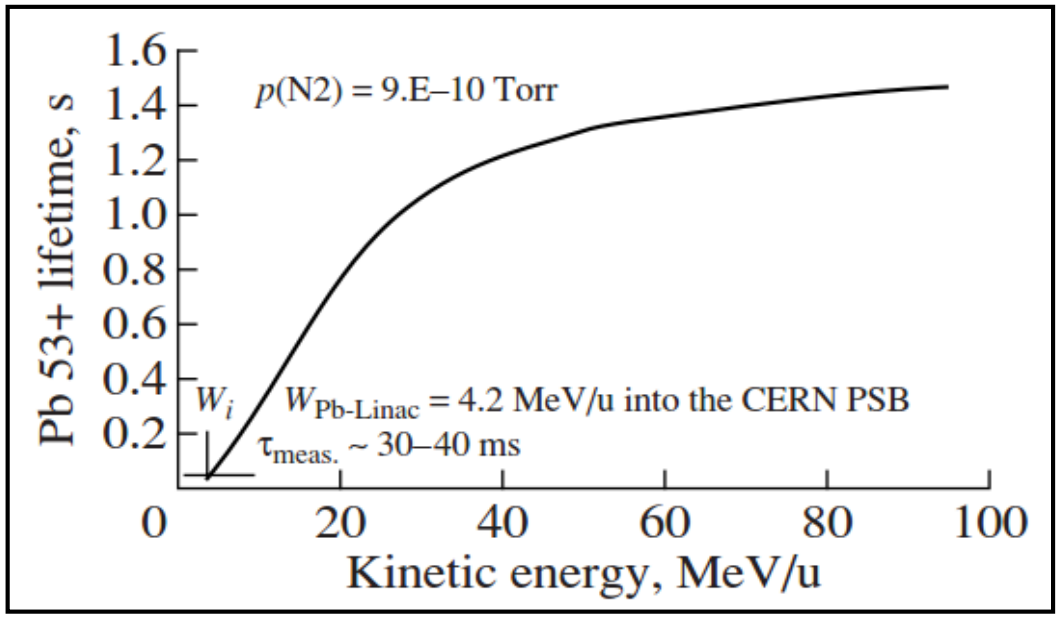


Beam Loss by Residual Gas Scattering – Summary

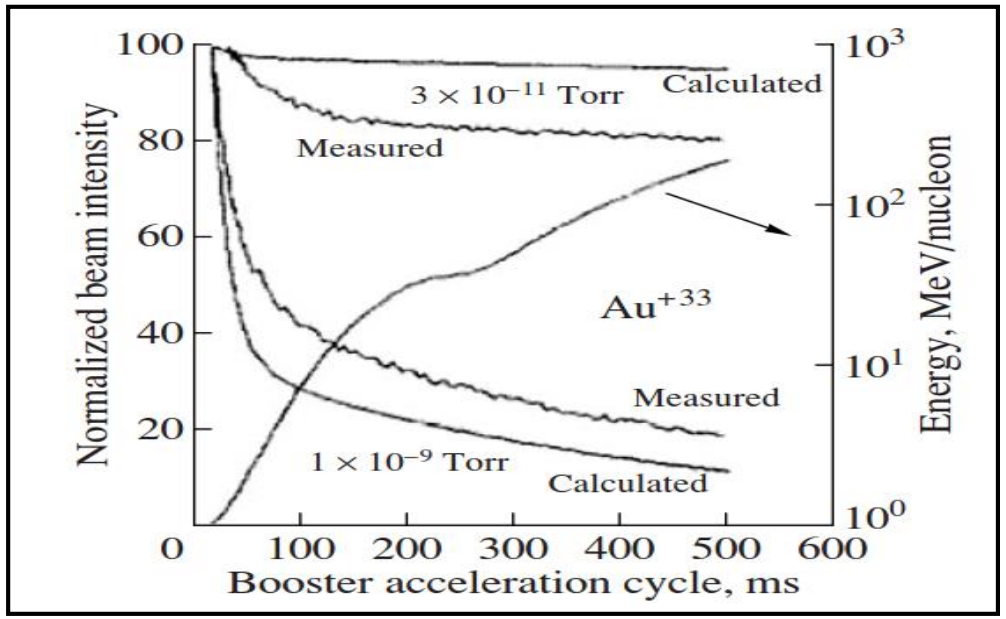
- Elastic and inelastic scattering residual gas scattering have similar contribution to the electron beam losses in a storage rings.
- Both beam loss mechanisms have strong dependence on atomic numbers (Z-number) of the gases. Both are proportional to the size of the gas molecules (N). For example, Ar has a factor of $(18^2*1/1^2*2)=\mathbf{162}$ higher scattering cross section than H_2. Contamination of long-chain hydrocarbons (large N) also induce more significant beam losses.
- For clean storage ring vacuum systems, average pressure ~ 1 nTorr is usually sufficiently low, so that beam losses due to the residual gas scattering processes are negligible, comparing to beam-beam effects.
- However, forward photon radiation from Bremsstrahlung scattering can generate background for light source users and HEP detectors. Thus vacuum level much better than 1 nTorr is usually required in the interaction region of a HEP collider and in the light source IDs.

Ion Beam Loss – Charge Exchanges

- For ion accelerators, charge exchange is the major process of interactions of ions and residual gases. The change of charge-state (via stripping or capturing electron) leads to the beam loss.
- The loss of electrons (stripping) prevails over capturing for higher energy ions (> 20 MeV/u). So the partially stripped ions are more sensitive to residual gas pressure.
- With very large ion charge exchange cross sections, most ion accelerators (especially the boosters) require very low base pressure (<10^{-11} torr).



Proton Synchrotron Booster @CERN



BNL Booster

Ion Trapping and Dust Trapping in Electron Beam

Ion and 'dust' Trapping in electron beam

- The circulating electrons in a stored beam collide with residual gas molecules producing positive ions and free electrons.
- The free electrons are repelled by the electron beam (to the vacuum chamber walls), while the ions may be captured (trapped) by the electron beam.
- If other possible natural or artificial clearing mechanisms are not present, the neutralizing ions accumulate up to the point where the remaining trapping potential is effective zero, i.e., until the number of static neutralizing particles is equal to the beam particles.
- The average neutralization factor is defined by:

$$\eta \equiv \frac{n_i}{n_e}$$

→ n_i is the total neutralizing charge, measured in units of electronic charge;
→ n_e is the number of stored electrons

REF. A. Poncet, "Ion Trapping, Clearing, Beam-Ion Interactions", CERN Accelerator School Proceeding, 1993, p.859

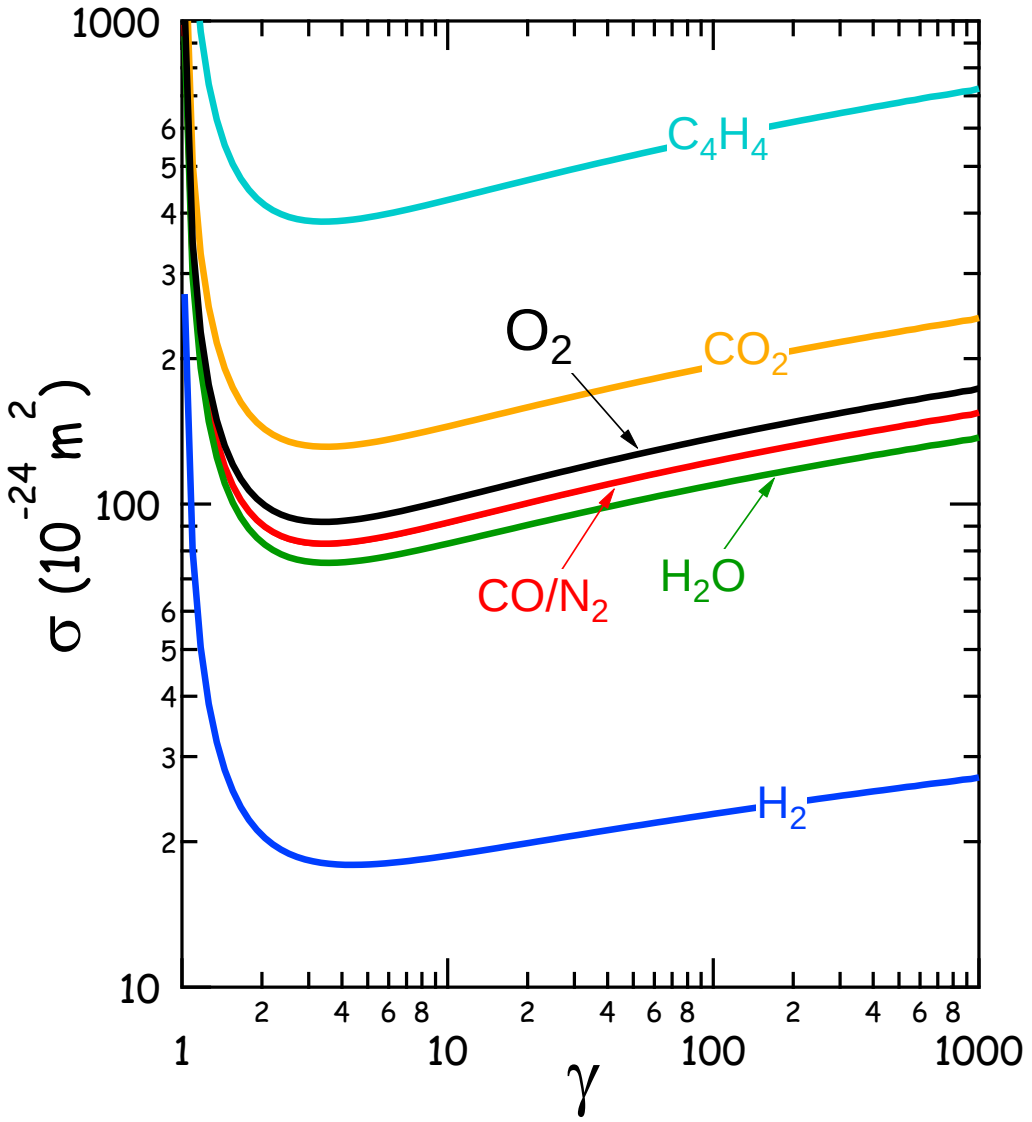
Ionization Cross Sections

$$\sigma^i = 4\pi\left(\frac{\hbar}{m_e c}\right)^2\left\{M^2\left[\frac{1}{\beta^2}\ln\left(\frac{\beta^2}{1-\beta^2}\right)-1\right]+\frac{C}{\beta^2}\right\}$$

where: $\beta = 1/\sqrt{1-\gamma^2}$

$$4\pi\left(\frac{\hbar}{m_e c}\right)^2 = 1.87\times10^{-24}\,m^2$$

Molecules	M^2	C
H_2	0.5	8.1
N_2	3.7	34.8
CO	3.7	35.1
O_2	4.2	38.8
H_2O	3.2	32.3
CO_2	5.75	55.9
C_4H_4	17.5	162.4



Ionization Rate (or Time)

- The ionization rate is proportional to the cross section (σ_m) and the density (n_m) of the residual molecules:

$$\frac{1}{\tau_m} = n_m n_e \sigma_m (\beta c) = 3.3\times10^{22} P_m n_e \sigma_m (\beta c)$$

where n_e is the number of stored electrons, βc the velocity of the electrons, and P_m pressure in torr. For multiple components in the residual gases, the total ionization rate is:

$$\frac{1}{\tau_i} = \sum_m \frac{1}{\tau_m}$$

- For a storage ring with >200 mA electron beam current, and a typical residual gas pressure of 1 nTorr (most hydrogen and CO), the ionization time τ_i is usually in seconds.

Gas	σ_{col} (m^2)	ρ_{gas} (m^{-3})	τ (sec)
H_2	3.1×10^{-23}	3.0×10^{13}	3.6
CO	1.9×10^{-22}	3.5×10^{12}	5.0
CH_4	2.0×10^{-22}	1.8×10^{12}	9.5

Calculated for a pressure of 1 nTorr, with a gas composition of 85% H_2, 10% CO and 5% CH_4

Natural Clearing Rate (or Time)

- Trapped ions may experience inelastic scattering from the stored electrons, and gain sufficient energy to escape the potential well, V. This is a 'natural' clearing mechanism. The clearing rate for singly charged ions can be calculated as:

$$R_c = \frac{4\pi m_p c^3 r_p^2}{\beta} \cdot \frac{N_e Z_i}{eV} \cdot \ln\left(3\times 10^4 Z_i^{-2/3}\right)$$

where m_p, r_p are mass and radius of proton, respectively, and Z_i is charge the trapped ions.

- Estimated natural clearing rate and time for CERN's Electron-Positron Accumulator (EPA) with $6x10^{11}$ electrons (300 mA) are:

	H^+	H_2^+	CO^+	CO_2^+
Clearing Rate (s^{-1})	$3x10^{-3}$	$6x10^{-3}$	0.04	0.07
Clearing Time (s)	350	166	25	15

Compare this with ionization time (seconds) !!

Ion Trapping – CW vs. Bunched Beams

- All the above discussions are regarding CW-like electrons (or anti-proton) beams.
- The calculation showed a very short ionization time (seconds of less), and a very long natural clear time (100s seconds for light ions).
- It is also shown (see REF) that the limitation on ion accumulation is proportional to the residual gas density (that is, the vacuum pressure.)
- So at certain conditions, significant trapping of hydrogen ions occurs even at deep UHV condition, such as at CERN's anti-proton accumulator (AA), with $5x10^{-11}$ torr vacuum.
- Another CW beam condition exists in a energy-recover LINAC (ERL), such a proposed Cornell ERL, where ion trapping will be significant, if only rely on natural clearing.

Ion Trapping – CW vs. Bunched Beams Cont.

- However, for a storage ring populated with n_{bunch} evenly spaced electron bunches, it is shown that ions are trapped only with their molecular mass above a critical mass A_{cr} can be trapped:

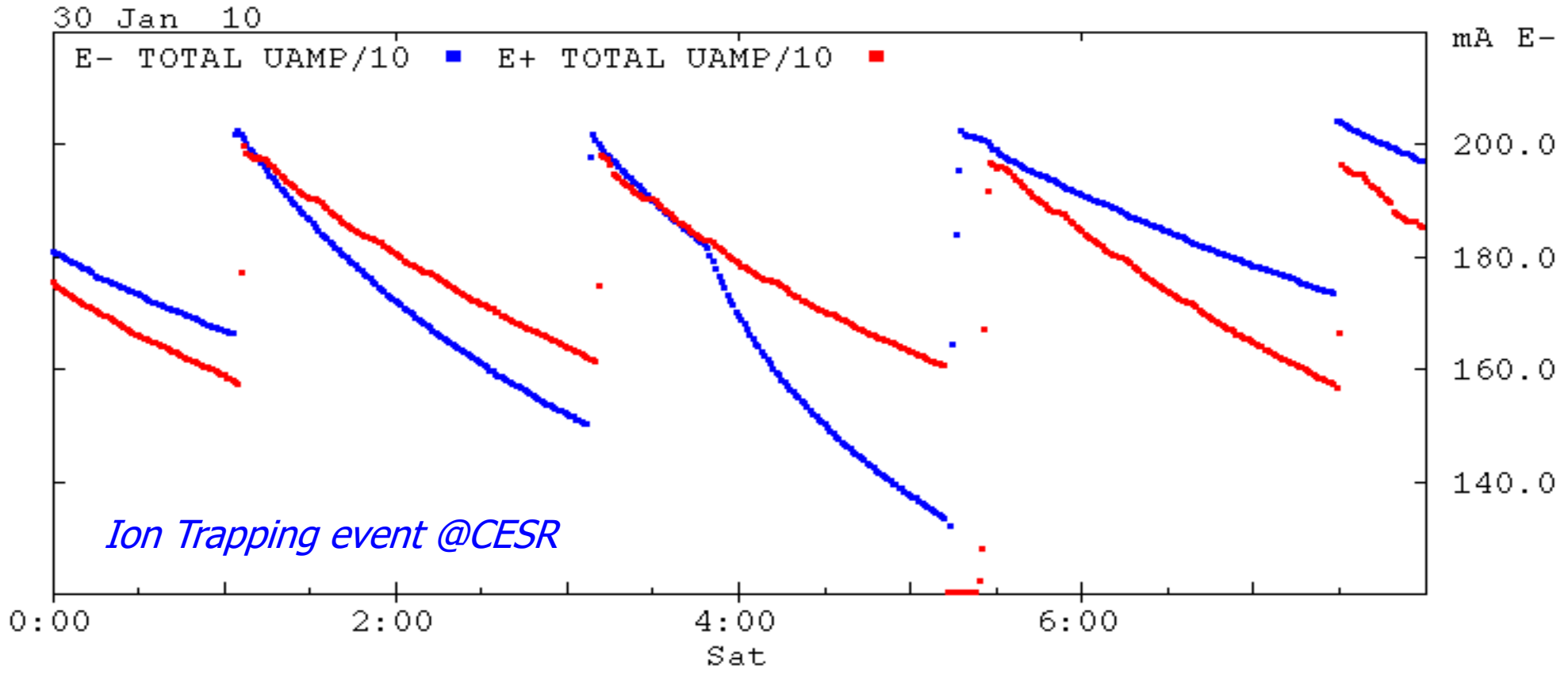
$$A_{cr} = \frac{N_e}{n_{bunch}} \cdot \frac{2\pi R_{ring}}{n_{bunch}} \cdot \frac{r_p}{2\sigma_y\left(\sigma_x + \sigma_y\right)}$$

electrons in a bunch — bunch spacing — transverse beam size

- Usually, A_{cr} is between 0.1 to 100, so that electrons will never be trapped by positively charged beams.
- If $A_{cr} > 44$, there will be no ion trapping in a clean UHV system. For intermediate situations of $1 < A_{cr} < 44$, more detailed analysis is needed.

Effects of Neutralization (Ion Trapping)

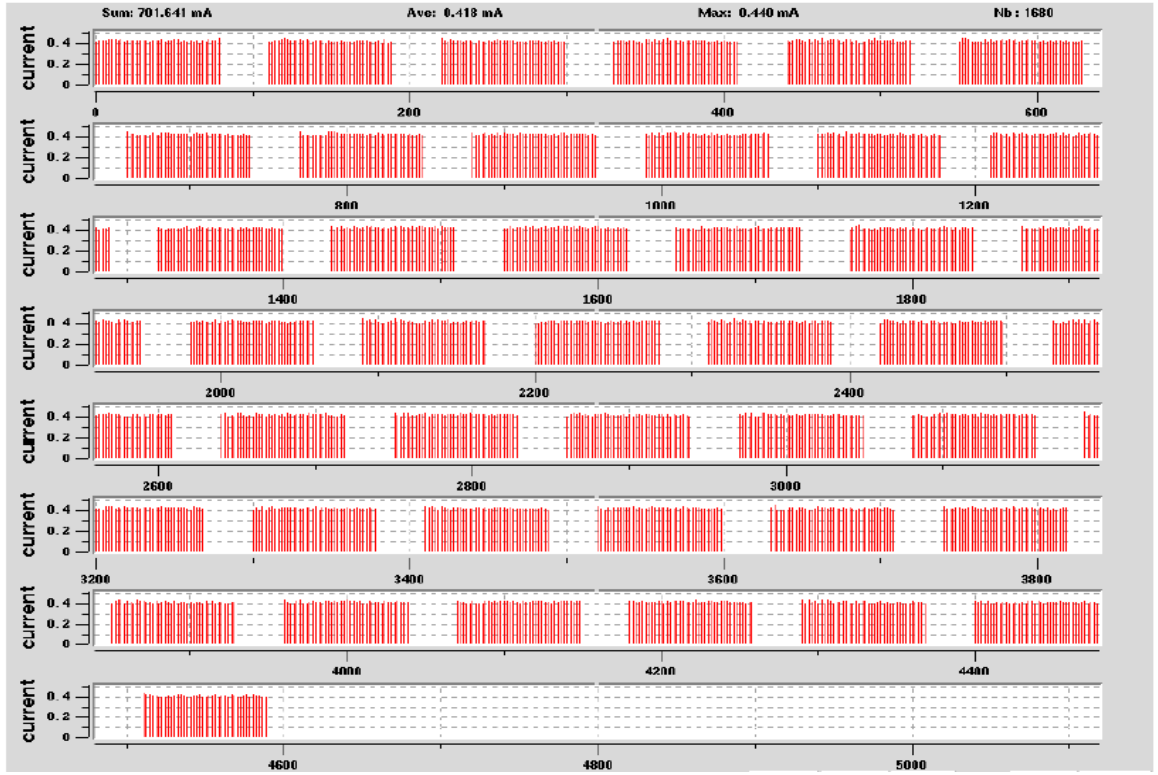
- Reduces beam lifetime, due to increased local pressure and scattering center density
- Causes tune-shift and emmittance growth
- Induce background to HEP detectors and X-ray user stations.



