Control of the Electron Cloud in Future High Intensity Accelerators

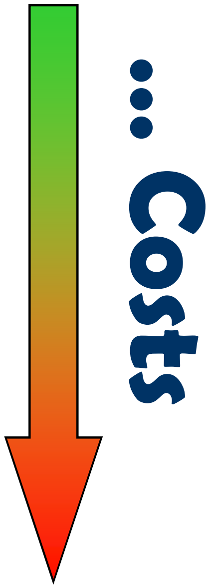
Mauro Pivi
SLAC

October 8 - Cornell University
ECLOUD10 Workshop

Thanks to M. Palmer, M. Furman, R. Kirby, K. Harkay, F. Zimmermann, G. Rumolo, C. Celata, L. Wang, T. Raubenheimer, R. Macek, R. Cimino, T. Demma, J. Fox, C. Rivetta, G. Dugan, Y. Suetsugu, K. Ohmi, S. Guiducci and to many colleagues sharing enthusiasm and work …

How to mitigate the electron cloud instability?

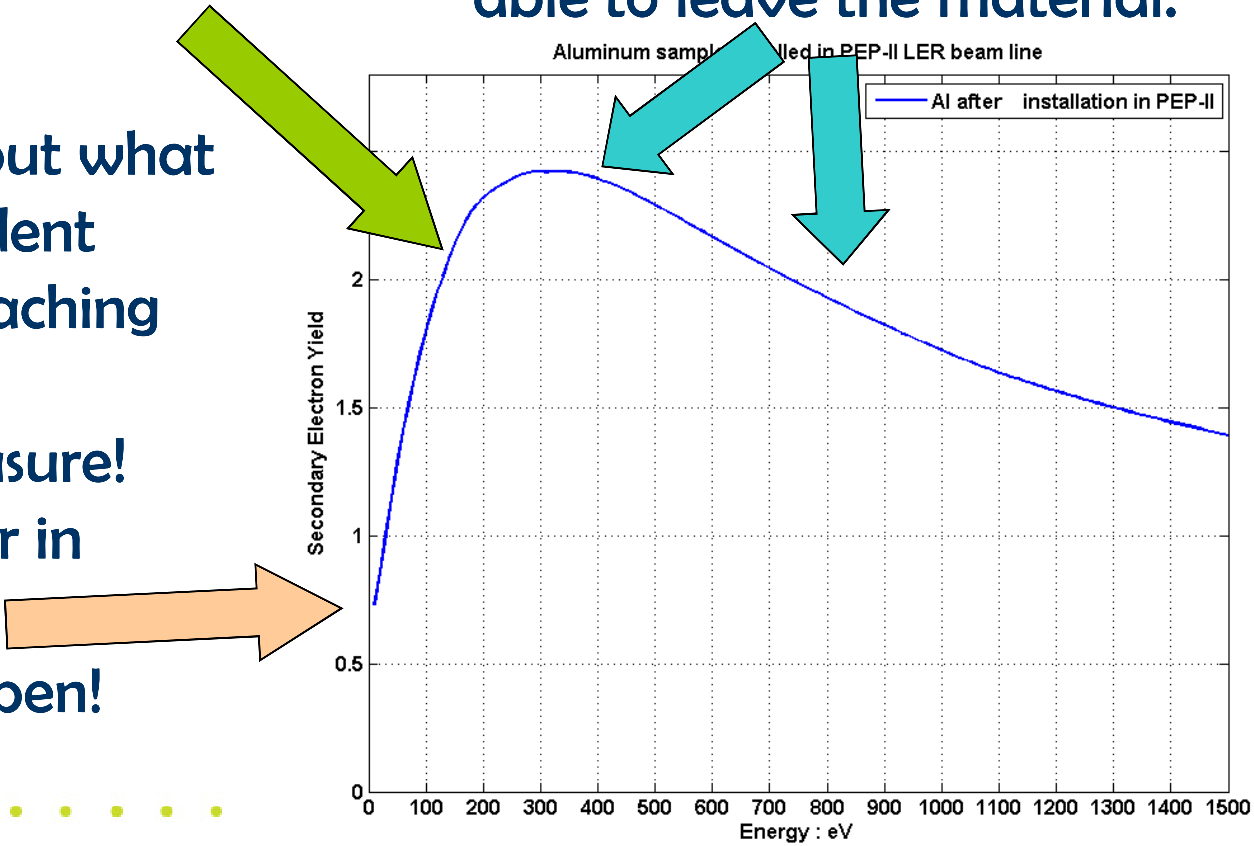
- Surface approach. Decrease the Secondary Electron Yield (SEY) by:
  - **surface coatings: TiN, NEGs, Carbon**
  - **Increasing surface roughness: Grooves**
- Perturb electron dynamics by:
  - **using biased "clearing electrodes"**
- Control beam instability growth by
  - **Feedback systems**
- Other … more exotic: freon, etching, radicals



Secondary electron yield

As the incident electron energy **increases**, the penetration depth increases and more secondary electrons are generated.

To a certain e- energy, secondaries generated **deeply** into the bulk are less likely to reach the surface and thus fewer and fewer electrons are able to leave the material.



Big debate about what happen at incident energies approaching → 0eV.

Difficult to measure!

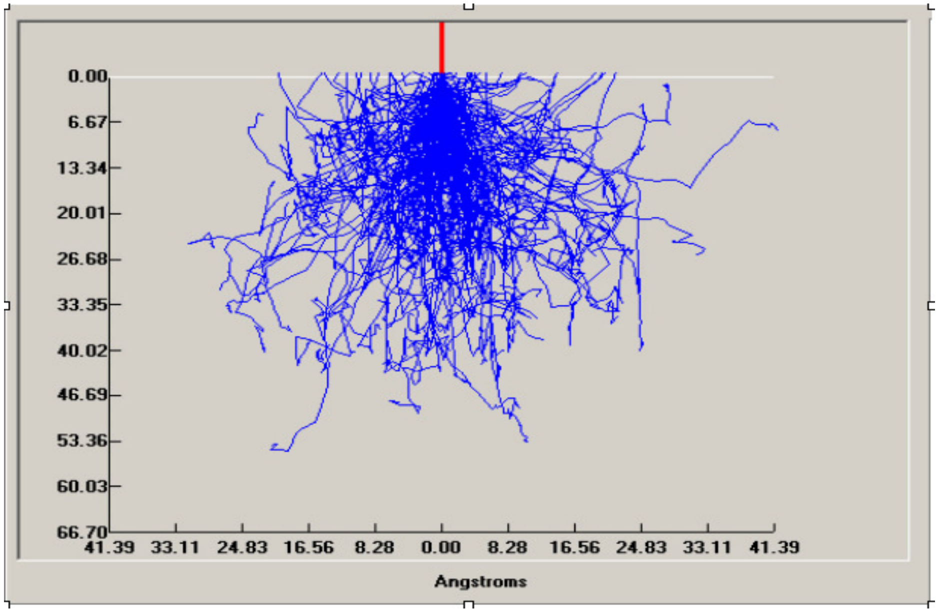
Is the SEY 0, 1 or in between?

Debate is still open! [Cimino *et al.*]

Secondary electron yield

Simulated 500 eV electron incident on a TiN surface.

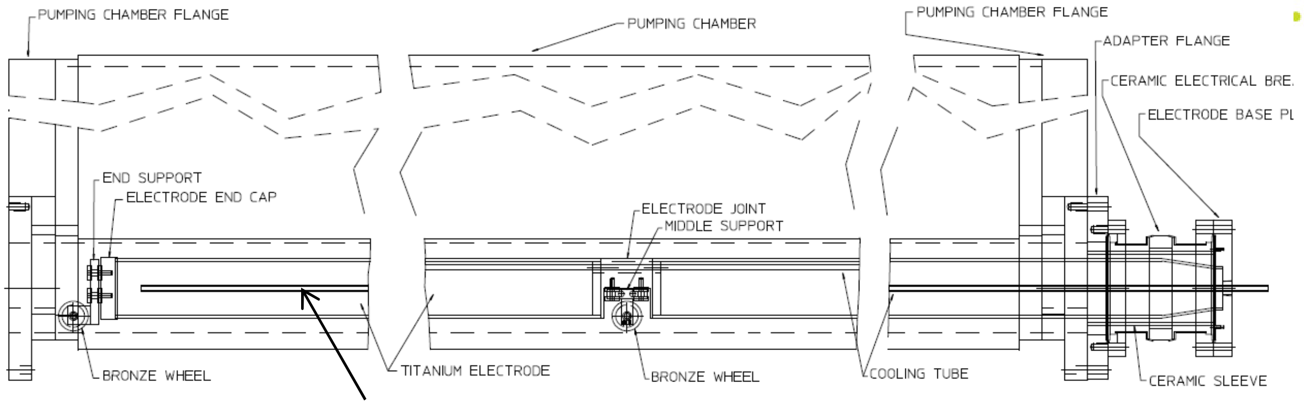
e- beam incident direction is orthogonal to the surface.



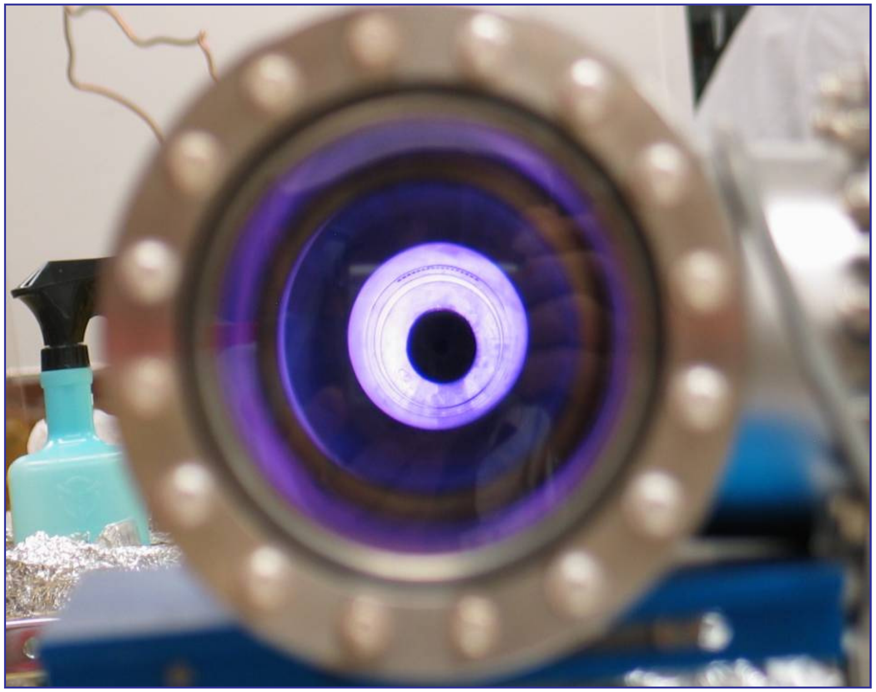
The shower of **secondaries** is shown. Dimensions are in **Angstroms**: Meaning we need just **few nanometers** of coatings! Typical TiN coating thickness is 100nm (1000 Å) which should be plenty …

Coatings by sputtering process

- coating must be **thin** because the thermal expansion of TiN is 1/3 of Al



Ti cathode

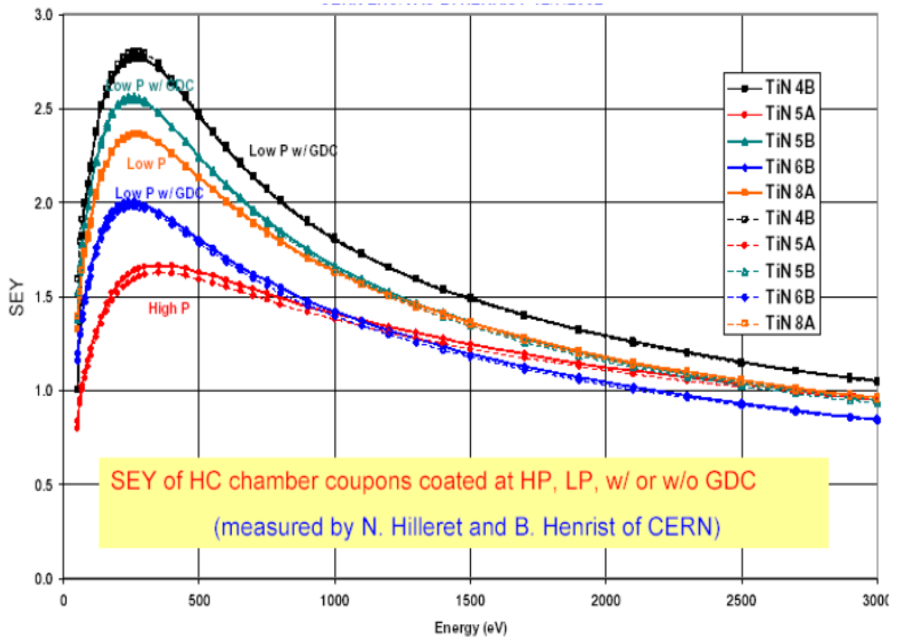


thick coating creates **high stress** between TiN and Al

- Should be thick enough to resist "**20 years** of ion bombardment"
- **50 nm** TiN film has been calculated to withstand such hydrogen-ion bombardment.

TiN coating

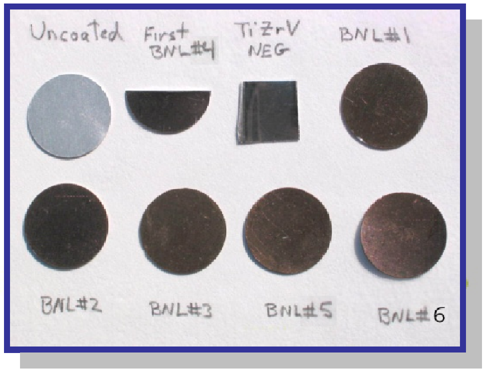
- Coatings are assumed to reduced the secondary emission yield (SEY) on the surface. Contrary to believes, TiN doesn't have a low secondary electron yield (SEY) … at least at the start!



