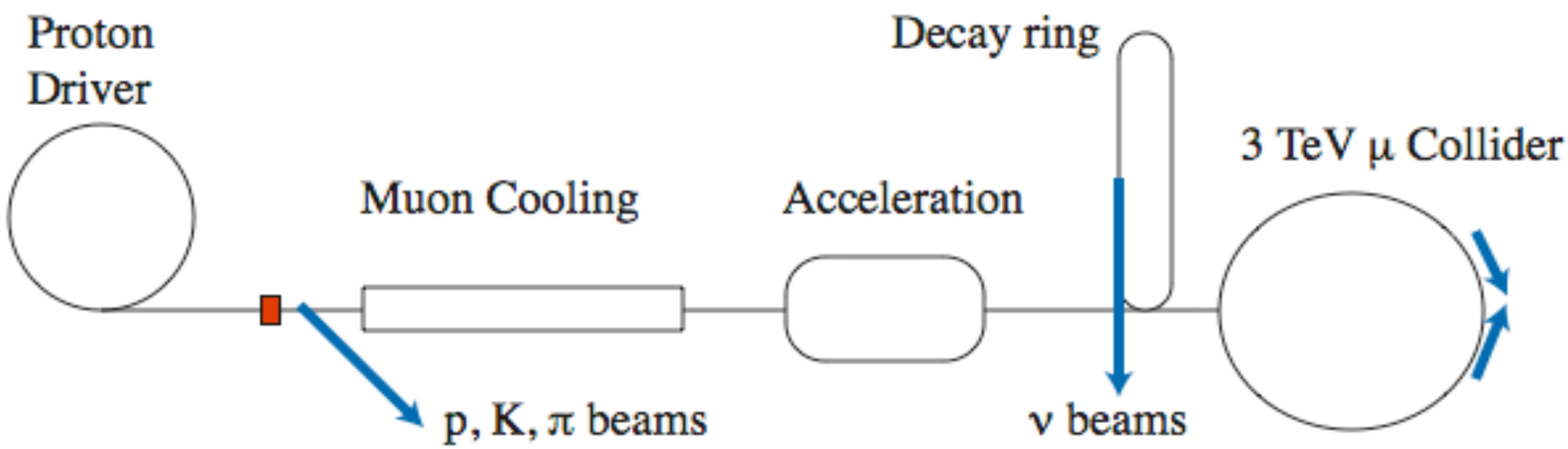
High Gradient Limits in Linacs

J. Norem
ANL/HEP

High Gradient rf for CLIC
U of Md.
1/23/8

There is another High Gradient Collaboration - in the NFMCC



- We have a ~ ten year head start.
- Supported by the NFMCC and, lately, by ANL internal funding.
- A highly diverse and multidisciplinary effort.
- We look at all technologies: SCRF, Normal and DC, dielectrics.
  - Success at solving some classic problems.
- We are proposing solutions which could raise SC and NC gradient limits by >3X.

Many people have contributed.

Normal Conducting		
A. Hassanein	Plasma Phys	ANL Numerical Modeling
Z. Insepov	Fracture kenetics	ANL Numerical Modeling
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Y. Torun	RF, instrumentation	IIT
R. Rimmer	cavity design, expts.	JLab
D. Li,	cavity design, expts.	LBL
M. Zisman	Expt design	LBL
D.N. Seidman	High E / materials	Northwestern U
S. Veitzer	Plasma modeling	Tech-X
P. Stoltz	Plasma modeling	Tech-X
Superconducting		
M. Pellin	ALD, expts	ANL/MSD
G. Elam	ALD, expts.	ANL/ES
J. Moore	ALD, expts.	MassThink LLC
A. Gurevich	SCRF theory	NHMFL
J. Zasadzinski	SC theory and exp	IIT
Th. Proslier	SC theory and exp	IIT

We have been successful.

- We have accumulated good data on breakdown sites and cavity behavior.
  Unique apparatus (B~5T) permits detailed study of asperities
  Interest in Be, thin walls, gas filled, DC, intense beam loading, etc.

- We understand and model breakdown and operational limits.
  Integrated model of breakdown and gradient limits.
  Well documented: ~70 pages in refereed journals. Many other papers

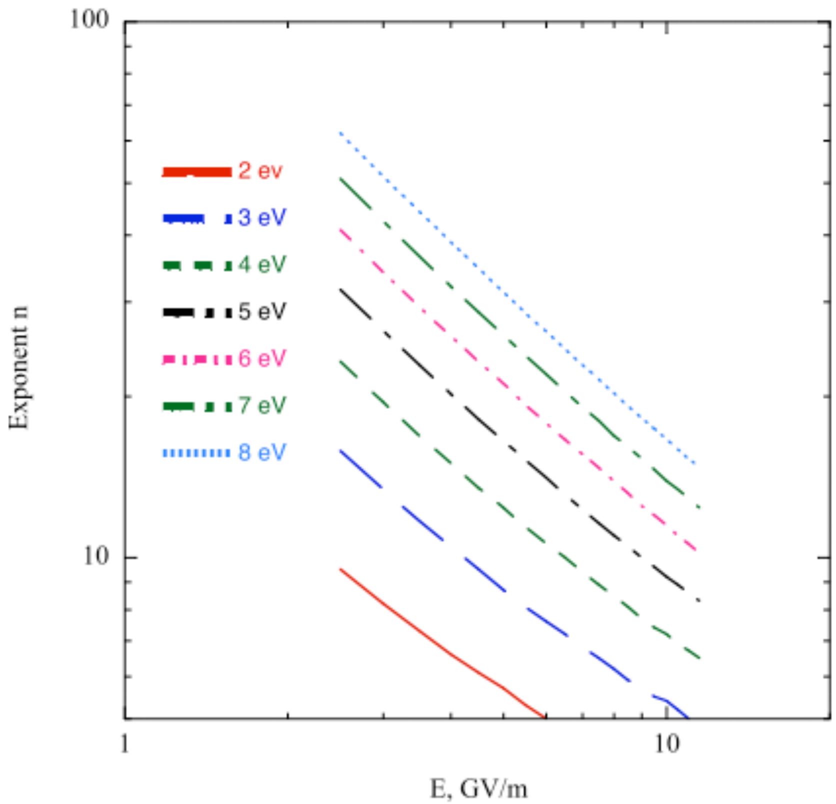
- We try to expand the model to explain the worlds high gradient data
  High f, SCRF (Q-slope, field emission, etc). DC, Mat'ls Sci,