Ion Clearing Measures

- The most straight forward and commonly deployed ion clearing measure is to leave gaps in the bunch fill pattern, so that the A_{cr} is sufficiently large (say > 44).
- However, leaving large gaps is not always practical, or limits the beam current in small storage rings.
- Clearing the ions with active DC electrodes is the other option.
- Cares must be taken in the ion clearing electrode to minimize beam impedance.

KEK-B Filling Pattern Example

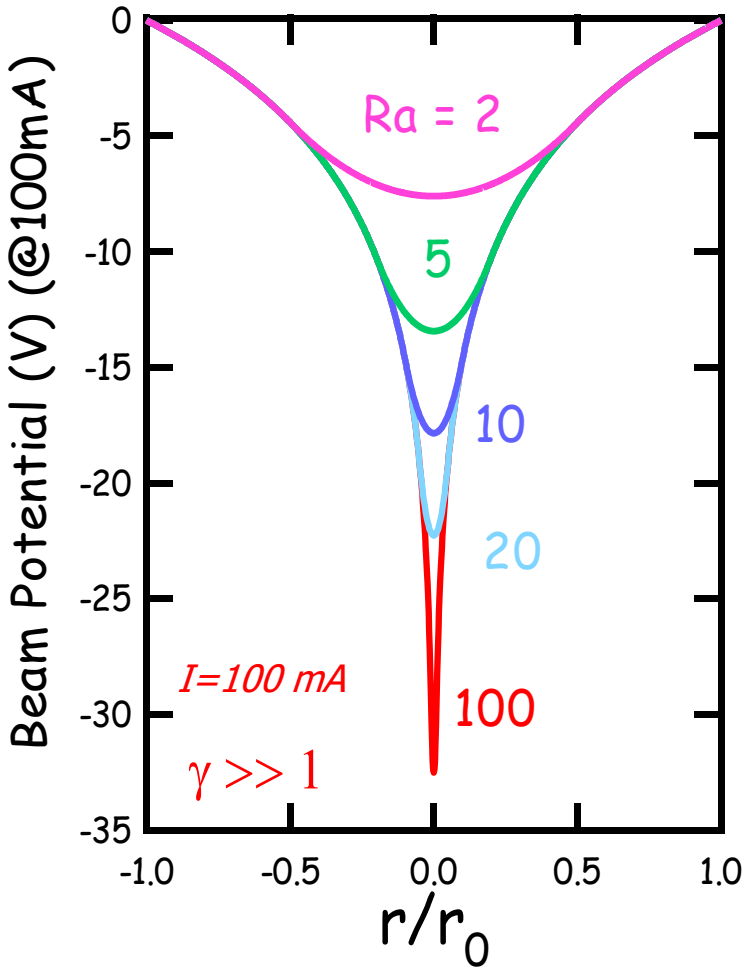


Beam Potential and Trapping Well

- For a beam with uniform transverse charge distribution, beam radius a, and a round beam pipe of radius r_0, the beam potential well is:

$$V = -59.92\frac{I}{\beta}\begin{cases} -\frac{R_a^2 x_r^2}{2} + \frac{1}{2} + \ln(R_a) & x_r \le 1/R_a \\ -\ln(x_r) & x_r > 1/R_a \end{cases}$$

where I is beam current in ampere,
$x_r \equiv r/r_0$, $R_a \equiv r_0/a$.



- The beam potential well depth is:

$$V_{\min} = 59.92\frac{I}{\beta}(\tfrac{1}{2} + \ln R_a)$$

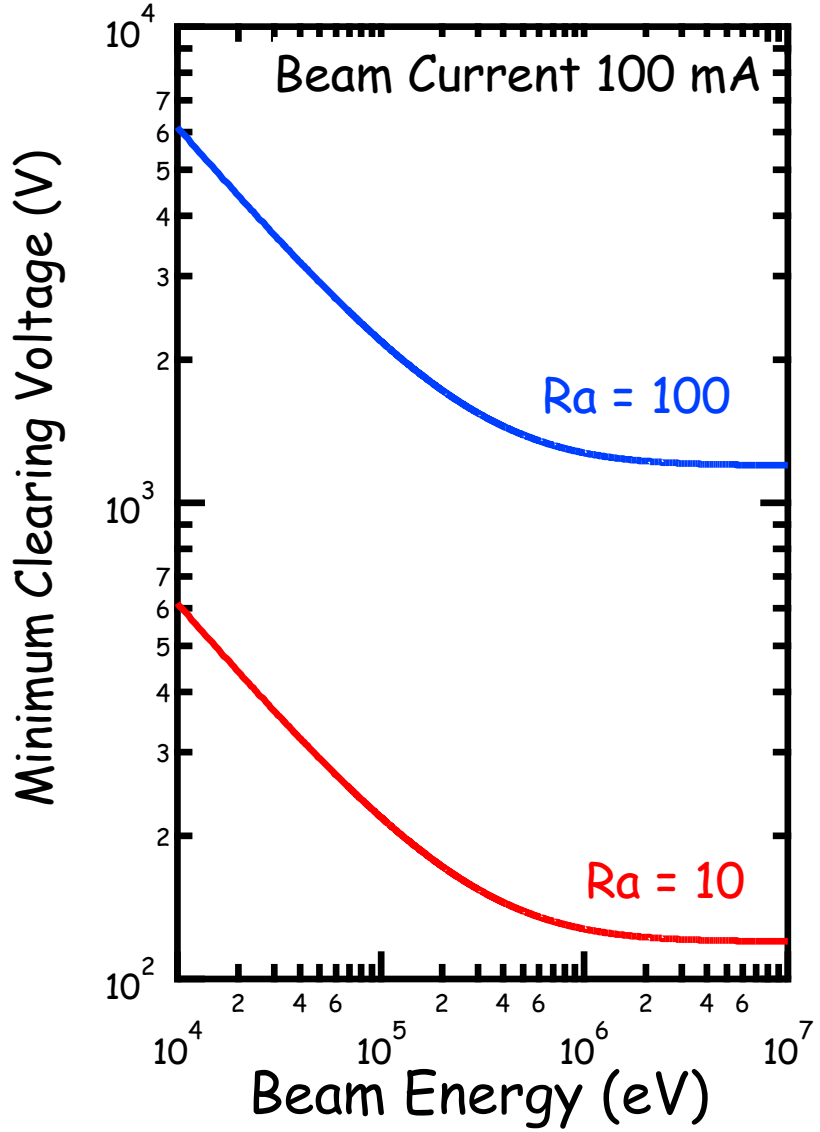
Ion Clearing Voltage

- To swipe out trapped ions, the clearing electrode voltage, U_{ce} should be greater than the maximum beam field,

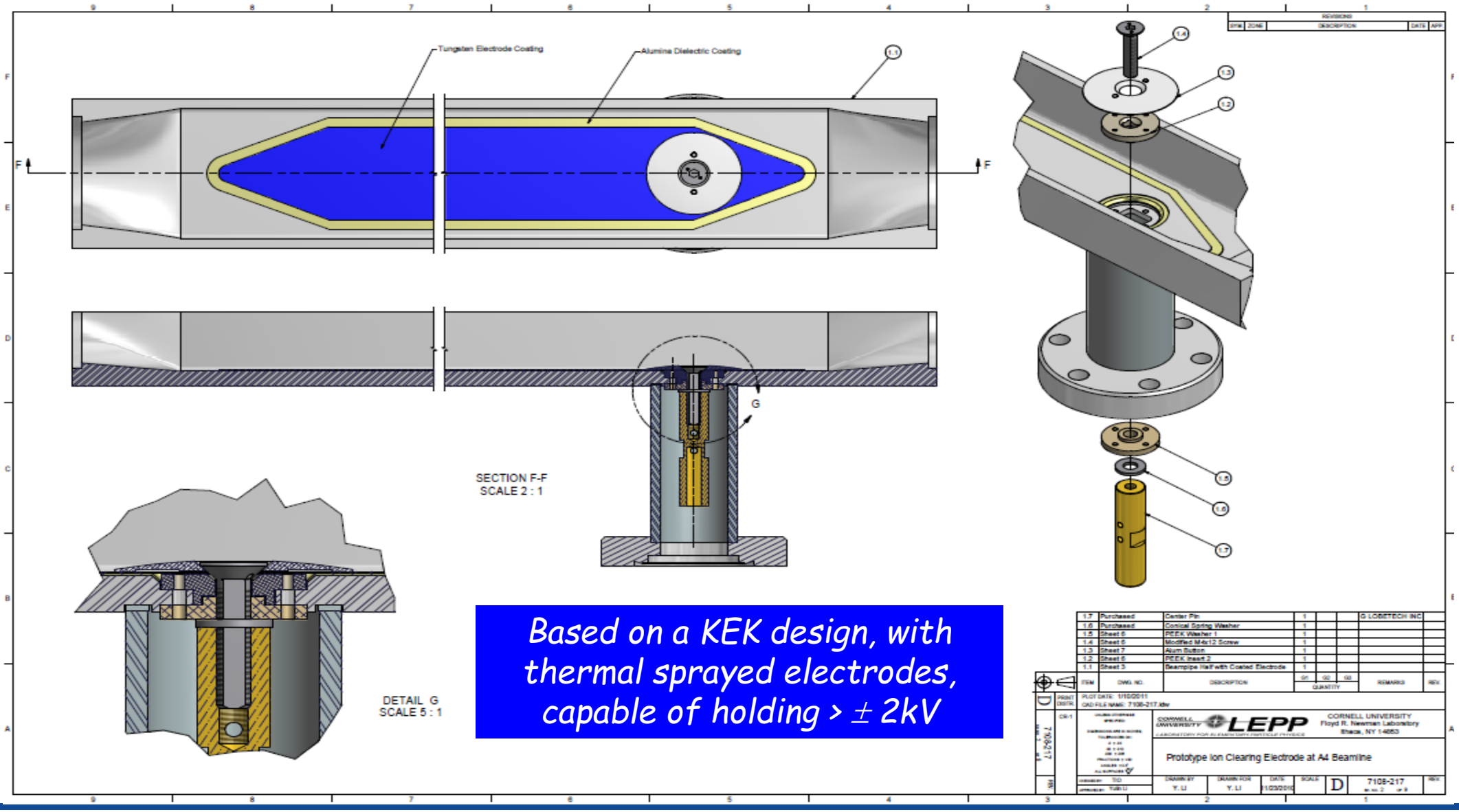
$$\frac{U_{ce}}{2r_0} \geq E(a) = \frac{I}{2\pi\beta c\varepsilon_0 a} = 119.8R_a \frac{I}{\beta}$$

- The degree of beam neutralization is not uniform in the storage ring. The trapped ions may be driven to deeper beam potential wells, i.e. at smaller $\beta(s)$.

- The clearing electrodes thus should be placed at these low $\beta(s)$. The length of the electrode should be reasonably long so overcome the drift speed of the ions.



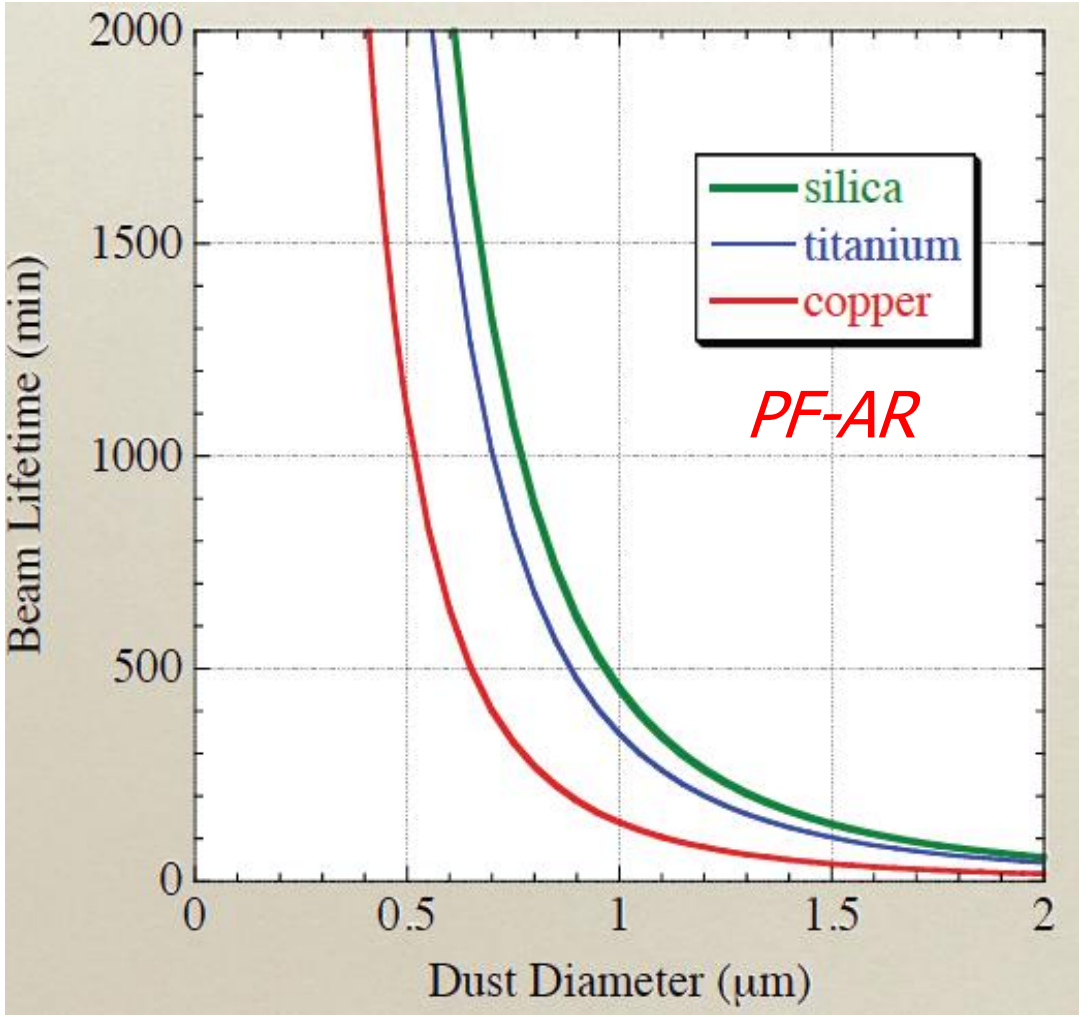
A Low Impedance Clearing Electrode Design



Based on a KEK design, with thermal sprayed electrodes, capable of holding > ± 2kV

Dust Trapping in Electron Beams

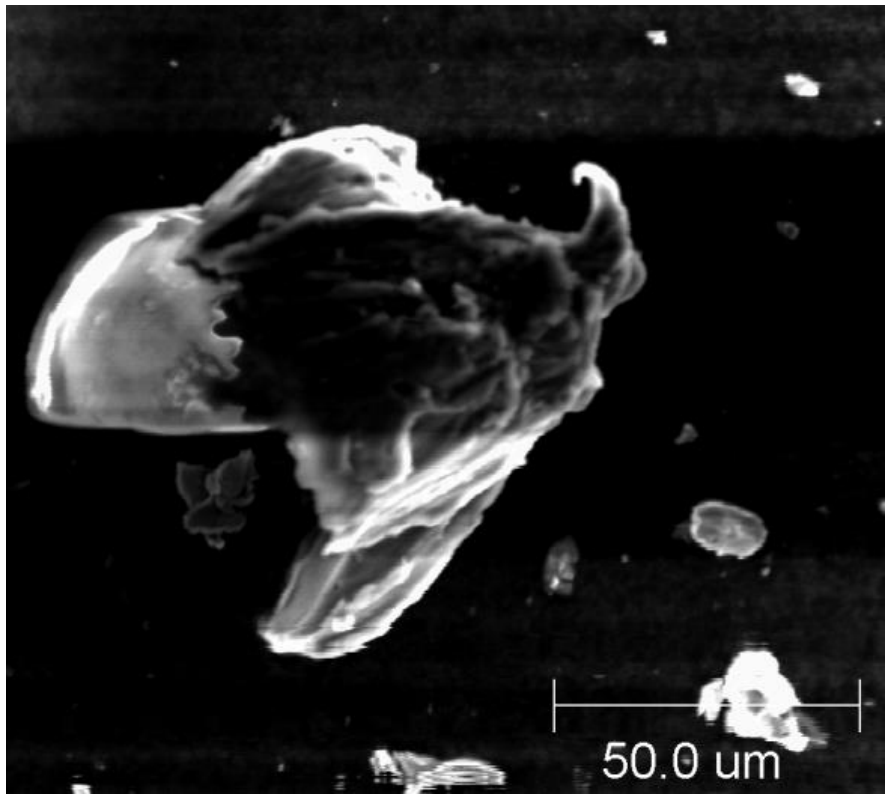
- Positively charged dust particles can be captured by electron or anti-proton beams.
- The captured dust particles will be heated up by beam scattering (mainly bremsstrahlung). For dust with very high melting temperature, the trapping will last, can induce server beam loss and radiation.
- Dust trapping occurs at locations where dusts are often created, such as DIPs, in vacuum HV devices, pulsed magnets, etc.

