Development of Large Grain/Single Crystal Niobium Cavity Technology at Jefferson Lab

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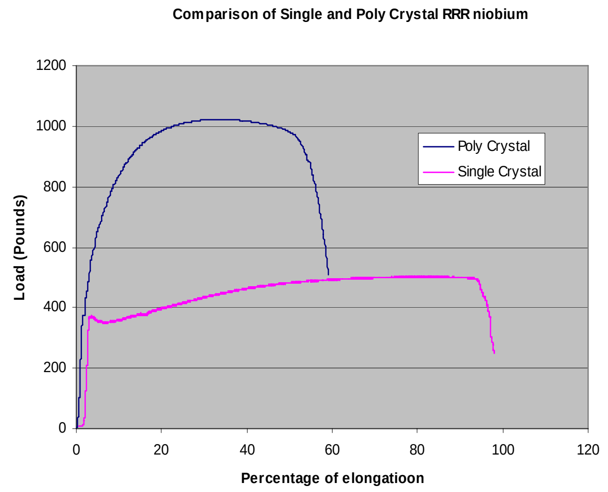
- ❖Overview
  - What has been done
  - What will be done in the future
- ❖ Test Series
  - ✓Comparison of Material from different Vendors
  - ✓Single Crystal Cavity Performance
  - Anodization Tests/T-Mapping:
    - Understanding Q -drop

Jlab/CBMM Collaboration

- Development started ~ 2 years ago with the need for understanding mechanical properties of niobium from different manufacturers (G. Myneni)
- Ingot material supplied by CBMM with large grains (T. Carneiro)
- Mechanical properties –especially elongation – excellent, permitting forming of cavity cells
- Investigate influence of grain boundaries on "Q-drop"



Activities at JLab

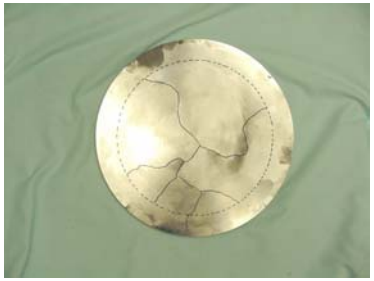
- Jlab received a grant from ILC America to explore the potential of large grain/single crystal niobium for high performance cavity application
- Metallurgical/material investigations in collaboration with NIST(spring back, formability, residual stress, internal friction, interstitial interactions..) and NCSU (oxidation behaviour for different crystal orientations)
- Exploration and evaluation of material from different vendors with different properties/ cost effectiveness
- Development of “streamlined” procedures, e.g. BCP vs EP, material removal, “in situ “ baking…
- Shedding some light in the mechanism of “Q-drop”

What has been done

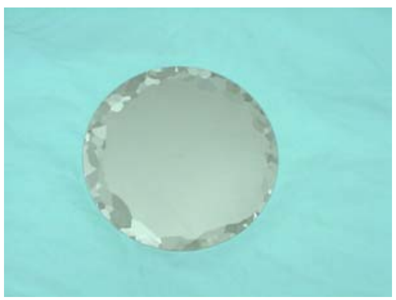
- Cavities have been fabricated and tested from 4 different manufacturers:
  CBMM (4 different ingots)
  Ningxia (3 different ingots)
  W.C. Heraeus (2 different ingots, 1 used for single crystal-DESY)
  Wah Chang (1 ingot)
- The material has been cut by wire EDM, saw cutting + machining, and wire saw cutting
- Single cell cavities ranging in frequency from 1300 MHz to 2300 MHz of different shapes and beta values (TESLA, LL_ILC,OC,HG,LL, PD) have been fabricated and tested
- Multi-cell cavities (2 HG (7-cell), LL_ILC(7 cell) have been fabricated and tested or are under test
- In total we have fabricated and tested 17 single cell cavities and 3 multi-cell cavities and carried out close to 100 tests

Large Grain/Single Crystal Niobium[2]

CBMM



Ingot “D”,800 ppm Ta



Ingot “A”, 800 ppm Ta

Ingot “B”, 800 ppm Ta

Ingot “C”, 1500 ppm Ta

Ninxia

Wah Chang

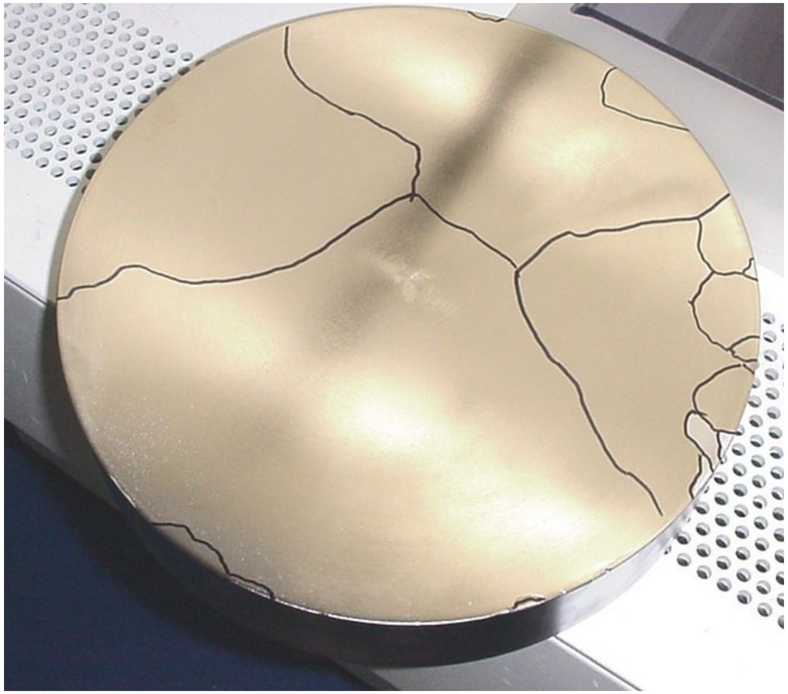
Heraeus

CBMM Ingot "E"

RRR- value : 300 Ta- contents: 490 ppm

1 TESLA single cell cavity
1 ILC LL single cell cavity

are being fabricated



Summary of large grain/single crystal single cell tests(1)

- 9 different ingots with different properties (RRR,Ta)
- 15 different cavities (1300 MHz to 2300 MHz)
- Different treatments (cutting/bcp/anodizing/furnace/material removals)
- All tests after in-situ baking (3 hrs to 48 hrs, vacuum/oxygen/air)
- All tests – N = 51 after "in-situ" baking - limited by "quench"

Test Results (Jlab)

- In all tests/all cavity types the cavity performances were limited by “Quench”
- Therefore, for comparing the results, the magnetic quench field is the right property to look at
- For “calibration” the table below lists the required performance in terms of H_{max} for ILC and XFEL cavities

Project	E_{acc} [MV/m]	H_{max} [mT]
XFEL	28	119
ILC(BCD)	35	149
ILC (ACD)	45	162

Test Results (Jlab)

