2. Cavity Materials & Materials R&D

2a Cavity Material

General Requirements_ Overview

Specifications for high purity niobium (RRR) sheet, used for fabrication of cavity cells and auxiliary components such as HOM- and FP-couplers and beam pipes have been developed over the years. Material produced to these specifications by various companies in Japan (Tokyo Denkai), Germany (W.C.Heraeus) and the US (Wah Chang) and used for cavity fabrication has resulted in high performance prototype and production cavities, when combined with appropriate QA measures during sheet production such as e.g. clean rollers or eddy current or squid scanning for defects prior to deep drawing of cavity cells.

Recently, single cell and multi-cell cavities have been produced at JLab from large grain ingot material or from single crystal, cut directly from the billet by either wire EDM or saw cutting. This is an exciting new development, and has the potential of simplifying the production sequence and consequently the cost. Initial experience indicates that very smooth surfaces can be obtained with the single crystal material or even the large grain material using the BCP (chemical) etch process only, thus avoiding the necessity for using the more complex electro-polishing (EP) processing. This might be related to less defects, a reduced intrinsic strain in the single crystal material and a significantly reduced number of grain boundaries.

Nb/Cu laminated material has been successfully used to produce high gradient single cell cavities at DESY and KEK from Nb/Cu tubes by hydro-forming. Explosion bonding, back-extrusion and hot rolling techniques were successfully used to produce the composite tubes. The laminated Nb/Cu approach takes advantages of the bulk Nb performance (Nb layer ~ 0.5 mm thick) combined with the increased thermal conductivity and stiffness of the copper backing resulting in possible significant cost savings (W. Singer, SRF2005 estimates ~30 % per "naked" cavity). Welding presents a difficulty in that the Cu must be removed at the weld joints before e-beam welding and that there are risks of contamination/leaky joints. This material is probably best suited when used with hydro-formed multi cell assemblies.

Low frequency (< 500 MHz), lower gradient cavities historically use a thin layer of Nb deposited on Cu. Cavities made from deposited Nb suffer from very strong Q slope and do not appear suitable for high gradient ($\geq$15 MV/m), high Q LC application. Research continues with different deposition techniques (e.g. plasma-deposition) to try to understand and improve the SRF properties.

Other types of superconductors, such as Nb_3Sn, NbN and MgB_2 are experimental and far from being useful for project application. There are also fundamental questions related to the limiting RF field and its dependence on κ in these high κ materials.

Options under consideration

- Nb RRR fine grain sheet
- Nb single crystal or large grain
- Nb/Cu lamination
- Nb deposited on Cu
- Other superconductor

BCD choice

Nb RRR fine grain sheet

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros

- Specifications exist and are – with some exceptions[1]- met by industry.
- This material is best known. Measurements of the thermal conductivity, Kapitza resistance (under different surface conditions), mechanical properties and mechanical anisotropy, texture and formability have been published. Post purification with Ti at different temperatures and durations has been studied.
- Many examples of high performance cavities (single+multi-cell) made from this material exist!
- Studies of possible cost-savings in a mass-production scheme were performed.

LEXT con-focal laser microscopy of a 100x75μm^2 region of polycrystalline Nb after chemical polishing with BCP 1:1:2. Courtesy of P. Lee (University of Wisconsin).

---

[1] Mechanical properties (yield strength, elongation, tensile strength), grain size and hardness are sometimes not met.

Cons

- For accelerating gradients ≥ 28 MV/m EP for final surface treatment seems to be necessary to give a smooth surface finish, even though there exist examples of cavity performances beyond this level after BCP treatment (rougher surface) only. In any case, “in situ” baking is necessary to remove the “Q-drop”, typically starting at gradients ≥ 22MV/m, corresponding to peak magnetic surface fields ≥ 80 mT (G.Ciovati,SRF2005). In-situ baking seems to be more effective in electro-polished cavities.

  At this time it is statistically unclear, if titanization at 1200°C-1400°C is required for best performance of this material. The titanization with subsequent etching increases the RRR from ~300 to ~600, providing better thermal stability of the material. However, the mechanical properties degrade significantly (yielding!).
- The process of producing sheet from ingot material is inherently expensive because of rolling, cleaning and annealing steps and loss of material (edges, etc..) Also, in comparison to large grain ingot material the sheet manufacturing process appears more prone to introduction of defects.

