Using ALD Coatings to Cure Breakdown

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ANL/HEP

NFMCC Meeting
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Arc Modeling at Argonne.

- Starting in 2002, with support from ANL LDRD funds, we have been modeling arcs.

- The original aim was twofold:
  1) Learn how arcs worked so we could cure them
  2) Bring additional funding (perhaps from the ILC) into the muon effort

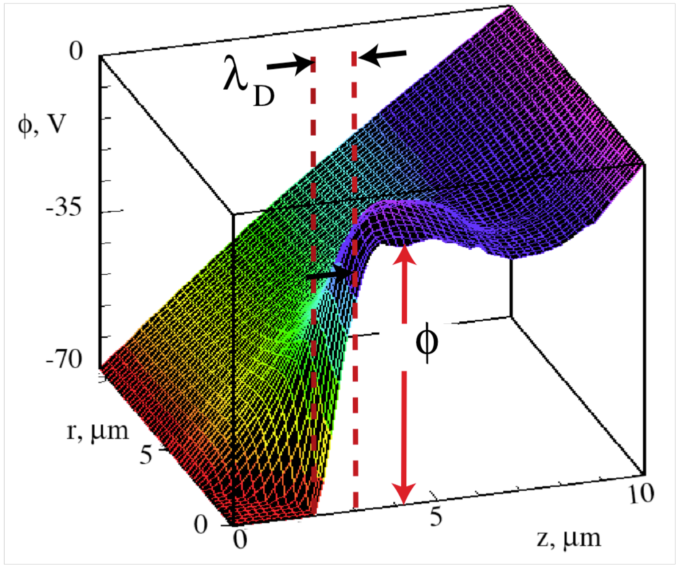
- The effort was not entirely successful:
  1) We now have a solid arc model (the first?), and a potential cure for arcing.
  2) We never got an additional penny from DOE for this work.

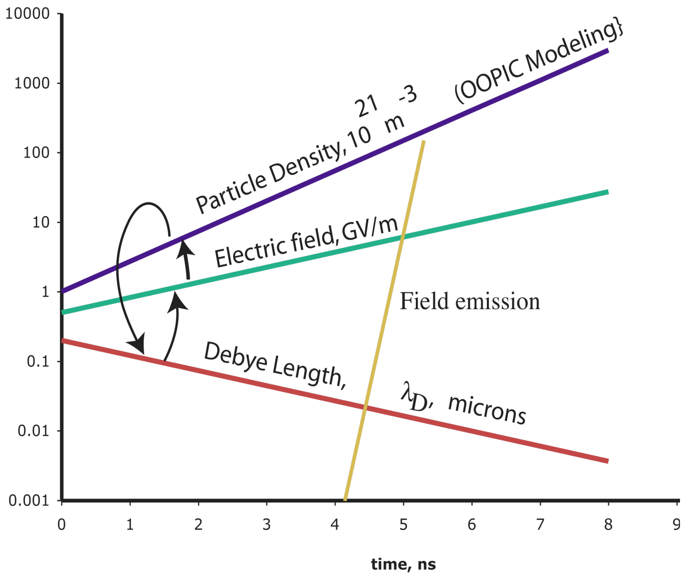
- We are refining and extending the model, which seems to apply to all accelerator, and some plasma physics problems.

- We find that a lot of other work seems to be based on misleading assumptions.
  (We've got a little list.)

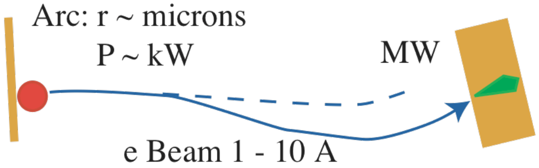
Our breakdown model is basically simple.

- Coulomb explosions trigger breakdown - fatigue (creep) and Ohmic heating help.
- Breakdown arcs are initiated by FE ionization of fracture fragments.
- The arcs are very small, dense, cold, and charged +(40-100) V, (OOPIC and V_{burn}).
- Small Debye lengths, $\lambda_D = \sqrt{\frac{\epsilon_0 KT}{n_e q_e^2}} = \sim \mathrm{nm}$, produce fields, $\boldsymbol{E} = \phi/\lambda_D \sim$ GV/m.
- High electric fields produce micron-sized unipolar arcs.
- Unipolar arc energy produces craters and cracks with high field enhancements.





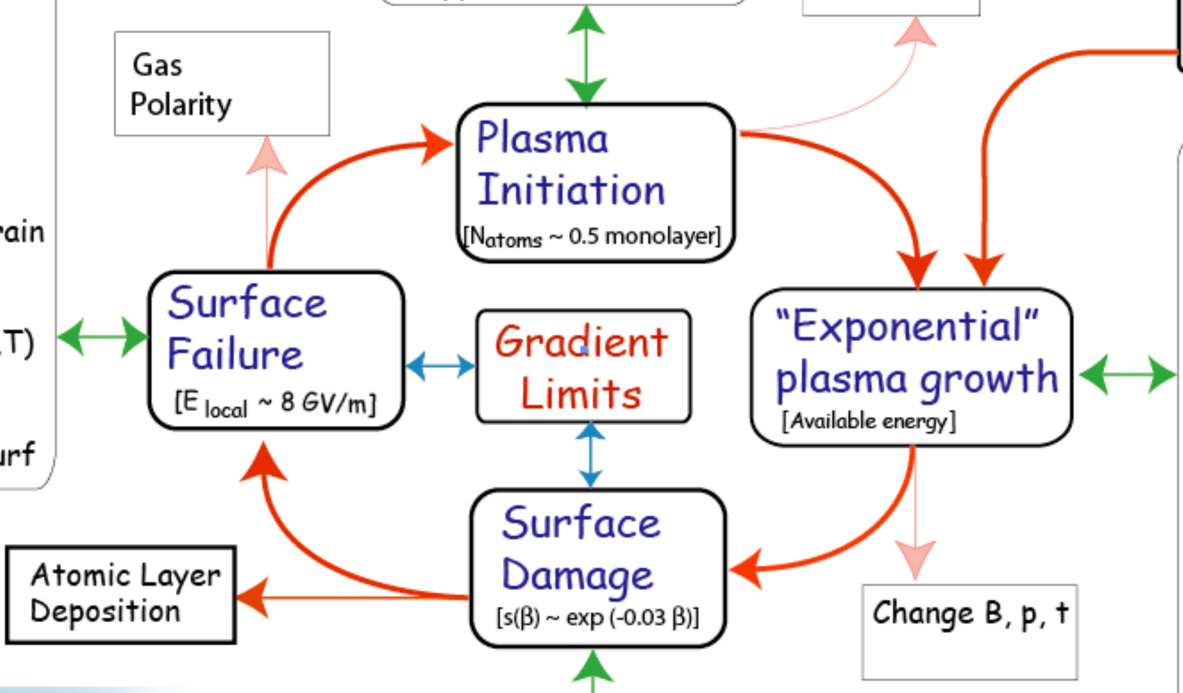
The model describes many aspects of arcs.



Arc Mechanisms

Fracture
Ohmic heating
Polarity dependence
Creep / Fatigue
Material dependence
Surface modification
Adsorbed gas
Oxides
Mechanical stress/strain
DC/rf comparisons
BD rate(E)
FE, RD emission I(E,ϕ,T)
Space charge limit
Thermal dependence
Weighted aver. of Esurf

Microgeometry depend.
Coulomb Explos.
Evolution of ionization
Mass Thresholds
Space pot. evolution
Neutral gas density
Trapped electrons



Gas
Polarity

Remove E

Plasma Initiation
[N_{atoms} ~ 0.5 monolayer]

Surface Failure
[E_{local} ~ 8 GV/m]

Gradient Limits

"Exponential" plasma growth
[Available energy]

Surface Damage
[s(β) ~ exp (-0.03 β)]

