High Gradient Limits
- and ways to get around them

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Three interesting new efforts:

- We have an rf breakdown model which seems to explain all the classical behavior of rf cavities.

- Nanofabricated SCRF composites: a completely new way to make rf superconductor, that should not be subject to the known gradient limiting mechanisms.

- We are continuing to support GCIB, which is relevant to both normal and superconducting rf systems.

. . . in addition to Muon Collaboration / MICE work.

Modeling Cavity Limits

- Starting with measurements of dark currents in the summer of 2001, we have developed a model which now seems to describe all aspects of this problem.

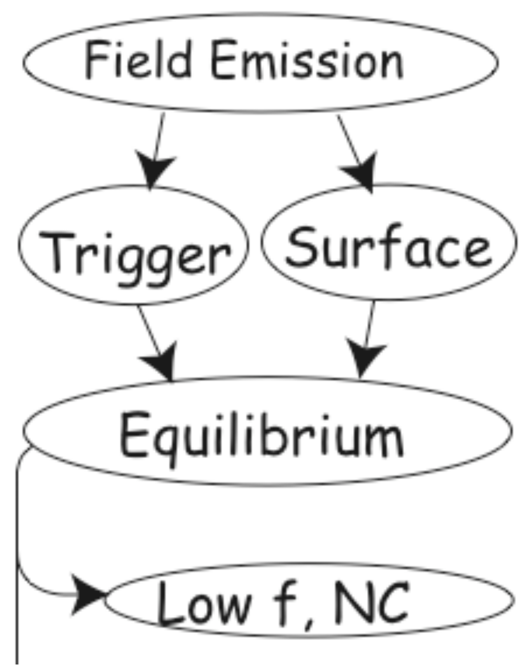
- The model is based on the electro-mechanical stress.

  - Field emission measures E_{local}.

  - Mechanical tearing initiates events.

  - Enhancement spectra are important.

  - An equilibrium develops between the rf fields and the surface.



This model seems to predict everything . . .

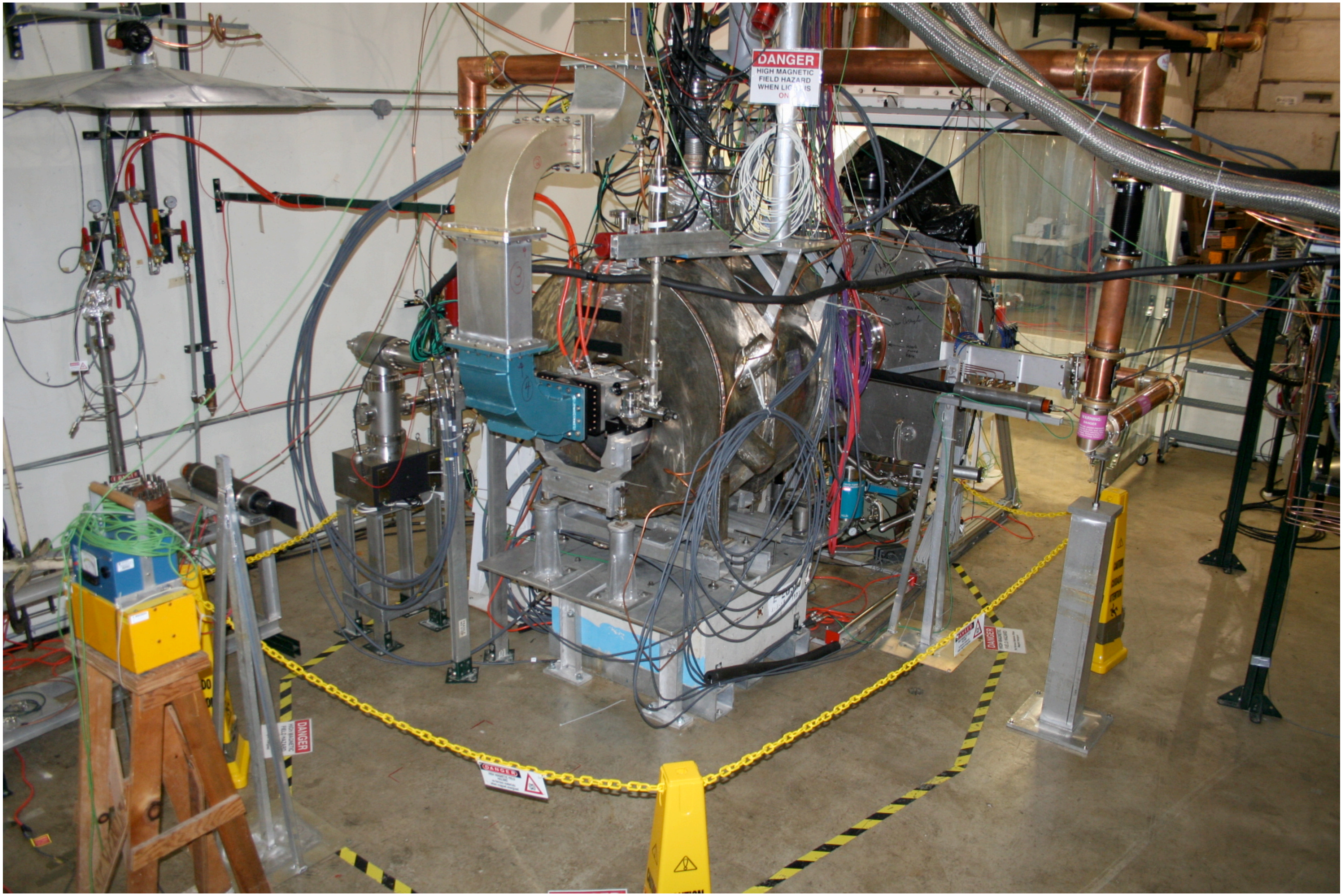
- Materials, conditioning, rate ve E, rates within pulse, rate vs pulse length, correlated breakdown events, long term breakdown rate, DC breakdown events, surface effects in high pressure gas, temperature dependence, frequency dependence, fully conditioned state, surface topology, multipactor, memory of conditioning, superconducting high power processing, rf/DC emission, E_{Max} vs geometry, etc, etc.

