R&D Paths Towards Achieving Ultimate Capabilities

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- Some introductory remarks
- What are the limits?
- Some suggestions for discussion

Introduction(1)

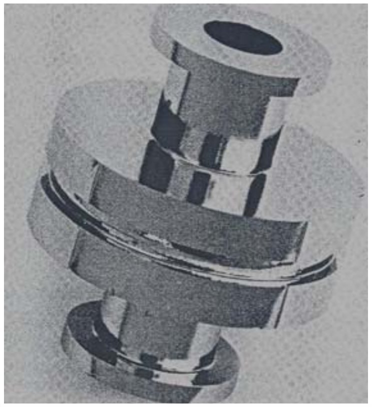
What is needed from the laboratories/research institutions for some serious R&D?

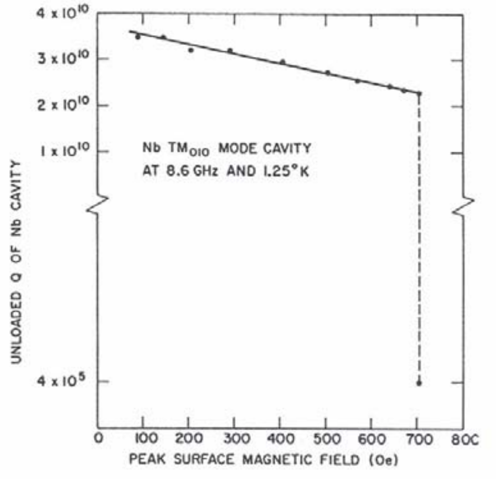
R&D is not a short term enterprise:

- first Nb activities started in 1963 at HEPL
- first thin film Nb activities started in 1980 at CERN
- first Nb_3Sn activities started in 1975 at Siemens AG,Kernforschungszentrum Karlsruhe and Uni Wuppertal

Introduction(2)

HEPL Appl.Phys.Lett 16, 333(1970)





Siemens AG Phys.Lett 45A(1973),241

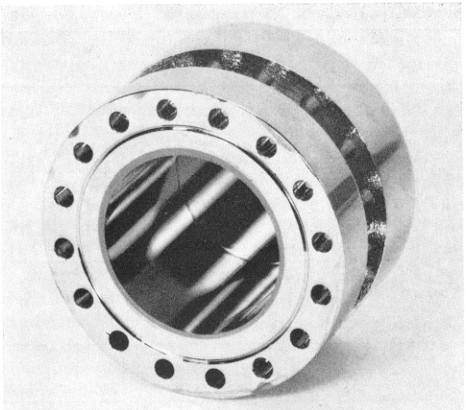
TE$_{011}$ (X-band):

RG Nb, Electropolished

Oxipolished , Anodized

H_{peak} = 159 mT

Q @ H_{peak} = 10^{10}



Not so much progress in 30 years!!

Introduction(3)

- Long term commitment
- Serious interest, no ambivalence
- "Walk the walk" instead of "talk the talk"
- A structure, which supports R&D e.g a "basic research" group with good scientists, engineers and technicians
- A "rethinking" such that R&D is not always the lowest priority, but is on the same level as projects
- Funding (If there is a will, there is a way!)
- A coordinated program
- Flexibility in "shaping" the program as it goes along
- Periodic review of the status of the program
- Accountability

Basic R&D?

- Requires time
- Requires continuity
- Requires appropriate scientific knowledge and skills

None of these requirements – with maybe a few exceptions- are fulfilled by the SRF accelerator Community

- Projects are usually started too early without the necessary R&D completed
- There is usually an "insane" schedule attached to the projects
- There is usually little scientific involvement
- Any (little) R&D is conducted in support of projects

R&D in Support of Projects

The main emphasis is on achieving reliability and reproducibility in performance:

Procedure development, documentation, training.., schedule,safety

Accelerator Project needs

- Presently there is only one planned project, which needs to achieve the "ultimate" performance of cavities or close to it : TESLA(ILC)
- All other plans "on the books" are cw proposals and because of cryogenic losses and rf source requirements cannot be built with cavities operating above E_{acc} ~ 20 MV/m (Jlab upgrade: 31 W/cavity at 20 MV/m, Q~$8x10^9$ at 2.07K), unless the Q-values are improved accordingly

Limits(1)

Basic limits of sc material:

- BCS Surface resistance (Δ/kT_c , l, λ,ξ)
- Critical magnetic field (H_{SH} ?)

