# “What is the best treatment for highest Q and medium gradient for CW applications?

- For CW applications the gradient becomes cost limited by the dynamic heat load.
- The cost of refrigeration for a several GeV CW accelerator becomes substantial, so that the optimum gradient for lowest cost is likely to be in the 15 – 20 MV/m range.
- Higher Q’s will likely drive the optimum gradient higher and the cost lower.
- Hence the goal of the discussion is to help identify the best treatment that will give the highest Q at medium gradients.
- The frequency for the accelerator also has a bearing on the dynamic heat load, since BCS resistance decreases as f^2, but the shunt impedance (per unit length) decreases with f.  But we wont have time discuss low frequency results…sorry

# Our Panel of Experts

- Alexander Romanenko – Fermilab
- Anna Grasselino – Fermilab
- Mathias Liepe – Cornell
- Pushapati  Dhakal - Jlab
- Detlef Reschke – DESY
- Julia Vogt – BESSY

# Guiding Questions

- Lots of information presented in previous talks here
  - Put together as much as possible
- Surface Treatment
  - 1) Is BCP or EP the superior treatment for highest Q?
- 2) Does tumbling help to reach higher Q's ?
  - (above the statistical spreads).
- Material
  - 3) Does large grain material give higher Q's
  - (above the statistical spreads).

# 120 C Bake

- 4) It is well known that 120 C bake lowers the BCS resistance component. But it also raises the residual resistance (spoiling the oxide).
- 5) Is baking recommended for high Q?
  - Can the residual resistance be restored by HF rinsing?
  - How does 120 C baking affect the medium field Q-slope?
  - How does HF rinsing affect the medium field Q-slope?

# Medium Field Q-Slope

- 6) What is (are) the cause (s) of the medium field Q-slope (MFQS)?
  - Is it simple a thermal effect
- 7) Which component of the resistance increases with field during MFQS?
  - BCS or residual?

# High Temperatures and New Treatments

- 8) Does higher temperature (800 C and above) annealing raise Q ?
- 9) Are there any new treatments that give higher than standard BCS Q?
- Include promising results from new materials such as Nb3Sn.

# Preserving the Q in the CM

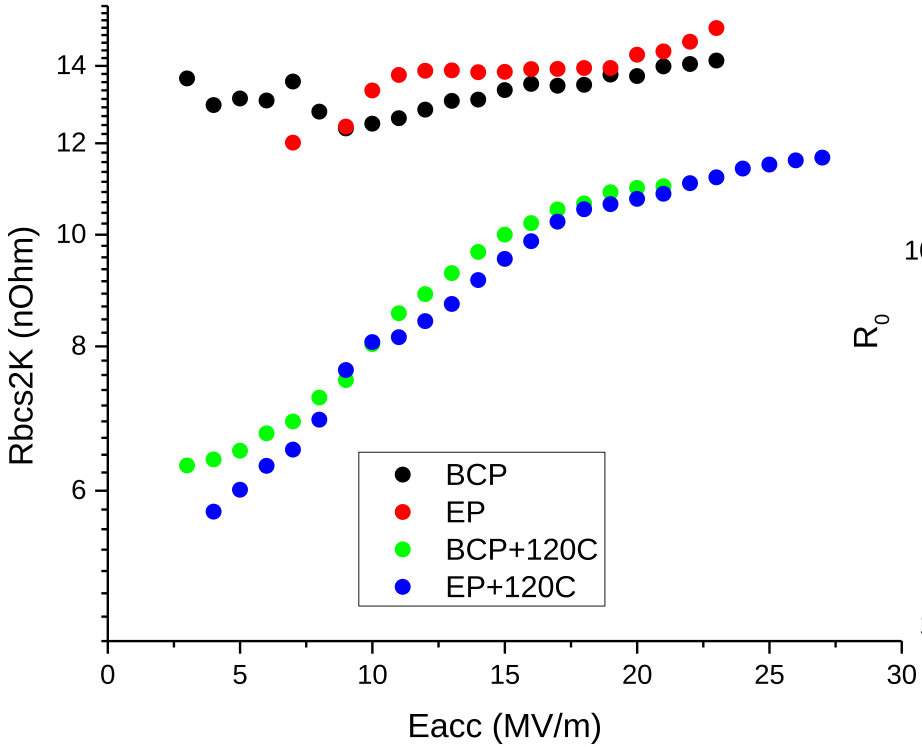
- 10) What are the precautions/procedures to maintain higher Q's from vertical test to cryomodule?
- DC magnetic field shielding, avoiding flux trapping due to thermo currents etc.

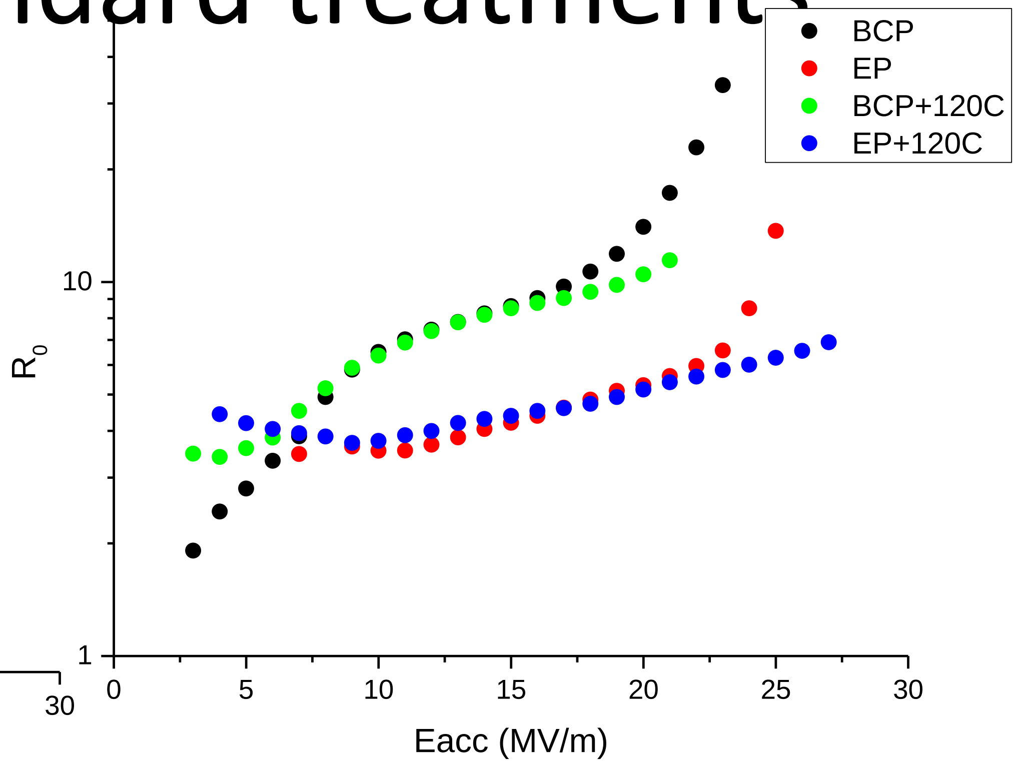
# 1) Is BCP or EP the superior treatment for highest Q?

- When both get 120  C to minimize BCS resistance

1.3 GHz, 2K…..Alexander

# Effect of standard treatments



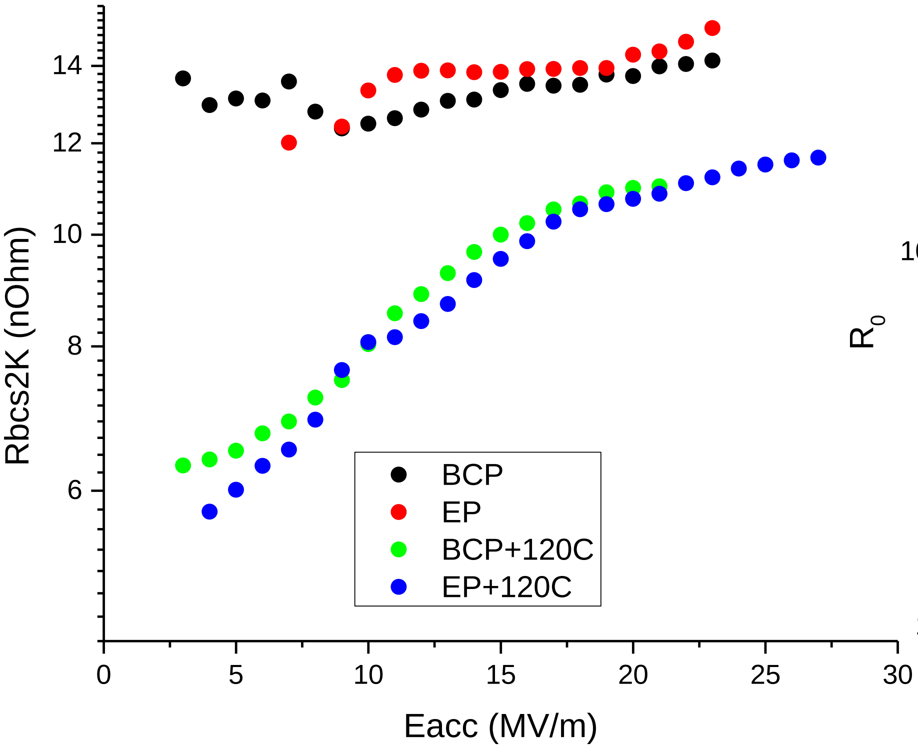

"BCS" resistance

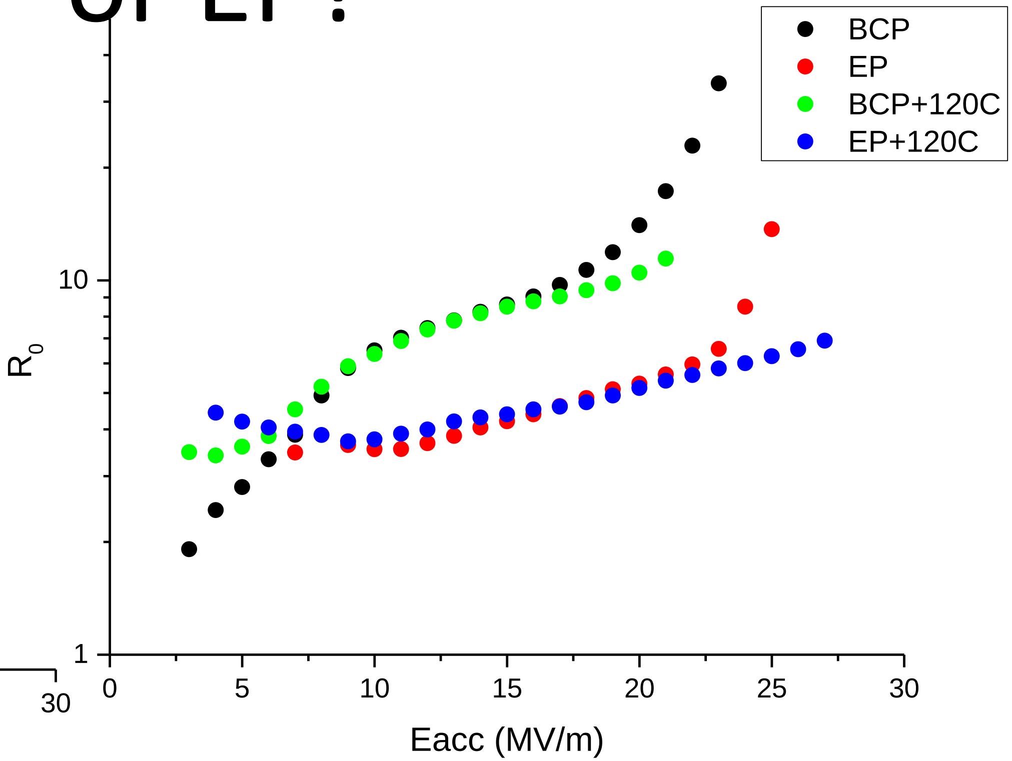
Residual resistance

"BCS" resistance

Residual resistance

# BCP or EP?



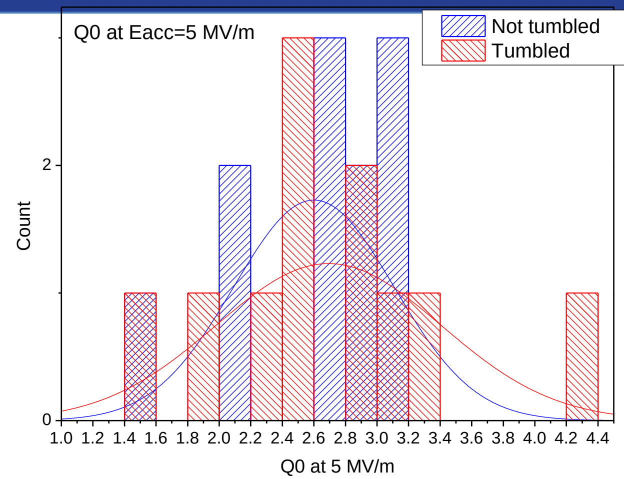

- Is BCP or EP the superior treatment for highest Q?
  - EP - gives less field dependence of the residual => higher Q at the operating gradient
    - however if it is due to trapped flux – may be mitigated by the slow cooldown/flux expulsion techniques
  - If BCS-dominated (e.g. 4.2K) – does not matter much

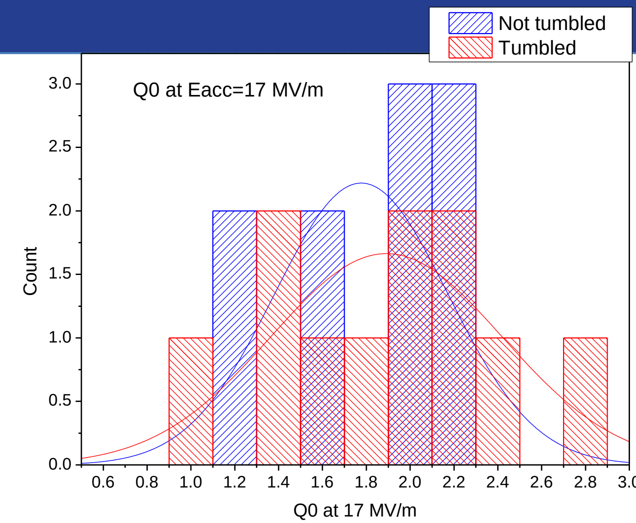
# 2) Does tumbling help to reach higher Q's ? (above the statistical spreads).