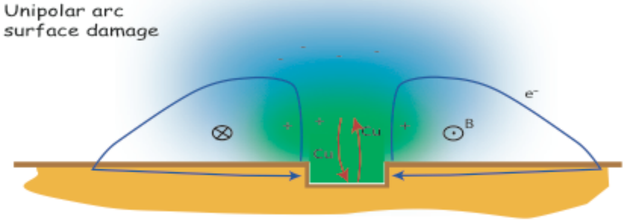
Atomic Layer
Deposition

Change B, p, t

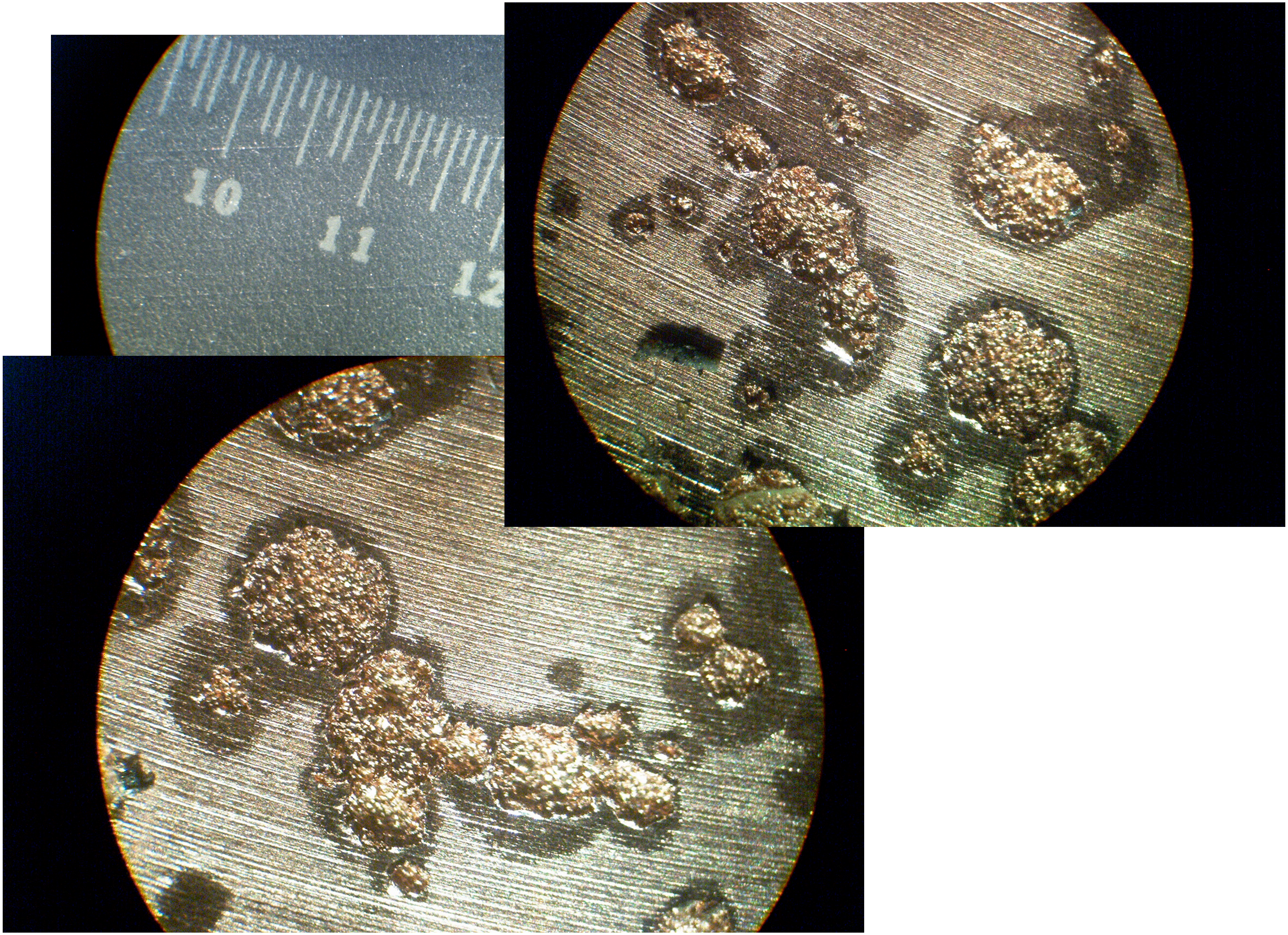
Laser Ablation
e beam welding
Micrometeorites
Tokamak edges

Stored energy
Frequency dependence
Fueling
  self sputtering etc
    temp dependence
  ion wall heating
  line radiation heating
  ohmic heating.
Magnetic fields
Ion etching
Explos. Elect. Emis,
Plasma growth times
Cavity discharge time
Cavity discharge current
  how it is absorbed
  interactions with B
Space charge limits
Liquid surface stability
Particulate generation
Unipolar arcs
Arc electrons to wall

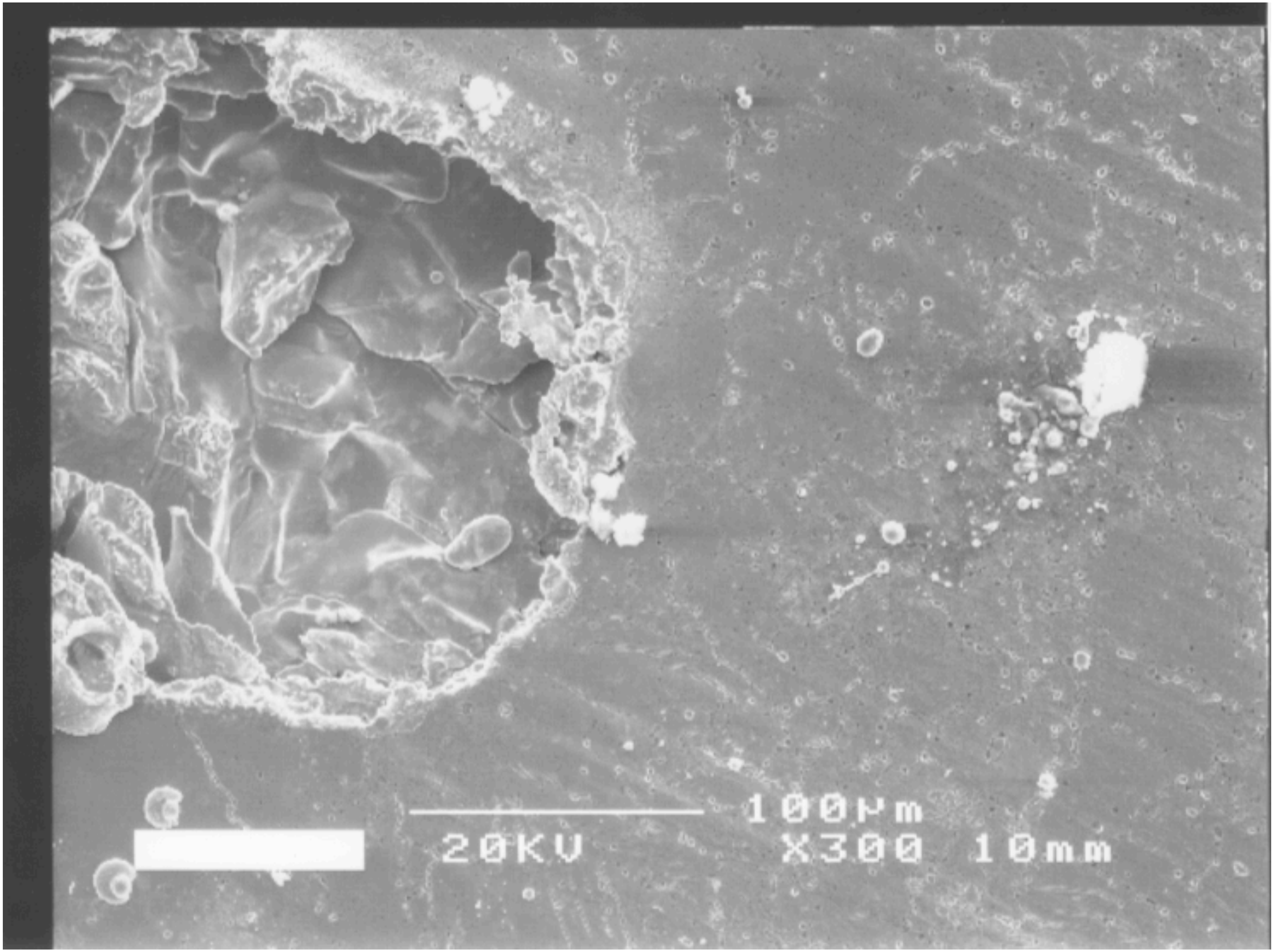
Unipolar arc physics
  Ablation mechanisms
Enhancement Spectra
Crack formation
Physical dim. of asperities
Emax - damage equilibrium