Field emission ("non-resonant e^- –loading") is not a fundamental limit

- field as high as 1000 MV/m have been measured on small samples, in test cavities fields as high as 145 MV/m have been reported in cw operation , Epk = 220 MV/m Pulsed

Multipacting ("resonant e^--loading") is not a fundamental limit

- but often shows up as an annoying fact

Electron Loading is still the major contribution preventing achievement of material limits in multi-cell cavities:

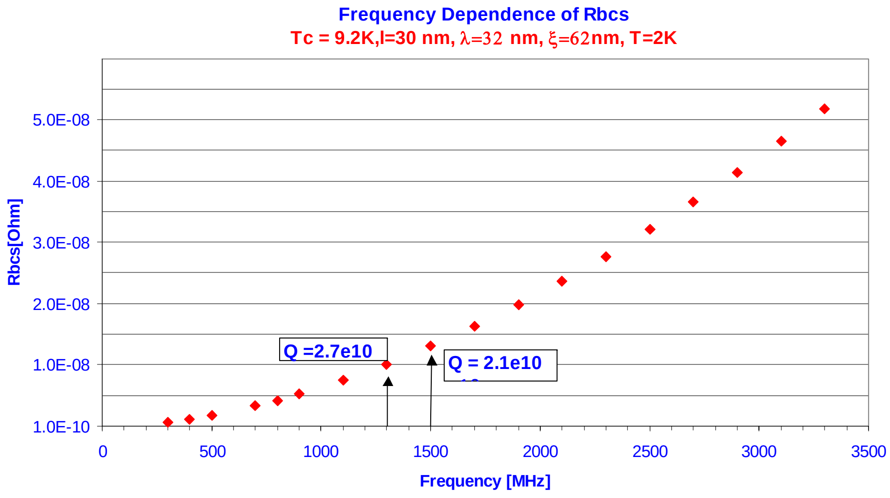
→ contamination control

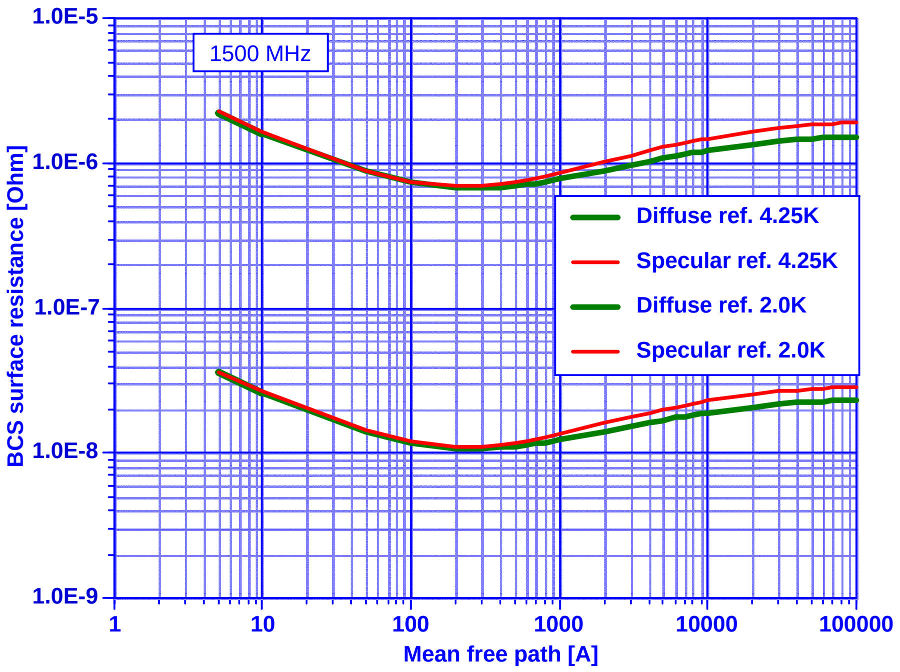
Limits(2)

BCS Surface resistance:

$$\boxed{R_{BCS} = A(\lambda_L,\xi_o,l) \times f^{\alpha} \times e^{-\Delta/kT} \quad \text{for } T < T_c/2}$$

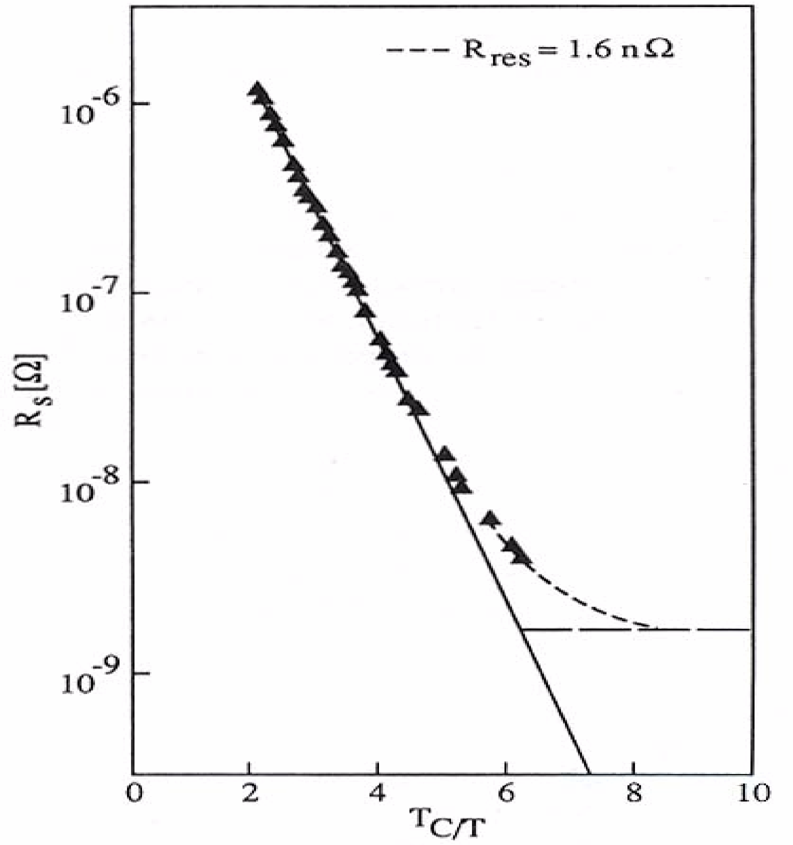
Niobium:





Limits(3)

Residual resistance prevents to achieve BCS surface resistance



Residual Resistance(Low Field)

Properties

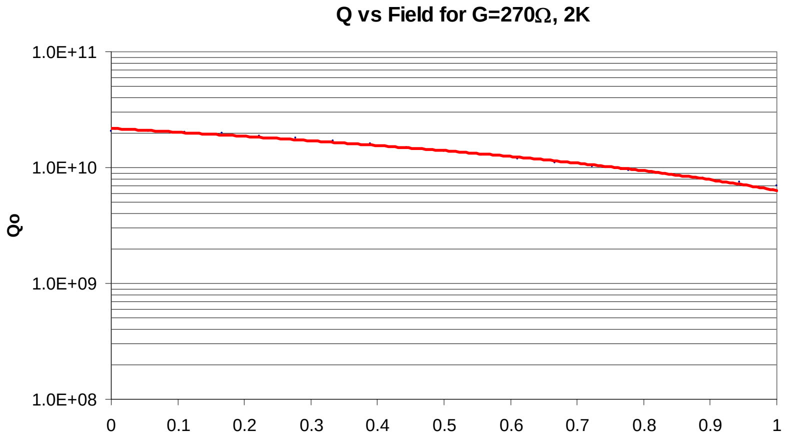
- **Temperature independent**
- **Proportional to f^2 on the same surface, independent in different cavities**
- **localized or "patchy"**
- **Varies widely with surface preparation**
- **as low as 1 nΩ, typically 5 nΩ < R_{res} < 30 nΩ**
- **Lower after heat treatment in UHV at T > 800 ^{0}C**