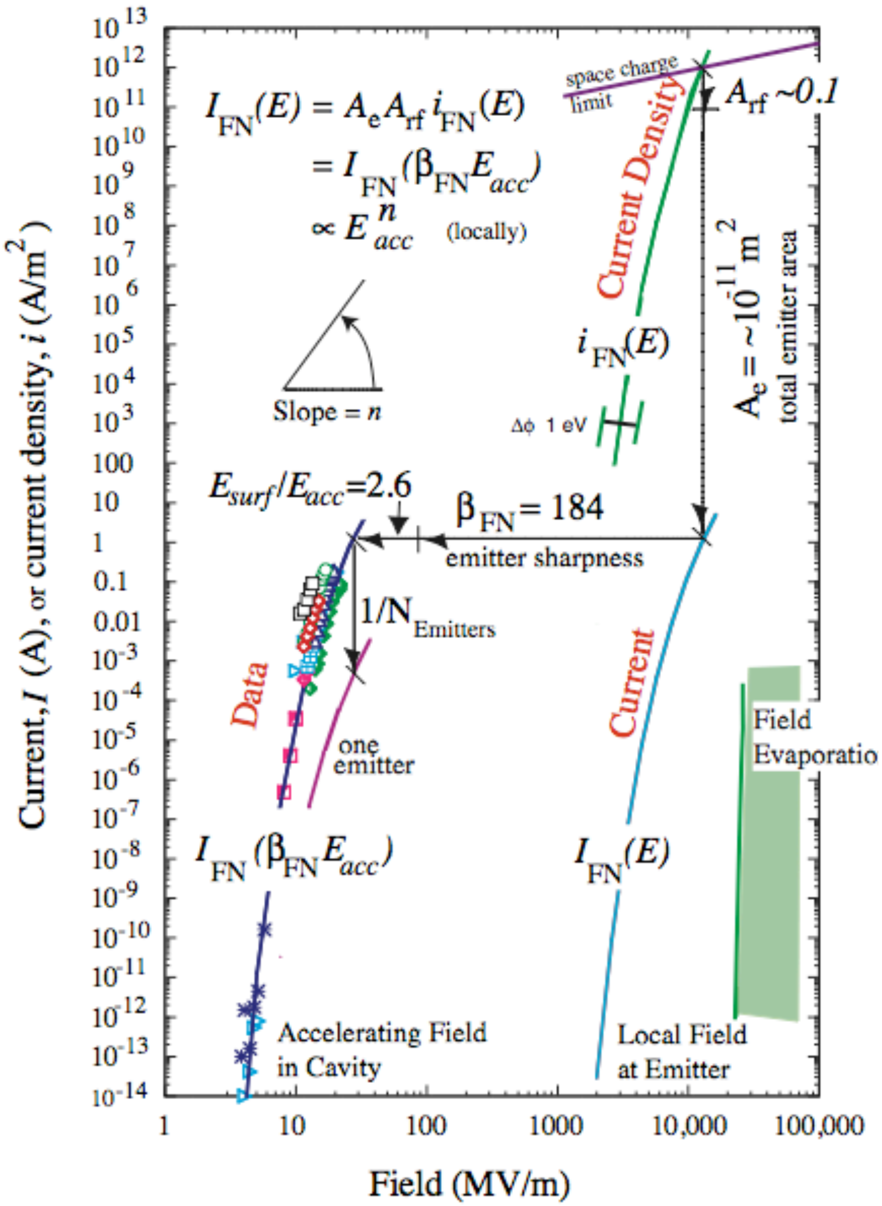
- . . and find ways to increase gradients by large factors.

4 slides that explain everything ➽ ➽

1) Local electric fields are easy to measure.