  Reproducibility of mechanical properties from sheet to sheet is still an issue although the process is well advanced. The issue of skin rolls, affecting texture and micro-structure still needs to be addressed. Other related issues are micro-yielding (Myneni, SRF2005), spring back (half cells formed from different sheets/heats of material end up with different frequencies), grain size distribution and texture. Interesting work is ongoing on Equal Channel Angular Extrusion (ECAE), consisting of extruding the niobium through an angled, narrow channel. ECAE promises to produce even smaller grain size, better uniformity and better formability. It is unknown, whether this process introduces unwanted impurities.

Potential cost impact

Presently Nb material costs ~ 10-15% of the complete module. Thus if the modules are ~1/3 of the total LC estimate, a reduction in material cost of a factor of 2 could result in ~2% project savings. With the expected reduced cost of cavity fabrication, material cost may become a larger fraction of the module cost and consequently, reduction in material cost may become more significant. In terms of absolute $’s, the savings could be in the range of ≥ 100 Mill.

Potential cost savings in Nb are currently expected from the single-crystal (or large grain) or the Nb/Cu laminate approaches. Another possible avenue of cost reduction is via a relaxation of the impurity content specifications, in particular for Tantalum. Cost savings can potentially also be generated as a result of mass-production for an ILC size project (back-flow of “scrap-material”, economy of scale). The cost impact of large production quantities needs to be better understood, however.

Potential Mods to BCD with impact (tech, cost, difficulty/time scale).

The effect of impurities in the Nb is being investigated (e.g. Tantalum). It may be possible to relax specifications on impurity content without compromising the cavity performance. Such a possibility is indicated by recent prototype cavities made from higher Ta content material at JLab (800 and 1500 wt ppm), which reached very high fields.

Understanding and optimizing the industrial production process, e.g. number of melts to reach the specified RRR/impurity content, should lead to high quality material at a cost savings. ECAE and other procedural steps, for instance, could yield material with better formability. Benefits from this research are also expected for the alternate cavity fabrication technologies, such as for hydro-forming.

Singer-SRF05 – hydro-formed multi-cell cavities made from polycrystalline sheet material at DESY.

Technical advantages, increased tech potential

Modifications of existing specifications for poly-crystalline niobium are only justifiable, if cost savings can be realized and technical performance is not compromised.

Potential cost impacts ??

Risk and Reliability impacts ??

It seems obvious that any deviation from the existing technology (fine grain RRR niobium, standard fabrication) has certain risks; it is not clear to which level of verification any alternative to the baseline has to be pursued; however, a few multi-cell cavities (~ 4-6) seem an appropriate number to judge the feasibility of a new approach.

R&D necessary (at different levels)

- The impact of the impurity content on the cavity performance (e.g. Tantalum) should be studied further; the starting point of the existing study (JLab, DESY, Reference Metals) was the claim of cost reduction benefits by the participating material supplier. It is not clear how many melts are needed to achieve the specified RRR – value; however, the impurity level of interstitial impurities such as H,C,N,O affect RRR significantly and possibly improved vacuum conditions during EBM would reduce the # of melts and therefore cost. In this context new measurements of the content of light as well as heavy impurities in bulk and surface (and their effect on RRR) need to be conducted. This work would also benefit the refinement of the fine grain Nb sheet specifications.
- The mechanical properties of fine grain rolled sheet material is still poorly explored. Recent results by Bieler et al. (MSU) indicate that stronger reduction favors the 111 orientation parallel to sheet normal, which is the best configuration for forming. These new findings haven't yet been translated to the industrial level. What does industry know? Reproducibility? Grain size control? Yield strength? Spring back? Texture? Equal Angle Extrusion?? Smaller grain size?? This is especially important for alternate production technologies such as hydro-forming.
- Current sheet quality control measures (eddy current scanning, optical inspection) allow detection of ~100 µm size defects. Thermal model calculations have indicated that detection of normal inclusions at the 1-10 µm range is needed to guarantee ultimate cavity performance for the specified RRR-value of ≥300. DESY, the University of Giessen and Heraeus are developing a Squid Scanner aiming at 10 µm resolution. Amac Int. and Fermilab recently were awarded a phase I SBIR funding for the development of a SQUID scanner operating on curved surfaces / half cells.
- Better understanding of the effect of different surface treatments, i.e. chemical polishing and electro-polishing (and or different degrees of mixture of both) on the cavity performance, surface roughness, oxide thickness and composition in sheet material is also a R&D priority (this has at various levels been done in the past – with little success – and is again at various levels going on now, e.g. CARE for EP, L.Philipps - SRF2005, Cr.Boffo – SRF2005, Geng – SRF2005…)