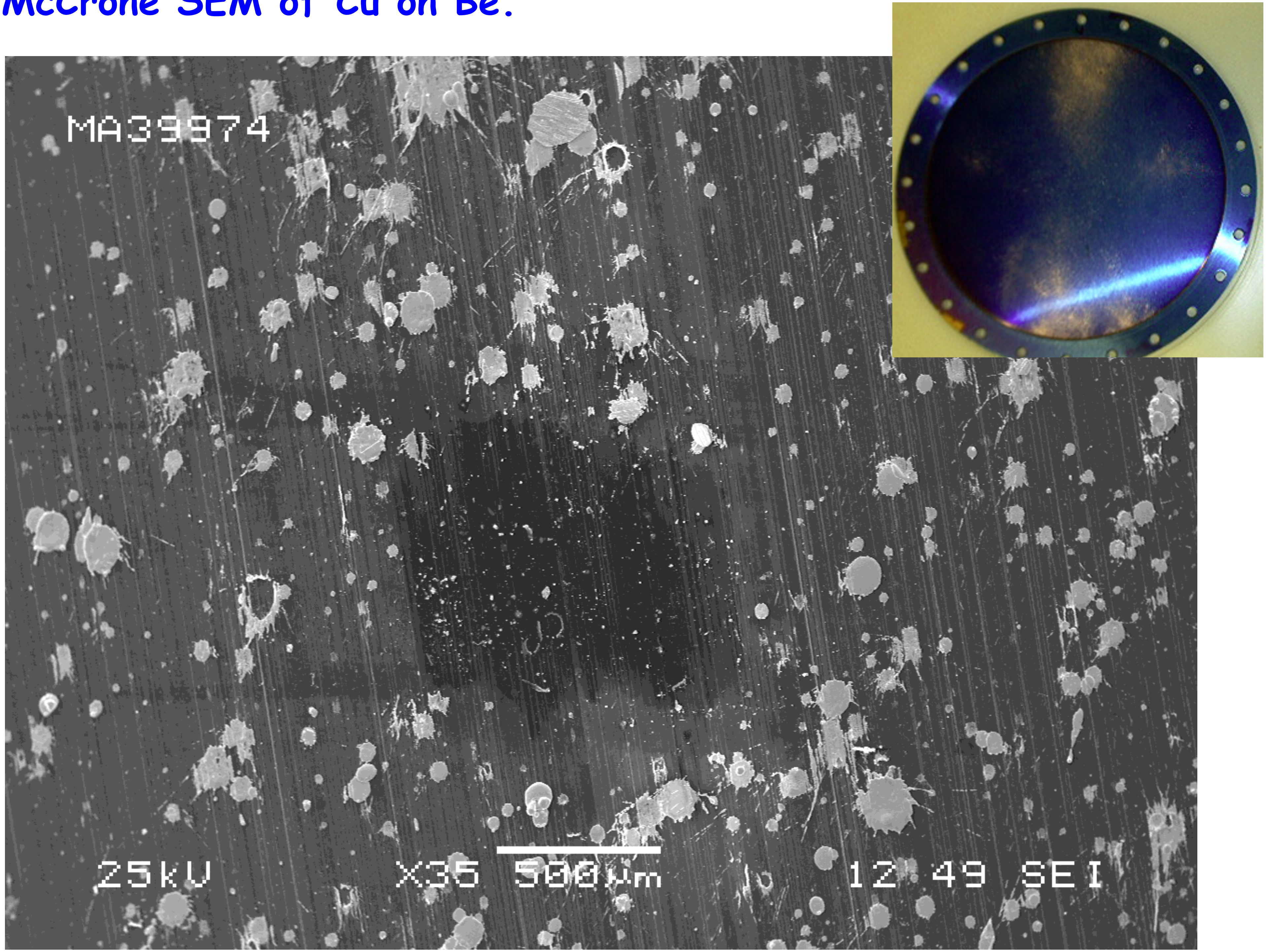
Microphotos of pits in the Cu plate from pillbox.



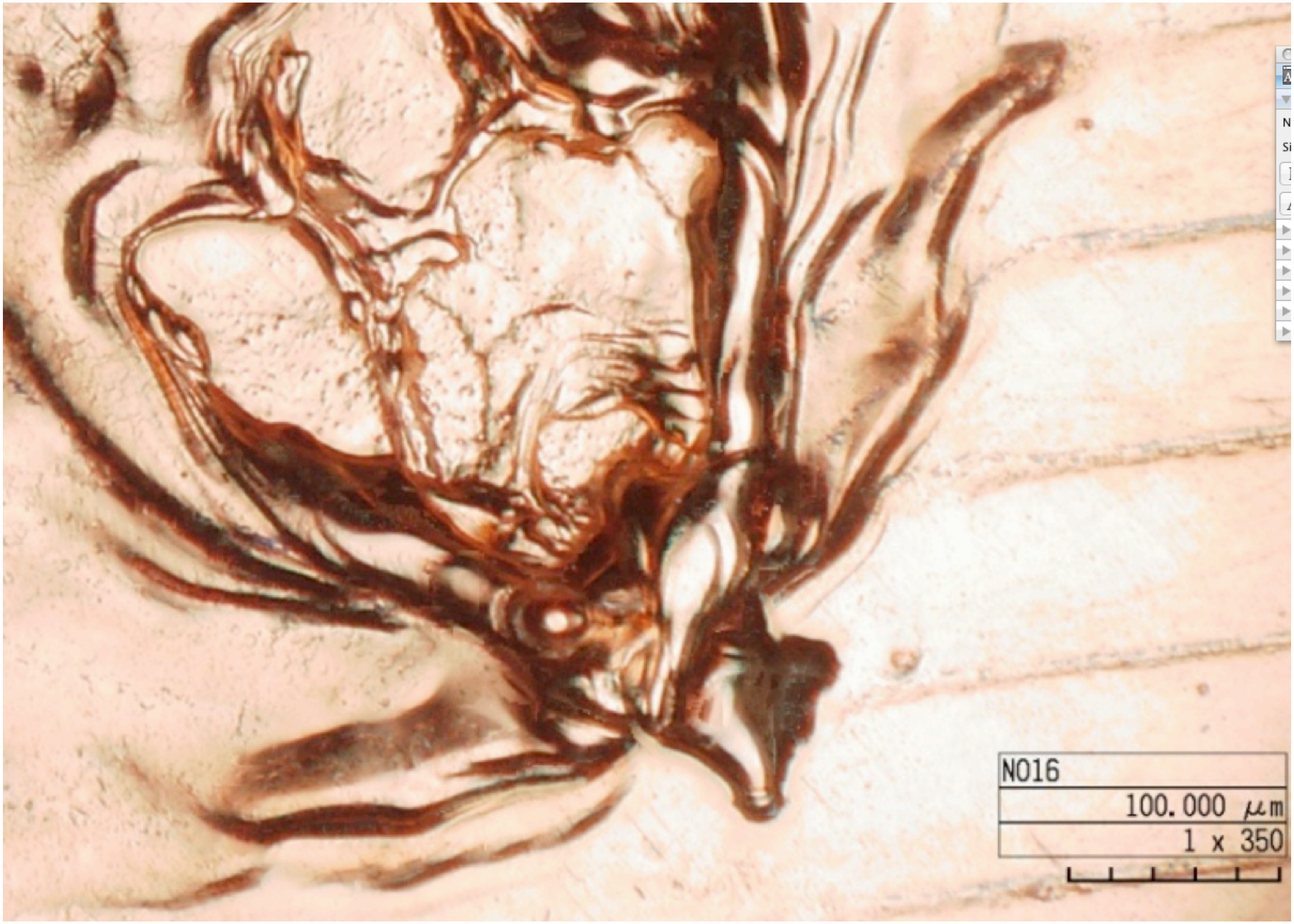
Surfaces are highly damaged.