But we need:

- Better basic data: Surface, plasma, discharge properties.

- Active interests: E_{max} vs B, high pressure gasses.

The experimental work is done at the Fermilab MTA.



Bibliography

Major papers (~70 pages in refereed journals):

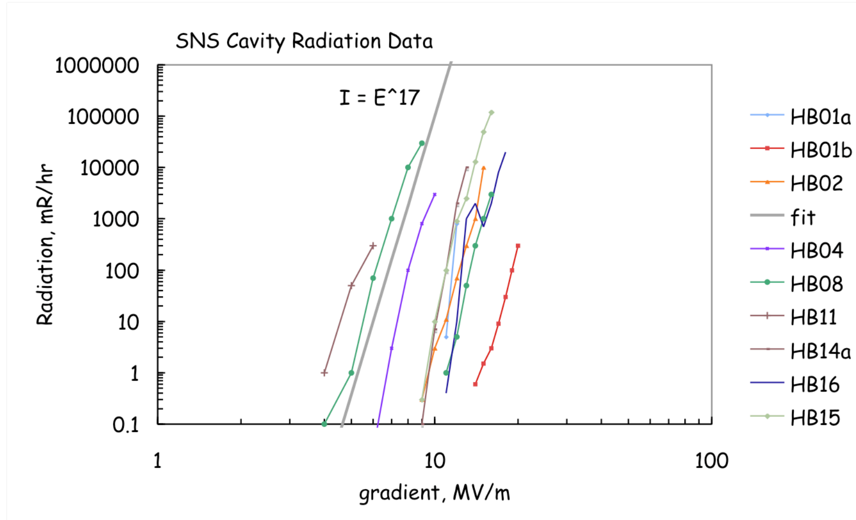
- X ray Spectra, Nucl. Instrum. Meth. Phys. Rev. A. **472**, 600 (2001)
  http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0139/muc0139.pdf
  Measurements of x-rays from a single cell cavity
- Open Cell Cavity, Phys. Rev. STAB **6**, 072001 (2003)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.6.072001
  Measurements of 6 cell cavity, dark current measurements, w/wo B fields, comp. with other cavities, tensile stress
- Cluster emission, Phys. Rev. STAB **7**, 122001 (2004)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.7.122001
  Emission of clusters, thermal and field dependence,
- Breakdown mechanics, Nucl. Instrum. and Meth A **537**, 510, (2005)
  http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0286/muc0286.pdf
  General theory of tensile stress triggered breakdown
- Magnetic fields, Phys. Rev. STAB **8**, 072001 (2005)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.8.072001
  Measurements with 805 MHz pillbox, measurement of $s_2(\beta)$
- Surface damage, Phys. Rev. STAB **9**, 062001 (2006)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.9.062001
  Relationship between surface damage and maximum operating fields.

Nanofabricated SCRF Composites

How SC structures fail:

Field emission and breakdown

Field emitted electrons heat and quenches the superconductor.

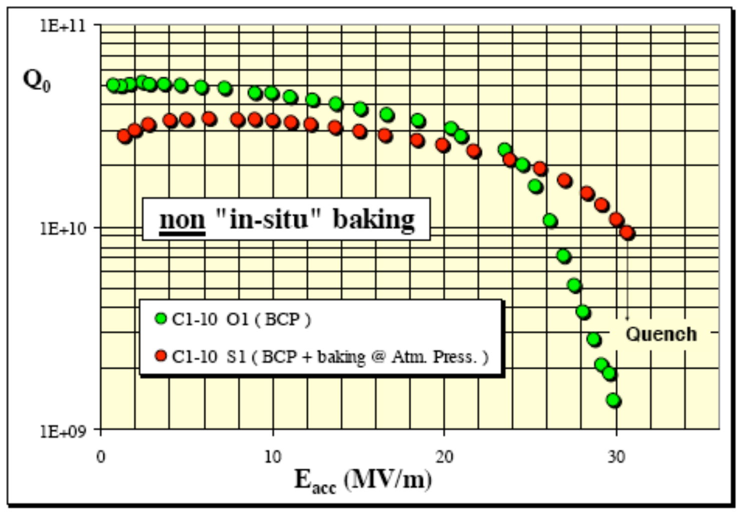


Multipactor

Resonant amplification of low energy electrons.

Quench fields

Cavities quench when *B* > 180 mT



High field Q-slope

Cavity losses rise with impurities and defects.

Thermal

Increased thermal conductivity stabilizes quenches.

Can one design materials that can't fail in these ways?