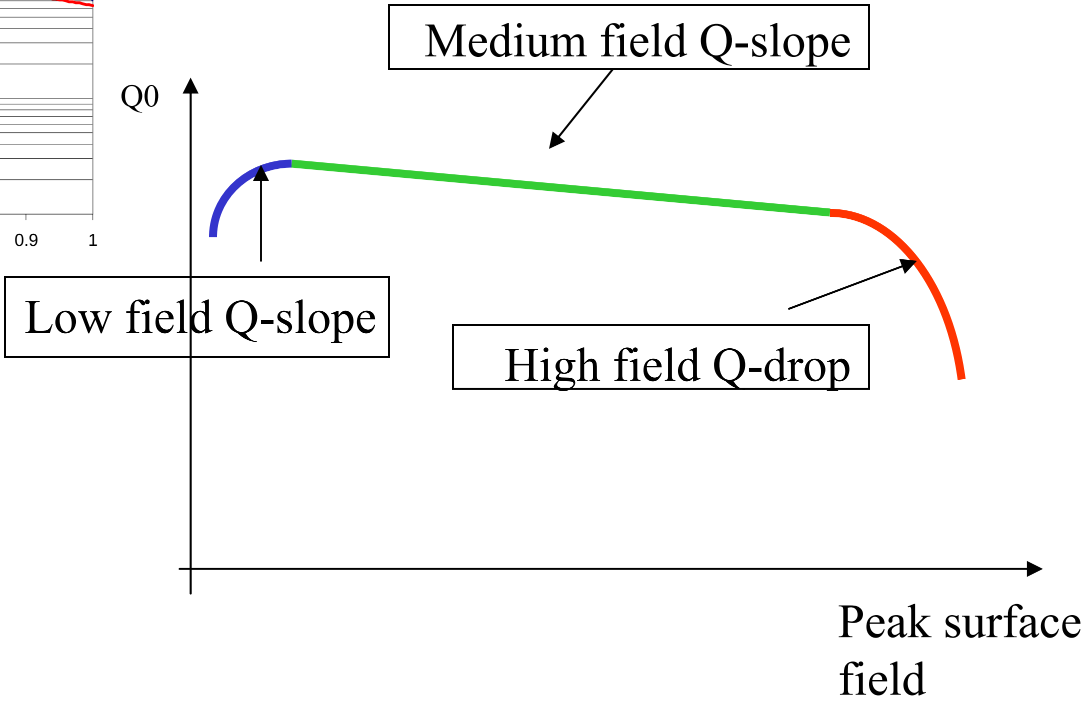
Contributions

- **Dielectric losses such as gases , chemicals, adsorbates, dust..**
- **Normal conducting defects (e.g.foreign material inclusions)**
- **Surface imperfections such as cracks, scratches, delaminations.**
- **frozen-in magnetic flux from ambient fields : ~ 0.3 nΩ/ mG**
- **Hydride precipitation (" Q-disease")**
- **Large density of localized electron states exists in highly disordered metal-oxide interface: can lead to absorption of photons**

Limits(4)

Critical Magnetic Field (H_c, H_{SH}): H ~ 180 mT for Nb





Medium field Q-slope

Low field Q-slope

High field Q-drop

Peak surface field

Limitations(1)

Cavity performance is limited by:

- ⇨ **electron loading (Contamination)**
- ⇨ **Q – drop (Surface, interface, grain boundaries)**
- ⇨ **Quenches (defects, H_{SH})**

- Over the last 4 decades much has been learnt about Nb surfaces, treatment procedures and cavity manufacturing; existing procedures-if applied properly- will result in high performance cavities for application in an accelerator(e.g. TESLA)
- The niobium surface – its oxide structure – is very complex as we have heard and can influence cavity performance

Limitations(2)

Many attempts have been made over the years to correlate cavity performance and surface features:

- Diagnostics (T-mapping, X-ray mapping…with subsequent surface analysis)
- “Sample” cavities

TE_{011} - cavity(endplate, calorimetric)
Tri-axial cavity
Quadrupole cavity(Calorimetric)
➡ TEM cavity

“Mushroom” Cavity
“Turtle” cavity
“Rim” cavity
“Multi-mode” cavity

Limitations(3)

- However, there are local differences in facilities and equipment and the procedures have to be developed in each lab
- In addition to surface properties,material properties influence these limitations:

  Thermal conductivity, Kapitza resistance, interstitial, impurity concentration (hydrogen)
- Very often "environmental" effects are responsible for inferior cavity performance:

  Vacuum, cleanliness level, feedthroughs, cables, peripheral parts…

Limitations(4)

- Investigations on samples using " traditional" surface analytical tools such as AES,SIMS,XPS... have been useful and most likely continue to give some insights in the complex composition of Nb surfaces
- However, it seems to be a long dreamed " dream" (and so far the past 40 years have confirmed that) to correlate the findings from such sample tests with cavity performance. After all, these methods use " outer" (valence) electrons, whereas the sc properties are determined by conduction electrons.
- Therefore methods such as penetration depth, magnetization, pinning, susceptibility seem to be well suited to correlate sample features with cavity performance

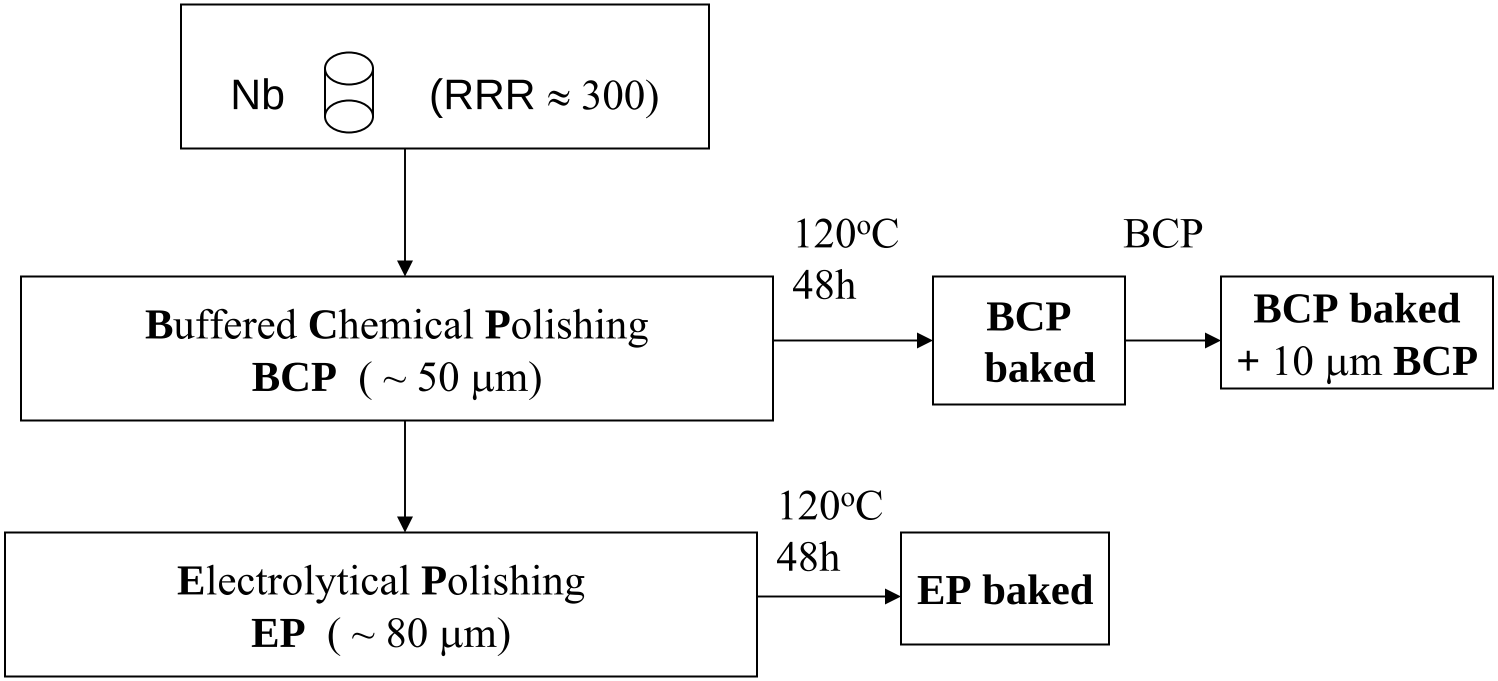
Limitations(5)