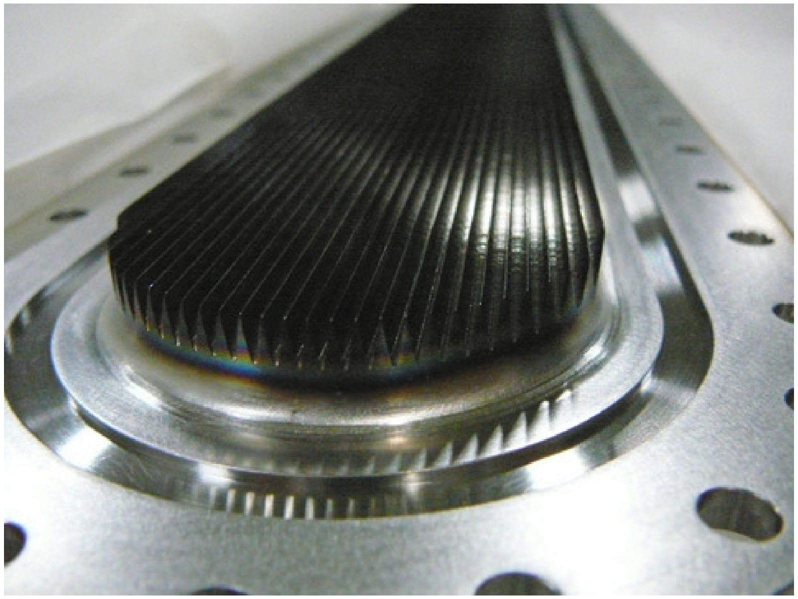
TiN samples produced at BNL, measured at CERN. A correlation between coating pressure and SEY is shown.

"as-received" SEY is as high as 2.7 (!) see side plot, but typically is ~1.7

The "conditioning" effect brings effectively its SEY low



TiN coatings



Our TiN samples
should look like this!

But they look like this …

it's fine … SEY matters!

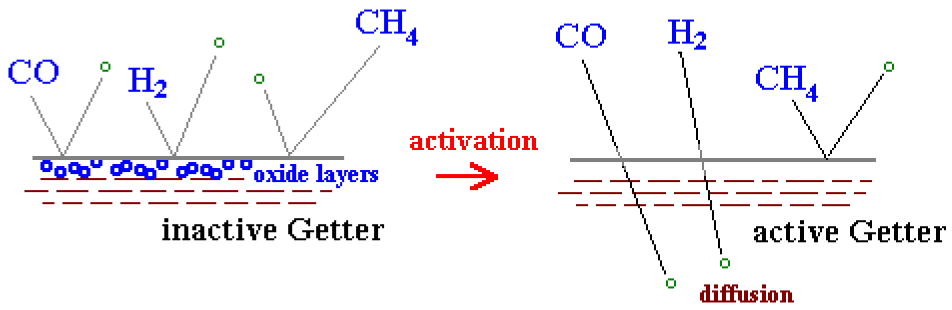
NEG coating

- TiZrV thin film non-evaporable getter (NEG) coating:

  acts as a getter pump able to reduce the pressure to less than 10^{-9} Torr. NEG coating can be applied to spaces that are narrow and hard to pump out, which makes it very popular in particle accelerators.
- It requires “activation” for pumping: >2 hours at ~200ºC
- During activation the SEY drops! That’s where we come in …
- After saturation, the NEG should be re-activated: comfortable lifetime is 20 cycles.

TiZrV NEG thin film coating

Non Evaporable Getter pump

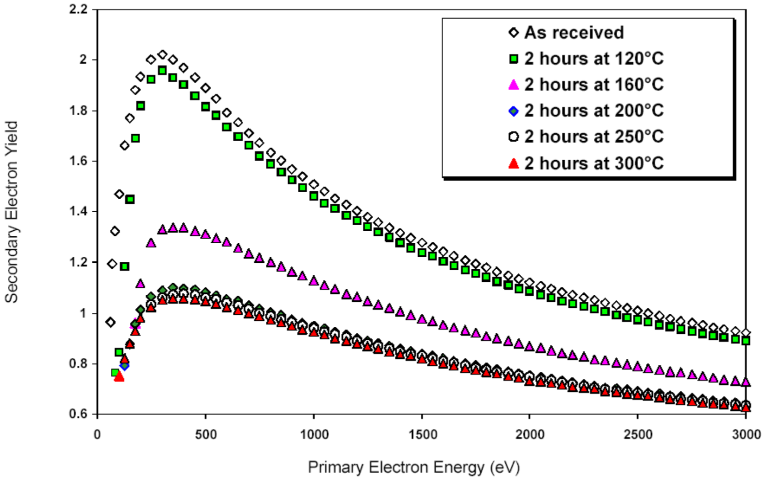


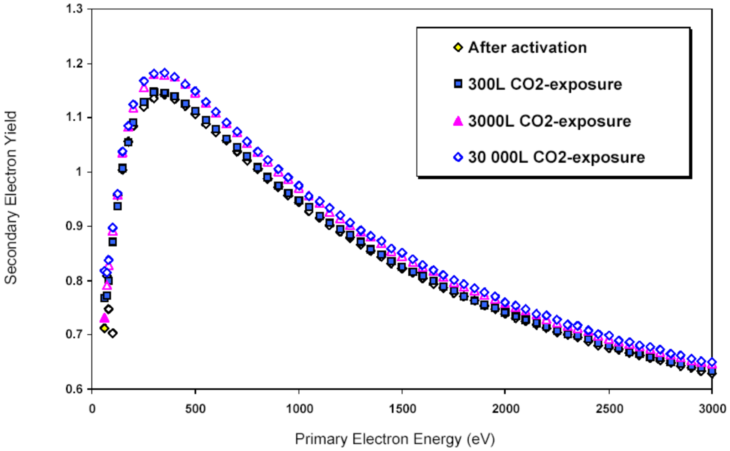
Commercial NEG:

St 101 activ. T~ 750°C for 30’ (Zr 84%, Al 16%)
St 707 activ. T~ 400°C for 1 h (Zr 70%, V 24.6%, Fe 5.4%)

TiZrV (CERN) activ. T~ 180°C

not pumping noble gases and CH4, Ar





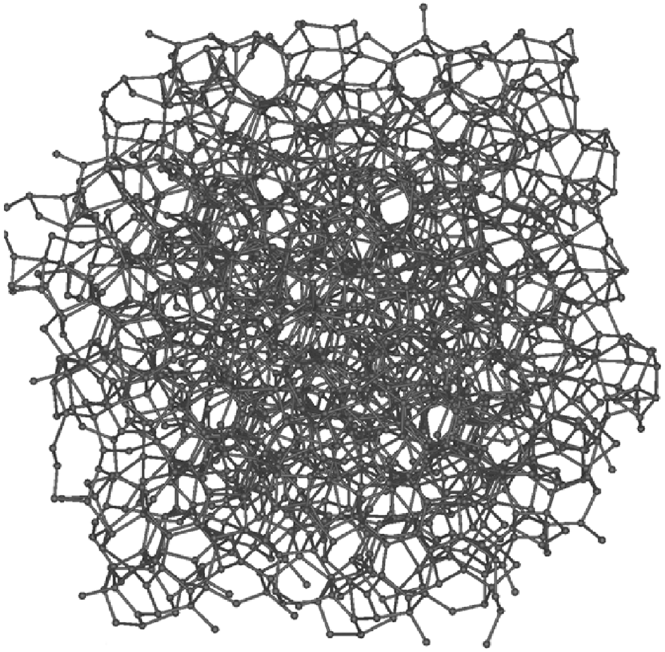
Up: SEY of TiZrV NEG on Cu (Sheuerlein et. al. CERN) and activation.

Down: Influence of CO2–exposure (in Langmuir 1L=1.33 10.6mbar·1sec) on SEY of activated NEG.

amorphous-Carbon coating

Generally, Carbon has SEY ~ 1 even without activation nor conditioning!

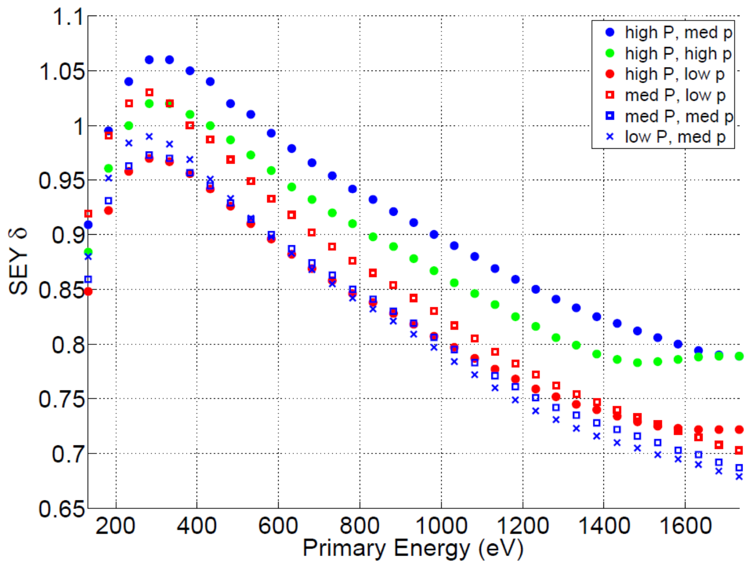
Amorphous carbon or free, reactive carbon, is an allotrope of carbon that does not have any crystalline structure. Air venting also shows no performance deterioration.



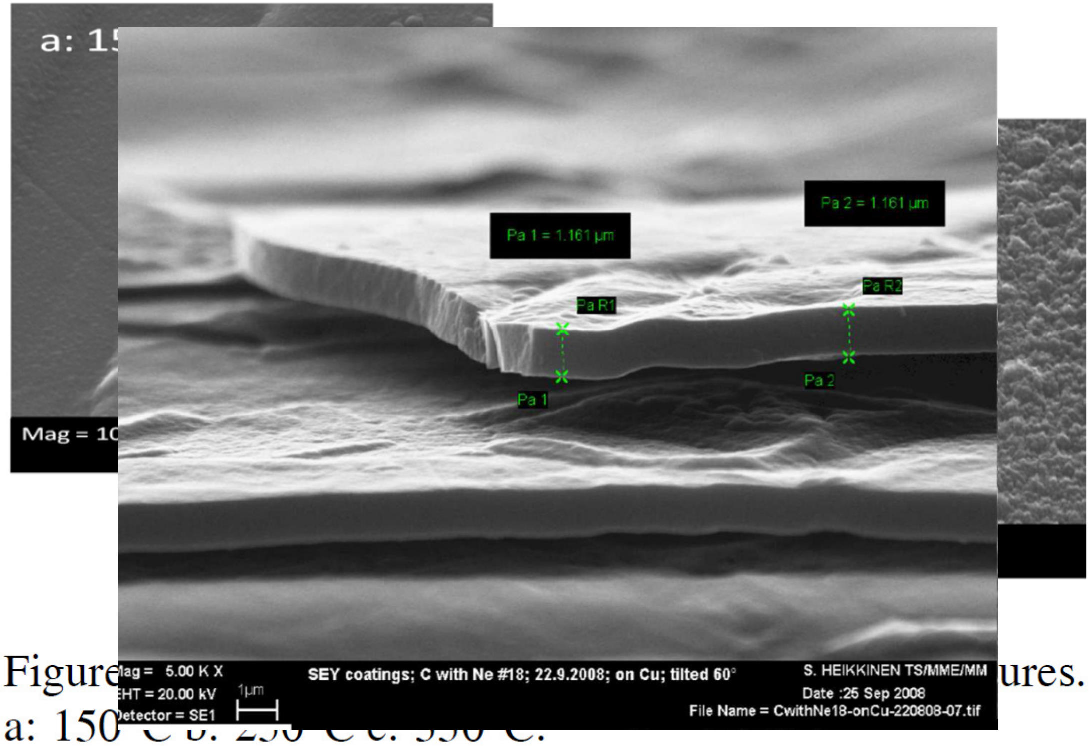
Though, Carbon may be released by high SR power (especially in lepton machines, downstream of bend/wigglers) with formation of carbon oxides in the vacuum … need to keep an eye on the Residual Gas Analysers!

amorphous-Carbon coating

CERN objective: coating the whole SPS ring (8 Km, 1000 vacuum chambers) still ongoing.



C. Yin Vallgren *et al.* CERN at IPAC10

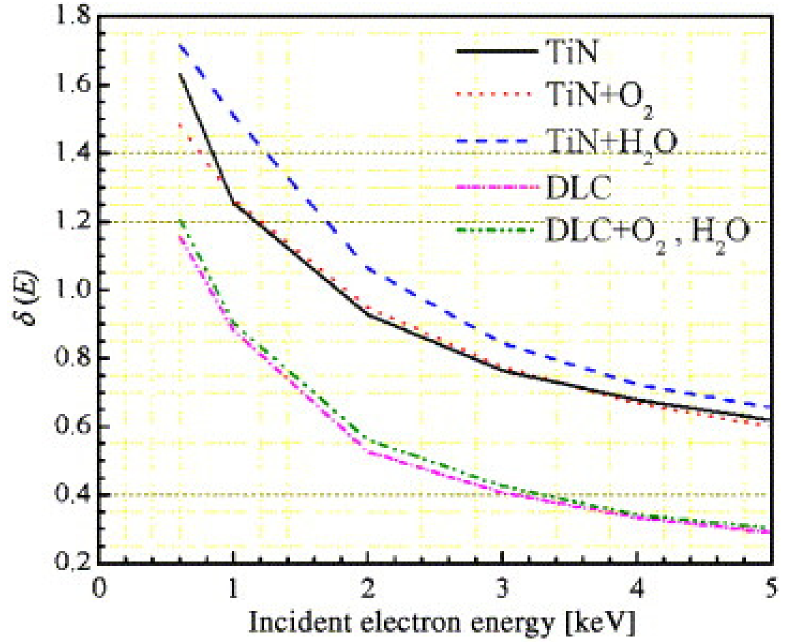


Amorphous Carbon: DC magnetron sputtering. SEM images, thickness: 50 to 1500 nm. **Variation of roughness with coating temperatures.**

Diamond like Carbon coating

Diamond-like carbon (DLC) exists in seven different forms[1] of amorphous carbon materials that display some of the unique properties of diamond: hardness, wear resistance, and slickness.

