Studies of Accelerator Gradient Limits at Argonne HEP

Norem

- We have been looking at different aspects of gradient limits for ~ 10 years, mostly at Fermilab, as part of the Muon Accelerator Program.

- While the most visible part of this is ANL effort to make SRF cavities with ALD, there are two other interesting projects:

1) We have been studying and **modeling** different aspects of breakdown using a variety of techniques, for some time. Our model assumes:
   - Coulomb explosions (fracture) of solid surface as the breakdown trigger,
   - Field emission driven ionization of fragments to produce small, dense arcs,
   - Increasing surface field, driven by plasma potential and small Debye lengths,
   - Unipolar arcs as the primary surface damage mechanism.

- We just hosted a workshop on Unipolar arcs last Friday, with Purdue University, to look at arcs in accelerators, fusion devices and other applications.

Muon Accelerator Program

Argonne NATIONAL LABORATORY

2)The other effort we are pursuing is **"Breakdown-Proof" rf cavities**.

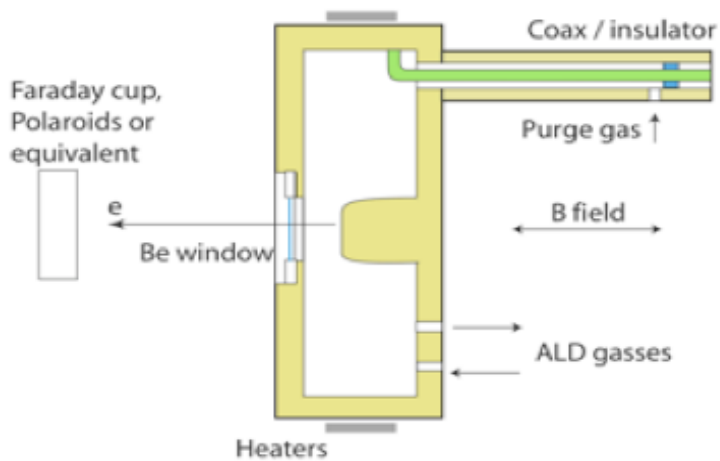
- Our modeling, and a lot of our own and other peoples data, seems to imply that arcs are triggered by very small (~few nm) asperities with high local electric fields (7 – 10 GV/m)

- If the small asperities are rounded off with ALD, the fields should drop like 1/r.

- Since breakdown rates go like E^{30}, we expect breakdown should be eliminated.

- This is the experiment:

We can do this in a simple cavity. The experiment would involve:
First: Condition the cavity and measure the dark currents at maximum gradient.
Then: Coat the cavity with ALD using known thickness of different metals.
Measure the field emission and maximum gradient as a function of ALD coating thickness.



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... for a brighter future

Atomic layer deposition for superconducting and warm rf cavities

-**Thomas Prolier** (MSD), Michael J. Pellin (MSD), Jim Norem (HEP), Jeff Elam (ES), M. Kelly (PHYS).

-John Zasadzinski (IIT),

-Alex Gurevich, I. Chiorescu (FSU)

-P. Kneisel, G. Ciovati (Jefferson lab.)

-L. Cooley (Fermilab)

-C. Antoine (CEA)

U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

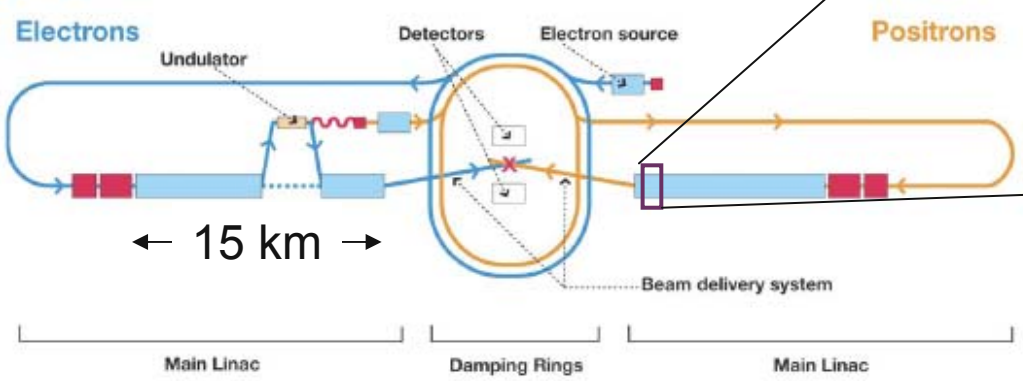
A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

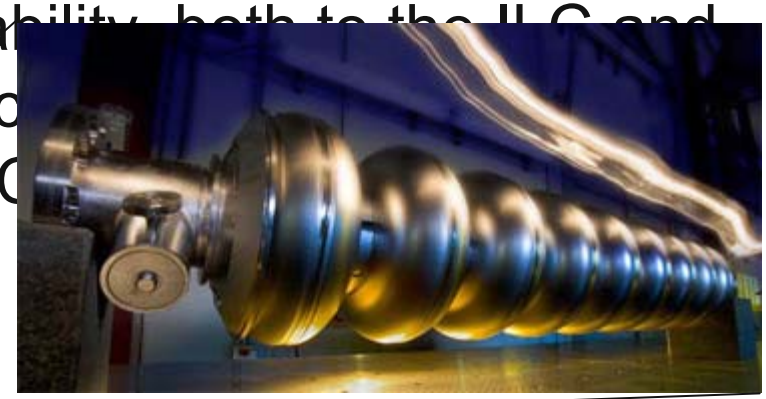
Superconducting Radio-Frequency (SRF)

Department of Energy – Office of Science

- DOE-OS is in the particle accelerator business (ILC ($19B), RIA($0.4 B), NSLS-2($0.5B) , SNS($1.8B), APS, APS-ERL, etc.)

- Orbach to HEPAP 2/22/07 "DOE is committed to continuing a vigorous R&D program of accelerator technology SCRF is a core capability having broad applicabilit
to other future accelerator-based fac
FY2008 request for ILC R&D and SC





1 m

- 30 km of ultra pure Nb bellows
- 2 K
- very high electrical and magnetic fields

Goals

SRF technology is crucial for all future HEP Accelerators. Significant advances in acceleration gradient, cavity reproducibility, operating costs, and cavity production costs must be achieved to allow breakthrough understanding of the fundamental structure of nature.

Here we aim at transformative technology changes in SRF technology by developing a predictive understanding of the materials physics issues currently limiting SRF technology and by applying this understanding to significantly improve cavity performance.

Why Argonne: 1/ Four Decades of SRF Experience

- **World's first superconducting linac for ions, ATLAS (1978-present)**

  68 superconducting niobium cavities
- **The leader in development of new high-performance cavities for ion-linacs**
- **A dedicated full-time cavity cold test capability**

  A small but experienced 4-man SRF team plus ATLAS Ops leader

  with over 70 man-years direct SRF experience
- **A large state-of-the-art cavity rf surface processing facility** Jointly operated by ANL and FNAL at

2/ crossroads of expertise

- **State of the art material science/ chemistry techniques and expertise (MSD,CNM,ES,PHYS…)**

Outline

- Administrative Details
- Current Status
- Scientific Progress

Administrative Details

- History
  - Nearly 2 years ago a group coalesced between HEP and MSD to understand & improve SRF devices

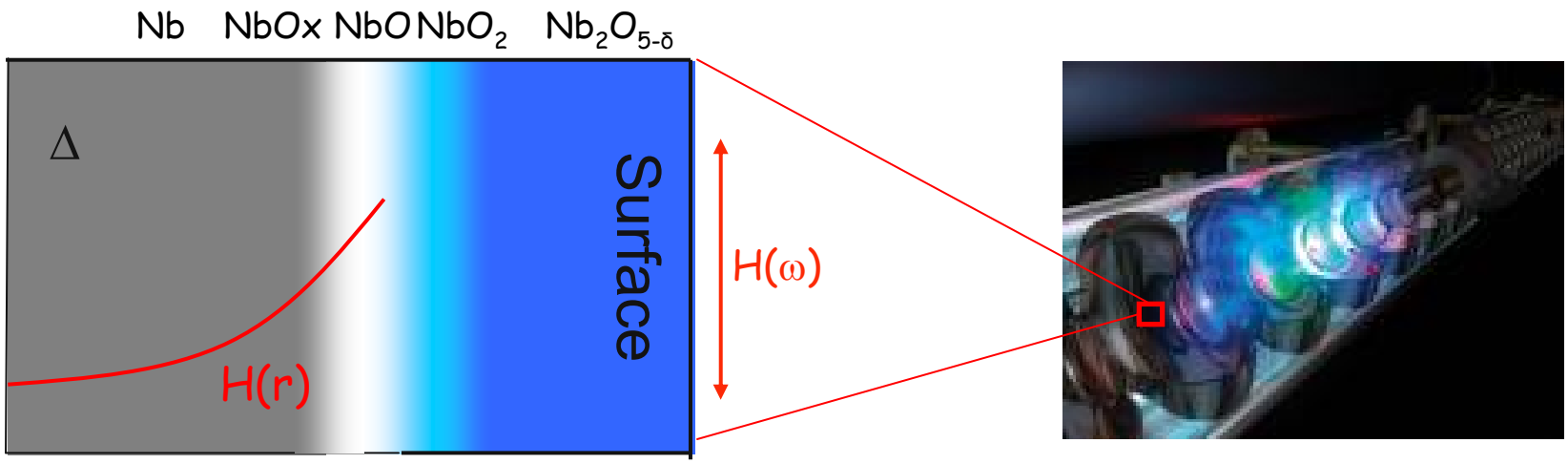
- Funding Details
  - 2 year of funding as ANL Strategic LDRD
  - FWP DOE-HEP started Sept. 2009
  - LDRD "Thin superconducting films" Oct. 2009

- New Hire
  - Thomas Prolier
  - Jeffrey Klug (postdoc)
  - Nick Becker (student, IIT)
  - Subcontract with IIT and FSU.