Designing materials

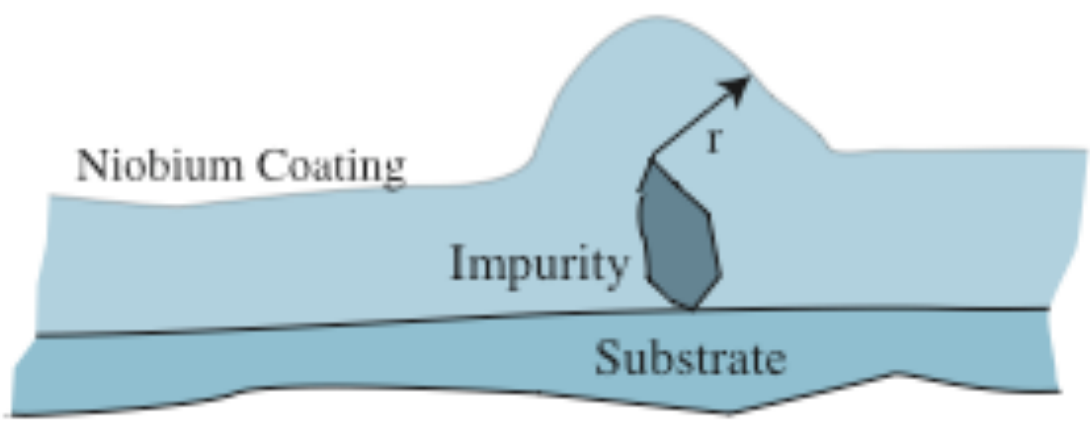
Field emission and breakdown:

Most FE comes from contaminants, since the niobium surface is smooth,.

FE is due to high local fields caused by small local radii. **$E \propto 1/r$**.

With conformal coatings >200 nm, high local fields & breakdown won't occur.

Atomic Layer Deposition can grow coatings on impurities with large local radii.



Multipactor:

Producing low secondary emission coatings can avoid this mechanism

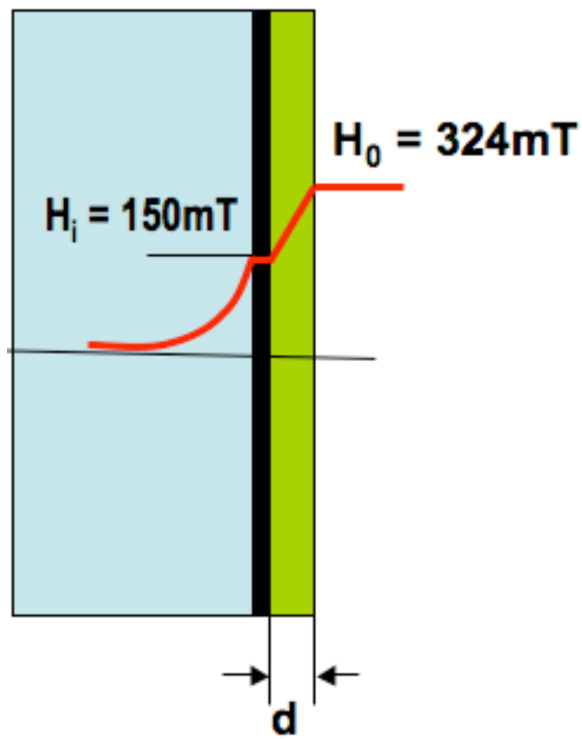
Quench fields

Alex Gurevich, NHMFL, has produced a “cure”, implying E_{acc} >> 50MV/m.

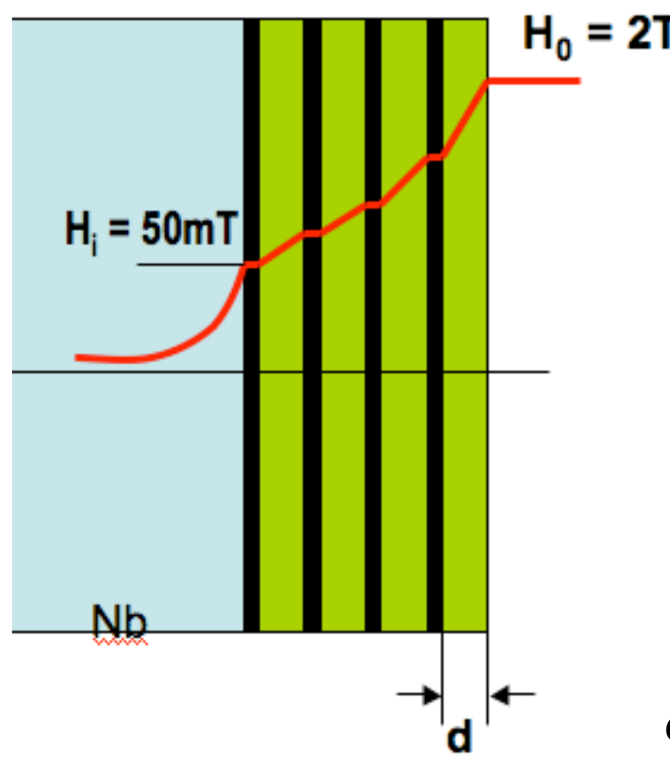
The primary niobium layer is covered with an insulator and superconductor.

The top layer has high T_c, screens quench fields from the bulk niobium.

Multiple layers permit almost arbitrarily large accelerating fields.



would give E_{acc} ~ 100 MV/m



E_{acc} ~ 550 MV/m

d~30-50nm

<u>High field Q-slope</u> (anomalous loss at high fields)

The high field Q-slope seems to be caused by impurities and defects in the superconducting material.

Many explanations proposed.