In 1973 we used at KfK magnetization and low frequency penetration depth measurements to investigate bulk and surface properties of niobium at KFK

Several investigations were conducted afterwards at Uni Wuppertal, KEK, Uni Hamburg and DESY

At the 2003 SRF workshop Sarah Casalbuoni et al reported about (AC susceptibility)

Superconductivity above H_{C2} as a probe for Niobium RF-cavity surfaces



Nb (RRR ≈ 300)

Buffered **C**hemical **P**olishing
BCP (~ 50 µm)

120°C
48h

BCP baked

BCP

BCP baked
+ 10 µm **BCP**

Electrolytical **P**olishing
EP (~ 80 µm)

120°C
48h

EP baked

-Volume characterization

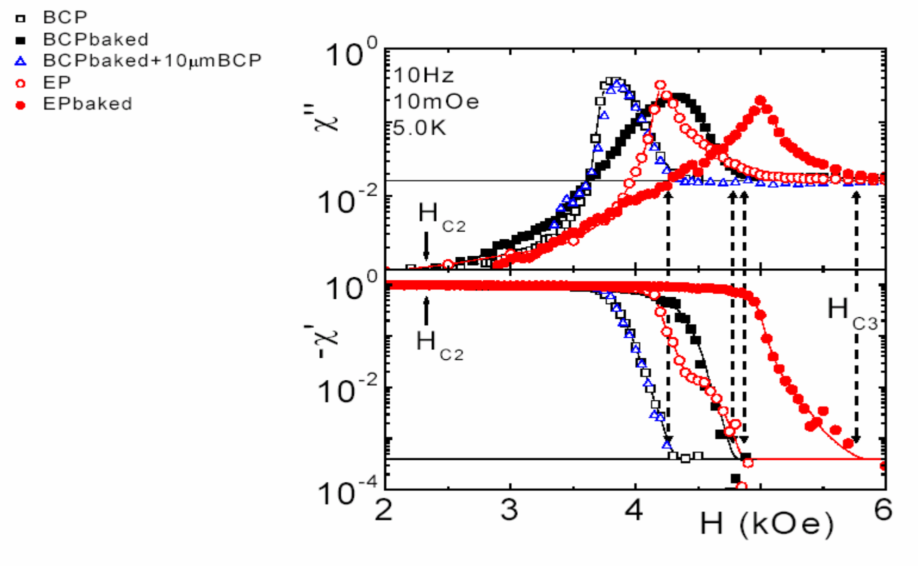
-Surface characterization: $\cdot\,\chi(H\ ,H_{AC},\omega\ ,T) \Rightarrow H_{C3}$

$\cdot\,M(H) \Rightarrow J_C$

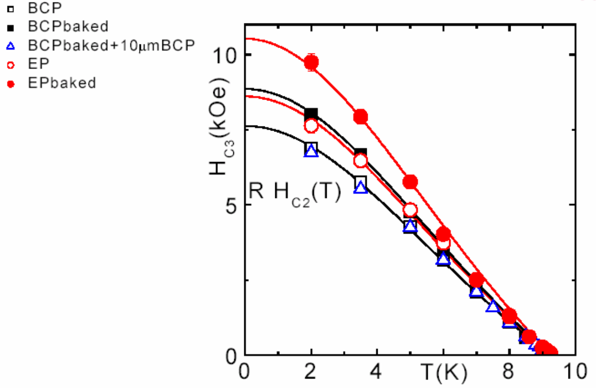
-Conclusions

Surface Superconductivity (S. Casalbuoni)