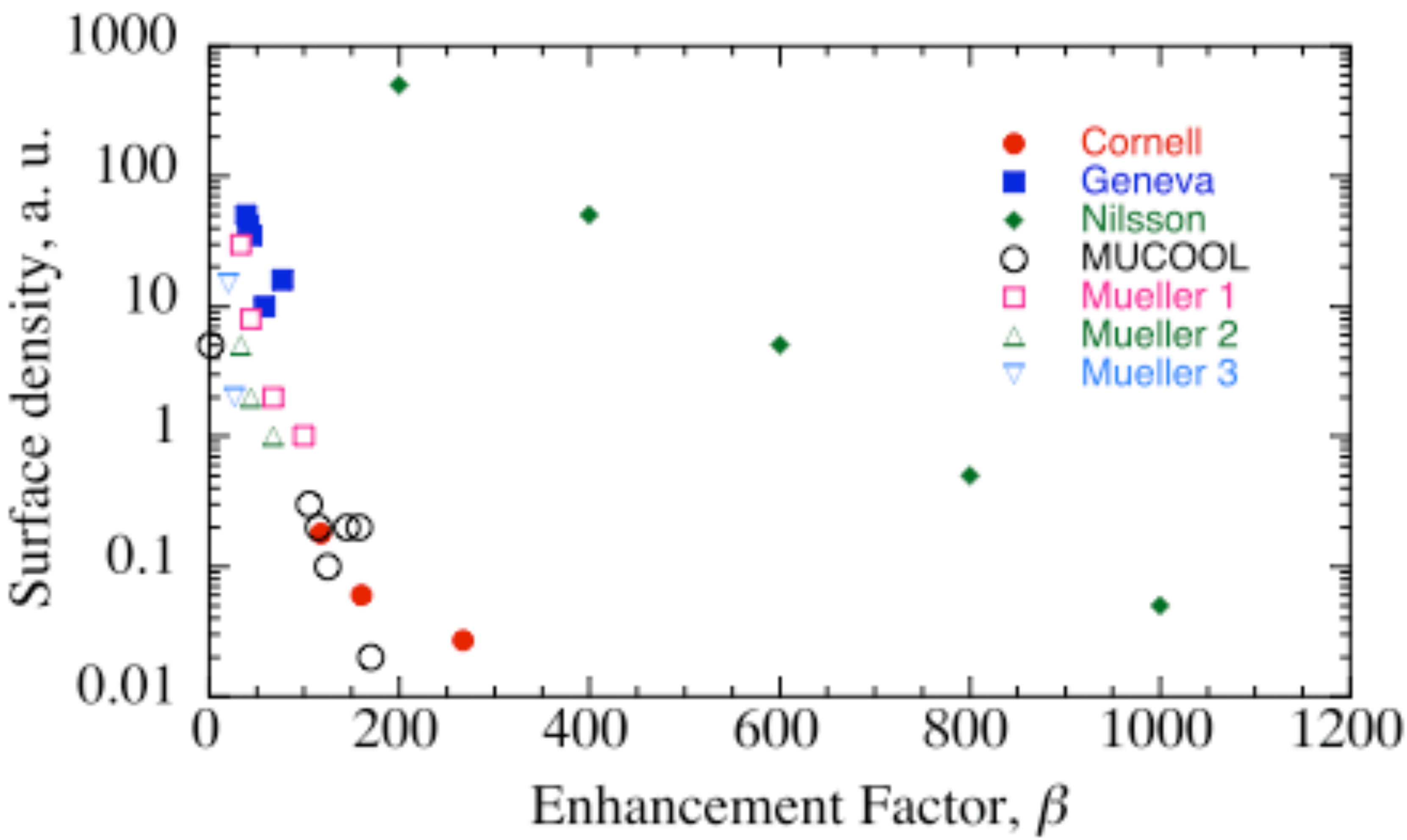
- FN can be approximated by $I = E^n$.
- The local surface field = f(n, ϕ).





2) Enhancement spectra are also measured, in many environments.

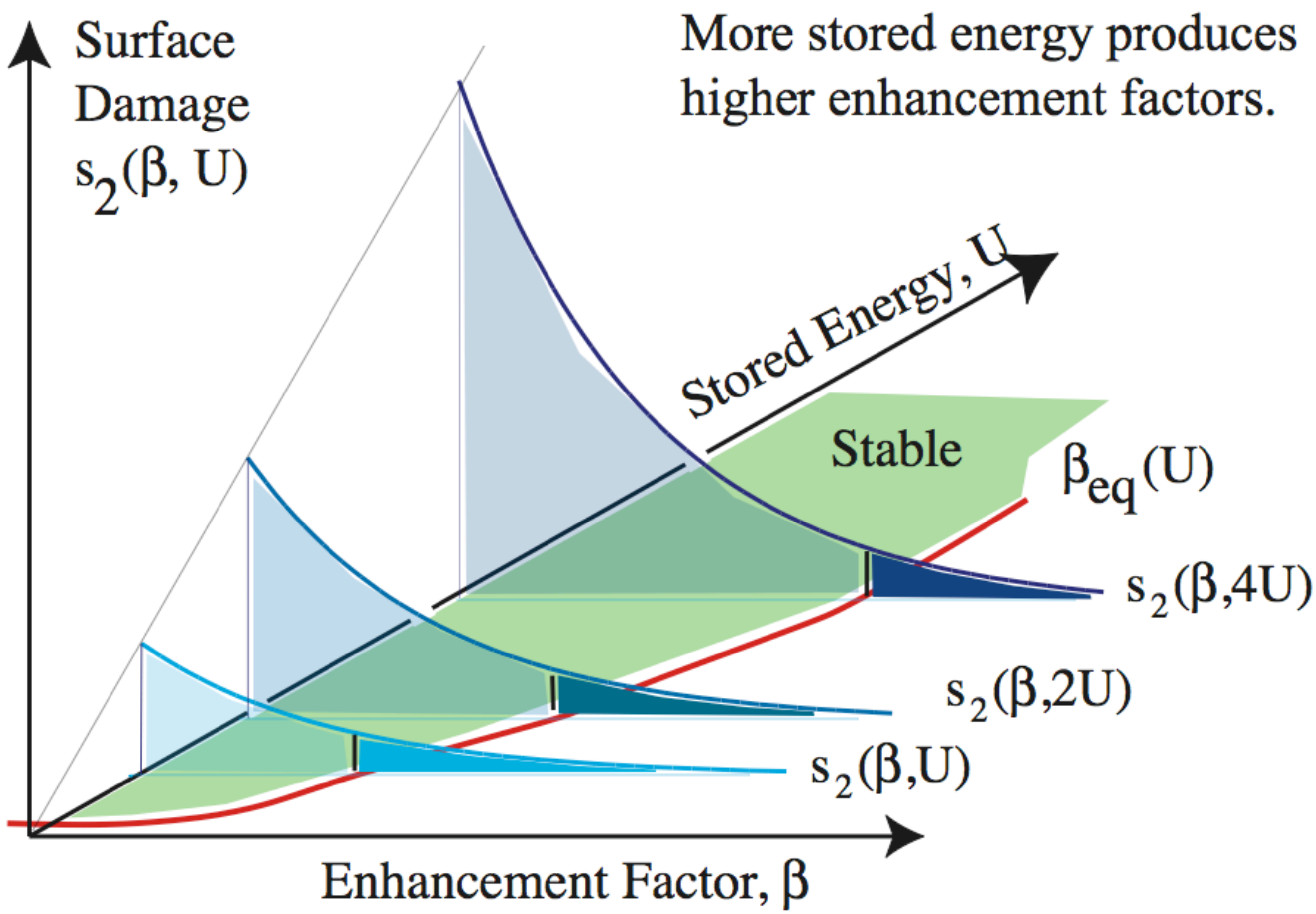
- We assume that the density of emitters looks like $Ae^{-C\beta}$.
- A wide variety of data is consistent with this parameterization.