# 2) ANNA

## *Marginally – note: tumbled cavities go through extra 800C cycles*

Single cells

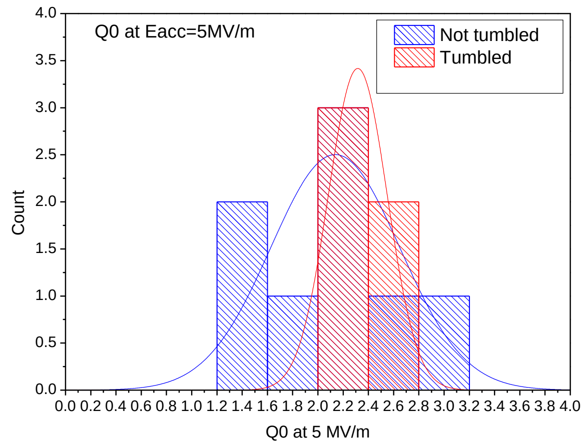


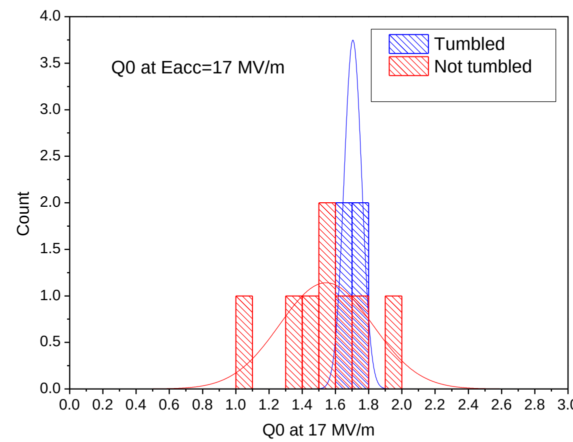




| | N total | Mean | sigma | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Not tumbled | 11 | 2.6 | 0.50796 | 1.43 | 2.73 | 3.14 |
| Tumbled | 11 | 2.69273 | 0.71337 | 1.53 | 2.51 | 4.24 |

| | N total | Mean | sigma | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Not tumbled | 10 | 1.777 | 0.39556 | 1.16 | 1.95 | 2.17 |
| Tumbled | 11 | 1.89182 | 0.52759 | 0.99 | 1.98 | 2.87 |

Nine cells



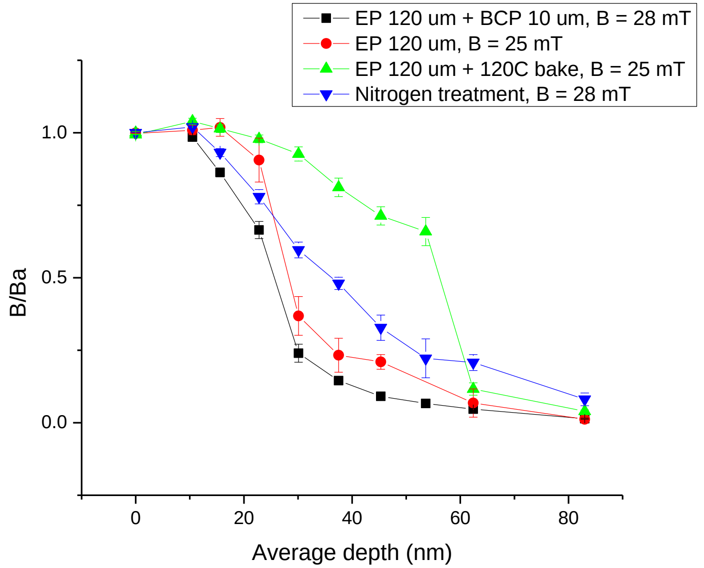




| | N total | Mean | Sigma | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Not tumbled | 8 | 2.1375 | 0.51026 | 1.42 | 2.26 | 3 |
| Tumbled | 5 | 2.316 | 0.23352 | 2.08 | 2.39 | 2.62 |

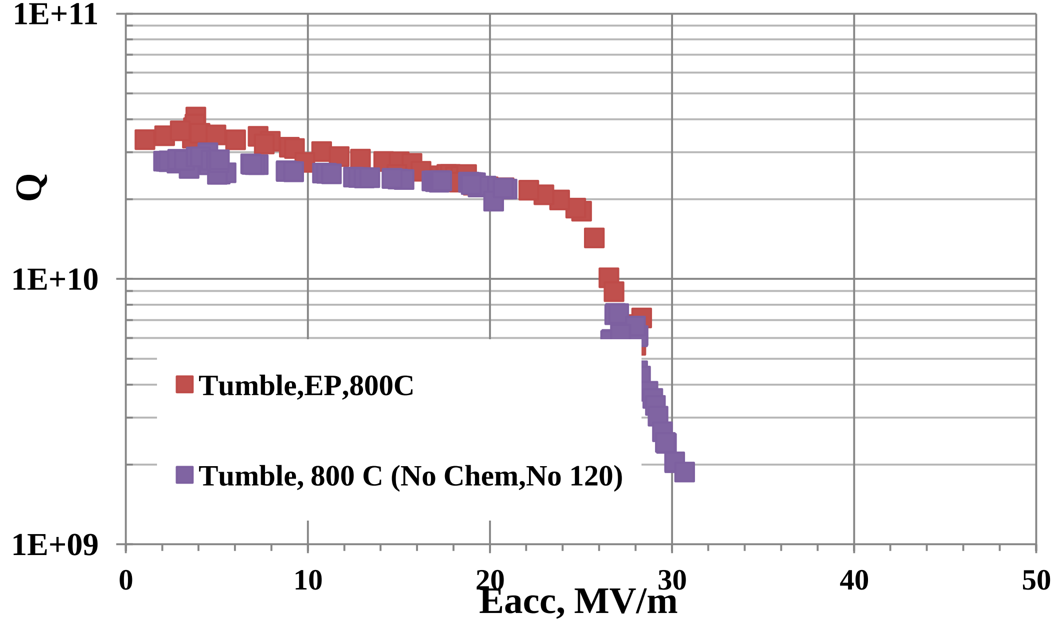
| | N total | Mean | Sigma | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Not tumbled | 8 | 1.54375 | 0.27969 | 1.07 | 1.545 | 1.98 |
| Tumbled | 4 | 1.705 | 0.05323 | 1.65 | 1.705 | 1.76 |

# 2) Does tumbling help to reach higher Q's ? (above the statistical spreads) So far even with mirror finish surface (no chemistry post tumbling) no Q improvement observed

*A. Romanenko et al, LE-muSR, tbp*




*C. Cooper et al, tbp*



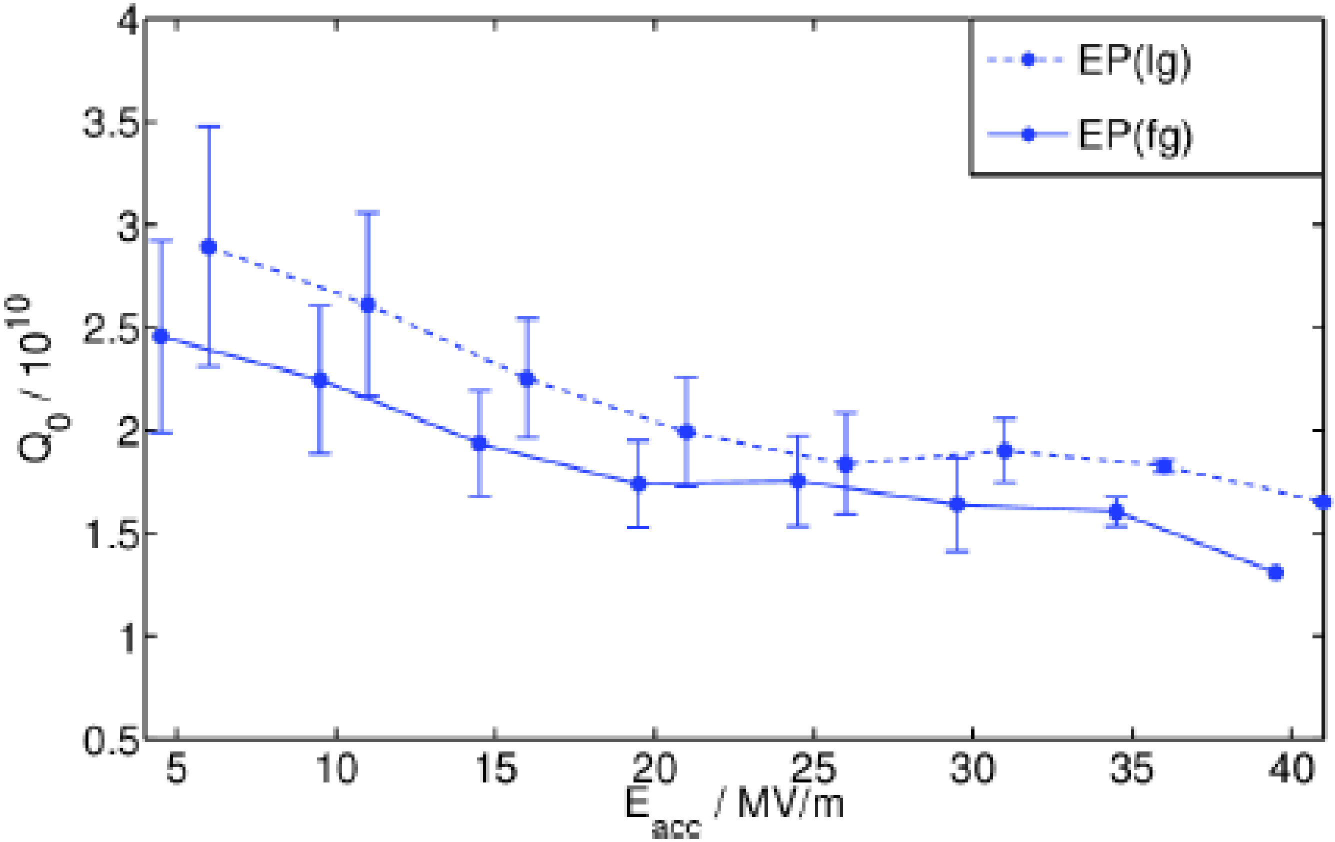

Dead layer due to nanoroughness? Room for Rs improvement if surfaces are mirror smooth (ie <50 nm roughness)?

- Cavity tumbled with last steps (mirror finish only) – significantly smoother surface, but no improvement found
- Notice also HFQS at same onset

3) Does large grain material give higher Q’s (above the statistical spreads).

# Vertical Test: Comparison of LG vs. FG Cavities at DESY

- Based on 11 LG-Cavities + 18 FG Cavities
- Number of entries/data point decreasing with increasing gradient
- Statistical error shown

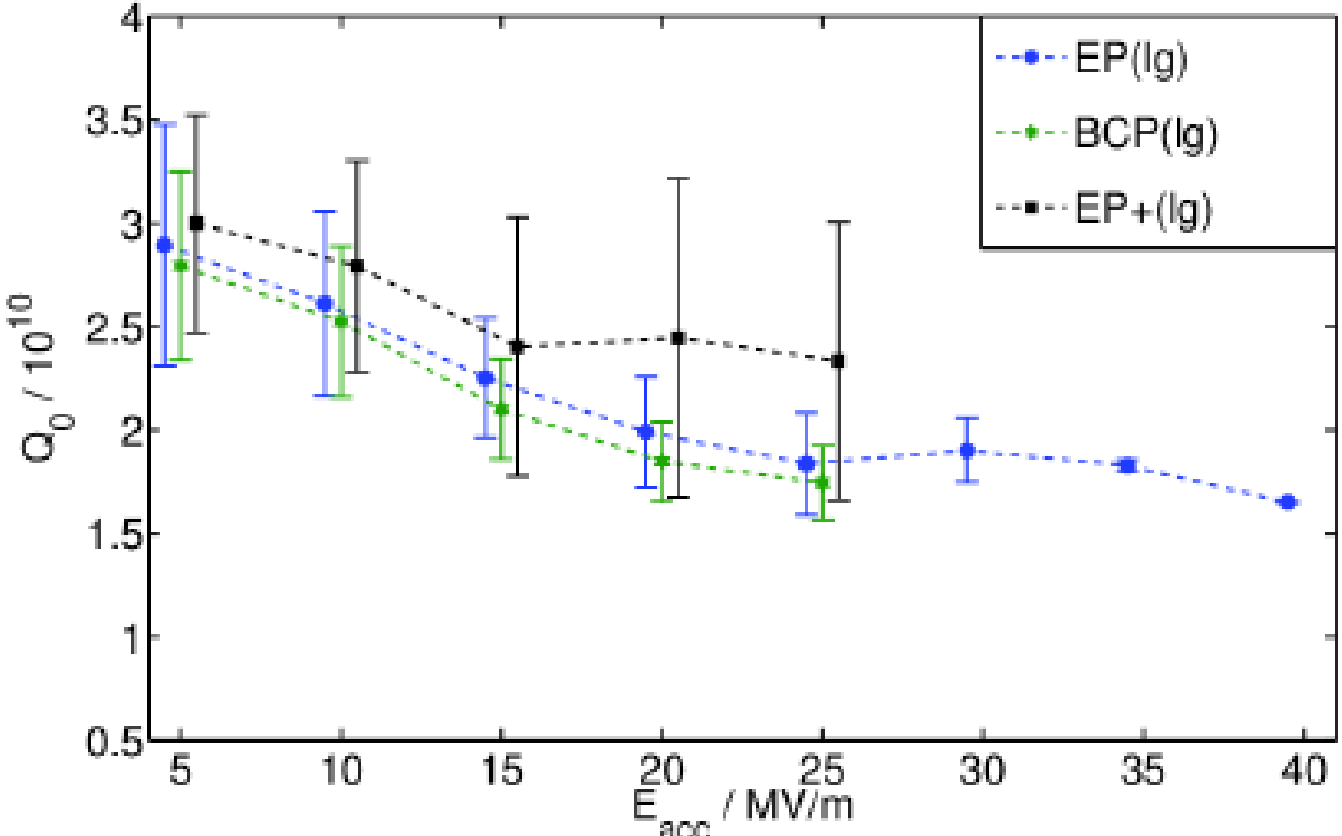


European XFEL

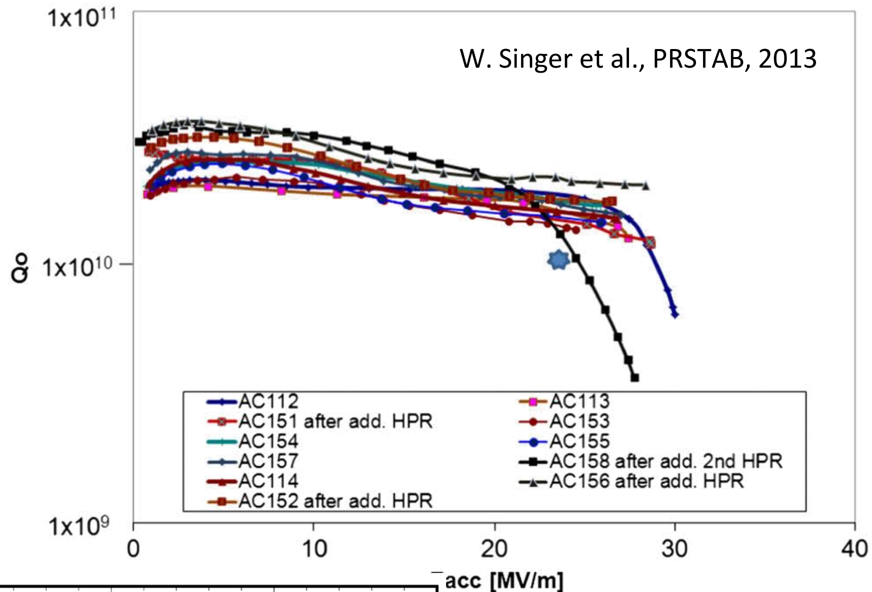
# Vertical Test of LG Cavities at DESY



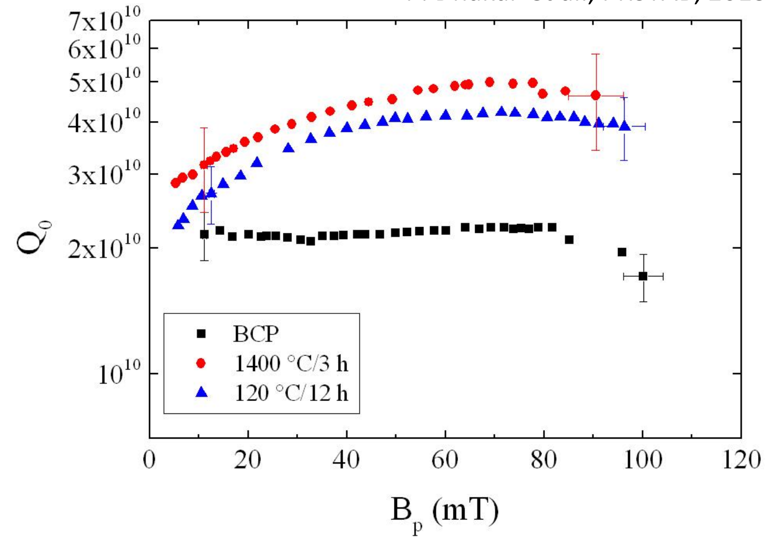
- Based on 11 LG-Cavities
- Only 4 LG Cavities with EP+
- Number of entries/data point decreasing with increasing gradient
- Statistical error shown