Ambiguous results

summary

Table 1: Summary statement of comparison between experiments and theoretical models
(Yes or No: theory **can** or **can't** explain experimental result)

	Q-Slope Fit	Slope before baking (EP ■ BCP)	Slope Improvement after baking	Slope after baking (EP < BCP)	No change after 2 m. air exposure	Exceptional Results (BCP)	Quench (EP > BCP)	BCP Quench unchanged after baking	Validity
Magnetic Field Enhancement	Y	N (β_m et $H_C \neq$)	Y ($H_C \uparrow$)	Y ($\beta_m <$; $H_C >$)	-	N (high β_m)	Y ($\beta_m <$; $H_C >$)	N ($H_C \uparrow$)	Y
Interface Tunnel Exchange	Y (E^8)	N ($\beta * \neq$)	Y ($Nb_2O_{5-y} \downarrow$)	Y (low $\beta *$)	N ($Nb_2O_{5-y} \uparrow$)	N (high $\beta *$)	-	-	Y
Thermal Feedback	Y (parab.)	Y	Y ($R_{BCS} \downarrow$ $R_{res} \uparrow$)	N	-	N	-	-	N (coeff. C)
Magnetic Field Dependence of Δ	Y (expon.)	N ($H_C \neq$)	Y ($H_C \uparrow$)	Y ($H_C >$)	-	N	-	-	N (thin film)
Segregation of Impurities	?	N (≠ segreg.)	N (only O)	-	-	Y (cleaning)	-	-	Y
Bad SC Layer	N	Y (n.c. layer)	Y (dilution)	N	N (bad layer ↑)	-	N	N ($H_{C2}' \downarrow$)	N (unrealistic)

Unlike plasma deposition, sputtering or CVD, the ALD process essentially involves growing pure, bulk layers that could eliminate all these causes.

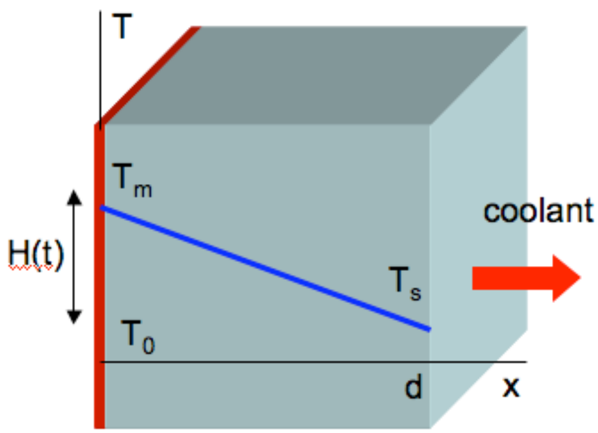
Thermal problems

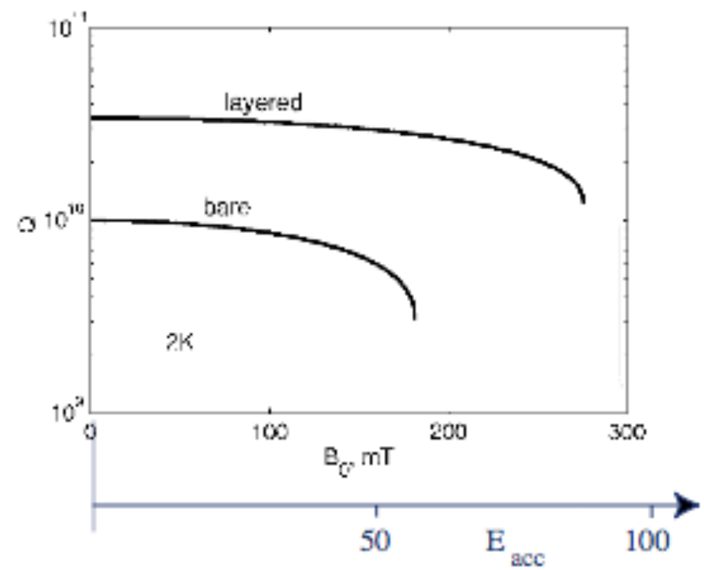
Flaws in the niobium, rf dissipation and limits in the thermal conductivity can cause failures.

Layered structures should be more stable since, they give:

choice of substrate

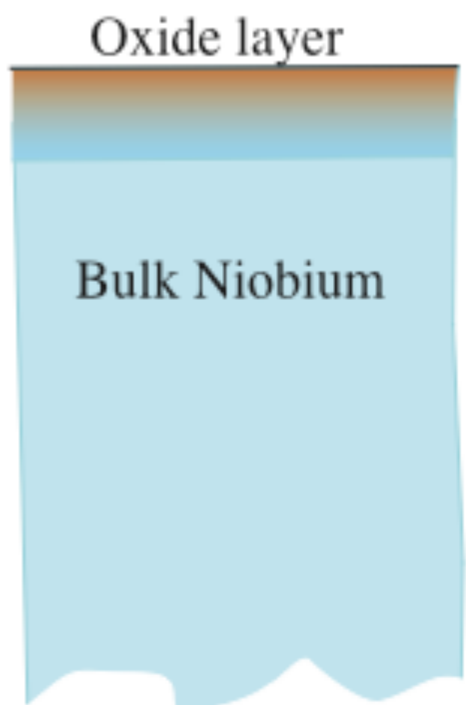
lower rf losses.