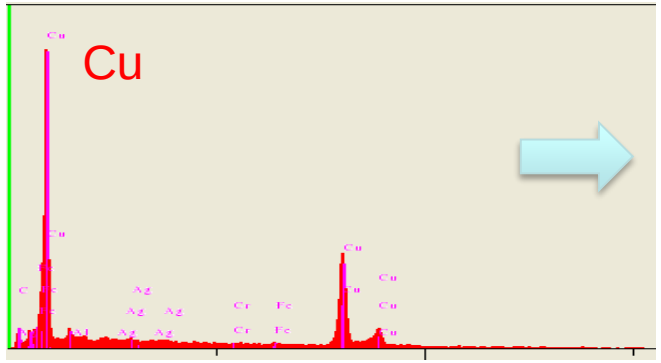


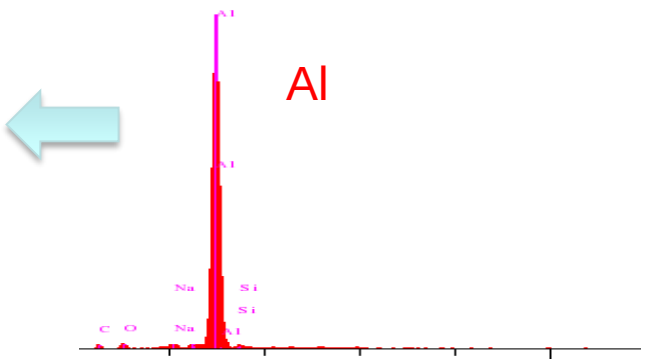
From: **Y. TANIMOTO**, Photon Factory, KEK, IBIC12, Tsukuba, Oct. 2nd 2012

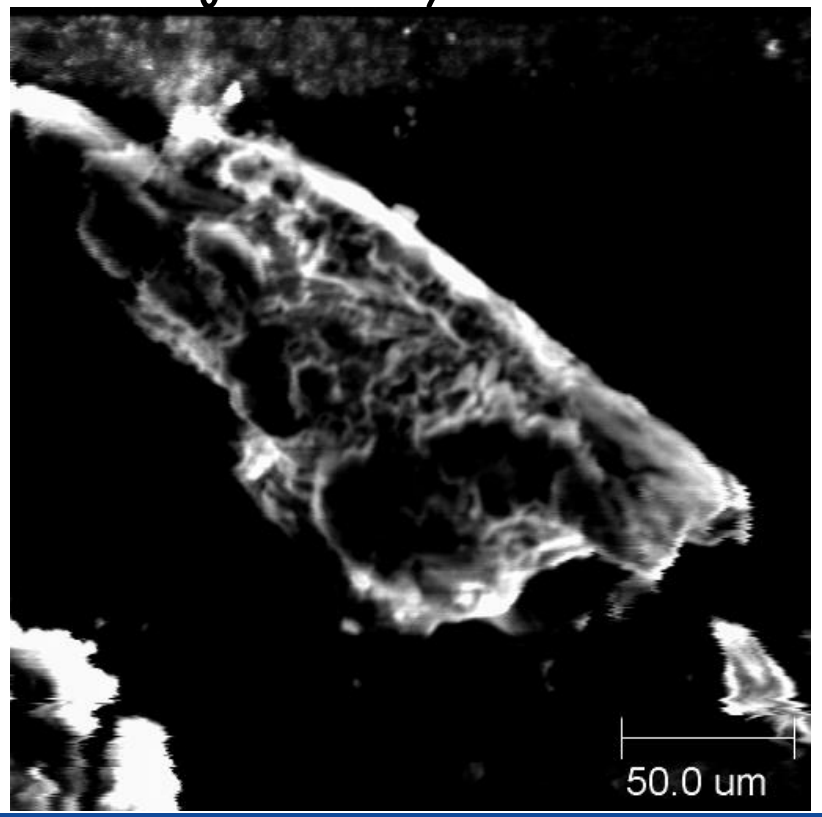
Dust Trapping Example in CESR

- At CESR, we experienced frequent (suspected) dust trapping during electron injections.
- During a maintenance shutdown, we inspected the injection septum chamber, and cleaned out many dusts. AES showed primarily Cu and Al.
- After the cleaning, very few dust trapping events during electron injection cycles.









Electron Cloud and Mitigations

Many thanks to Dr. Y. Suetsugu of KEK for sharing his AVS 2012 invited presentation on this subject.

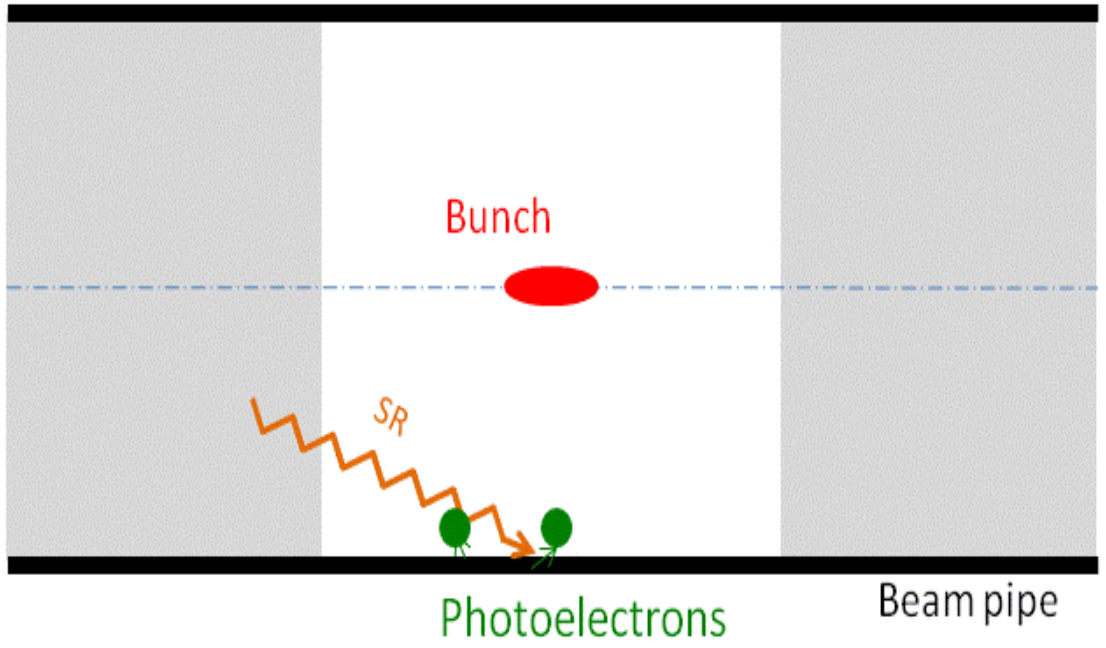
Electron Cloud in Positive Charged Beams

- Photons emitted from bunches hit the inner wall.
- Photoelectrons are produced by the photons and attracted to the positron beam.
- Electrons accelerated by electric field of the bunches hit the wall, and the secondary electrons also are produced.
- These electrons form the electron cloud around the beam, and interact with beam.

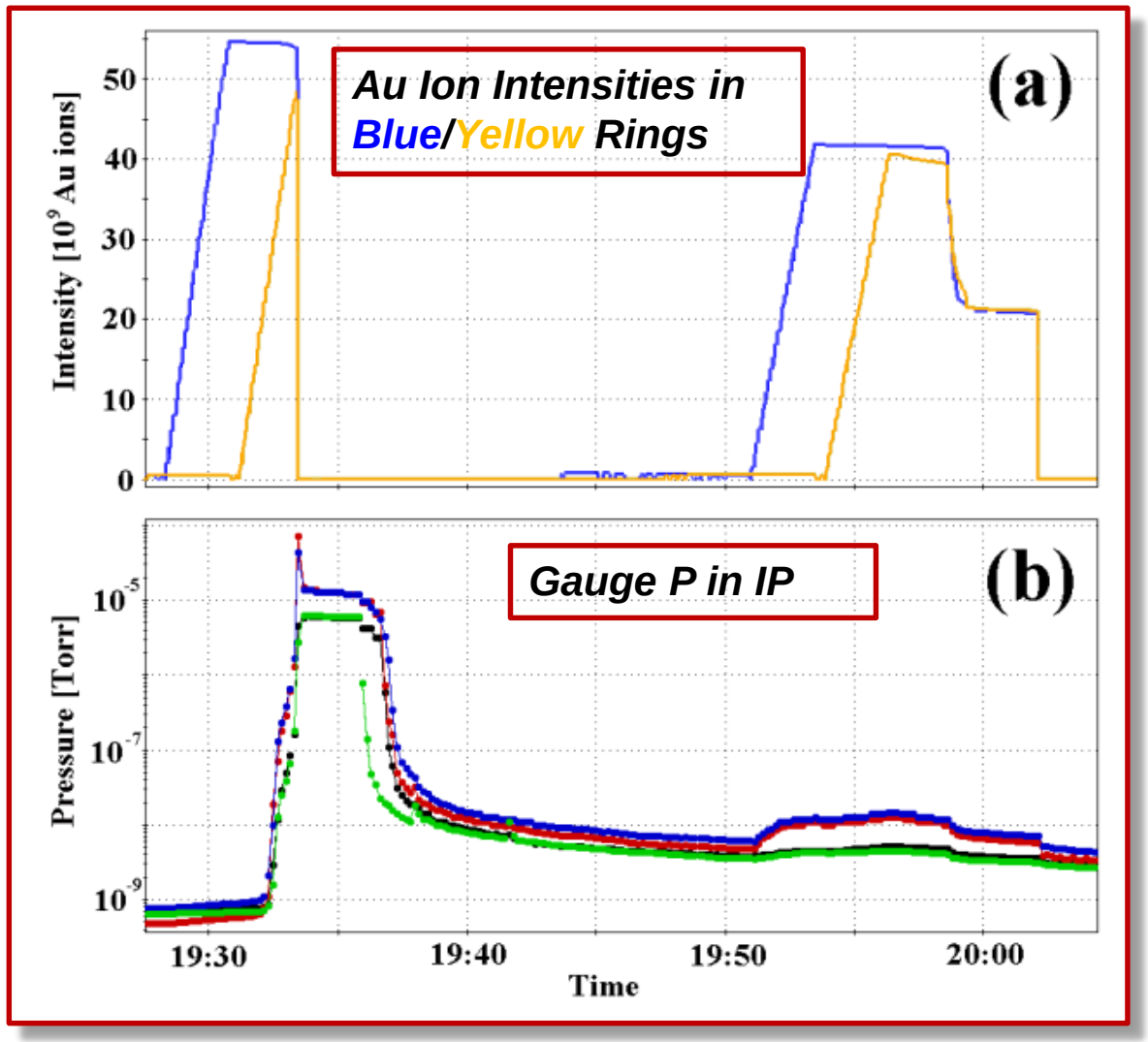
E-Cloud

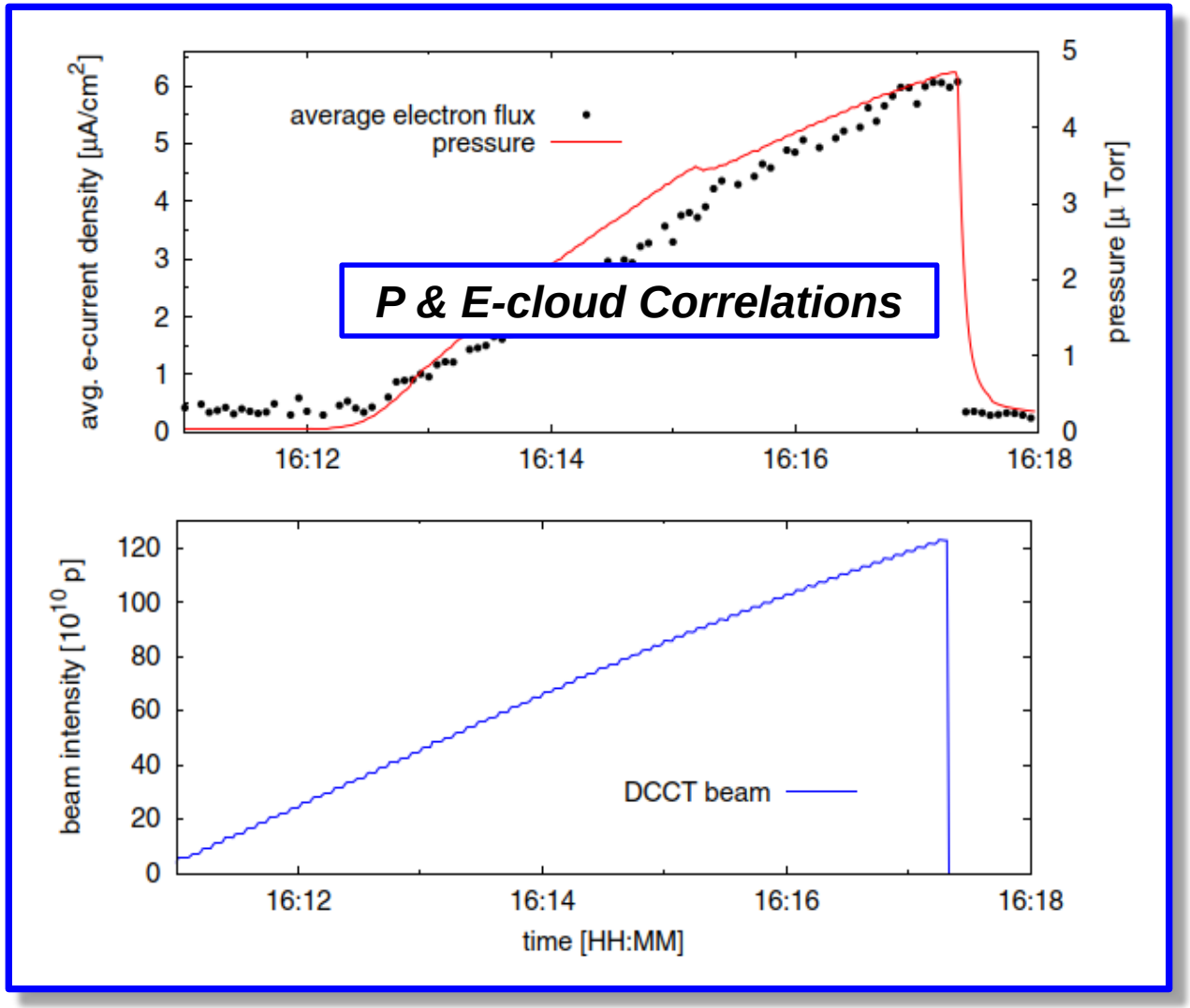
Beam instabilities, blow up of beam sizes & nonlinear pressure rise

Critical issue for ILC e^+ DR and SuperKEKB



E-Cloud Effect Example – RHIC Observation





"Electron cloud observations and cures in the Relativistic Heavy Ion Collider", W. Fischer, et al, *PHYS. REVIEW STAB*, **11**, 041002 (**2008**)

Things Affect Electron Cloud Build-up

There are three factors that influence the build up of electron cloud (at least for the positron machines).

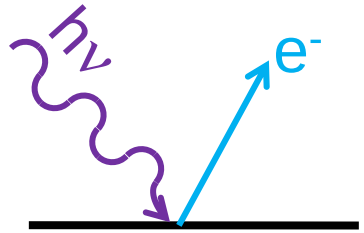
1. Primary electron generations – mainly due to SR generated photon electrons in positron machines)

2. Primary electron acceleration by the bunched positrons

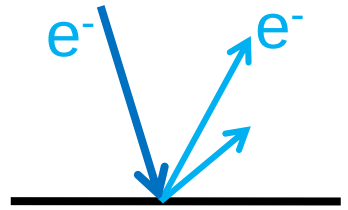
3. Electron multiplications (multipacting) via secondary electron generations on chamber walls

Counter-measures against the EC Buildup

- ***Reduce photoelectron emission***
  - *Photoelectrons = Seed of EC*
  - *Antechamber scheme beam pipe*
  - *Rough surface at irradiated surface*



    - ***Reduce secondary electron yield (SEY)***
      - *Secondary electrons multiplies EC.*
      - *Important for high-intensity beam*
      - *TiN, carbon (amorphous carbon), NEG coatings*
      - *Groove structure on the inner surface*
      - *Rough surfaces*

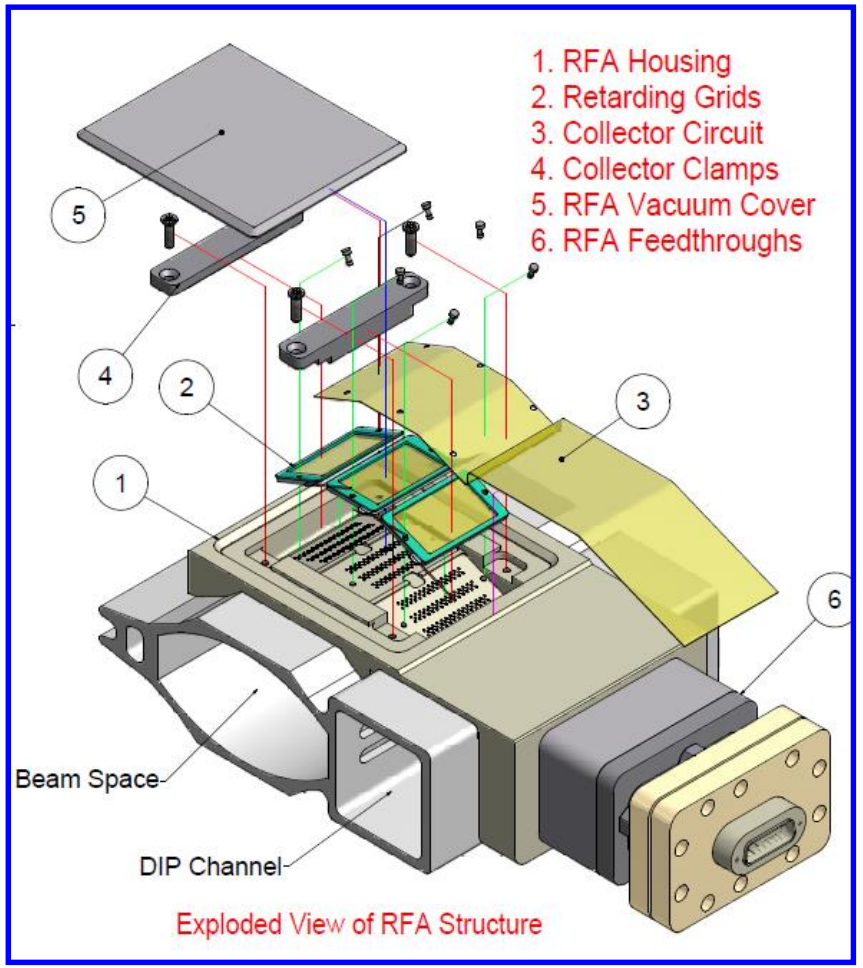


        - ***Prevent electrons from approaching to beam***
          - *EC around beam is more important for beam dynamics.*
          - *Solenoid field along the beam pipe*
          - *Clearing electrode in the beam pipe*

➡ ***All are deeply related to the vacuum system***

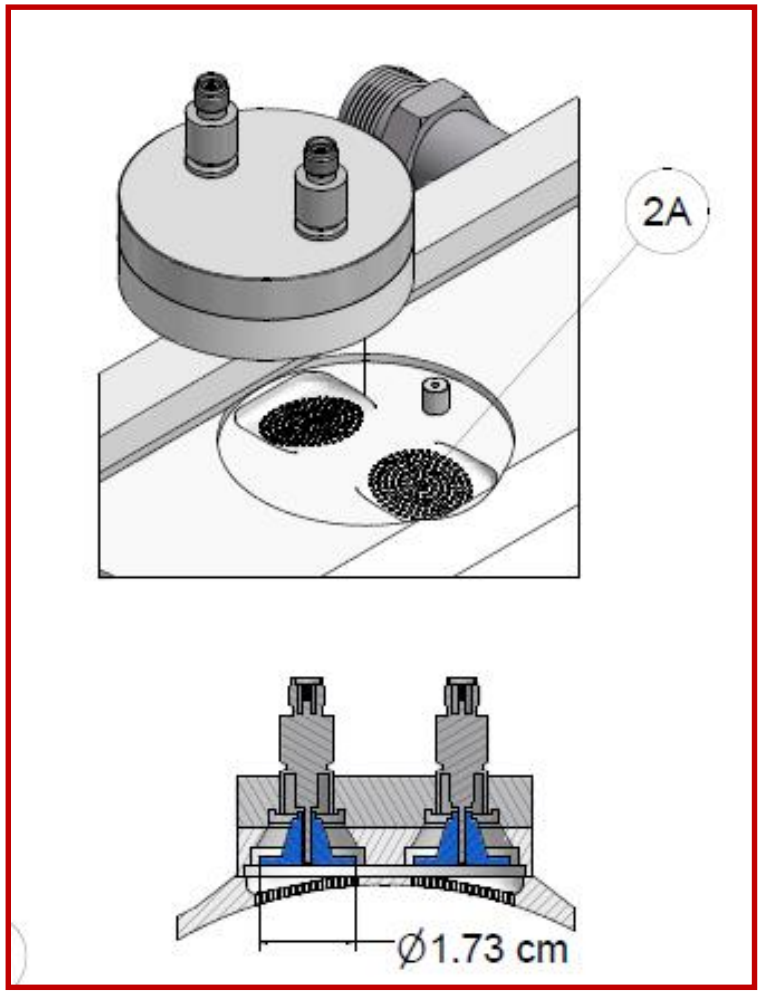
EC Studies at CesrTA

We have converted CESR into an EC study Test Accelerator (CesrTA, 2008-2014), and build EC detectors in many kinds of field conditions (including drifts, dipole, quadrupole, wiggler).