Nucleation of surface superconductivity: H_{C3}



Temperature variation of H_{C3}

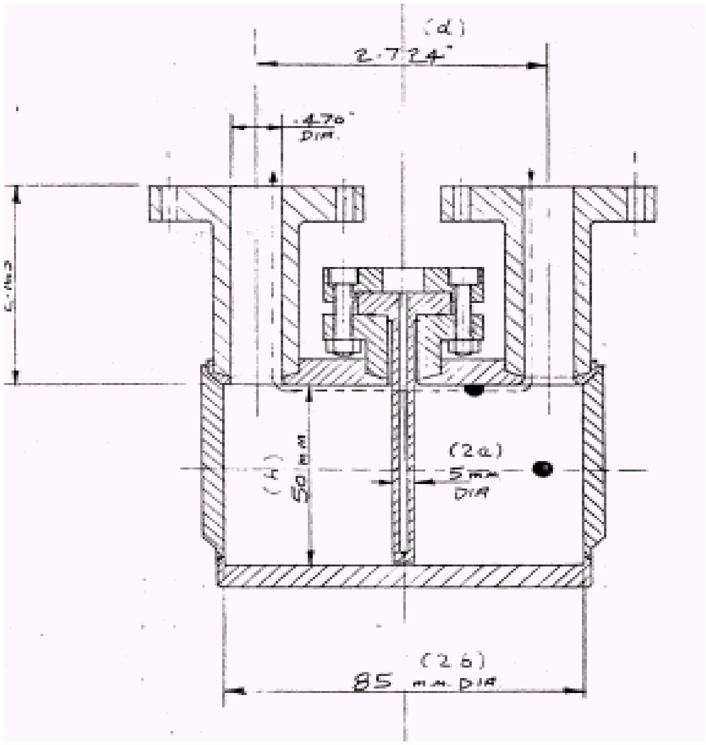


	BCP	BCPbaked	EP	EPbaked	BCPbaked + 10μmBCP
H_{C3}/H_{C2}	1.86(3)	2.16(3)	2.10(3)	2.57(2)	1.86(3)

H_{C3} is increased by baking for EP and BCP
H_{C3} is increased by EP
EP+baking gives the larger H_{C3}

Sample Cavity

W. Bauer et al,"Design of a coaxial TE_{011} cavity for measurements of metallurgical properties and sc rf breakdown fields on the same sample", BNL Report AADD73 11(1973)



Highest H-field on the sample
No joint currents

- Investigation of effect of grain boundaries (single crystal - polycrystalline niobium)
- Effect of carbon and oxygen concentrations during heat treatment on rf fields
- influence of carbon and oxygen concentration on dislocation substructure and grain size
- effect of EBW, EP, OP and surface smoothness on rf fields
- investigation of other materials such as NbTi,NbZr,Nb_3Sn
- samples can be used for magnetization/ penetration depth measurements

Limitations(6)

The most successful method is T-mapping:

defect location,electron loading,loss distribution, global heating..

- The only information on multi-cell cavities is presently extracted from passband mode measurements (Q vs E, quench fields)
- It would be very desirable to take T-maps during every vertical test, most desirably "live" to investigate:

multipacting, processing , Q-drop, loss distribution

- Such information could be fed back into surface preparation techniques (bcp, HPR, nozzle configuration, assembly technique..): if e.g FE occurs always in a particular cell or the losses are high , one could change the rinsing, drying(horizontal,vertical)…

However, such T-mapping systems are presently very time consuming to build, time consuming to attach and expensive: app. $ 10/sensor, ~600 sensors/single cell

Limitations(7)

If one could take advantage of thin film technology, sensors and leads could be evaporated on a flexible substrate (like a shower cap) and wrapped around the cells at room temperature with

Apiezon grease as a contact agent.

- Development of thin film carbon resistors with a negative dR/dT ("Allen-Bradley" type)(has been done ~20 years ago at Cornell by e-beam deposition)
- Find a substrate, which does withstand cryogenics and is possibly flexible at room temperature
- For use in superfluid helium,

  develop an insulator

  Example: heater

Contamination/Cleaning(1)

- Particles stick to surface because of adhesion
- Four basic adhesion forces:

  van der Waals forces,

  capillary forces

  electric double layer

  electrostatic image forces

- They are affected by many parameters:

  size and shape of particle, its charge,nature of substrate,roughness, wettability, humidity of surroundings, hardness of particle and substrate,temperature…

Contamination/Cleaning(2)

- Any cleaning method has to overcome these forces to dislodge the particles from the substrate
- However, as particles get smaller, they are more difficult to remove by e.g. shear forces generated by a e.g. water jet:

$Q = k/ a_p^{0.83}$

a_p = particle radius, Q=flow rate

(R.Gim et al;"Fluid dynamics of liquid jets used for particle removal from Surfaces" Particles on Surfaces, p.379)