ACDs choices prioritized

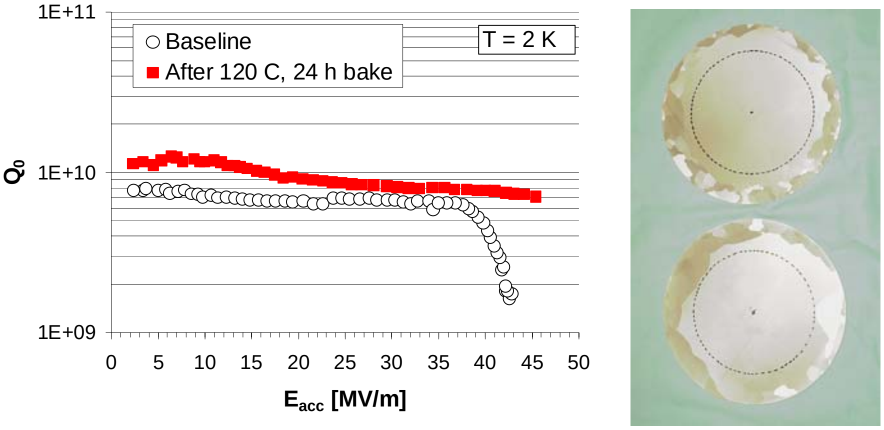
Overview-

1) The most exciting new idea is the large grain/single crystal material, as stated in the overview for this section, mainly because it opens the possibility of "streamlining " the procedures at comparable performance, which could result in significant cost savings..
2) Nb/Cu laminate has the potential for significant cost savings. Support of this development is also important.

ACDs

Pros & Cons of specific ACD

1) Single crystal and large grain (These are treated together because the materials development i.e. crystal formation development is the same.)



P.Kneisel, SRF-05, Result of 2.3 GHz single crystal, single cell cavity.

Single crystal (& large grain)- priority 1 ACD

Pros

Initial results of the efforts at Jlab are very encouraging! The table below gives a summary of the results obtained from 5 different ingots with different grain sizes , RRR-values and impurity contents (Ta)

Suppl.	**Ingot**	**RRR /Ta [ppm]**	**Type / Nc**	**F [GHz]**	**Q [10^{10}] (2K, E_{max})**	**E_{acc} [MV /m]**	**Fabrication**
CBMM	A	280 /800	HG / 1	1.5	**1.25**	**34**	*W-EDM*
CBMM	B	280 /800	HG /1	1.5	**0.93**	**32**	*W-EDM*
CBMM	C	280 /1500	ILC_LL / 1	1.3	**1.4**	**34**	*S-cut / W-EDM*
CBMM	B	280 /800	OC / 1	1.5	**0.5**	**25**	*S-cut (80 μm)*
CBMM	B	280 /800	HG / 1	1.5	**0.48**	**27.5**	*S-cut, removal test ~ 75 micron removal*
CBMM	A (single)	280 /800	HG / 1	2.2	**0.5**	**38** *(185 /165 mT)*	*W-EDM*
CBMM	A (single)	280 / 800	ILC_LL /1	2.3	**0.7**	**45**	*W-EDM*
CBMM	A	280 /800	HG /7	1.5	**1**	**25.8** *(quench, no baking)*	*W-EDM*
CBMM	C	280 /1500	ILC_LL /7	1.3			*S-cut / W-EDM In fabrication*
Ninxia		330-360 /150	OC / 1	1.5	**0.21**	**33** *(Q-drop still after bake)*	*S-Cut, machined*
Wah Chang	C1 /C2	> 300 / < 500	HG /1	2.2		*Not yet tested*	*W-EDM*
Wah Chang	B1 /B2	> 300 / < 500	HG /1	2.2		*Not yet tested*	*W-EDM*

P. Kneisel – Summary table of current status of single crystal and large grain cavity fabrication at JLab.

At DESY,W. Singer has started with the production of single cell cavities from Heraeus and Ninxia large grain material. Irregular deformation (“earing”) was encountered during deep-drawing of the half-cells. Fermilab is currently ordering such material. Wah Chang advertised to offer large grain/single ingots in the near future. JLab has purchased and received a 500 kg ingot from CBMM with Ta =800 ppm and will fabricate 2 TESLA cavities from this material after initial qualification with single cells (the material is sufficient for ~ 16 nine-cell cavities).