Studies ongoing



K. Yamamoto et al. Vacuum 81 (2007) 788–792

Conditioning effect

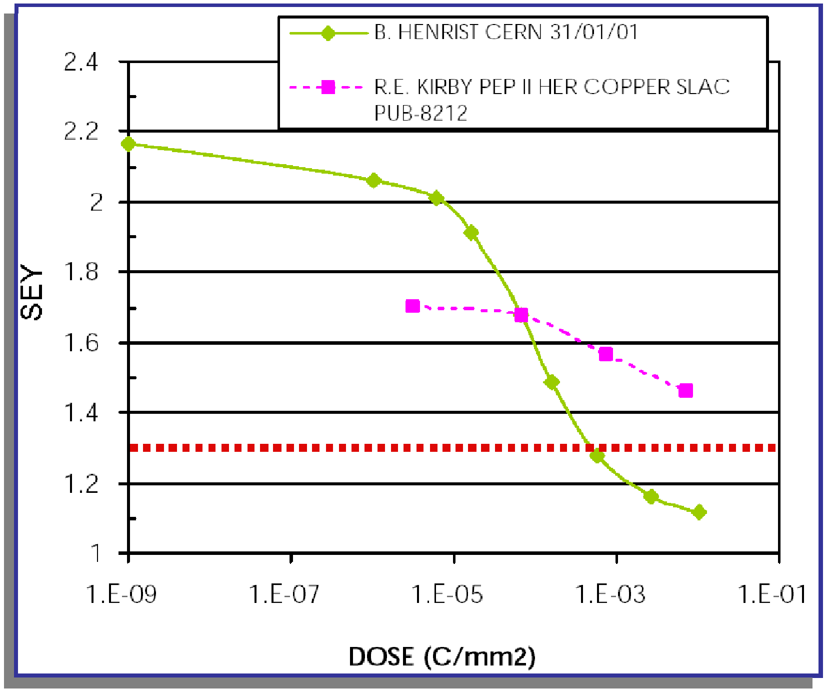
What is conditioning?

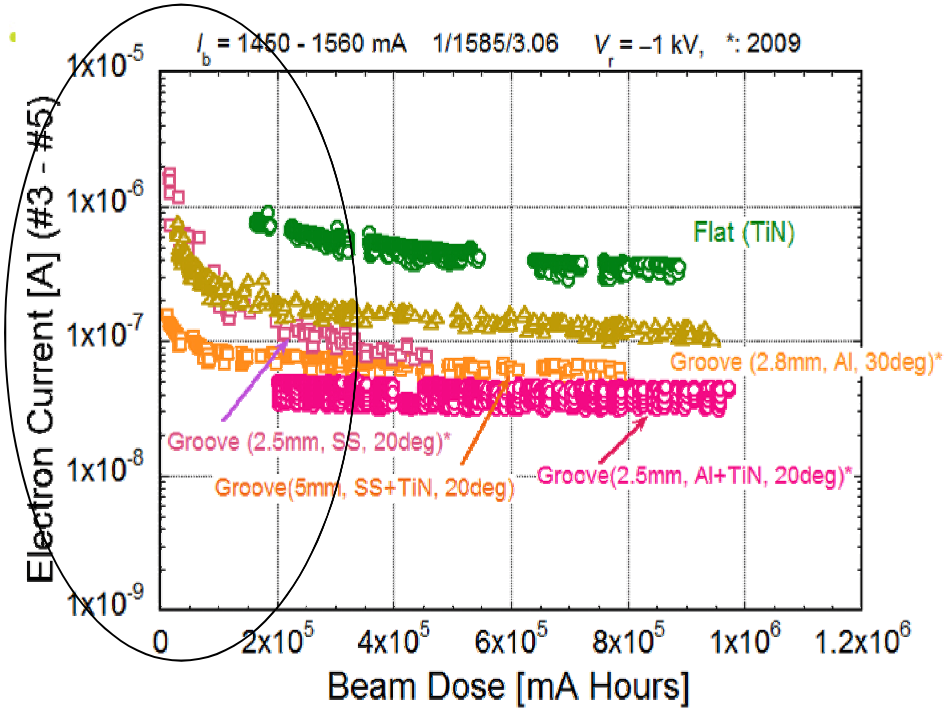
- Conditioning or “scrubbing” is the bombardment of the surface with **electrons, photons or ions** followed by a **decrease** of the secondary electron yield. The three species have different effects on the surface.

- Attention: if the surface is re-vented to air the effect of conditioning is partially or **totally lost** due to oxides and water.

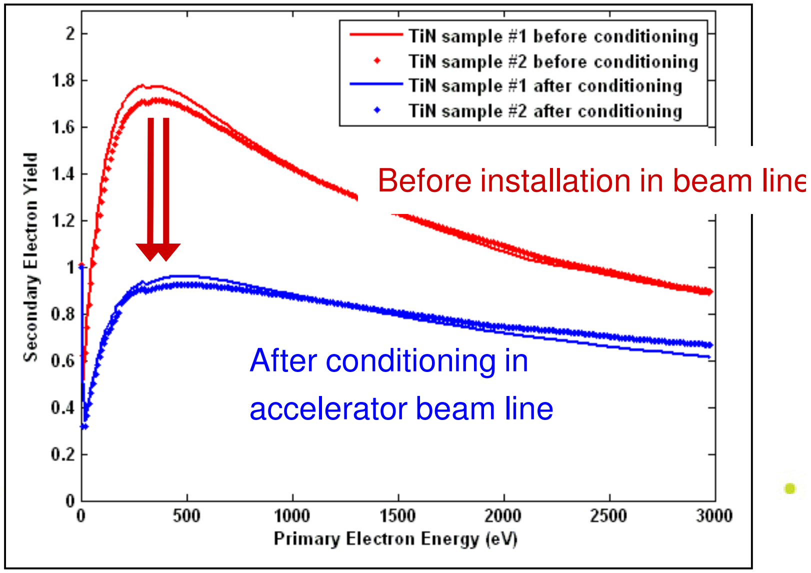
Conditioning in the lab and in beam line

in the lab with e- beam





in beam lines



Conditioning

- conditioning is not just “cleaning=removing gas from” the surface! (at least **not only**)
- With electron/photon/ion beams, Carbon oxides may **break down** and **Carbon re-deposit** on the surface.

  Carbon has SEY near 1 … et voila’

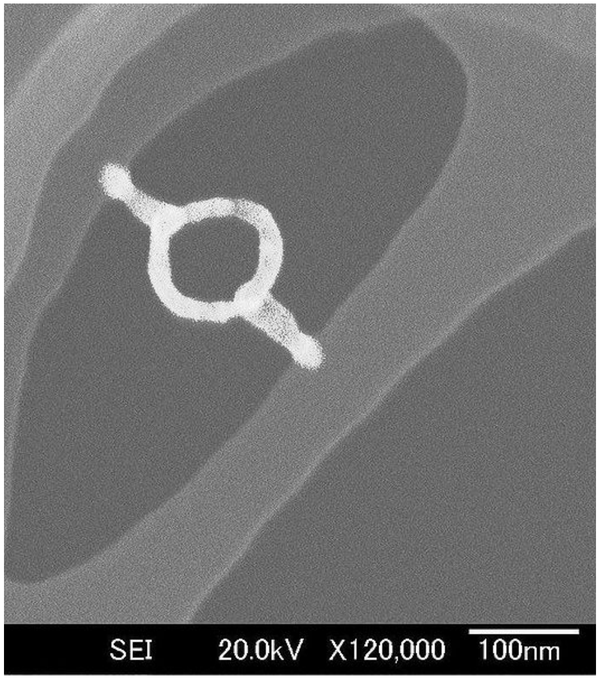
- Not end-of-story though! we saw Carbon **growing or very much decreasing** on surfaces depending on accelerator environment!!

  In either case, **SEY decreases** …

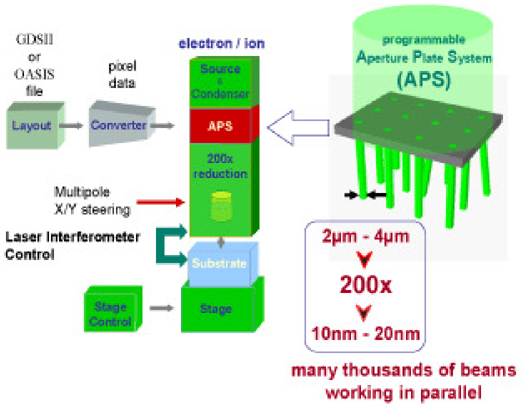
Nanoworld: Electron/Ion Beam-Induced Deposition

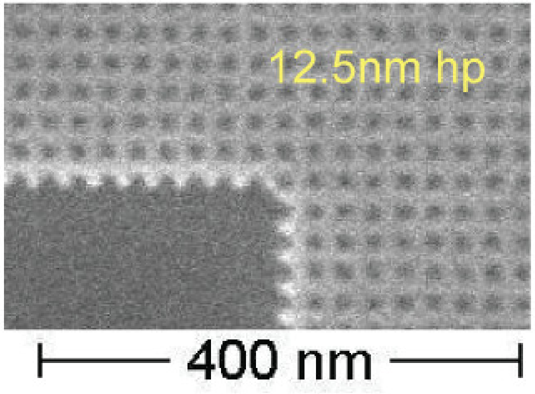
Industrial process of decomposing gaseous molecules by electron/ion beams leading to deposition of non-volatile fragments onto a nearby substrate.

High spatial accuracy (nanometer) and 3-D structures!



Letter Φ deposited from $W(CO)_6$ by EBID!

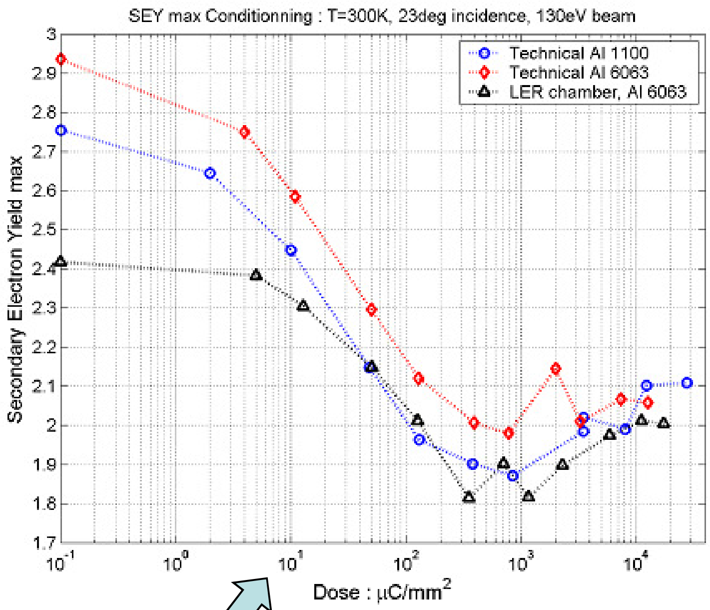




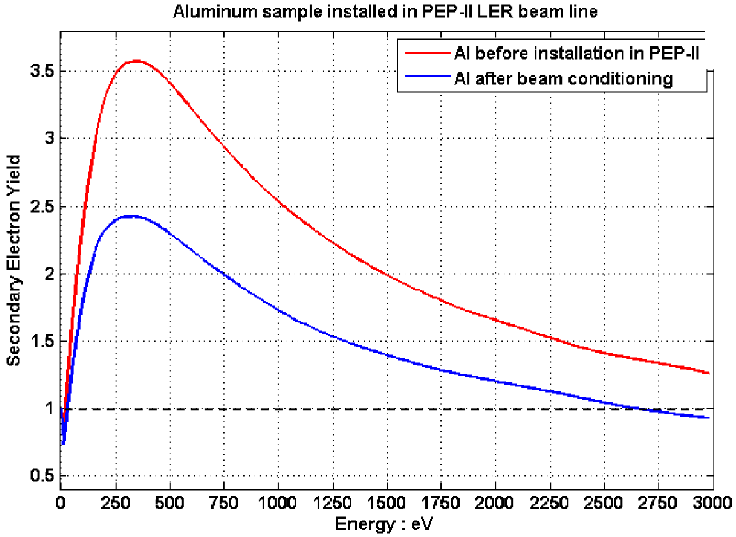
Nano-patterning

Conditioning aluminum …

Electron or photon conditioning seems not effective to lowering the SEY of Aluminum, which stays high. Measurements at SLAC and CERN agree well.



3 months in an accelerator beam line with e- and lots of photons around. SEY > 2!



Dose of electrons on Al in a lab controlled experiment. SEY~1.8 at best.

Most of **CesrTA and Dafne** are made of Aluminum chambers!