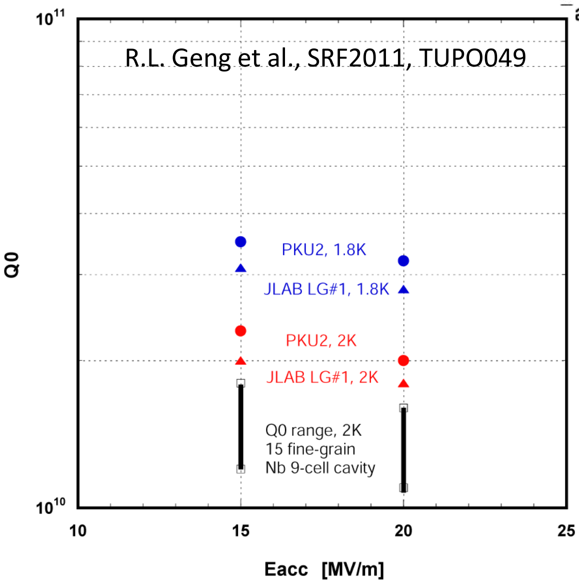


# Jlab: Pushpati




P. Dhakal et al., PRSTAB, 2013




Compared to fine-grain 9-cell TTF shape cavities EP processed according to the ILC recipe and tested in the same Dewar, LG cavities have a clear better Q0 above statistical spreads.

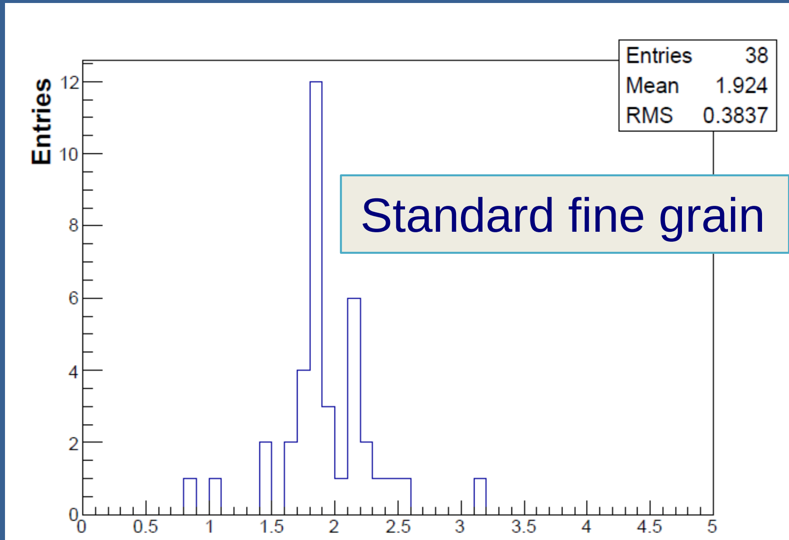
**"The Rise of Ingot Niobium as a Material for Superconducting Radiofrequency Accelerating Cavities" P. Kneisel, G. Ciovati, P. Dhakal, K. Saito, W. Singer, X. Singer, G. R. Myneni**
**arXiv:1304.1722**

# Anna: Does large grain material give higher Q's (above the statistical spreads)

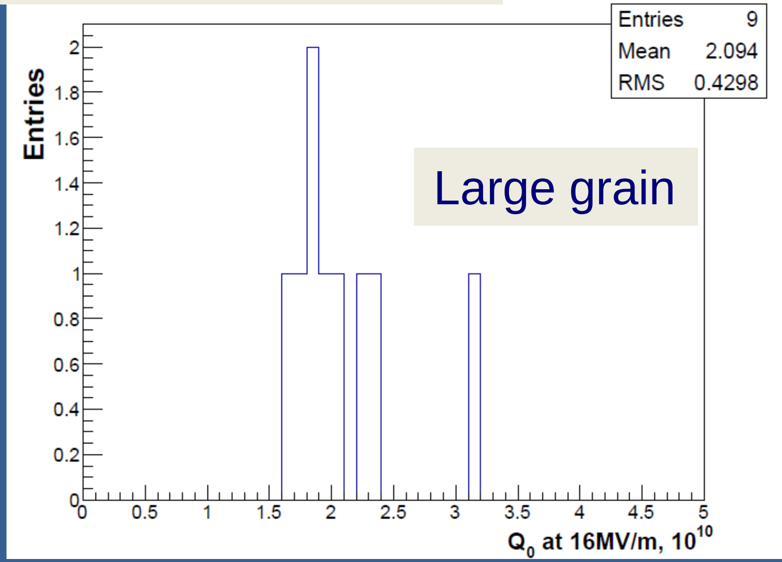
FNAL analysis of DESY data <u>by O. Melnychuk, see TUP100</u>

- DESY data for ILC 9-cells
  - $<Q_0@16$ MV/m$>$=1.9E10 @2K
- DESY LG material, same cavity type
  - $<Q_0@16$ MV/m$>$=2.1E10 @ 2K

- Very small difference between fine- and large-grain material in VT
- 60% lower heat load in CM (LG vs FG) quoted at this workshop consistent with lower trapping efficiency of LG
- BUT, if attention is paid to CM cooldown and shielding (see HZB and Cornell), no clear advantage of large grain vs fine grain
- In summary, <u>LG is just less prone to gain residual (when things are not done right)</u>




Analysis by O. Melnychuk



# 120 C Bake/HF Rinse

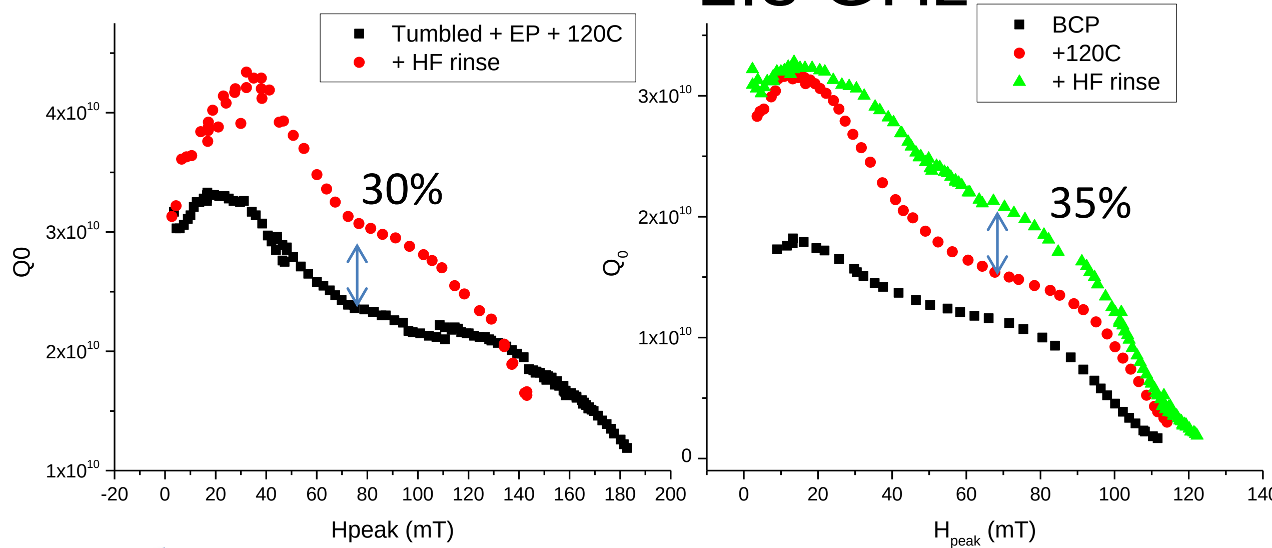
- 4) It is well known that 120 C bake lowers the BCS resistance component. But it also raises the residual resistance.
- 5) Is baking recommended for high Q? Can the lower residual resistance be restored by HF rinsing? How do the answers depend on frequency choice?
  - How does 120 C baking affect the medium field Q-slope?
  - How does HF rinsing affect the medium field Q-slope?

# 120C/HF combination…Alexander

- Is baking recommended for high Q?
  - Depends on the frequency, T, at T=2 K, 1.3 GHz helps marginally, 650 MHz, 325 MHz – does not help, makes worse, e.g. for single spokes (325 MHz) instead of 4 nOhm (unbaked) we get 6-8 nOhm
    - However always helps at 4.2K
  - If combined with the HF rinse – benefits all frequencies
  - For new doping treatment - no
- Can the lower residual resistance be restored by HF rinsing?
  - Yes, 120C baking-induced increase can be negated

**A. Romanenko et al, Phys. Rev. ST Accel. Beams 16, 012001 (2013)**

1.3 GHz




650 MHz cavity results (A. Grassellino)

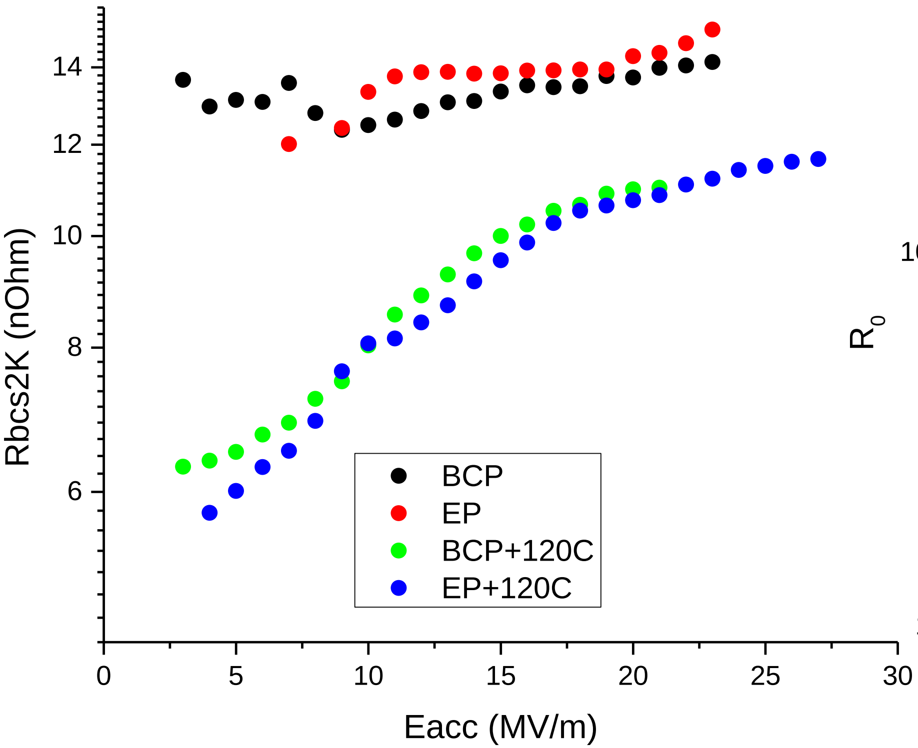
| Treatment( | Low(field( $Q_0$( | Low(field( residual( resistance( [nΩ]( | Low(field( BCS( resistance( [nΩ]( |
|---|---|---|---|
| EP# | 5e10# | ~1.7# | ~3.3# |
| EP+120C# | 5.3e10# | ~3.5# | ~1.5# |
| EP+120C +HF#inse# | 8e10# | ~1.7# | ~1.5# |

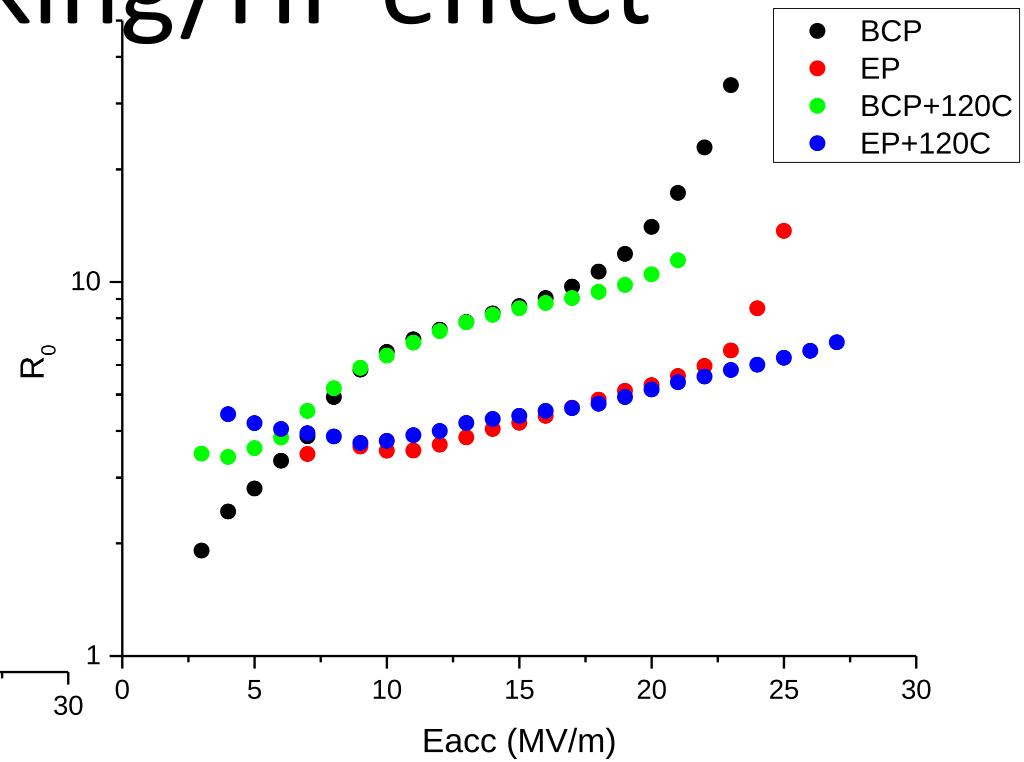
650 MHz

# 120C baking/HF effect

“BCS” resistance

Residual resistance




- How does 120 C baking affect the medium field Q-slope?
  - Increases Rbcs(B) slope
- How does HF rinsing affect the medium field Q-slope?
  - Decreases residual resistance contribution -> makes slope in Rbcs(B) more apparent

