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Ultimate Capabilities of Superconducting Cavities?

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Acknowledgments
Thanks to: *Hasan Padamsee, Matthias Liepe and Sam Posen*

They have supplied all of the information conveyed in this talk but opinions and judgments expressed herein must be blamed on me

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Contents

Introduction

The answer to the question depends on available materials, the basic physics of RF superconductivity and on engineering. The knowledge of the basic physics has been time dependent and is still evolving today. Not surprisingly the engineering aspect both of architecture and construction procedures continues to improve. Regarding materials, niobium remains the only practical material although other materials have been discussed and tried for many years. Recently there have been some new developments which seem to show promise. These will be discussed.

In discussing performance limits, it has become natural to deal with $B_{max\text{-}surf}$ and Q separately. At the current state of the art, they can be maximized separately but not simultaneously.

References

a. Padamsee, Knobloch and Hays – RF Superconductivity for Accelerators (Wiley 2008)
b. Padamsee, RF Superconductivity (Wiley 2009)

Assumption:

This is the type of accelerating structure that we're considering

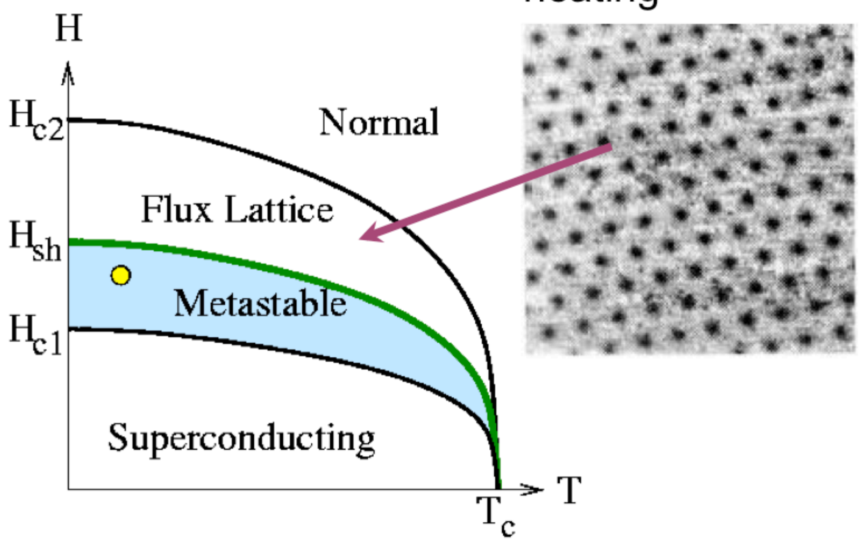
Not this or some other shape

Niobium material

Accelerating Field Performance

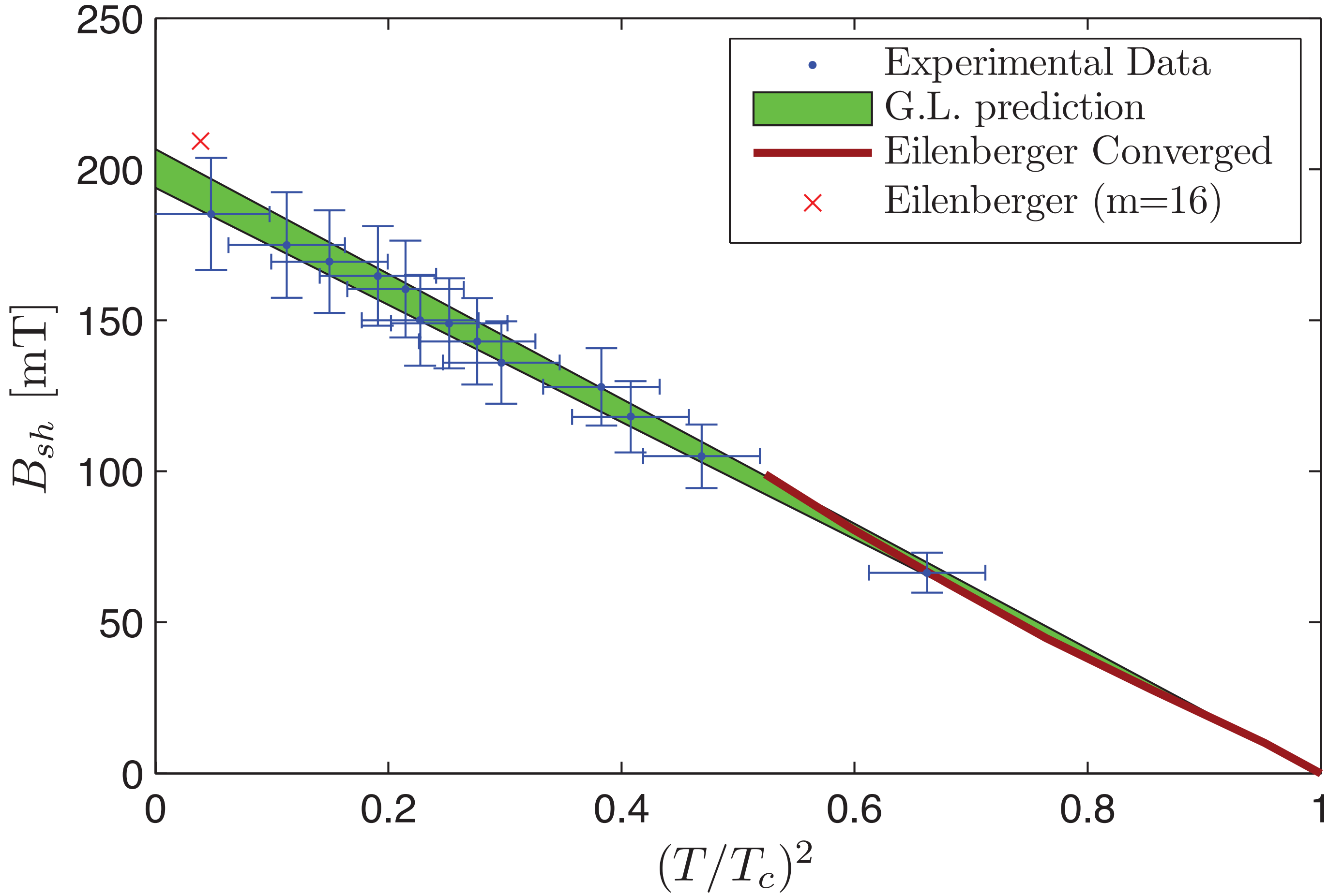
The phase diagram - conceptually

RF motion of fluxoids causes heating



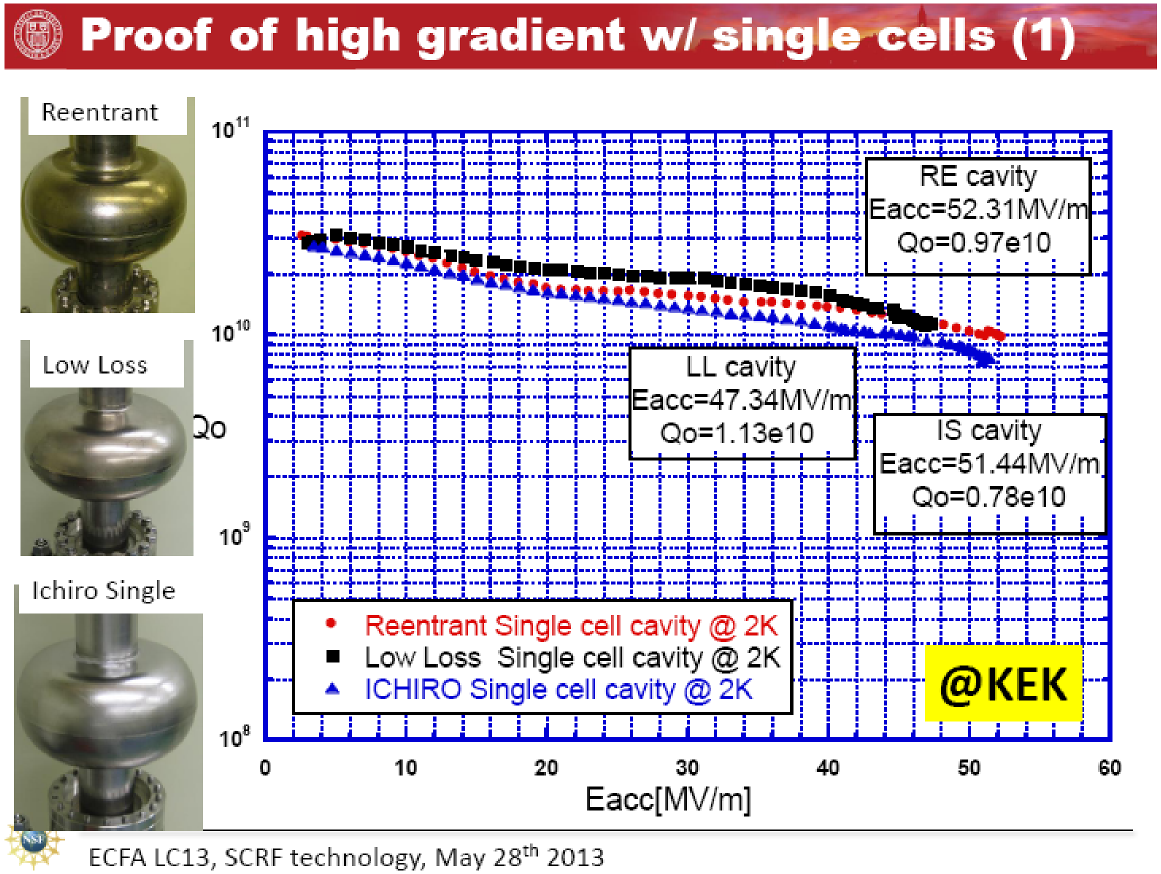
Cornell theorist J. Sethna recently completed a first principle calculation of H_{sh} …agrees w/ data