Single crystal or large grain material promises the following potential advantages:

- Reduced costs
- Comparable performance
- Very smooth surfaces with BCP, no EP necessary
- Possibly elimination of “in situ” baking because of “Q-drop” onset at higher gradients
- Possibly very low residual resistances (high Q’s), favoring lower operation temperature (B. Petersen), less “cryo power” and therefore lower operating costs
- Higher thermal stability because of “phonon-peak” in thermal conductivity
- Good or better mechanical performance than fine grain material (e.g. predictable spring back..)
- Less material QA (eddy current/squid scanning)

Cons

The first results with this material were obtained only recently. Little experience exists at present and the following issues need to be resolved:

- Technology to provide large single crystals needs to be developed (it is the preferred option to use single grain material for cavity fabrication)
- However, large grain material with a few crystals might be ok:
    - How uniform is the forming process?
    - Is there a significant slippage of grains during forming?
    - Is there the possibility of vacuum leaks through grain boundaries?
    - Do grain boundaries cause problems during EBW?
    - Is there preferential etching at grain boundaries?
    - Do mechanical properties depend on crystal orientation?
    - Is oxidation depending on crystal orientation and if so, is there a preferred orientation?
- Effective billet slicing needs to be developed. Wire EDM currently is the preferred technique: how does one slice 360000 sheets in a few years, when it takes ~ 1 day/sheet?
- Specifications need to be developed and the first material received from the different vendors needs to be qualified;
- Appropriate acid agitation during BCP needs to be developed to achieve smooth surfaces and uniform material removal;

Technical advantages, increased tech potential

The single crystal or large grain approach promises potentially higher and more consistent gradient/Q performance.
It may lead to easier Nb material production, because the sheet forming process (forging, rolling, cleaning, annealing..) is eliminated.
It may permit to use BCP instead of EP for cavity processing, if appropriate agitation during BCP is applied.

Potential cost impacts

Technical advantages may lead to simplification of fabrication and processing which in turn will lead to cost savings. Consistent gradient/Q results or lower residual resistances would also lead to cost savings. There exist some initial cost estimates, which suggest potential savings in the order of a quarter of billion $’s; however, not enough is known for this emerging technology (e.g. BCP vs EP, much reduced QA, material costs on large scale, slicing of ingot..) to make a believable estimate of the cost impact at this time.

Risk and Reliability impacts

Initial measurements at JLab of the surface roughness of single crystal after BCP indicate, that very smooth surfaces (several times smoother than EP surfaces on polycrystalline niobium) can be achieved with appropriate agitation of the acid. Because of the smoothness, cleaning after the chemical process might be more effective and this may lead to better cavities performance with less dark current.

R&D necessary (at different levels)

- Initial R&D is underway. This program needs to be pursued vigorously. There are plans at JLab for fabricating and testing a number of single and multi cell cavities (two high gradient 7-cell, two Tesla type 9-cell, all from CBMM material with 800 ppm-wt Ta), single cell cavities from Heraeus and Ninxia material are being developed by W. Singer’s group at DESY. Fermilab is also considering such a program. These programs will serve to develop the optimal processing techniques and allow development of the ingot preparation technology in industry.
- Fast, cheap (this excludes any method, which uses cutting tools generating “waste” material close to the dimensions of the discs) cutting techniques need to be identified and tested, preferably on cavities.
- The dependence of mechanical and etching properties from the crystal orientation need to be better understood; first experience with large grain forming has shown earing, when soft dies were used at ACCEL; most likely, this is an indication of the dependence of the mechanical properties on crystal orientation. Much less problems were encountered at Jlab with both female and male dies being aluminum. The single crystal formed very well. Possible remedies to this problem need to be explored if the large grain material should ever be considered

seriously. NIST has applied for a grant to the NRC to investigate the forming process on large grain and single crystal material.