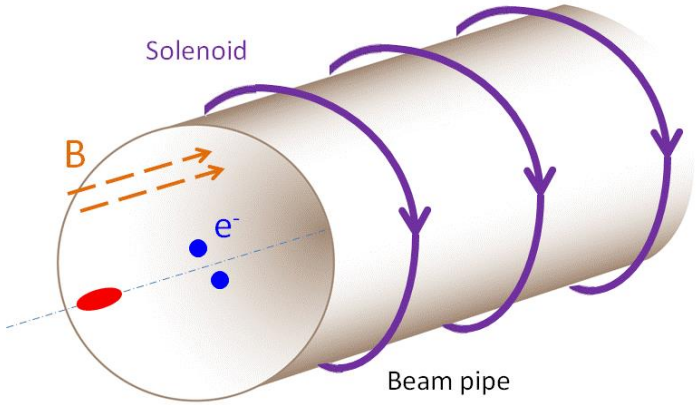
Retarding Field Analyzers for measuring DC EC distribution

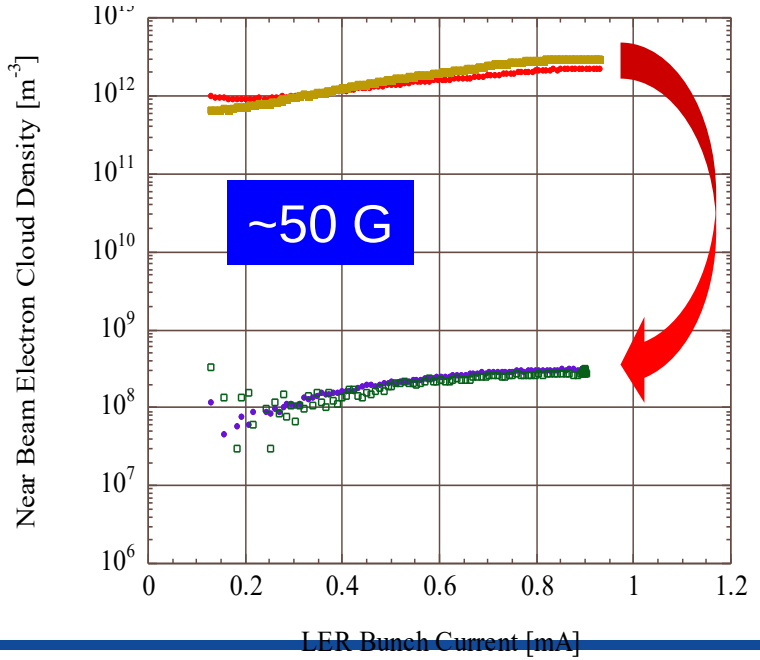
RF-shielded pickups for measuring EC growth



EC Suppression in Drift – Solenoid

- Very effective in drift space
- Effectively functioned at KEKB positron ring
- Also applied in PEPII, SLAC

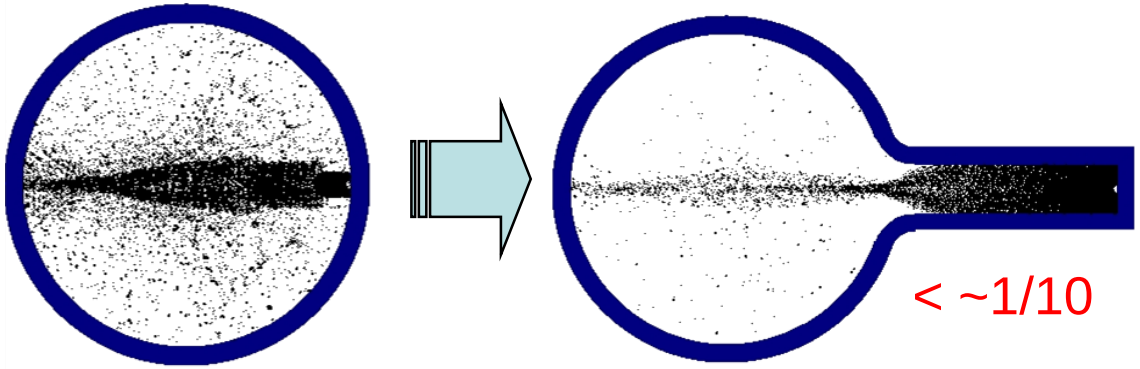


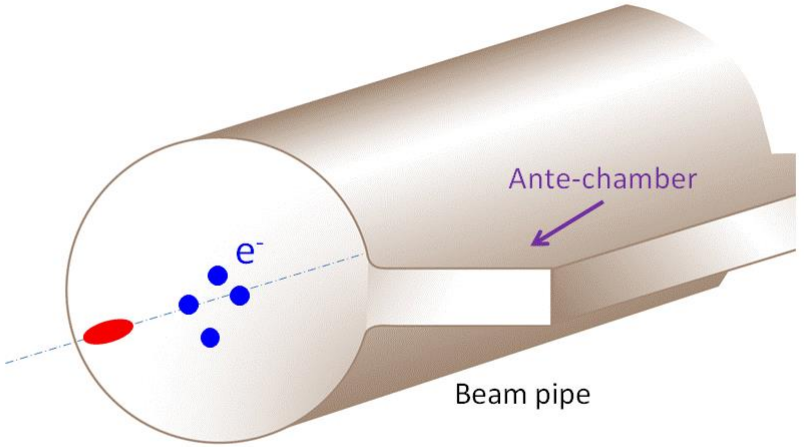


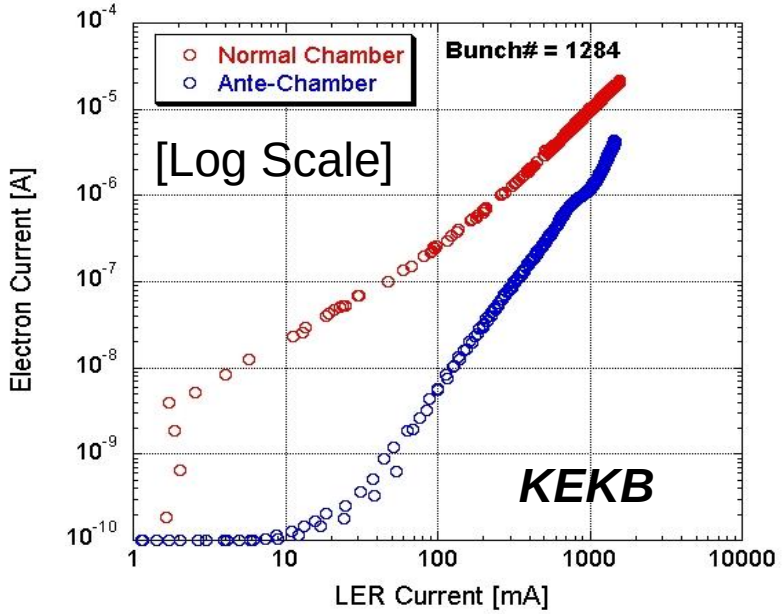
- *Electron density decreased by orders of magnitude*
- *Not available in magnets*

Reduce Primary Electrons – Ante-Chamber

- *Effective to reduce photoelectrons*
  - *Irradiated surface is far from beam*
  - *Rough surface enhances the effect*

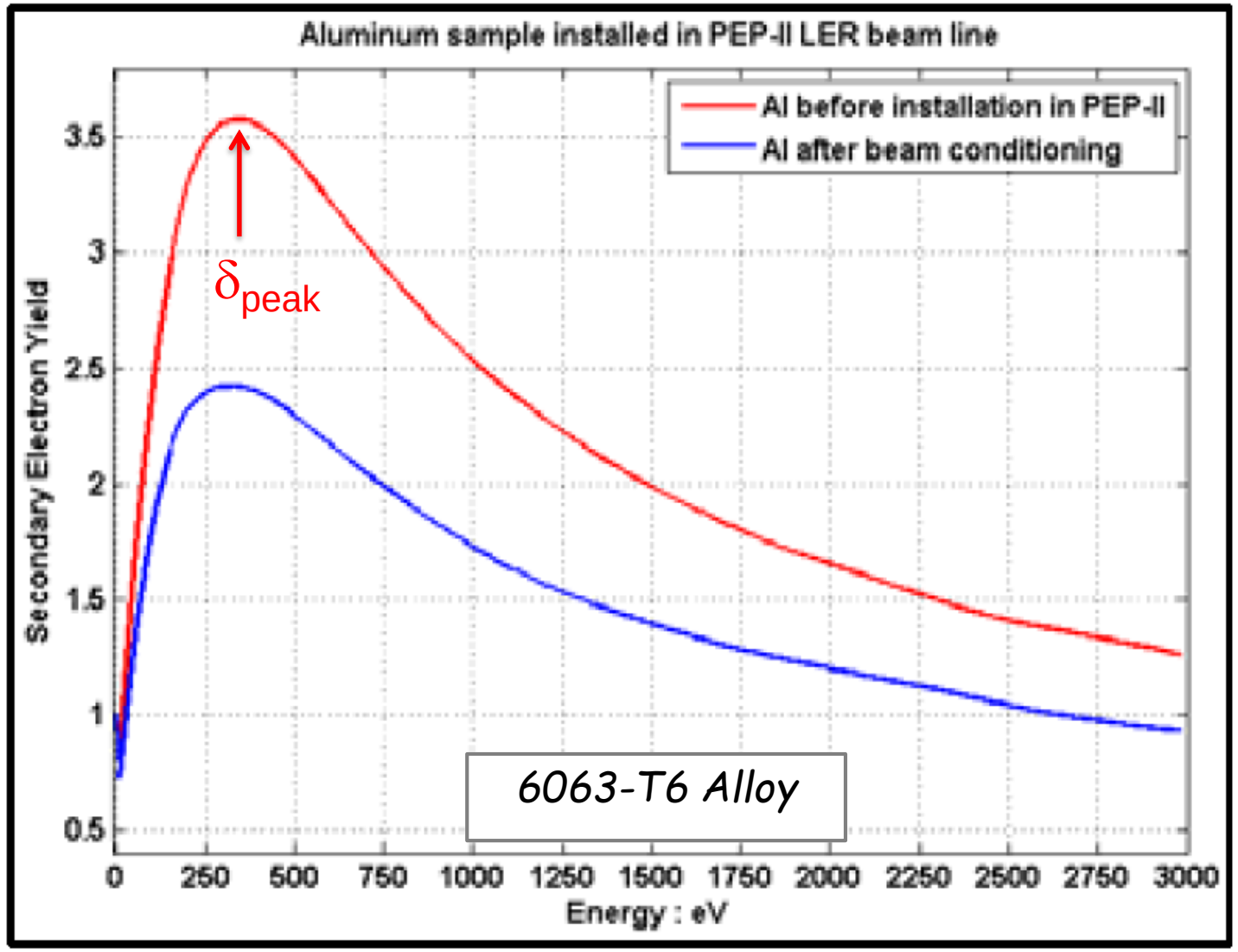






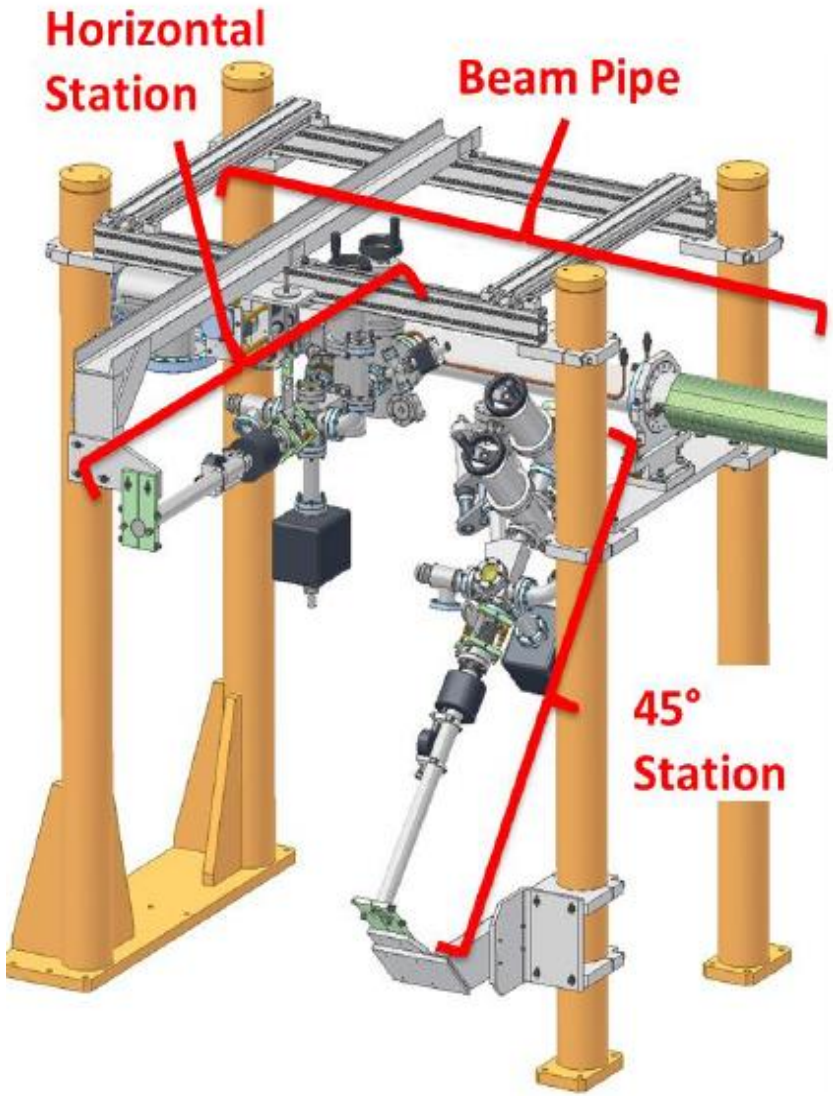
- **Reduction <1/100 at low beam current (<100 mA)**
  - Photoelectron is well suppressed.
- **Reduction by a factor of 4 at high current (>1500 mA):**
  - Secondary electron is important.

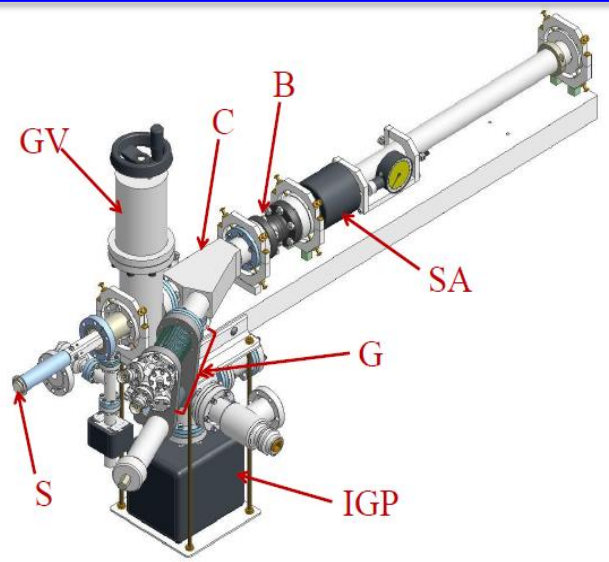
Secondary Emission Yield – Aluminum Alloy



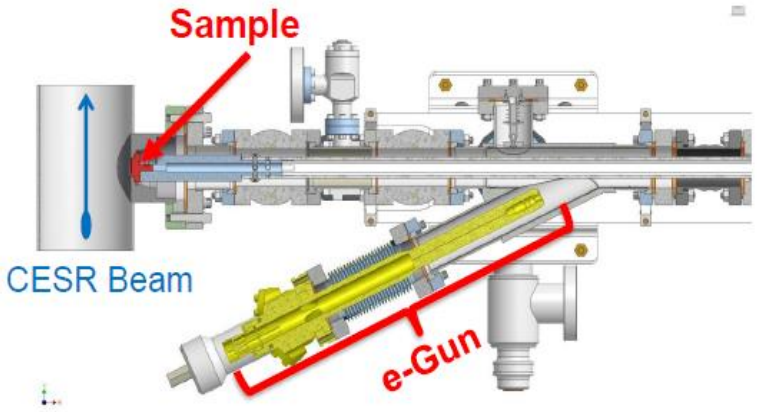
- The most commonly used aluminum alloys (6061 and 6063) have very high secondary emission yield (SEY), even with significant 'conditioning'.
- This is very undesirable for high performance accelerators for positively charged particles, such as RHIC, ILC e^+ DR, KEK B HER, LHC, etc.