- The measured "quench fields" for the different large grain materials and cavity types ranged for 1-cells between

$$121 \text{ mT} < H_{quench} < 160 \text{ mT}$$

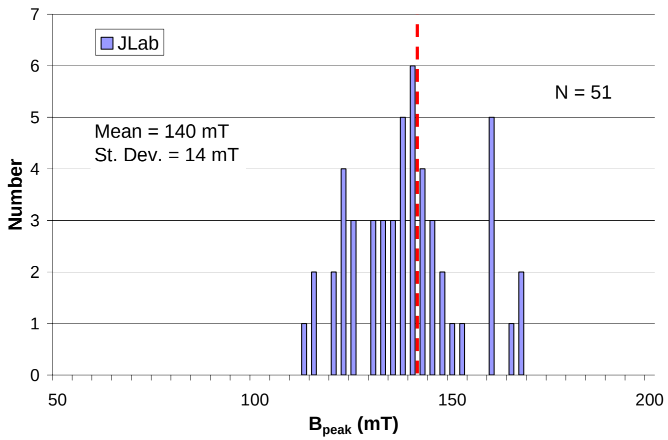
- The single crystal cavities (two at 2.2 GHz, one at 1300 MHz provided by DESY) had quench fields of

$$150 \text{ mT} < H_{quench} < 160 \text{ mT}$$

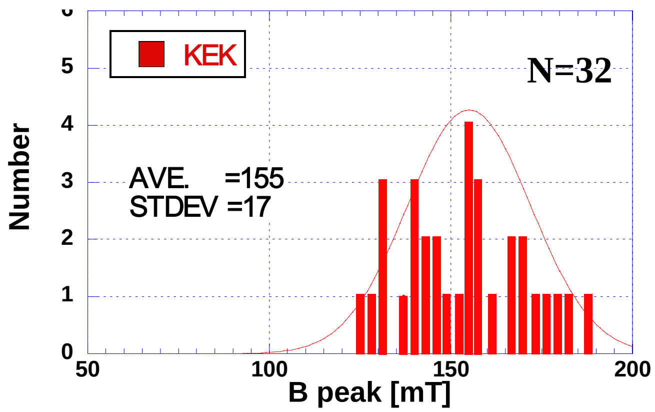
- In all of the multi-cell cavities we encountered fabrication problems (holes during EBW, tuning problems) and the results were inferior: best result was a quench field of 114 mT. Further tests will follow

Summary of large grain/single crystal single cell tests(2)

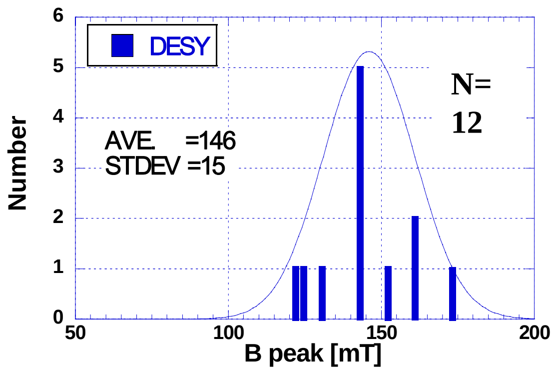
Jlab



KEK



DESY



Plans: What is in the “pipeline”?

- Two 9-cell TESLA cavities (nearly completed, for FNAL)
- Five single cell TESLA-type cavities from Ningxia Niobium (in fabrication)
- One TESLA-type single cell from CBMM ingot”E”(in fabrication)
- One ILC_LL single cell from CBMM ingot “E” (in fabrication)
- One 1-Amp FEL single cell from CBMM ingot “B” (in fabrication)
- One 5-cell 1-Amp FEL cavity from CBMM ingot”B” (in fabrication)
- Two “single crystal” TESLA-type cavities from CBMM ingot “B” in collaboration with DESY(X. + W. Singer)
- Five ILC_LL single cell cavities from W.C.Heraeus niobium (waiting for material, some fabrication of beam pipes,flanges)

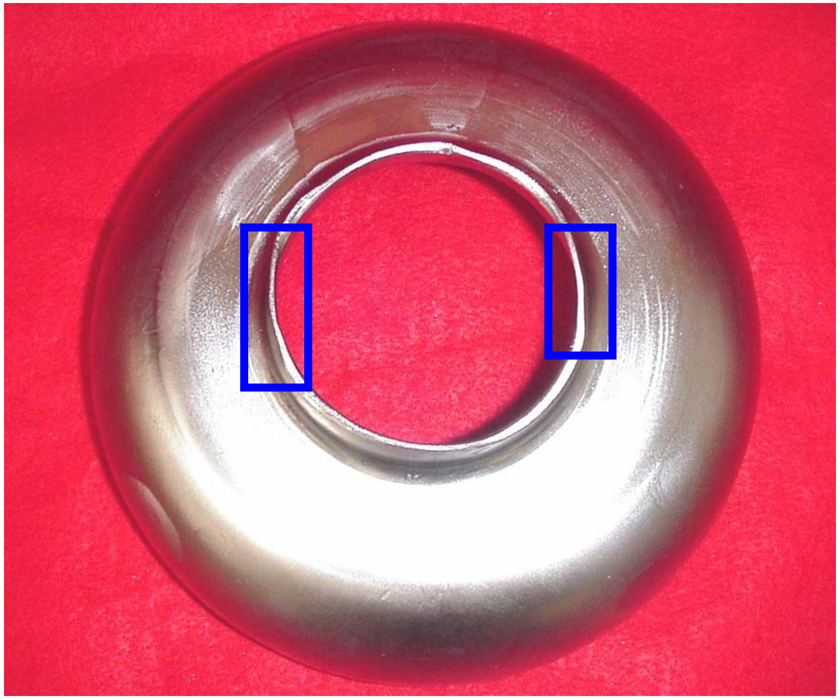
What did we learn?

Fabrication Issues (1)

- Large grain sheets deep draw with ragged edges
- Sometimes the material is thinning or ripping at the irises, if the grains "meet" in these areas
- There is some spring back after the deep drawing, making the half cells "oval"
- The same happens after the trimming for EBW
- Assembly for EBW sometimes more difficult than with fine grain material. However, no problem with single crystals
- On a few occasions, holes occurred during welding

Fabrication Issues (2)

Half cell from CBMM Ingot "B"



R & D Topics

During the course of our work in the last 2 years, we have identified several R&D topics

- Effective cutting: wire EDM too slow?
- Forming: how uniform, grain slippage
- Welding/Vacuum: do grain boundaries cause problems?
- Surface roughness: appropriate acid agitation during bcp, uniformity of material removal
- Mechanical properties depending on grain orientation?
- Internal stresses and strains due to deep drawing using neutron diffraction techniques
- Dependence of oxidation on grain orientation

Heraeus

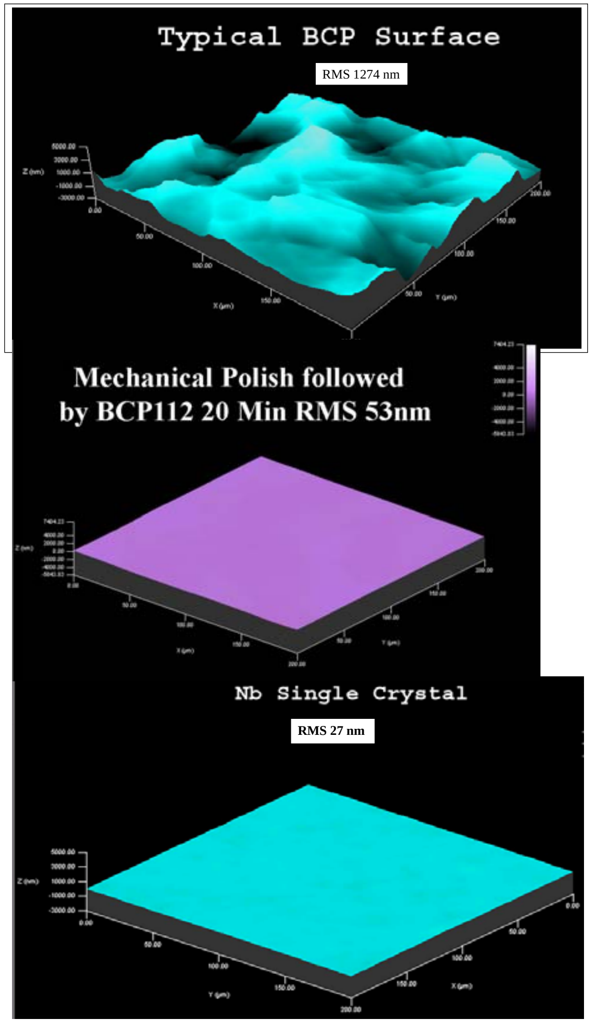
High purity Niobium RRR discs cutted from ingot