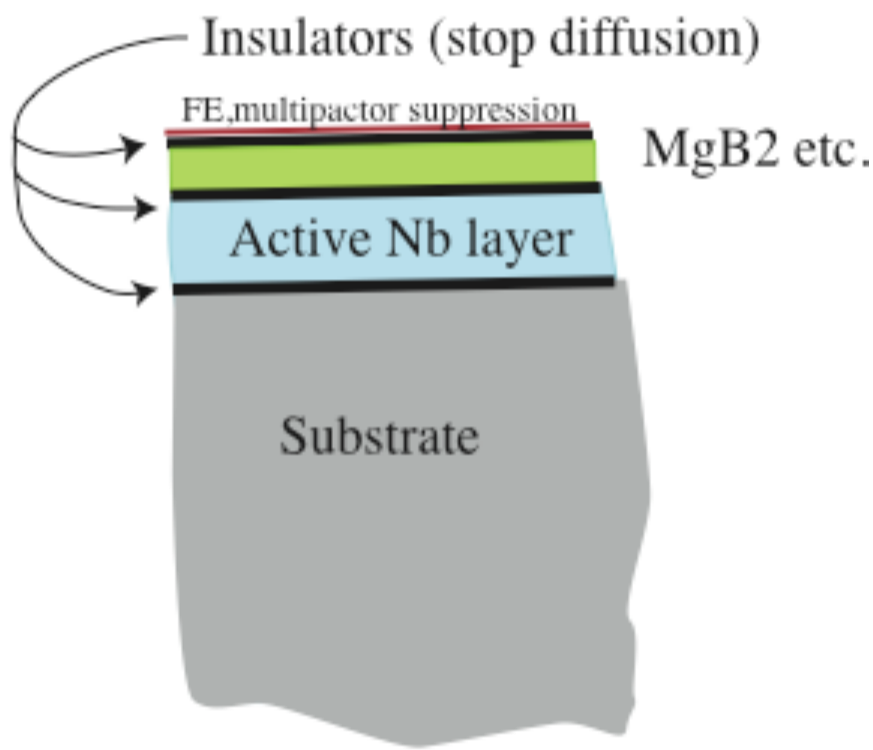




What might this composite look like?

- Normal SCRF | Composites





- Top, active layer in composite must have high T_c: NbN, MgB_2, Nb_3Sn

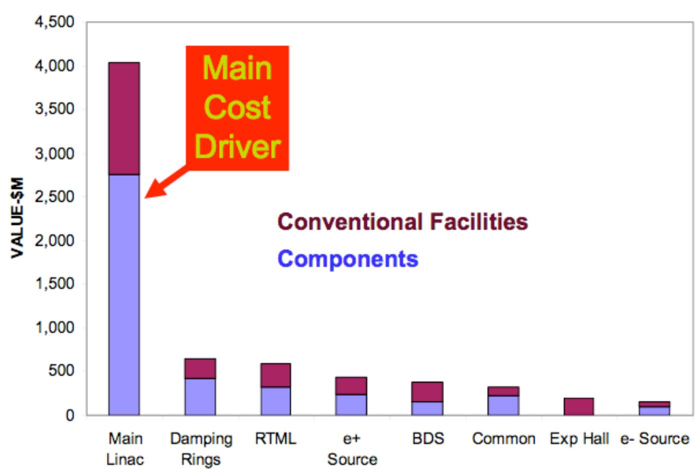
How will this technology impact the ILC?

- Peter Garbincius has pointed out that this technology would not have a significant cost impact if composite structures are substituted for standard SCRF ones.

- The cost is in the complexity, and the number of components,
  Linac cost = (component value + manpower) (infl, cont. etc.) ($32/E_{acc}$).
  = (4 + 1.2) (1.5) ($32/E_{acc}$)

- **Can we run at 100, instead of 32 MV/m?**
  FE and BD, multipactor Q-slope could be OK
  More stored energy, but higher Q, better thermal design

- **This would lower the ILC cost by ~5 B$! ! !**



Recent Experimental Data: Niobium surfaces with APT

- Atom Probe Tomography (APT) by Seidman at Northwestern has recently shown that the composition of the oxide layer on niobium is dependent on baking.

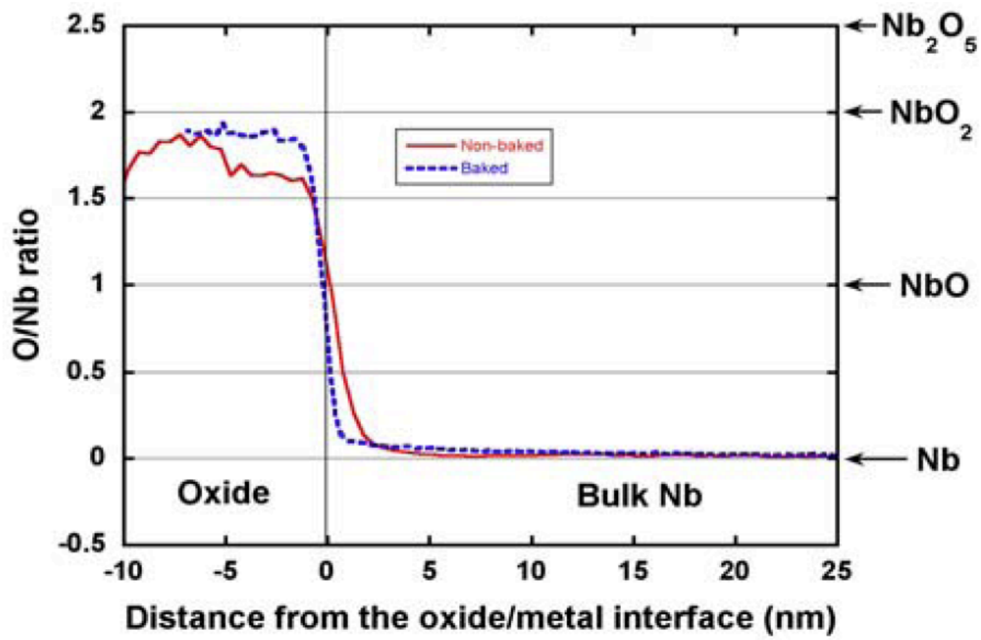


Fig. 5. O/Nb ratio from the 3D reconstructions of unbaked and baked niobium tips. The stoichiometry of the oxide is deduced from the profile. The profile clearly demonstrates that the thickness of the oxide decreases after baking. The chemistry of the oxide, however, does not change.