Prediction: other materials have higher H_{sh}, and potential for higher performance



How well have we done in approaching this fundamental limit?

As usual, the record is held by single cell cavities:



E_{acc}= 47-52 MeV/m

These winning shapes are designed to minimize $B_{surf-max}/E_{acc}$ - unfortunately these shapes increase $E_{surf-max}/E_{acc}$ making the controlling of field emission a major challenge – there are others too

Here is the data about the shapes:

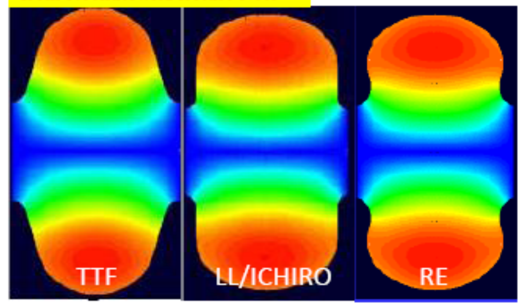
Alternative shape cavities

New Cavity Shape with low Hp/Eacc

$$E_{acc} = \frac{H_{CR}^{RF}}{H_{pk} / E_{acc}}$$

TTF: TESLA shape
Reentrant (RE): Cornell Univ.
Low Loss(LL): Jlab/DESY
LL/ICHIRO: KEK
Low Surface field(LSF): SLAC/Jlab

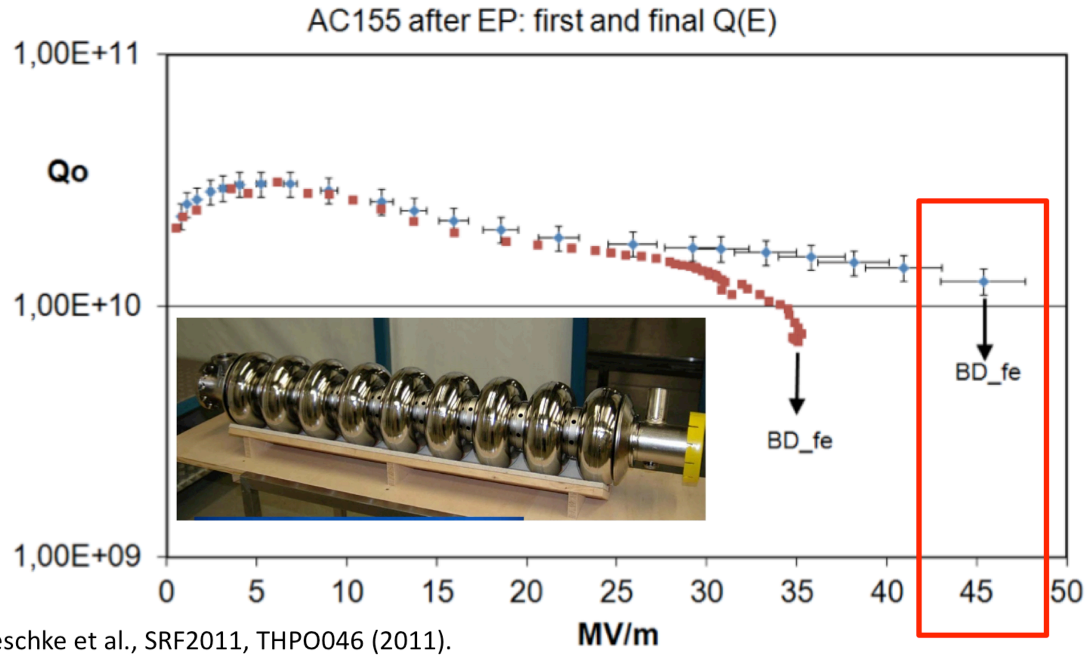
from J.Sekutowicz lecture Note



shape	TTF	LL/ICHIRO	RE	LSF
Iris Diameter [mm]	70	60	60	60
Ep/Eacc	1.98	2.36	2.28	1.98
Hp/Eacc [Oe/MV/m]	41.5	36.1	35.4	37.1
G*R/Q [Ω²]	30840	37970	41208	36995
Eacc max[MV/m]	42.0	48.5	49.4	47.2

How are we doing with multicell cavities?

High Q_0 via Large Grain Nb, 45 MV/m



D. Reschke et al., SRF2011, THPO046 (2011).

Eacc

TESLA shape cavity

Advanced-Shape Multi-Cell Cavities Developed But Limited by Field Emission to ~40 MV/m

Cornell Re-Entrant 9-cell # 1

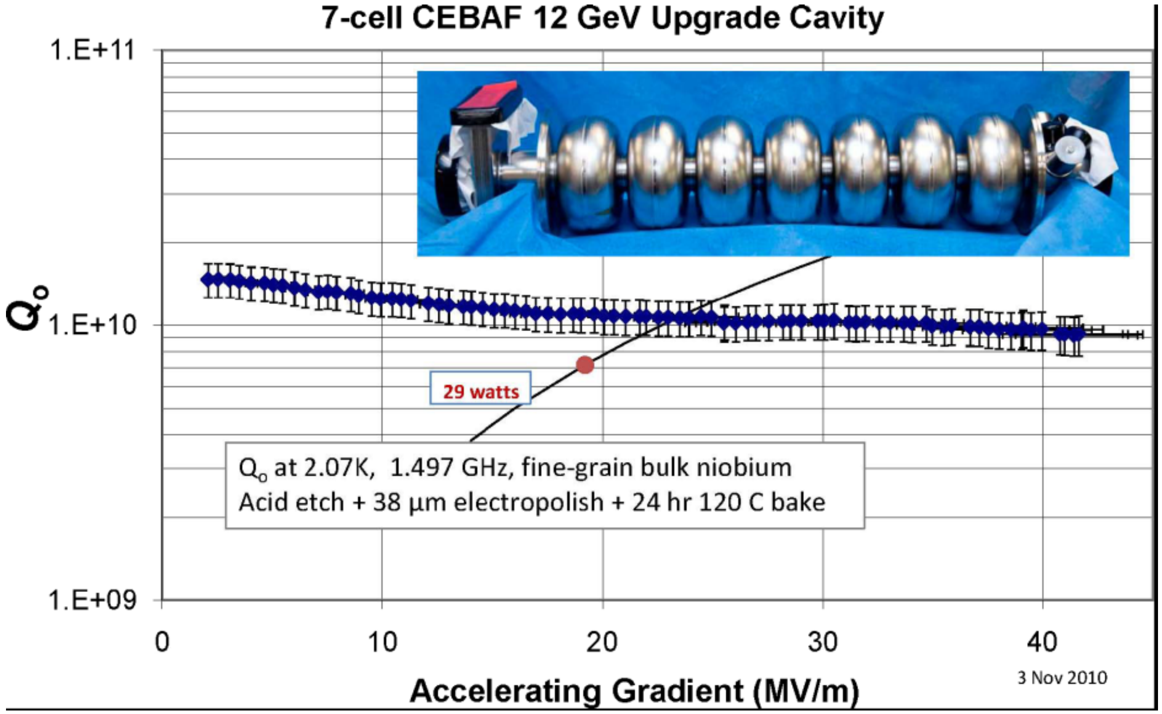
KEK/Jlab S0-study on ICHIRO#7 in 2010

Step-II : full cavity

Ichiro#7

w/ end groups

42 MeV/m demonstrated with the 7 cell CEBAF upgrade cavity



Thus, provided all best procedures have been applied, quenches caused by field emission have been the primary limiting factor with multicell cavities. Field emission results in electrons striking a small area somewhere in the cavity and thus raising the temperature there above the critical temperature.