- **first discs with a big central grain**

B.Spaniol,LINAC 2006,paper TUP024

Surface Roughness

BCP provides very smooth surfaces (A.Wu, Jlab)

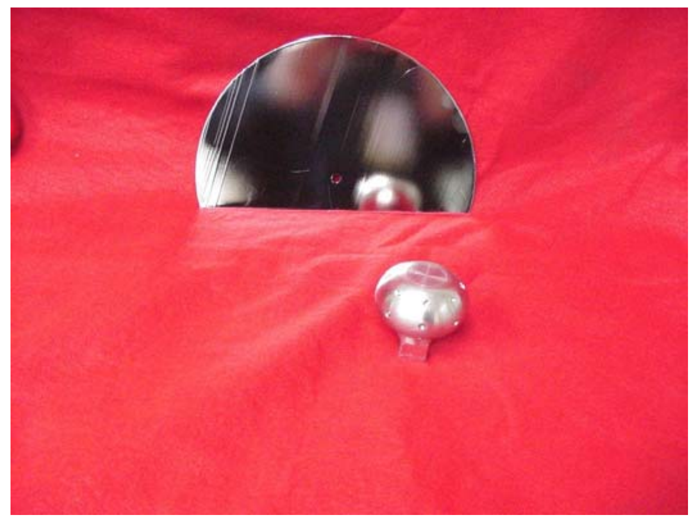


RMS: 1274 nm fine grain bcp

53 nm after ~ 35 micron, single Crys

27 nm after ~ 80 micron, single Crys

251 nm fine grain ep



Potential Benefits of Single Crystal Nb

- **Reduced costs**
- **Comparable performance**
- **Very smooth surfaces with BCP, no EP necessary**
- **Better Cleaning (FE reduction?)**
- **Elimination of Q-drop with short baking times**
- **Less material QA (eddy current/squid scanning)**
- Possibly very low residual resistances (high Q’s), favoring lower operation temperature(B.Petersen)
- Higher thermal stability because of “Phonon-Peak”
- Good or better mechanical performance than fine grain material (e.g.predictable spring back..)

Potential Benefits of Single Crystals

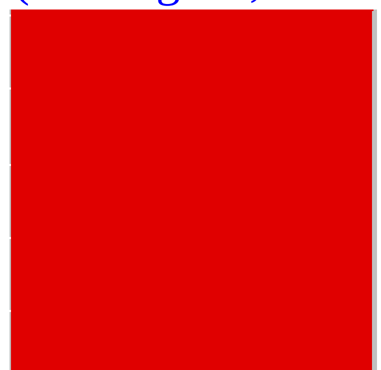
- Very smooth surface finish with BCP only
- Better cleaning (less FE ?)

Mechanically polished,

~ 90 micron bcp 1:1:2

FE studies at Univ.Wuppertal

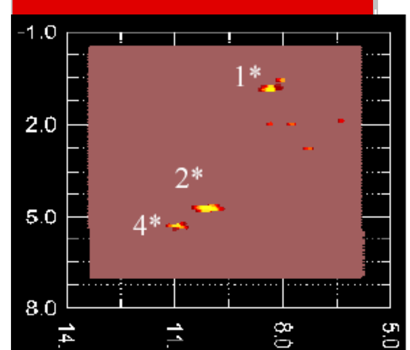
(A.Dangwal, G. Mueller)



Single crystal, bcp ~ 35 micron

E – 120 MV/m

0 emitters



Poly-crystal

E = 120 MV/m

8 emitters

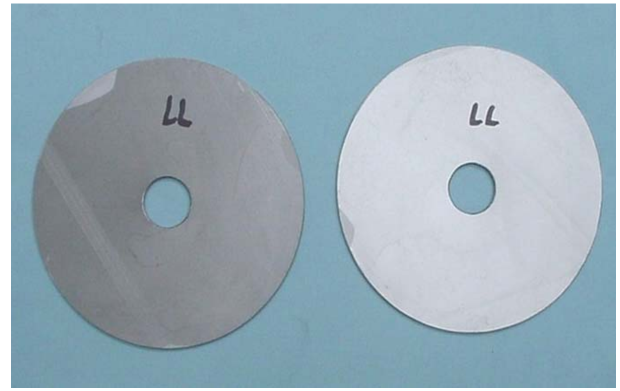
Single Crystal Cavity(1): CBMM Ingot"A"