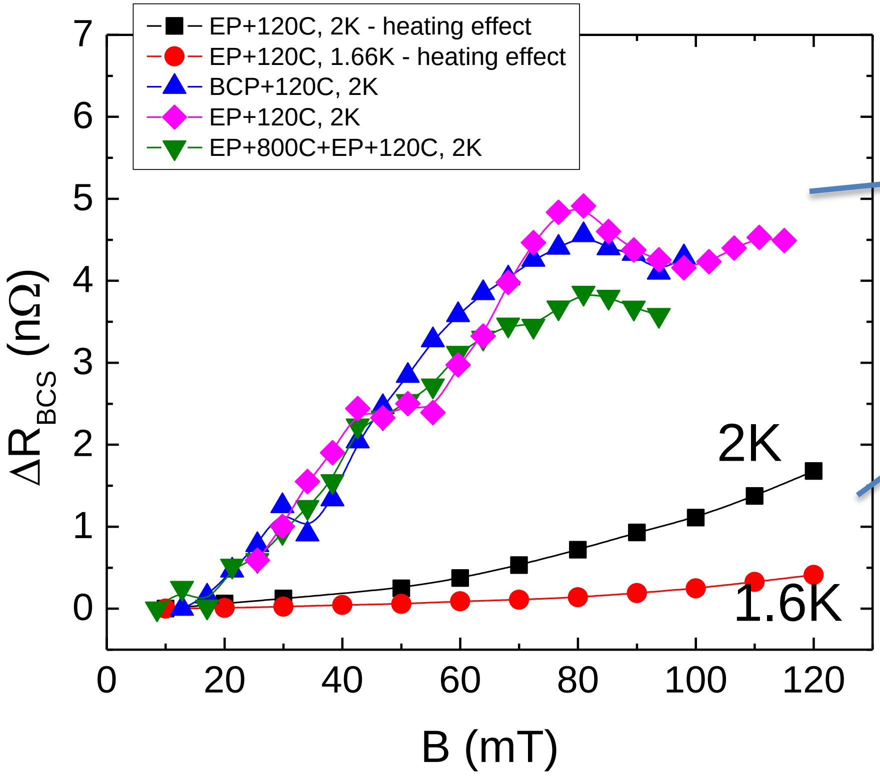
# Medium Field Q-Slope

- 6) What is (are) the cause (s) of the medium field Q-slope (MFQS)?
  - Is it simple a thermal effect
- 7) Which component of the resistance increases with field during MFQS?
  - BCS or residual?

# Role of thermal feedback…Alexander

- What is (are) the cause (s) of the medium field Q-slope (MFQS)? Is it simply a thermal effect, i.e. the RF surface temperature rises, so the BCS resistance increases, which continues in a feedback loop?
  - NO

ΔRbcs = Rbcs(Trf) – Rbcs(Tbath) – "thermal feedback"




This is what we see in 1.3 GHz cavities

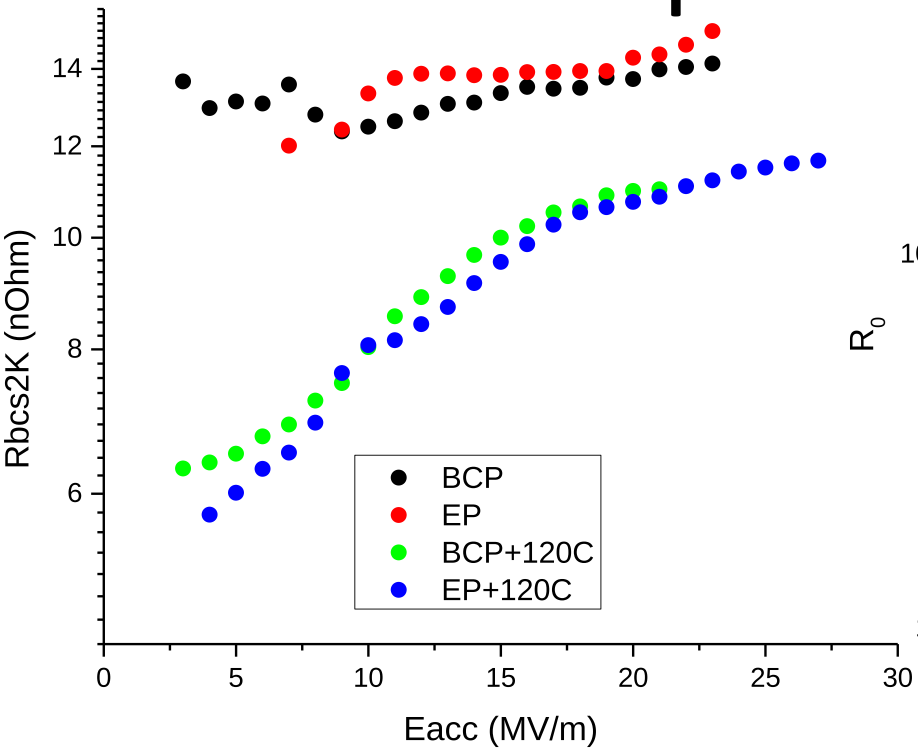
This is how much thermal feedback can provide (worst case scenario – based on the temperature mapping results - hottest spot taken)

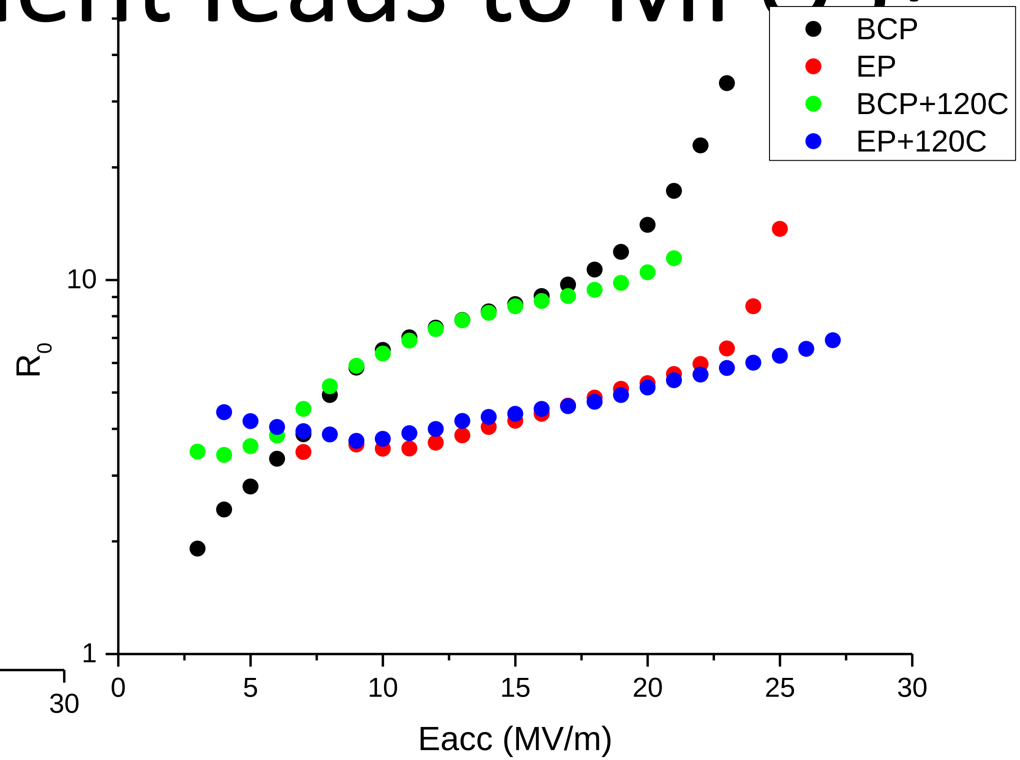
Negligible effect on $R_{BCS}$ at T <= 2K

“BCS” resistance

Residual resistance

# Which component leads to MFQS?



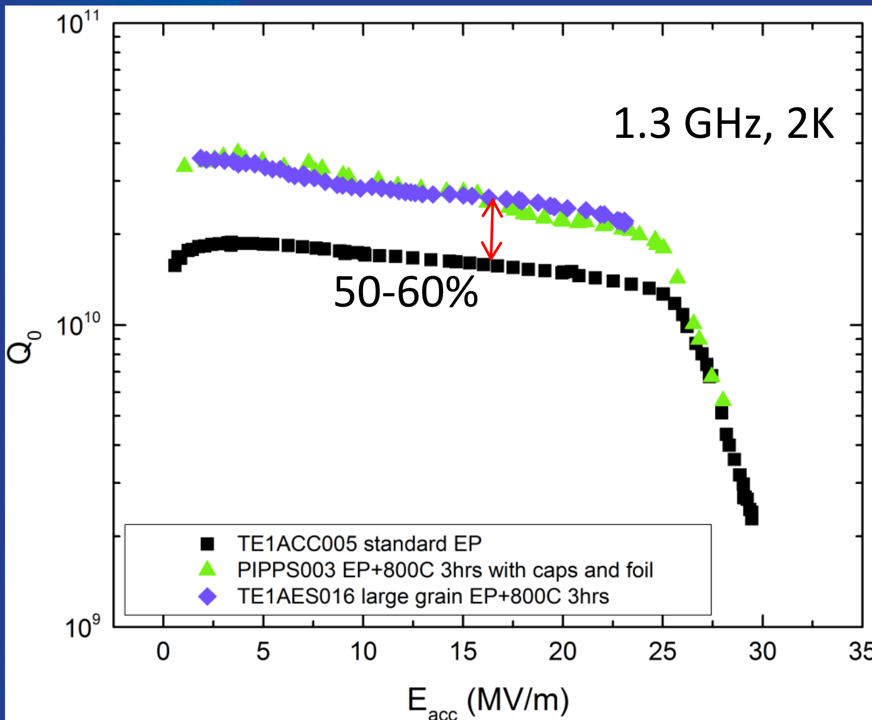

- Which component of the resistance increases with field during MFQS, the temperature independent part (residual) or the temperature dependent part (the BCS part?)
  - In cavities without 120C bake – primarily residual
  - With 120C bake - both

# High Temperatures and New Treatments

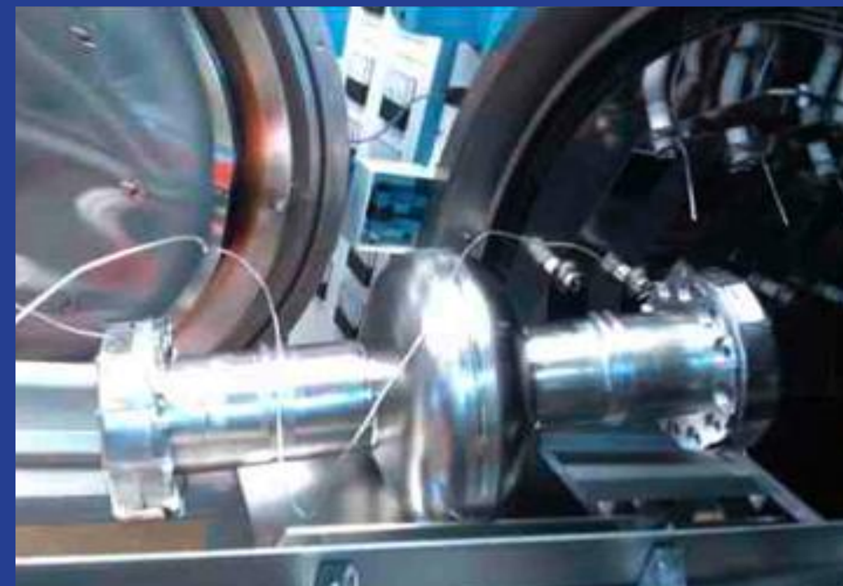
- 8) Does higher temperature (800 C and above) annealing raise Q ?
- 9) Are there any new treatments that give higher than standard BCS Q?
- Include promising results from new materials such as Nb3Sn.

# ANNA 8) Does higher temperature (800 C and above) annealing raise Q ?

*Yes, if annealing is the last processing step*



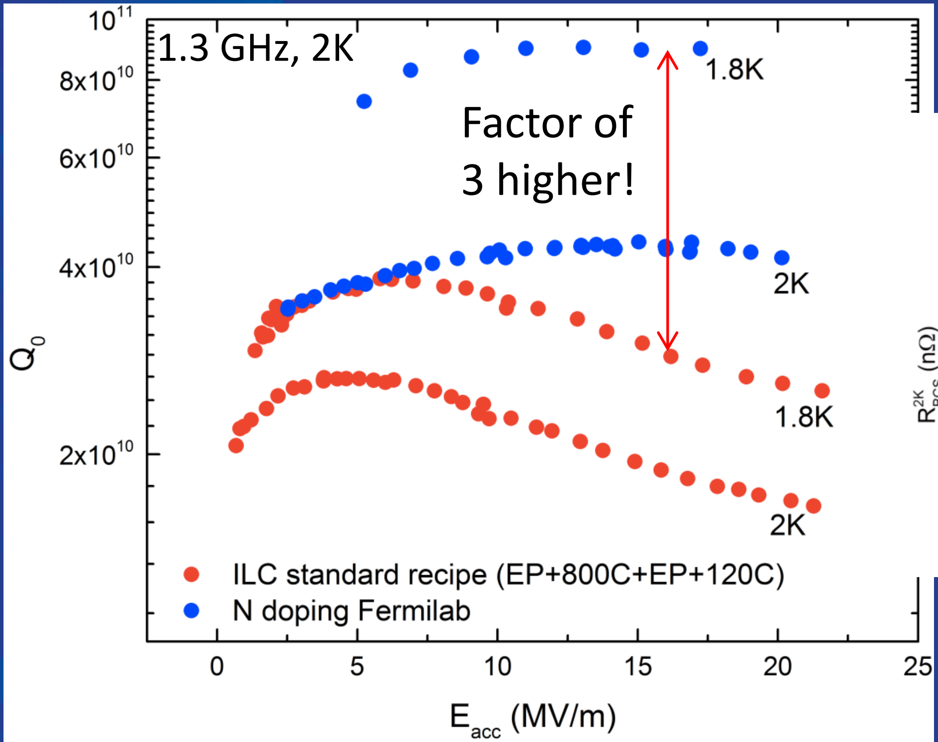

A.Grassellino et al, http://arxiv.org/abs/1305.2182

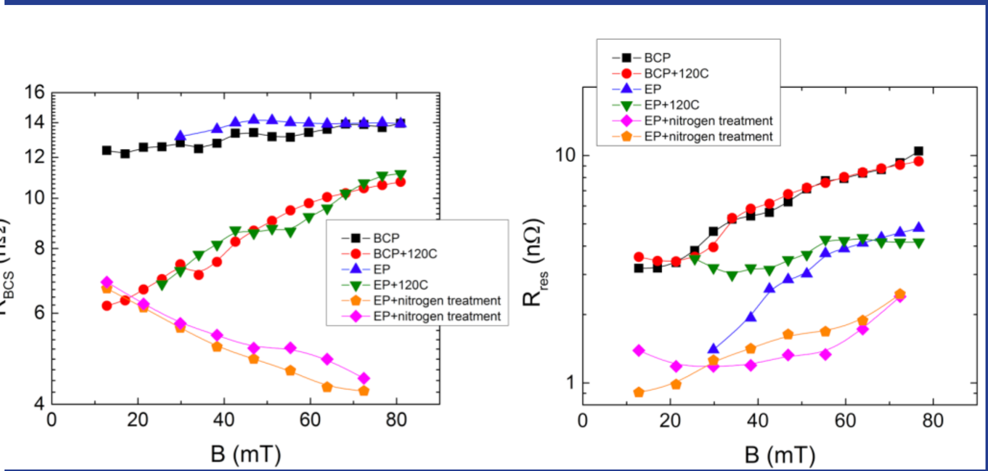


- *EP + 800C 2 hrs + 20 micron EP + C* → *higher Q*
- *Systematically low $R_0$ ~ 1nΩ, $R_{BCS}$ of a mild baked cavity (more room T venting studies needed)*
- *Extra cost savings from skipping the post furnace chemical processing*