Current Status (1st year milestones)

- **Understanding performance Limitations**
  - Experiments: Nb oxides magnetic (PCT, EPR) new collab. With FSU for On-chip cavities. How to cure them: ALD (1 p.)
  - Theory: modeling dissipation -> explain the Q values (1 p.)
- **New techniques to improve cavity**
  - Multilayer structure -> superconductors made by ALD (2 p. +patent): NbN, NbTiN, NbSi ect…
  - Customized PEALD apparatus for coupon tests (being purchased)

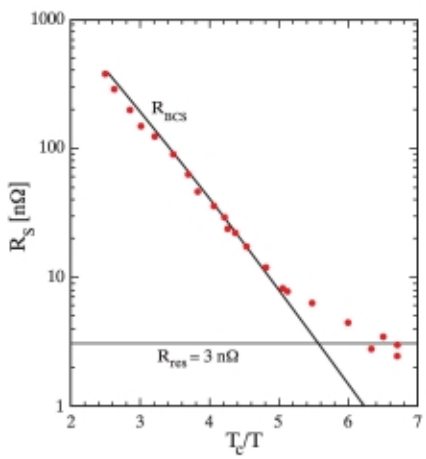
State of the art: What is known? What can we bring?

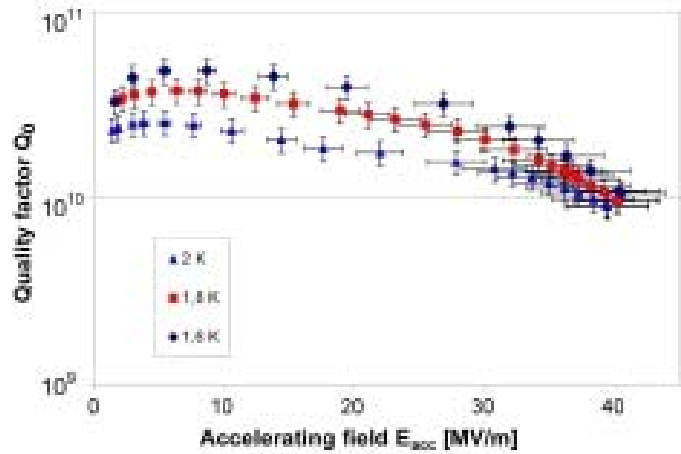


$Rs = R_{BCS} + R_{res}$

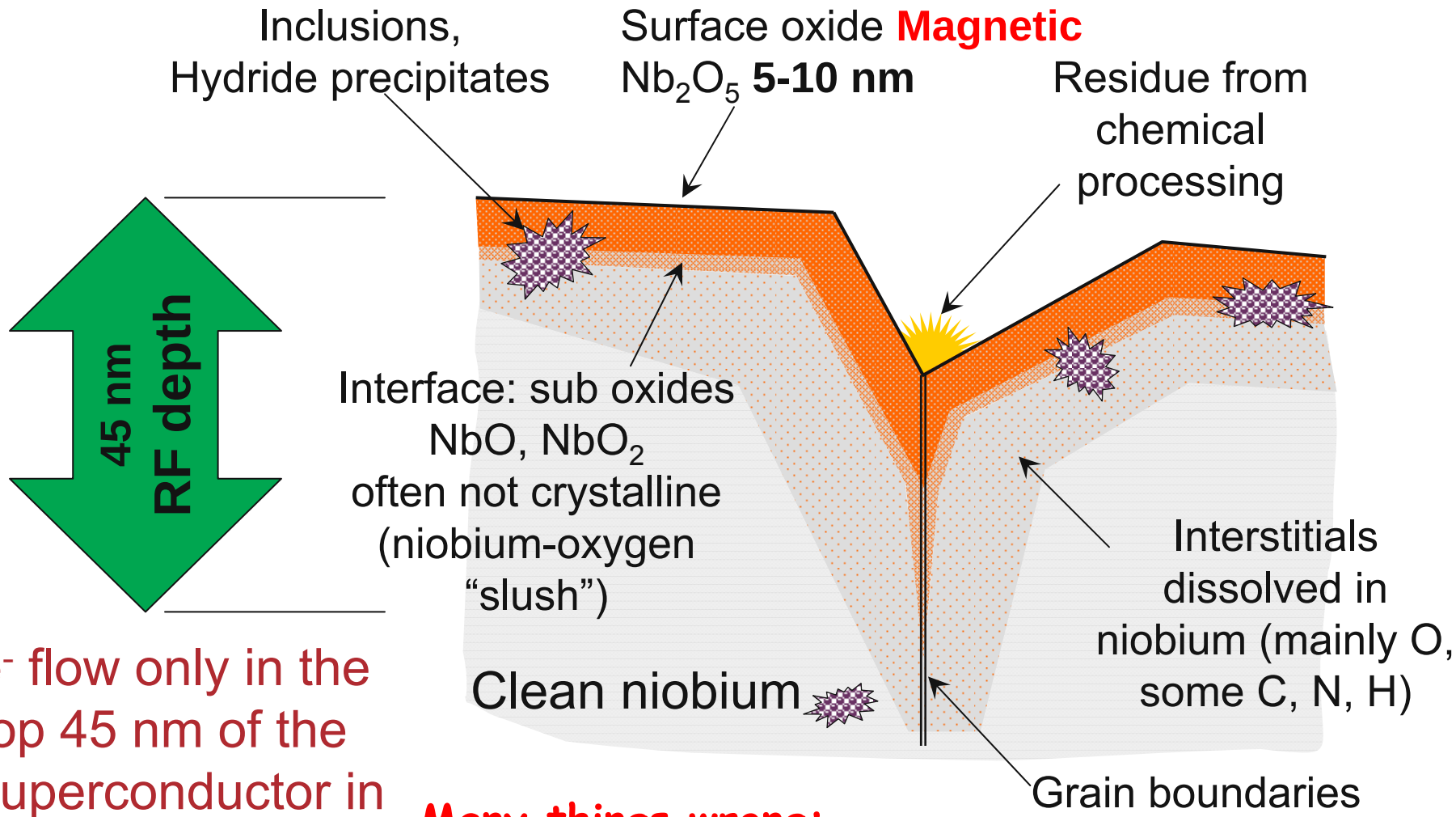
$R_{BCS} = C\lambda^4\omega^2/\exp(-\Delta/kT)$

SRF Impedance is a surface effect (λ~50 nm) -> control dissipation and Q factor.





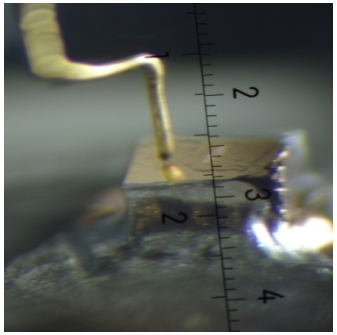
Niobium surfaces are complex, important (lower critical field, and currently poorly controlled at the nm level



e^- flow only in the top 45 nm of the superconductor in SRF cavities!!!

Many things wrong;
what is responsible for Q-Slope & Gradient Limits?

Measurements of the superconductivity and surface oxide properties



- **Point contact tunneling (Jefferson/ANL)**:

-Non-ideal -> dissipation is increased, magnetic impurities
-Correlate with RF test surface treatment found to improve performance
-Hot spots: strong magnetic impurities concentration

- **Electron paramagnetic resonance and SQUID (IIT/ANL)**:

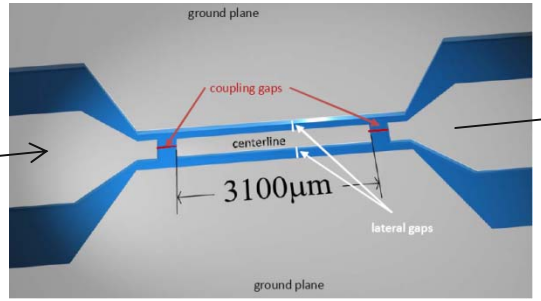
-Confirmation of the presence magnetic impurities