HG Cavity Shape:2.3 GHz

E_{peak}/E_{acc} = 1.674

H_{peak}/E_{acc} = 4.286 mT/MV/m

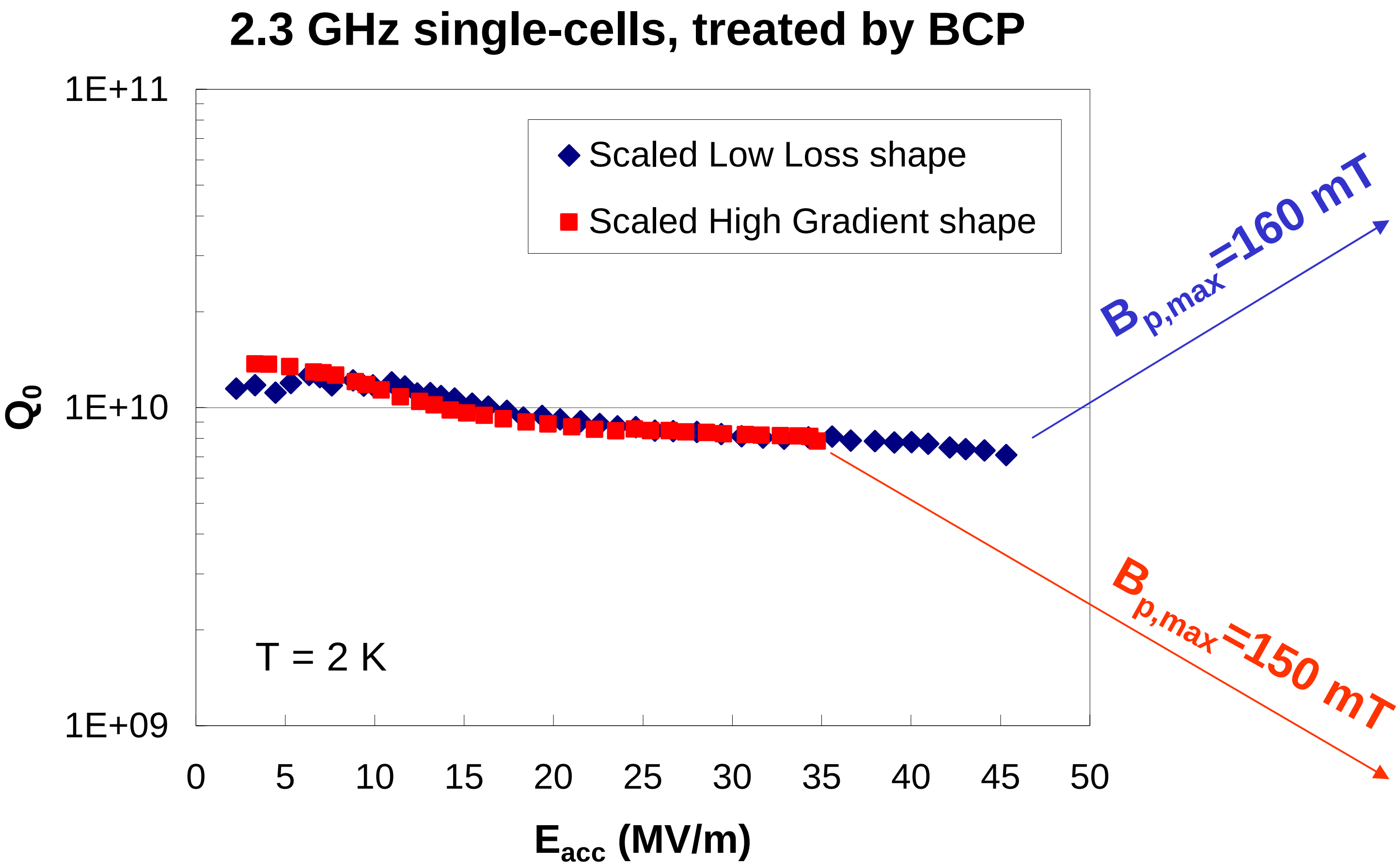
ILC LL cavity Shape:2.3 GHz



E_{peak}/E_{acc} = 2.072

H_{peak}/E_{acc} = 3.56 mT/MV/m

Single-crystal cavities(2)



P. Kneisel et al., Proc. of PAC'05, Knoxville, TN, 2005, p. 399

Test Series

Material Comparison with TESLA Single Cells

W.C. Heraeus

Ningxia

CBMM

Evaluation of large grain niobium from different vendors

Manufacturer	Ta Contents	RRR	Sheet Cutting Method
CBMM	~800 ppm	~ 280	Wire EDM
W.C.Heraeus	< 500 ppm	500	Wire Saw
Ningxia	< 100 ppm	330	Saw + machining

Fabrication and Treatment

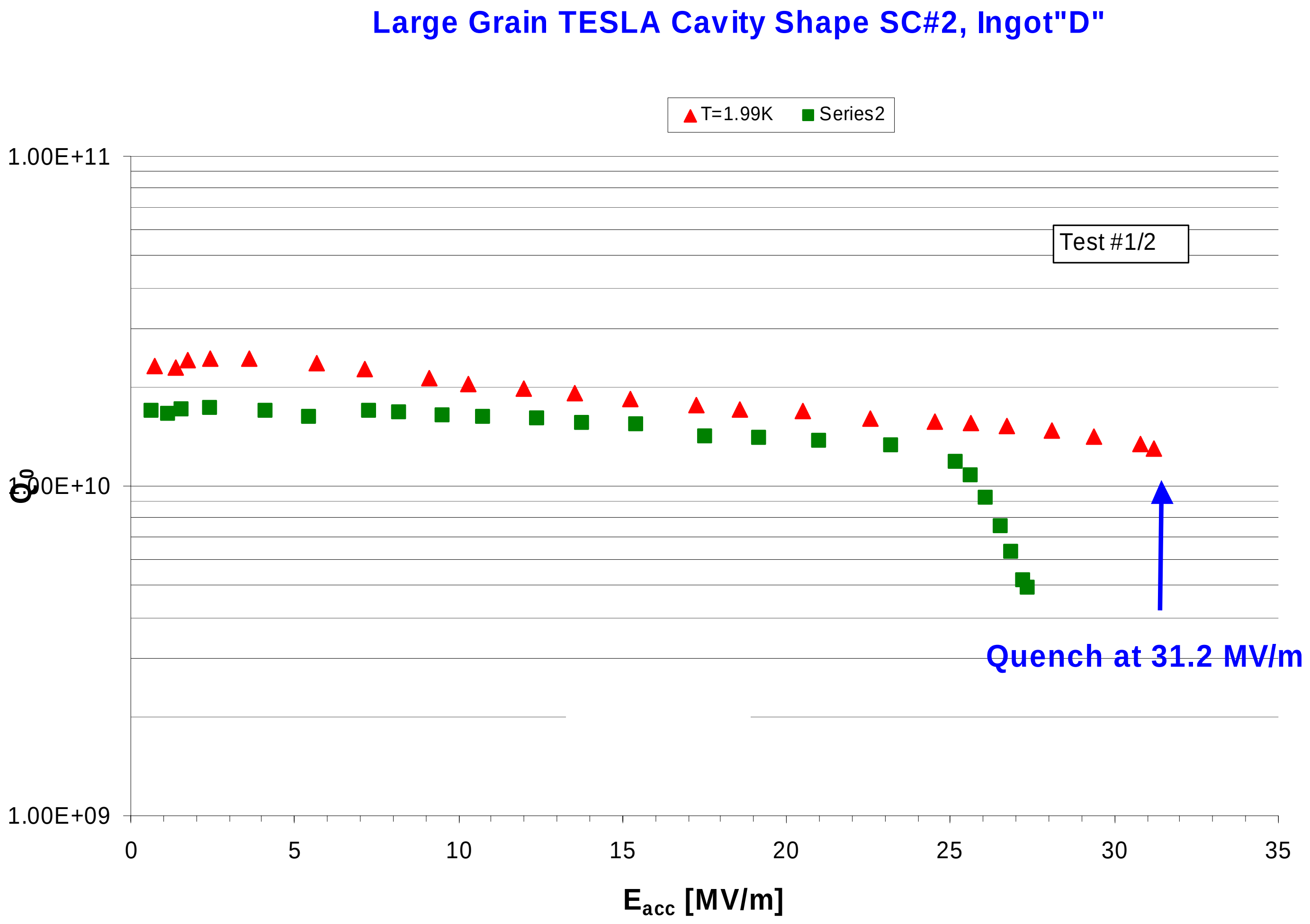
Fabrication

- Standard deep drawing after cutting of sheets (wire EDM/CBMM, saw cut/Ningxia, diamond saw/Heraeus)
- Machining
- Welding of beam pipes to half cell
- Mechanical grinding
- Equator weld

