Performance of Large Grain and Single Crystal Niobium Cavities#

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Abstract

We have fabricated and tested several single and one multi-cell cavity made from large grain niobium of four different ingots.
Two cavities at a frequency of ~ 2.2 GHz were made from single crystal sheets. For four single cell cavities of the HG – and OC shapes, a 7-cell cavity of the HG – shape – all resonating at 1500 MHz – and an ILC_LL single cell cavity at 1300 MHz large grain material was used.
We explored also different chemical polishing baths such as a 1:1:1 and a 1:1:2 buffered solutions and explored the change of cavity performance as a function of material removal.
The results from these preliminary investigations will be reported.

Introduction

In 2004 a program to investigate and understand the mechanical properties of high purity niobium and its dependence on grain size and impurity levels was started as a CRADA between Reference Metals (CBMM) and Jlab. Other niobium producing companies were invited to participate in this program, but at that point in time declined.
As part of this CRADA, CBMM supplied two ingots (ingot "A" and "B") of large grain niobium with a Ta contents of ~ 800 ppm and RRR – values of ~ 280. This material showed excellent mechanically properties; in particular, ingot "A" contained a very large crystal in its center and a single crystal sample from this ingot for measurement of the stress/strain behaviour showed an extremely large elongation of nearly 100% - a factor of two larger than obtained with fine grain polycrystalline material as indicated in figure 1.

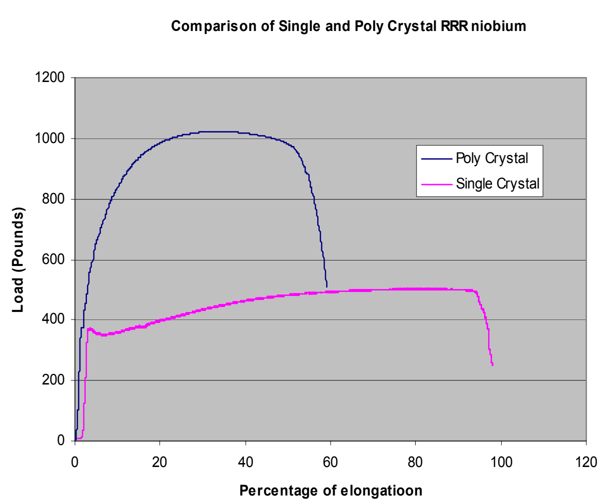


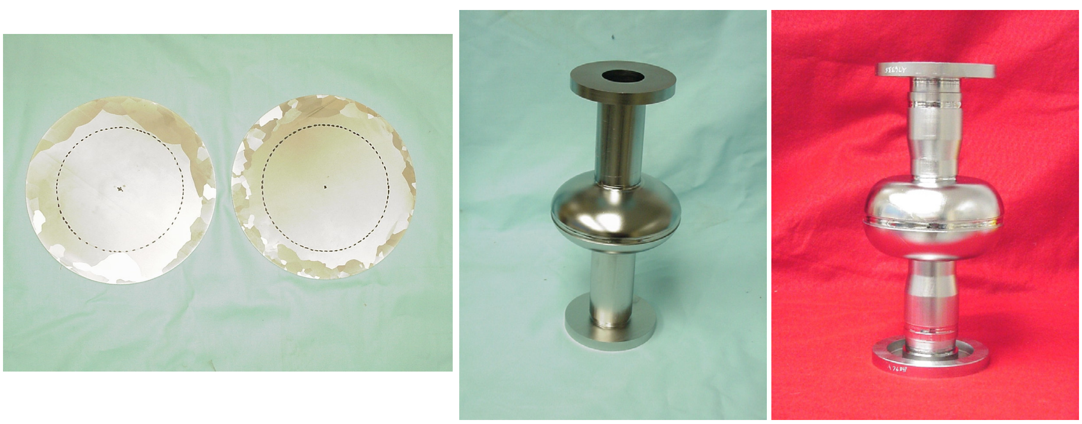
Figure 1: Stress-strain behaviour of single crystal and poly-crystalline niobium

This excellent formability encouraged us to fabricate initially a single cell cavity from this ingot. Meanwhile, several single and one multi-cell cavity have been manufactured from different ingots and tested as discussed below .