- **Theory: Modeling how magnetic impurities affect the Q?(FSU/ANL)**

-Explain the residual resistance and the magnitude

- **How to test on cavities (varying impurities, concentration…) (FSU/CNM)**

-On-chip cavities: measure Q
easy and fast turn around

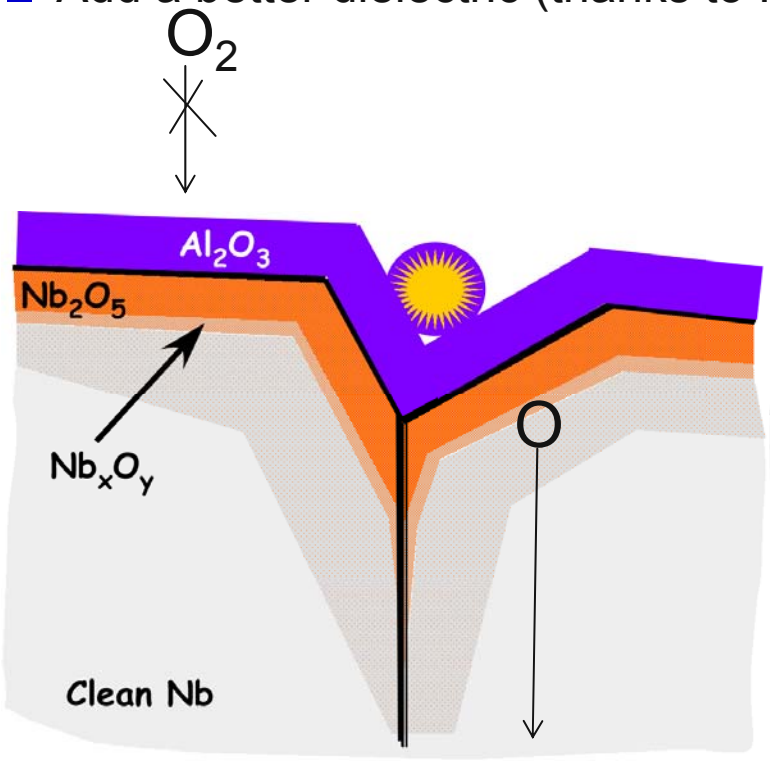


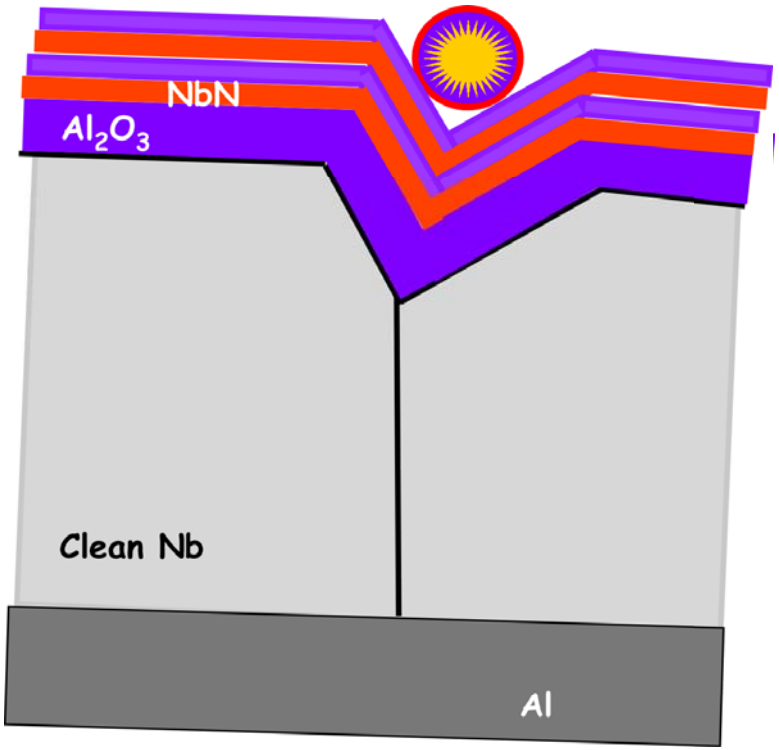
RF in

RF out

How to make better cavities

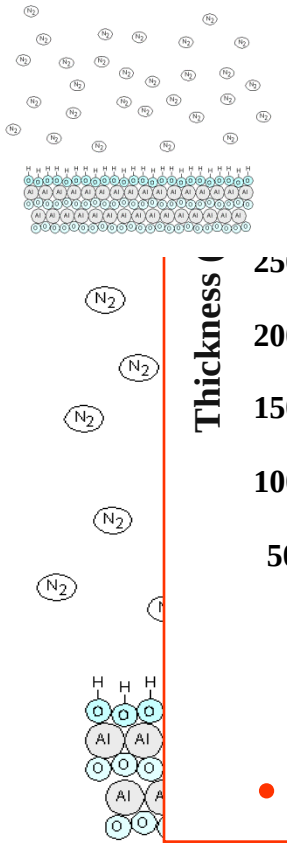
- Add a better dielectric (thanks to Intel) and bake