# 9) Are there any new treatments that give higher than standard BCS Q?

*Yes, the bake in nitrogen or argon*




**A.Grassellino et al, 2013 *Supercond. Sci. Technol.* 26 102001**

- *Total surface resistance of 3 nΩ @ 17 MV/m, 1.3 GHz, 1.8K*
- *Rbcs ~ 4 nΩ @ 2K and 1.5 nΩ @ 17 MV/m, 1.3 GHz*
- *Compare to std Rbcs ~ 9 nΩ @ 2K and ~ 4-5 nΩ @ 1.8K*
- *Currently, best treatment for reproducible high Q at mid field at 1.3 GHz (and 650 MHz too, see TUP050)*

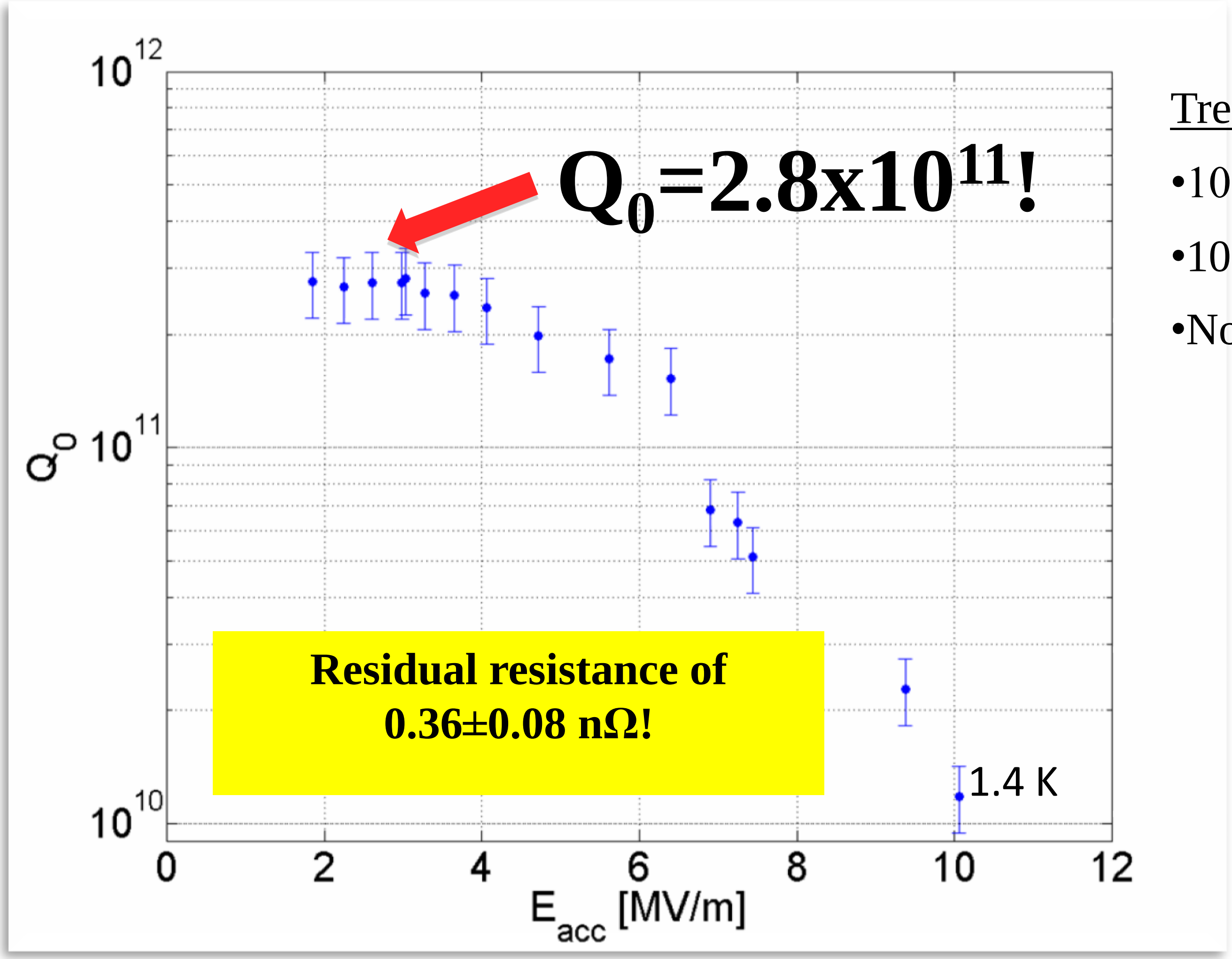
# Liepe: Message 1

High temperature heat treatments can do good things:

- Low residual resistance (sometimes)
- High $T_c$ / large energy gap
- Small mean free path

Bake in low pressure $N_2$ atmosphere might help to optimize BCS parameters.

# Example 1: Long 1000 C Heat Treatment

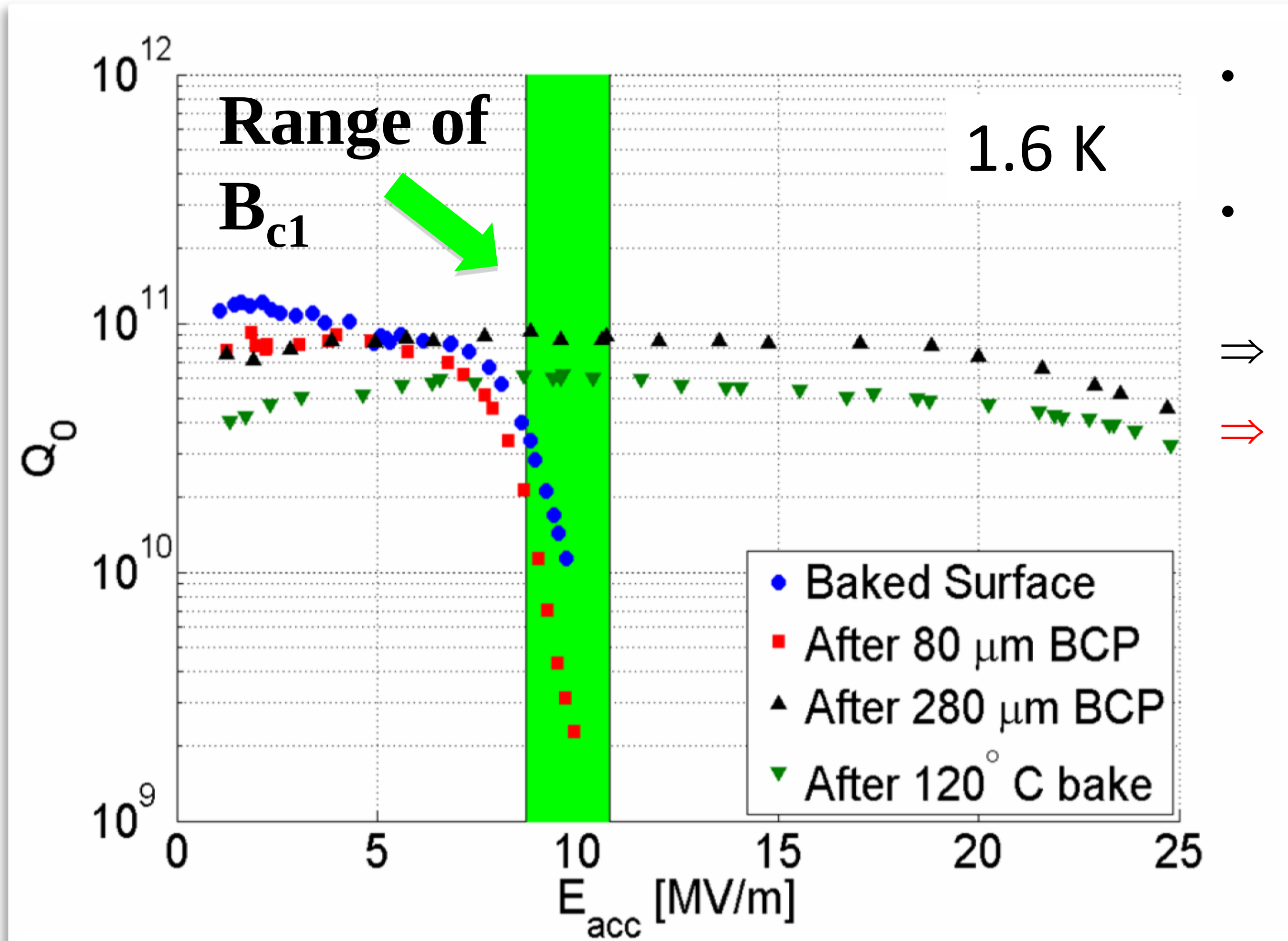



Treatment:

- 100 µm bulk BCP
- 1000°C for 5 days
- No additional chemistry

More details: See Daniel Gonnella's poster TUP027

# After additional Chemistry




- Anti-Q-slope up to 10 MV/m
- Operation well above $B_{c1}$ with very high Q0

⇒ no vortex entry

⇒ $B_{c1}$ is not a fundamental limit for SRF !!

More details: See Daniel Gonnella's poster TUP027

# Material Parameters

| Property | 1000° C Bake | 80 µm BCP | 280 µm Total BCP | 120° C Bake |
|---|---|---|---|---|
| $T_C$ [K] | 9.3 ± 0.9 | 9.3 ± 0.9 | 9.3 ± 0.9 | **9.5 ± 0.9** |
| $\Delta/k_B T_C$ | 1.78 ± 0.02 | 1.78 ± 0.02 | 1.79 ± 0.1 | **1.96 ± 0.2** |
| $\ell$ [nm] | 8 ± 2 | 8 ± 2 | 7 ± 2 | 6 ± 2 |
| $R_{res}$ [nΩ] | **0.36 ± 0.08** | **1.2 ± 0.3** | **1.3 ± 0.3** | 5 ± 1.2 |
| $\kappa_{GL}$ | 7 ± 1 | 7 ± 1 | 8 ± 1 | 10 ± 2 |
| $B_{c1}$ [mT] | 45 ± 14 | 44 ± 14 | 42 ± 15 | 36 ± 16 |

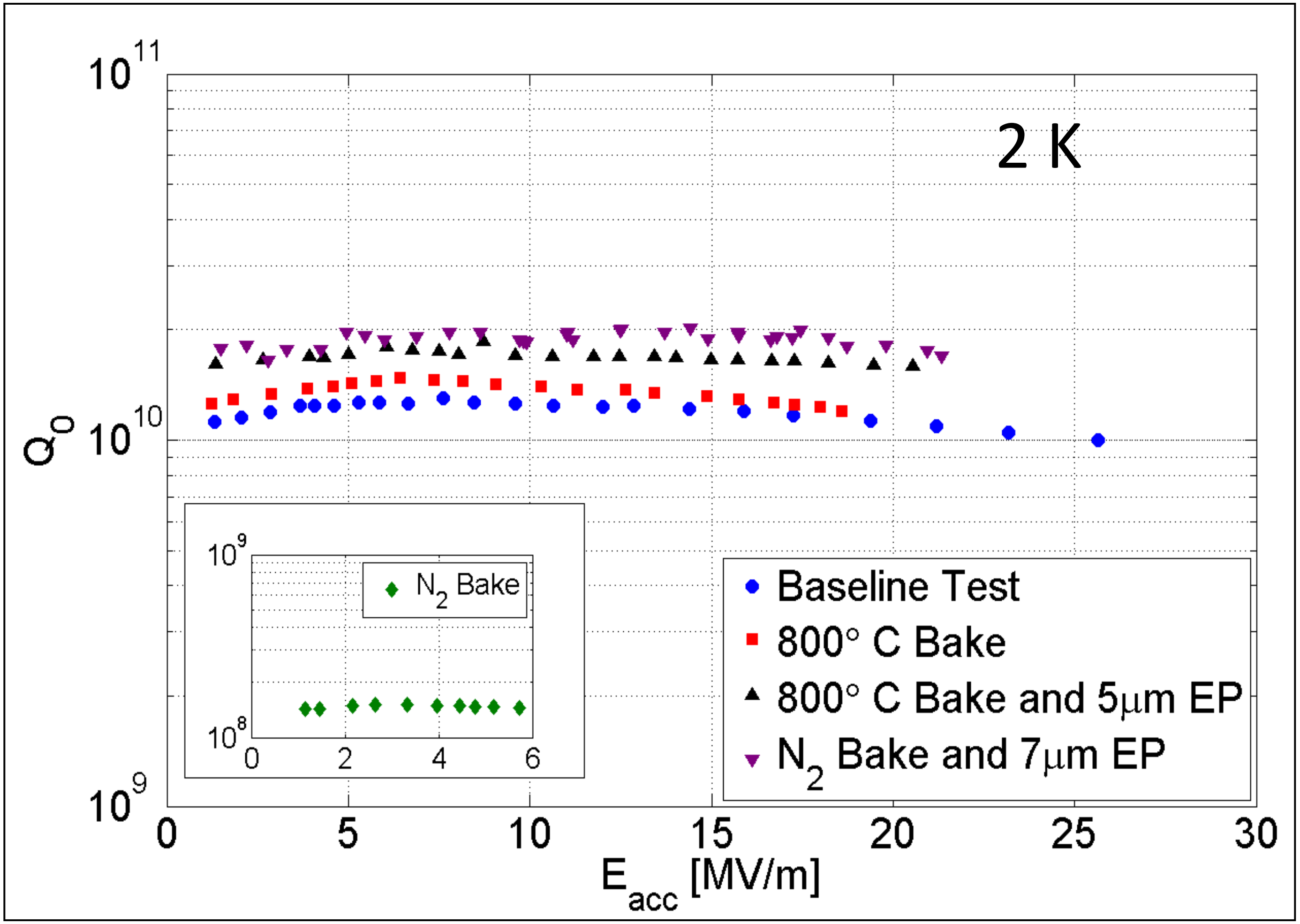
⇒ Low residual resistance

⇒ Small mean free path

⇒ 120C bake increased energy gap

More details: See Daniel Gonnella's poster TUP027

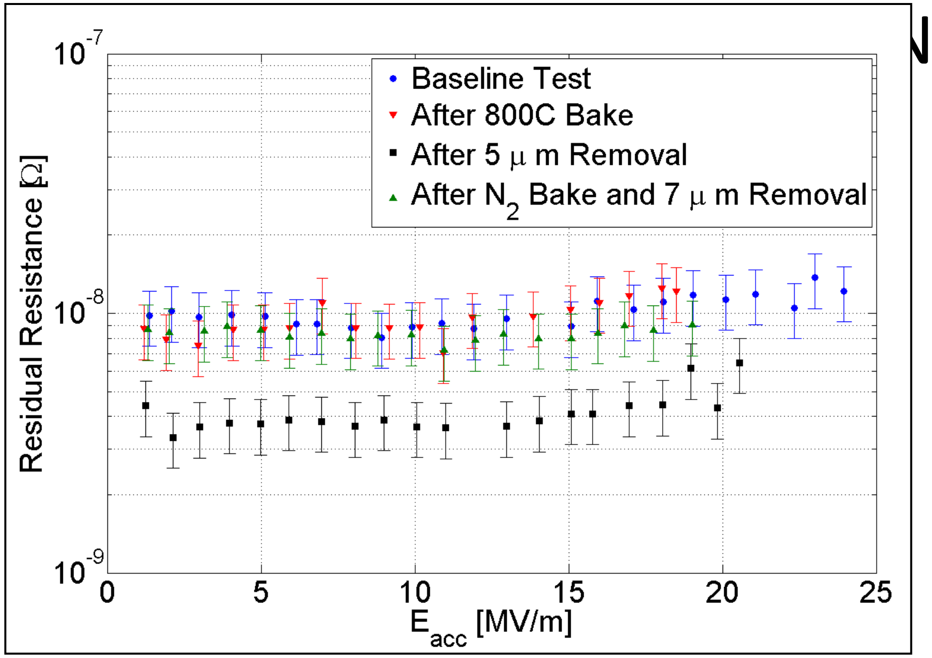
# Example 2: 800 C Heat Treatments with and without