Experimental Experiences

a. Material

- Since the first ILC workshop in November of 2004 we have fabricated and tested five single cell cavities of 1300 MHz and 1500 MHz from material sliced off both by wire EDM and saw cut from three different ingots (“A”, “B” and “C”) supplied by CBMM. The cavities had three different shapes: old “Cornell” shape (OC), high gradient shape (HG) and ILC-low loss shape (LL)
- In addition we have fabricated and tested two single crystal cavities of a scaled HG and LL shape, respectively, from ingot “A” at ~ 2.3 GHz as shown in figure 2.



(a) (b) (c)

Figure2: Ingot “A” with a large center crystal (a), from which a scaled high gradient (b) and a scaled low loss (c) cavity was fabricated.

- From large grain material with intentionally somewhat smaller grains supplied by Wah Chang we have built two 2.3 GHz_cavities of the HG shape; these cavities will be used to investigate the possibility of a grain size dependence of cavity performance in conjunction with cavities made from the single crystal and poly-crystalline niobium .At the time of this workshop, these cavities have not yet been tested.

- A niobium supplier from China - Ningxia – supplied two discs of large grain niobium and a 1500 MHz single cell cavity (OC) was fabricated and tested from this material.
- We have fabricated a 7-cell HG –Jlab-Upgrade cavity, which has been tested with some initial problems: during electron beam welding three holes developed in an equator weld , which were successfully repaired with high RRR niobium plugs.
- We are in the process of fabricating an ILC_LL 7-cell cavity from material of ingot “C”, which has a Ta contents of 1500 ppm.

b. Experimental Results

The experimental results obtained until this workshop are summarized in table 1

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	**0.85**	**25.6** *quench*	*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	**0.87**	**36.6** *After baking*	*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*

Table 1: Summary of rf tests on cavities made from large grain/single crystal niobium at Jlab.N_C = number of cells

In figures 3 to 8 several of the results summarized in table 1 are shown

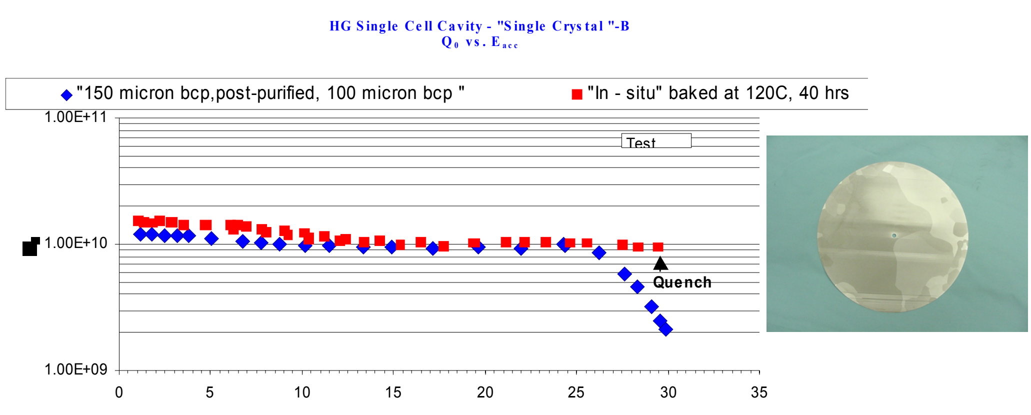


Figure 3: Performance of cavity made from ingot "B"