- Also, as the surfaces get smoother, the van der Waals Forces increase

$F \sim 1/z^2$

z = distance between substrate and particle

Contamination/Cleaning(3)

There exist many cleaning methods:

- High pressure Water Jet Cleaning
- CO_2 Snow Cleaning
- Ice Scrubber Cleaning
- Ultraviolet – Ozone Cleaning
- Ultrasonic Cleaning
- Megasonic Cleaning
- Isopropanol Vapor Displacement
- Aerosol Jet Cleaning (supersonic aerosol jet)
- Laser Steam Cleaning

Contamination/Cleaning(4)

- Extensive high pressure ultra-pure water rinsing works – most of the time (DESY procedures)
- Control of the particle count, TOC, Si content…

  are essential
- Nozzle configuration (shape, material) and pressure/flow rate at the surfaces are not optimized and might depend on cavity geometry
- Flow pattern inside cavity during HPR might be important: Mass flow not optimized
- Possible sources of re-contamination are in many cases not known:

  auxiliary parts,gloves,pumps, valves, other vacuum components….

Contamination/Cleaning(5)

- HPR in combination with Megasonics
- For "in situ" cleaning (horizontal cryostat) CO_2 - Snow seems to be attractive and is developed at DESY
- UV –Ozone seems to be an alternative method for the same purpose (V.Nguyen Tuong, Proc.2nd SRF Workshop, CERN (1984),p.91
- Hot water rinsing after chemical surface treatment
- Ozonized Water Rinsing (successfully used for Tristan cavities at KEK)

Q - drop: Questions

- What causes a Q -drop in a cavity and why does it occur at different fields? Physics?
- Is the "Field-Enhancement-at Grain-Boundaries" - model by J. Knobloch still valid?
- What role do grain boundaries/ segregation (weak links) play?
- Is the Q-drop an electric or magnetic field effect and under which physical conditions is it eliminated ?
- Does Hydrogen play a role beyond Q - disease?

Hydrogen in Niobium(1)

- Hydrogen in Nb causes “ Q-disease“
- Remedies are: Hydrogen degassing, fast cooldown
- However, additional chemical treatment (bcp) increases H concentration in surface/bulk
- Is this avoidable at all? (W.G. Koerber, report DESY M-91-07)
- Niobium is typically protected by a dense oxide layer, HF can dissolve it, but material removal takes only place in the presence of an oxidant(HNO_3, BCP)
- This reaction is highly exothermic: the reaction enthalpy is – 433.5 kcal/mol
- To avoid a „run-away“ situation, the acids are buffered, cooled and agitated

Hydrogen in Niobium(2)

- However, when the acid is removed the reaction in the viscose surface layer continues without appropriate removal of the reaction energy
- A highly activated niobium surface remains (Nb^*)
- In contact with water (rinsing) the following reaction takes place

$$2\ Nb^* + 5\ H_2O \longrightarrow Nb_2O_5 + 10\ H \uparrow$$

- This reaction can be avoided, if the generated heat is transferred immediately to an oxidizing agent (nitric acid)

$$2\ Nb^* + 4\ HNO_3 \longrightarrow Nb_2O_5 + 2\ H_2O + 3NO + NO_2$$

Is it worthwhile to try this rinsing method?

Hydrogen in Niobium(3)/Grain boundaries

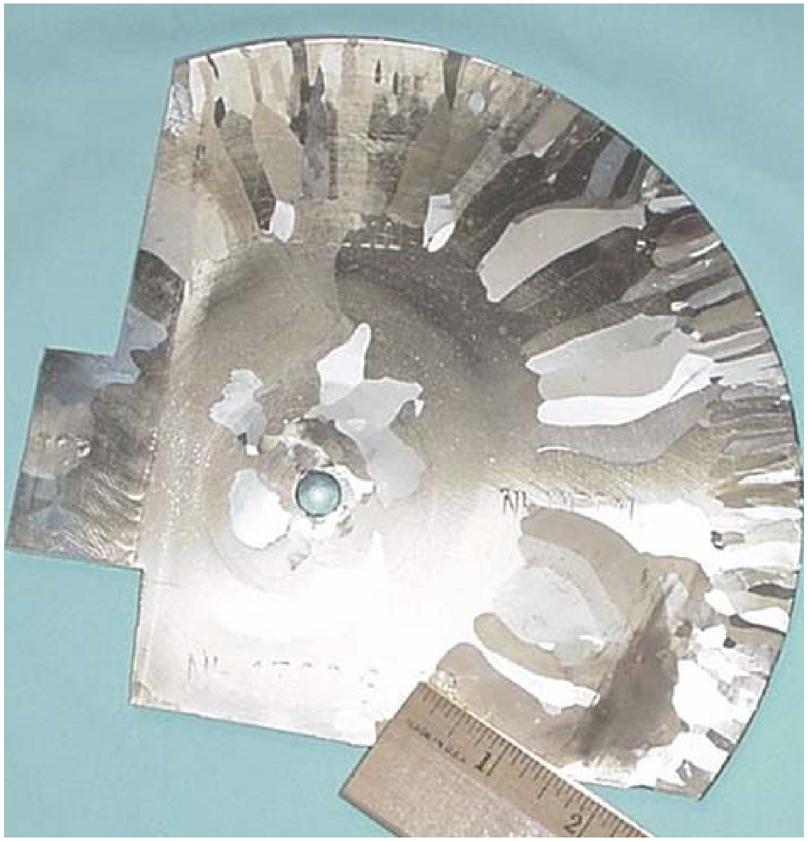
- Hydrogen in metals has the tendency to interact with crystal defects: impurities, dislocations, grain boundaries
- In pure metals the surface and grain boundaries are the principle defects. Hydrogen is concentrated near the surface and segregates into grain boundaries.
- It has been recognized for quite some time that grain boundaries are energetically favored by impurity atoms for segregation (oxygen, carbon, Ti...) and some work has been done to look at the influence of grain boundaries on Q vs E - behavior in cavities