Load-locked SEY Stations at CesrTA



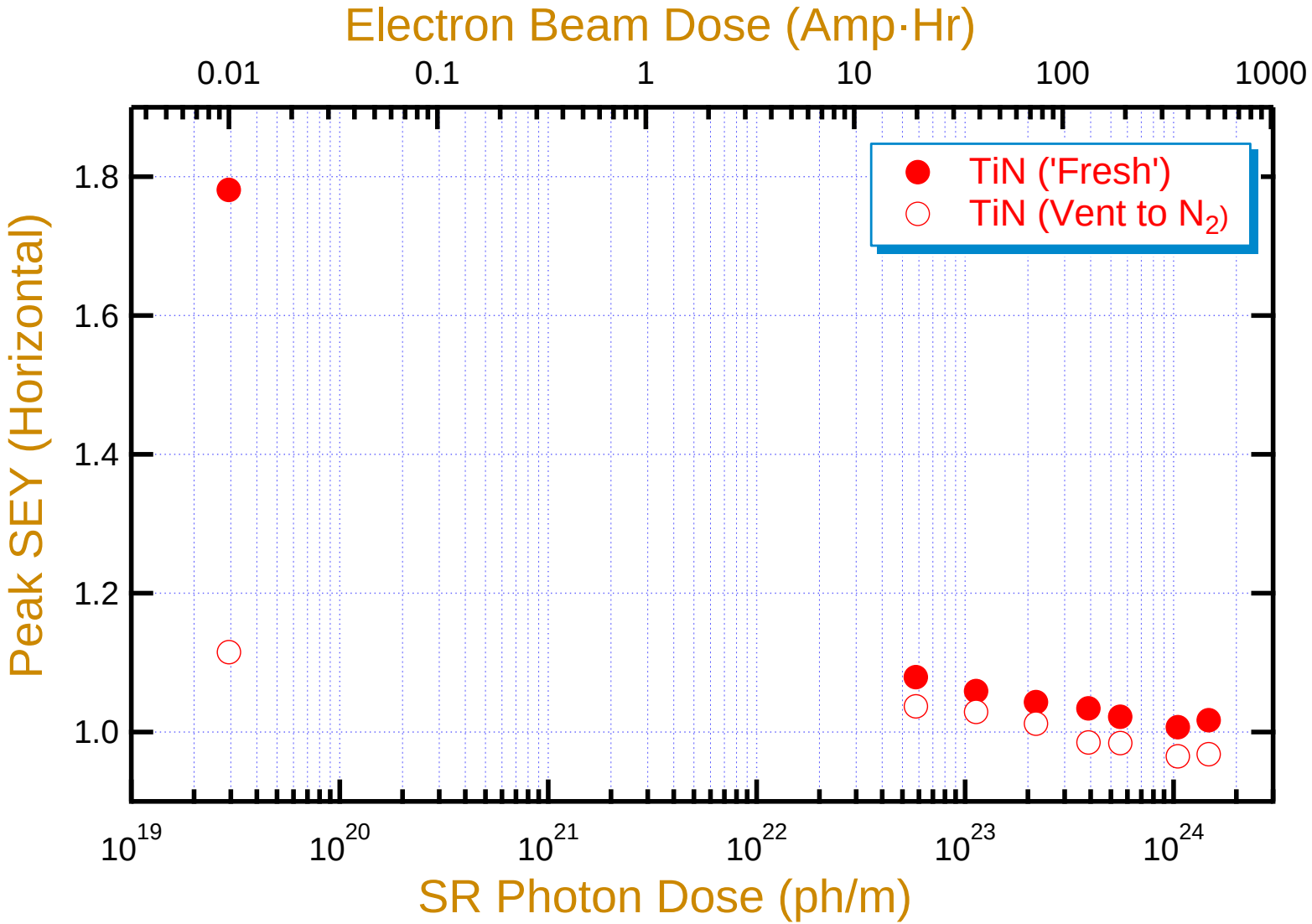


S: sample; G: electron gun; C: vacuum crotch; B: ceramic break;
SA: sample actuator; GV: gate valve; IGP: ion-getter pump



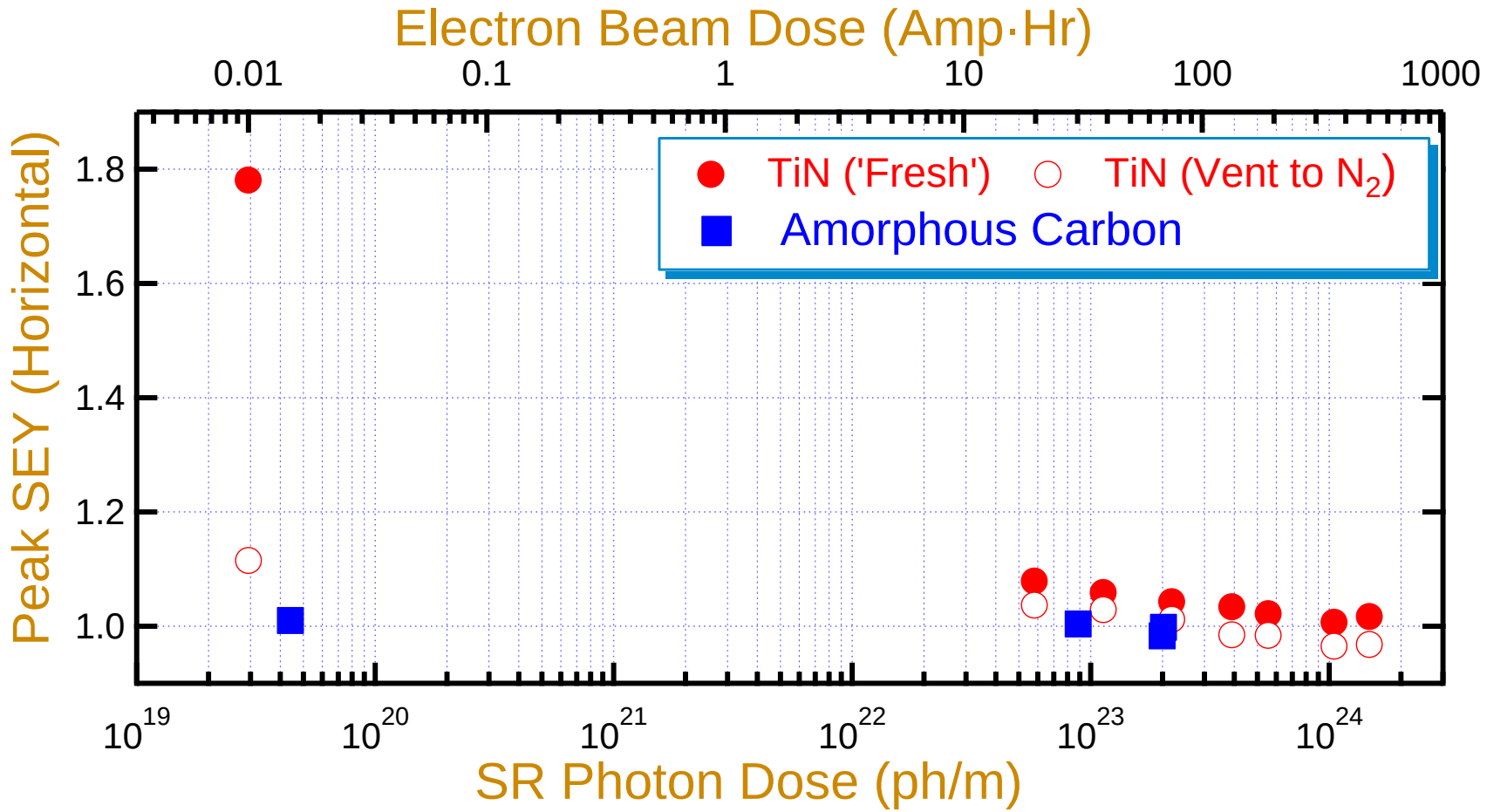
Two SEY stations, with sample load-lock, allow beam (SR) conditioning of samples and in-situ SEY measurement.

SEY Reduction Coating – TiN



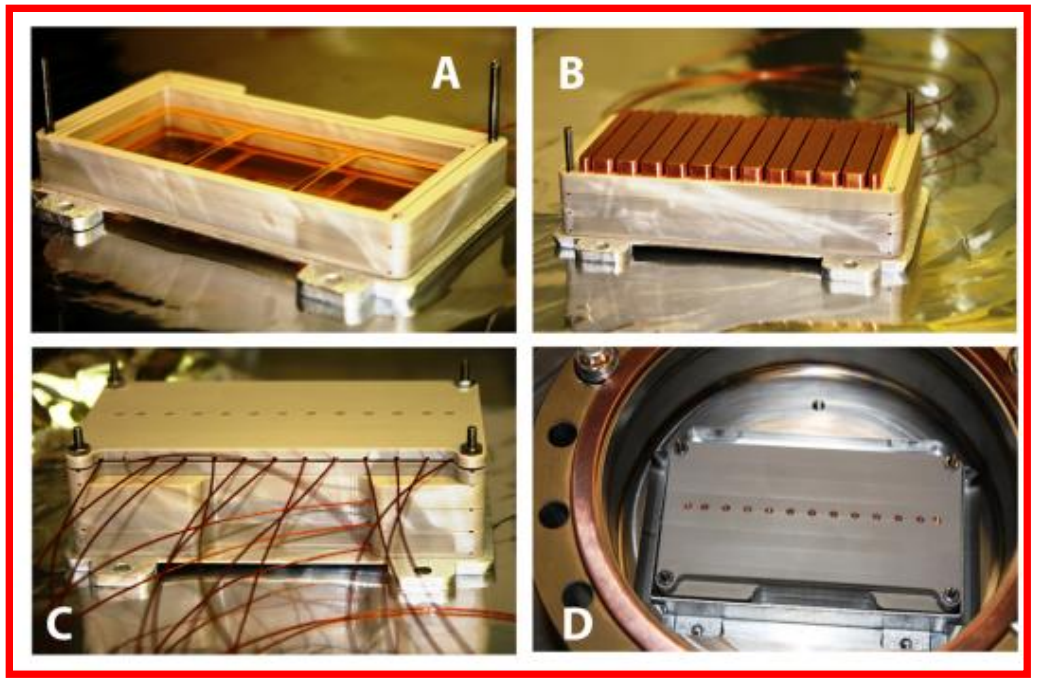
TiN coating has been chosen as the primary SEY-reduction coating for Super KEKB HER, and base design for the ILC e^+ Damping Ring

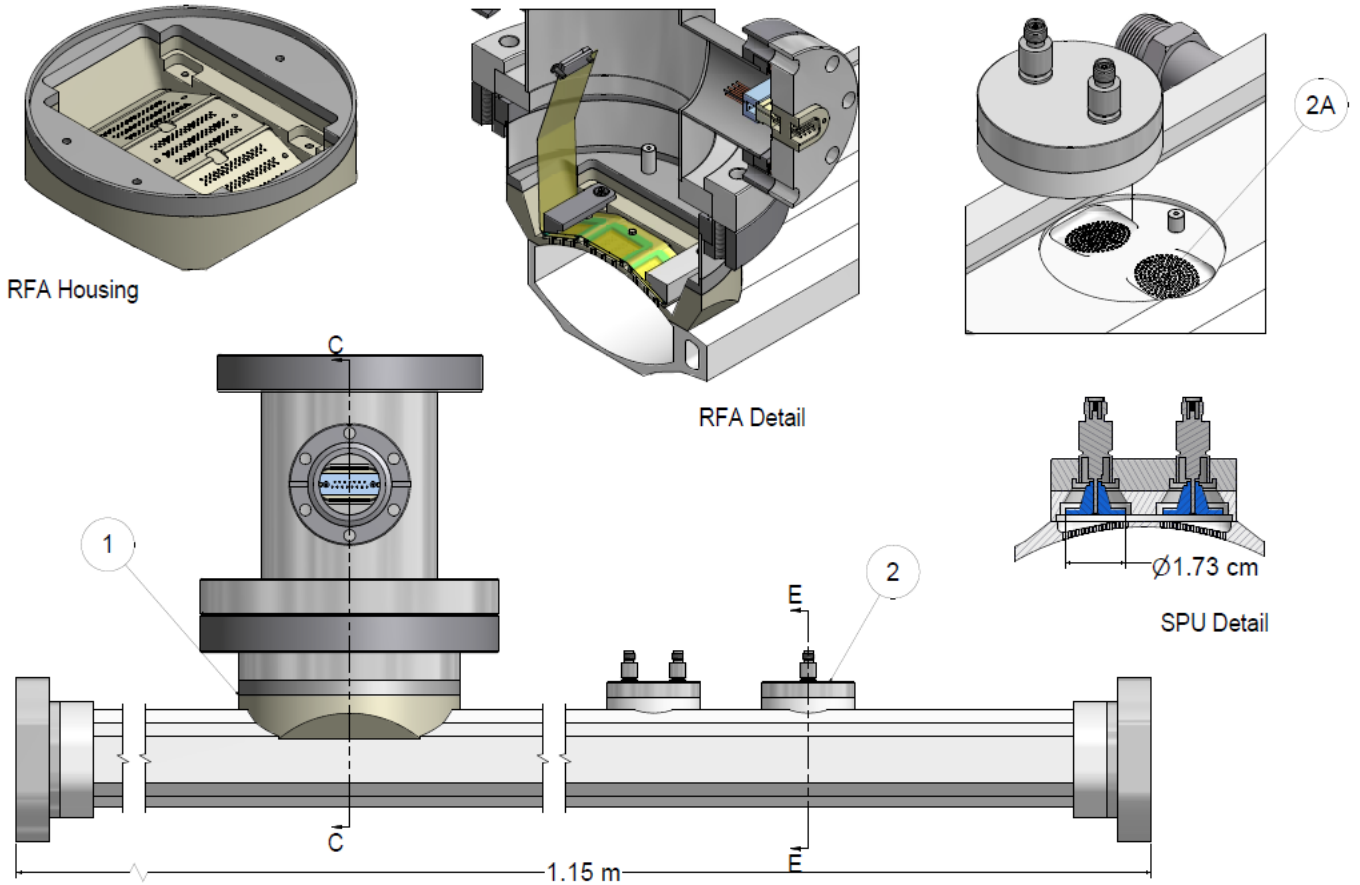
SEY Reduction Coating – Amorphous Carbon



- Amorphous carbon thin film exhibits close to unity δ_{peak}, without any conditioning.
- This coating was intensively investigated by CERN/CLIC team and tested at CesrTA.

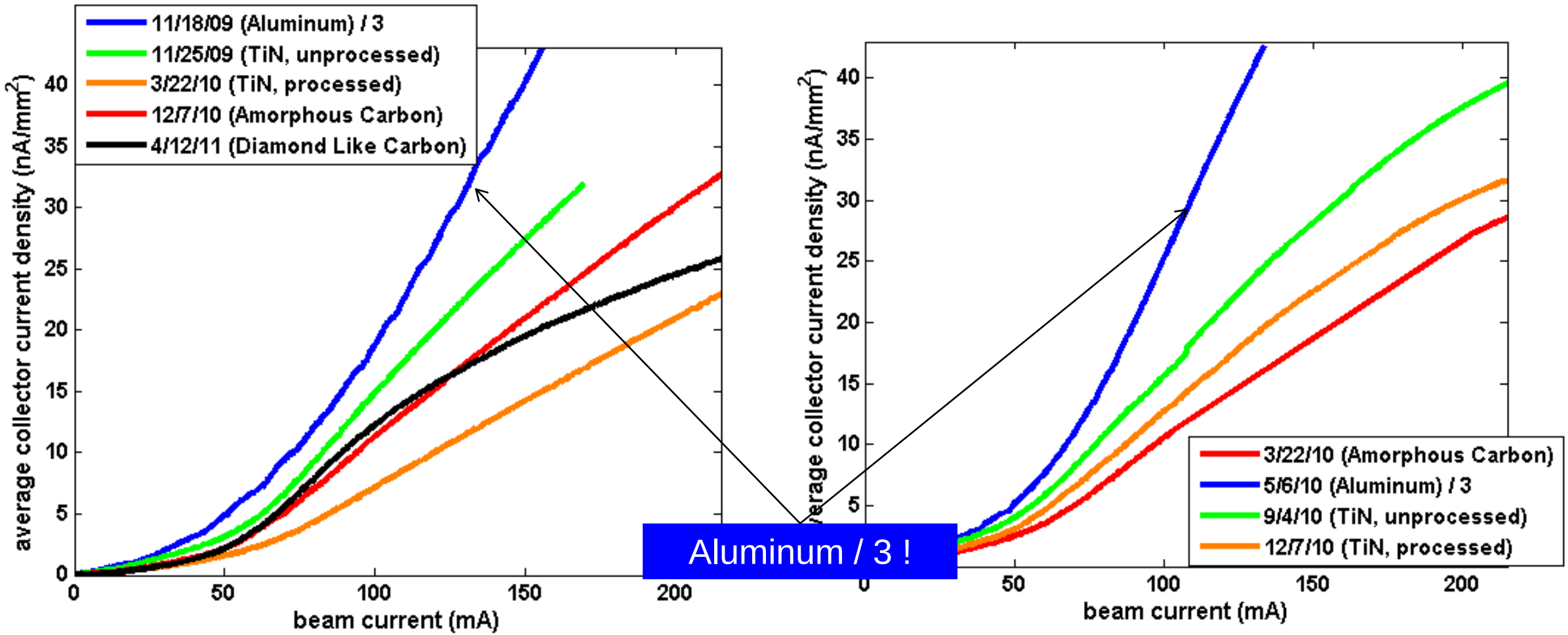
A CesrTA Chamber for Evaluation Coatings





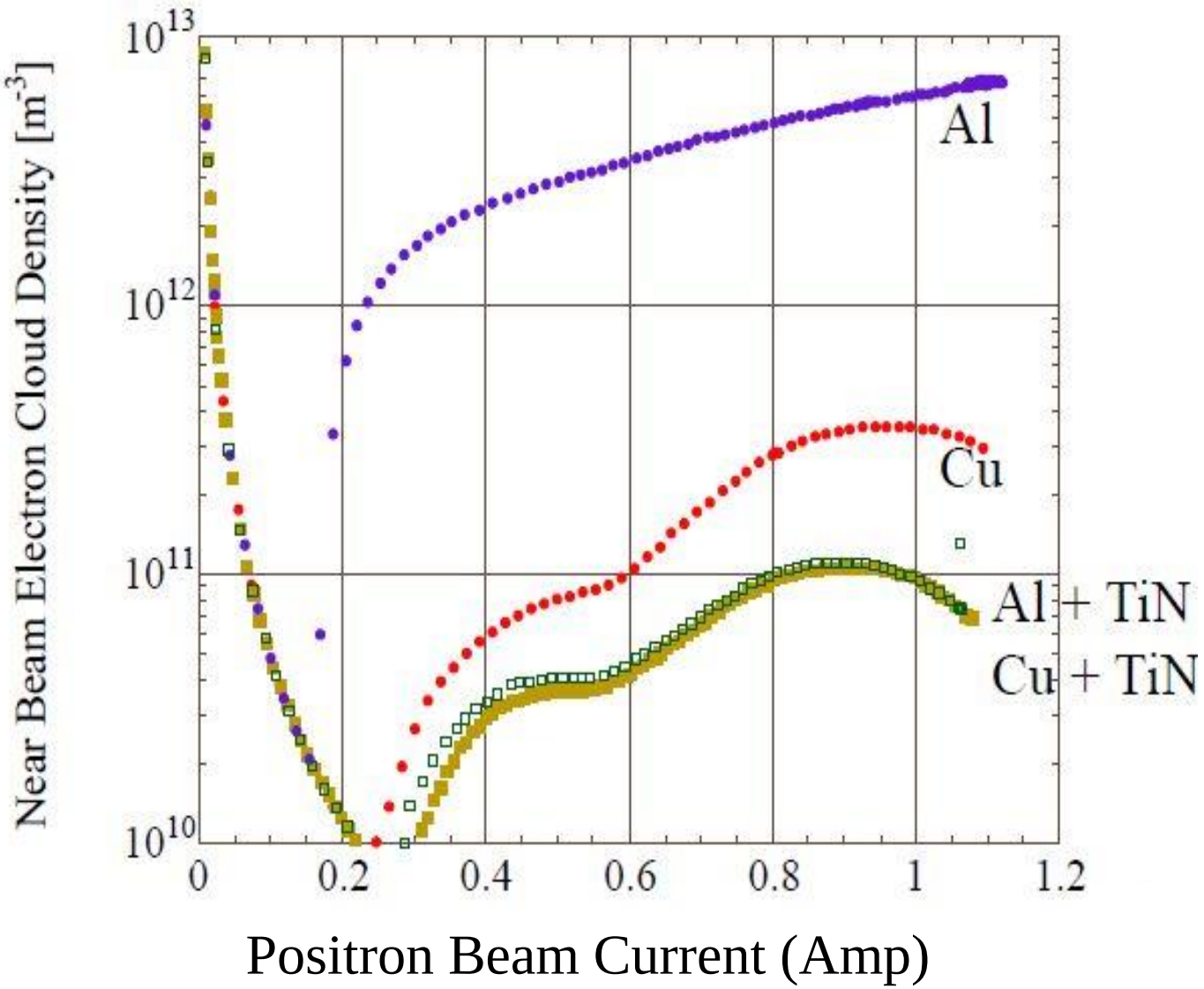
- Six vacuum chambers were constructed and rotated through CesrTA.
- The test chambers were equipped with EC detectors (RFA and SPU), as well vacuum instruments (CCG and RGA)