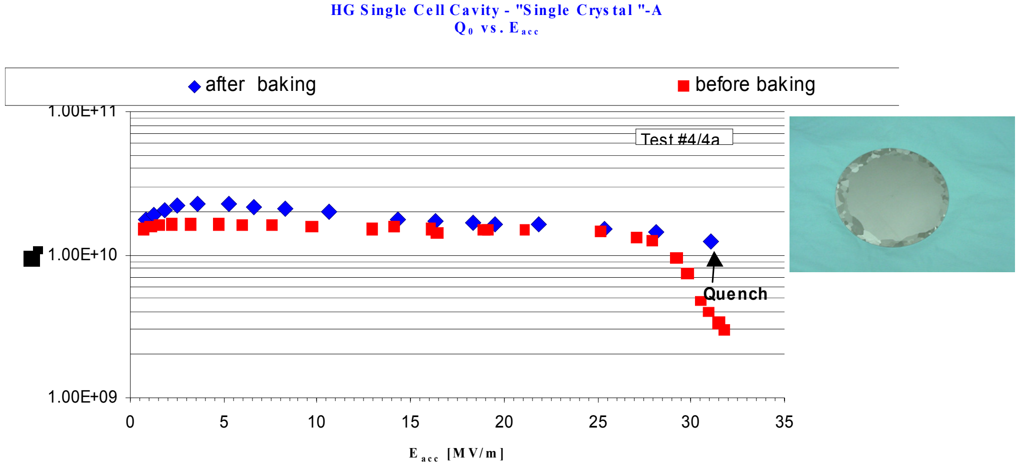


Figure 4: Performance of cavity made from ingot "A"

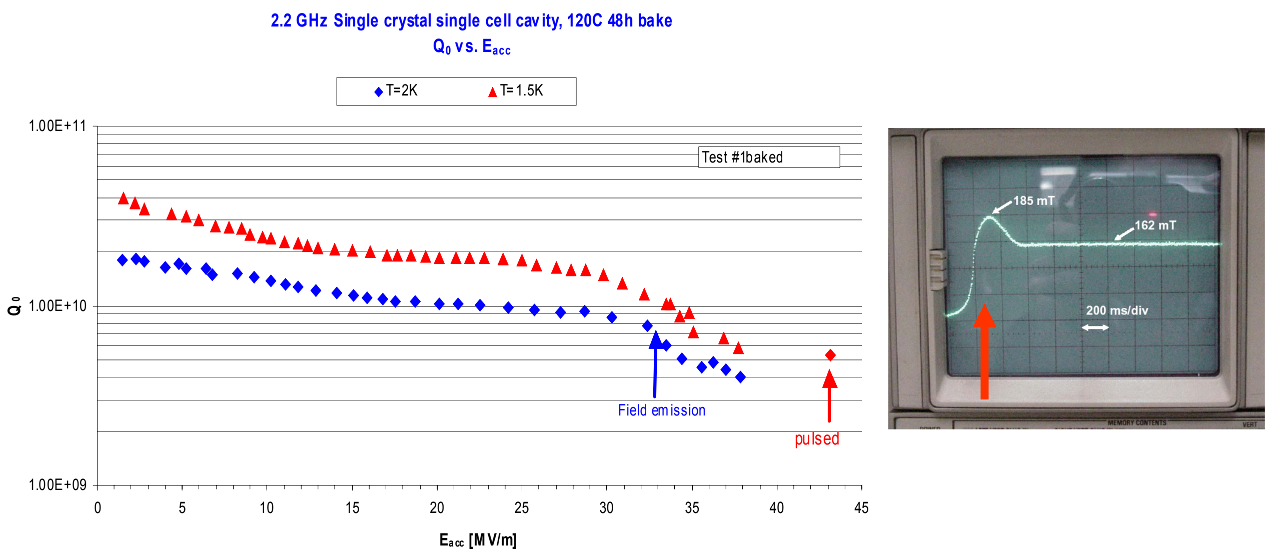


Figure 5: Performance of single crystal HG cavity after 100 micron of material removal by BCP, 800 C hydrogen degassing, add. 100 micron of BCP and "in situ"baking for 48 hrs at 120C; the cavity reached a field of 43 MV/m corresponding to a peak magnetic field of 185 mT under pulse conditions as shown on the oscilloscope trace