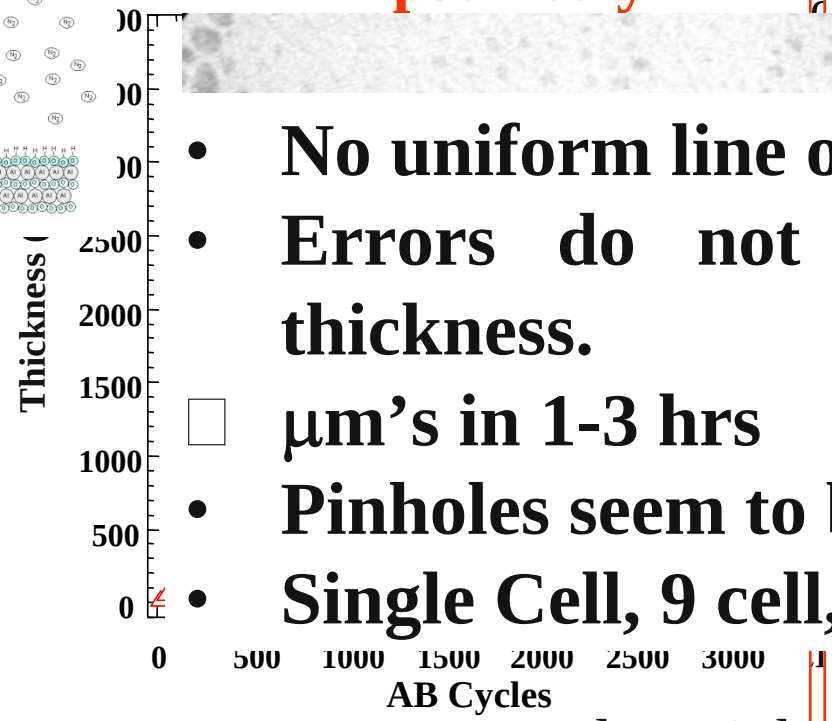


- It works on coupons ! -> improve superconductivity….go to higher temp

ALD Reaction Scheme



Ellipsometry



- Film growth is linear with AB Cycles

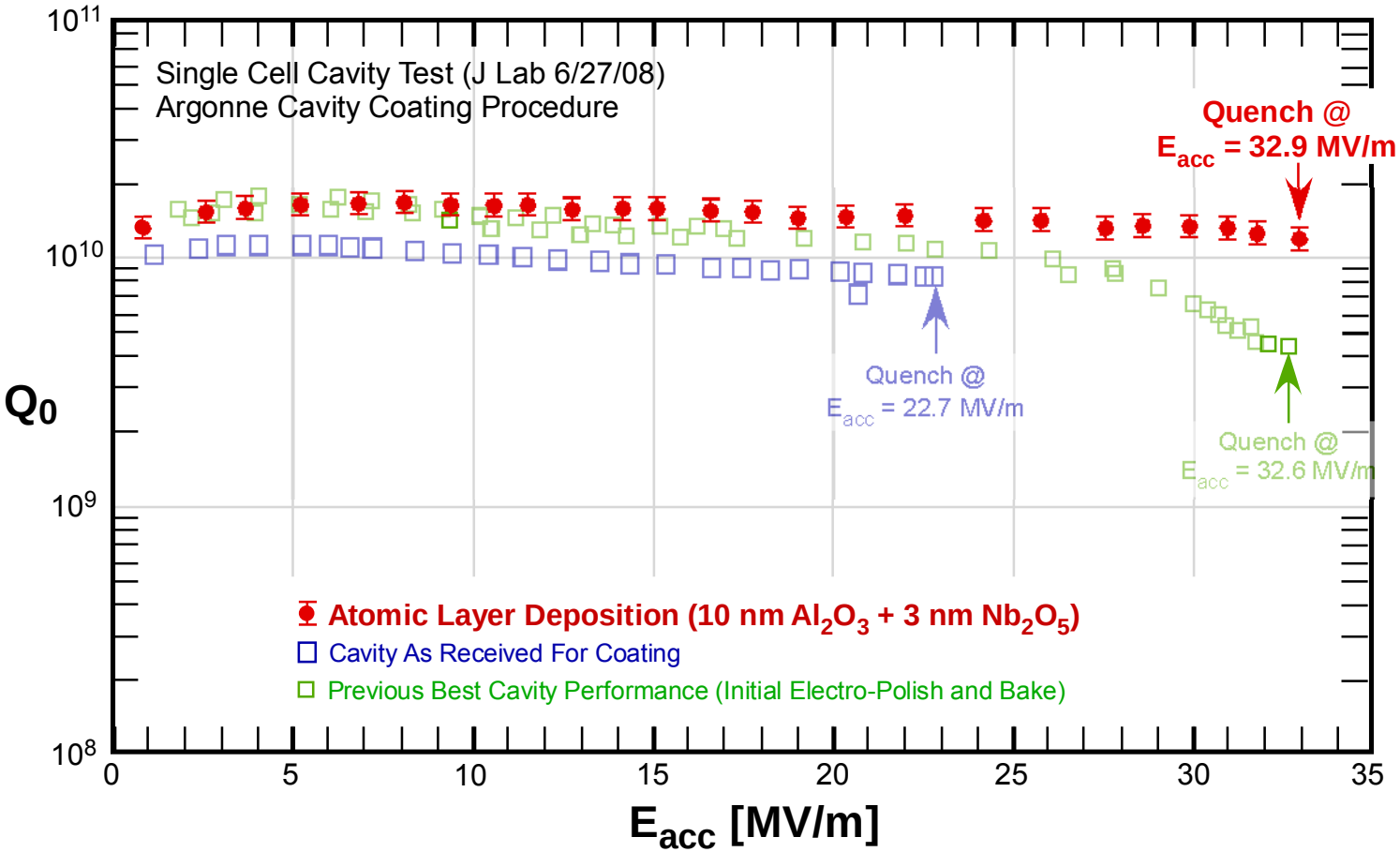
Atomic Force Microscopy

- RMS Roughness = 4 Å (3000 Cycles)
- ALD Films Flat, Pinhole free

- **No uniform line of sight requirement!**
- **Errors do not accumulate with film thickness.**
- **μm's in 1-3 hrs**
- **Pinholes seem to be removed.**
- **Single Cell, 9 cell, re-entrant, *in situ***

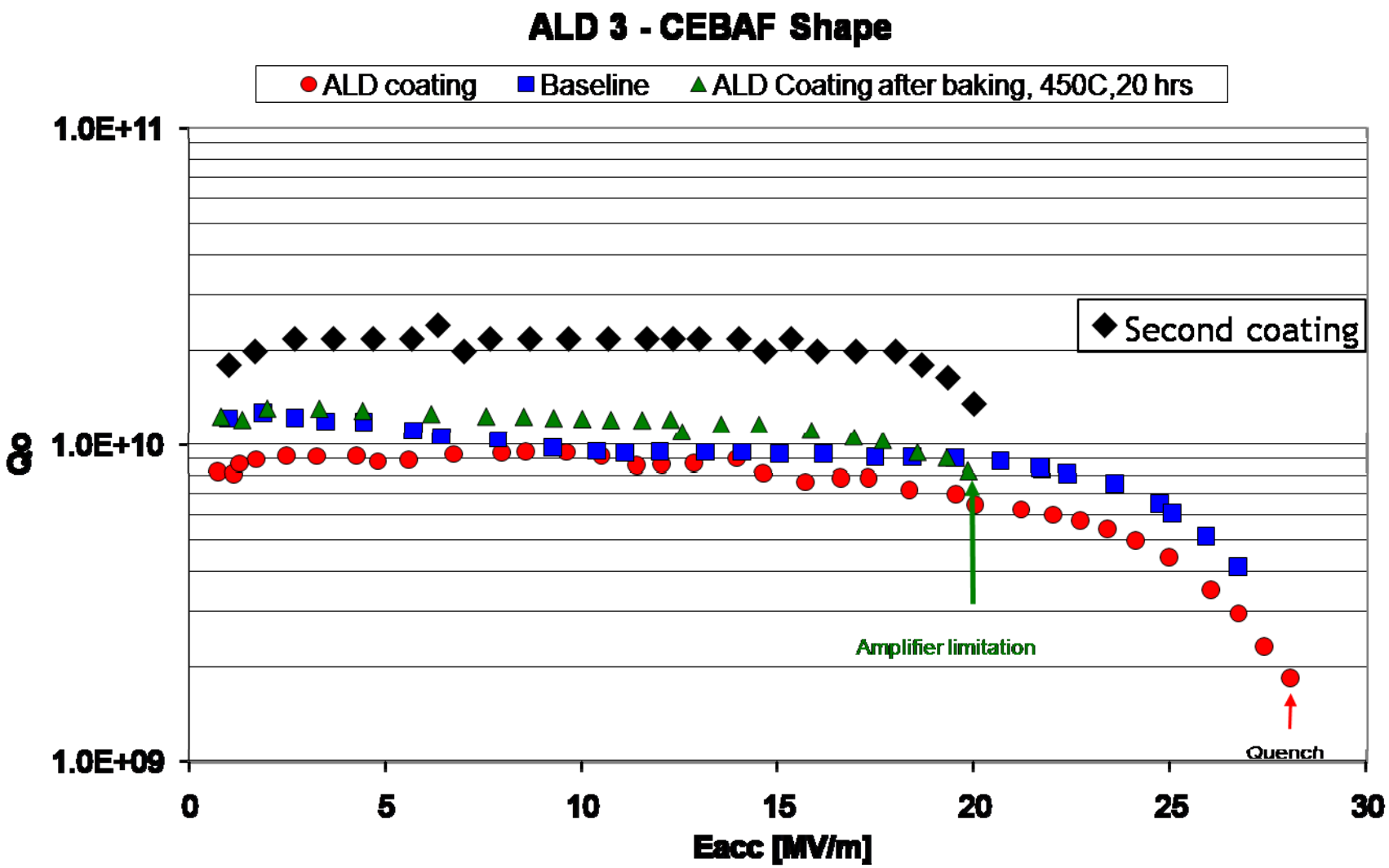
- Flat, Pinhole-Free Film

Cavity test 1:After ALD Synthesis (10nm Al_2O_3 + 3nm Nb_2O_5), 250°C

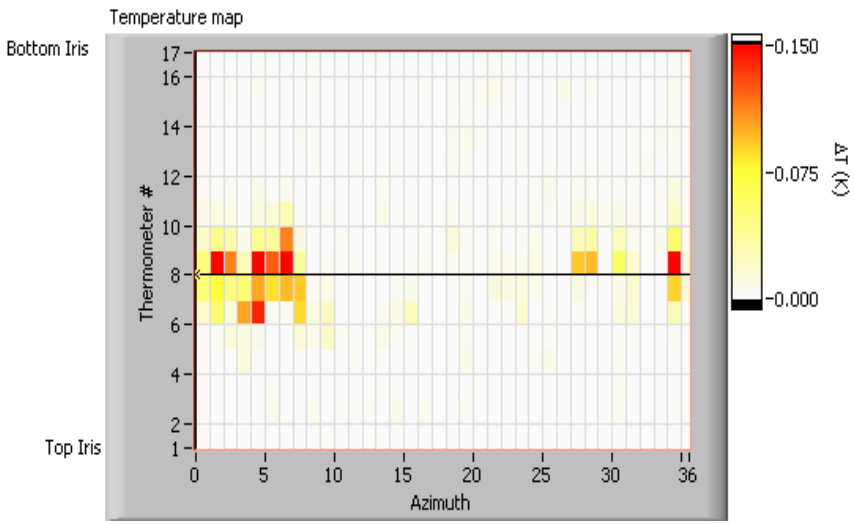


- Only last point shows detectable field emission.
- 2nd test after 2nd high pressure rinse. (1st test showed field emission consistent with particulate contamination)

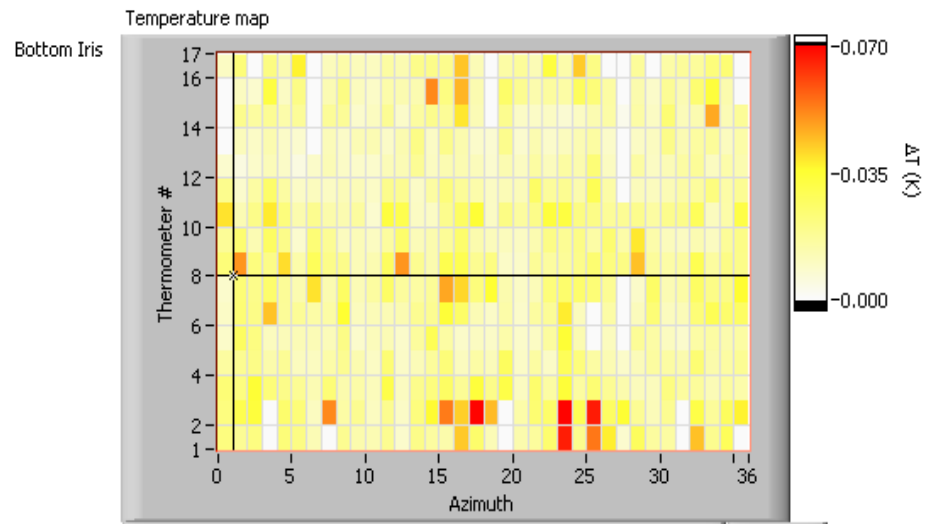
J Lab Cavity 3: Baking 450C/20hrs + Coating: 5nm Al_2O_3+15 nm Nb_2O_5



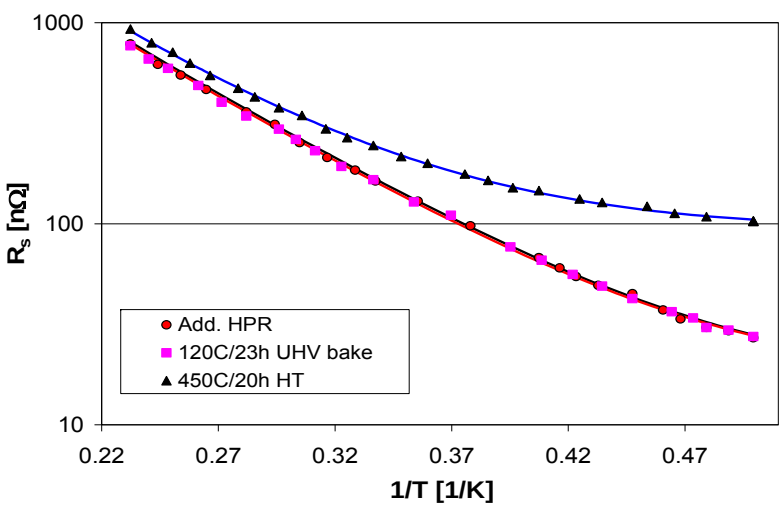
High Temp. baking: T maps and Rs(T)



T-map at the highest field measured during the test after 120 °C, 23 h UHV bake.