3) RF breakdown triggers are due to tensile stress & fatigue.

4) Gradient limits depend on the overall system parameters.

- Accelerating fields of ~460 GeV/m have been seen in copper – not really relevant.
- $\beta_{eq}(U)$ defined by $\int_{\beta_{eq}}^{\infty} s_2(\beta, U)d\beta \sim c$
- If the damage goes like $e^{-C\beta}$, then $E_{max} \sim 1/\ln(U)$.



Results of the model.

We can explain pretty much all the experimental data:

- Pulse length
- Electric field
- Materials dependence
- Conditioning status
- The fully conditioned state
- Gas type
- Gas pressure
- Magnetic fields
- Frequency dependence
- DC gaps
- Temperature dependence
- Correlated breakdown events
- Timescale of breakdown process
- Plasma spots
- Crater clustering
- PS and geometry dependence of gradient limits
- Surface heating
- Fatigue

- Disappearance of field emitters during breakdown
- Simple failure of atom probe tomography systems
- Surface morphology
- Superconducting systems
- Positive and negative potentials

- . . . etc.

See AIP Conf. Proc. 877

5) We also have elegant ways of raising gradients.

- The enhancement factor is determined by the radius of asperities.
- We have measured these to be around 20 nm radius.
- Increasing the radius will decrease the enhancements.
- ALD systems can "dull the points" with conformal coatings. 200 nm coatings can be done in a few minutes allowing ~ 1 GV surface fields.
- Huge gradient increases possible – SCRF and NC !

New Developments with SCRF and NC gradients:

- A new effort will involve Argonne Materials Scientists (+ local Universities) in accelerator problems. Argonne effort is based around Atomic Layer Deposition. So far, this is supported by internal Argonne funds.

- We have had great success with our initial efforts:

  1 A new, and persuasive, model of high field Q-Slope in SCRF systems (IIT).

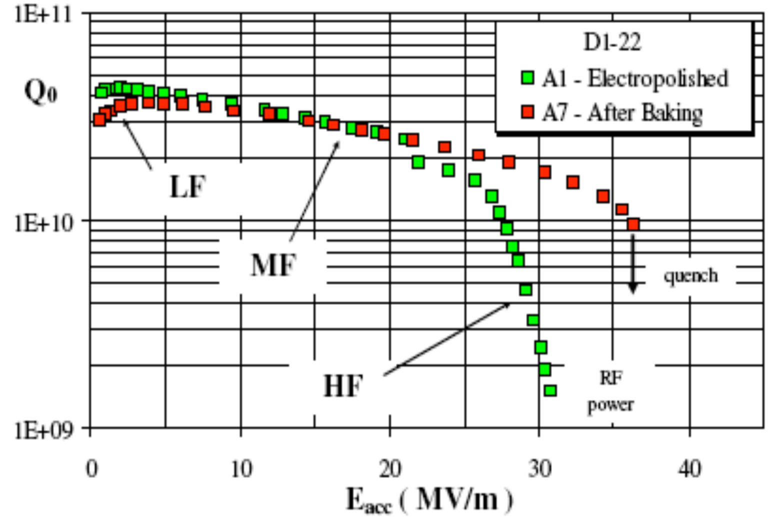
  2 A new way to control SCRF surface chemistry.

  3 Practical ways to simultaneously attack all(?) the SCRF limits.

  4 Ideas on improving normal conducting structures.

A new model of losses in SCRF systems.

- Q-Slope is an anomalous loss that appears at high gradients in SCRF systems.



- Theoretical and experimental effort has been inconclusive.

- We can present a better argument.

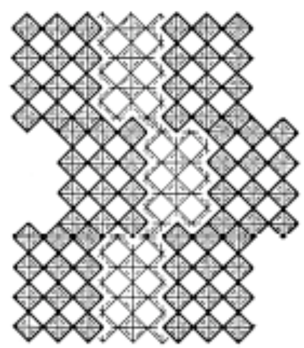
	Q-Slope Fit	Q-Slope before baking (EP = BCP)	Q-Slope Improvem[t] after baking	Q-Slope after baking (EP < BCP)	No change after 4 y. air exposure	Exceptional Results (BCP)	Q-Slope unchanged after HF chemistry	TE_{011} Q-slope after baking	Quench EP > BCP	BCP Quench unchanged after baking	Argum[t] Validity	Fund[al] Disagreem[t] Exper. ≠ Theory
Magnetic Field Enhancem[t]	Y simulat. code	N $\beta_m \neq B_{C2}^S \neq$	Y $B_{C2}^S \uparrow$	Y lower β_m	-	N high β_m	-	-	Y lower β_m	N $B_{C2}^S \uparrow$	Y	D_1
Interface Tunnel Exchange	Y E^8	N $\beta * \neq$	Y $Nb_2O_{5-y} \downarrow$	Y lower $\beta *$	N $Nb_2O_{5-y} \uparrow$	N high $\beta *$	N new Nb_2O_{5-y}	N improv[t]	-	-	Y	D_2
Thermal Feedback	Y parabolic	Y ≈ thermal properties	Y $R_{BCS} \downarrow R_{res} \uparrow$	N ≈ therm. propties	-	-	-	-	-	-	N C coeff.[t]	-
Magnetic Field Dependence of Δ	Y expon[tial]	N $B_{C2}^S \neq$	Y $B_{C2}^S \uparrow$	Y higher B_{C2}^S	-	-	-	-	-	-	N thin film	D_1
Segregation of Impurities	?	N segregation ≠	N only O diffusion	Y surface ≠	-	Y good cleaning	N chemistry	-	-	-	Y	-
Bad S.C. Layer Interstitial Oxygen $Nb_{4-6}O$	?	Y NC layer	Y O diffusion	N	N interstitial re-appears	-	N new bad layer	-	Y higher B_{C2}^S	N $B_{C2} \downarrow$	Y	D_1

We have discovered magnetic oxides (bad) on niobium surfaces.