It appears that smoothing the surfaces so that they can be thoroughly cleaned is the way forward – improved polishing methods such as specialized barrel honing or electro-polishing or "snow" cleaning………

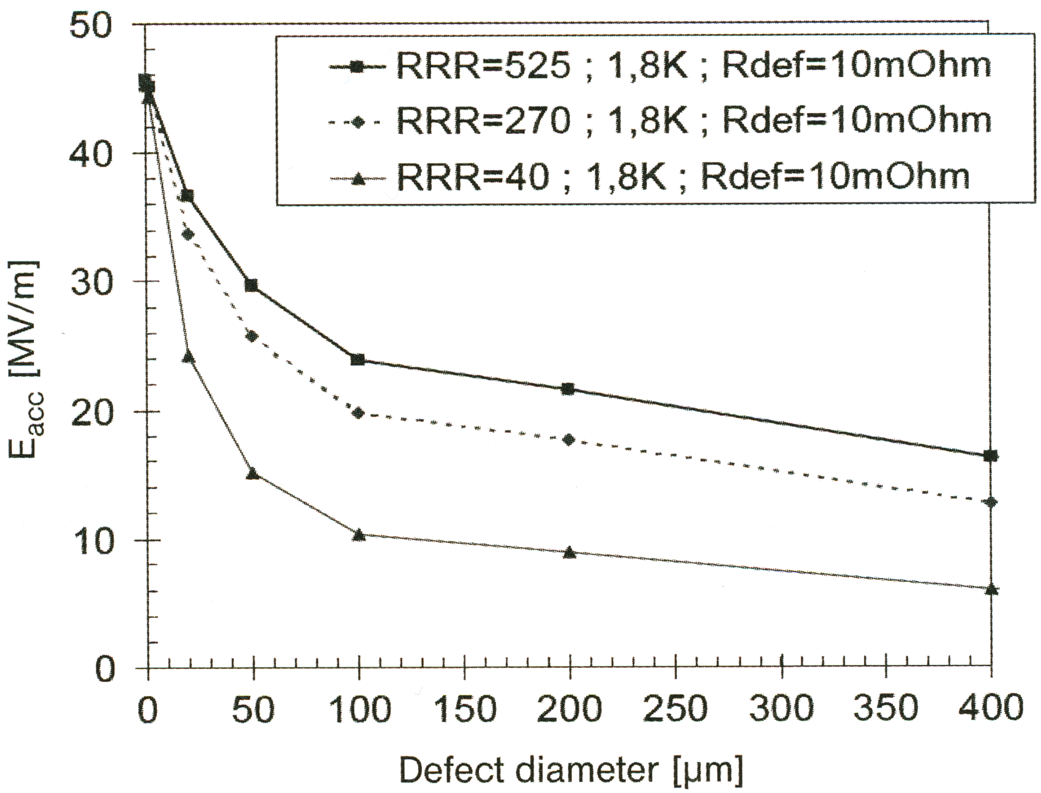
R&D NEEDED

IF FE is overcome by improved processing, then quenches at surface magnetic fields below the maximum for niobium (~ 52+ MeV/m) – "premature quenches" – will be the next barrier.

Temperature mapping of cavities at quench shows that when FE is not the limit, one sees strong, localized heating preceding the quench. Once the quench spot has been localized then it can, potentially, be repaired by local treatment. As the quench field rises, the size of the normal conducting spot causing the quench becomes smaller and smaller and thus more and more difficult to locate and analyze. The relation between maximum achieved field and size of the normal spot is approximately:

$$H_{\max} = \sqrt{\frac{4\kappa\left(T_c - T_b\right)}{aR_n}}$$

A numerical calculation using temperature dependencies of the quantities gives the result shown below. At fields corresponding to 40 MeV/m and above the spot size is below 10 micrometer for rrr~300 "typical" for today's cavity material



Summing Up the $E_{acc-max}$ Situation for niobium:

The single cell record of ~ 52 MV/m at 1.8K is very close to the max that is expected from the GL theory.

A first big step for multicell cavities would be to find a way to get high yield of the DESY record of 45 MV/m
NEED R&D ON SURFACE POLISHING/CLEANING METHODS THAT LEAD TO EASY REMOVAL OF ALL SURFACE RESIDUES THAT PRODUCE FE

The Ultimate realistic target could be ~50 MV/m in vertical testing so that operation at ~ 48 MV/m might be achievable.

NEED R&D ON BREAKDOWN SPOT LOCATION WITH MICRON PRECISION AND APPROPRIATE REPAIR METHODS (e.g. micro grinding, laser or electron fusion…)

Q Performance

$$R_s = R_{BCS} + R_{residual}$$

A record value for this at L-band in a single cavity where the two components were roughly equal at 1.4K is ~ 0.4+0.4=0.8 nΩ resulting in

$$Q \approx 2.8 \cdot 10^{11} \text{ (T=1.4K)}$$

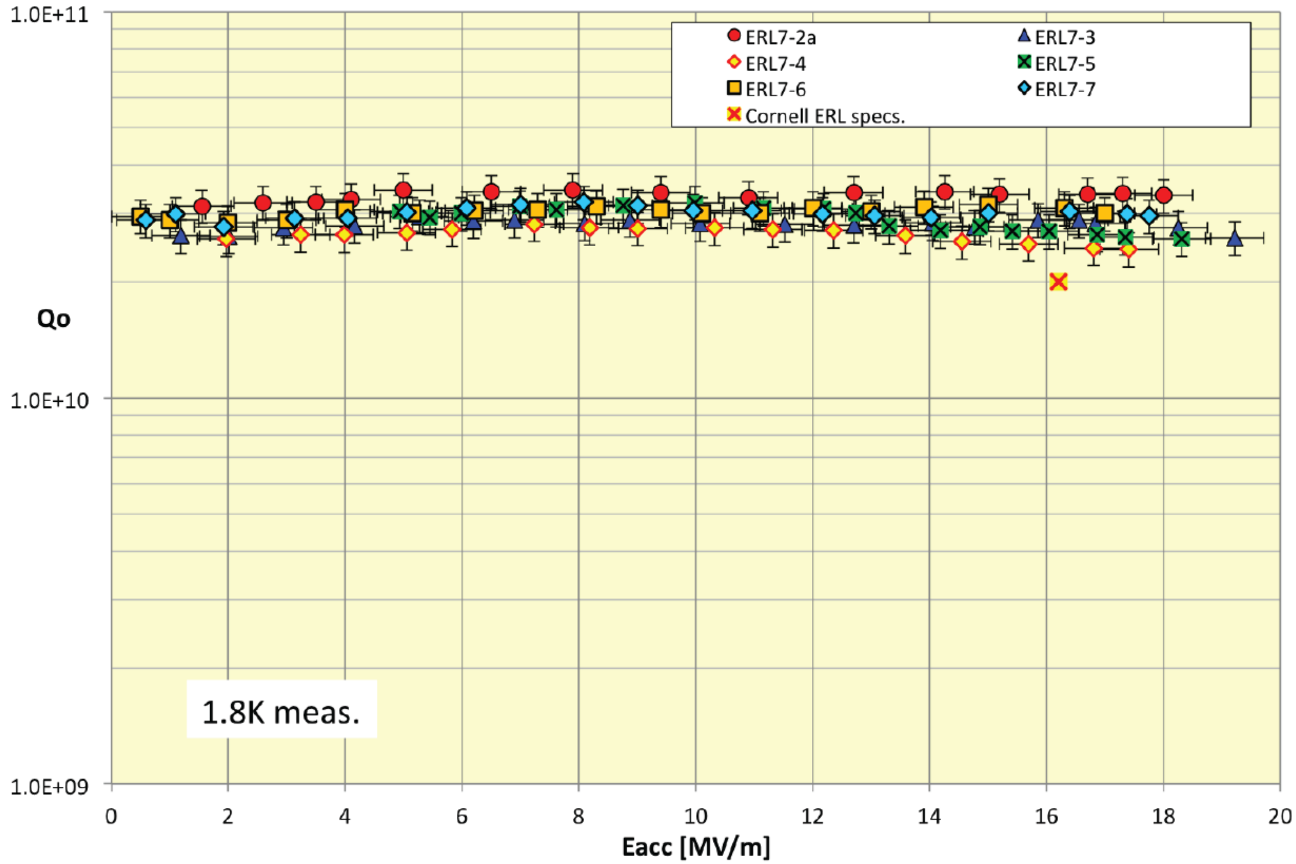
This was BCP treated and heated to 1000 °C for 5 DAYS to thoroughly outgas the hydrogen – not an economical procedure for mass production. Shows the limits though…………

High Q is very important for CW applications so considerable R&D has gone into understanding how to achieve it in multicell cavities.