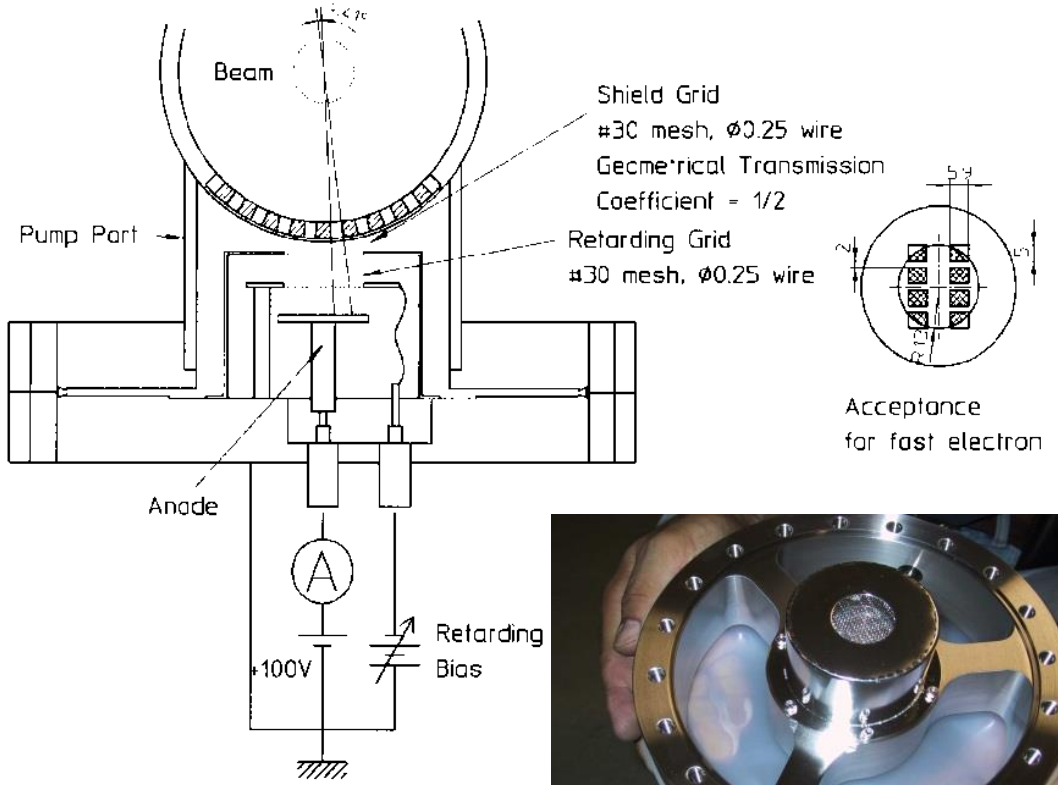
SEY Suppression by Coatings – RFA Results



20 bunch train of positrons, 14ns spacing, at 5.3GeV

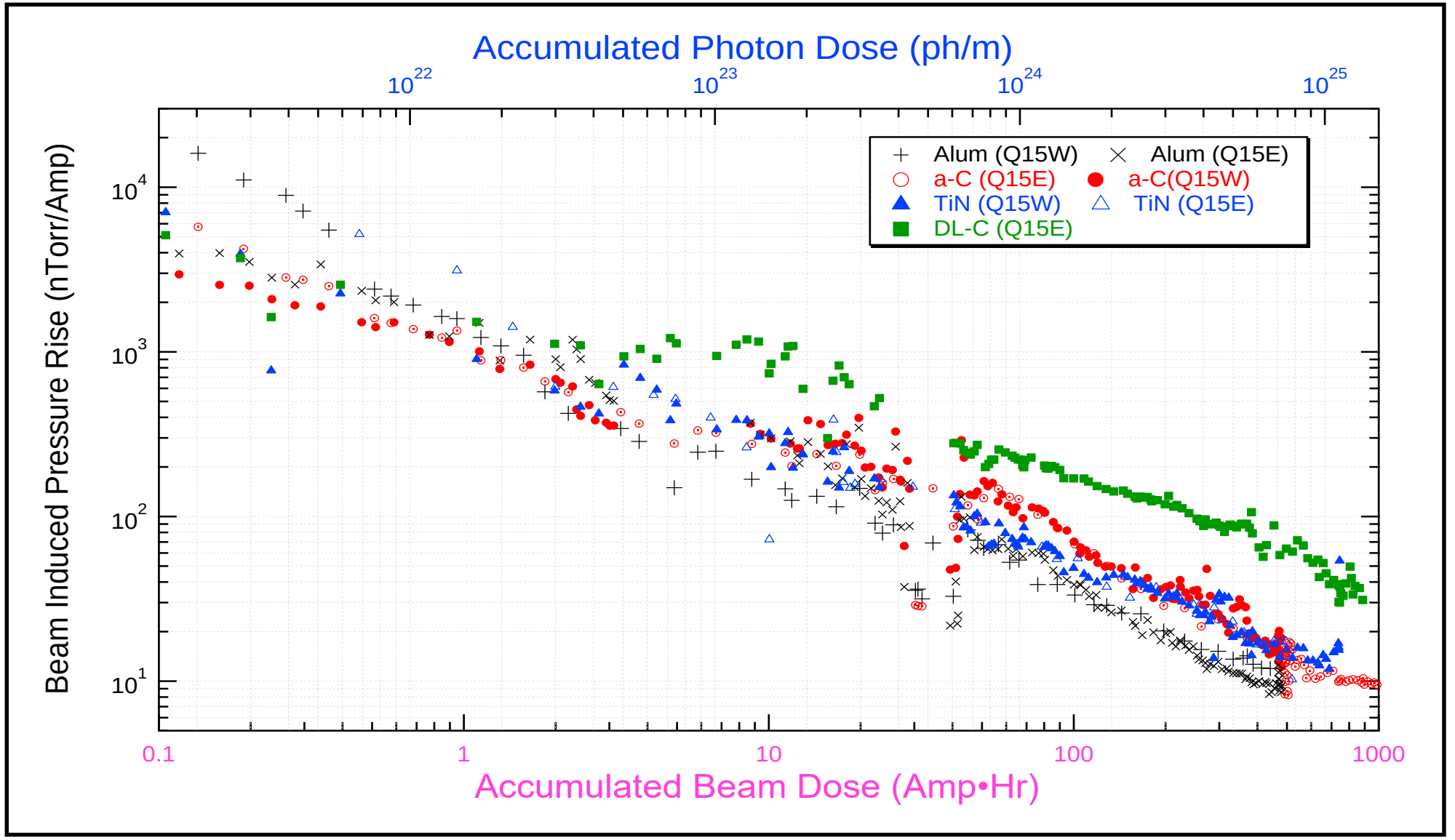
EC Suppression – TiN at KEK



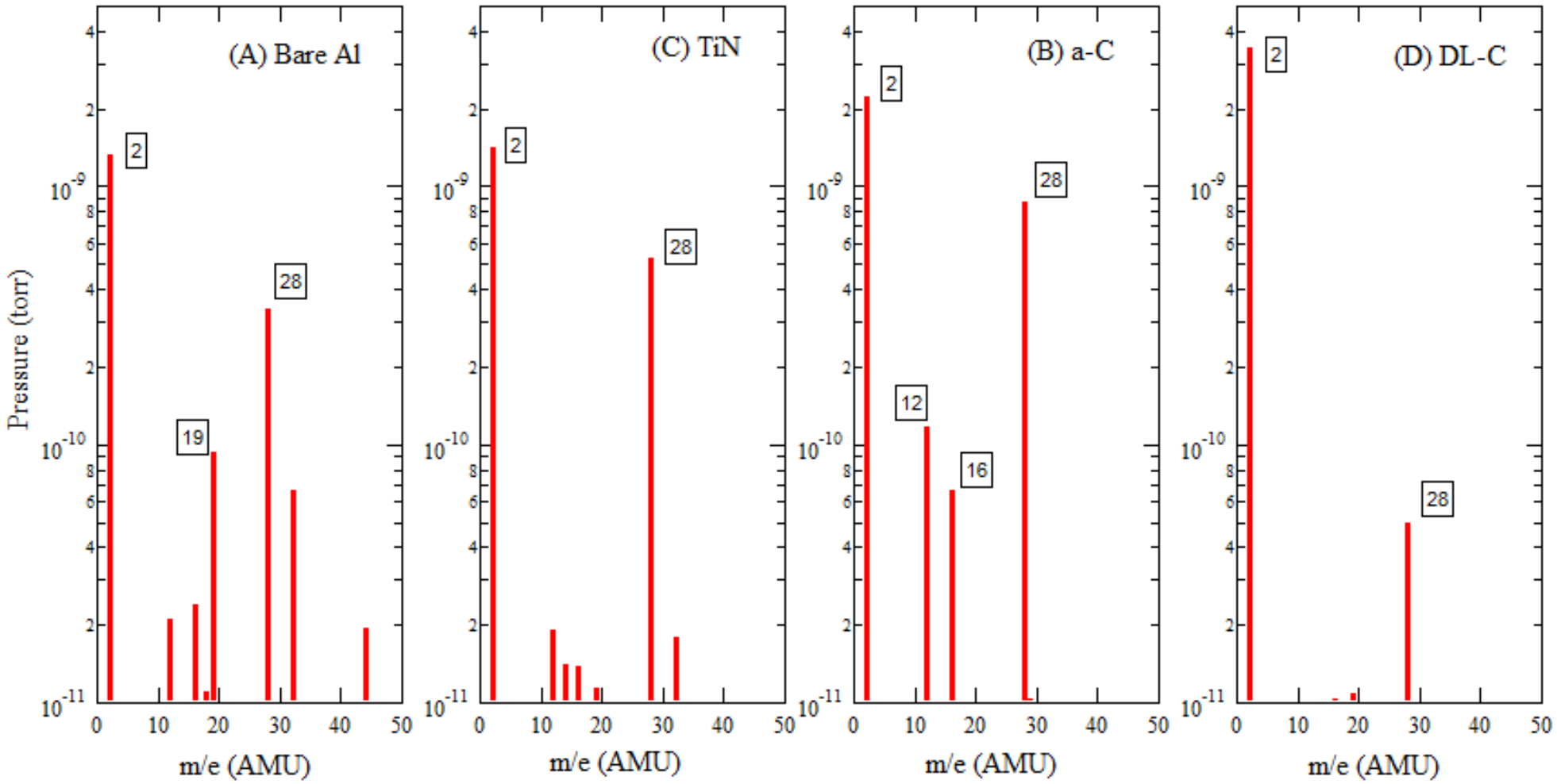


KEK EC Detector

Vacuum Performances of the Coatings

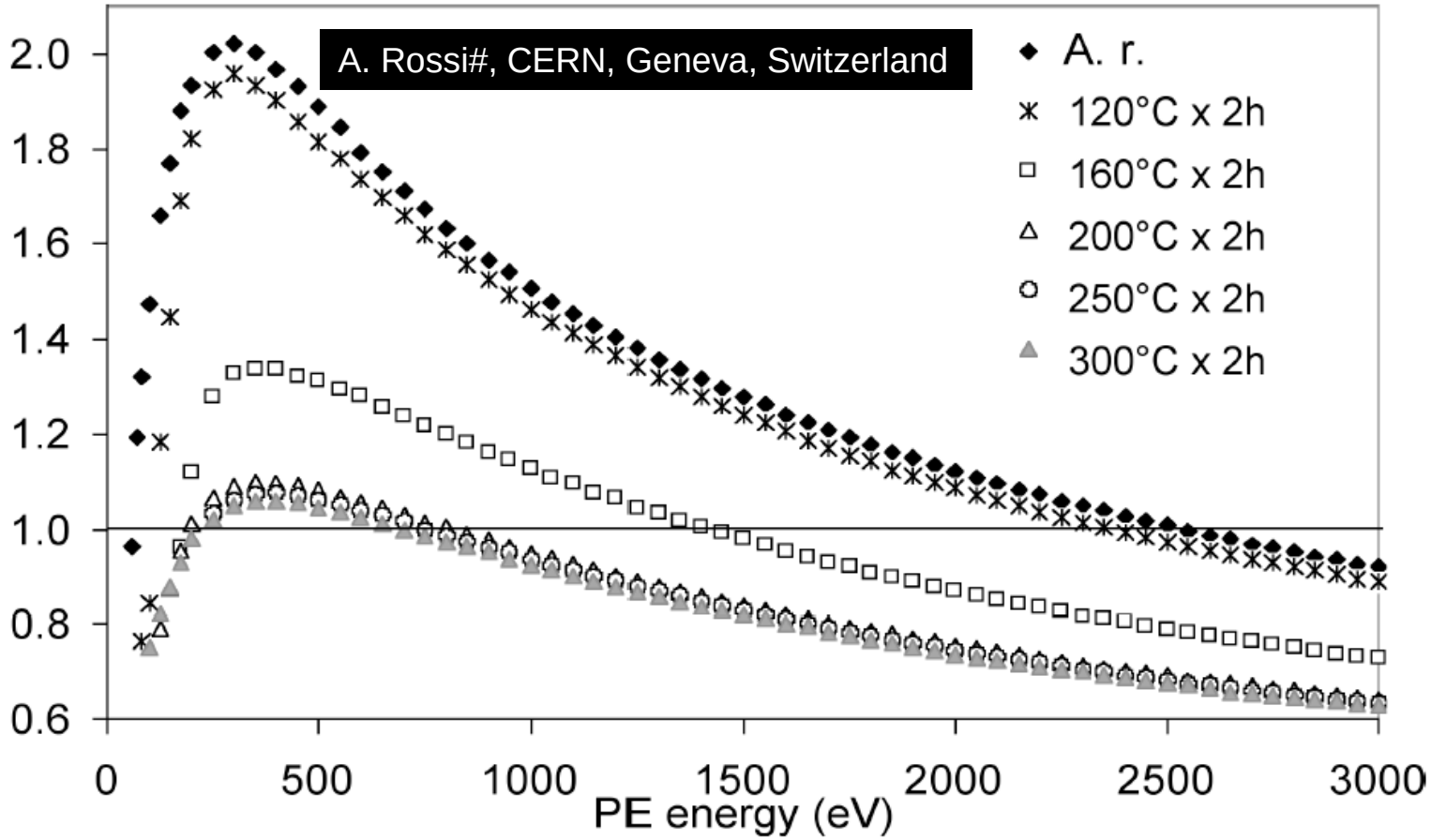


Vacuum Performances of the Coatings 2



RGA Spectra of Well-Conditioned Chambers with ~400 mA Stored Beam @ 5 GeV

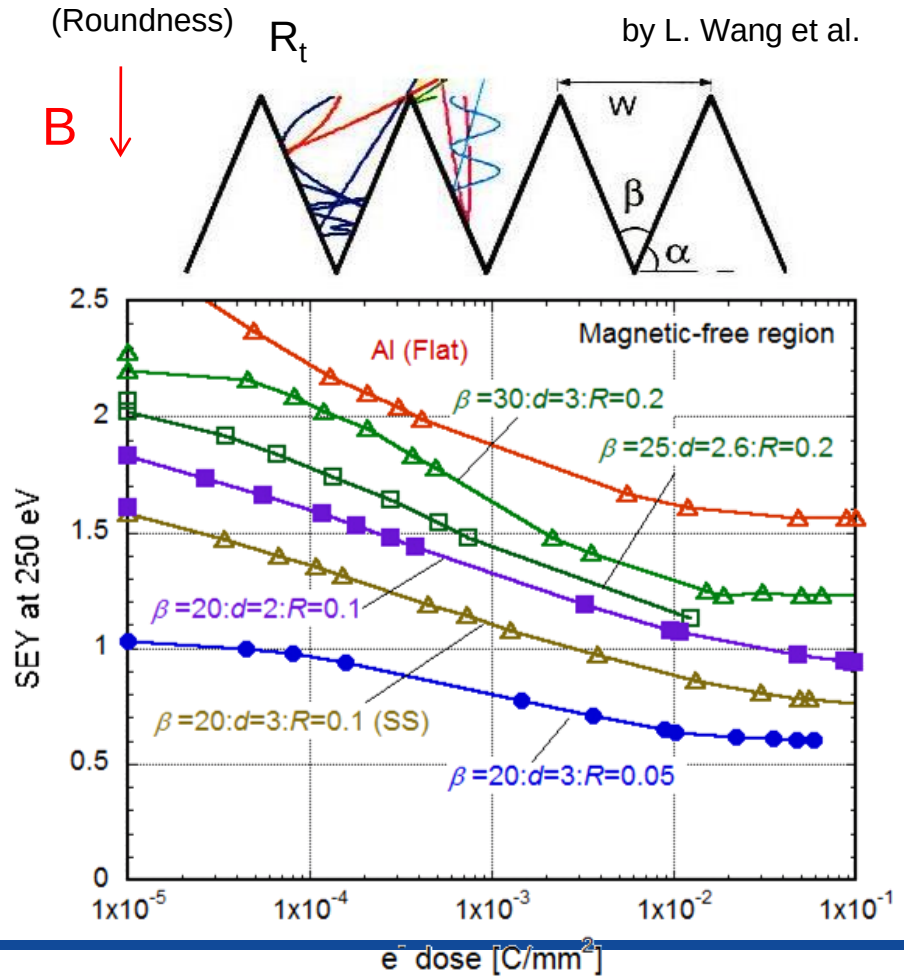
SEY Reduction Coating – NEG

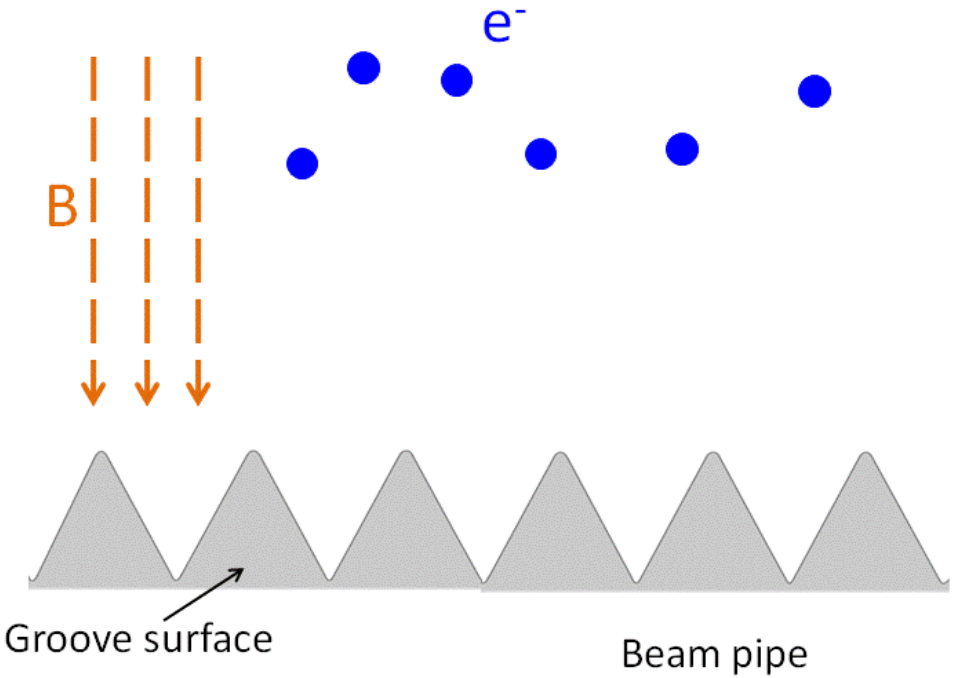


- NEG thin film also provide SEY reduction, with additional benefit of vacuum pumping. But it requires activation at elevated temperatures.
- NEG coatings have been applied at LHC worm beampipes and at RHIC.