Al_2O_3 should be an impervious cap on niobium – a big improvement

- All SCRF work so far have been done with “dirty” oxide surfaces.

- **We can produce clean, protected, surfaces – no Nb oxides.**

- An initial first step is to:
    1) understand how to deposit Alumina on Nb
    2) study its properties
    3) produce a coated sample
    4) bake, to drive (dilute) interfacial oxides into the material
    5) measure the properties of sharply defined superconductor.

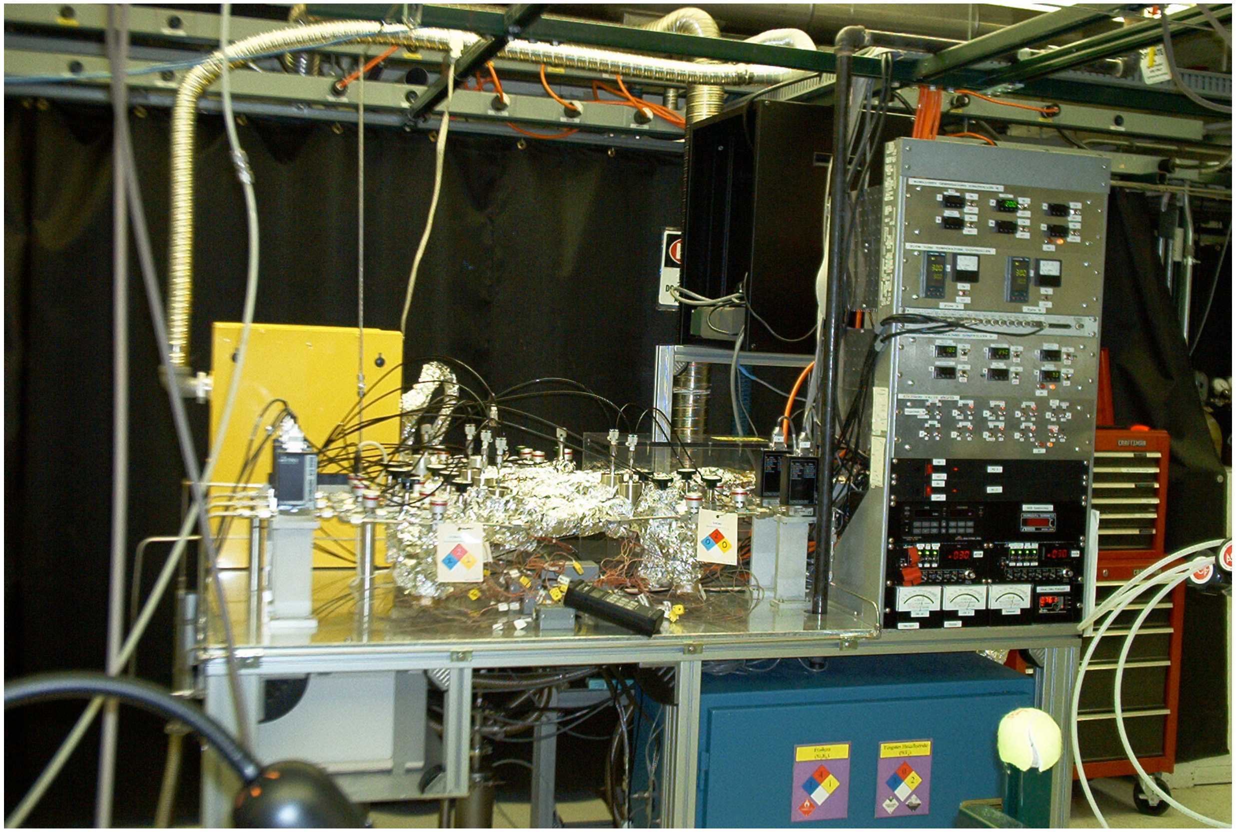
and

6) Try this with a cavity

- We expect big improvements in performance and stability.

We are using Atomic Layer Deposition (ALD) to deposit Al_2O_3.