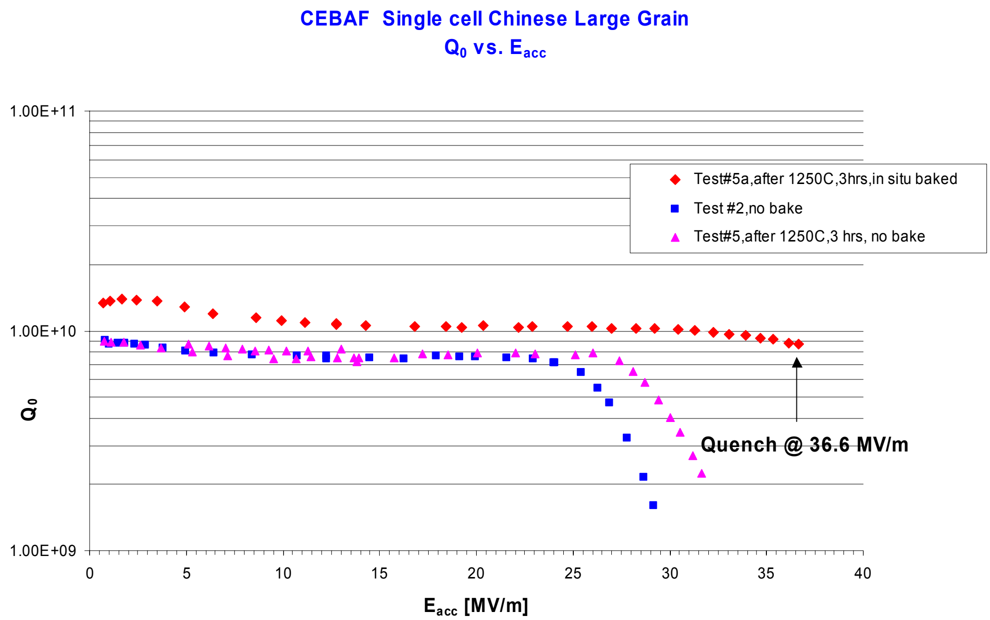


Figure 6: Q vs E_{acc} of a single cell OC cavity made from large grain niobium supplied by Ningxia [4]; shown are the performances before and after "in situ" baking. The "quench" field of E_{acc} =36.6 MV/m corresponds to a surface magnetic field of 166 mT.