- The theoretical and experimental investigation of the effects of grain boundaries need to be pursued further [University of Wisconsin].

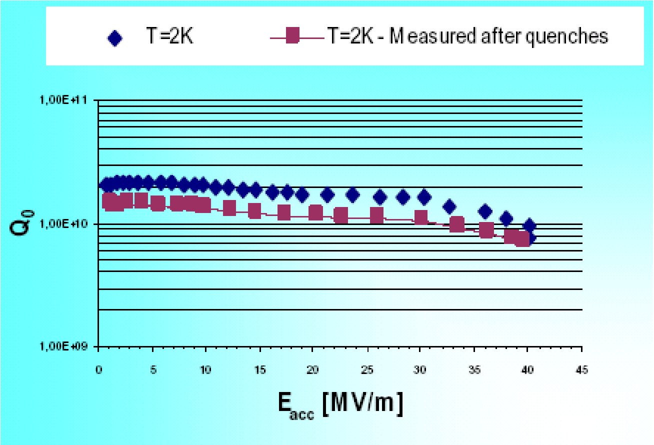
Time scales for R&D

It might be possible, at appropriate funding levels and other resources, to have further results from single and multi-cell cavities, which will support the expectations for the potential of this material. Hopefully by that time, producers will have the single crystal production know-how under control. (How strong is industry's motivation to work on such a development?)

Nb/Cu laminate- Priority 2 ADC

Examples of Nb/Cu single cell cavity 1NC2 produced at DESY by hydro-forming from explosively bonded tube are shown in the figure below. After preparation at Jlab, 180 micron BCP, annealing at 800°C, baking at 140°C for 30 hrs (P. Kneisel), one of these cavities achieved 40 MV/m. A similar result was achieved at KEK (K. Saito) from a hot rolled bonded tube [see W.Singer, SRF2005].

Some prototypes of Nb/Cu laminate cavities fabricated at DESY. Singer SRF-05



W. Singer – Nb/Cu laminated single cell cavity prototype 1NC2 – tested at JLab.

Pros

The laminated Nb/Cu approach takes advantages of the bulk Nb performance (Nb layer ~ 0.5 mm thick) combined with the increased thermal conductivity and stiffness of the copper backing resulting in possible significant cost savings. DESY has demonstrated the technology for multi-cell (3-cell) cavities at the laboratory level. In detail the possible advantages are:

- The Nb/Cu laminate approach promises cost reduction because of reduced amount of Nb per cavity (cost savings estimated by W. Singer to be up to 30% per (naked) cavity).
- Very high gradients, comparable to the best bulk niobium cavities have been achieved with prototypes, possibly showing the effect of thermal stabilization as a result of the copper.
- Stiffening against Lorentz-forces can be obtained without significant performance and cost penalty by increasing the thickness of Cu layer. In particular, the stiffening can be varied cell-to-cell.
- Seamless fabrication technique (hydro-forming) allows the elimination of equator welds in the high magnetic field region of the cavities.
- More or less all processes used for treatment of bulk niobium cavities (except for titanization) are applicable.
.

Cons

- A first pass production technique was developed at DESY and subsequently at KEK. Further refinement of the technique might be needed, especially in the bonding process between Nb and Copper (explosive vs hot rolling).
- The e-beam welding requires cutting away the copper to make a pure Nb weld. There is a risk of contaminated welds, which might leak because of cracks in the weld. Also, local RRR reduction typically ensues following the welding.
- Cu/Nb laminate cavities still quench, despite additional thermal stabilization!
- Thermo-currents introduced during the quenches (or during processing in a barrier) lead to frozen-in flux, which lowers the Q-value.
- Cool-down has to be very uniform over the cavity volume, because thermo-currents/ frozen-in flux will destroy the Q-value.
- The presently used methods of cooling down cryo-modules will most likely not work with the Nb/Cu composite material.
- This technology is probably not applicable with single crystal unless one would apply standard fabrication techniques (half cell forming from composite sheets and welding).
- Cracks appear in iris area during fabrication, when heat treating below the re-crystallization temperature of the Nb. Heat treatment at higher temperatures causes softening of the copper. Doping of Cu with Zr was tested. Intermediate temperature heat treatments were not sufficiently explored. More effort is required to get the tube-material to state where it can be transferred to industry.
- Industrialization process has not been started yet.