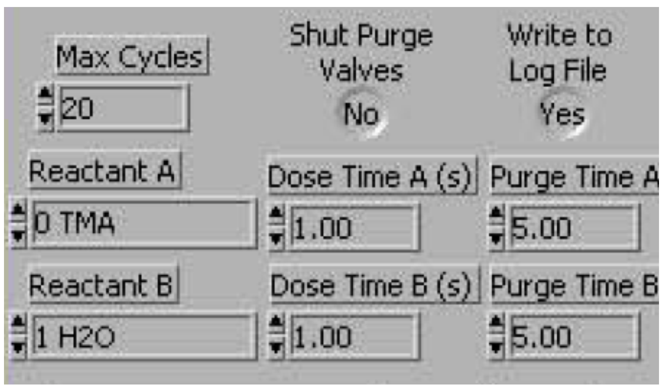
- People: M. Pellin (ANL/MSD),
  J. Elam (ANL/ES)
  J. Moore (ANL/MSD and MassThink)
  C. Antoine (FNAL)
  J. Norem (ANL/HEP)
- Equipment:

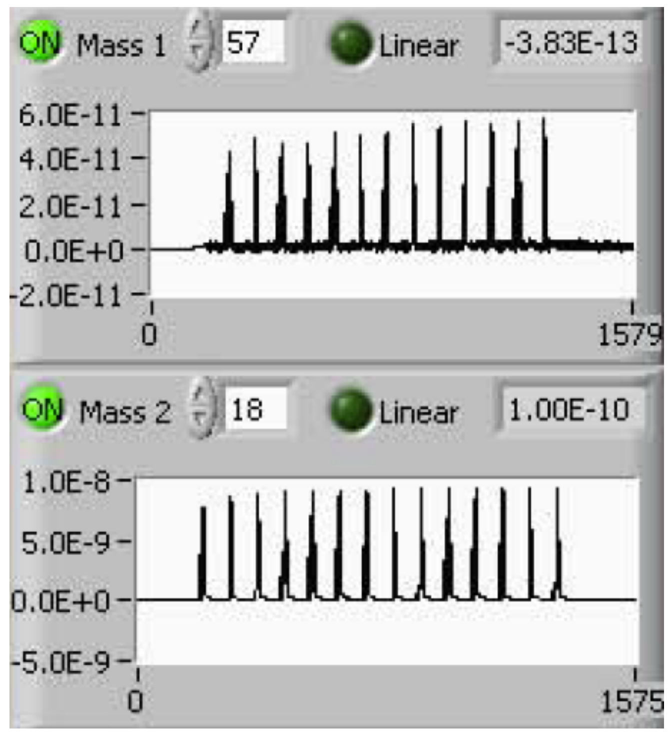


The sample shown has 20 cycles of Trimethylaluminum / H_2O.

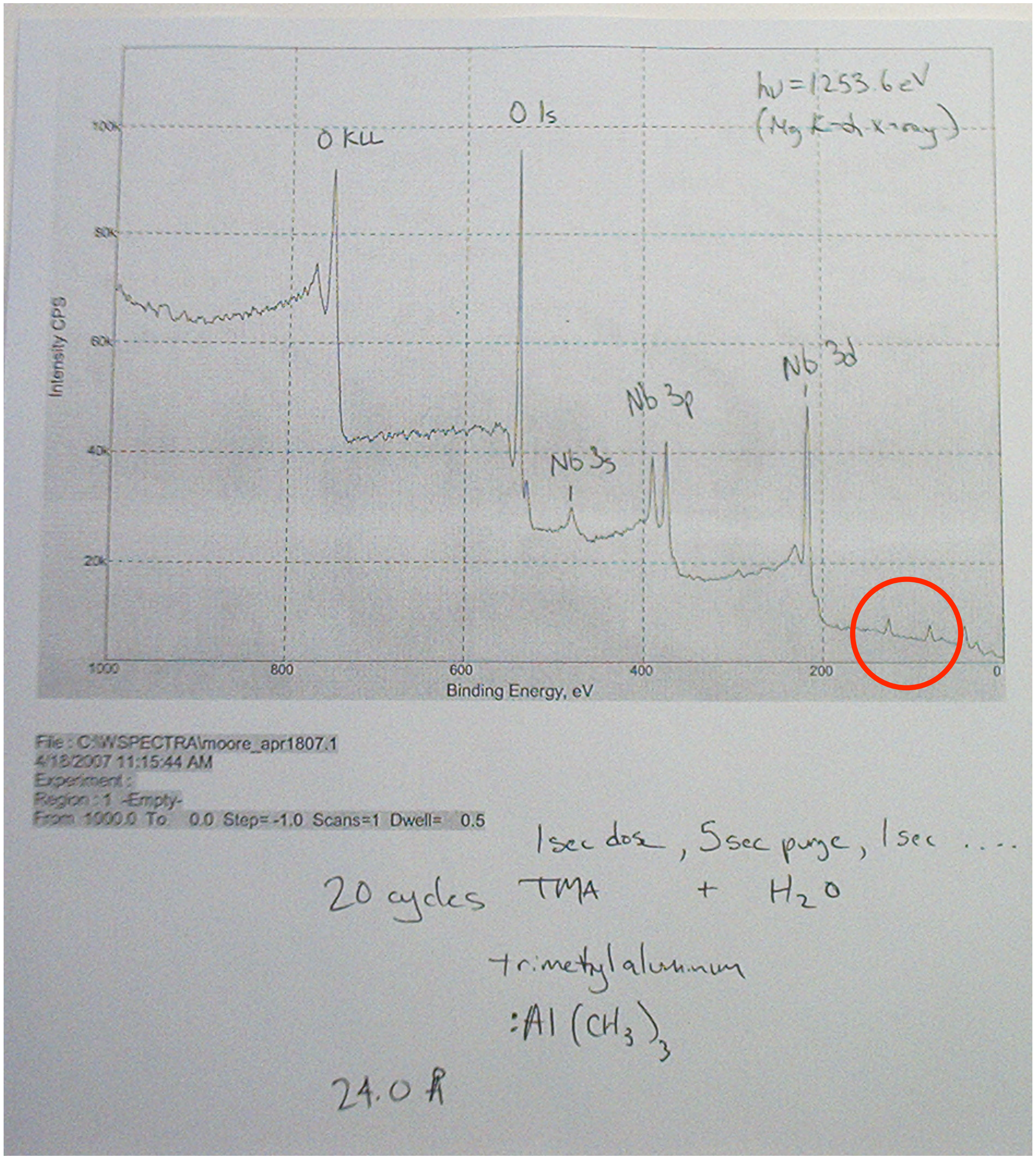
- A binary reaction sequence (A:B:A:B:A:B . .) allows self-limited, layer-by-layer growth very conformally over irregular, high aspect ratio surfaces.