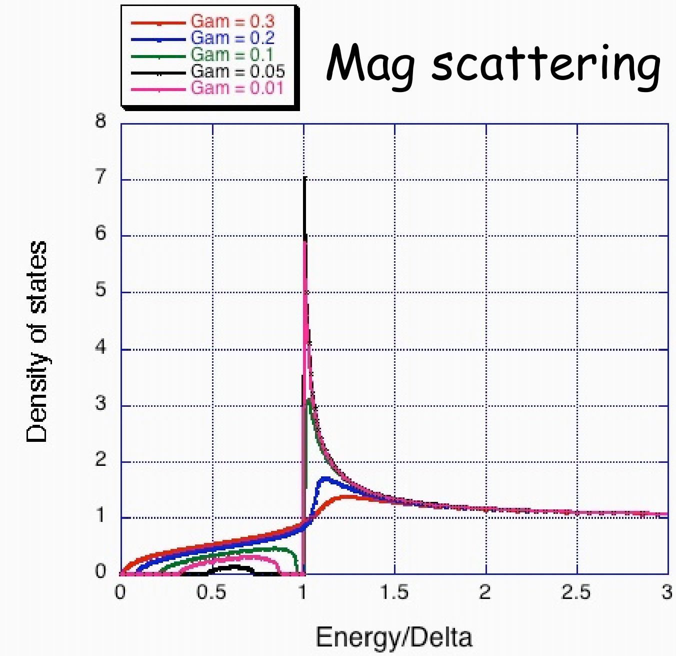
- John Zasadzinski of IIT believes that his point contact tunneling measurements clearly show that these magnetic oxides can break up Cooper pairs and explain high field Q-Slope.

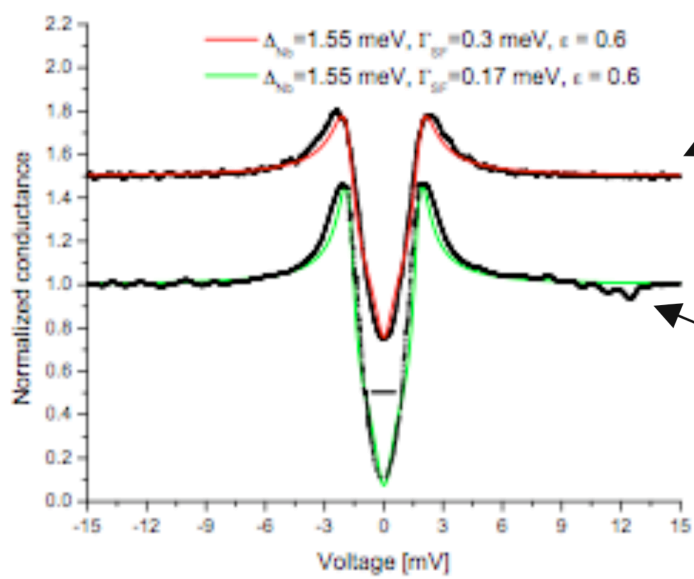
- Described at SRF2007.

- Strange oxides are involved.



$Nb_{12}O_{29}$





Fit using Shiba theory

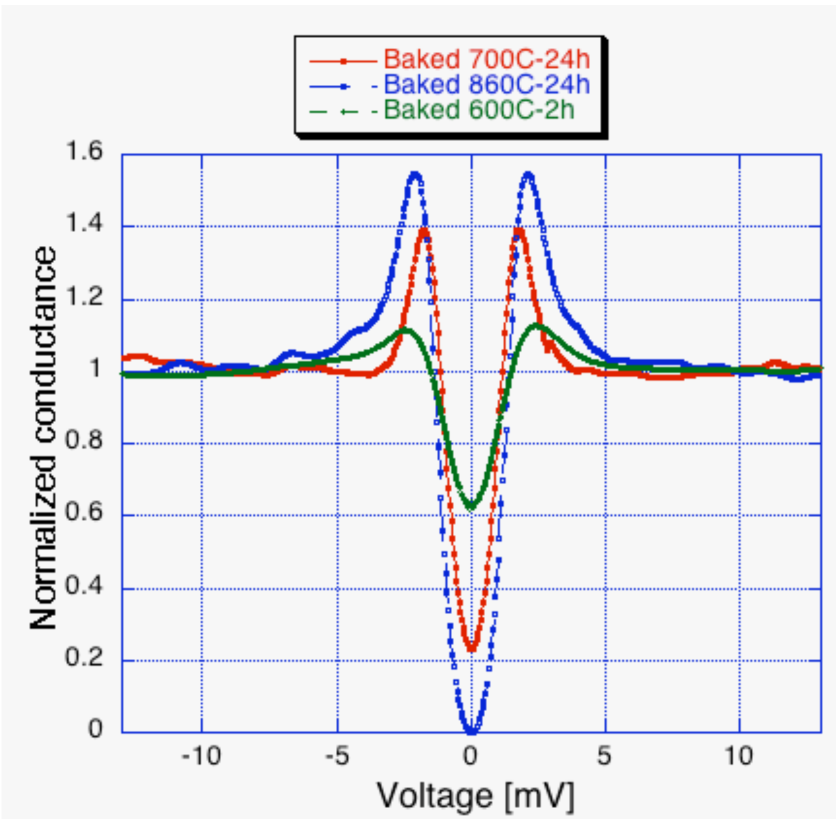
Baked Nb Crystal Shows reduced Magnetic scattering