Technical advantages, increased tech potential

Uncertain;
Possibly the reduction of Lorentz-force detuning at very high gradients will be an advantage (E_{acc} = 45 MV/m increases the detuning by 65% to several kHz!!). However, there is also a limit in how thick the copper backing can be made (e.g. the iris between cells).

Potential cost impacts

Reduced usage of Nb could result in up to ~2% savings in total project cost.
Assumptions: -1- cavity fabrication costs both for hydro-forming and standard EBW process are the same, -2- Cost of fabrication of bimetallic NbCu clad tubes is twice higher than cost of disc fabrication, -3- costs of non-cell parts like flanges, end tubes are the same in both types of cavities, -4- Nb disc fabrication is 20% of the total Nb cost,
Conclusion: NbCu clad cavity costs ~30% less than Nb cavity (according to Singer – SRF2005).

Risk and Reliability impacts

Potential risks are:
Leaks in EBW because of contamination from residual copper and cracking;
Q-degradations due to quenches and poorly controlled uniform cooldown;

R&D necessary at different levels and check points
time scales for R&D

A number of choices and details need to be made:

- Choice of bonding method: explosion bonding (DESY), hot rolling (KEK-Nippon Steel Co.), back extrusion (DESY);
- Fabrication techniques: e beam, hydro-form, Lorentz force stiffeners;
- How the end groups are handled: composite material (lots of EBW)?, solid niobium? Sputtered Nb on copper with end groups flanged onto cell structure? Superconducting joint?
- Can such composite cavities be “pipe-cooled”, which would change the whole cryo-concept?
- Complete cavities with end groups need to be fabricated and tested;
- Cavities must be placed in modules and tested;
- How the cavity is made rigid against Lorentz force must be developed in detail (varying the Cu thickness, for example);

Time scales for R&D

The Cu/Nb laminate technology is currently being pursued by DESY (Singer's group) and KEK (Saito's group). Good performance has only been demonstrated on single cell cavities, but technology for 3-cell cavities was developed (hydro-forming). A demonstration of this technology on complete 9-cell cavities with end groups is necessary! Industrialization of this technique must commence as soon as high gradient performance demonstration in several multi-cell cavities!

Other Materials- No Priority ADC
Films and other SC considered not feasible at this time for LC project.

2b Cavity Materials R&D

General Requirements_ Overview-

Over the last decade a set of procedures has been developed for the fabrication, surface treatment and assembly of superconducting niobium cavities, which lead to high performance cavities, if applied properly. These procedures include improved material QA by scanning for defects, extensive QA during cavity fabrication (cleanliness of weld joints), appropriate amount of material removal prior to heat treatments at 600 – 800°C for hydrogen removal (Q – disease!), BCP and EP, high pressure ultra-pure water rinsing (HPR) for extended periods of time", clean room assembly, "in situ" baking… The application of these procedures has in many cases now lead to performance levels, which approach the ultimate limits of the material. Nevertheless, the underlying physics is in some areas not well understood and a fundamental material R&D program should be aimed at clarifying the physical phenomena and aid to optimize the processes. In the context of a project of the scale of the ILC it is paramount that "black magic" be replaced by intellectual understanding of the processes. Fundamental materials R&D must be adequately funded.

Fundamental materials R&D – distinguished from "R&D in direct support of the project" as discussed above - has to do primarily with the nature of the RF surface and the influence of modifications of the Nb-oxide interface and surface contamination on performance of rf cavities.