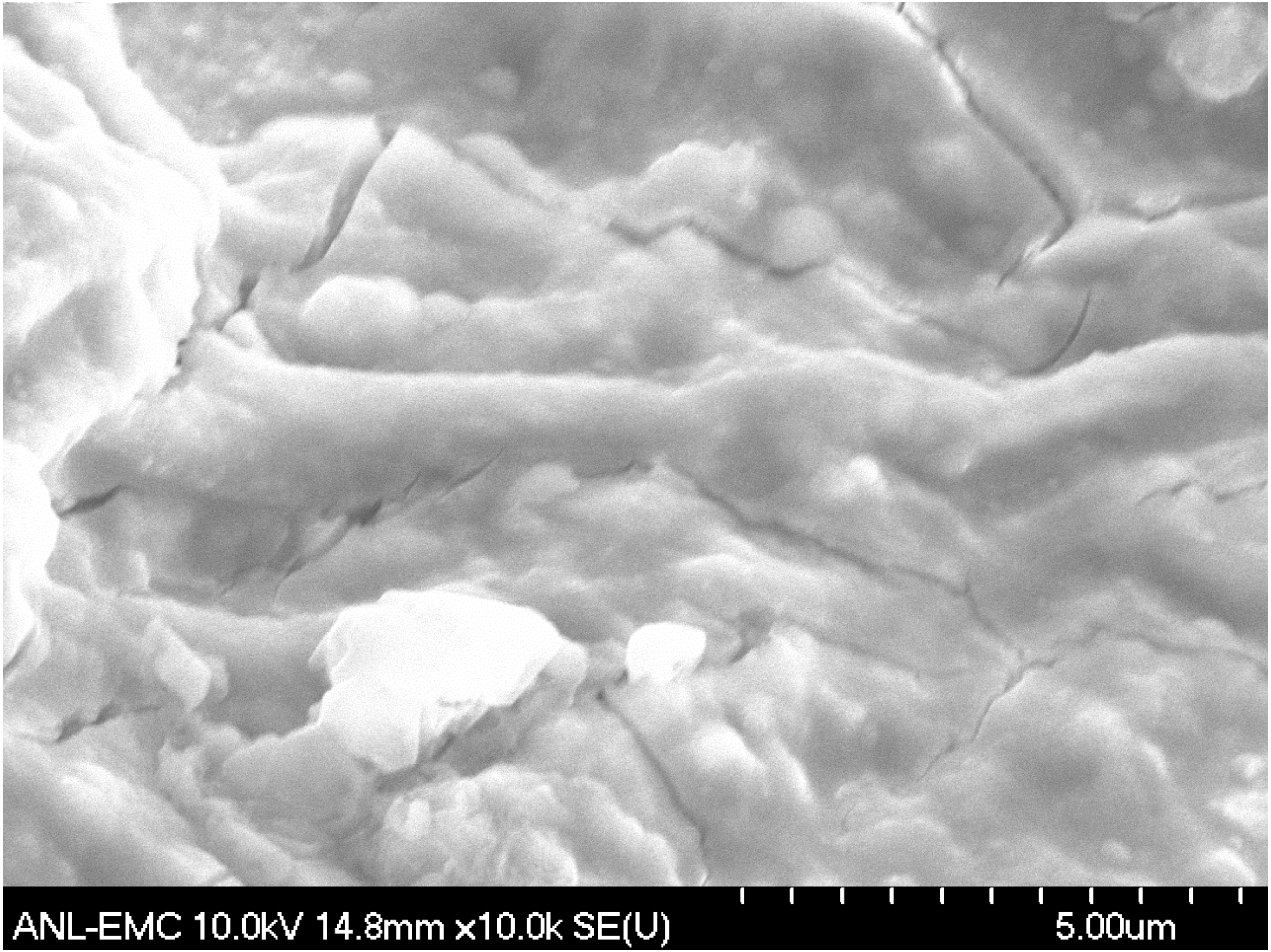
McCrone SEM of Cu on Be.



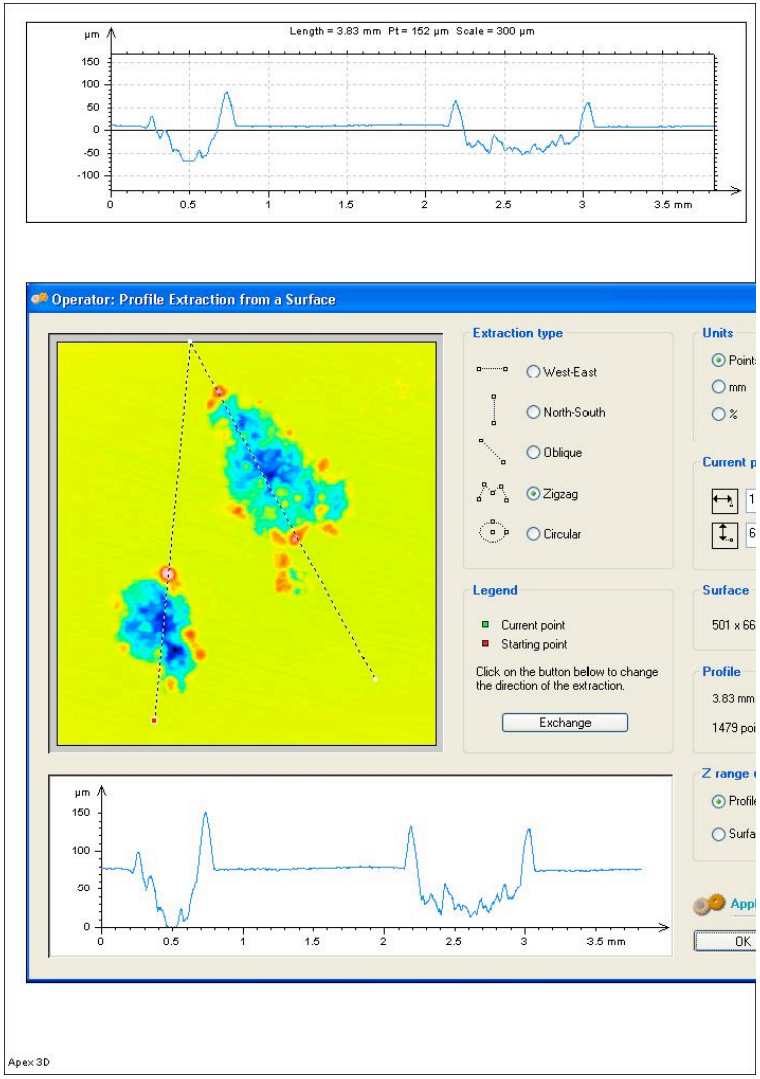
Bob Rimmers multifocus camers.



SEM picture of pit in copper plate.



Profilometer measurements by Genfa Wu



Operator: Profile Extraction from a Surface

Extraction type: ● Zigzag

Units: ● Point

Legend:

🟩 Current point

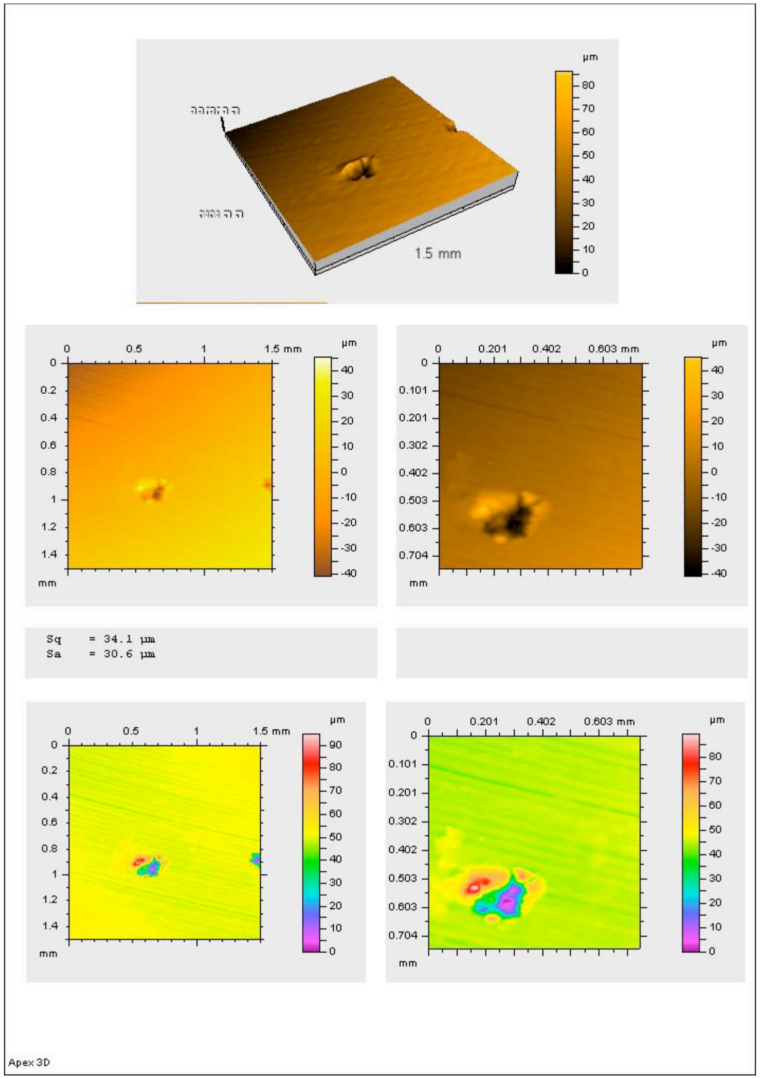
🟥 Starting point

Click on the button below to change the direction of the extraction.