Reduction of SEY by Grooved Walls

- **SEY is reduced by a structural effect.**
  - $\delta_{max} < 1$ is expected by simulations.
  - Available in magnet

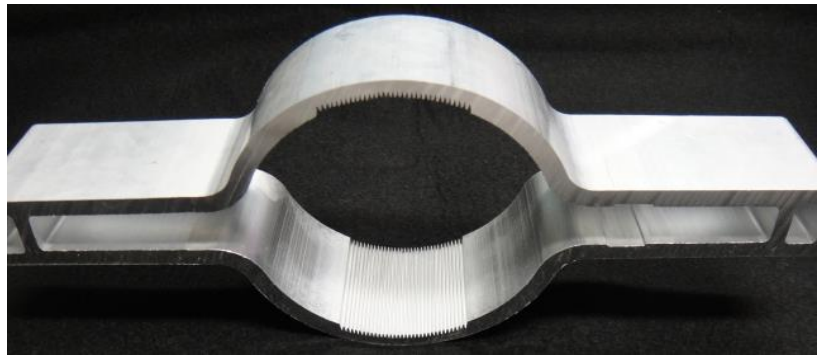


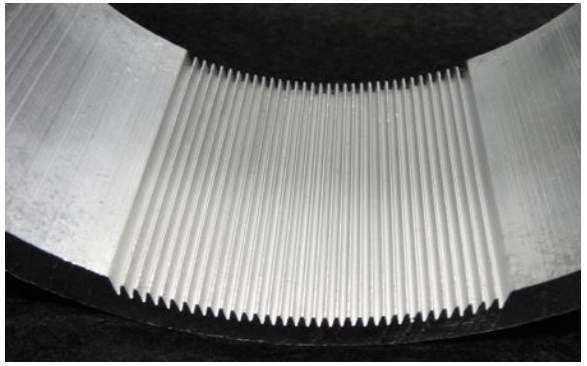


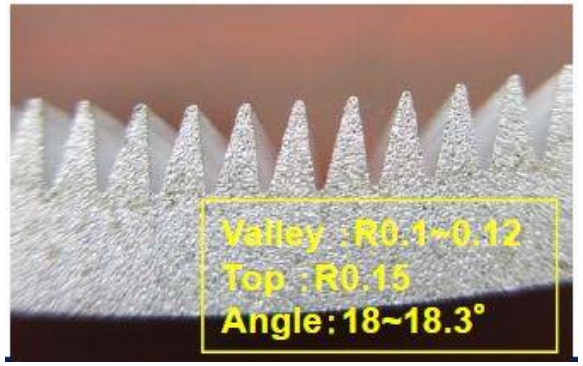
- *Groove with sharp edge and steep is better*
- *$\delta_{max} < 1$ was demonstrated in the laboratory using sample pieces, after sufficient electron bombardment.*

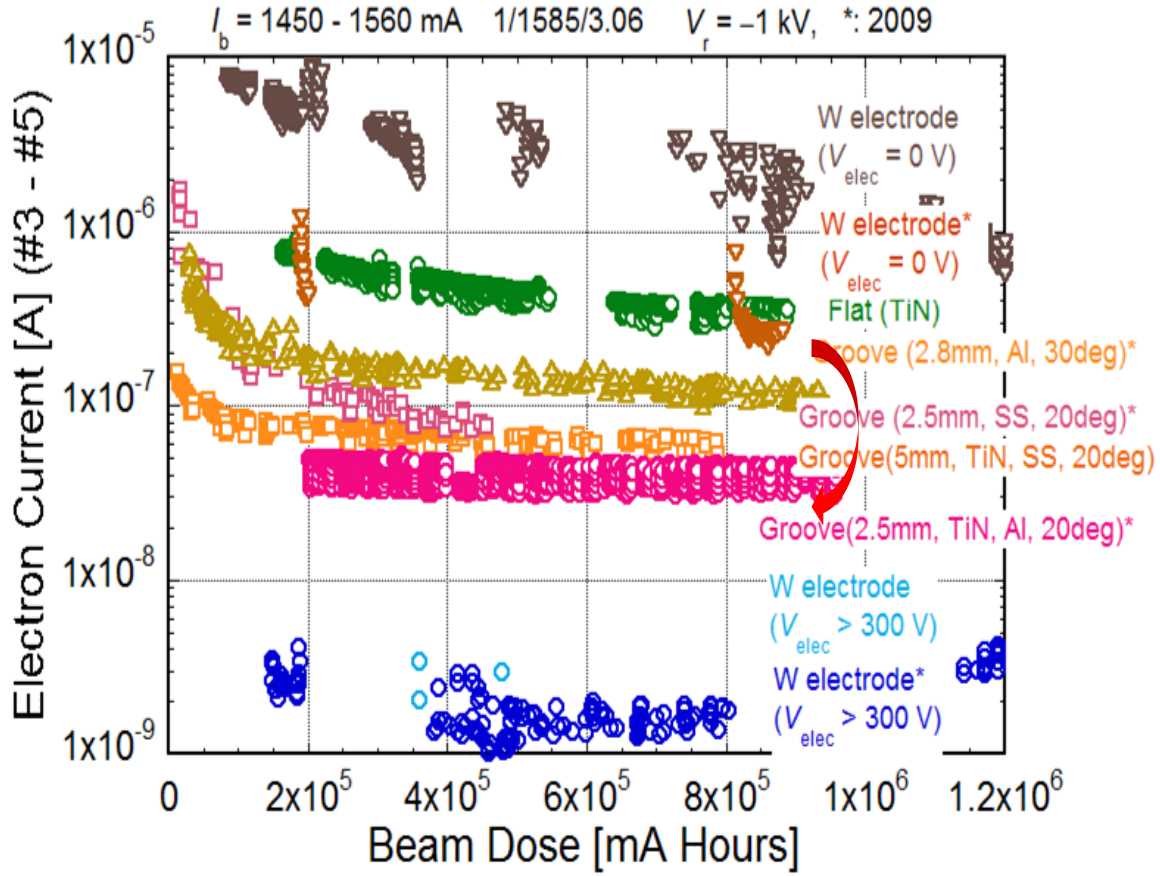
Reduction of SEY by Grooved Walls Cont.

- Experiment in KEKB in a wiggler magnet – Reduction by factors
- The effect was also demonstrated in CesrTA, Cornell university
- Forming during the extrusion is available for aluminum beam pipe
- TiN coating enhances the effect.



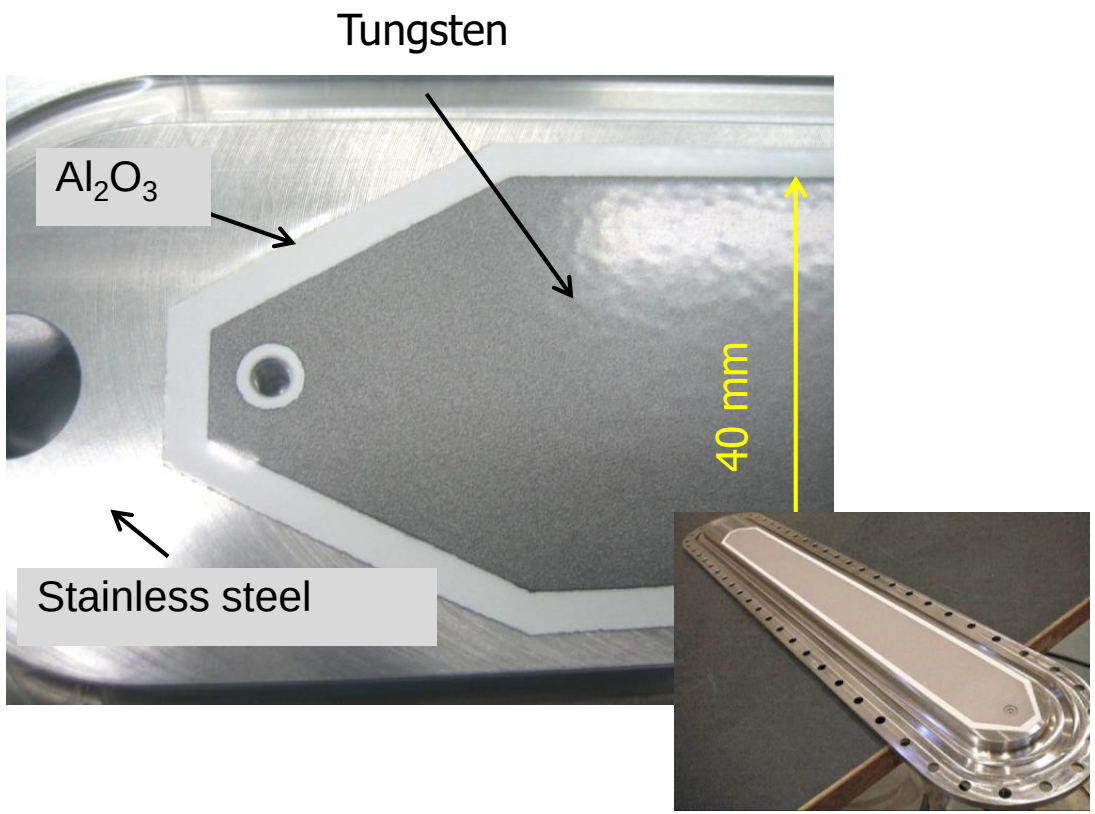


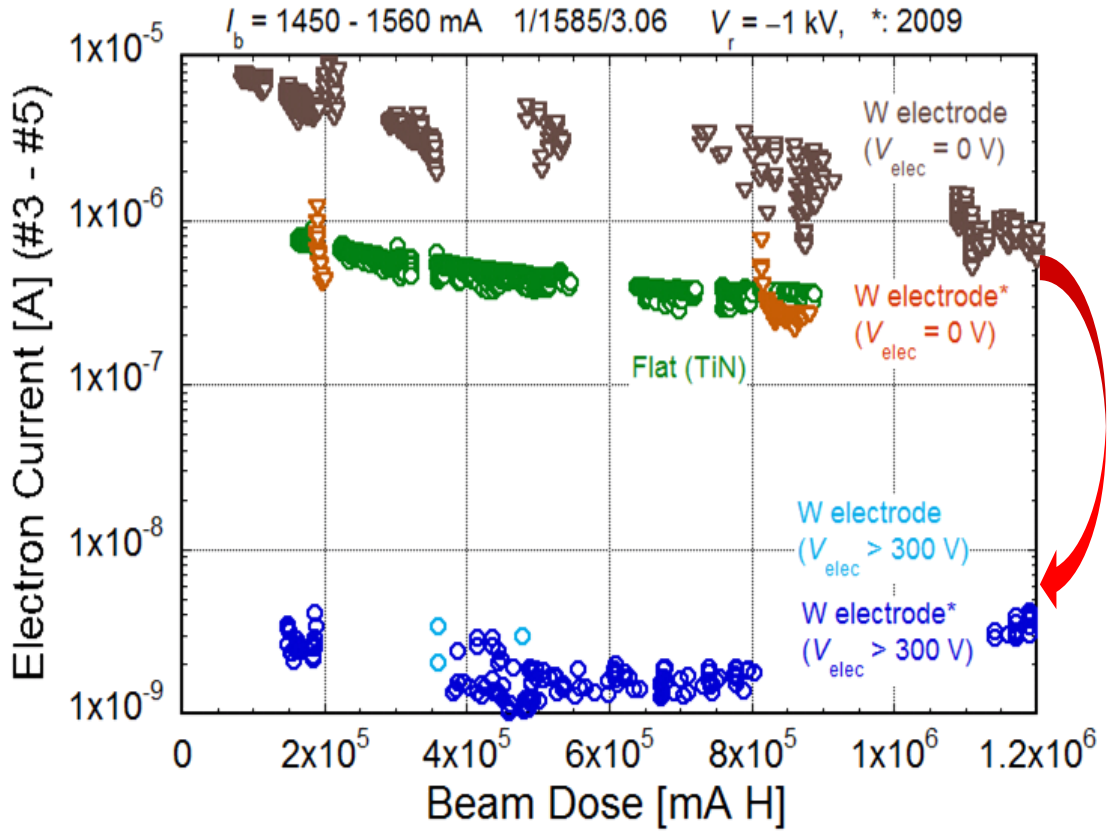




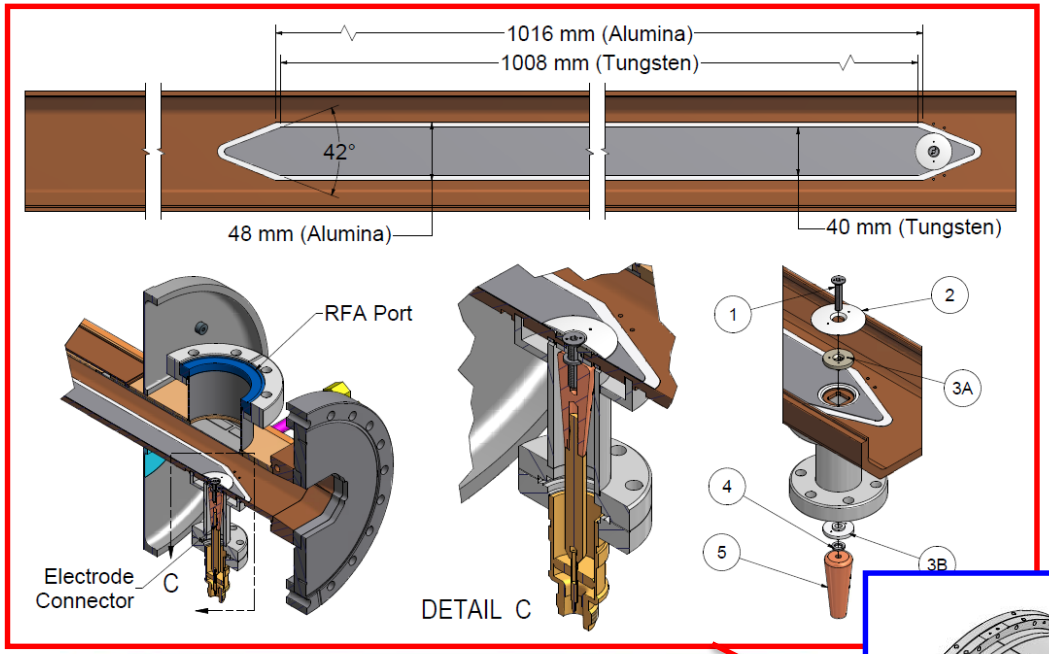
EC Clearing Electrode – KEK

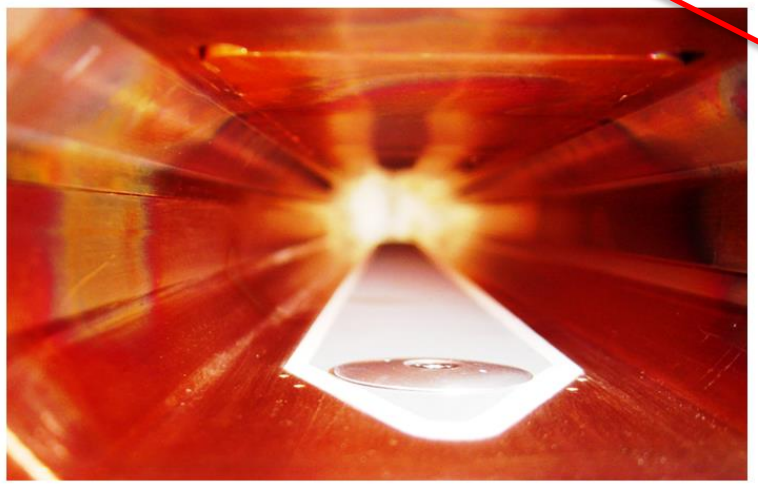
- Very thin electrode (0.2 mm Al_2O_3 + 0.1 mm tungsten) has been developed to achieve small impedance.
- Experiment in KEKB (Wiggler)– Reduction ratio: 1/100
- Also demonstrated in CesrTA, Cornell university, and SPS, CERN.

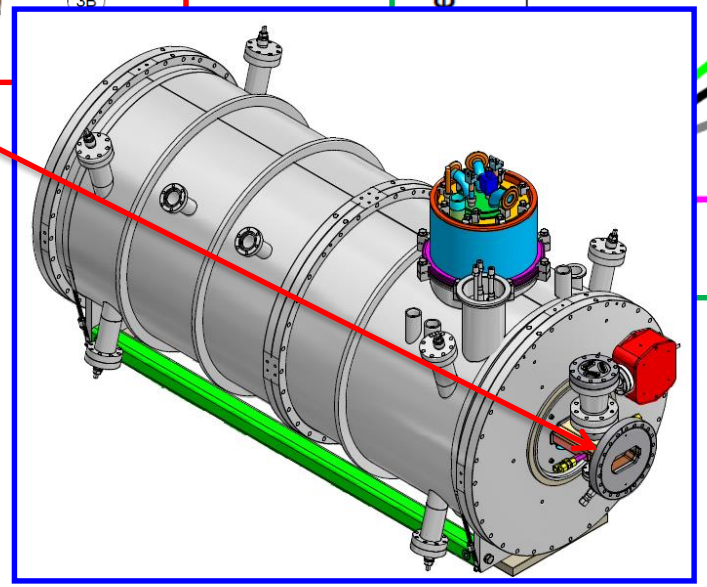


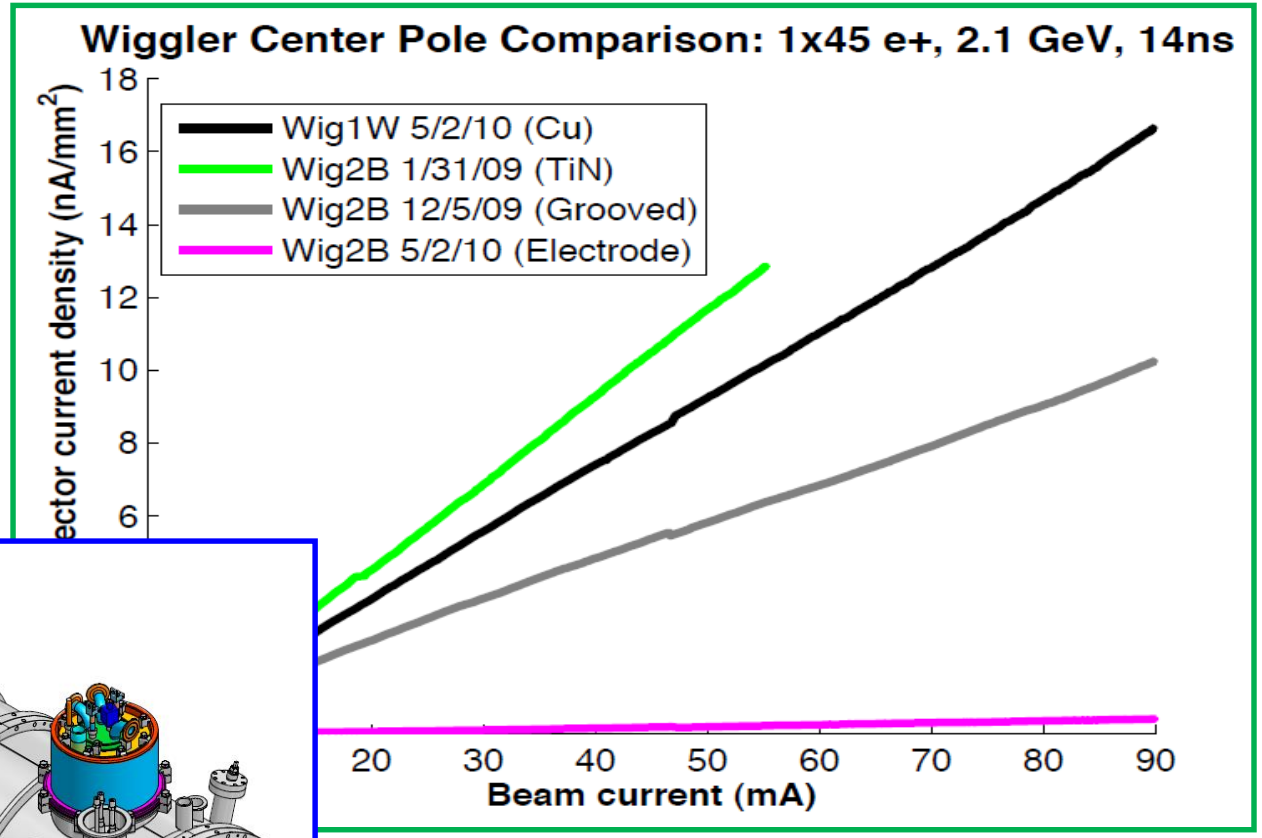


EC Clearing Electrode in CesrTA Wiggler









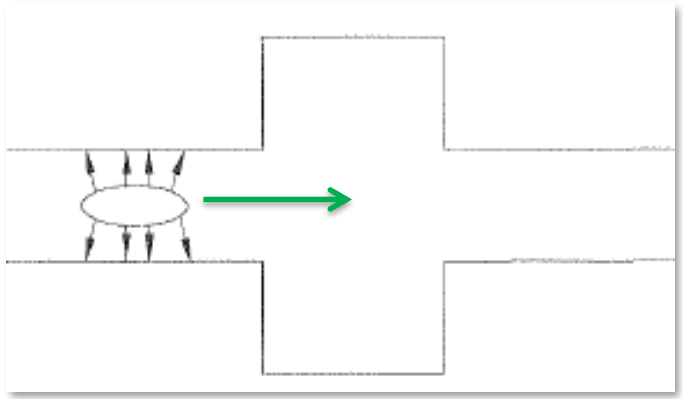
Wakefield and Impedance

Wakefield and Impedance

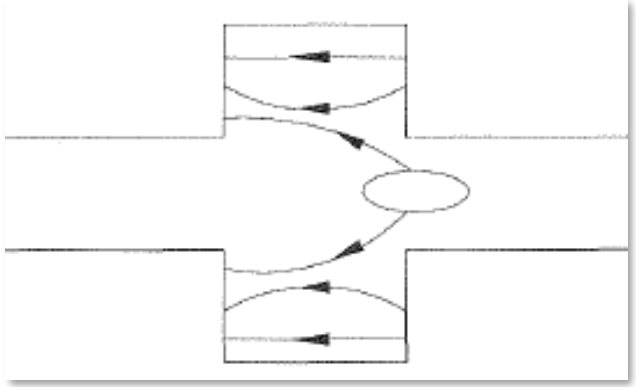
- Beam of relativistic charged particles excite electromagnetic field in the surrounding, which, in turn influence the beam behavior.
- The interaction is expressed in the form of wakefields (time-domain entity) or impedances (frequency-domain entity).
- In a perfectly smooth beampipe made of perfect conducting materials, there will be no excited wakefields, thus zero impedance. However, in practice, all vacuum chambers are made of resistive metals, with imperfect surfaces.
- Furthermore, there are necessary functional features on many vacuum chambers, such as pumping slots, SR masks, cavities, small gaps (for BPM buttons, etc.), aperture cross section changes, etc.
- The effect of the vacuum chamber impedances is to excite beam instabilities (longitudinal and/or transverse).