Roughness

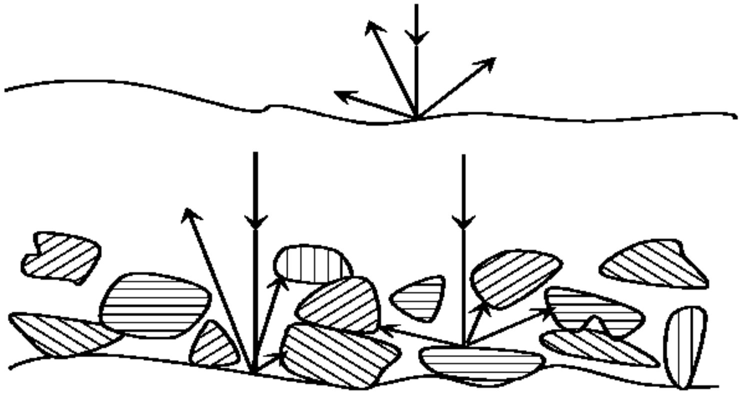
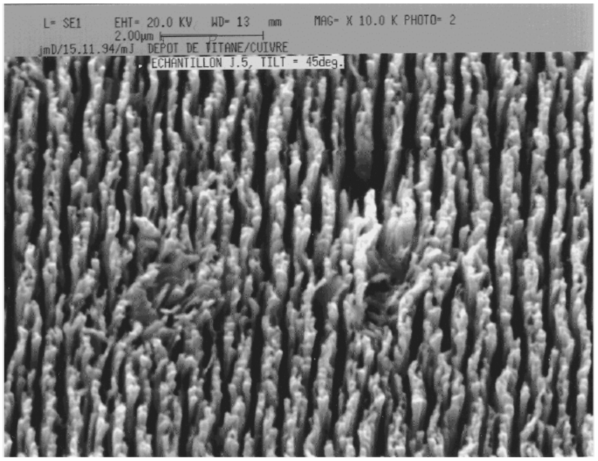


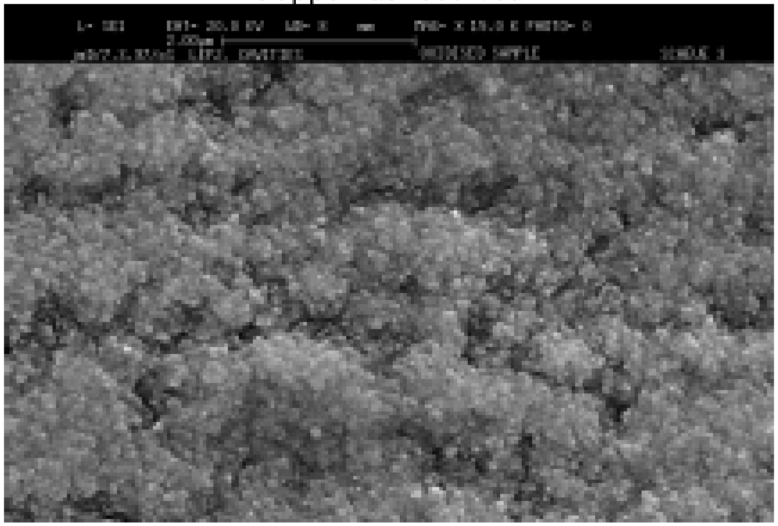
Figure 4: Influence of the surface roughness on the SEY. From a smooth surface the emitted electrons are more likely to escape than from a rough surface.

SEY decreases for rougher surface



V. Baglin CERN - EPAC 2000

Copper as received

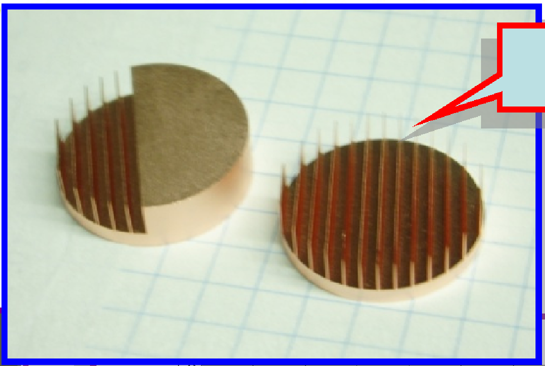


Copper after air bake

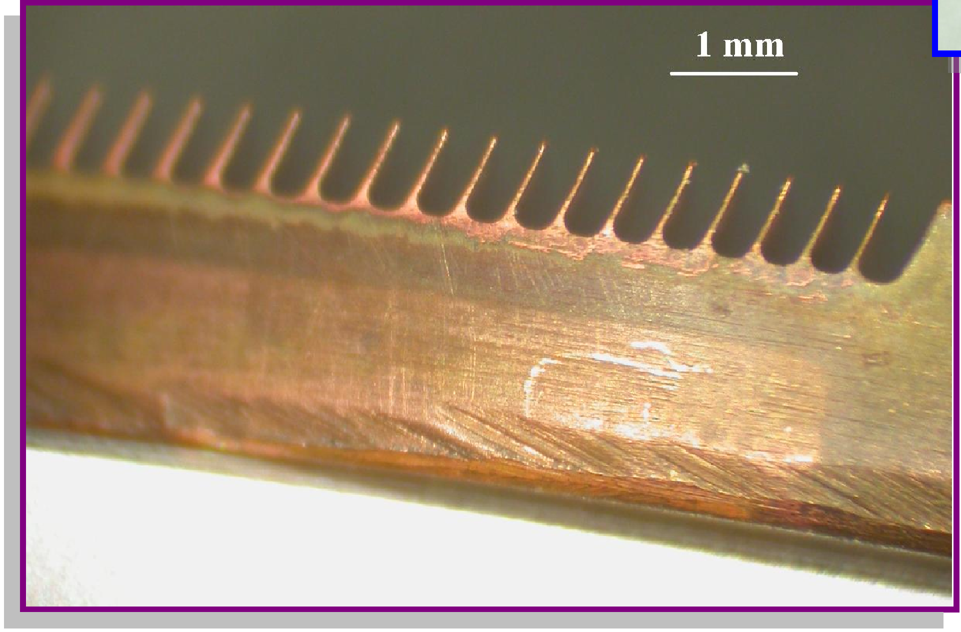
Grooves: Laboratory tests

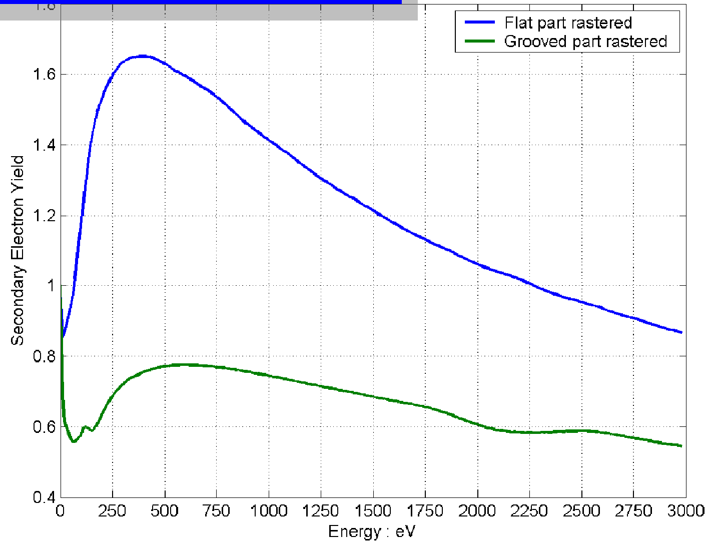
G. Stupakov and M.P. SLAC

Artificially increasing surface roughness.



mm deep (PEP-II)





Special surface profile design, Cu OFHC. EDM wire cutting. Groove: 0.8mm depth, 0.35mm step, 0.05mm thickness.

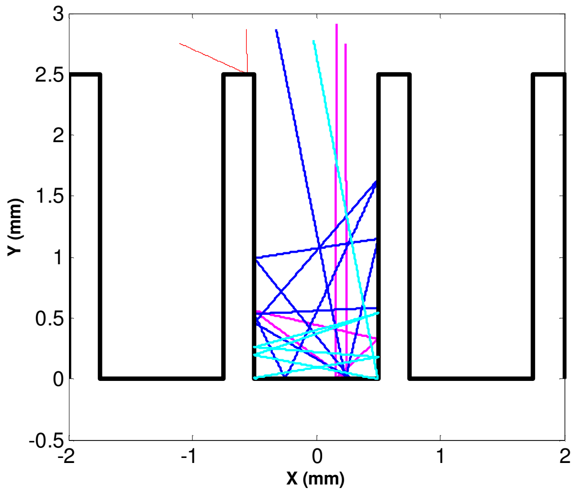
Measured SEY reduction << 1
Reduction depends on geometry

Triangular groove concept A. Krasnov LHC-Proj-Rep-617

Mechanism of reduction of SEY using grooved surface

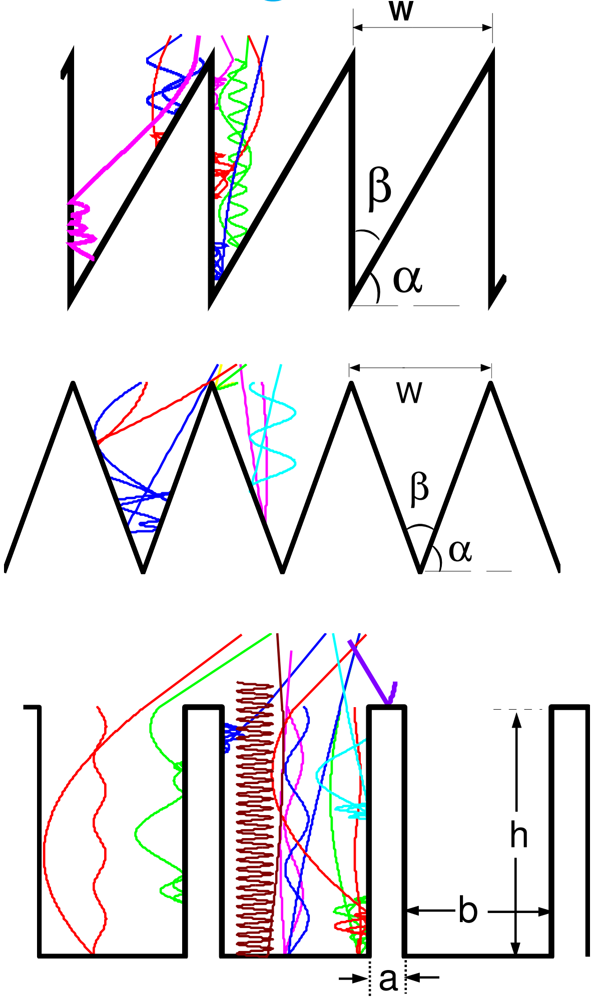
- **Trap the electrons near the surface……**