The two key performance criteria are Gradient and quality factor Q. The main performance limitations in today's bulk Nb cavities are:

- Limitation I: cavity gradients are beginning to reach the **RF critical field**. For niobium this limit is believed to be around 185 mT as an analysis of existing experimental data suggests [K.Saito, PAC 2003]. It is still not entirely clear, if the limit is Hsh (superheated), or Hc (thermodynamic) or another.
- Limitation II: In order to get most benefit in terms of accelerating gradient from this limitation, the RF cavity shape has to be chosen such as to minimize the ratio of the magnetic surface field to accelerating gradient H_{peak} / E_{acc}. Two new shapes – the re-entrant shape and the low loss shape – have been proposed, which allow theoretical accelerating gradients of > 50 MV/m at the expense of increased peak surface electric fields up to $E_{peak} \geq 110$ MV/m. Such fields can only be achieved:
  - if **field emission** is extremely suppressed: Therefore, main efforts have to go into control of contamination, the development of clean processing and assembly procedures- especial in complex assemblies such as cavity strings and cryomodules- and the prevention of re-contamination

  and

- Limitation III: **defects** in the material, which limit the achievable fields to values $H_{RF} < H_{crit}$, can be eliminated (or controlled to micron size, see thermal model calculations).

- Limitation IV: In addition, high purity niobium cavities exhibit at gradients ≥20 25 MV/m a strong **degradation of the Q–value (“Q-drop”)**, which significantly increases the cryogenic losses and limits the achievable gradients due to heating. This Q-drop can be eliminated/reduced by “in-situ” baking at a temperature of ~ 120°C for a duration >12 hrs and smoother surfaces (e.g. electro-polished) favor more significant improvements.
- Limitation V: **Residual resistances** of a few nΩ have been achieved, but not on a regular basis. Low residual resistances (≤3 nΩ) would allow to take advantage of the decrease of the surface resistance with decreasing temperature and an accelerator such as ILC could be operated at e.g. 1.8 K, reducing the cryogenic load and the operation costs.

R&D investigations (ongoing or under consideration)

The overarching goals of fundamental R&D should be to allow cutting processing cost or removing performance limits. The list below includes ongoing R&D projects (with name of main proponent and institutions involved) as well as suggested or proposed high priority R&D projects (no name). All projects should possibly aim at investigating all existing material options: fine grain, large grain, single crystal and Nb/Cu clad (sputtered, laminate).

- **Measurement of the RF critical field:**
  - RF critical field in pulsed regime at 11.4 GHz (R. Campisi & SLAC)
  - Coaxial samples in TE_{011} cavity (P. Kneisel - JLab)
  - Single crystal TE_{011} cavity at ~ 3.5 GHz (no EBW) (P. Kneisel - JLab proposal)

- **Understanding Q drop:**
  - Ongoing Studies at JLab, utilizing T-mapping (G. Ciovati, P. Kneisel,..etc)
  - Measurement of the baking benefit layer thickness (ongoing, Cornell University – G. Eremeev, H. Padamsee)
  - Cutting out hot spots and multi-facetted analysis (P. Bauer’s proposal)

- **Understanding low and medium field Q-slope (residual resistance)**
  - Ongoing studies at JLab, utilizing T-mapping on large grain material of varying grain size, single crystal and polycrystalline niobium; effect of grain boundaries/grain boundary density on residual resistance

- **Oxide-free or dry-oxide cavities (Improved oxygen diffusion model by G.Ciovati)**
  - Study the performance of oxide free cavities (preparation e.g. a la F. Palmer) - then prepare cavities with “known” oxygen content in bulk i.e. through ion implantation. (JLab)

- **Surface chemistry measurements**

- Nano-scale with 3D atomic probe tomography (Northwestern University / Fermilab)
- XPS studies (H. Tian / C. Reece JLab, ??)
- SIMS studies (Jlab/ NC)
- TE_{011} cavity with endplate "chemistry" (Jlab, L.Phillips et al, SRF2005)

- **Field emission**
  - It is not clear, whether FE is a fundamental limitation in superconducting cavities as it seems to be the case in normal conducting cavities: the stresses from the high surface fields "tear" the material apart. All experiments on Niobium surfaces with dc samples and cavities seem to indicate that FE is caused by artificial contamination; if appropriate contamination control measures are applied, surfaces can be field emission-free.
  - New cleaning techniques (dry ice – D. Reschke DESY,..)
  - Break-down studies and effect of coatings on breakdown (Northwestern University / Argonne Lab – J. Norem)]

- **Grain boundaries**
  - Measurement of chemical impurity content (Northwestern University / Fermilab)
  - Grain-boundary transport-measurements to estimate grain boundary resistance and critical current density (University of Wisconsin / Fermilab)
  - Effect of grain boundaries on cavity performance (see above, JLab)