The frontier at the moment is at ~ 1.8K which seems to be economically favored for CW applications like large linacs. Residual resistance is usually the limiting parameter and various approaches have been taken. One example will give a flavor of where the campaign for reliable achievement of high Q at intermediate fields (i.e. ~16 MV/m) is currently at:

Shown in the next slide are the Q vs E_{acc} curves for six 7 cell cavities which achieved 100% yield with no reprocessing. They were treated with BCP and 650°C UHV heating for outgassing of hydrogen. A final rinse with HF was found helpful for Q results

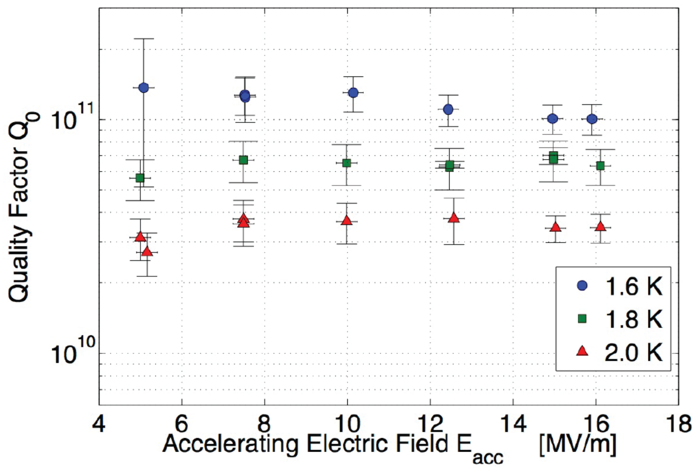
6 cavities with helium jackets of Ti



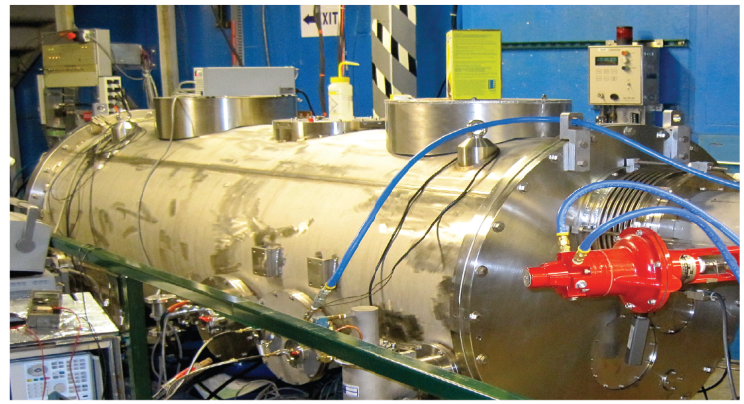
The vertical test results of the 7-cells for MLC.

Note that very slow cooldown was important to these results, ΔT top to bottom < 5K during passage through T_c

Now see the result of a horizontal test of one of these cavities fully dressed:



The measured quality factor Q_0 of the prototype ERL cavity as function of accelerating field. The design goal of $2x10^{10}$ at accelerating fields of 16MV/m was exceeded by almost 2, 3, and 5 at temperatures shown.



The Horizontal Test Cryostat that is used at Cornell to test the superconducting accelerating cavity in its full accelerator environment with beam pipes, power couplers, and Higher Order Mode absorbers.

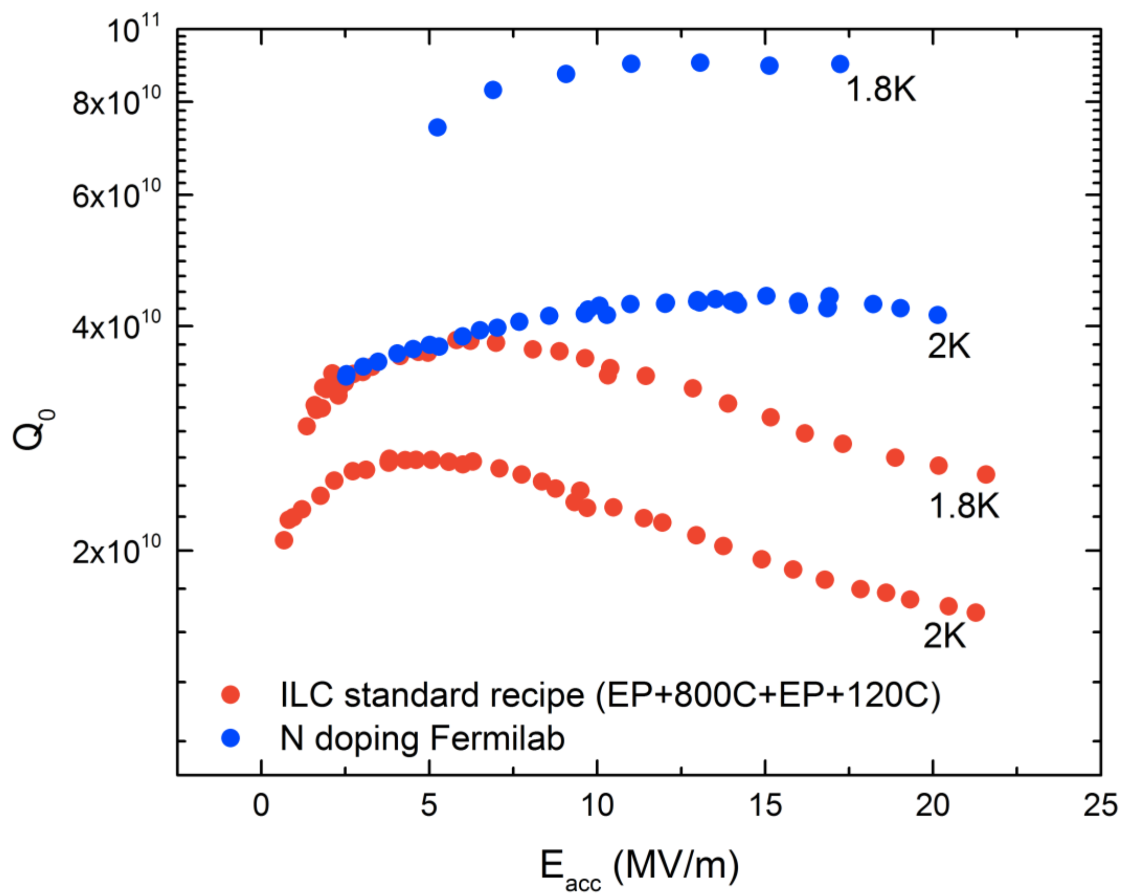
This cavity, one of the 6, was also cooled slowly - ΔT end to end <1K

Facts: the He jacket is Ti so we have bi-metallic system and potential for thermal gradient induced currents; the residual field in the vert. and horiz. Cryostats is ~1-2 mGauss thus hinting that some fluxoids, owing to thermal currents, entered at transition , increasing the residual resistance for the vert tests.

While there is much to follow up on here, it appears that one might aspire to Q's ~ 5E10 in practical circumstances for CW operations at intermediate fields.

Another approach shown in the next two slides involves "nitrogen doping" which may prove very useful going forward – still under development.