Drift region



Rectangular Groove without magnetic field

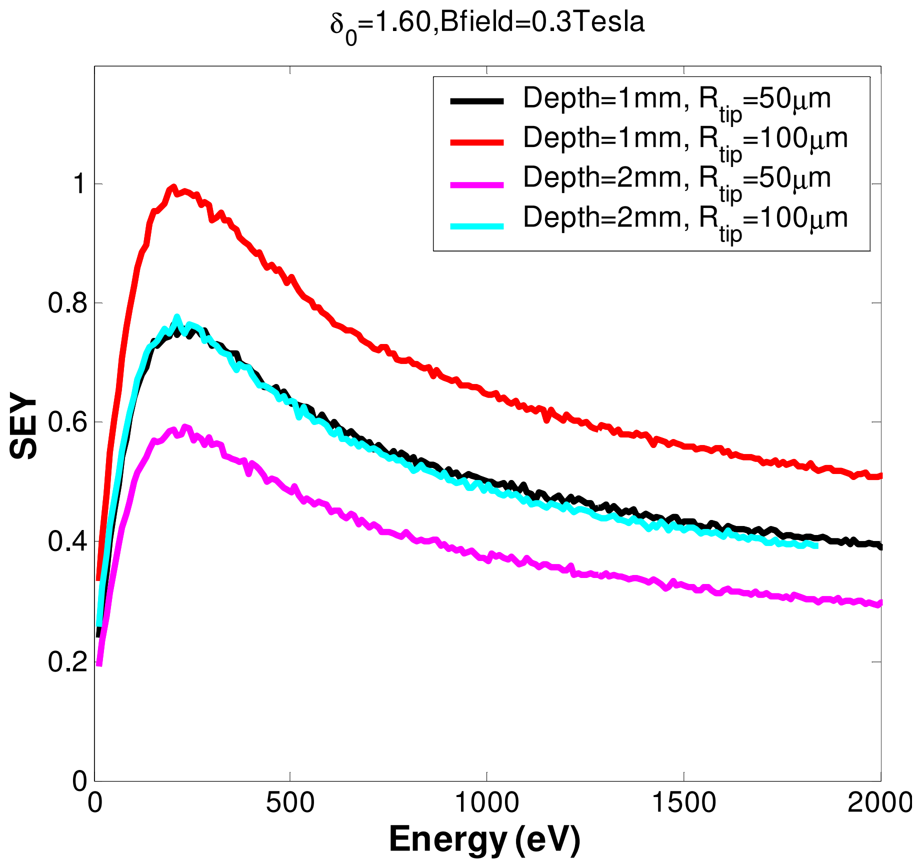
Magnets



L. Wang SLAC 2010

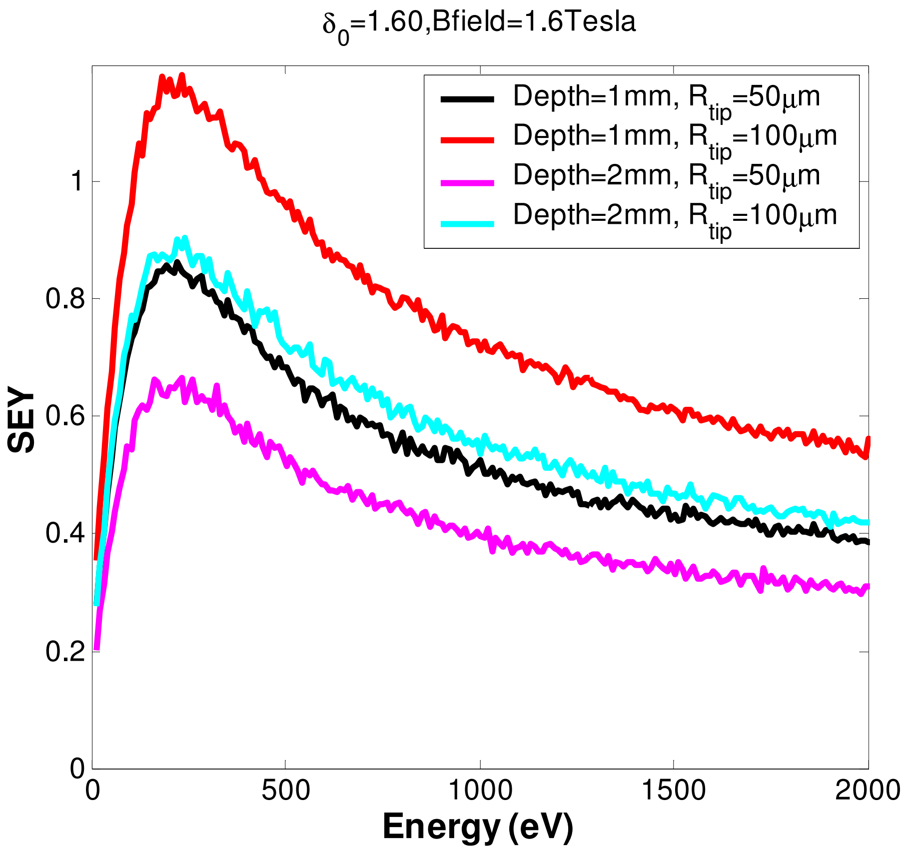
effect of Bfield and shape

- **There is a lager SEY in a stronger magnet**
- **There is a smaller SEY for larger groove with smaller roundness**
- **(a sharper tip is desired in order to reduce SEY!!)**



δ_0=1.60,Bfield=0.3Tesla

SEY with Dipole field=0.3T



δ_0=1.60,Bfield=1.6Tesla

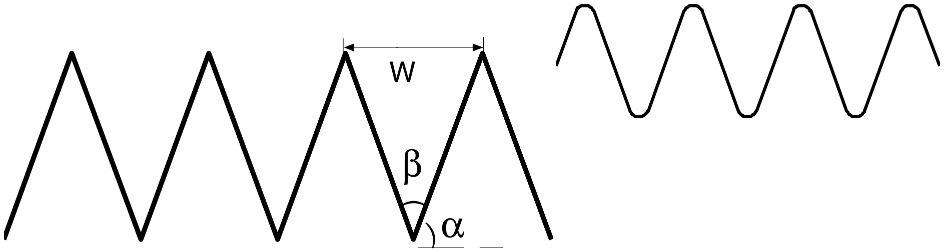
SEY with Dipole field=1.6T

L. Wang SLAC 2010

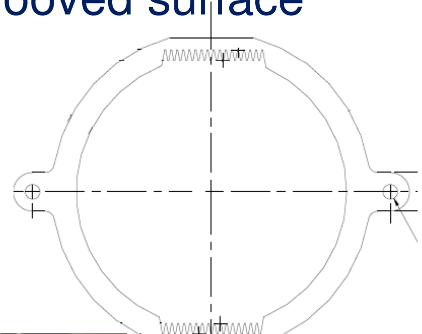
Impedance enhancement factor

(Code : Finite Element Method, PAC07 THPAS067, L Wang)

$$\eta = \frac{Z_{groovedsurface}}{Z_{smoothsurface}} = \frac{\int H^2 ds}{H_0^2 W}$$



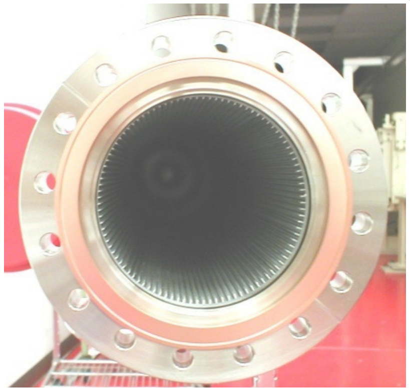
The total impedance enhancement= η * percentage of grooved surface
*percentage chamber length with grooved surface



Triangular groove in dipole and wiggler magnets

In magnets, grooves only top and bottom. Also, magnets cover only a fraction of the ring.

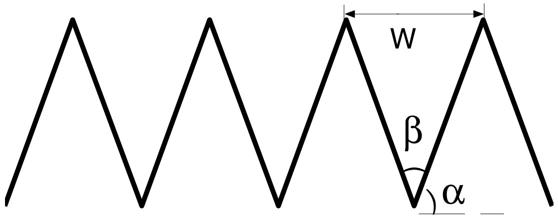
percentage of grooved surface ~ 2 %



Rectangular groove in drift region

percentage of grooved surface ~ 85%

Triangular Grooved surface in Magnet(dipole & wiggler)

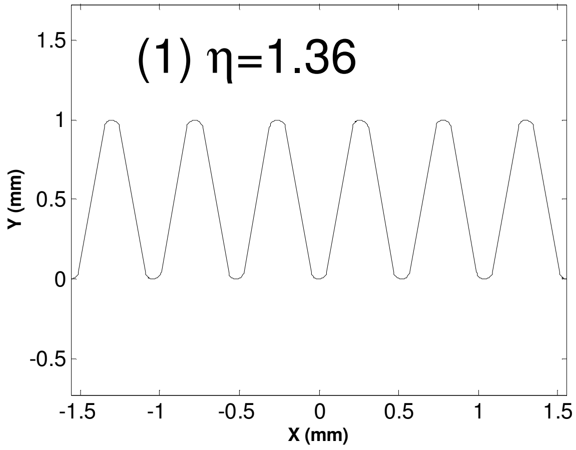


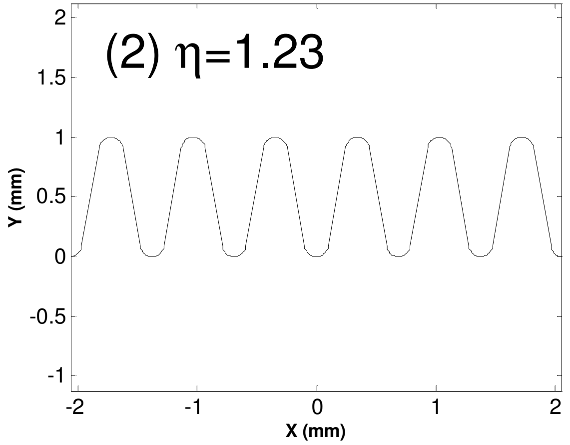
(1) α =80
  Groove depth: 1 mm
  Roundness: 50 um
  η=1.36

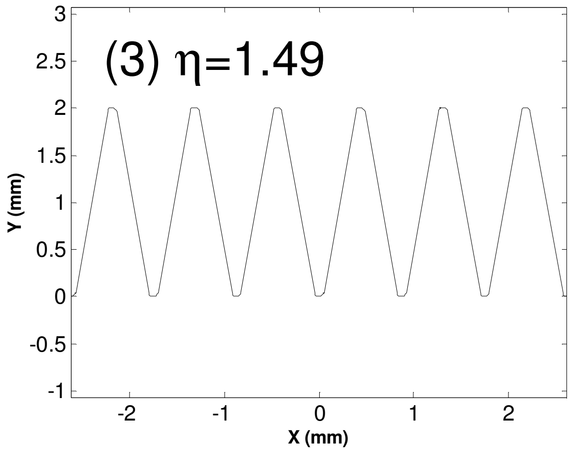
(2) α =80
  Groove depth: 1 mm
  Roundness: 100 um
  η =1.23

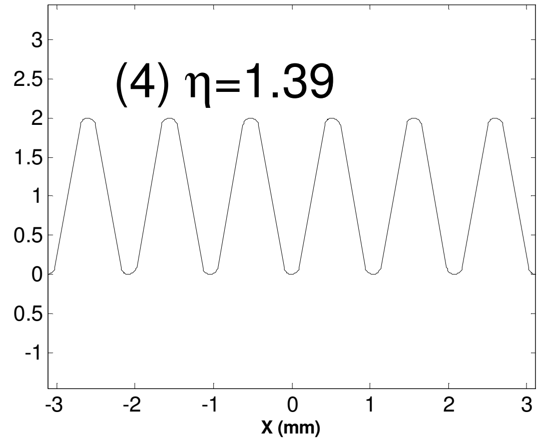
(3) α =80
  Groove depth: 2 mm
  Roundness: 50 um
  η =1.49

(4) α =80
  Groove depth: 2 mm
  Roundness: 100 um
  η =1.39









Grooves

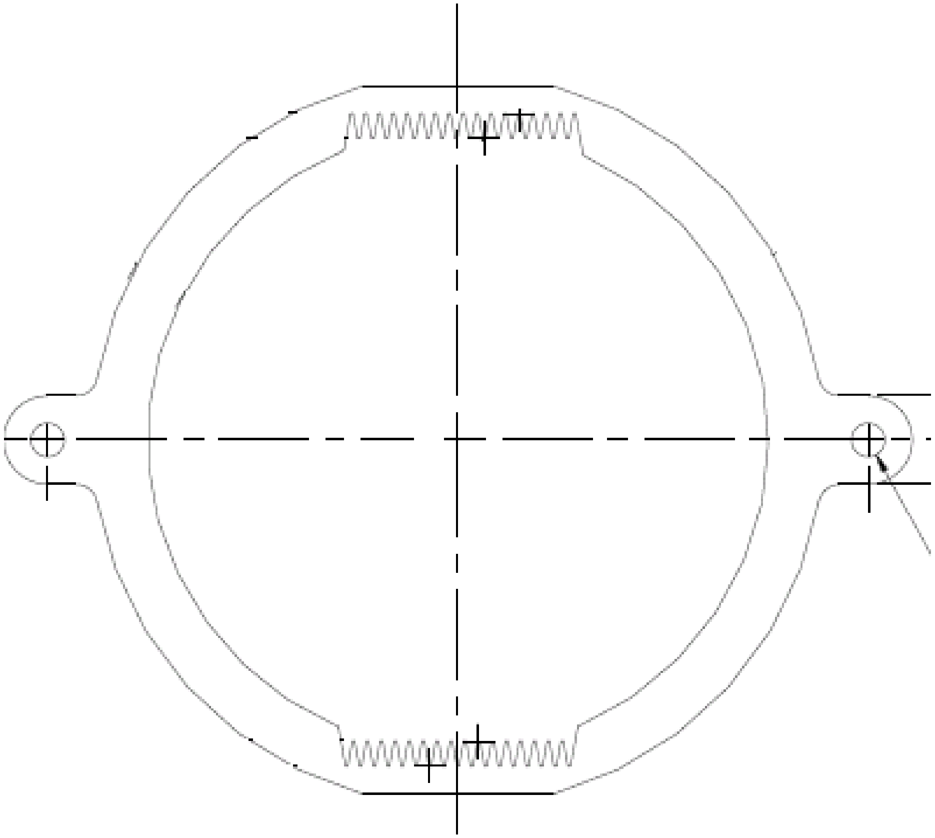
Pro'

- Very good suppression in magnets
- Lower e- cloud with respect to coatings (up to ~1 order of magnitude)

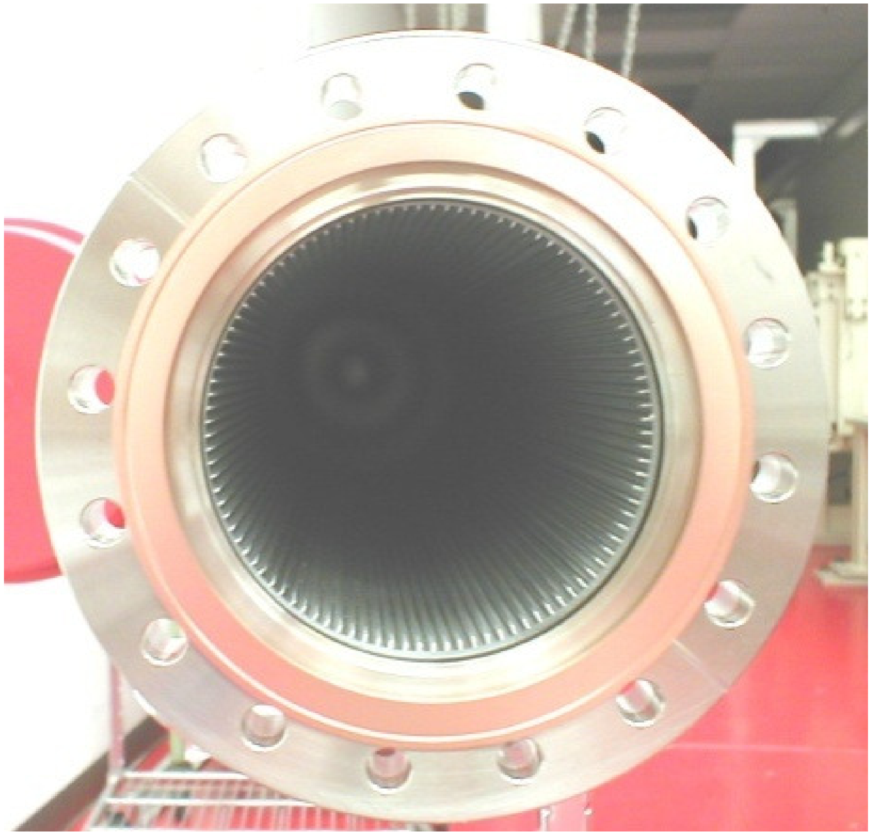
Contro'