T-map at the highest field measured during the test after 450 °C, 20 h heat treatment

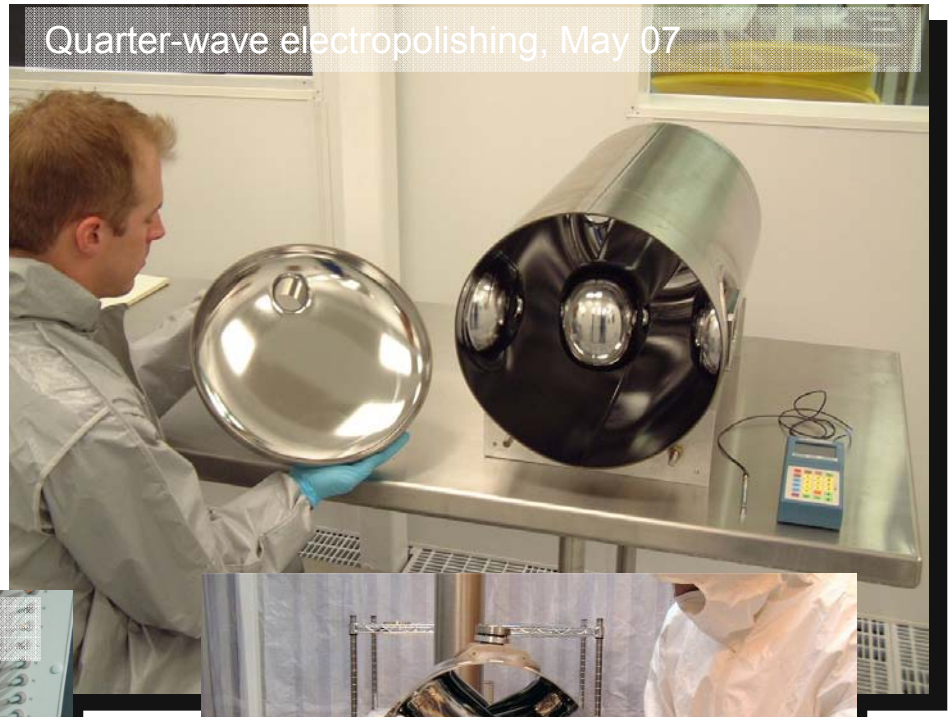


Treatment	Δ/kT_c	ℓ (nm)	R_{res} (nΩ)
Add. HPR	1.866 ± 0.018	19 ± 44	16.0 ± 0.8
120 °C/23 h bake	1.879 ± 0.005	18 ± 55	16.3 ± 0.5
450 °C/20 h HT	1.911 ± 0.026	58 ± 17	93.8 ± 0.2

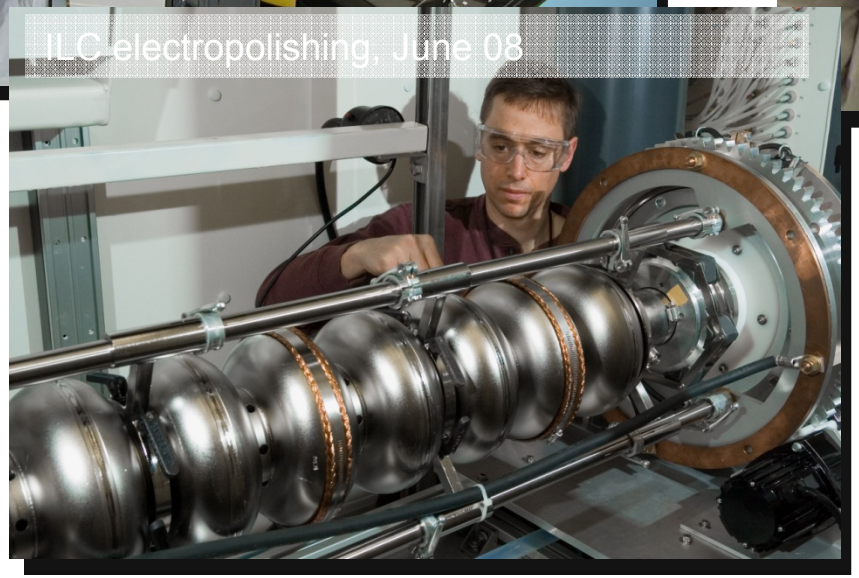
- **Ohmic losses**
- **But HT baking: Improved the super. properties**

Cavity RF Surface Processing: Electropolishing-Physics + testing

Entry into ANL Cavity Processing Room



Quarter-wave electropolishing, May 07



ILC electropolishing, June 08

Spoke cavity electropolishing, Jan 05

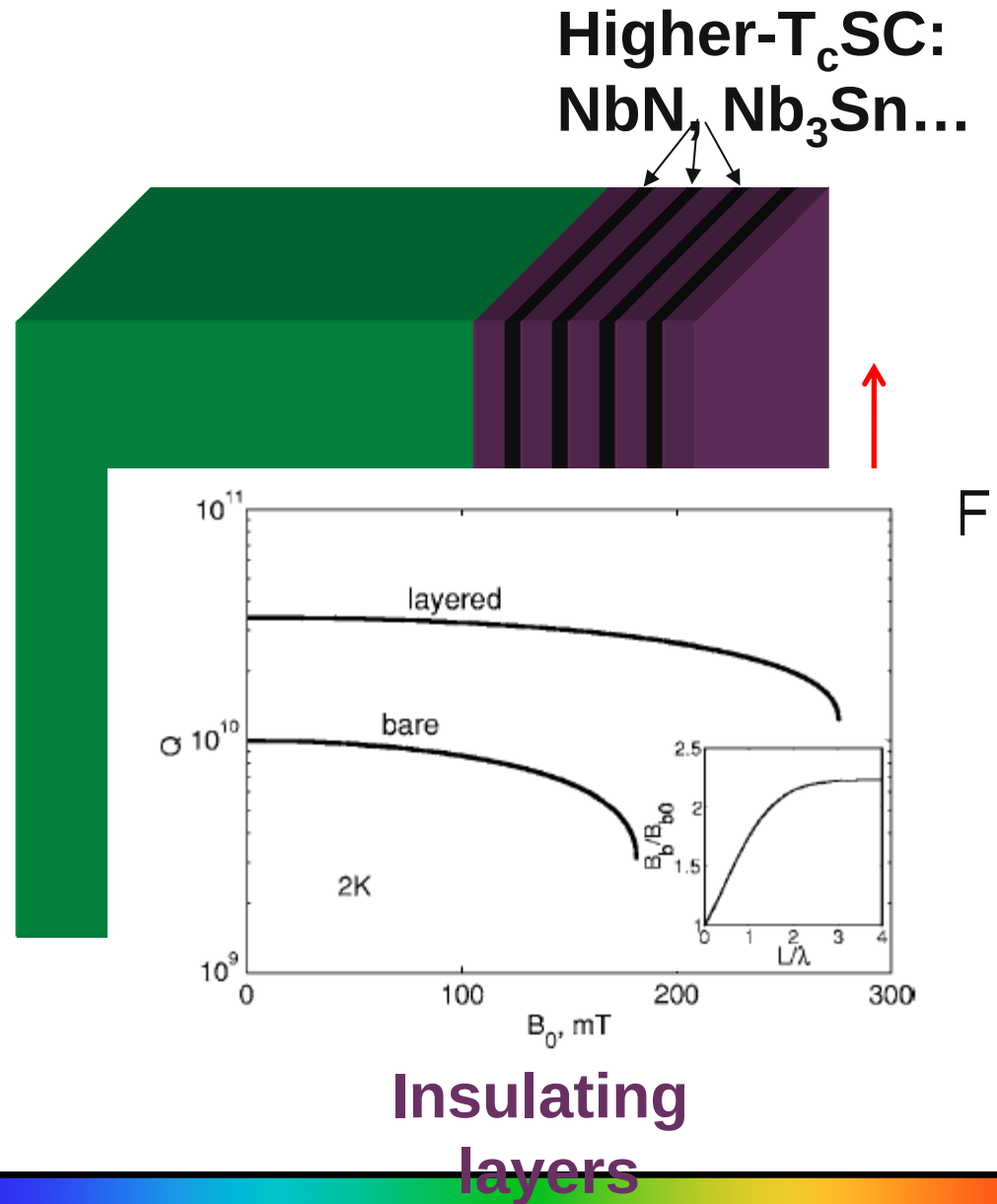
Summary

- Project is underway.
- Team is in place.
- Magnetic impurities: only model that correlate with RF test
- We have demonstrated the ability to produce high quality Nb metal interfaces.
- We have demonstrated the ability to extend this improvement to single cell cavities. Can go further.
- Next phase is to improve the material properties beyond those of bulk Nb metal.
- Long Run: If the new plasma assisted apparatus works as planned we hope to be able to deposit the entire structure (including the Nb underlayer) on more easily fabricated cavity materials (Al).