Surface: 501 x 66

Profile: 3.83 mm, 1479 poi

Z range: ● Profile



Sq = 34.1 µm

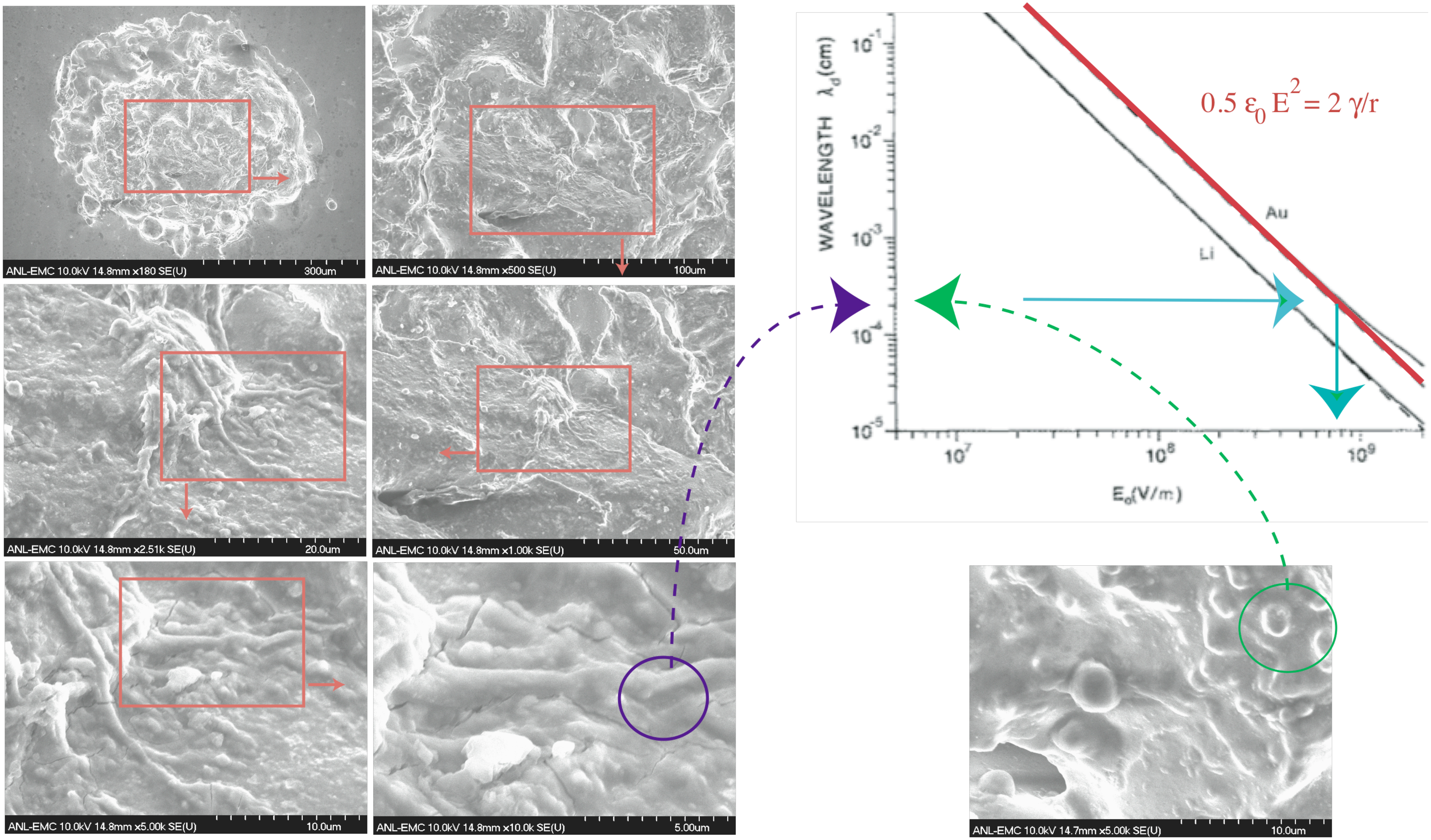
Sa = 30.6 µm

Probe size

The damage is not entirely random..

Things are chaotic at large dimensions, smoother at smaller ones, & structure ~ 2 μm.

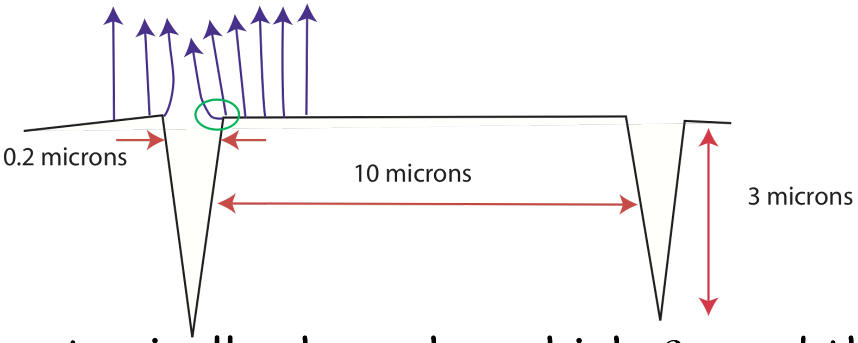
Setting electric pressure = surface tension gives an equilibrium.



Cooling, cracks and β's:

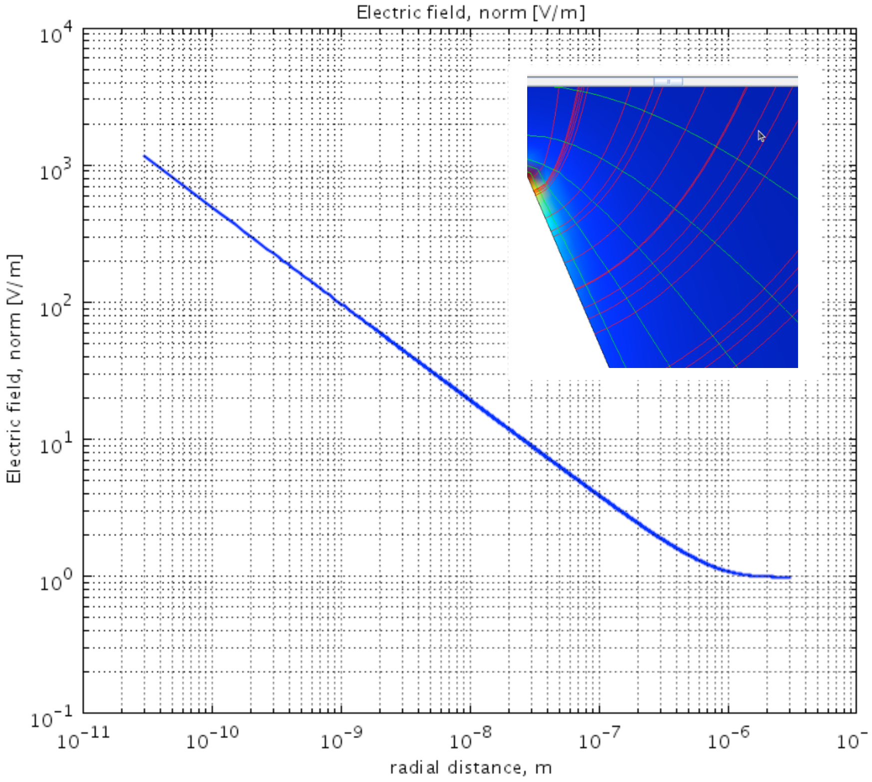
- Melted copper (~3 μm thick, at ~1000 degC) cools and cracks.

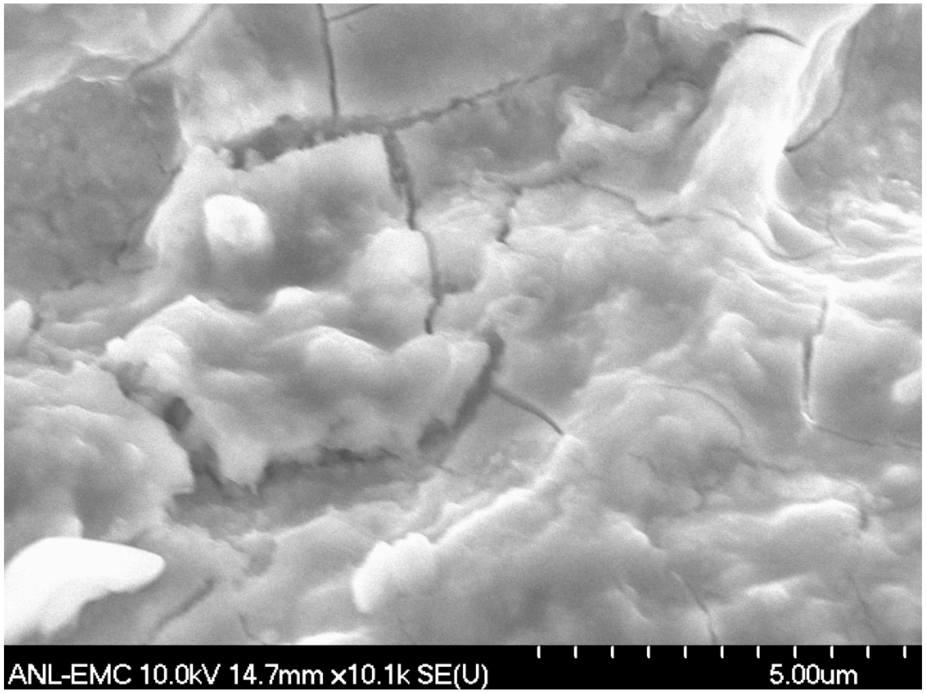
  Crack width: dx ~ $(17 \times 10^{-6}) * 1000 * x$ ~ 2% x, x = 10 μ => dx ~ 0.2 μ.