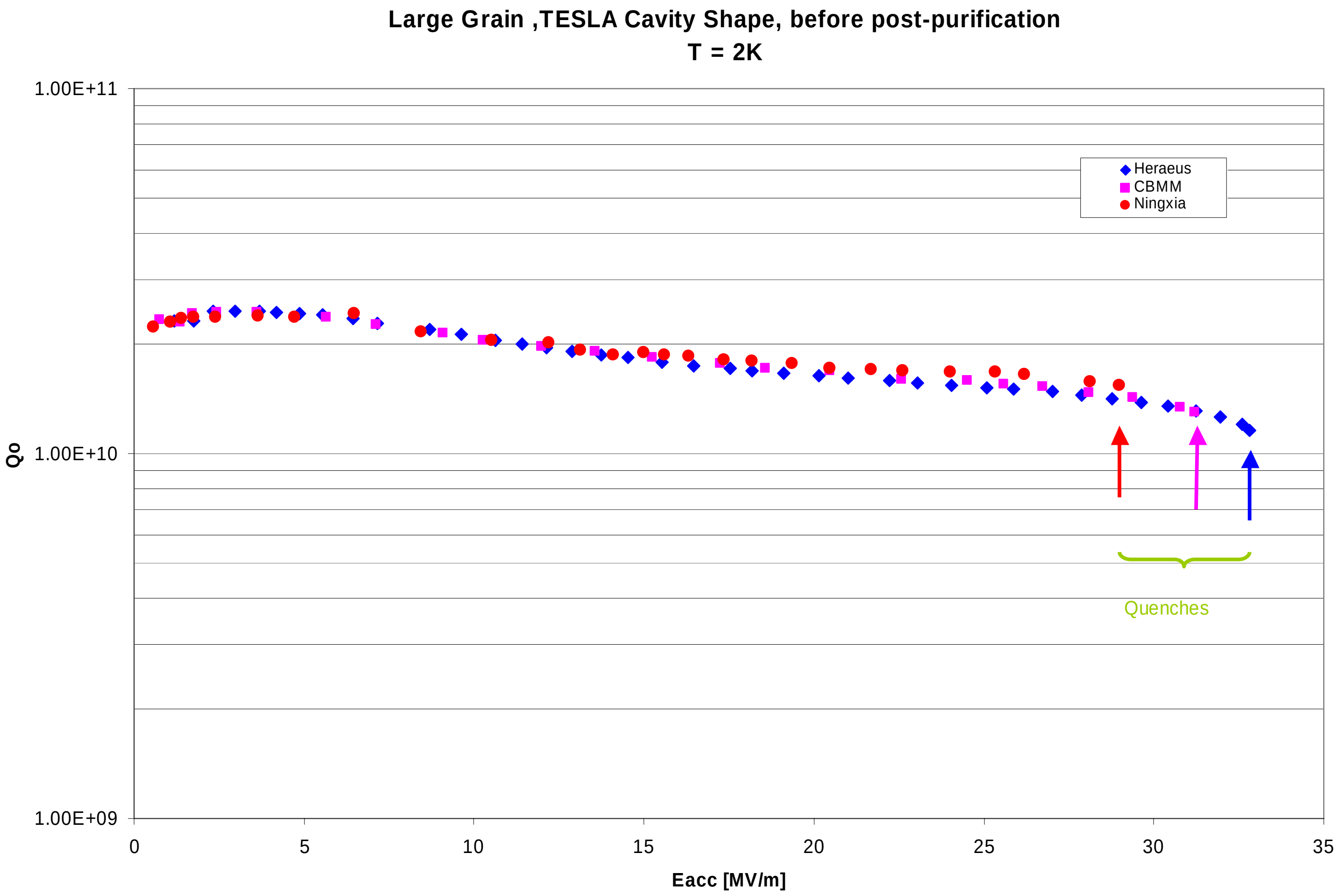
Surface Treatment

- ~ 50 micron bcp
- Hydrogen degassing at 600C for 10 hrs
- ~ 50 micron bcp, Test #1
- 12 hrs “in situ” baking at 120C, Test #2
- 1200 C, 3 hrs post-purification with Ti
- ~ 50 micron bcp, Test #3
- 12 hrs “in situ” baking at 120C,Test #4

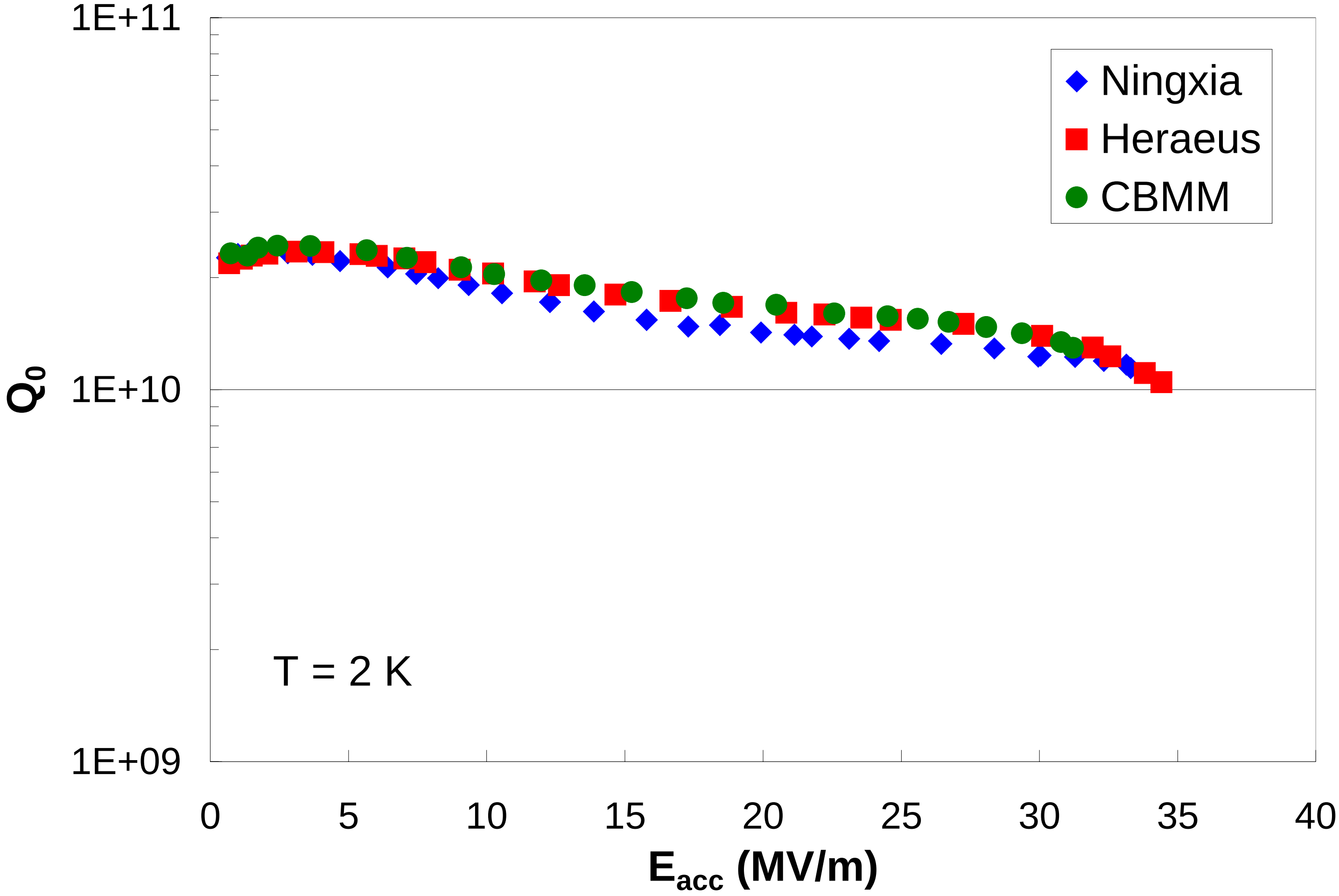
CBMM Large Grain Ingot"D": before post purification



Summary before post-purification



Summary after Post-Purification



Material Comparison

Supplier	Cavity Type	Ta - contents	RRR	Test ½ H_{max} [mT]	Test ½ Q_0 at H_{max}	Test ¾ H_{max} [mT]	Test ¾ Q_0 at H_{max}
W.C.Heraueus	TESLA	<500 ppm	500	**140**	1.15×10^{10}	**146**	1.05×10^{10}
Ningxia	TESLA	~ 100 ppm	330	**123**	1.5×10^{10}	**142**	1.14×10^{10}
CBMM	TESLA	~ 800 ppm	280	**133**	1.3×10^{10}	**131**	1.04×10^{10}
CBMM	Proton Driver	~ 800 ppm	280	**139**	7.5×10^{9}	**148**	6.9×10^{9}
CBMM	Proton Driver	~ 800 ppm	280	**133**	4.4×10^{9}	**135**	1×10^{10}