ALD Can Produce Layered SRF Structures with significantly higher H_{c1} than Nb

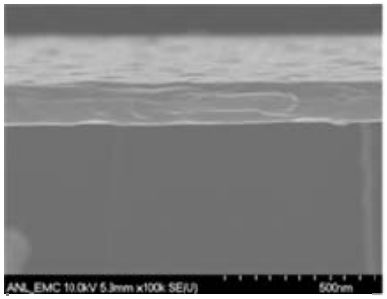
- Build "nanolaminates" of superconducting materials
- ~ 10- 100 nm layer thicknesses with 10 nm Alumina Between.
- H_{c1} Enhancement Scales with:
- $\sim T_{c,laminate}/T_{c,base}$

- **For NbN laminate layers -> ~1.5 H_{C1} enhancement**
- **50 MV/m -> 75 MV/m**

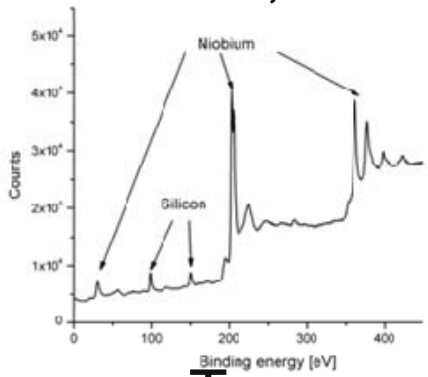


New Argonne ALD Materials for SRF: new chemistry

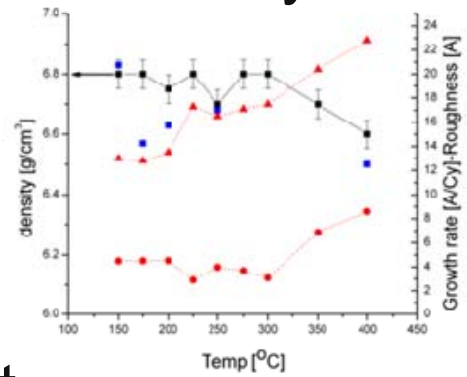
SEM



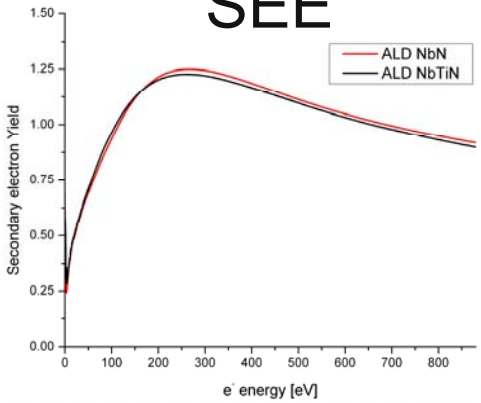
XPS, RBS



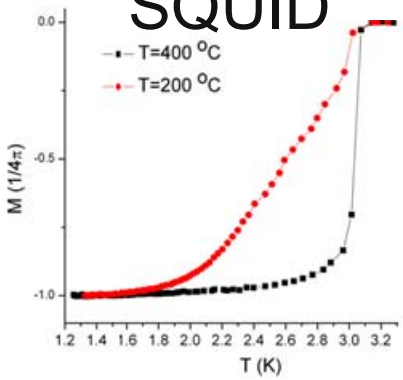
X-ray



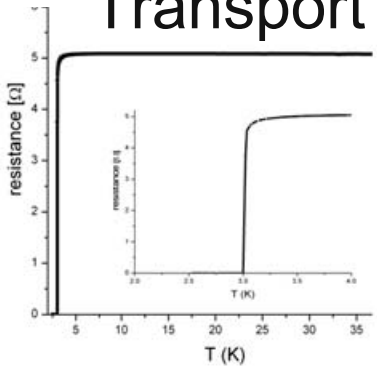
SEE

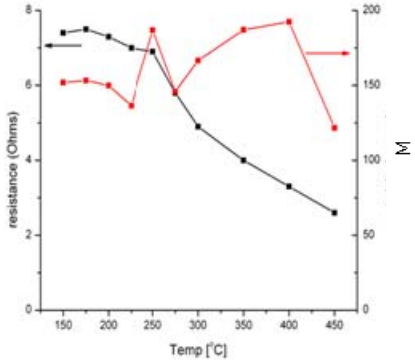


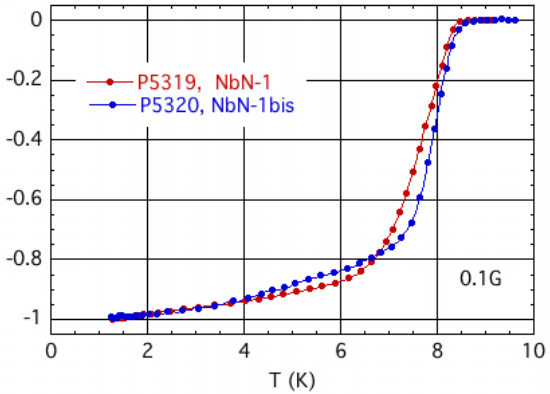
SQUID



Transport







NbSi: Tc=3.1 K for 33 nm film -> 3.1 K

NbN : Tc=5.1 K for 100 nm film -> 16 K

NbTiN: Tc=8.5 K for 26 nm film -> 14 K

Why? Oxygen in films (7-8%)
How? Gas filters, new materials

Argonne ALD facilities: Plasma ALD (PEALD)

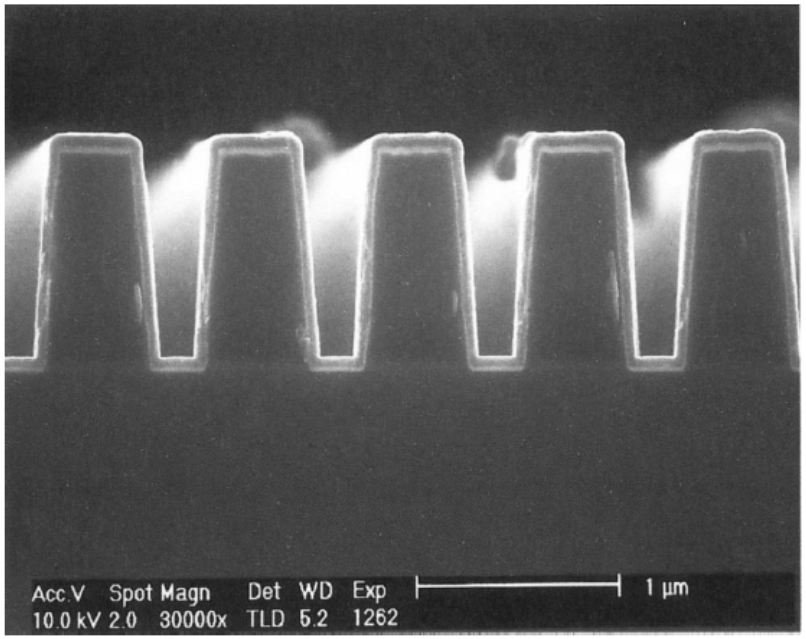
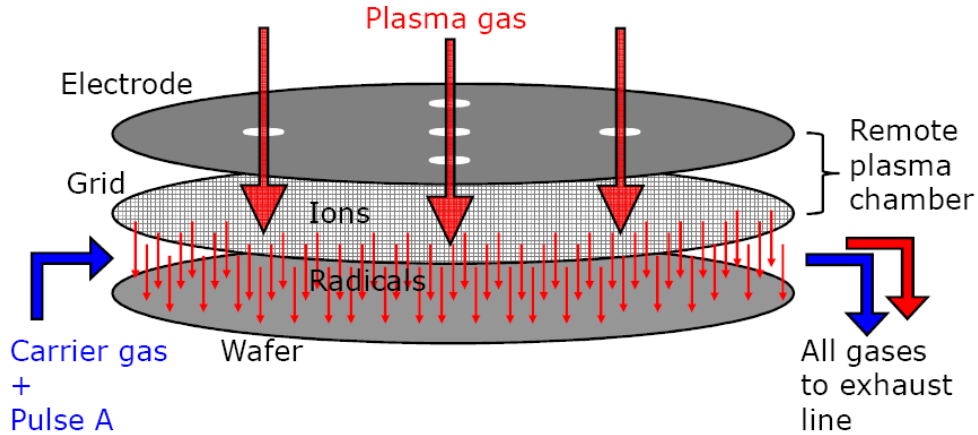


Figure 5. A cross-sectional FESEM micrograph of a 50 nm thick ALD film grown on 20 nm thick TiN at 250°C. The bottom and top distances were 0.25 and 0.45 µm, respectively, and the aspect ratio is 5.