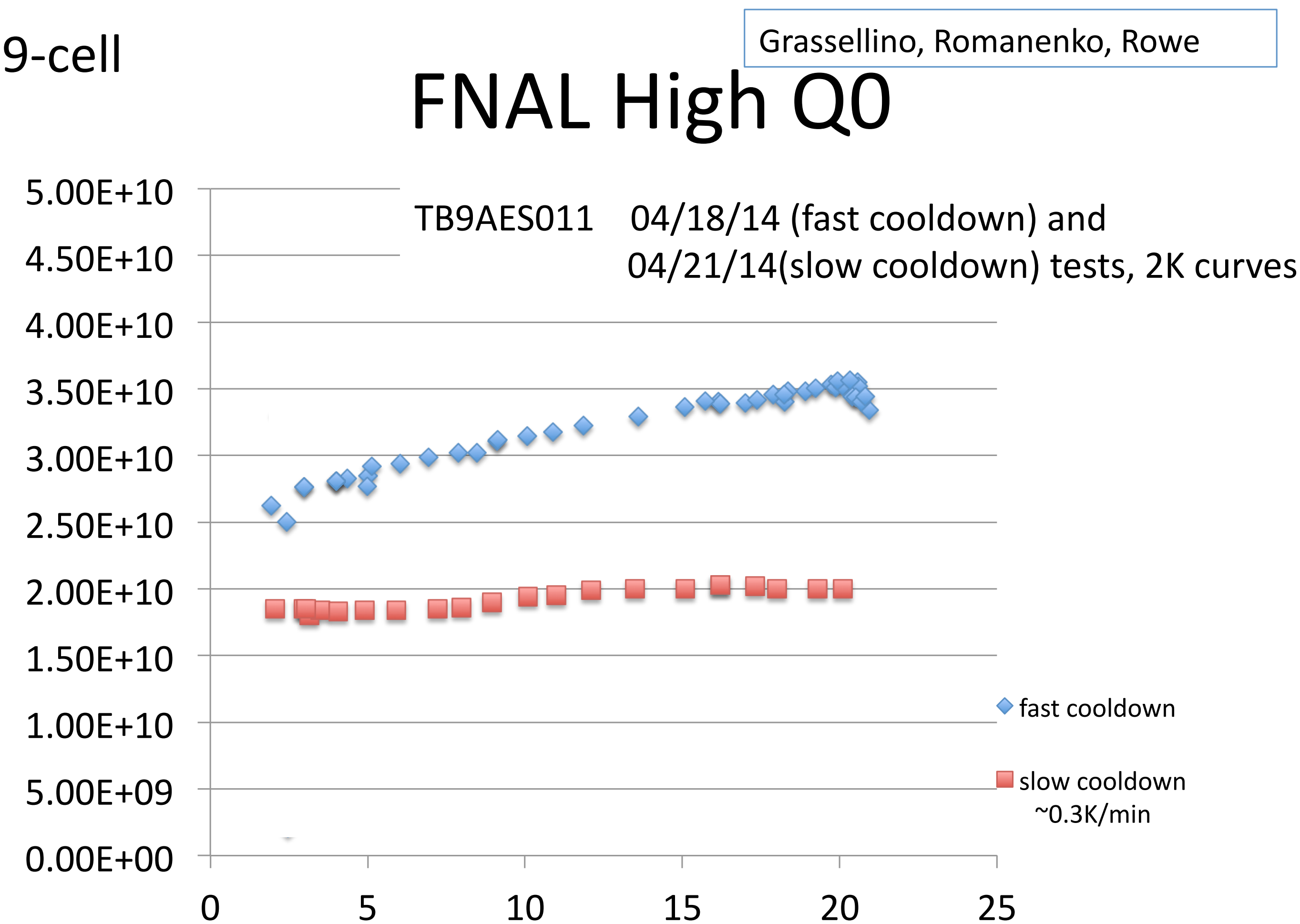
- 1-cells



10^{11}
$8x10^{10}$
$6x10^{10}$
$4x10^{10}$
$2x10^{10}$
Q_0
1.8K
2K
1.8K
2K
ILC standard recipe (EP+800C+EP+120C)
N doping Fermilab
0
5
10
15
20
25
E_{acc} (MV/m)

9-cell

FNAL High Q0



note: fast cooldown may turn out difficult difficult for cryomodules

That’s pretty much the Nb story. What about “exotic” materials?

Other Materials

Exotic materials and techniques

- Nb coating on Cu
  - Magnetron sputtering pursued > 20 years
    - best 15 MV/m @ 1500 MHz, 15 MV/m at 400 MHz
  - New methods: Energetic deposition
    - Sample Nb properties and RRR improvement demonstrated
    - No encouraging cavity results yet
- Multilayers, ALD, CVD….
    - 5 years.. no cavity results

      New fundamental studies contest potential benefits of multi-layer shielding

      see http://ipnweb.in2p3.fr/srf2013/papers/weioc04.pdf

Generalities about HiT$_c$ aka HTS Materials

Attraction: Higher T_c means potential for higher H_c

$$\frac{\mu_o H_c^2}{2} = 0.236\gamma T_c^2$$

Concerns: Hi T_c means smaller coherence length and thus greater sensitivity to small defects

$$\xi_o = \frac{\hbar v_F}{k_B T_c}$$

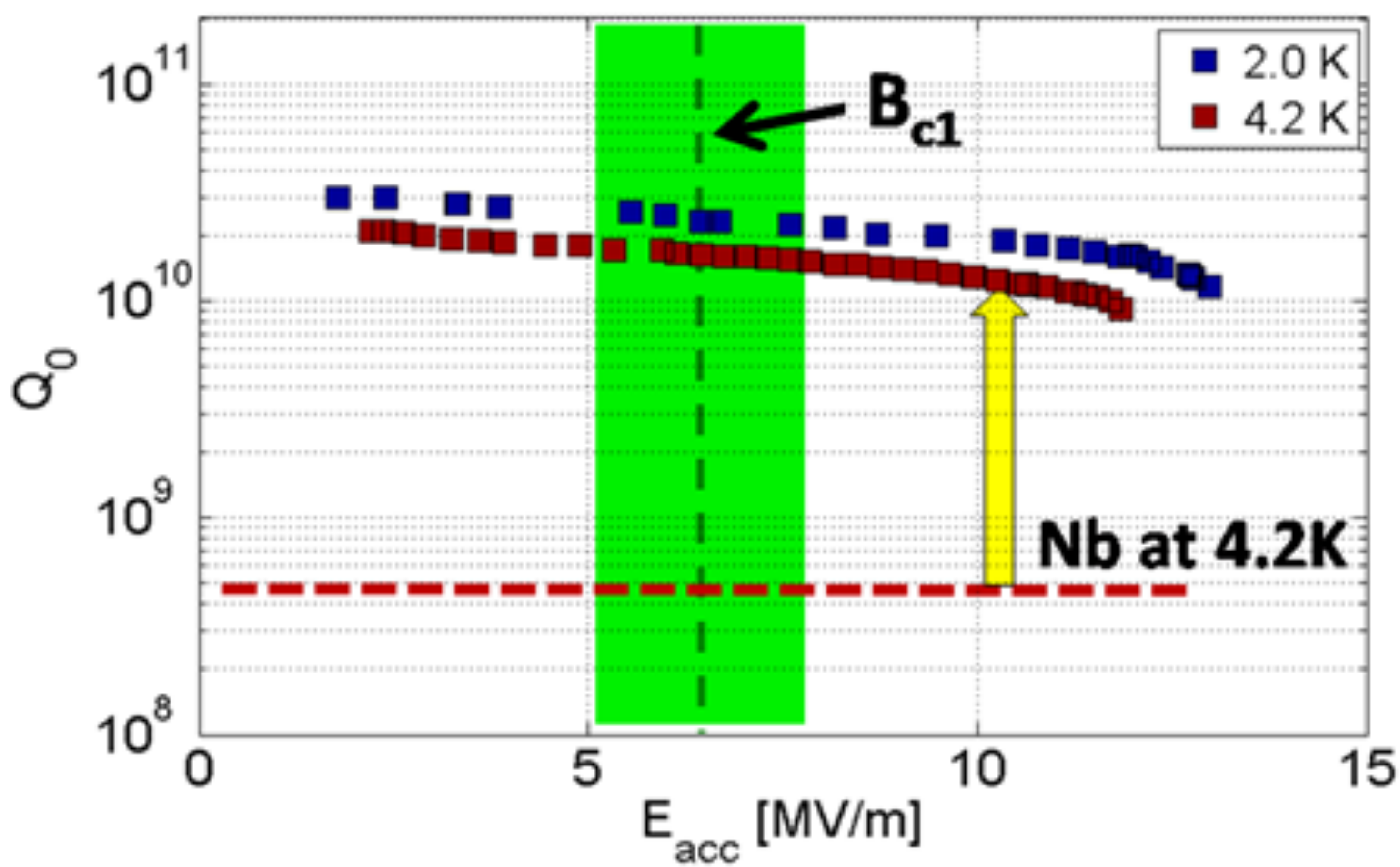
also watch the energy gap, some new materials have small gaps, Δ which means lower Q for a given temp