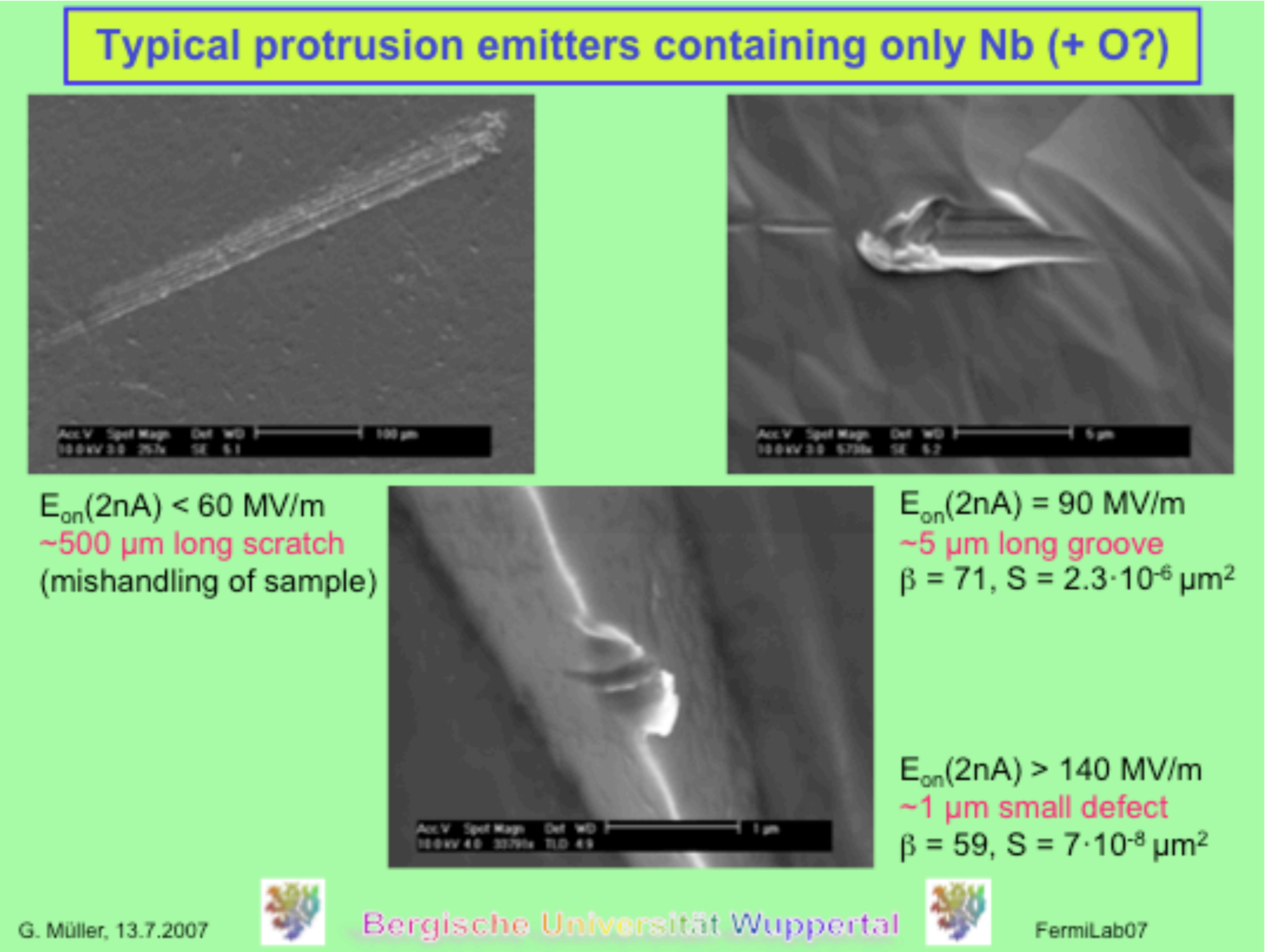
Can be modeled by a cone.

- Corners are atomically sharp, have high βs, and there are lots of them.





Field emission microscope measurements show high βs.



Typical protrusion emitters containing only Nb (+ O?)

$E_{on}(2nA) < 60$ MV/m
~500 µm long scratch
(mishandling of sample)

$E_{on}(2nA) = 90$ MV/m
~5 µm long groove
$\beta = 71$, $S = 2.3 \cdot 10^{-6}$ µm^2

$E_{on}(2nA) > 140$ MV/m
~1 µm small defect
$\beta = 59$, $S = 7 \cdot 10^{-8}$ µm^2