- Ring **impedance** goes up … (locally though)
- Small grooves (< 1 mm) are a manufacturing challenge

Grooves

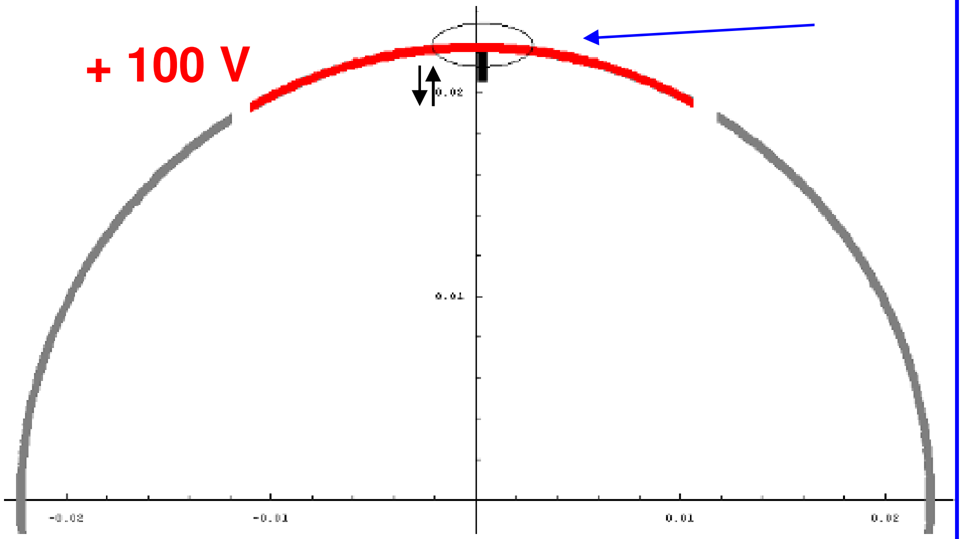


Triangular on top and bottom in bends and wigglers



Rectangular and all around in drifts

Clearing electrodes: principle



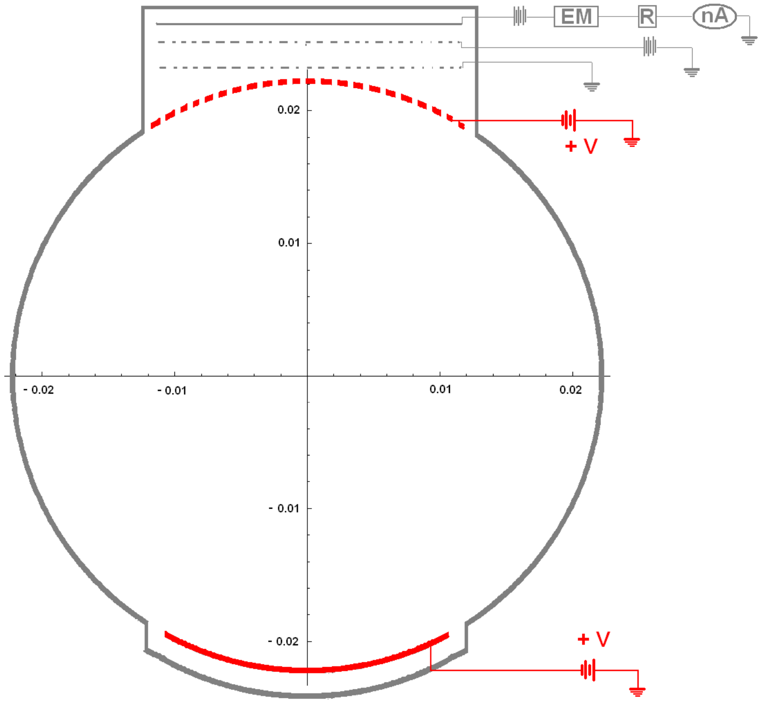
Typically:

$$V_{CE} = +100 \text{ V}$$
$$E_{CE} \approx 2{,}000 \text{ V/m}$$
$$m\ddot{x} = -e(E + v \times B) =$$
$$= -e(2{,}000\ V/m + v \times 0.2\ T)$$

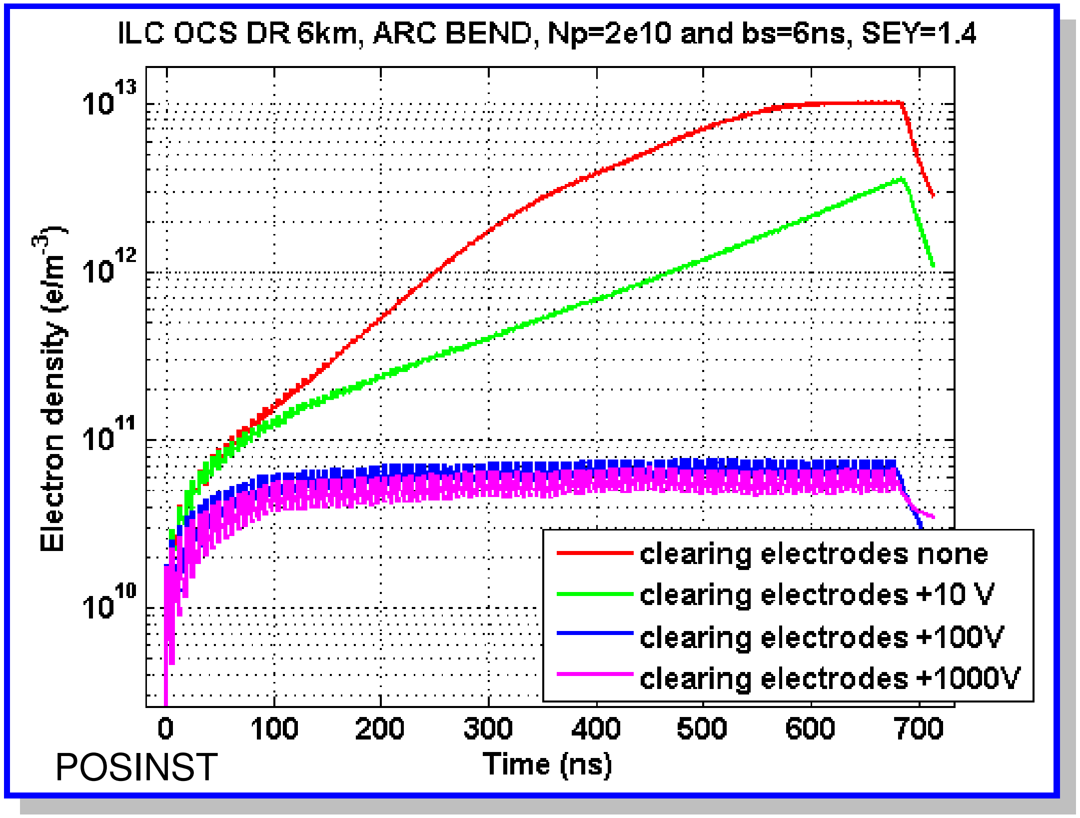
1. Secondary electron generated at rest near wall
2. Electron is **accelerated** to the center by the **beam**.
3. compute potential that attracts the electron **back** to the electrode **before the next bunch** pass by.
4. electron cloud is strongly suppressed!

Answer: e- is back at wall after 3ns, before the next bunch arrive after 6ns.

Clearing electrodes: principle



Test BEND chamber with curved clearing electrodes

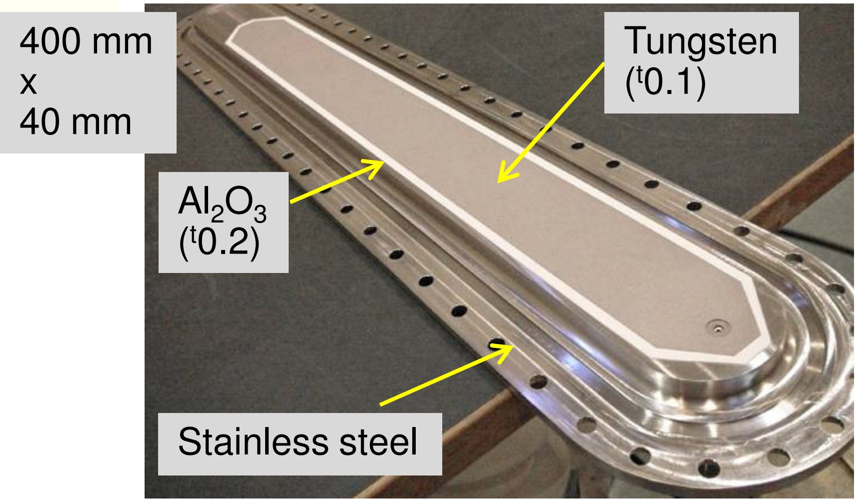


Simulations using clearing electrodes. ILC DR.

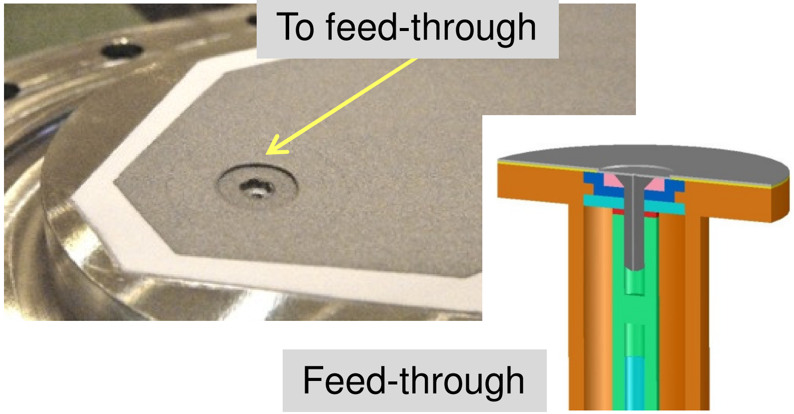
Clearing Electrode_1

- **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
  - – ±1 kV is OK.
  - – Flat connection between feed-through and electrode

An insertion for test with a thin electrode

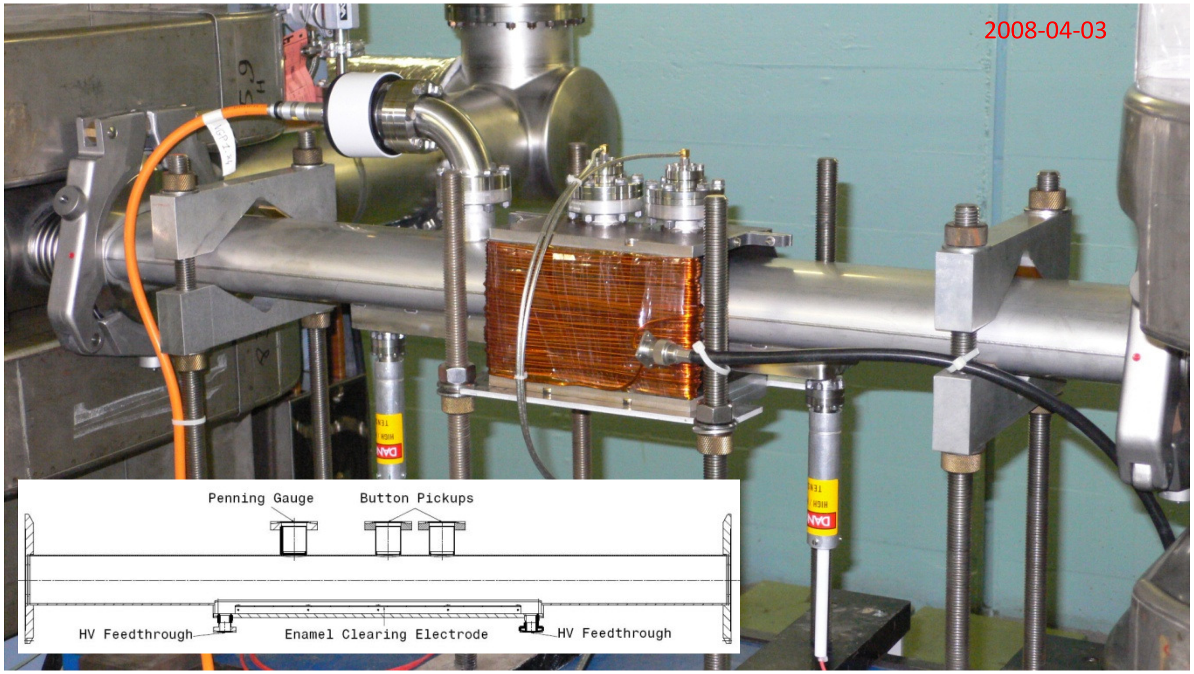


Connection to feed through



Y. Suetsugu et al. NIM-PR-A, 598 (2008) 372

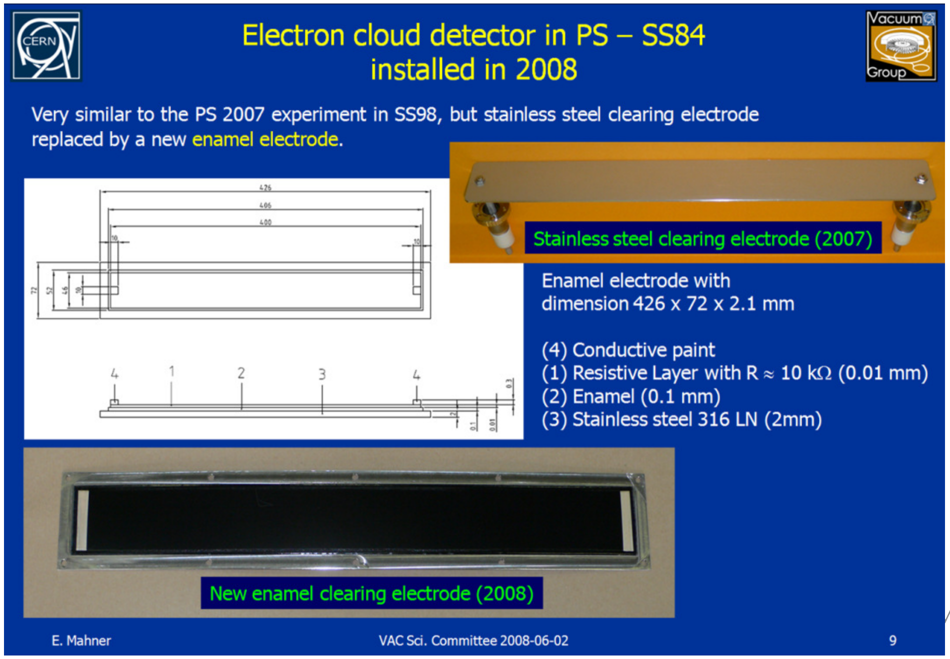
Edgar Mahner, CERN, TE-VSC Group



PS ss84 (2008)

2nd electron cloud setup in the PS

316LN st.st. vacuum chamber with shielded button pickups, enamel clearing electrode, shielded vacuum gauge, dipole magnet.