$$R_s = A\omega^2 \exp - \frac{\Delta}{k_B T}$$

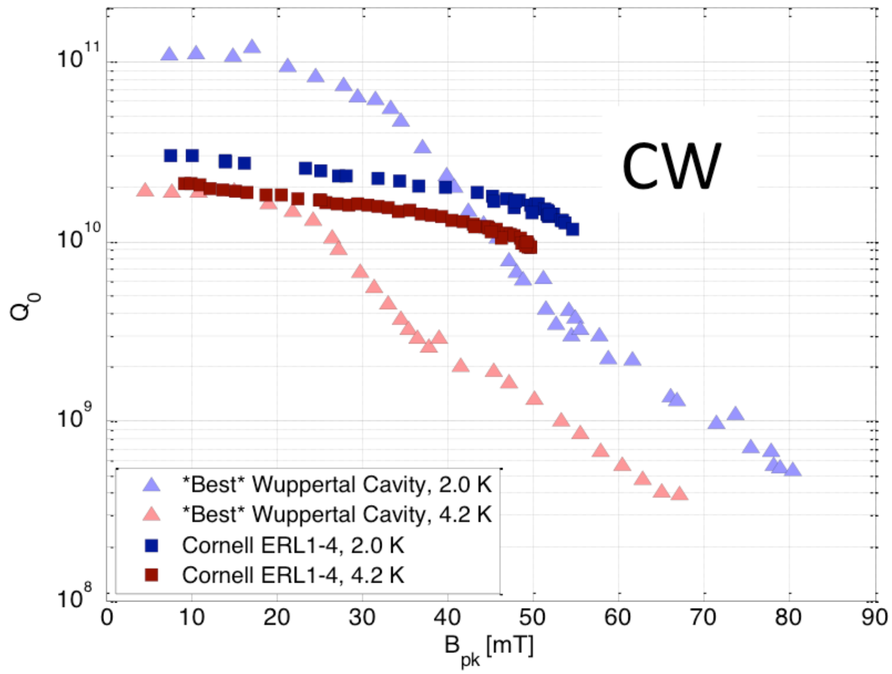
also may have difficult phase diagram and difficult mechanical properties…….

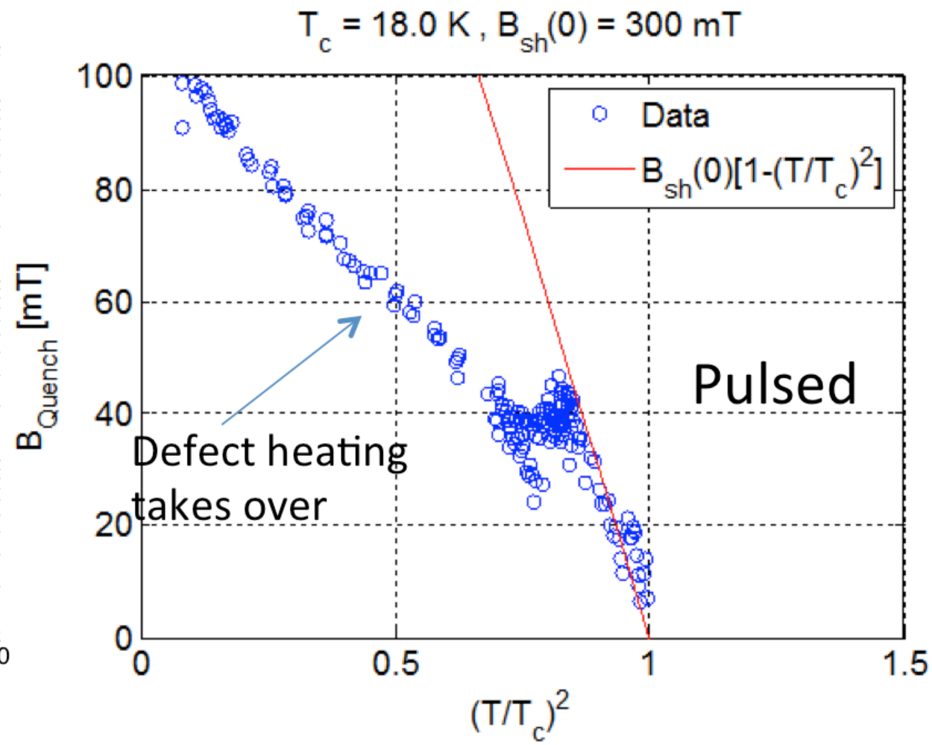
- HTS (candidates in order of increasing attraction)
  - YBaCuO - Reject- Has nodes in energy gap => Q will be low
  - MgB2 – Questionable advantages
    - Two energy gaps, lower gap is less than Nb3Sn gap, so surface resistance will be higher
    - Hc ranges from 0.26 – 0.6 (Nb, Hc = 0.2, Nb3Sn Hc = 0.4)
  - Pnictides – very new (e.g. LaOFeAs) & ceramic like
    - Tc best 50 K, some evidence for S-wave gap $\Delta\sim$ 8mev (Nb3Sn, Δ= 3.3mev) Could lead to high Q
  - Sorry to be so pessimistic, but facts are facts
  - Only Nb3Sn shows encouraging results

Recent 1-cell cavity results w. Nb3Sn



Nb3Sn - $B_{ultimate}$(T) Measurement at high T





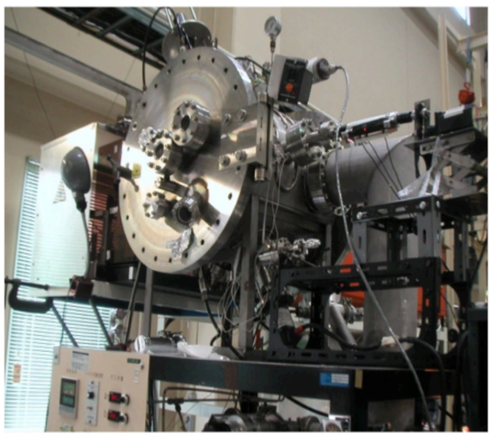
- Single cell 1.3 – 1.5 GHz cavities with Q = 10^{10} to 10^{11} demonstrated.
- CW gradients to 18 MV/m at Q =10^9
- Pulsed rf data at high temp data extrapolates to B_{sh} ~ 300 mT