Wakefield and Impedance Cont.

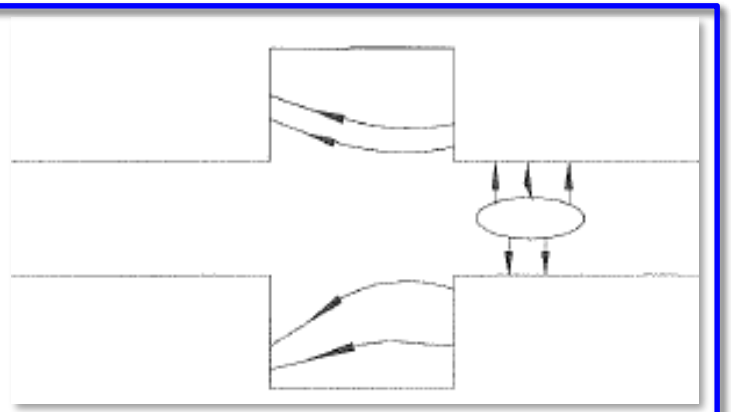
- In the design stage of an accelerator, a beam impedance budget is set based on the desired beam performances (beam current, beam emmittance, bunch length, etc.)
- Every vacuum components must be evaluated for their impedances. In majority geometries, there are no analytical formula for calculating the impedances. So the calculation heavily rely on numerical computer codes, such as MAFIA, Microwave Studio, etc.
- An example: wakefield excited in a pillbox.



(A) A point charge before encountering beam pipe discontinuity.



(B) The point charge couples energy into the cavity.



(C) coupled energy leaving a wakefield along the beam's trajectory.

Wakefield and Impedance Cont.

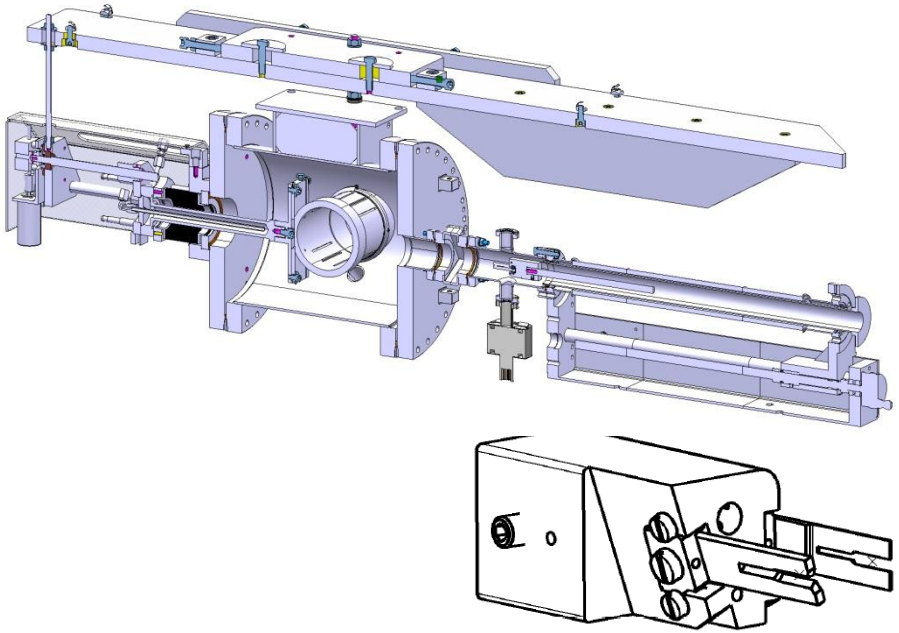
- In evaluation of beam impedance of a vacuum component, two factors must be considered.

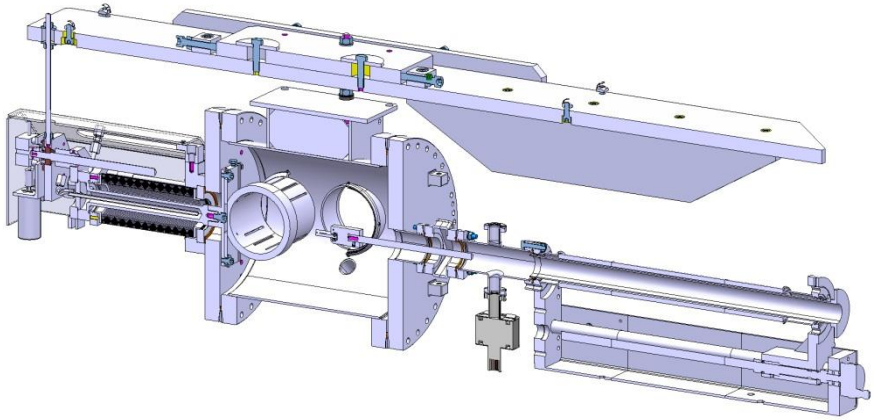
  → Impact to the stored beam, particularly if any high-Q trapped modes that can cause significant beam instability or emmittance dilution, etc.
  → The operational safety of the component, such as HOM heating, RF induced arcing, etc.

- Here are some 'rules' to follow:

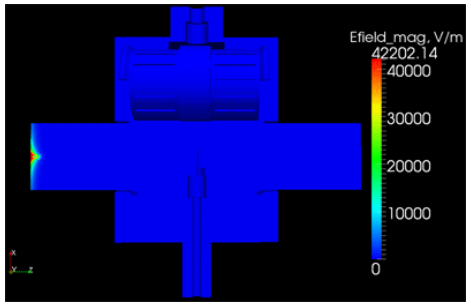
  1. Do not allow any sudden transitions between different beam pipe cross sections. A smooth transition or a RF shield must be designed and evaluated.
  2. Avoid non-conducting surfaces directly exposing to the stored beam. If necessary, an tapered transition (such as used in the EC clearing electrodes) must be provided.
  3. For devices with very small apertures, such as undulators, a smooth surface with high electric conductivity must be in place.
  4. Avoid cavities that may form high-Q resonators. If necessary, RF damping must be build in to remove wakefield excitation.

Wakefield Calculation – An Example

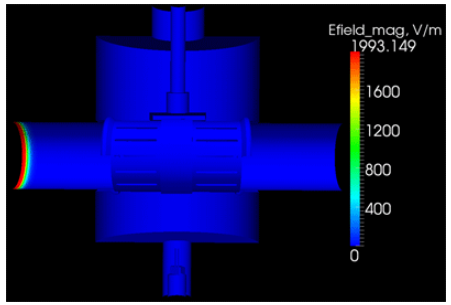




E-field magnitude of a single bunch pass in time domain (Gaussian bunch, length = [-4σ, 4σ], σ = 10mm)

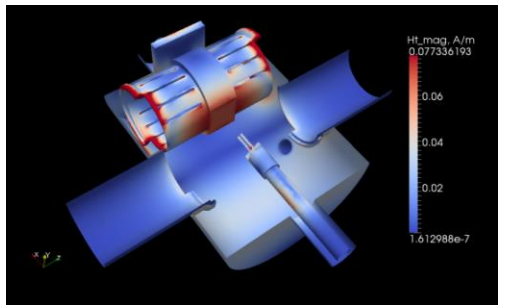


Total power loss for



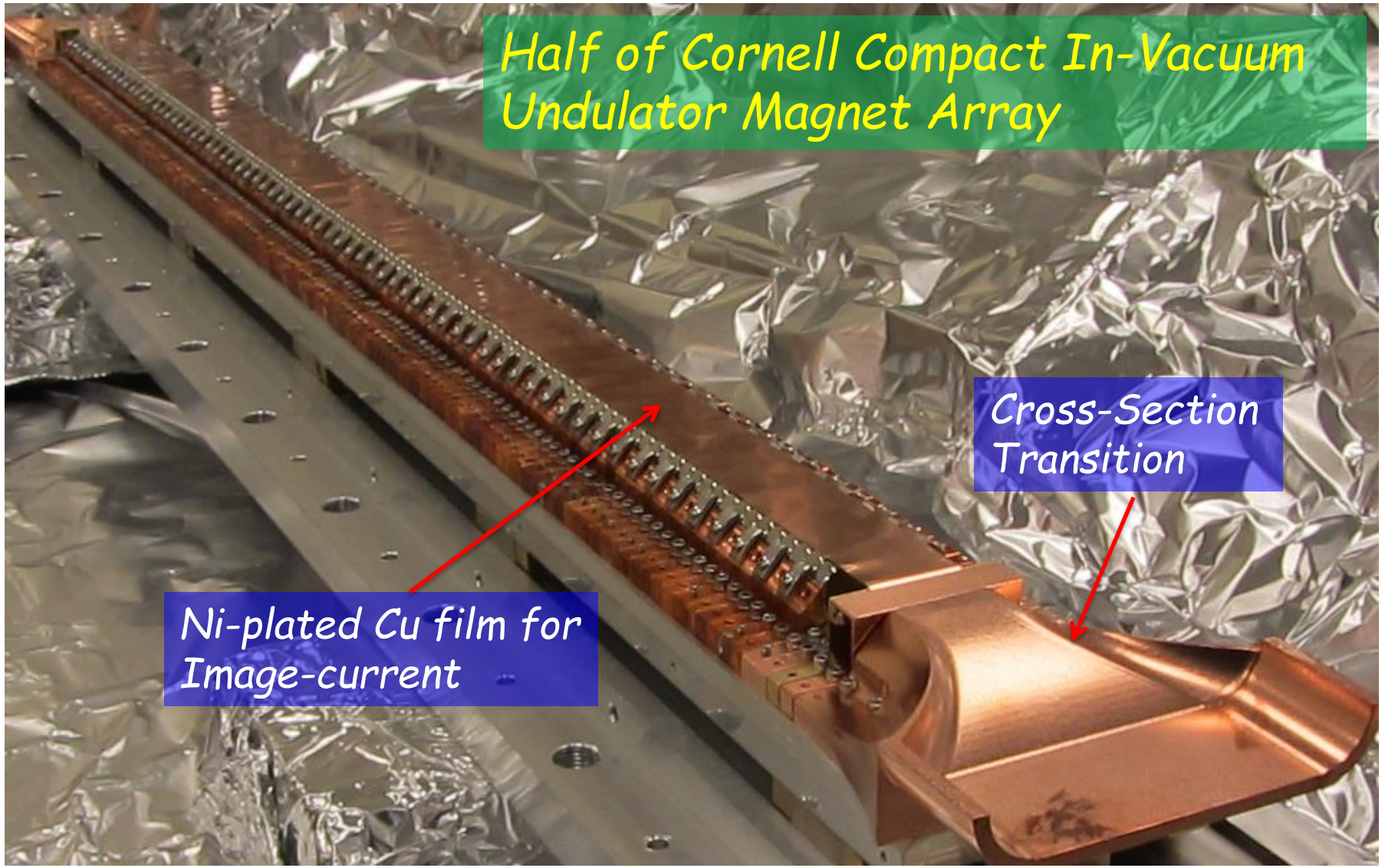
CHESS Operations = 35 W

H-field surface tang complex magnitude (Loss map) Mode F = 1.19 GHz, Q = 3309, P-loss = 0.075 W

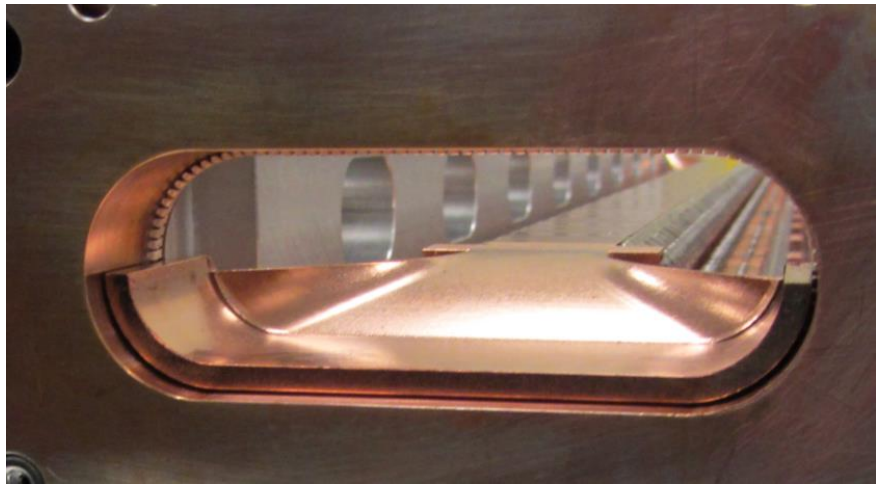


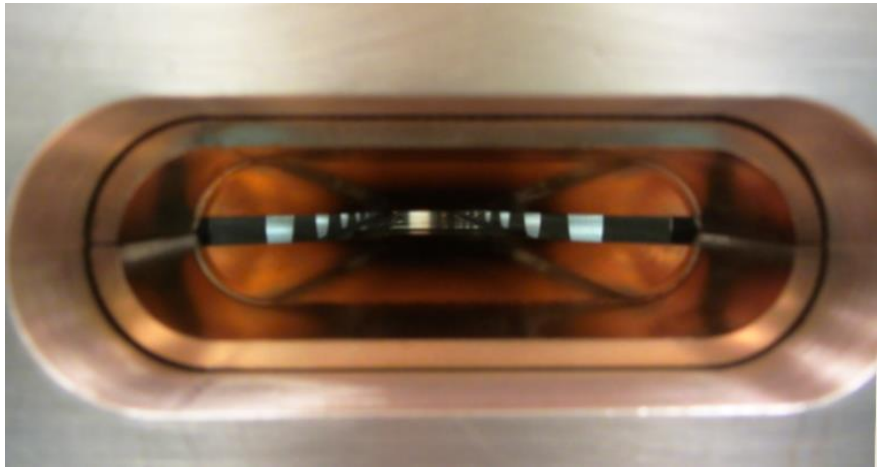
ODR Experiment: single10 mA bunch = 0.6 W

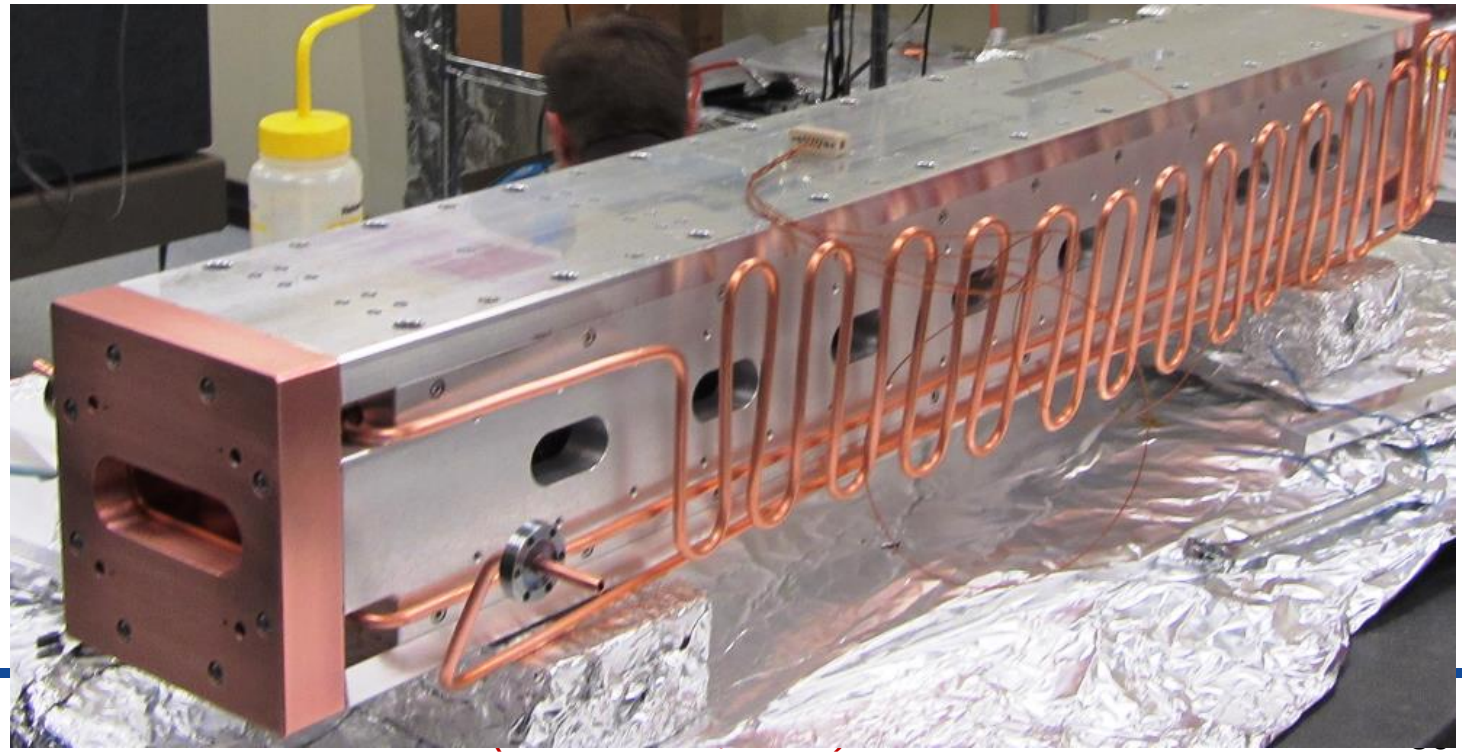
Minimize wakefield – An Example



Minimize wakefield – An Example Cont.







Minimize wakefield – An Example Cont.