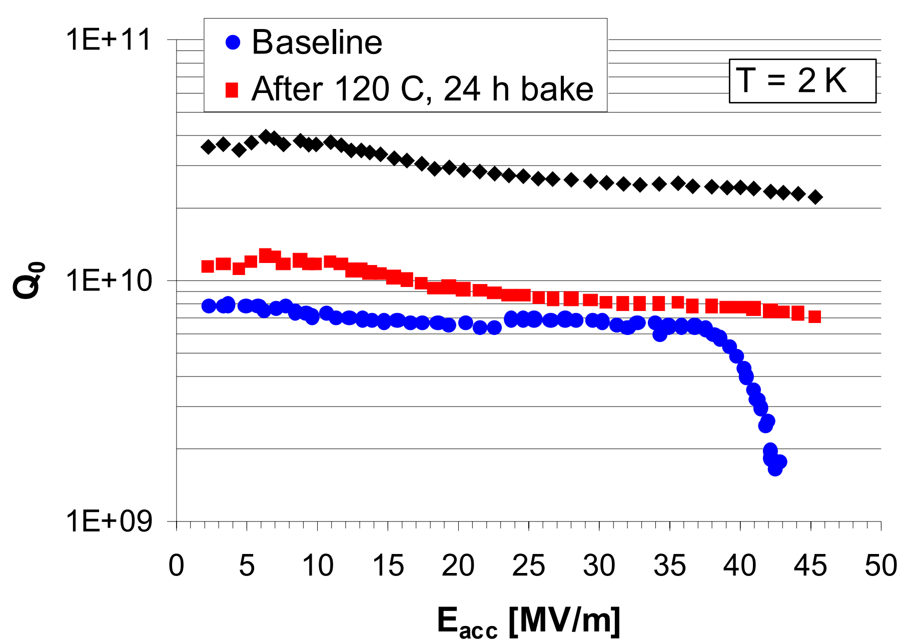


Figure 7: The single crystal low loss cavity as shown in figure 2c [f = 2.3 GHz ,E_{peak}/E_{acc} = 2.07, H_{peak}/E_{acc} = 3.56 mT/MV/m] performed very well and quenched at 45 MV/m with a high Q-value after "in situ" baking. The black diamonds in figure 7 are scaled values to a frequency of 1300 MHz.

In all cavity tests with large grain/single crystal material we measured the temperature dependence of the surface resistance between 4.2K and 1.6K. These data were subsequently analyzed with Halbritter's modified surface resistance program[1], which gives as a result fit parameters for residual surface resistance, energy gap and mean free path, whereas critical temperature, London penetration depth and coherence length were kept as fixed parameters. In several tests we measured extremely low residual resistances, which leads to the speculation that grain boundaries might play an important role in contributing to the residual resistance; an example for the single crystal cavity is shown in figure 8:

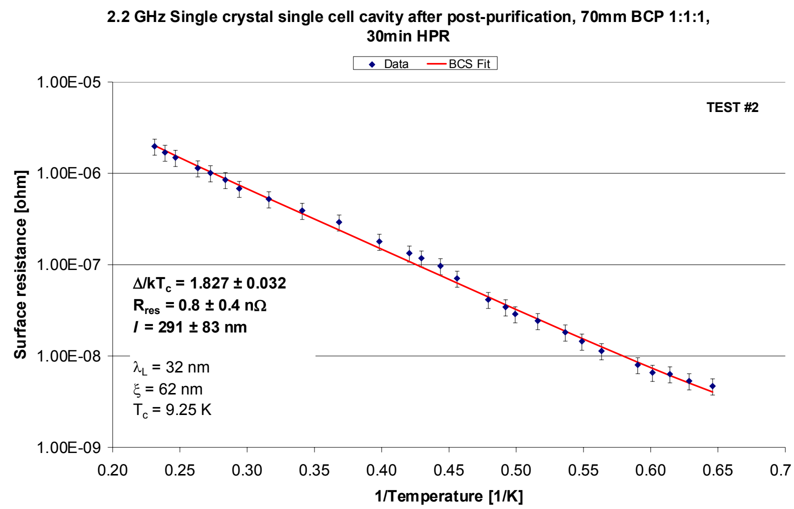
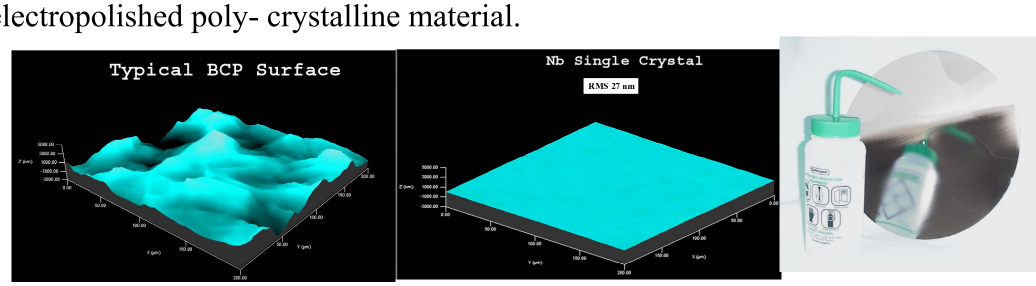


Figure 8: Measured temperature dependence of the single crystal 2.2 GHz cavity [4.2K≤T≤1.6K]

Discussion

All cavities made from the large grain/single crystal material have been treated by buffered chemical polishing (BCP) only. Surface roughness measurements – results are shown in figure 9 – indicated that very smooth surfaces superior to electropolished surfaces on poly-crystalline niobium can be achieved.[2] However, appropriate agitation of the acid during the surface treatment is necessary. The measured smoothness for a single crystal over an area of 0.2" x 0.2 " was nearly a factor of 10 better than on electropolished poly- crystalline material.