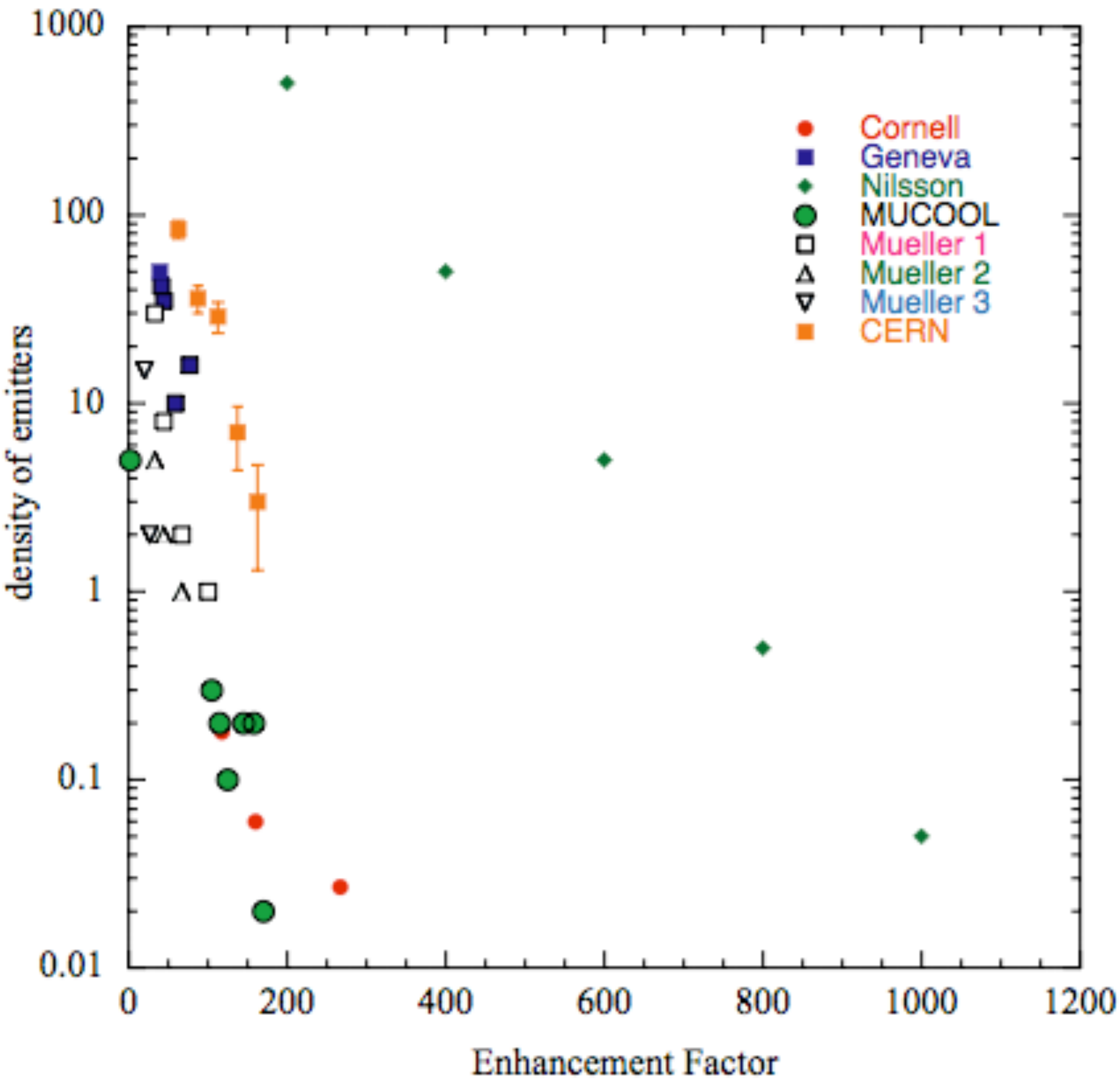
G. Müller, 13.7.2007

Bergische Universität Wuppertal

FermiLab07

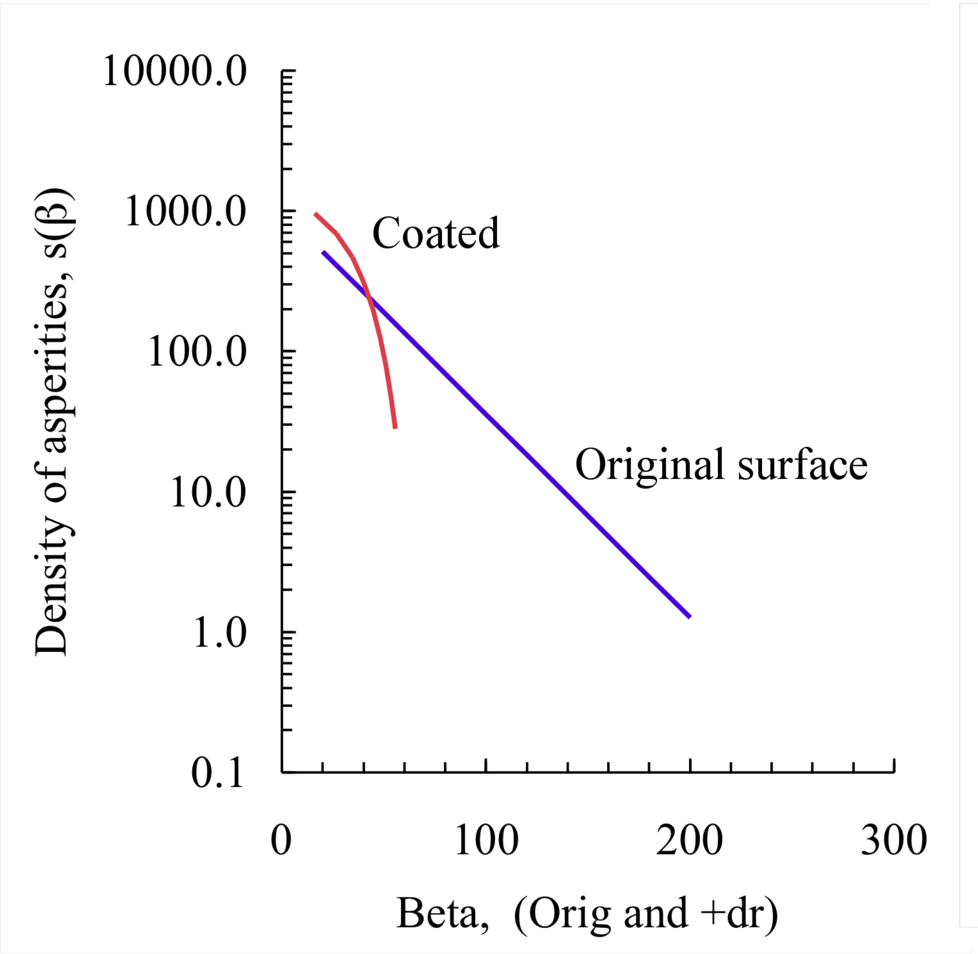
There is a spectrum of enhancement factors.

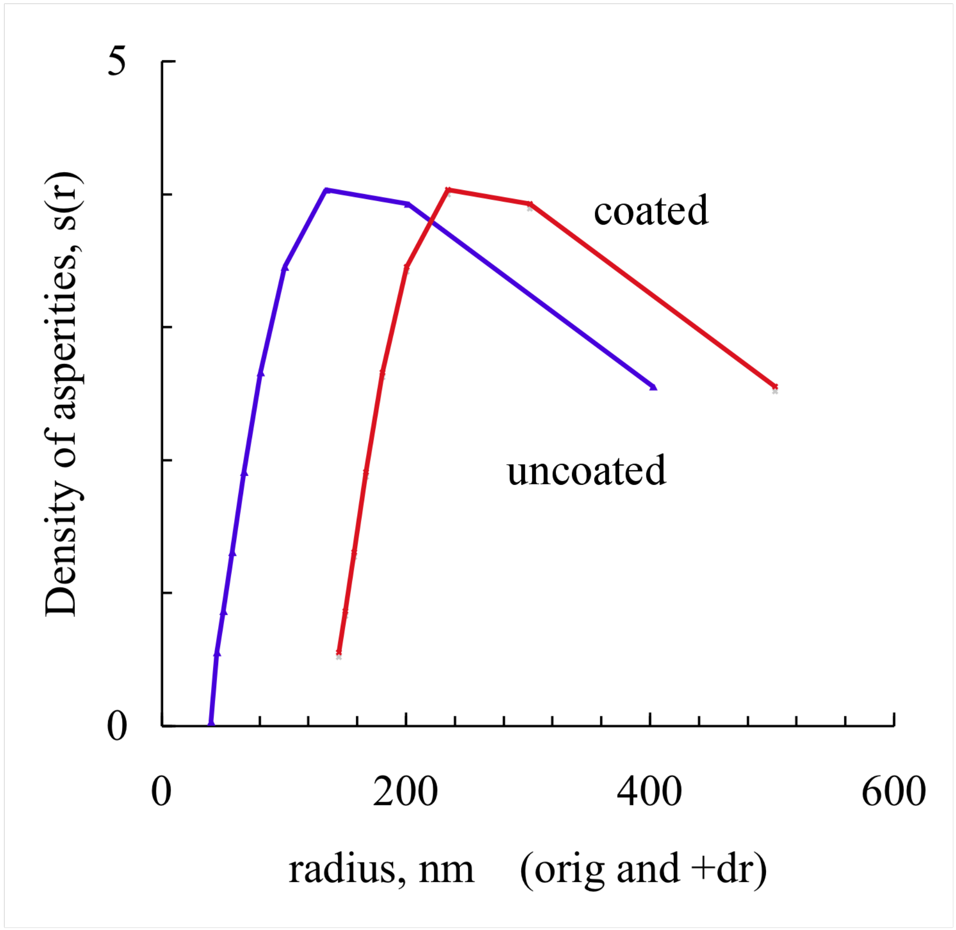
- Everyone sees roughly the same thing.



Smoothing the surface should make cavities "Breakdown Proof".

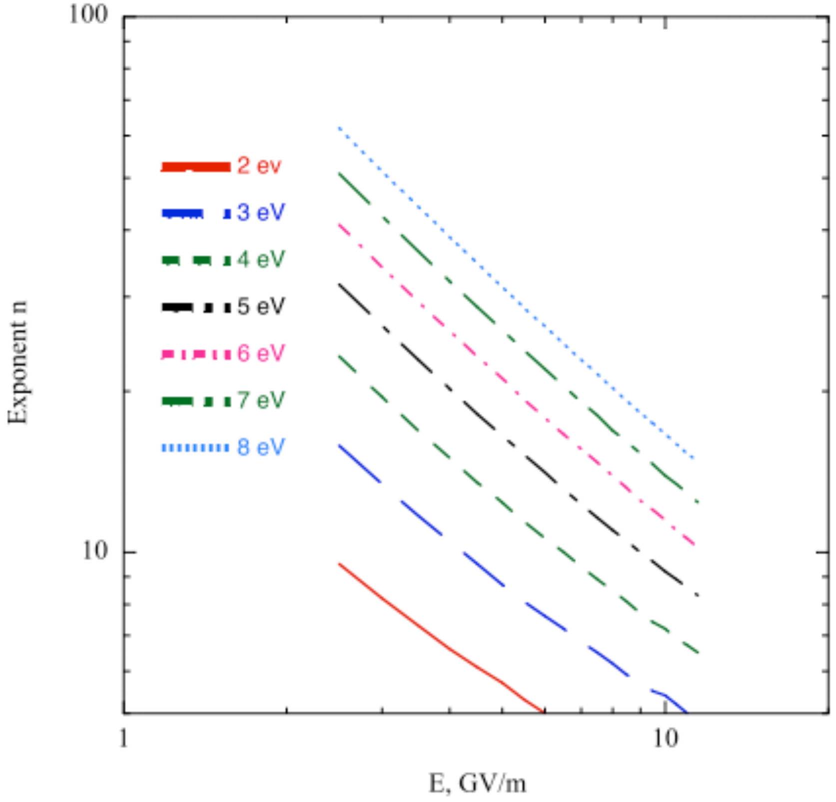
- What is the effect of increasing the emitter radius?