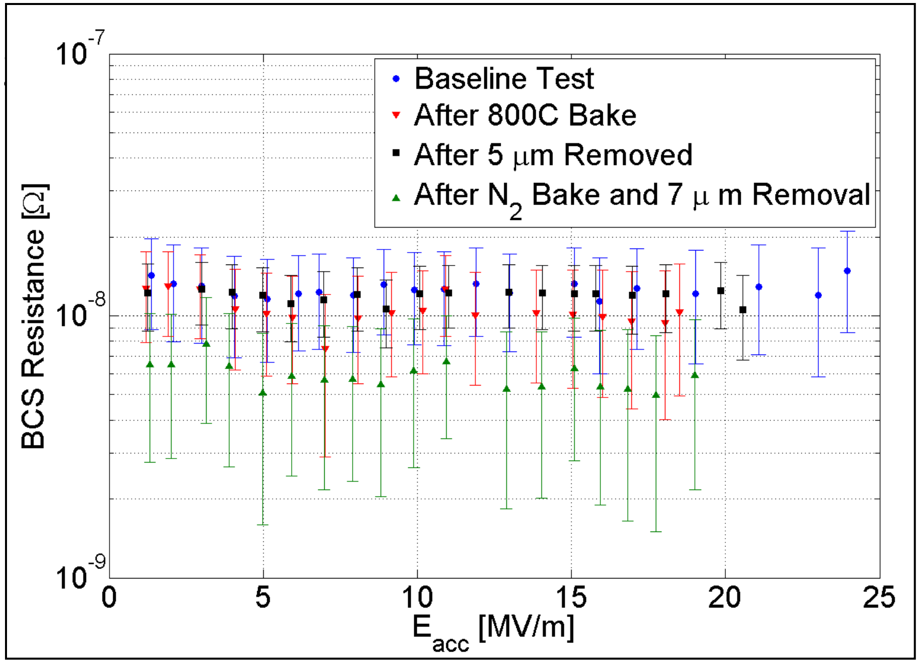



- N2 bake: 800C for 3 hours + 10 min with $10^{-2}$ torr $N_2$
- No strong field dependence up to 20 MV/m

More details: See Daniel Gonnella's poster TUP029

# 800 C Heat Treatments with and without low Pressure




- **$N_2$ treatment significantly lowered BCS resistance**

More details: See Daniel Gonnella's poster TUP029

# Material Parameters

| Property | 100 µm EP | 800C | 800C+ 5 µm EP | $N_2$ Treatment + 7 µm EP |
|---|---|---|---|---|
| $T_C$ [K] | 9.2 ± 0.9 | 9.1 ± 0.9 | 9.1 ± 0.9 | **9.2 ± 0.9** |
| $\Delta/k_BT_C$ | 1.75 ± 0.02 | **2.08 ± 0.03** | **1.97 ± 0.03** | **2.01 ± 0.02** |
| $\ell$ [nm] | 14 ± 4 | 2.4 ± 4 | 3.1 ± 0.9 | **5 ± 1** |
| $R_{res}$ [nΩ] | 9 ± 2 | 12 ± 3 | 4 ± 1 | 9 ± 2 |
| $\kappa_{GL}$ | 5.0 ± 0.8 | 22 ± 5 | 17 ± 5 | 11 ± 2 |
| $B_{c1}$ [mT] | 58 ± 12 | 22 ± 19 | 26 ± 18 | 34 ± 16 |

- **$N_2$ treatment improved BCS parameters for high $Q_0$**

More details: See Daniel Gonnella's poster TUP029

# Does higher temperature raise Q ? JLAB - Pushpati

Recent test on cavities heat treated in the temperature range 800-1600C showed the dramatic improvement in $Q_0$ mostly due to the reduction of residual resistance and enhanced gap.

Paper TUIOC04, SRF 13
PRSTAB, 16, 042001 (2013)
SUST 23, 102001 (2013)

In 70-80’s high Q cavities were heat treated the temperature much higher than 800 C.

With a proper furnace, chemistry after the high temperature heat treatment is not necessary.

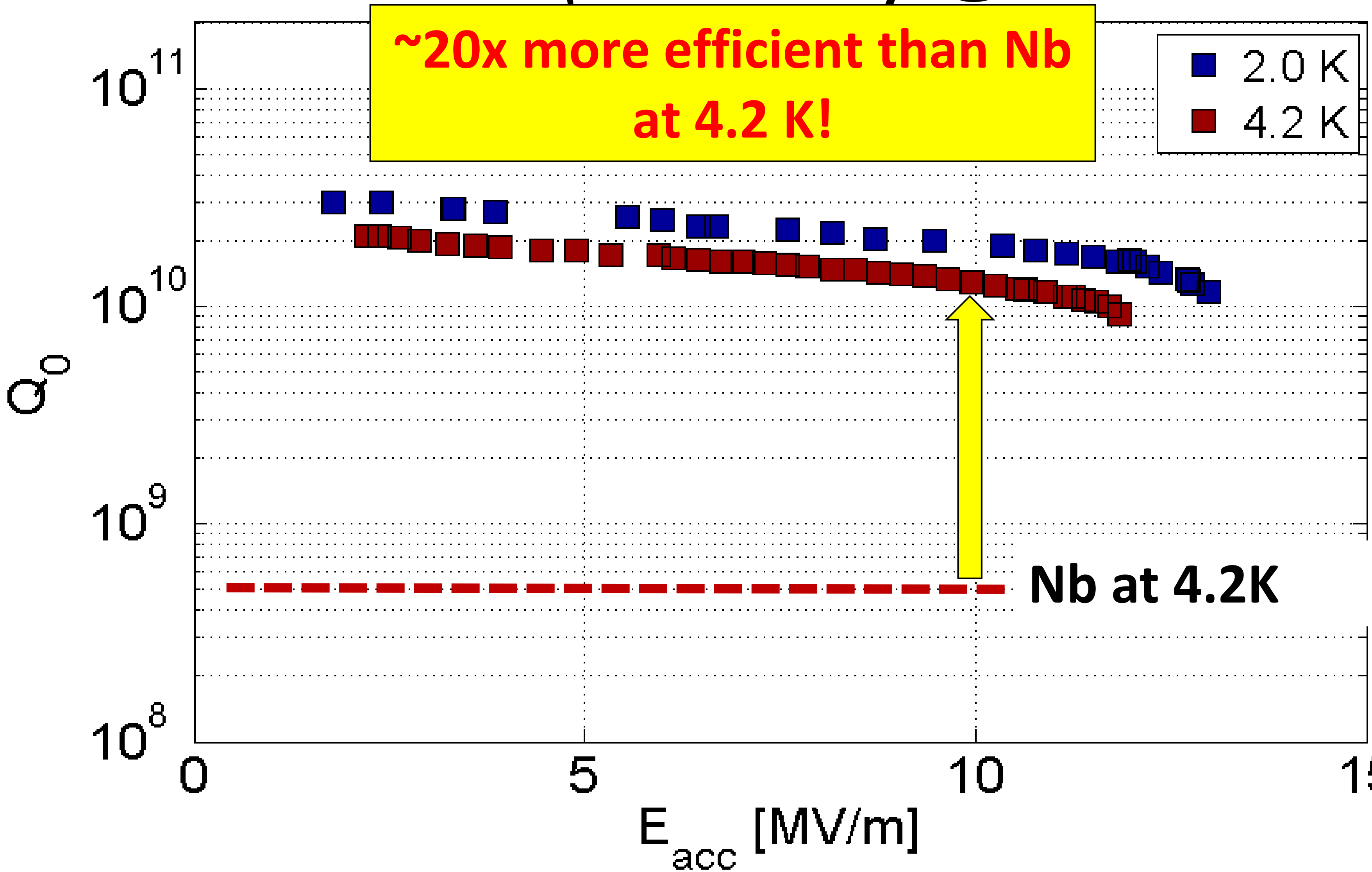
Low temperature baking may not be necessary for the medium field Q, since it tend to increase the residual resistance.

# Message 2

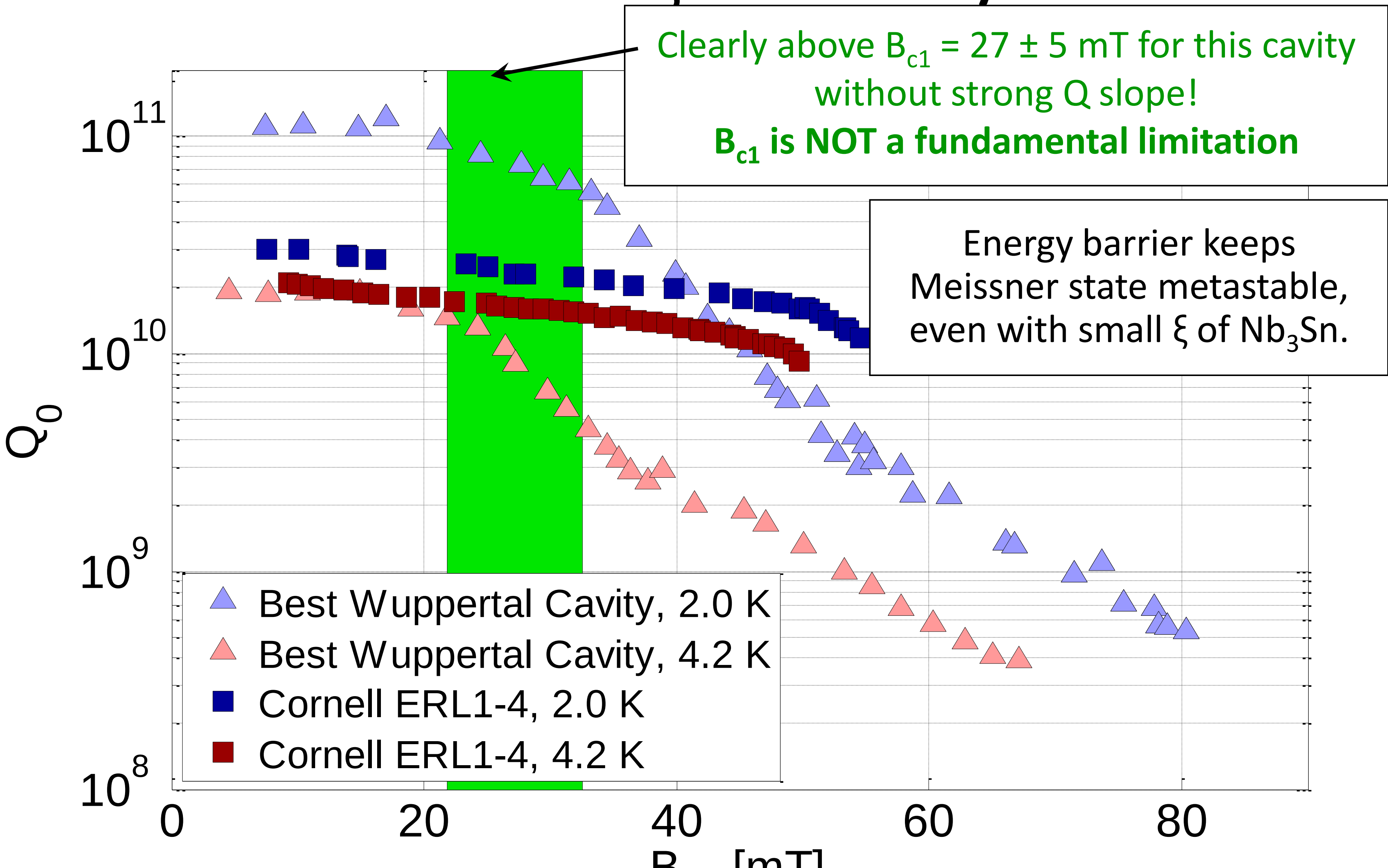
Alternative materials have greatest potential for high $Q_0$

**Sam's $Nb_3Sn$ cavity is the first accelerator cavity made with an alternative superconductor that outperforms Nb at usable gradients!**

# 1.3 GHz $Nb_3Sn$ Cavity @ Cornell



# Sam's $Nb_3Sn$ Cavity




More details: See Sam Posen's poster TUP087

# Preserving the Q in the CM

- 10) What are the precautions/procedures to maintain higher Q's from vertical test to cryomodule? DC magnetic field shielding, avoiding flux trapping due to thermo currents etc.