(a) (b) (c)

Figure 9: Surface roughness of bcp'd surfaces: (a) typical polycrystalline surface after removal of ~ 100 µm (roughness 1274 nm), (b) single crystal after 80 µm and mechanical polishing (roughness 27 nm), for comparison an electropolished poly-crystalline surface had a roughness of 252 nm; (c) reflectivity of bcp'd large grain niobium surface

During the course of these investigations, several potential advantages of the large grain/single crystal material became apparent as listed below:

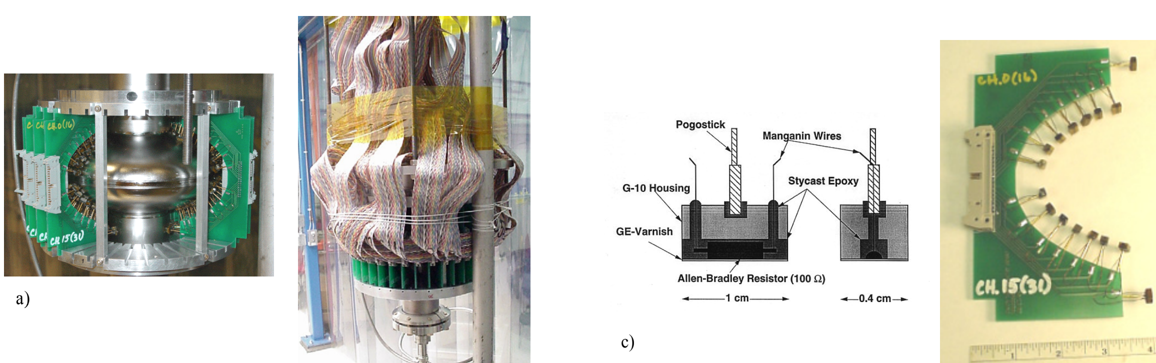
- Reduced costs for the material because the sheet fabrication step is eliminated
- Comparable performance to fine grain material
- Streamlining of procedures
  - ✓ Very smooth surfaces with bcp, EP not necessary; this in particular might simplify the procedures for attachment of He-vessels after vertical qualification of multi-cell cavities and the assembly procedures for cavity strings
  - ✓ Less material QA such as eddy current or squid scanning
  - ✓ Possibly elimination or shortening of "in situ" baking because onset value for "Q-drop" might be shifted to higher gradients
  - ✓ Predictable
- Higher thermal stability because of a "phonon peak" in the thermal conductivity
- Possibly very low residual resistances (high Q-values), favoring lower operations temperature with less cryogenic losses [3]

Future Plans

Obviously, more information about the performance of cavities made from the large grain/single crystal material is necessary. We are interested in two aspects, namely

a. can the material removal from the surface be reduced from the "standard" 150 – 200 μm to much smaller amounts? and
b. is the material behaving differently with respect to the "Q-drop" at high fields, what is the role of grain boundaries and what is the nature of the "hot spots"?

In answering these questions we want to employ temperature mapping [4] with the system as shown in figure 10, featuring ~ 600 Allen-Bradley carbon resistors.



b) d)

Figure 10: Temperature mapping system, consisting of 36 boards as shown in (c), each equipped with 16 Allen-Bradley carbon resistors (d)

Initial work has started in this area and figure 11 shows the result of T-mapping after removal of 70 µm from the surface of a large grain OC cavity by bcp. Shown are T-maps at increasing field levels in the "Q-drop" region of the Q vs E_{acc} performance .