=> Eacc > 80 MV/m >> Nb – Hsh = Hcritical

Nb_3Sn Preparation Methods

SRF2013 PARIS
16th International conference on RF Superconductivity

Pulsed Laser Deposition - KEK

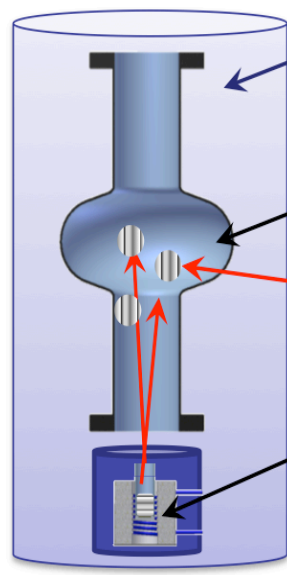


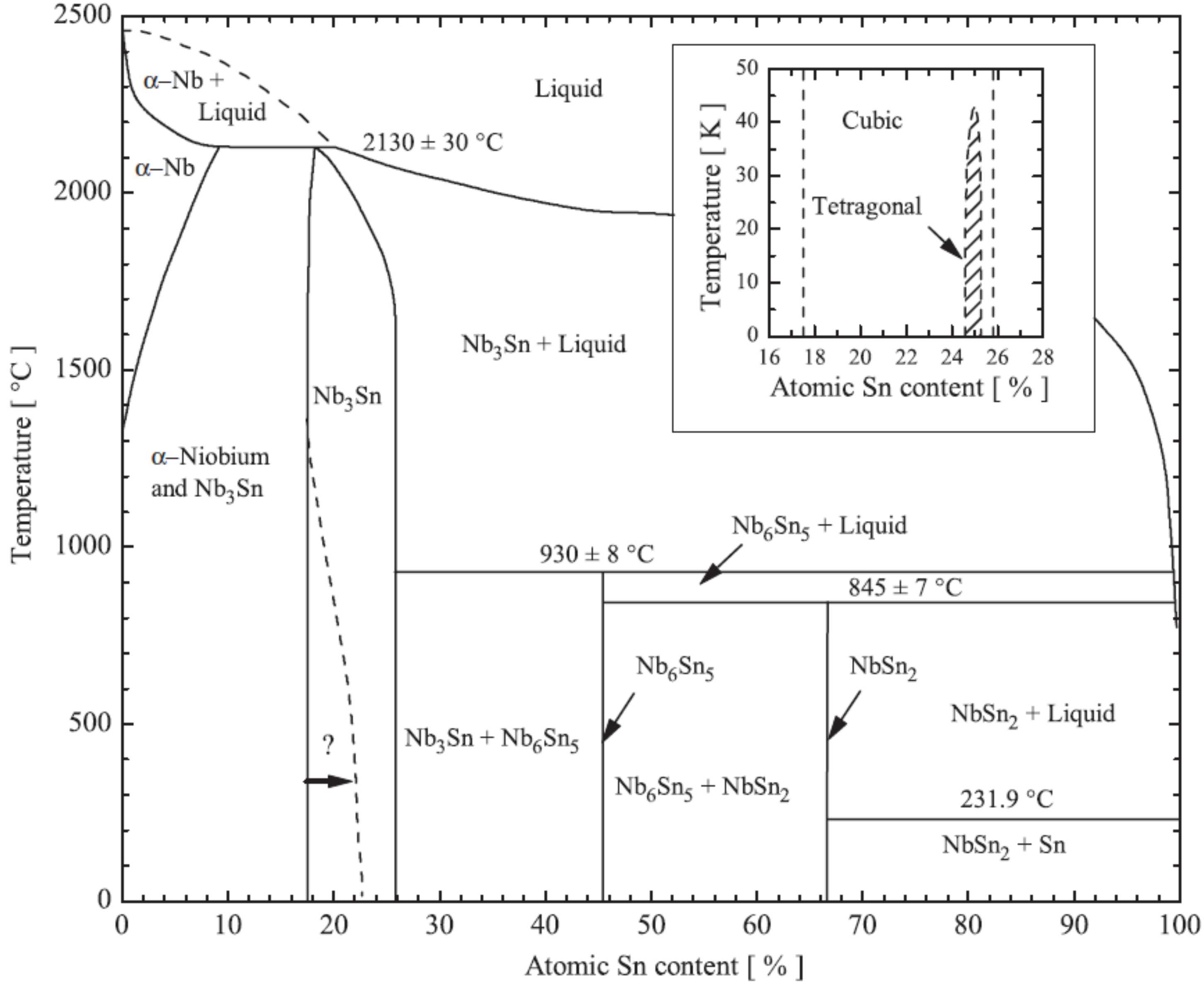
- Studies have started
- Also use PLD for MgB_2

S. Mitsunobu et al.

Vapor Diffusion –Siemens AG, U. Wuppertal, Cornell, and Jefferson Lab

- In UHV furnace, tin vapor alloys with Nb cavity
- Very promising RF results

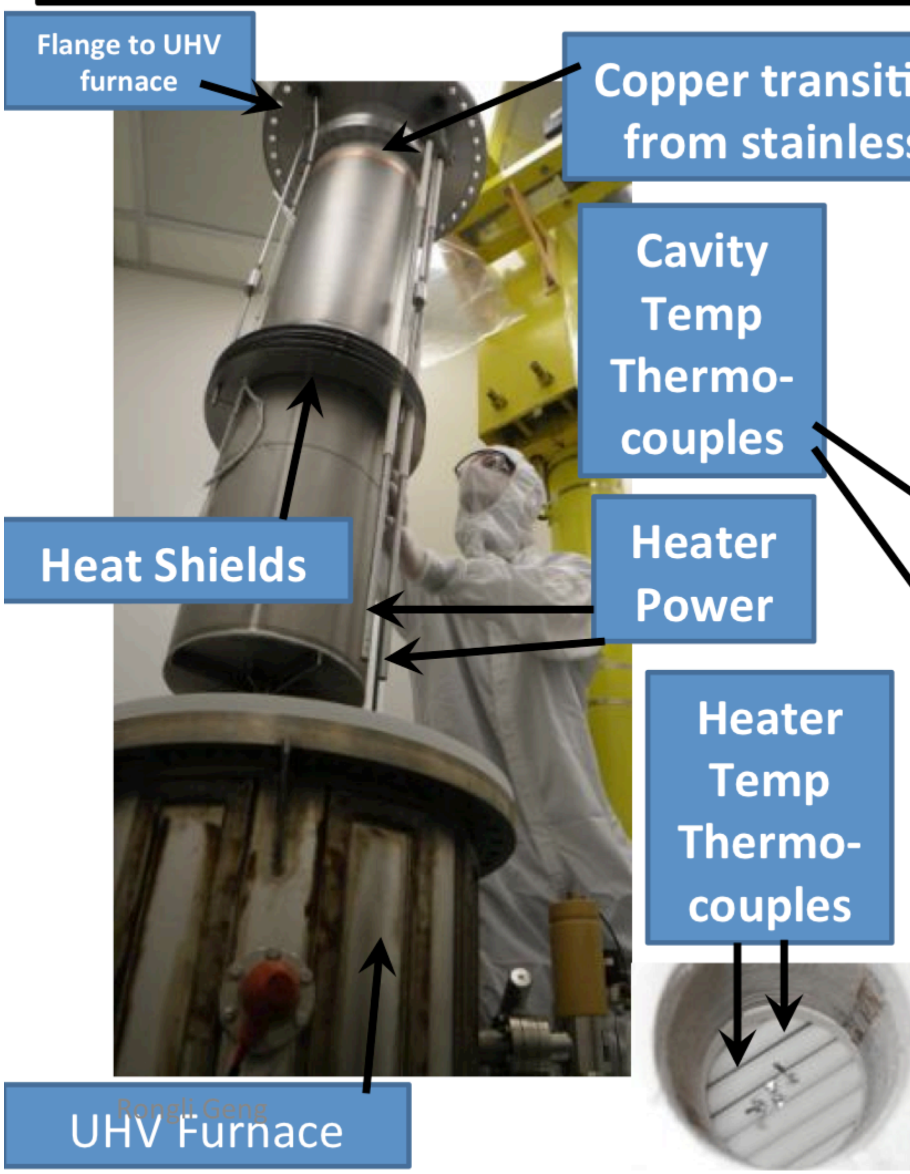


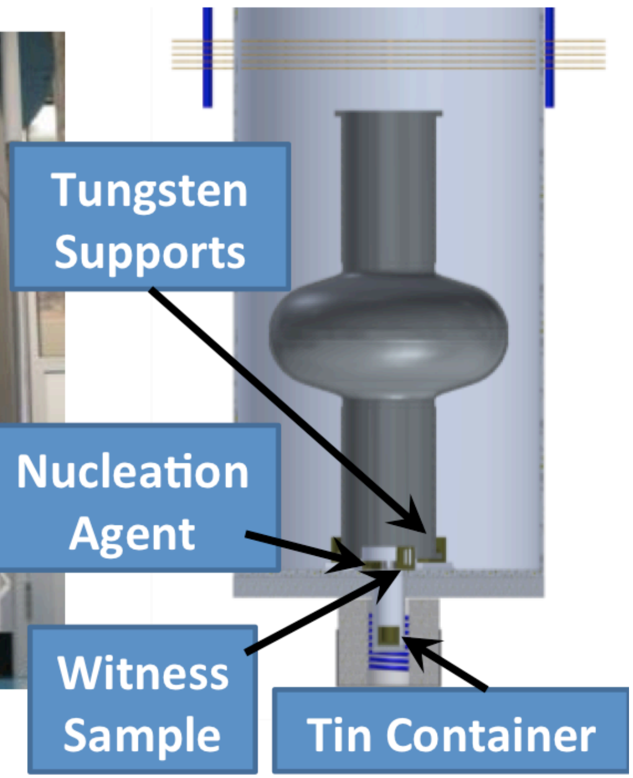


Liquid
α–Nb +
Liquid
α–Nb
2130 ± 30 °C
Nb3Sn + Liquid
Nb3Sn
α–Niobium
and Nb3Sn
Nb6Sn5 + Liquid
930 ± 8 °C
845 ± 7 °C
Nb6Sn5
NbSn2
NbSn2 + Liquid
?
Nb3Sn + Nb6Sn5
Nb6Sn5 + NbSn2
231.9 °C
NbSn2 + Sn
Temperature [°C]
Atomic Sn content [%]
Cubic
Tetragonal
Temperature [K]
Atomic Sn content [%]