Hydrogen in Niobium(4)/Grain boundaries

- Since grain boundaries are " weak links", especially if they are „filled" with oxides, it seems to be appropriate to use/develop experimental tools to investigate them, such as e.g. tunnel junction/Josephson junction type experiments/magneto-optical methods (P.Lee et al)
- Hydrogen has a magnetic moment; therefore it is planned at Jlab to develop a sensitive squid system, which can be used for such investigations (see Ganapati)

Grain Boundaries

- In collaboration with Reference Metals we will fabricate 2 single cell cavities of the HG variety with large grain material as shown here
- Discs of 1/8 " will be sliced by wire EDM from a 9" dia ingot, deep drawn and fabricated by standard methods
- Tensile tests of this material showed elongation in excess of 70%



Quenches(1)

- Thermal model calculations and T-mapping showed that quenches occur at defects
- Quench fields depend on RRR, defect size and defect resistance
- They are stabilized by RRR material: starting RRR and post purification
- Mechanical properties have to be watched
- Eddy current scanning/squid scanning of sheets pre-screen the material, however there are detection limits

Quenches(2)

- Systems with micron size resolution might be needed
- A scanning after the forming process would be most desireable: curved surfaces
- Magnetic field limits can be explored with X-band TE_{011} -cavities as in the "old " days besides the pulsed measurements implemented by Ricky et al

Alternate Materials(1)

- Are they of interest for R&D or for application?
- Do they promise better performance than Nb in application?

Nb/Cu: energetic deposition looks promising

as far as film structure is concerned, proof?

But: cost advantage only for low frequency, gradients and Q-values at high gradients not yet compatible with solid Nb, rework probably more complex than rework of Nb cavity, Nb/Cu cavities also quench, frozen-in flux during quench and cooldown (thermo currents); ″ real ″ cavities are very complex to coat,no indication that magnetic field limit is different from bulk

Alternate Materials(2)

Nb_3Sn:

- Existing method of vapor diffusion needs Nb substrate
- Co-evaporation (L.H. Allen, Stanford) gave poor results
- Strong Q-degradation with field (fundamental?)
- Thermo currents during cooldown and quenches
- Complexity of coating " real " cavities (T – distribution, formation of lossy/Sn -rich NbSn compounds...)
- If H_{SH} is the fundamental limitation, no advantage because of large κ – value

Nb_3Sn seems suitable for 4K operation and smaller gradients (low frequency, but costs for vapor diffusion are high)

Alternate Materials(3)

Cavities made from alternate materials suffer from the same or worse contamination problems than solid niobium cavities because of handling after the coatings.

Summary of suggestions(1)

- Make extensive use of T –mapping by developing a inexpensive and fast system
- Investigate changes in surface/bulk features by employing susceptibility measurements on samples of a e.g. TEM cavity
- Continue with the magneto-optical investigations as reported by Peter Lee, U.Wisconsin
- Develop Tunnel/Josephson junction measurements to investigate grain boundaries, density of localized states in the Nb/NbO interface as a function of surface treatment
- Investigate grain boundary effects on cavities with large grain size; are they related to Q-drop?
- Improve/optimize surface cleaning and cavity assembly procedures: pressure/flow, nozzle configuration…

Summary of suggestions(2)

- For the exploration of the magnetic field limits one might want to test X-band TE_{011}cavities as in the ″old ″ days besides the pulsed measurements implemented by Ricky et al
- Investigate , whether there is a frequency dependence of the Q-drop with e.g. a TEM cavity
- Investigate the importance of surface roughness on Q-drop by making use of seamless cavities (in progress at Jlab in collaboration with DESY)
- Investigate whether there is a difference in Q vs E behavior for ″wet ″ or ″ dry ″ oxide
- Develop scanning system for curved surfaces with increased sensitivity