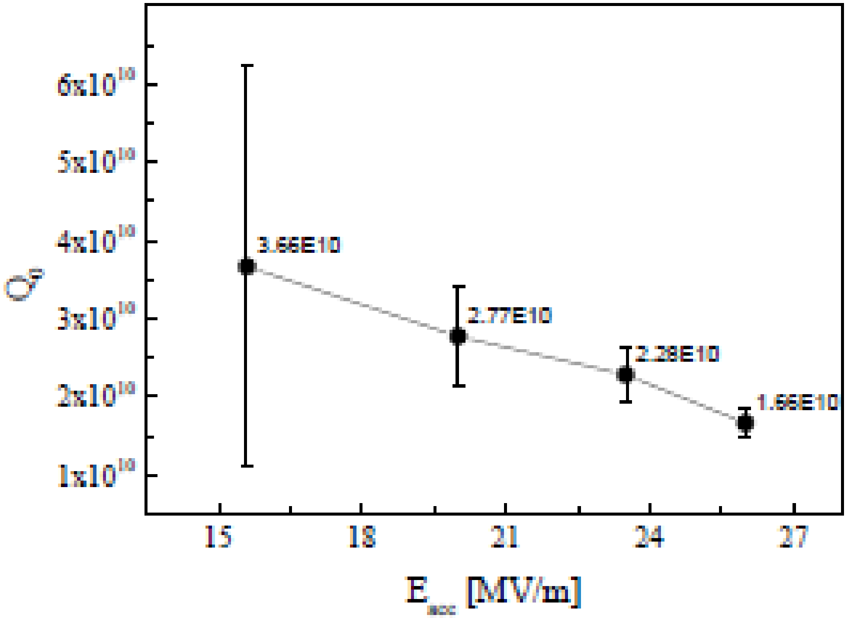
# precautions/procedures to maintain higher Q's from vertical test to cryomodule



- Clean Room assembly of the cavity parts. Mounting of the string in the clean room. Using the main coupler with two RF windows to allow the clean coupler installation on the cavity.
- Clean UHV conditions
- Using the cavity magnetic field shield (μ-metal). The shield is mounted on the LHe tank and provides enough shielding to keep the vertical test results within measurement error margins.

Module XM-3 data:

(pulsed; 2K)



# JULIA - THREE WAYS TO GET THE MOST OUT OF YOUR CAVITY…

Residual losses are often dominated by trapped flux

We know of three ways to reduce this:

1) Minimize the pinning centers , i.e. don’t give the magnetic flux a chance to get trapped.
2) Provide conditions for the magnetic flux to leave the material.
3) Don’t generate new flux by avoiding temperature gradients.

# 1) MINIMIZE THE PINNING CENTERS

| # | Crystal structure | Treatment | Fraction of trapped flux |
|---|---|---|---|
| 1 | Polycrystalline | None | 100% |
| 2 | Polycrystalline | BCP | 100% |
| 3 | Polycrystalline | BCP + 800°C bake out | (83.1 ± 0.8)% |
| 4 | Single crystal | BCP | [(72.9 + 0.1 lnv) ± 0.8]% |
| 5 | Single crystal | BCP + 800°C bake out | [(61.6 + 1.3 lnv) ± 0.8]% |
| 6 | Single crystal | BCP + 1200°C bake out | [(42.1 + 0.13 lnv) ± 0.6]% |

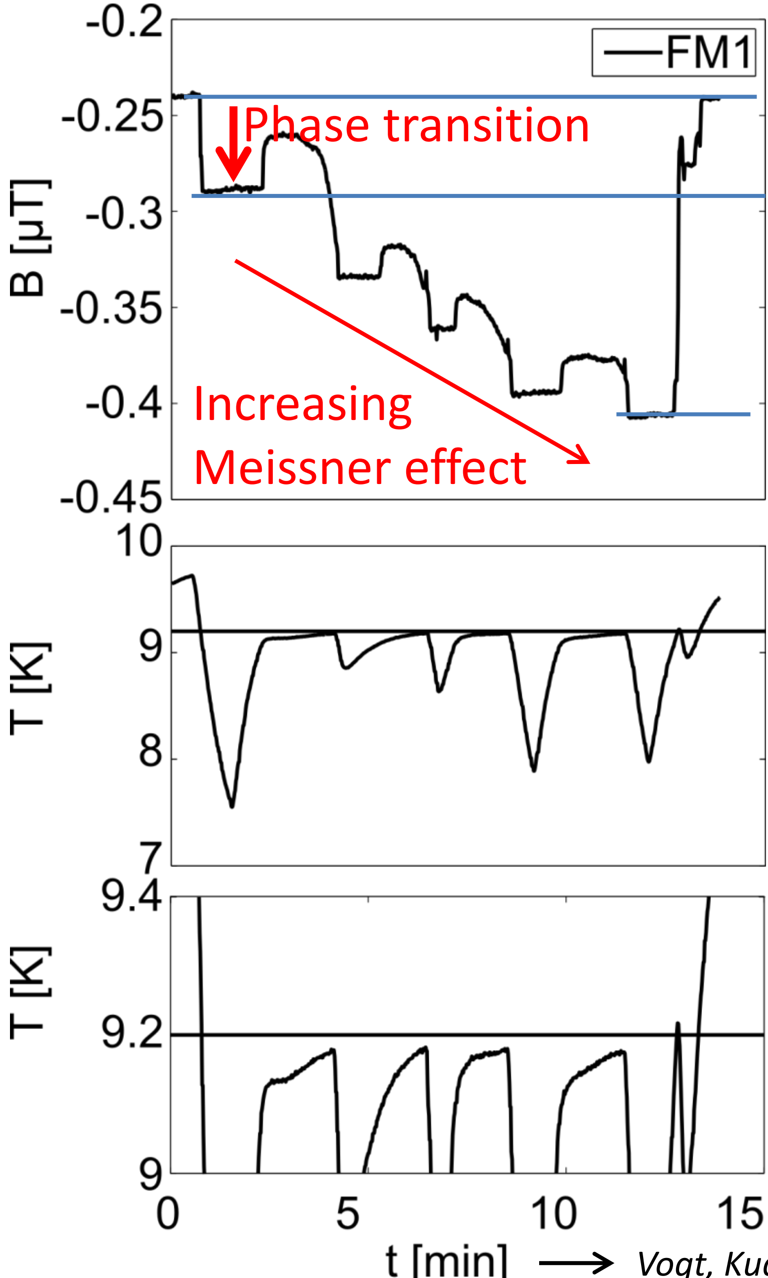
→ *Aull, Kugeler and Knobloch, PRSTAB 15, 062001 (2012)*

depends on cooling rate $v = \Delta T/\Delta t$

**Consistant with results that Q's of large grain cavities are greater.**
**For example W. Singer, MOIOA03: "Large grain cavities on average have 60% higher Q"**

→ **Use large grain and heat treated material!**

# 2) PROVIDE CONDITIONS FOR THE MAGNETIC FLUX TO LEAVE THE MATERIAL

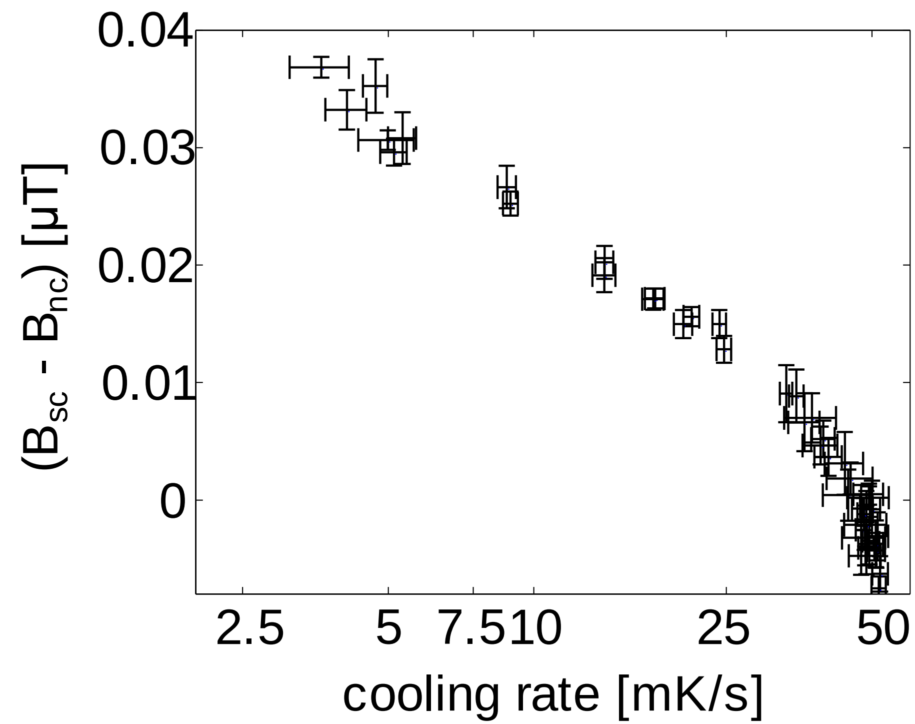



Level ambient field

Initially expelled flux: ΔB ≈ 50nT

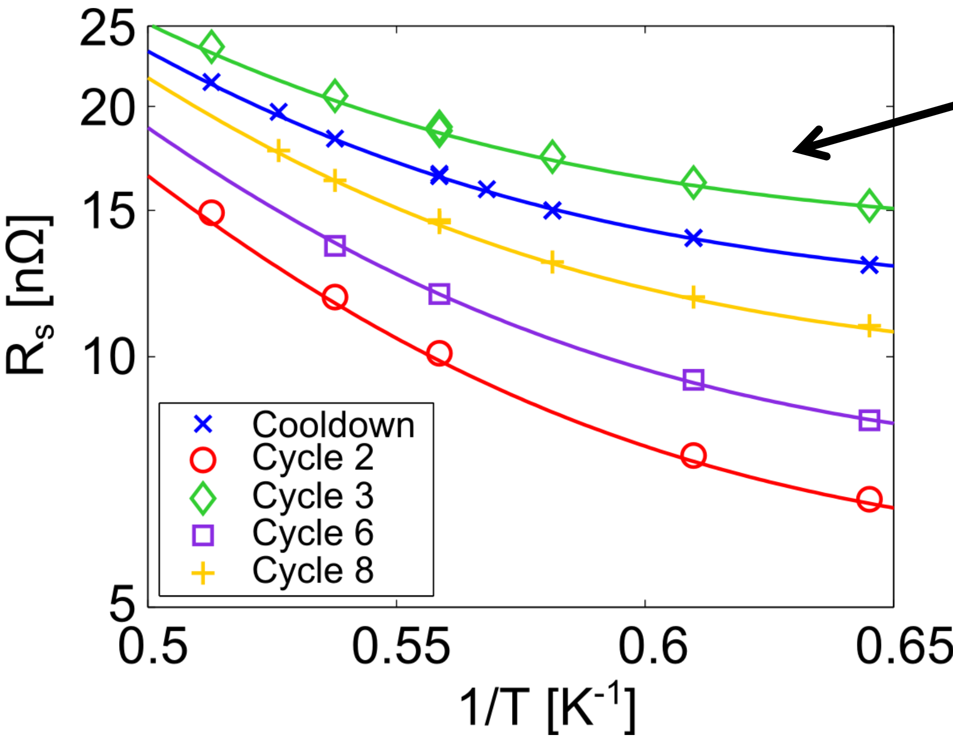
4 × more flux expelled

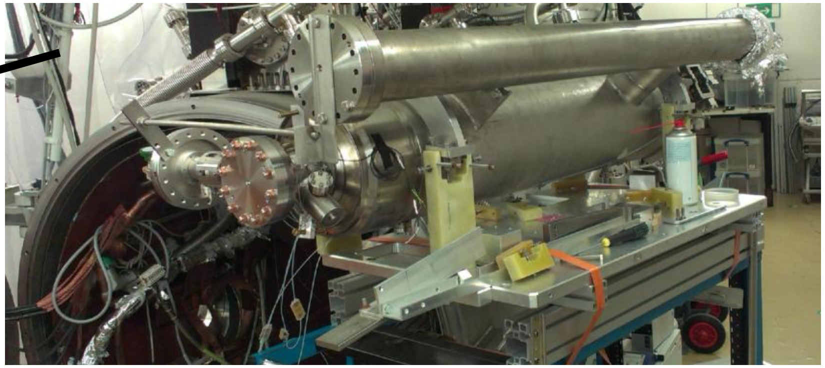
**Cool slowly through the phase transition**