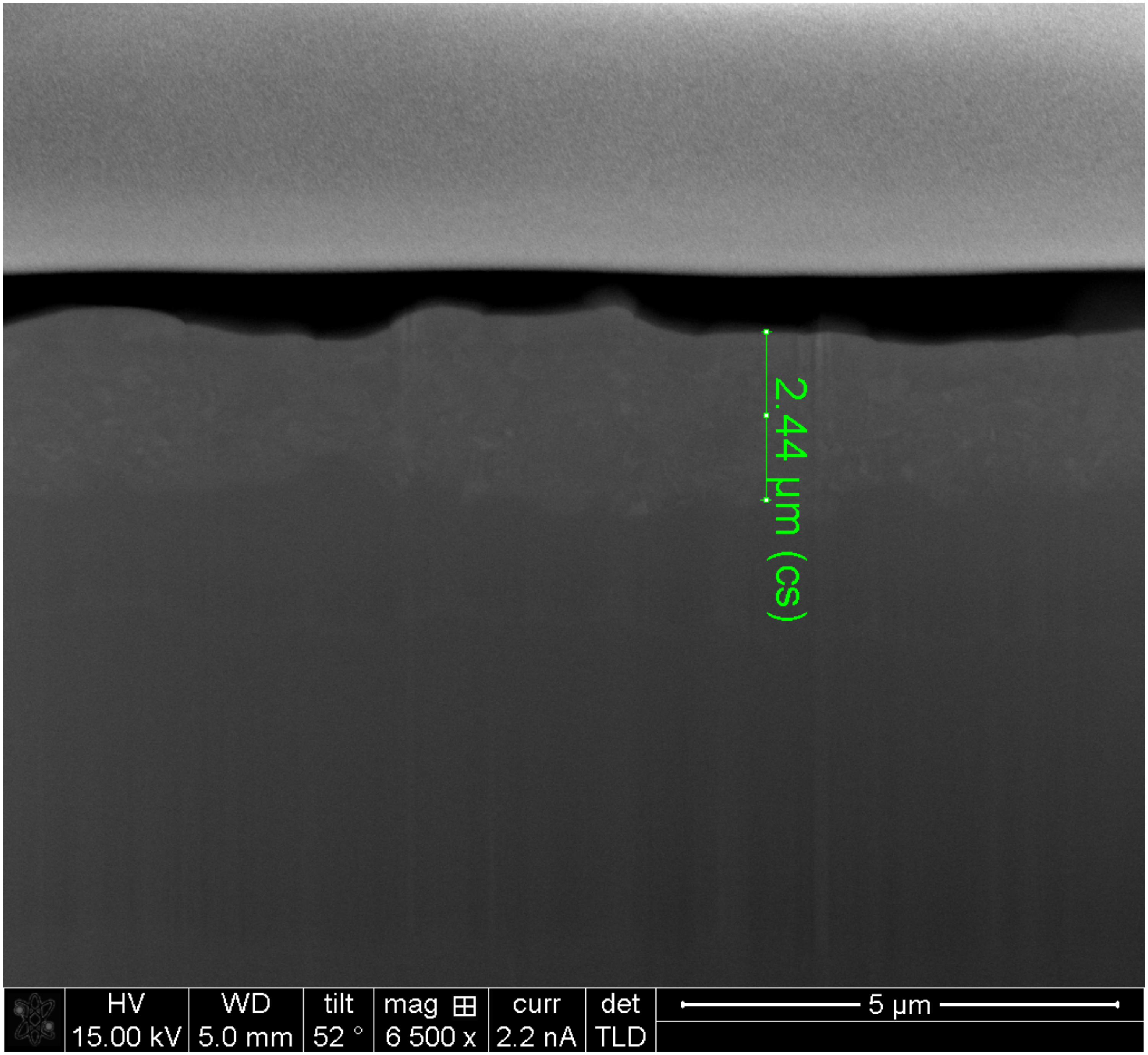
Nb_3Sn Coating Chamber
Cornell University

Coating chamber is inserted into UHV furnace. Separate vacuum system keeps furnace free from tin contamination

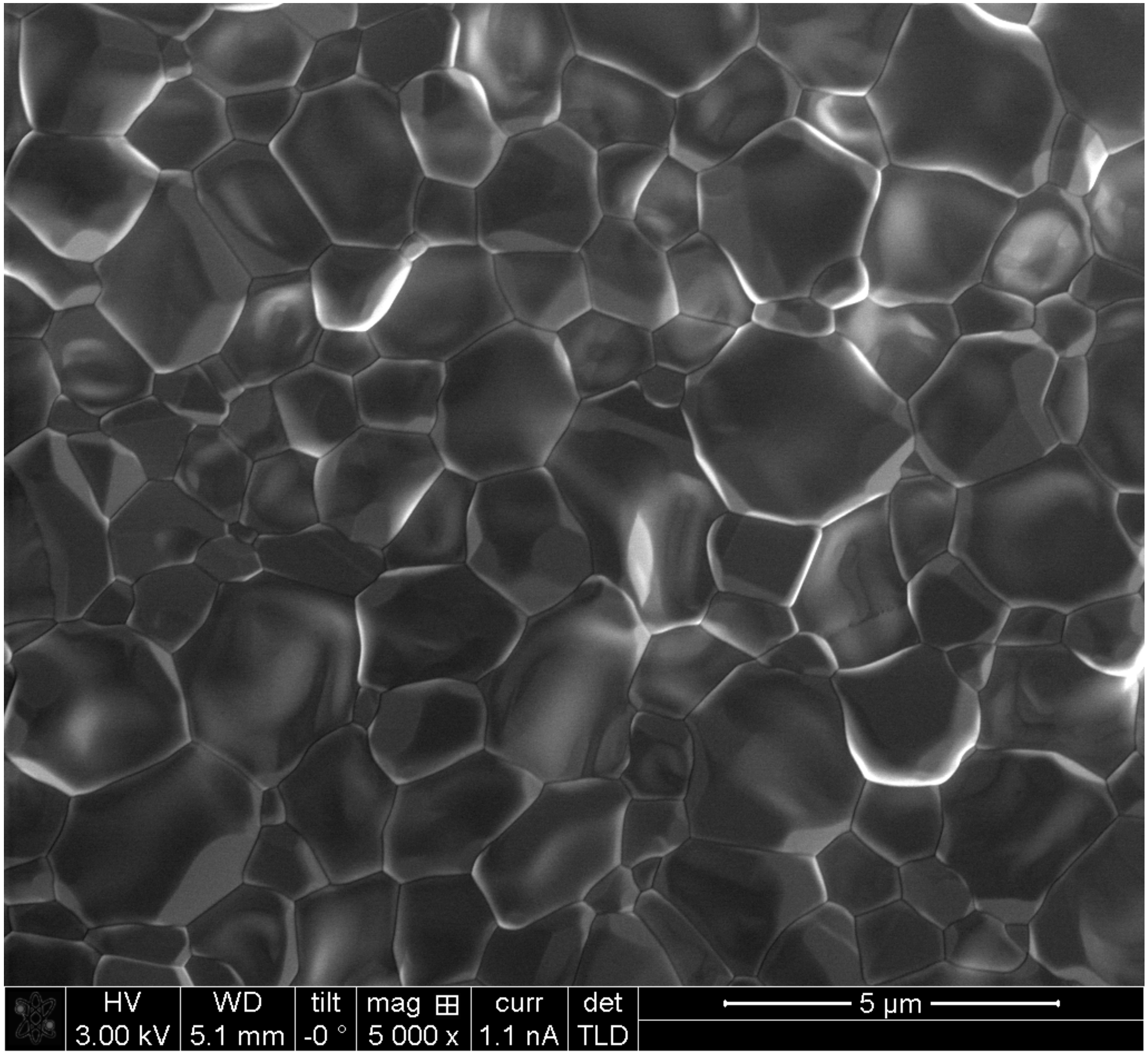




Courtesy Sam Posen, Cornell



2.44 µm (cs)
HV
15.00 kV
WD
5.0 mm
tilt
52 °
mag
6 500 x
curr
2.2 nA
det
TLD
5 µm



$\xi \sim 3$nm not large w.r.t. grain boundary thickness?

One can guess (and it's true) that this is a difficult morphology to deal with – many intergrain boundaries for transmitting the current with liklihood of poor stoichiometry at some or all of them.

So, what's different than it was ~20 yrs ago. Mostly the availability of today's surface analytical instruments that will permit us to make high resolution micrographs of the transverse section of the Nb3Sn surface AND a depth profile of the stoichiometry with TEM/EDX

By this means we may be able to find the correct diffusion and anneal cycles to get larger grains and uniform composition across the grain boundaries.

If successful it appears that we may hope for ~80MV/m gradients at very good Q, i.e. $>10^{10}$

Lots of R&D required -

Nothing yet has been done with the pnictides and RF to show whether the Hi T_c accompanied by the extraordinarily large Δ will be useful given the really samll coherence length.

There remains significant headroom for improvement in superconducting cavity performance with niobium and with Nb3Sn. One can hope that perhaps some even more advanced material will open up the sky but don’t hold your breath.

The scientific and technical challenges are great. The challenges of obtaining the needed resources however may be much greater!

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