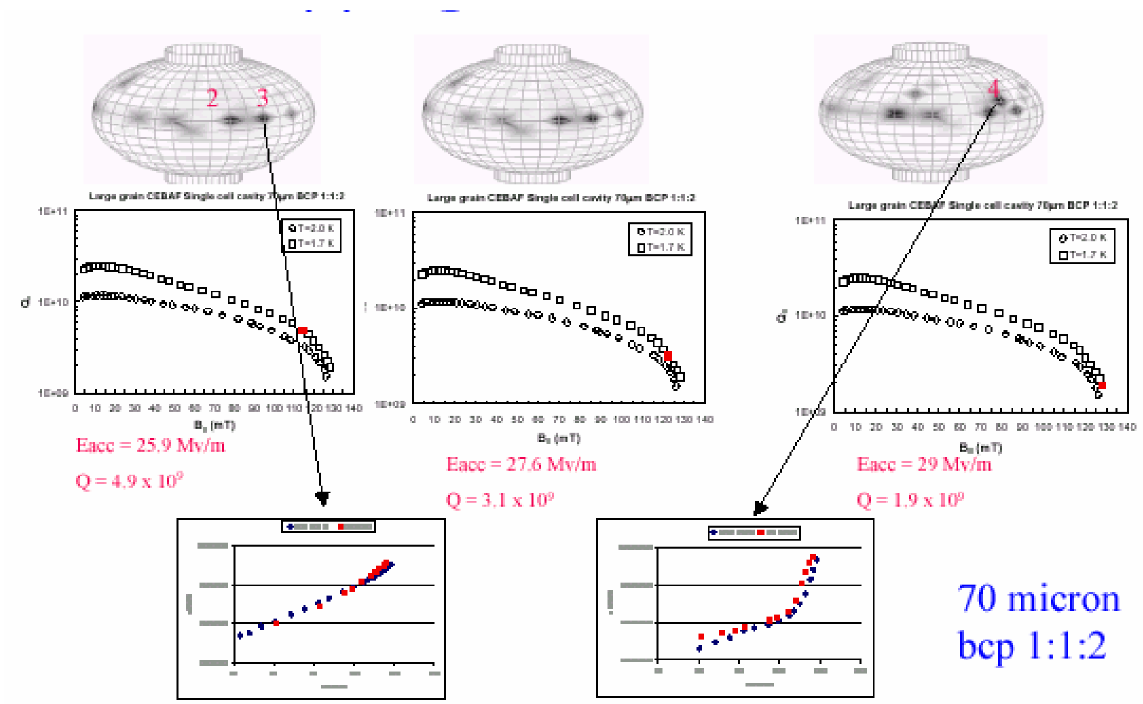


Figure 11: Example of T-maps at different field levels in the Q-drop region of a large grain OC cavity

Summary

We have fabricated and tested several cavities made from large grain and single crystal high purity niobium. The results are very encouraging: with the single crystal cavities magnetic surface fields as high as 185 mT have been measured, being close to the critical magnetic field of niobium. In addition, several tests showed very low residual resistances leading to the speculation that grain boundaries might most likely contribute to the residual resistance.

Large grain/single crystal niobium offers several potential advantages over fine grain niobium as indicated above; the major advantage in the context of an accelerator such as the International Linear Collider (ILC) might be a non-negligible reduction in cost due to less expensive material and streamlined procedures at comparable cavity performances. However, this needs to be demonstrated in the future on multi-cell cavity assemblies.

In addition, it seems to be desirable to develop the technology of producing large size, high purity single crystal niobium ingots.

Acknowledgement

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References

[1] J. Halbritter, G. Ciovati
[2] A. Wu, private communication
[3] B. Petersen, ERL 2005
[4] G. Ciovati, Thesis 2005, Old Dominion University

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