Summary

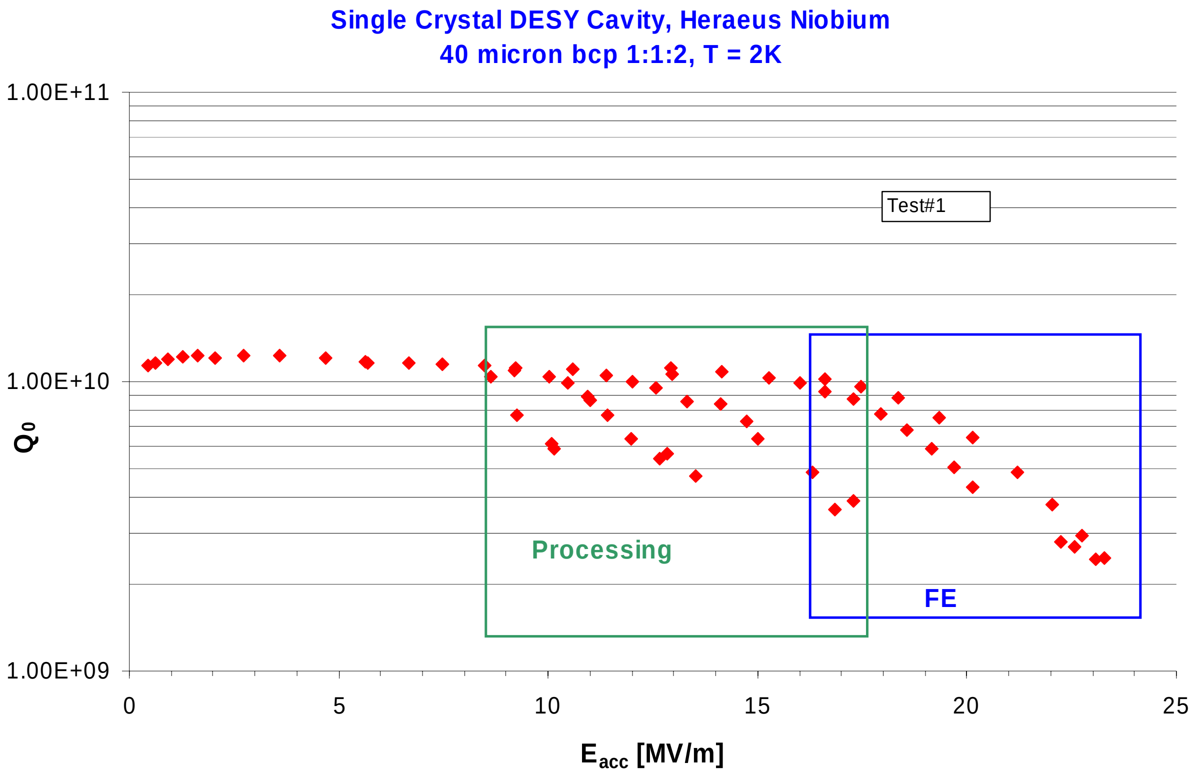
- Materials with different properties (RRR,Ta..) and prepared by different cutting methods behaved very similar after BCP only
- It is not clear yet, what the important features for best performance are
- There is a significant price difference in the different materials
- We are going to fabricate 5 single cell cavities each from Ningxia and W.C.Heraeus material to get some statistics
- The 9-cell cavities for FNAL are being fabricated from CBMM large grain niobium

Single Crystal TESLA Cavity(DESY/Jlab)

- This cavity has been fabricated by ACCEL from single crystal W.C.Heraeus RRR niobium under the guidance of Xenia and Waldemar Singer
- The center single crystal was enlarged by rolling with intermediate annealing steps and deep drawing was used for forming of half cells.
- It has been shipped to Jlab for surface treatment and testing
- A test series is in progress, during which successively material is being removed by BCP only, starting at 40 micron after fabrication and the cavity performance is being tested.
- The tests consist of R(T) and Q vs E measurement at 2K after the BCP treatment and subsequent measurements after "in situ" baking at 120C for 12 hrs.

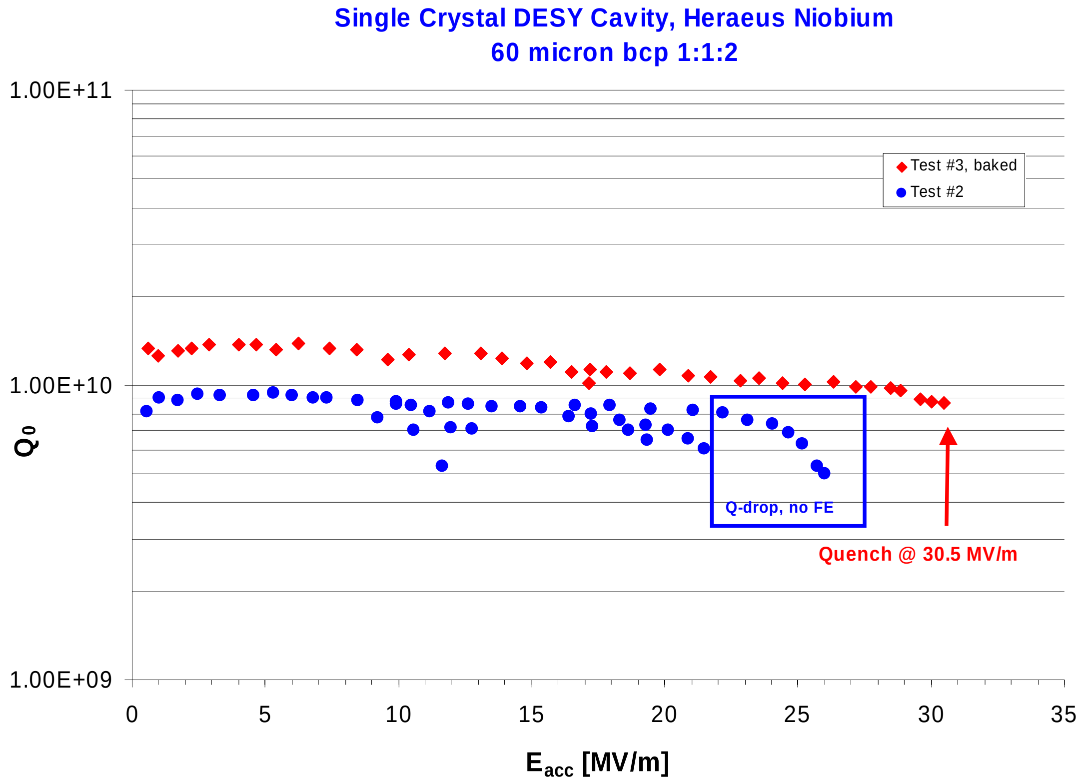
Single Crystal Cavity(2)