Electron cloud detector in PS – SS84 installed in 2008

Very similar to the PS 2007 experiment in SS98, but stainless steel clearing electrode replaced by a new enamel electrode.

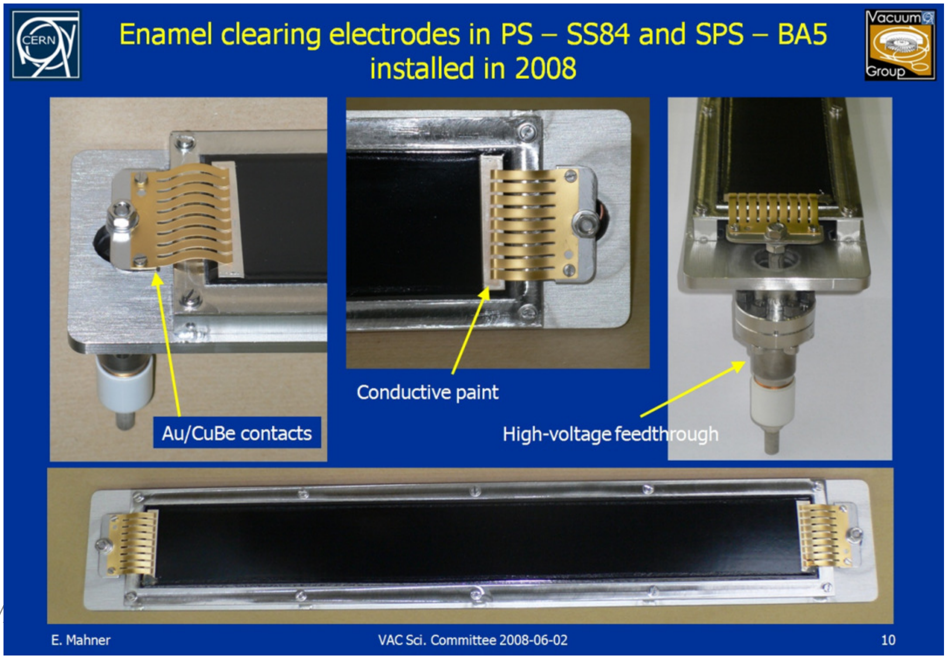
Stainless steel clearing electrode (2007)

Enamel electrode with dimension 426 x 72 x 2.1 mm

(4) Conductive paint
(1) Resistive Layer with R ≈ 10 kΩ (0.01 mm)
(2) Enamel (0.1 mm)
(3) Stainless steel 316 LN (2mm)

New enamel clearing electrode (2008)

E. Mahner VAC Sci. Committee 2008-06-02 9



Enamel clearing electrodes in PS – SS84 and SPS – BA5 installed in 2008

Au/CuBe contacts

Conductive paint

High-voltage feedthrough

E. Mahner VAC Sci. Committee 2008-06-02 10

Clearing electrodes

Pro'

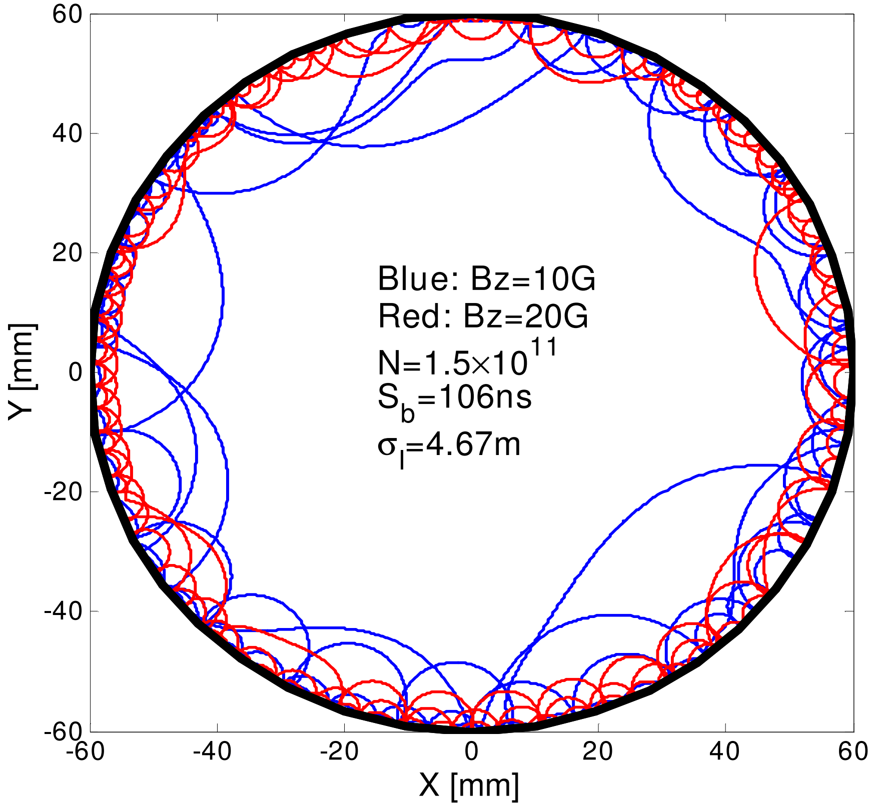
- Really 'clearing' out the cloud!
- Order of magnitude with respect to other methods

Contro'

- Ring **impedance** goes up … (locally though)
- Expensive (not much though compared to ring costs)
- To be designed into vacuum chambers

Solenoids

Solenoids generate coupling that might need to be corrected. Especially if we aim at ultra-small (ILC 2pm) emittance!



CLOUDLAND

Very effective in DRIFTs!

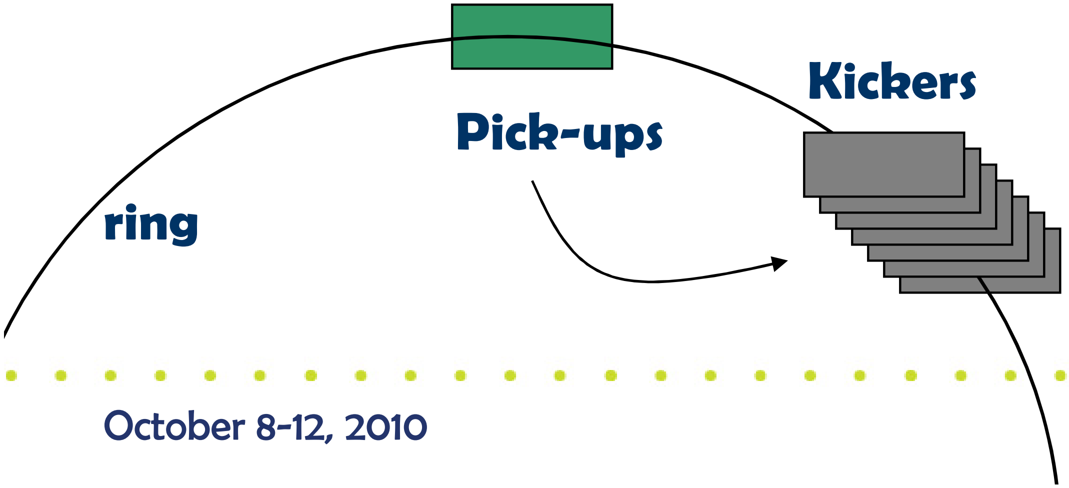
In weak Quadrupole field 0.1 T/m, a solenoid of 60-600 G could be effective [simulations F. Zimmermann].

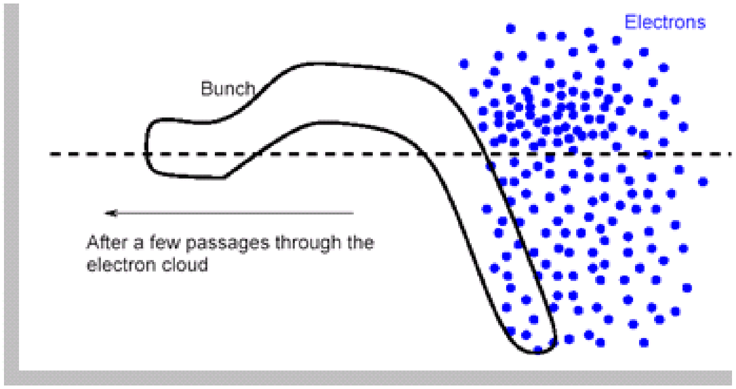
Feedback systems

- Coupled-bunch instability. A classical feedback system works!
- But to correct the head-tail instability or TMCI that occur intra-bunch is it possible to use a feedback system??

Single-bunch feedback system: Never being built before …

- Assume a bunch that starts to go unstable with a "banana" shape …

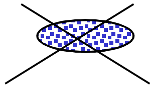




Single-bunch Feedback System

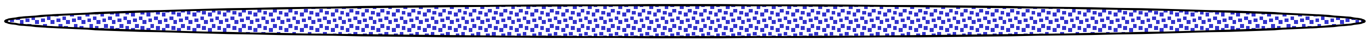
- pick-up the signal of each slice of the bunch and try to kick each slice differently … to suppress the growth …

- If the bunch is short, forget it … we don’t have enough resolution to kick individual parts of the bunch …

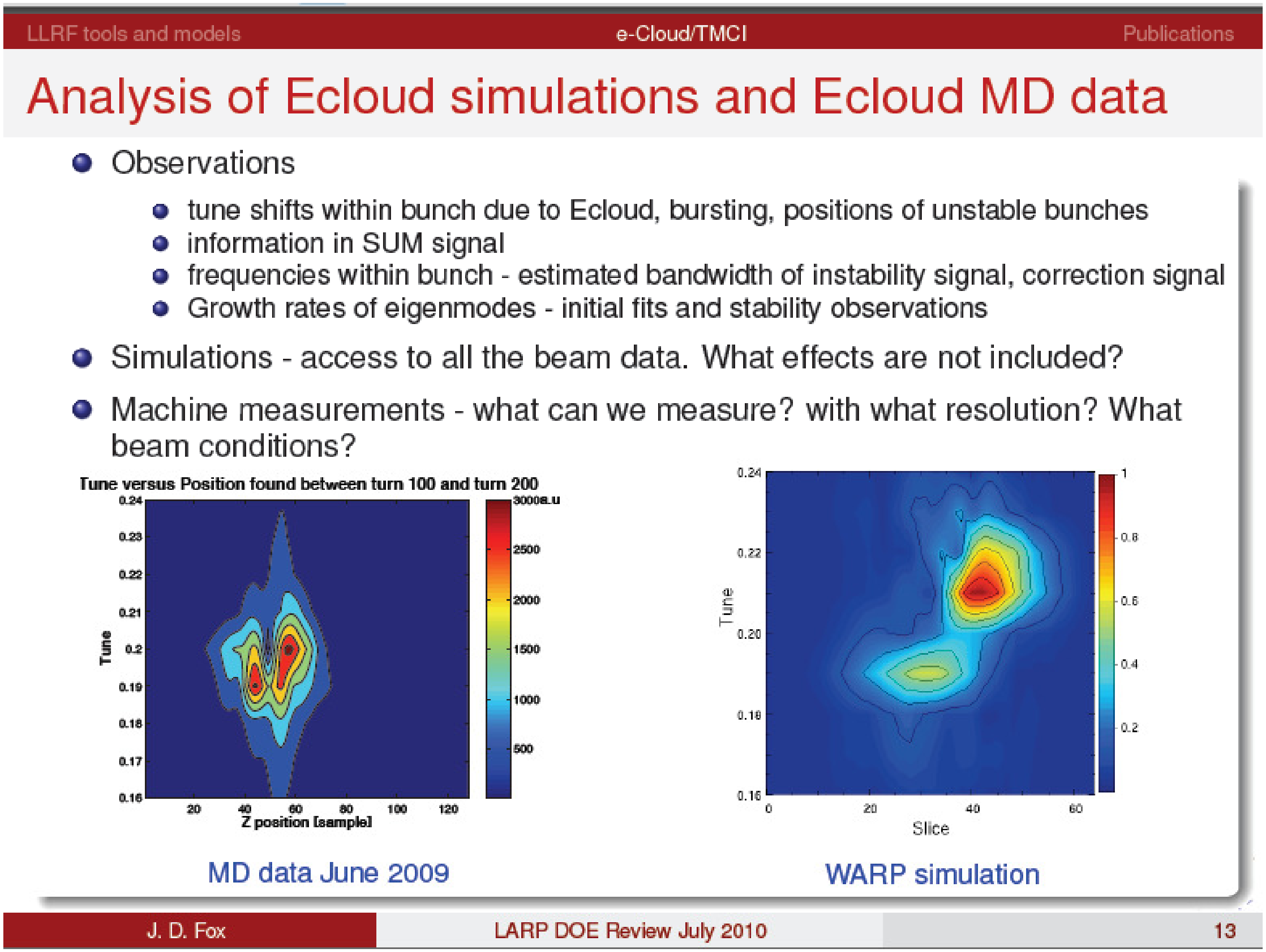


- But if the bunch is long enough, we may try!