Film Material Type	Plasma Gas
Oxides	O_2 / Ar O_2
Nitrides	NH_3 N_2 N_2 / H_2 NH_3 / Ar NH_3 / N_2
Metals	Ar / H_2
Carbides	CH_4 / Ar

Elemental Metals: Al, Cu, W, Mo…
& alloys: NbN, TiN, Pt/Ir etc…

Purer materials-> bulk properties

⇨ Ordering PEALD

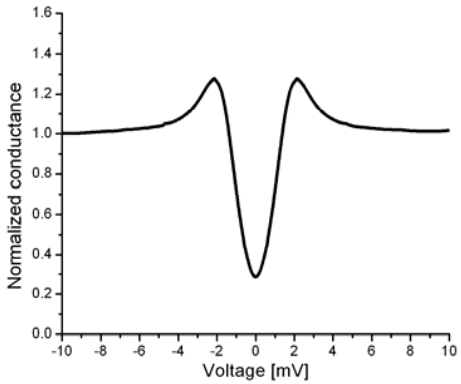
Proposal for this year

1. Finish Producing the First SRF Single Cell Cavity with a “BCS” grade Superconducting Layer
   a) Coating and Testing Several Cavity Types
   b) Mild Baking No Longer Necessary?
   c) Adjust Alumina Layer Thickness for optimum performance
   d) Adjust Baking Cycle for optimum performance
   e) Atomic Layer Etching for Oxygen Removal & Improved performance.

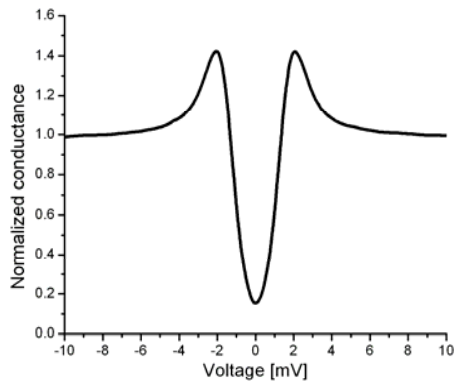
2. Build Layered Structures With SRF Properties Better than Nb alone
   a) Optimize NbN ALD synthesis methodology
      i. Coupon work using PCT and XPS
      ii. Lower Critical Field Testing
      iii. RRR Testing
   b) Cavity testing to demonstrate performance concordance with coupon methods
      i. Several Cavity Types
      ii. Several Cavities
      iii. Robust Methodology

PCT, XPS Insight into Mild Baking Procedure Improvement: Small changes in O stoichiometry->Magnetic Oxide reduction

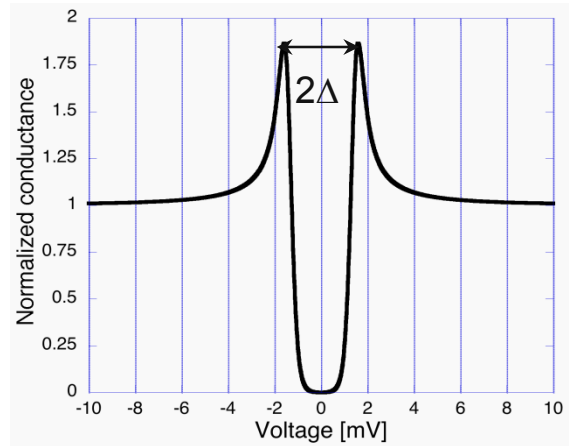
Cavity-grade niobium single crystal (110)-electropolished



Unbaked Niobium



Baked Niobium 120C-24h



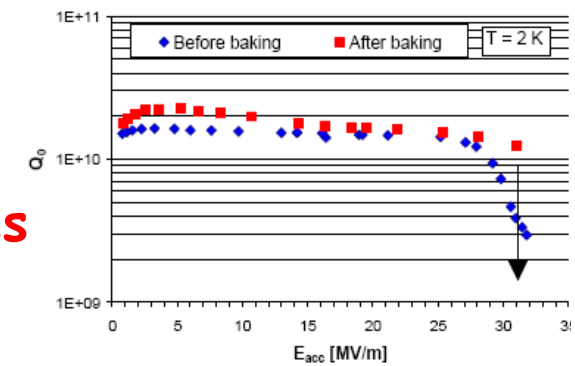
Ideal BCS, T~1.7K

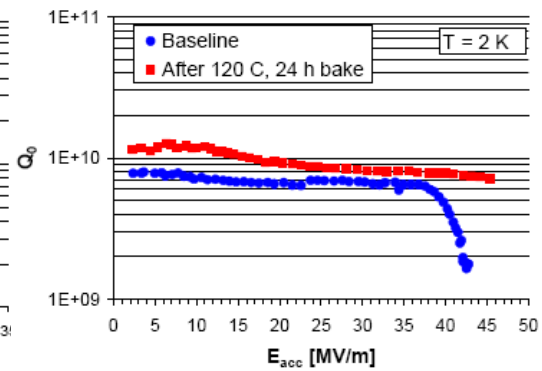
- **Average ZBC ratio = 1.6**
- **Qo improvement × 1.6**

Cavities have dissipative losses due to Cooper pair breaking!

-> $Nb_2O_{5-\delta}$, $NbO_{2-\delta}$

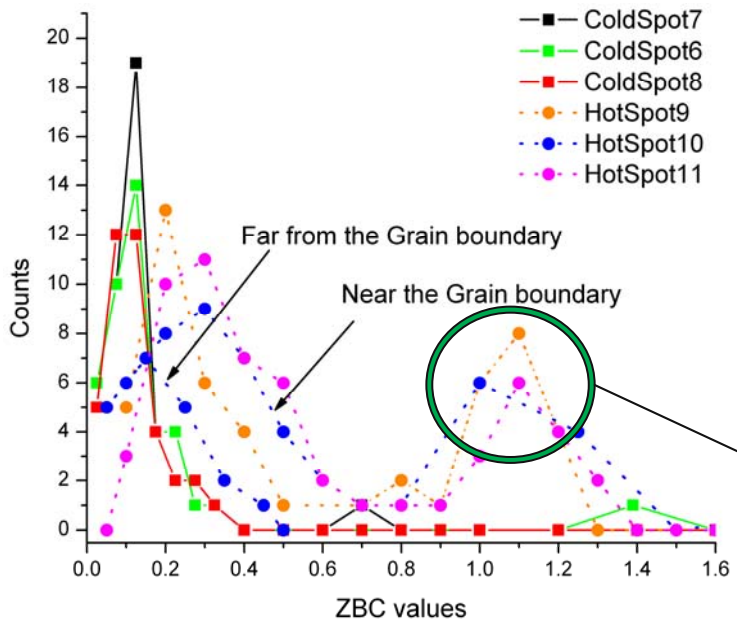
T.Proslier, J.Zasadzinski, M.Pellin et al. APL 92, 212505 (2008)

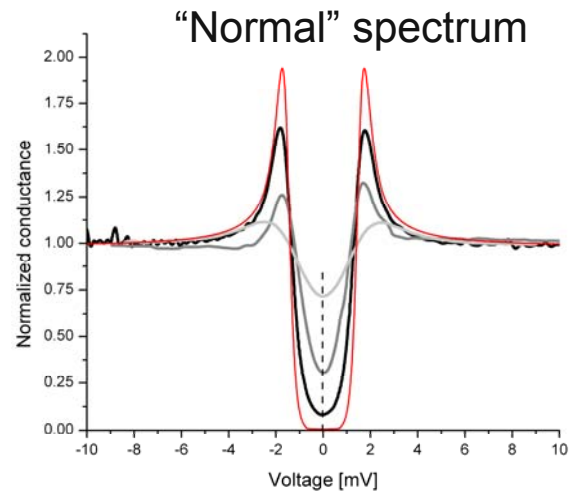


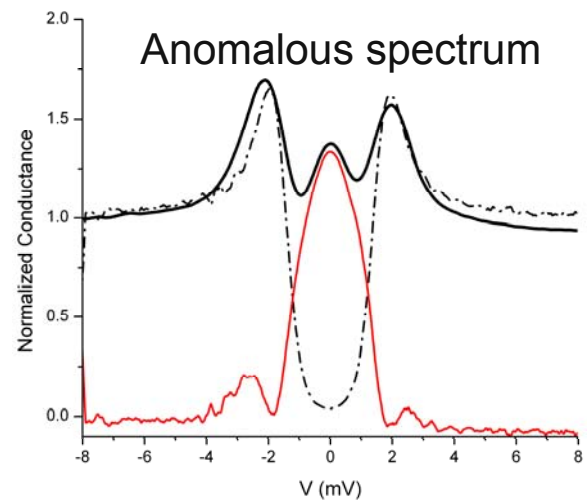


ILC-Single crystal cavities P.Kneisel

New results: Hot and cold spots in SRF cavity (from J-lab)