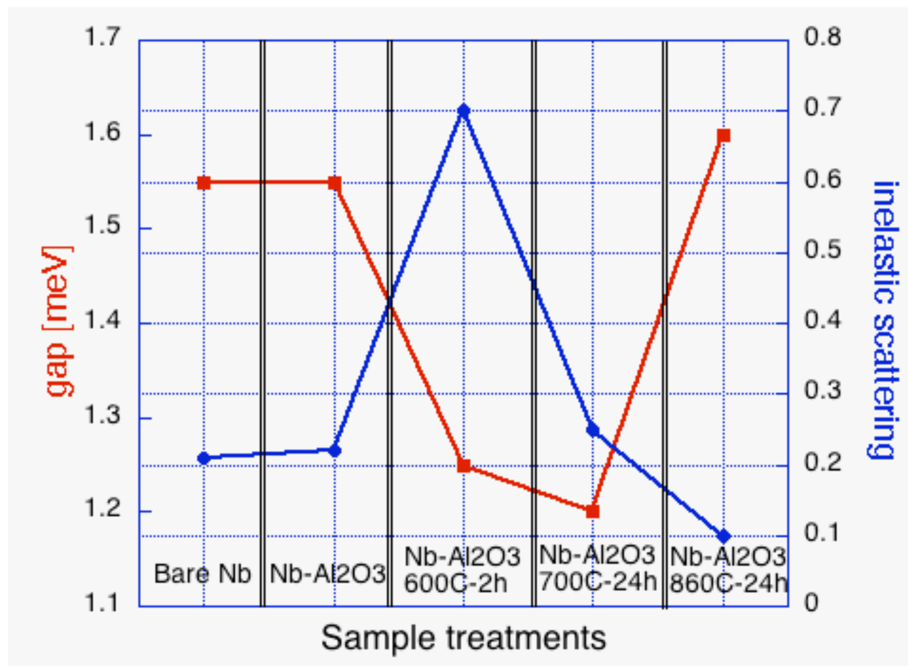
We have demonstrated we can control the surface.

- Using Atomic Layer Deposition, Mike Pellin et. al. have shown that it is possible to control the oxide composition and density in the near surface region of niobium.

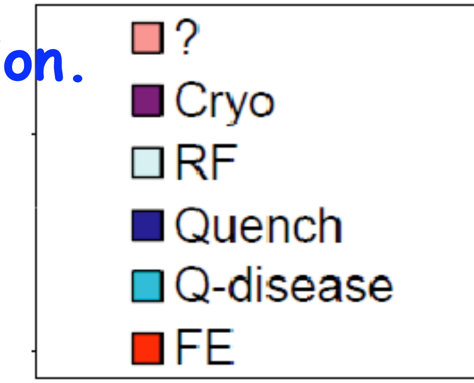
- We are trying to coat a JLab cavity to show that this technique will produce practical accelerator components.

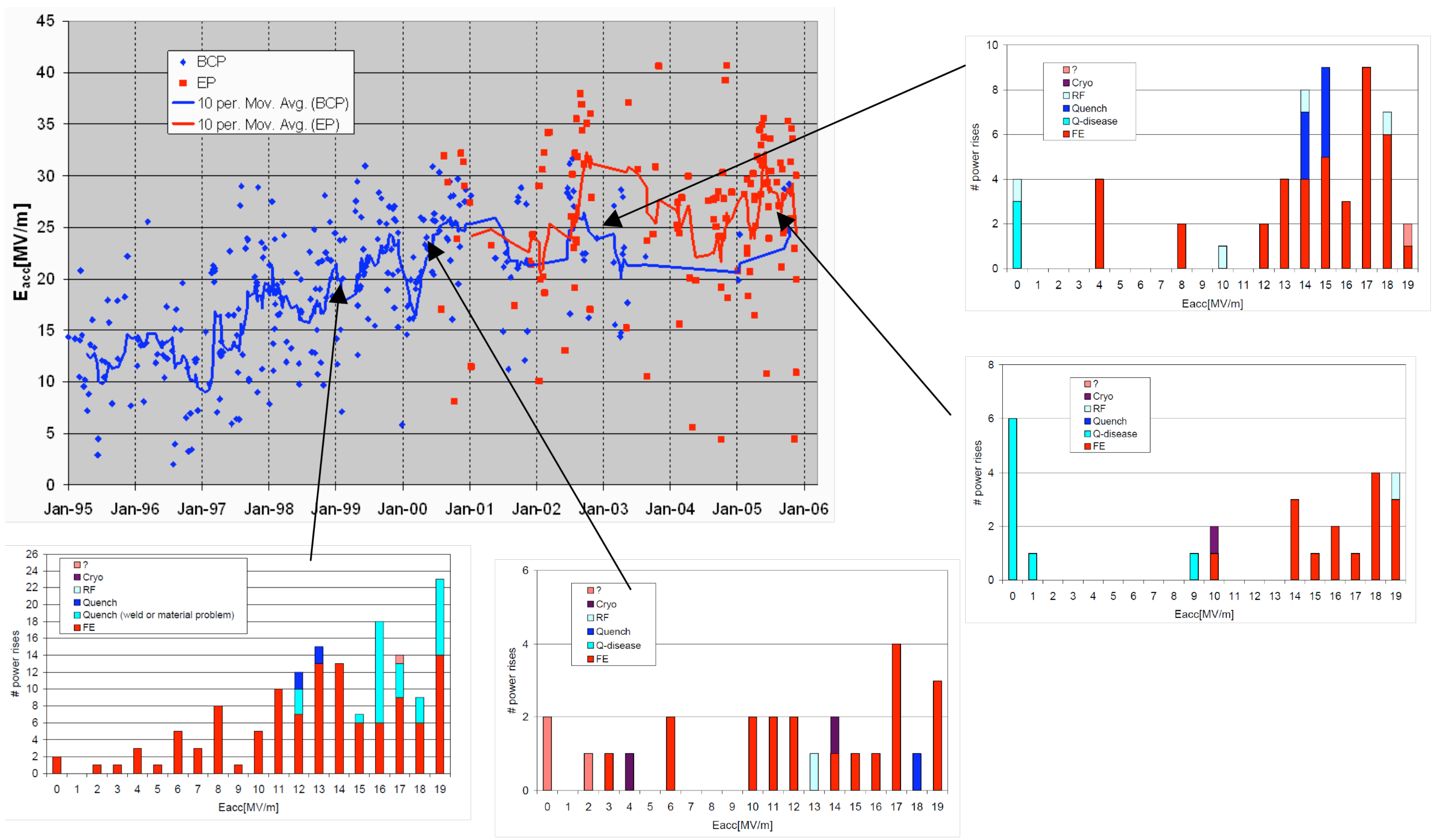
Point contact tunneling measurements show removal of oxides.