  First tests for the 60m long PSR bunch were positive …
  Now … we are building a feedback system for the LHC injector SPS: 1ns (rms) long bunch.



Single-bunch Feedback System



LLRF tools and models | e-Cloud/TMCI | Publications

Analysis of Ecloud simulations and Ecloud MD data

- Observations
  - tune shifts within bunch due to Ecloud, bursting, positions of unstable bunches
  - information in SUM signal
  - frequencies within bunch - estimated bandwidth of instability signal, correction signal
  - Growth rates of eigenmodes - initial fits and stability observations
- Simulations - access to all the beam data. What effects are not included?
- Machine measurements - what can we measure? with what resolution? What beam conditions?

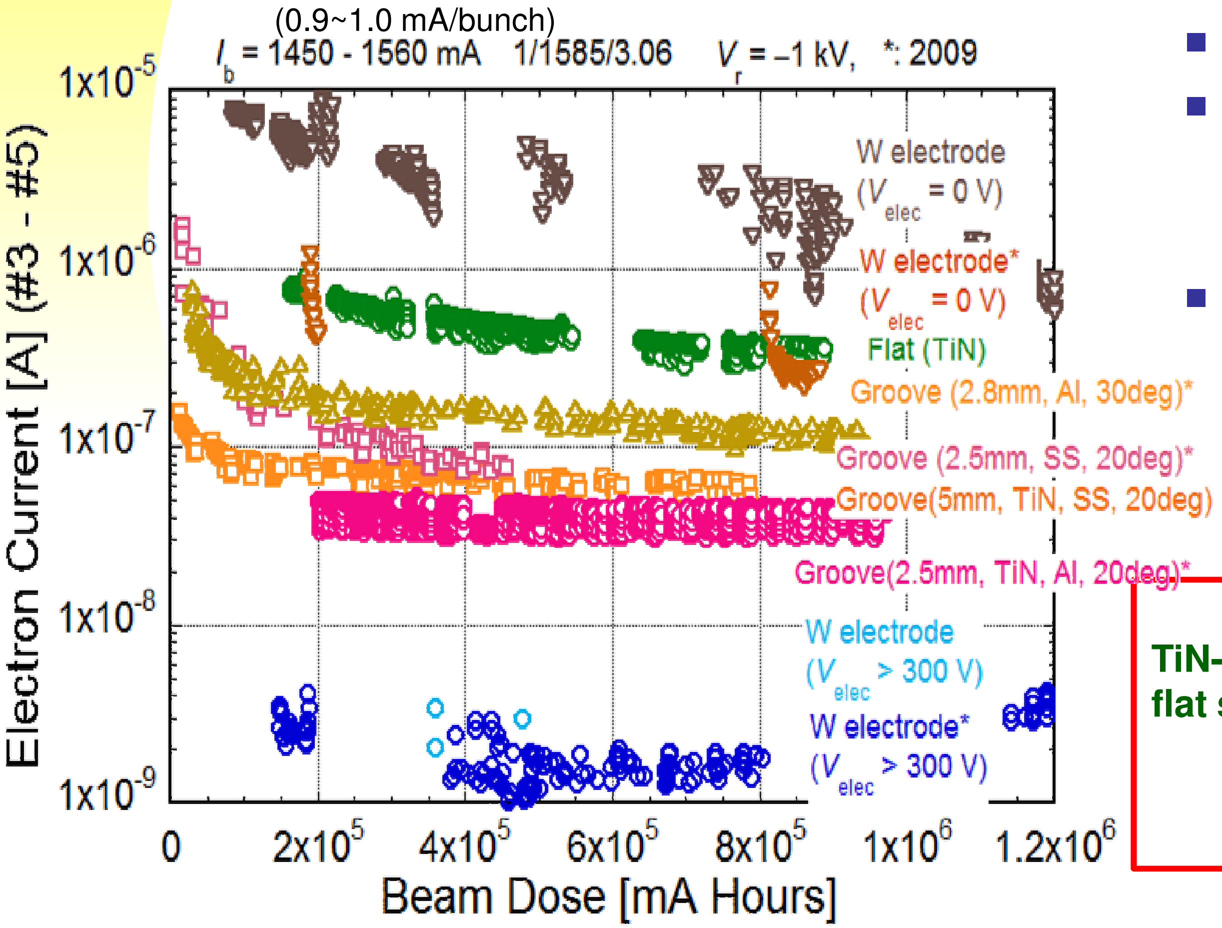
MD data June 2009

WARP simulation

J. D. Fox | LARP DOE Review July 2010 | 13

Comparing mitigations at same ring location

- Comparison between clearing electrode and groove
  - All data so far are plotted in one figure



- For 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**

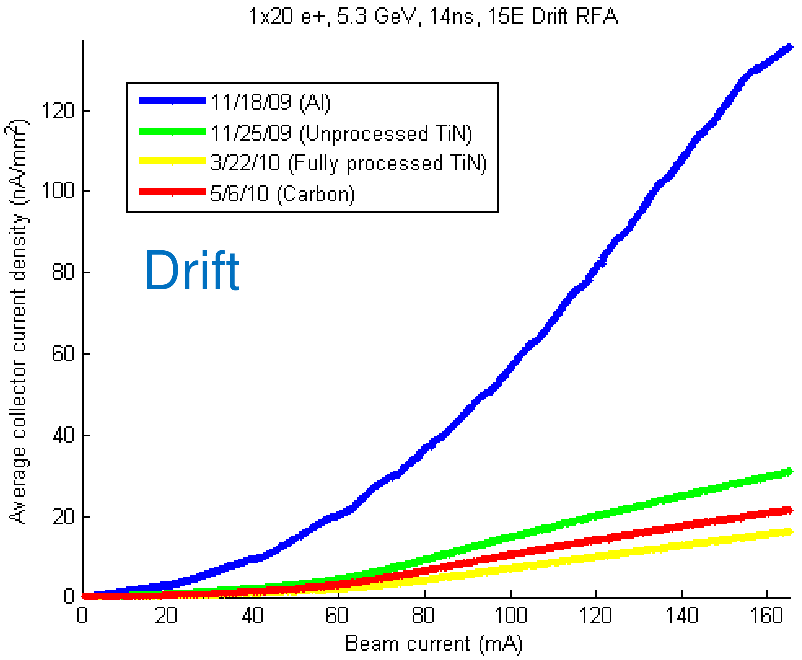
1/6~1/10 ~1/10

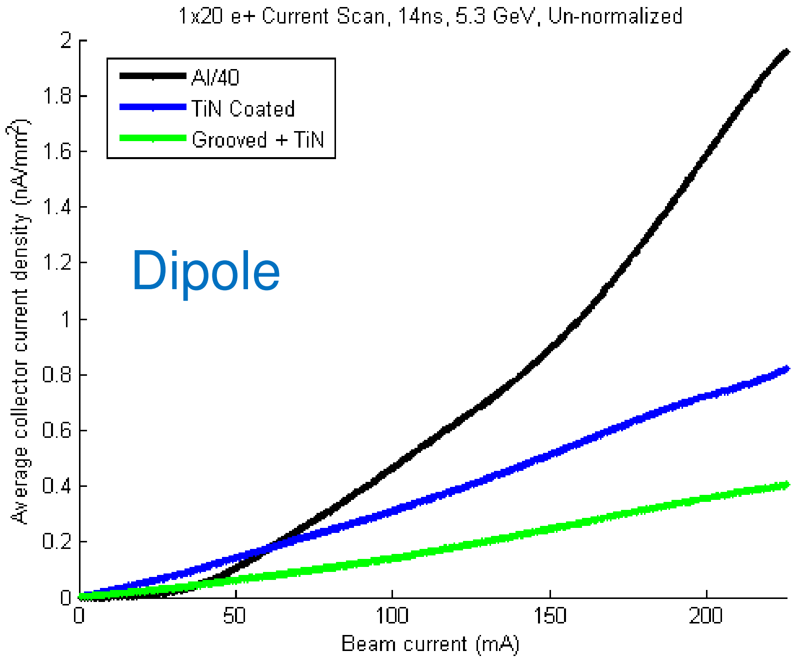
…

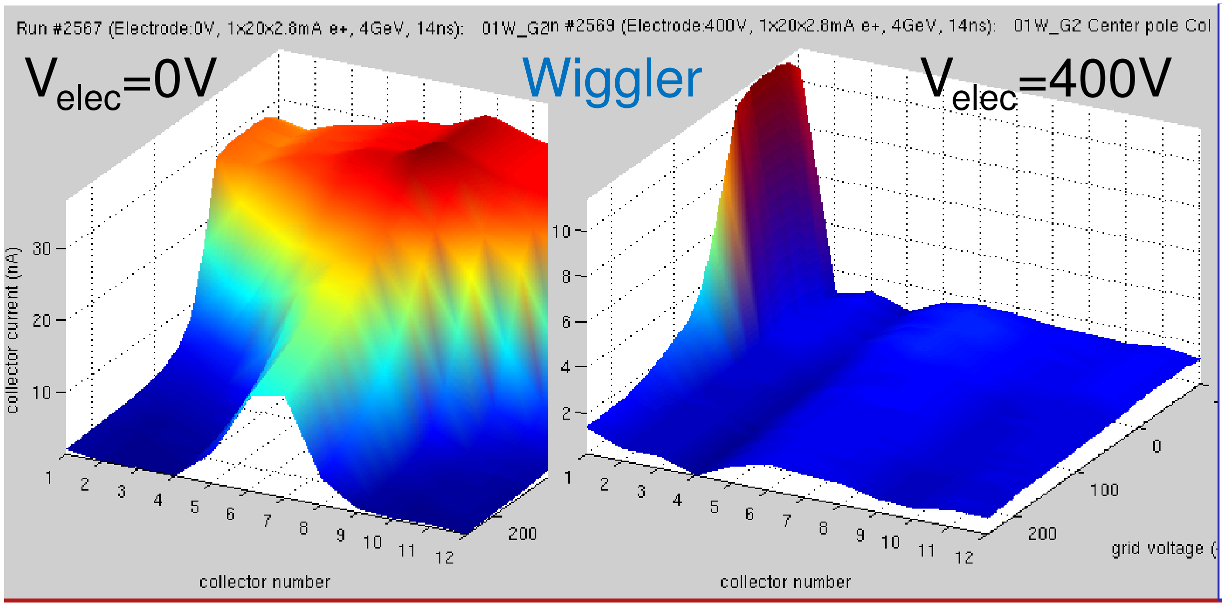
Comment could be:

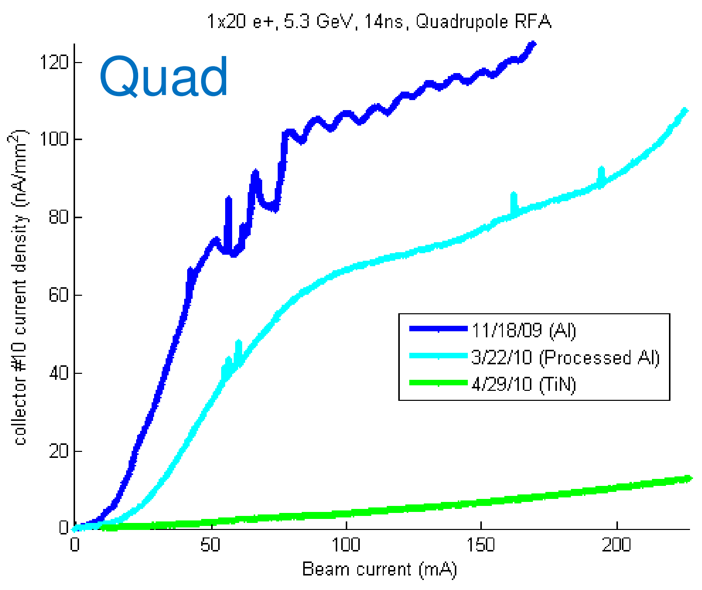
- We arranged mitigations on one side of the vacuum chamber
- If we apply on both sides, coatings and grooves may approach the clearing effect of the electrodes …

Examples


1x20 e+, 5.3 GeV, 14ns, 15E Drift RFA
Drift
Average collector current density (nA/mm^2)
Beam current (mA)
0
20
40
60
80
100
120
140
160
11/18/09 (Al)
11/25/09 (Unprocessed TiN)
3/22/10 (Fully processed TiN)
5/6/10 (Carbon)


1x20 e+ Current Scan, 14ns, 5.3 GeV, Un-normalized
Dipole
Average collector current density (nA/mm^2)
Beam current (mA)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
100
150
200
Al/40
TiN Coated
Grooved + TiN


Run #2567 (Electrode:0V, 1x20x2.8mA e+, 4GeV, 14ns): 01W_G2
Run #2569 (Electrode:400V, 1x20x2.8mA e+, 4GeV, 14ns): 01W_G2 Center pole Col
V_{elec}=0V
Wiggler
V_{elec}=400V
collector current (nA)
10
20
30
2
4
6
8
10
collector number
1
2
3
4
5
6
7
8
9
10
11
12
0
100
200
grid voltage (


1x20 e+, 5.3 GeV, 14ns, Quadrupole RFA
Quad
collector #10 current density (nA/mm^2)
Beam current (mA)
0
20
40
60
80
100
120
50
100
150
200
11/18/09 (Al)
3/22/10 (Processed Al)
4/29/10 (TiN)

Summary

… Join the electron cloud work!!

Thank you!