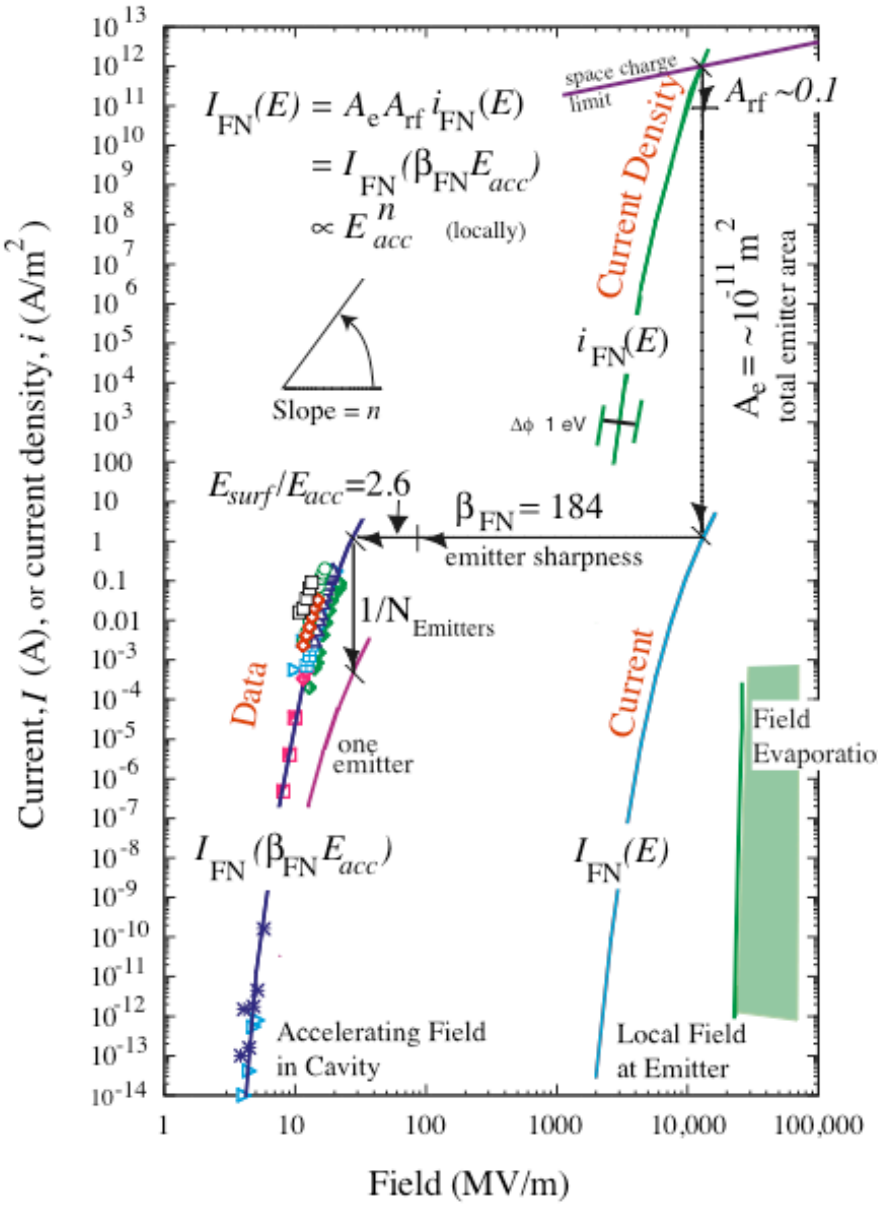




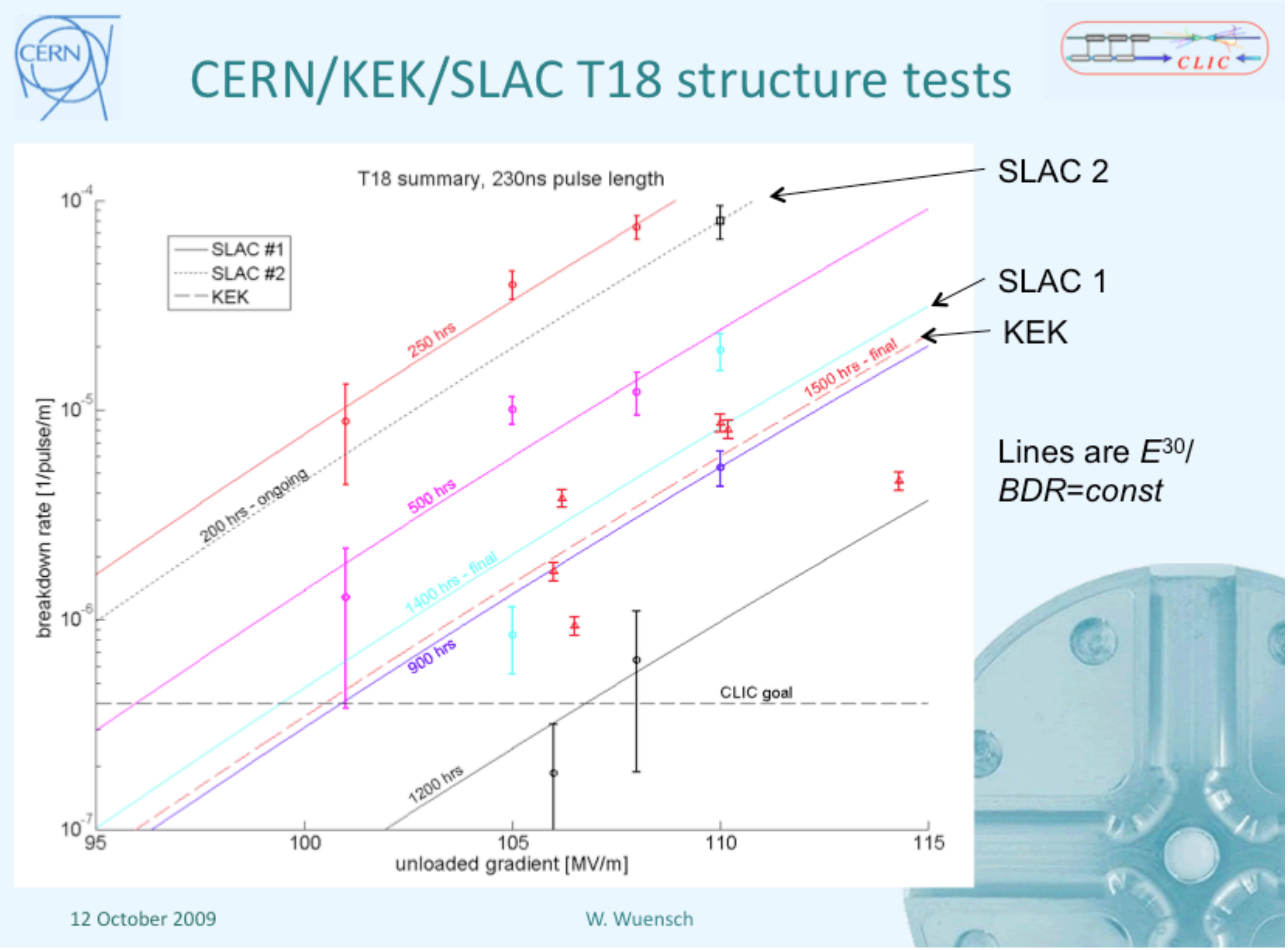
- This argument is scale invariant.

Field emission goes like E^{14}.





Breakdown rates go like E^{30}.



CERN/KEK/SLAC T18 structure tests

SLAC 2

SLAC 1

KEK

Lines are E^{30}/
BDR=const

12 October 2009

W. Wuensch

ALD can extend common sense to the nanoscale.

- We would never tolerate random cm or mm scale sharp points in cavities.
- We do have many asperities with radii ~4 – 10 nm, which we cannot remove.
- Conformal coatings can eliminate small radii.
- Since $I_{FN} \sim E^{14}$, and $BDR \sim E^{30}$, and $E \sim 1/r$, increasing the radius of nano-asperities by a factor of three would reduce I_{FN} by ~ 10^7 and the BDR by ~ 10^{14}.
- Atomic Layer Deposition can produce conformal, conducting coatings of a number of materials.
  - These coatings have been demonstrated at ~75 MV/m in SRF structures.
  - The primary experimental problems are associated with power couplers etc.
  - Tungsten seems to be the best thing to try first.

“Breakdown Proof”: proof-of-principle and RF cavity tests

- The primary questions are the radius of the asperities, and deposition chemistry.
- We are considering an experiment that uses pre-sharpened pins that we can sequentially coat and measure the field emission current. Depositing a known thickness of material conformally on the tips we should be able to “turn off” field emission, and measure the radius of the emitter (breakdown site).
- We can also do this in-situ in a cavity. The experiment would involve
  - First: Condition the cavity & measure the dark currents at maximum gradient.
  - Then: Coat the cavity with ALD using known thickness of different metals.
  - Measure the field emission as a function of ALD coating thickness.
- The cavity might look like this.