The <u>main</u> problem with SCRF is still Field Emission.

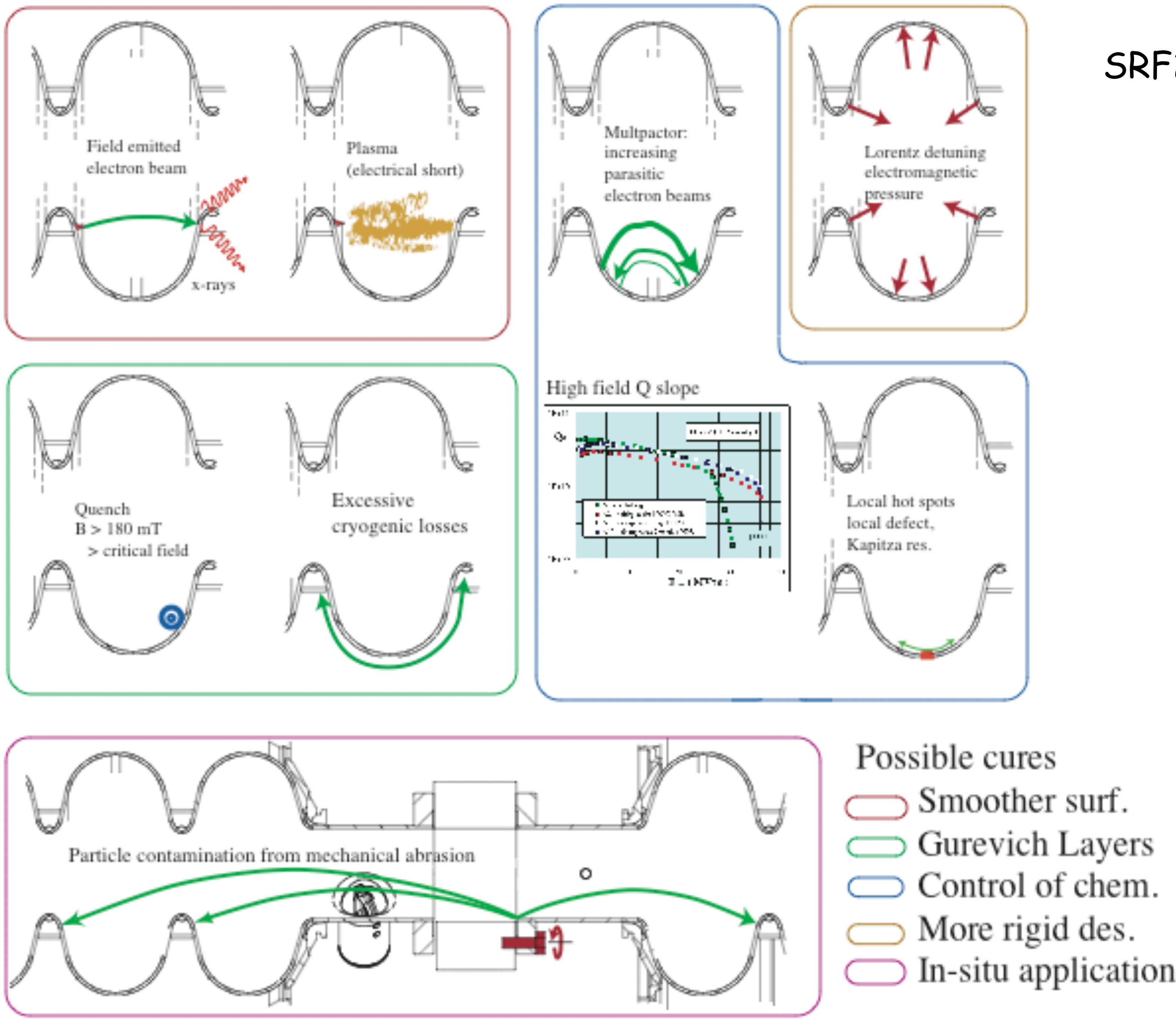




L. Lilje's summary of DESY cavity databank, DESY, 200

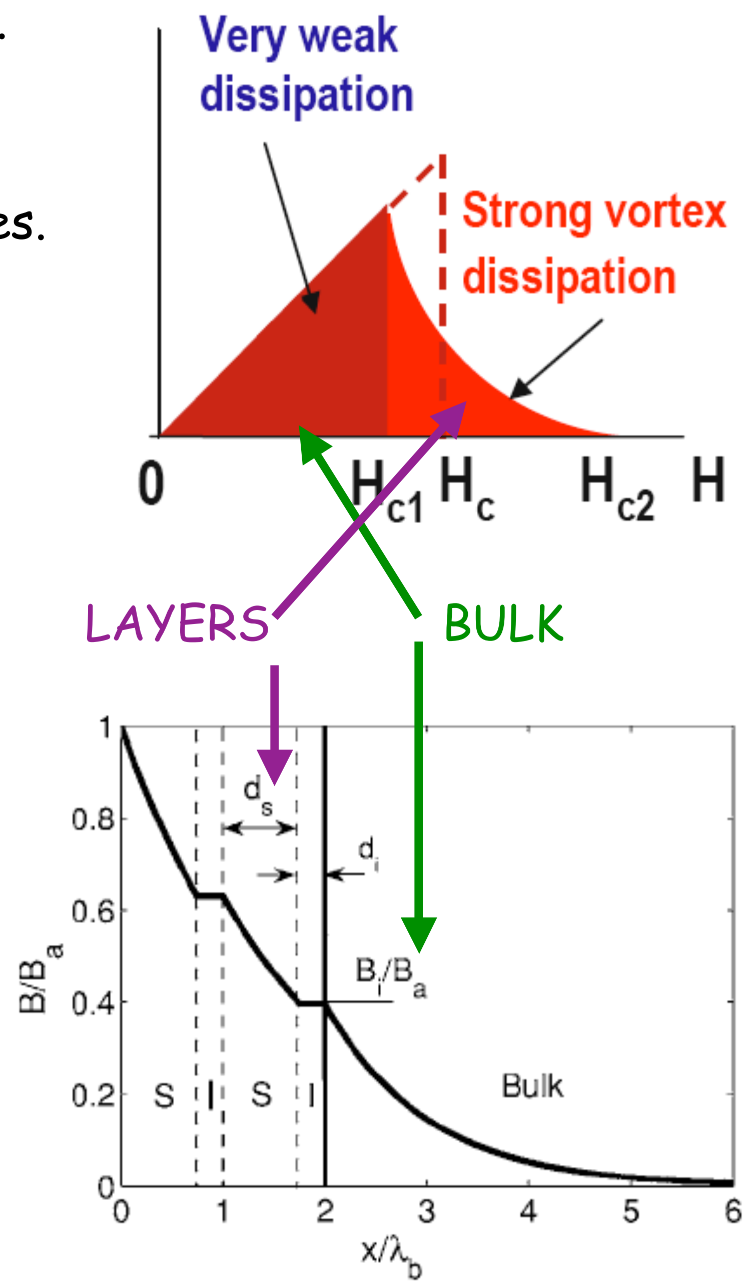
Can all SCRF problems can be solved with ~100 nm ALD coatings?

SRF2007



Why do layered superconductors have higher quench fields?

- Vortices in superconductors move in AC fields.
  ⇒ rf losses.
- Nb can reach the highest field without vortices.
  ⇒ Use as bulk material.
- Vortices aren't stable in thin layers.
  ⇒ Use to "screen" AC fields from bulk.
- This is a hard geometry to construct.
  Nb is "bulk" material, i.e. top 200 nm.
  Nanometer precision required for layers
  No shorts or voids in insulators.
  ALD can do it.



See A. Gurevich. Appl. Phy. Let. **88** 012511, (2006)

Normal conducting systems (μ cooling, CLIC) can also benefit.

- ~100 nm smooth coatings should eliminate breakdown sites in NCRF.

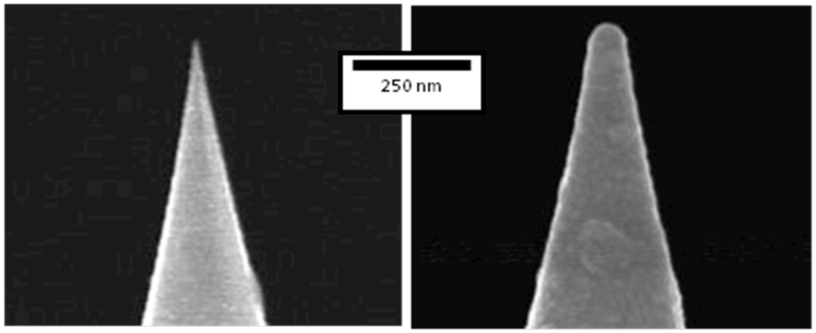


Figure 3: Scanning Electron Microscope images of nearly atomically-sharp tips, before and after coating with a total of 35nm of material by ALD. The tip, initially about 4 nm, has been rounded to 35nm radius of curvature by growth of an ALD film. Rough surfaces are inherently smoothed by the process of conformal coating.

- Copper, however, is a hard material to deposit, and it may be necessary to study other materials and alloys. Some R&D is required. This is underway.

- The concept couldn't be simpler. Should work at all frequencies, can be *in-situ*.

Gas filled cavities and dielectrics

- Muons Inc is doing experiments with high pressure gas rf cavities.
- Two effects of radiation damage:
  - a) integrated structural damage, atomic displacements, etc. – old stuff
  - b) instantaneous ionization damage – not generally considered
- Two dielectric failure modes:
  - 1) Resistive dissipation of cavity energy.
    - Recombination times are very long (~sec)
    - Loss tangent increases during radiation
      - Experimentally measured
  - 2) "instant" loss of cavity energy due to runaway high energy δ rays.
- We will do the experiment.

Conclusions

- We have developed a model which seems to explain high gradient limits.

- We incorporate information on DC, SCRF, High f, Low f, gas filled, beams, etc.

- We also explain High field Q-Slope, SCRF surface effects.
  This work (is/is being) extensively documented.

- The model shows how to cure cavity breakdown.

- I think we can increase SCRF and NC gradients by >3X.
  Can we fix the SNS linacs with *in-situ* coatings?