40 micron bcp

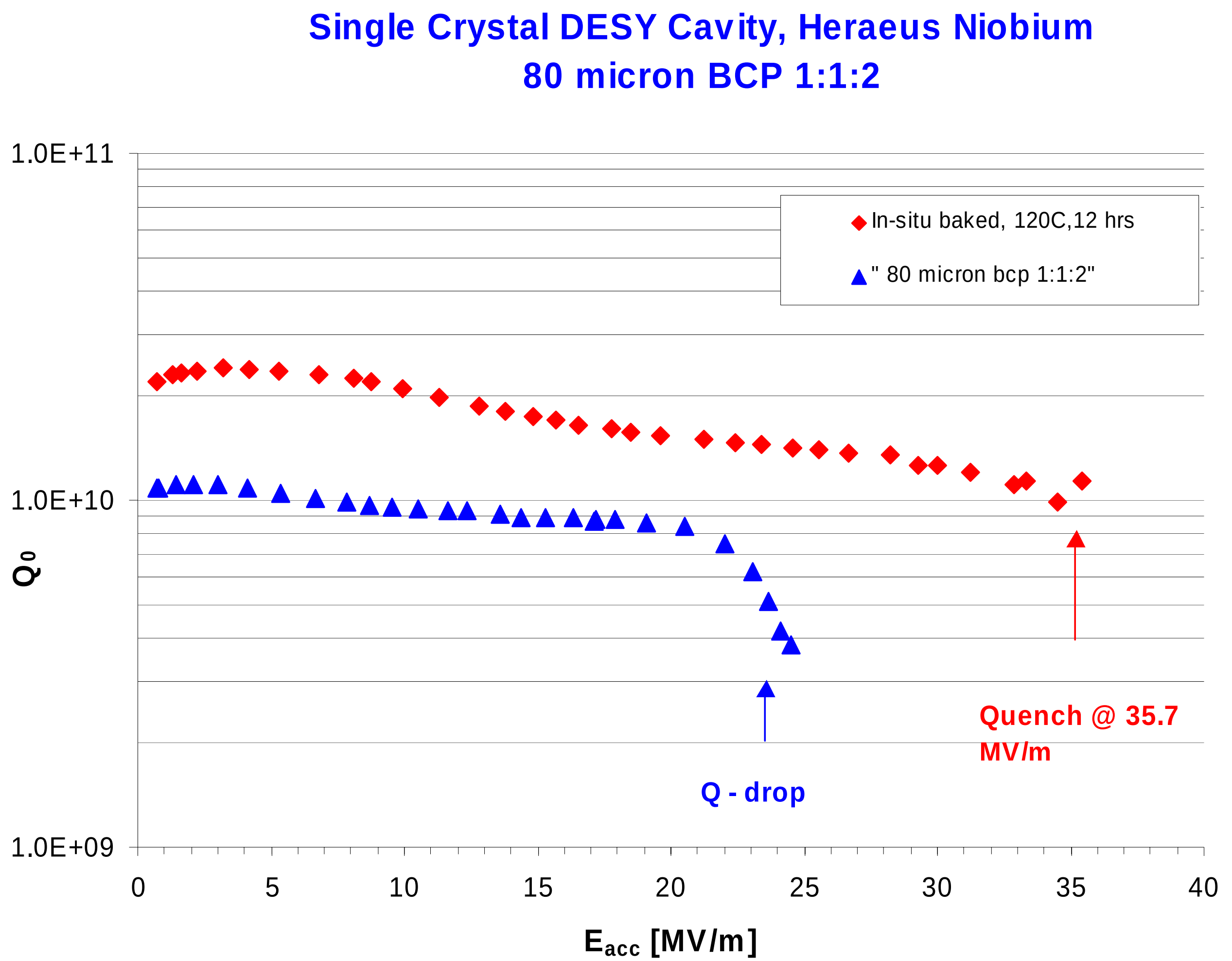


Single Crystal Cavity(3)