Hot spots: show dissipative behavior

Higher ZBC and anomalous spec.

lower gap values ($1.3<\Delta<1.55$)

Cold spots: "normal" dissipation

Low ZBC values

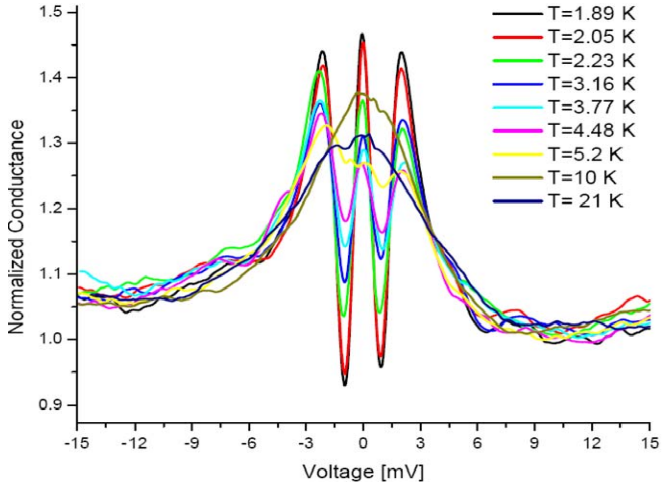
Normal gap values ($1.5<\Delta<1.55$)

Correlates with cavities results!

Origin of peculiar spectrum and dissipation?

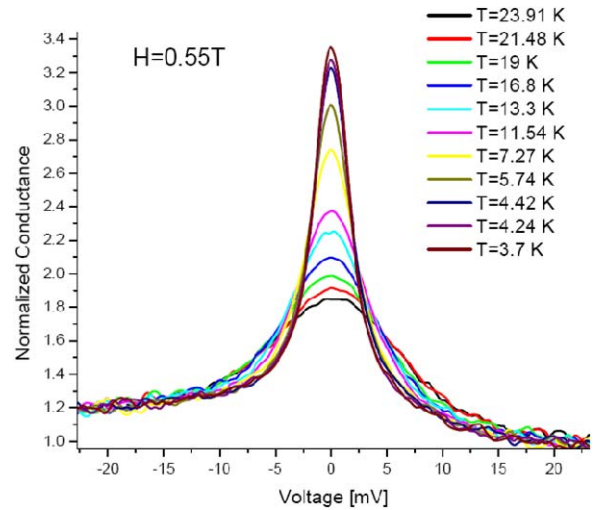
New results: Hot and cold spots in SRF cavity, Origin

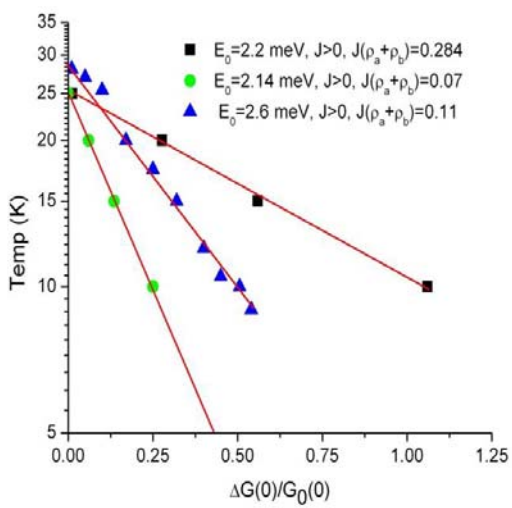
Temp. dep: peak at 0 mV bias increases



High bias peak:
LOSSES!!

Kill superconductivity by applying a mag. Field

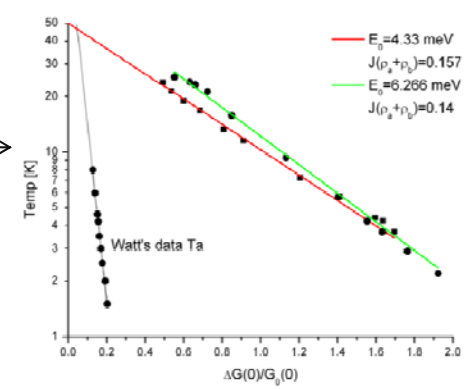




fits with Appelbaum theory -> Magnetic impurities in the oxides !!
J>0 -> antiferromagnetic coupling

-First time measured on Nb oxides

-Same behavior observed on unbaked Nb coupons !



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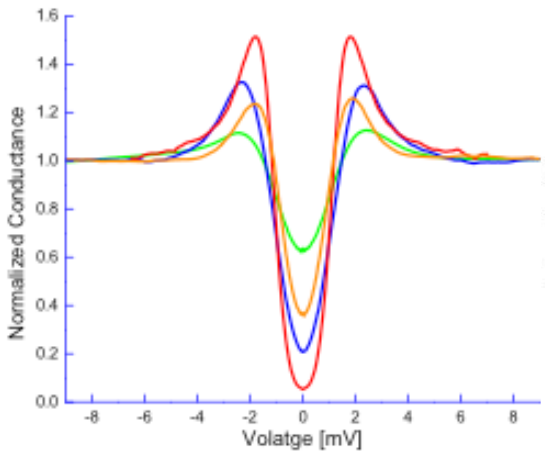
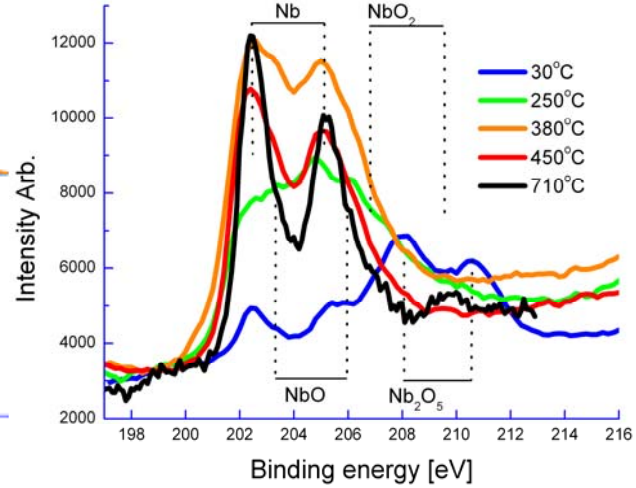
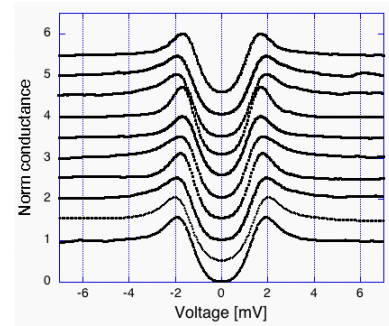
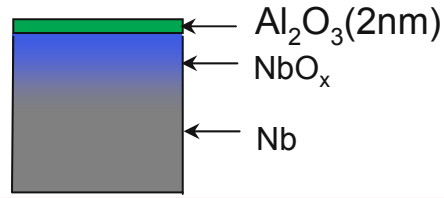
Baking, but now protected from O (Al_2O_3)

Atomic layer deposition (ALD)

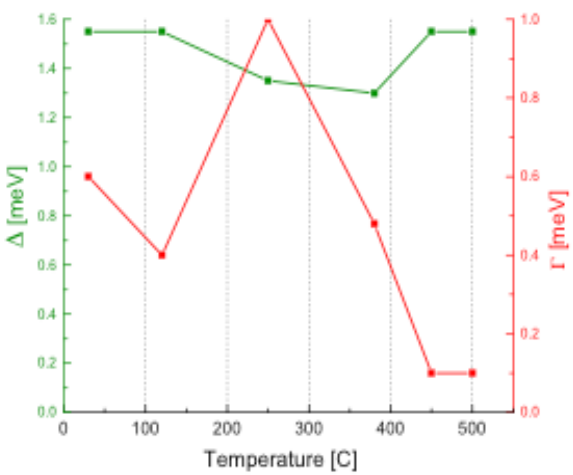


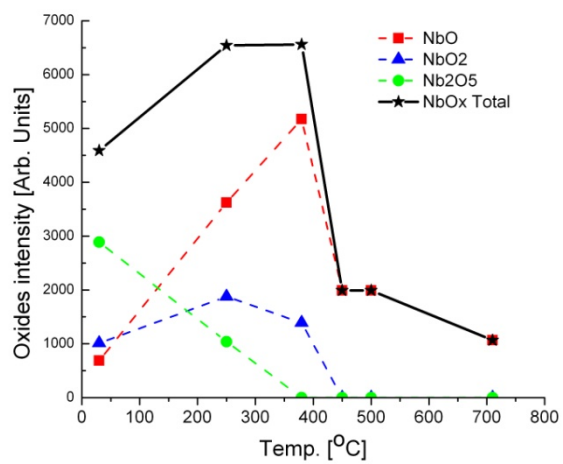






Heating ->
Reduction + diffusion of the oxides





- Δ (1.55meV = Nb).
- Γ (dissipation)
- 500 °C bake should significantly reduce dissipation

Th.Proslier, J. Zasadzinski, M.Pellin et al. APL 93, 120958 (2008)