- **Magnetic flux penetration:**
  - Magneto-optics and magnetization measurements of samples processed as cavities (University of Wisconsin / Fermilab)
  - Tests with superimposed, axial (frozen) DC field in cavity (G. Ciovati)
  - Investigation of frequency dependence of Q-drop using for example a coaxial cavity (?): is there a frequency dependence as suggested from some data, is there a cut-off frequency for flux penetration?
  - Flux gate/squid scanning system on cavity to detect flux penetration at e.g. onset of Q-drop or at grain boundaries
  - Coaxial samples from the TE –coaxial cavity will be investigated with respect to magnetization behavior and low frequency penetration depth measurements will be performed (Jlab)

- **Chemistry Development:**
  - Effect of chemistry (Effect of BCP/EP combinations on surface roughness, sulphure in EP, eliminating HF);
  - Cold or hot HPR, alcohol HPR;

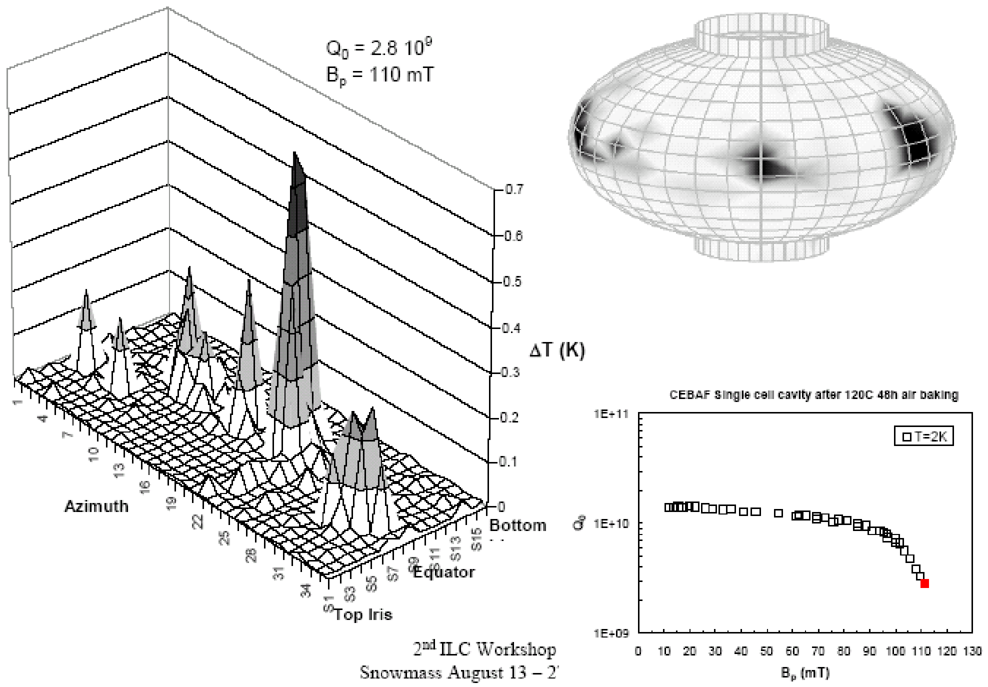
- **Defects, such as normal-conducting inclusions**
  - Development of micron-resolution screening elements, such as the SQUID scanner (Fermilab/AMAC)

- **RF superconductivity theory**
  - Calculations to estimate surface resistance contribution due to magnetic vortex penetration in RF fields (possibly Fermilab-University of Wisconsin, A. Gurevich, JLab – G. Ciovati?)
  - Estimate surface resistance contribution of weak-links (grain-boundaries, patches with suppressed superconductivity) (possibly Fermilab-University of Wisconsin, A. Gurevich, JLab – G. Ciovati?)
  - Linear and Non-linear BCS resistance in the clean and dirty limits (possibly Fermilab-University of Wisconsin, A. Gurevich)

- **Verification of the acoustic hot spot model**
  - Changing the outer cavity surface after test with a short etch, re-measuring to evaluate effect on Q-drop.

- **Residual Resistance**
  - See low and medium Q-slope above

The figure below shows an example by G. Ciovati of "hot-spots" appearing during the Q-drop. The origin of these hot-spots is unknown and needs to be understood.



G. Ciovati, SRF2005, "Hot-spots" appearing during the Q-drop.