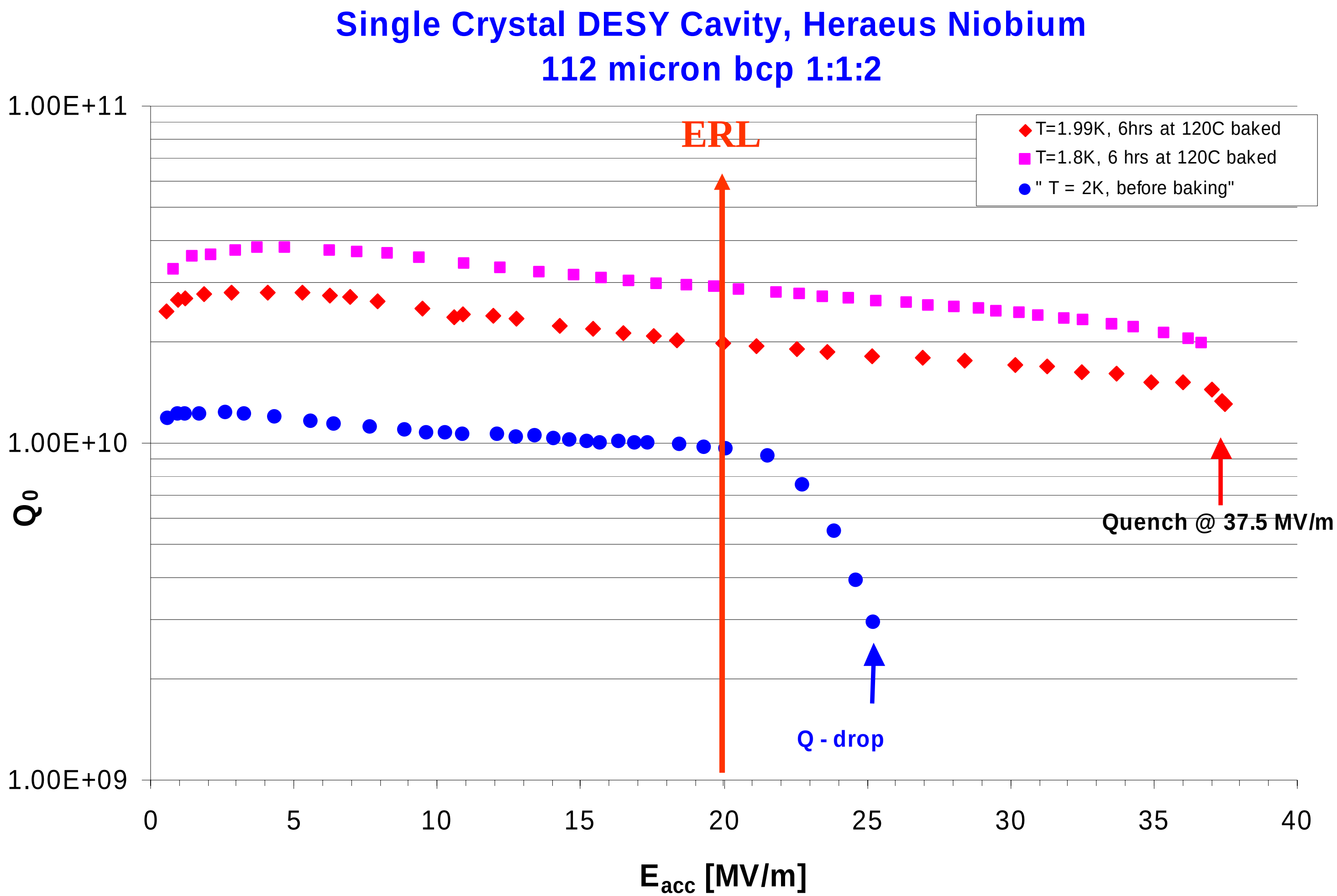
60 micron bcp



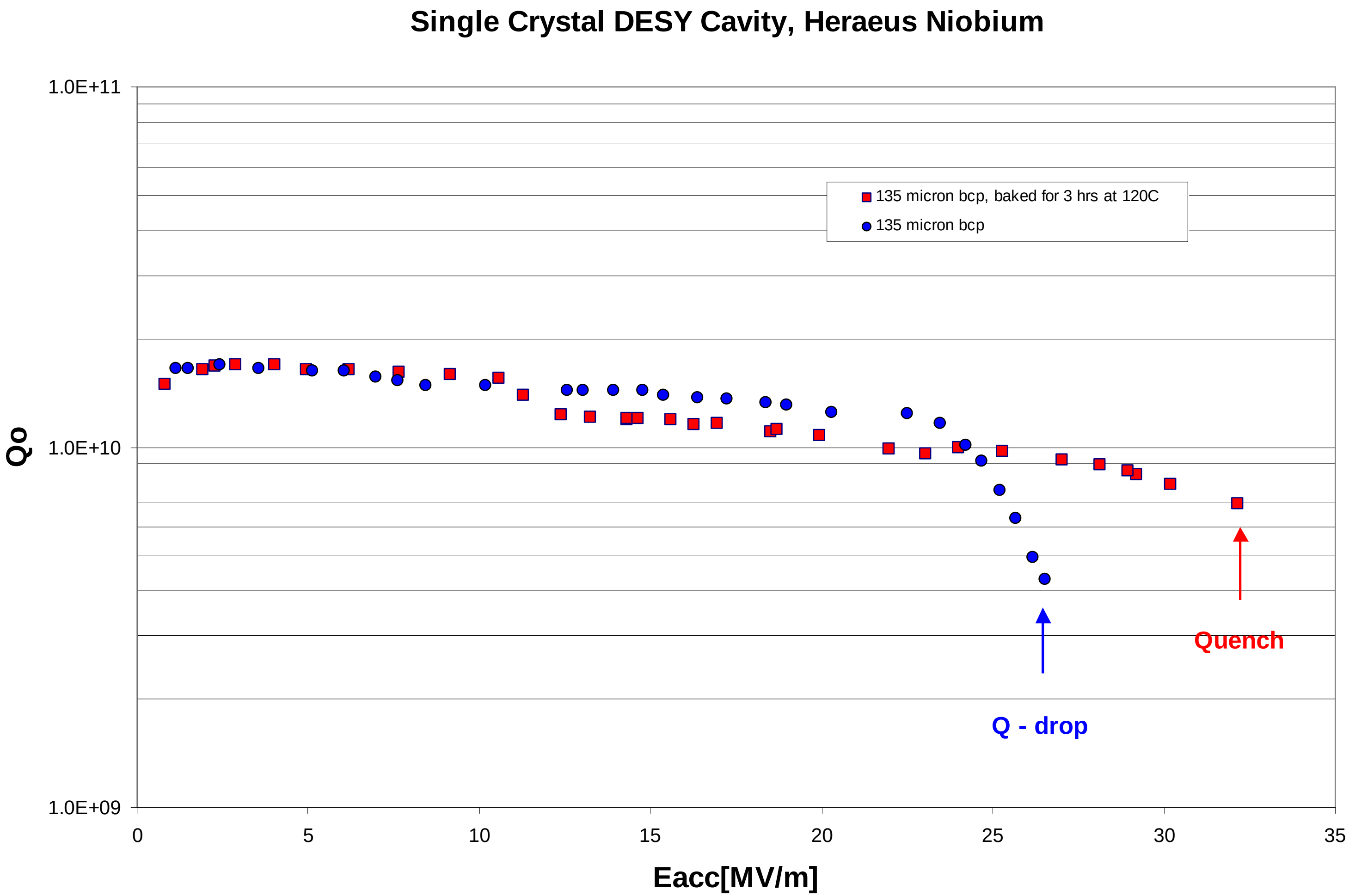
Single Crystal Cavity(4)



Single Crystal Cavity(5)



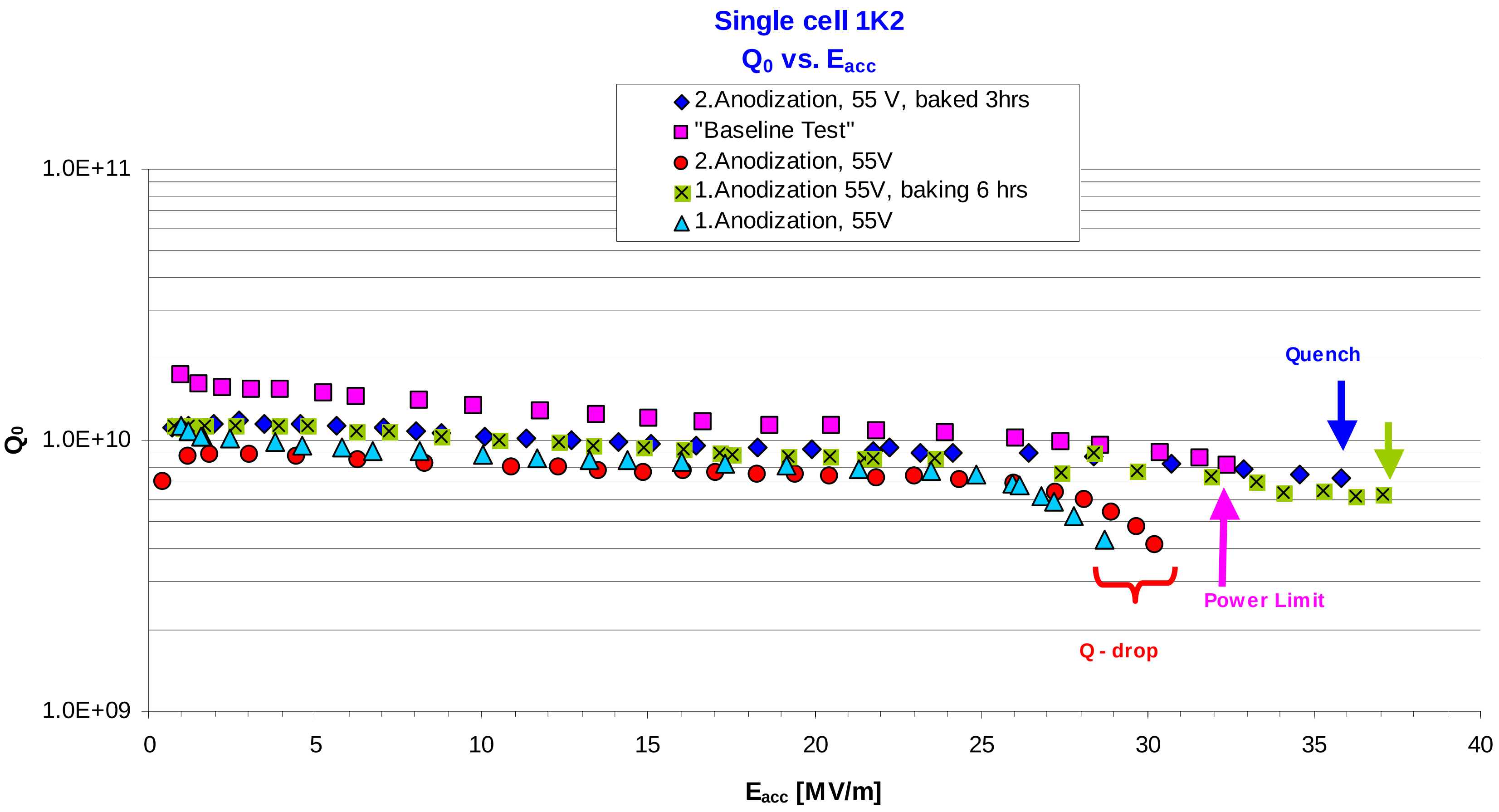
Single Crystal(6)



"Streamlining of Procedures"

- BCP 1:1:2 instead of EP
- ~ 50 % of material typical removal (112 micron vs ~ 200 micron)
- No intermediate furnace treatment after cavity fabrication
- No Q – disease (not verified)
- Only 6 hrs/or even 3 hrs of "in situ" baking at 120C vs typically 48 hrs: is this another advantage of large grain/single crystal niobium?

Baking Time?



Single cell 1K2
Q_0 vs. E_{acc}
2.Anodization, 55 V, baked 3hrs
"Baseline Test"
2.Anodization, 55V
1.Anodization 55V, baking 6 hrs
1.Anodization, 55V
1.0E+11
1.0E+10
1.0E+09
Q_0
0
5
10
15
20
25
30
35
40
E_{acc} [MV/m]
Quench
Power Limit
Q - drop

Acknowledgement

This work would not have been possible without the support of several colleagues from Jlab:

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Isiah Daniels

Danny Forehand