- Once everything is set up the process is straightforward.





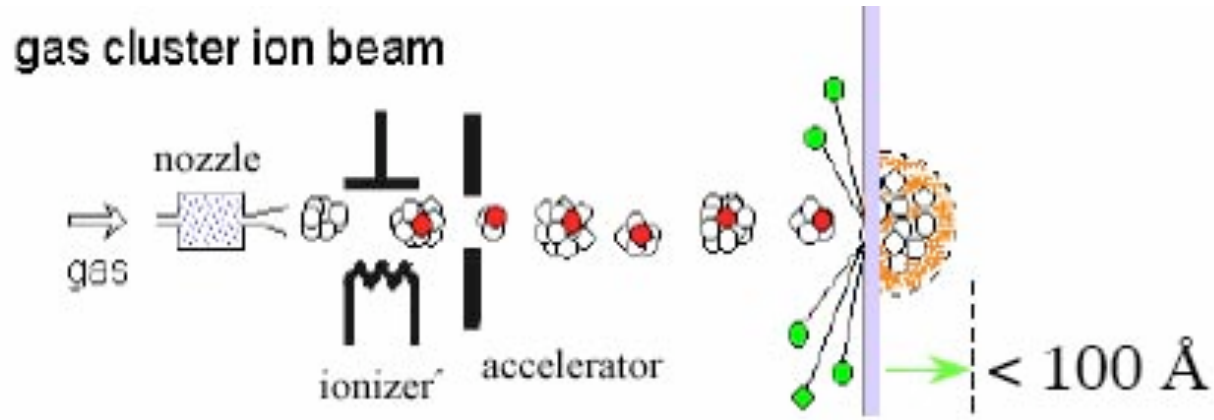
X-ray Photoelectron Spectroscopy confirms the Al_2O_3.

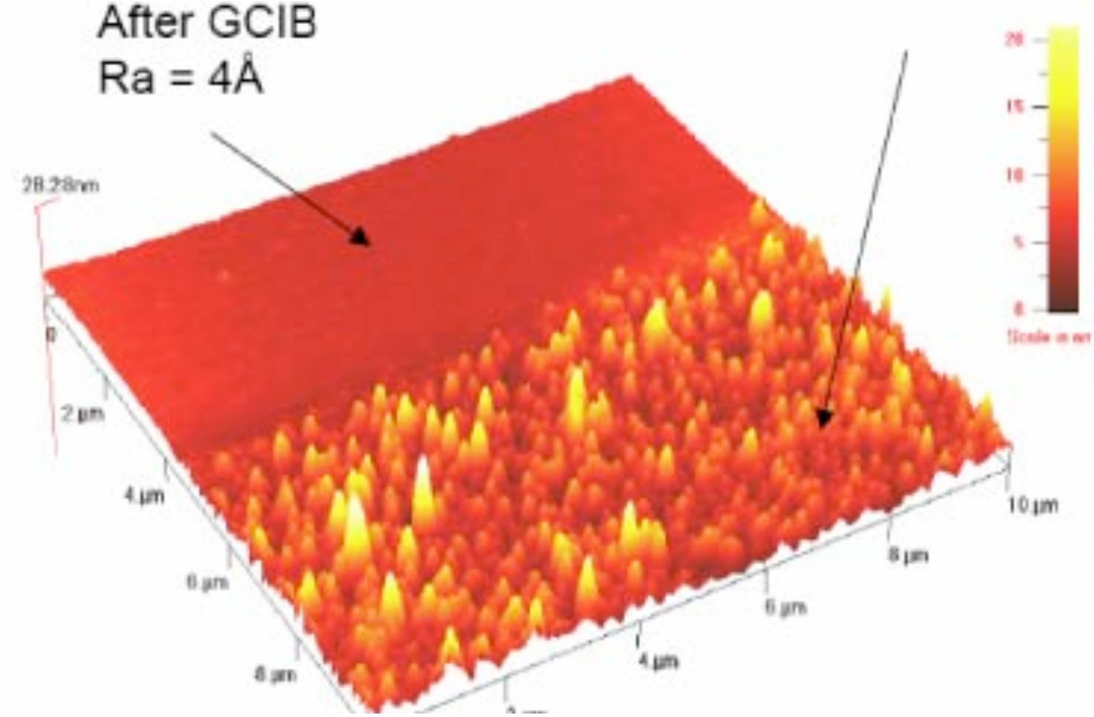


Now we need a linac cavity to test.

Gas Cluster Ion Beams.

- both NC and SCRF
- Cornell, FNAL, SLAC Fermilab have tested this.
- Can smooth hard metals.





Summary

- Muon Collaboration / MICE effort has produced a number of results that are generally relevant:

  - The first (after 107 years) model of breakdown that explains all the data.

  - A better method of making rf superconductor.
    We are coating samples, will do a cavity.

  - New ways of processing rf materials.