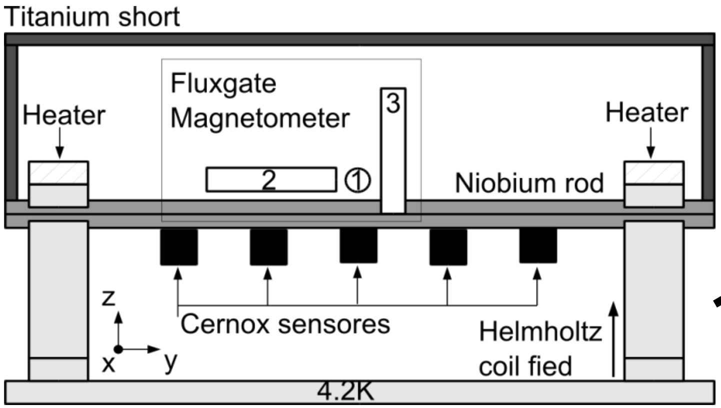


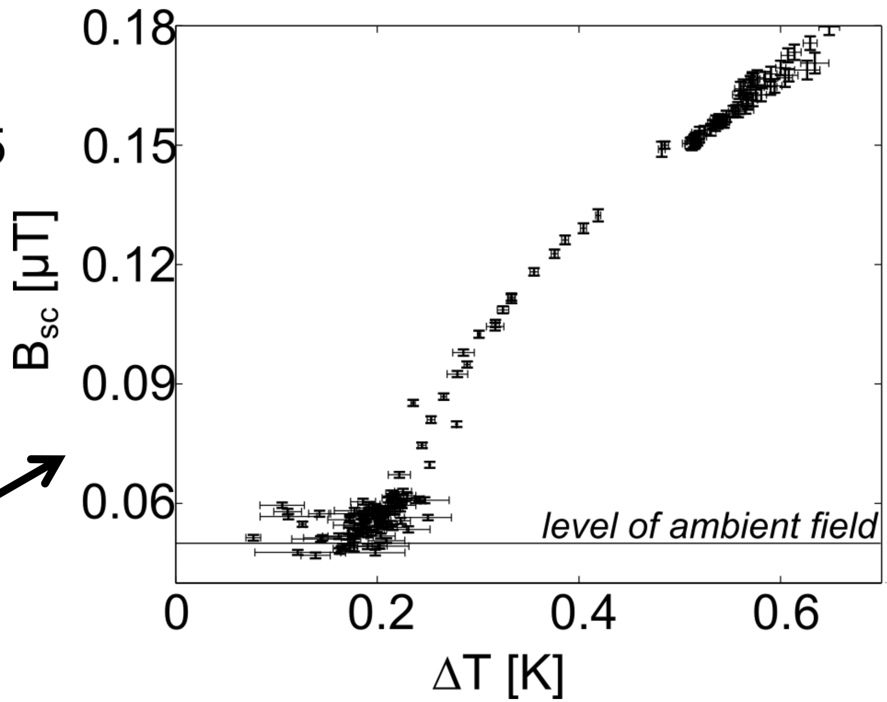

*Vogt, Kugeler and Knobloch, IPAC2013, WEPWO004*

# 3) AVOID GENERATION OF FLUX



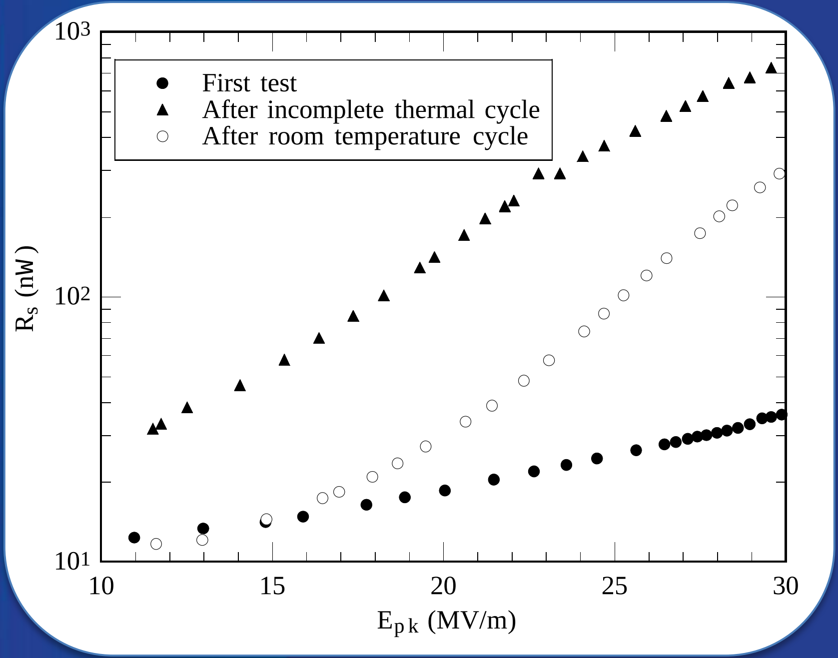



→ **Avoid temperature gradients!**

# Anna: What are the precautions/procedures to maintain higher Q's from vertical test to cryomodule?

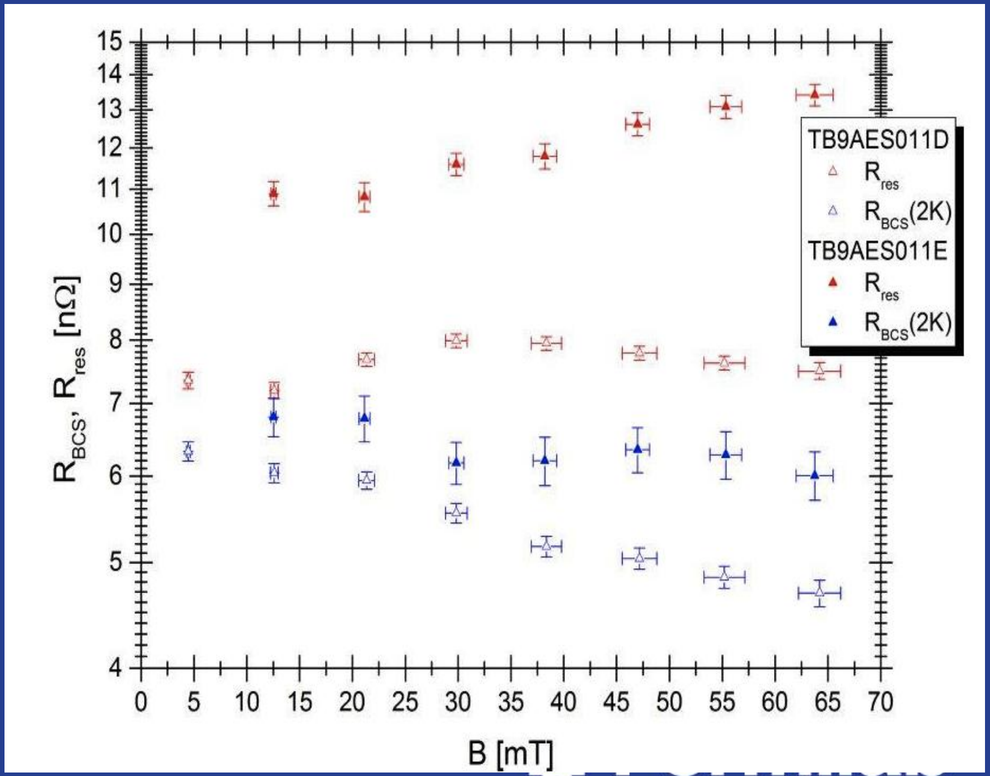
## Prevention of hydrogen reabsorption post furnace treatment is crucial




Knobloch and Padamsee, 8th Workshop on RF Superconductivity, Padova, Italy. SRF 981012-12

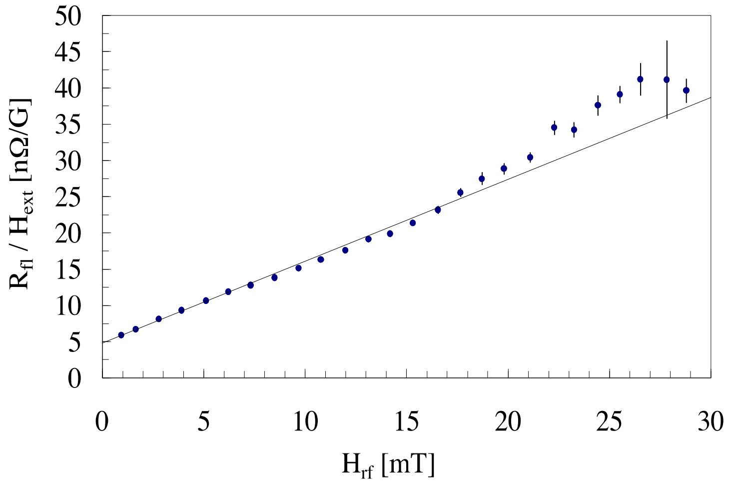
Cavities with some amount of hydrogen worsen at second cooldown

M. Checchin and A. Grassellino, to be published



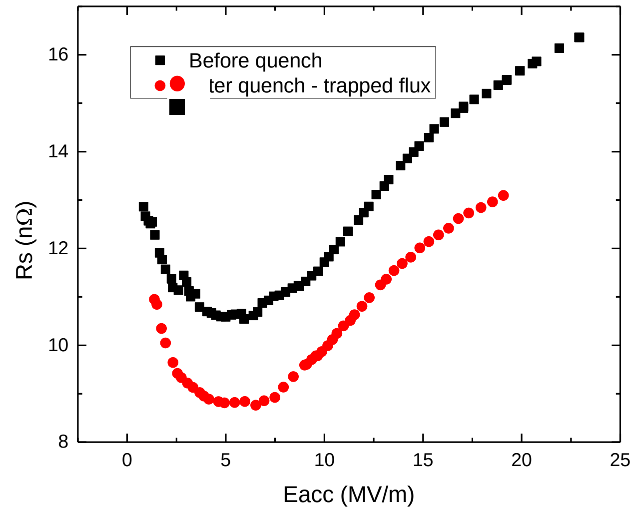
# What are the precautions/procedures to maintain higher Q's from vertical test to cryomodule?

Shielding and cooldown are crucial: R0 due to trapped flux worsens at operating gradient

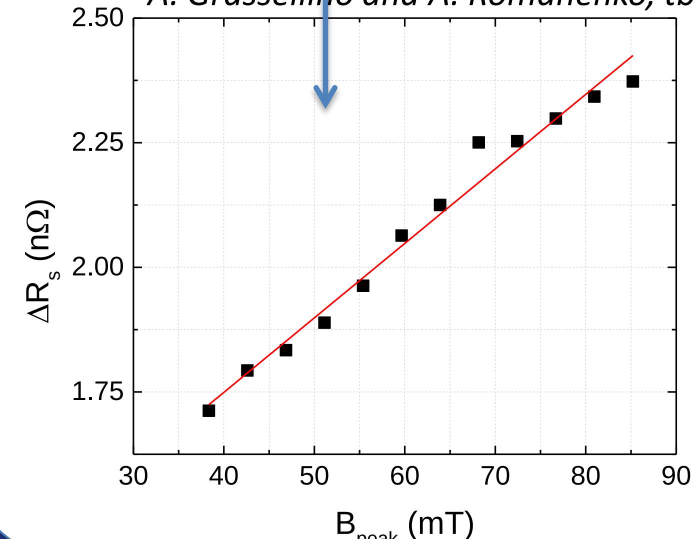



Benvenuti, Calatroni et al, Proceedings of the 1997 Workshop on RF Superconductivity, Abano Terme (Padova), Italy

U.S. DEPARTMENT OF ENERGY

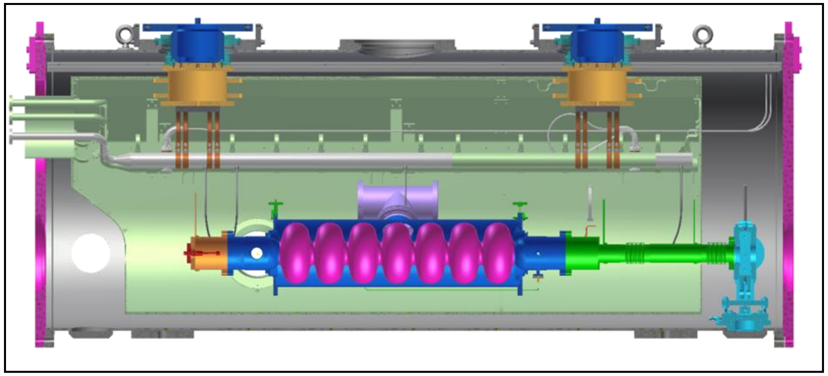


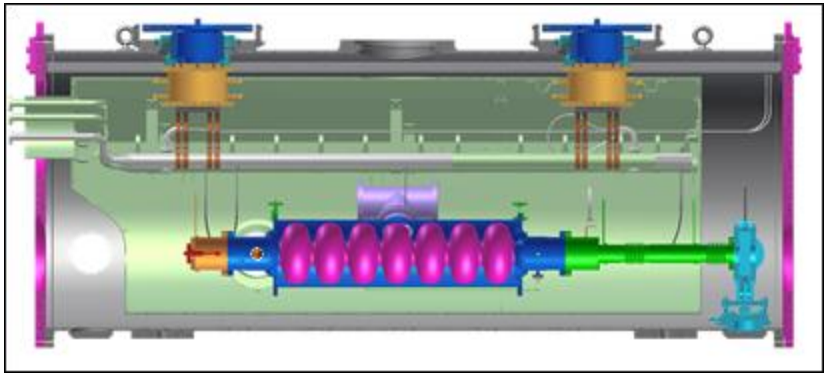

*A. Grassellino and A. Romanenko, tbp*

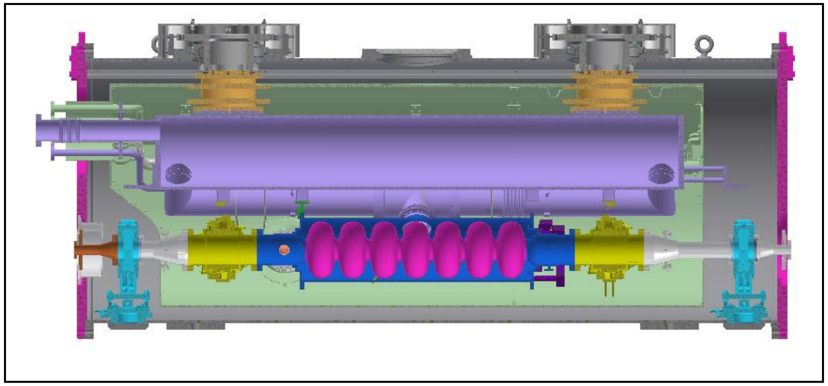


# Mathias - Cornell Record-High $Q_0$ in Cryomodule

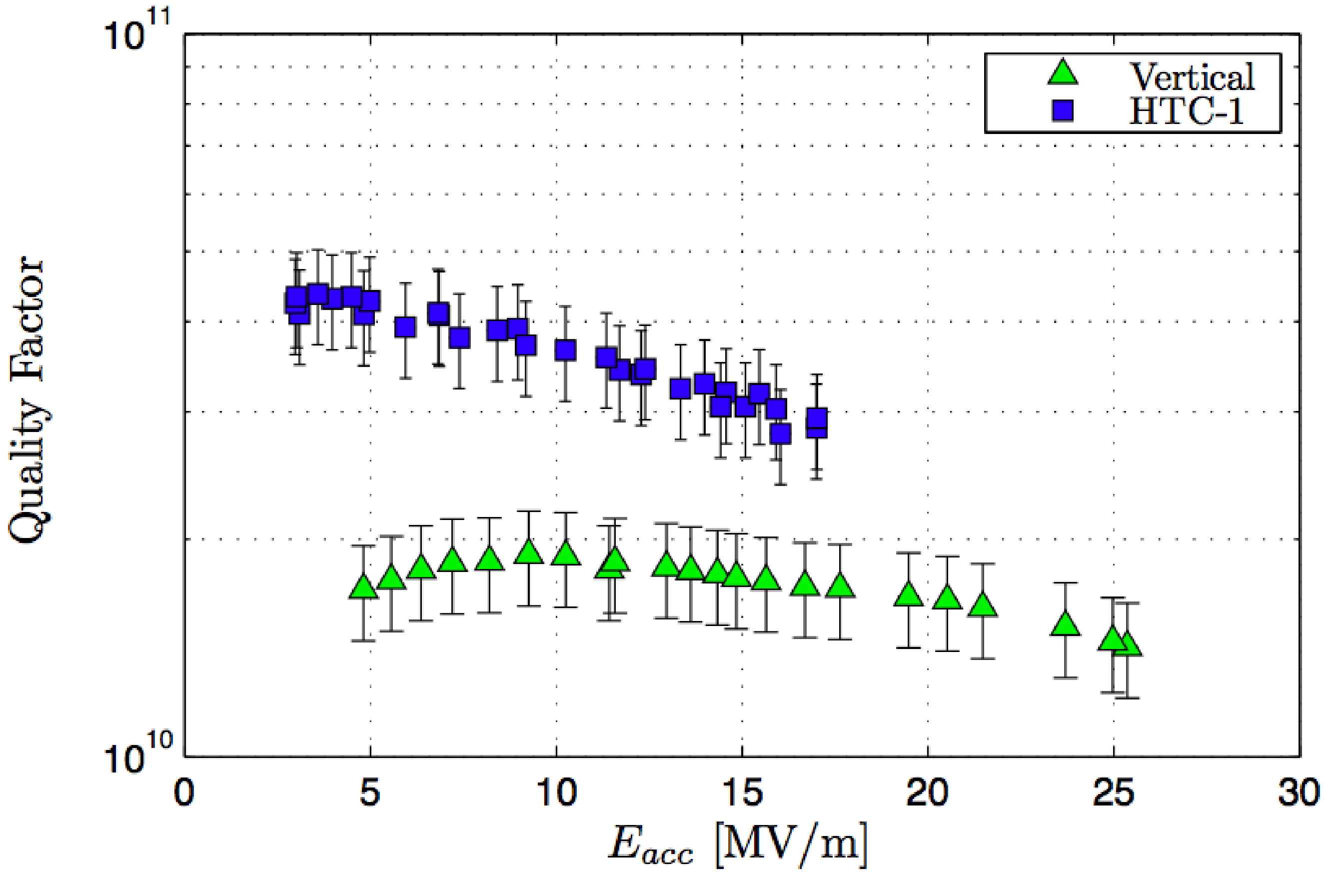
- HTC-1: Follow vertical assembly procedure as closely as possible
- HTC-2: Include side mounted, **high power RF input coupler**
- HTC-3: Full cryomodule assembly-high power RF input coupler and **beam line HOM loads**





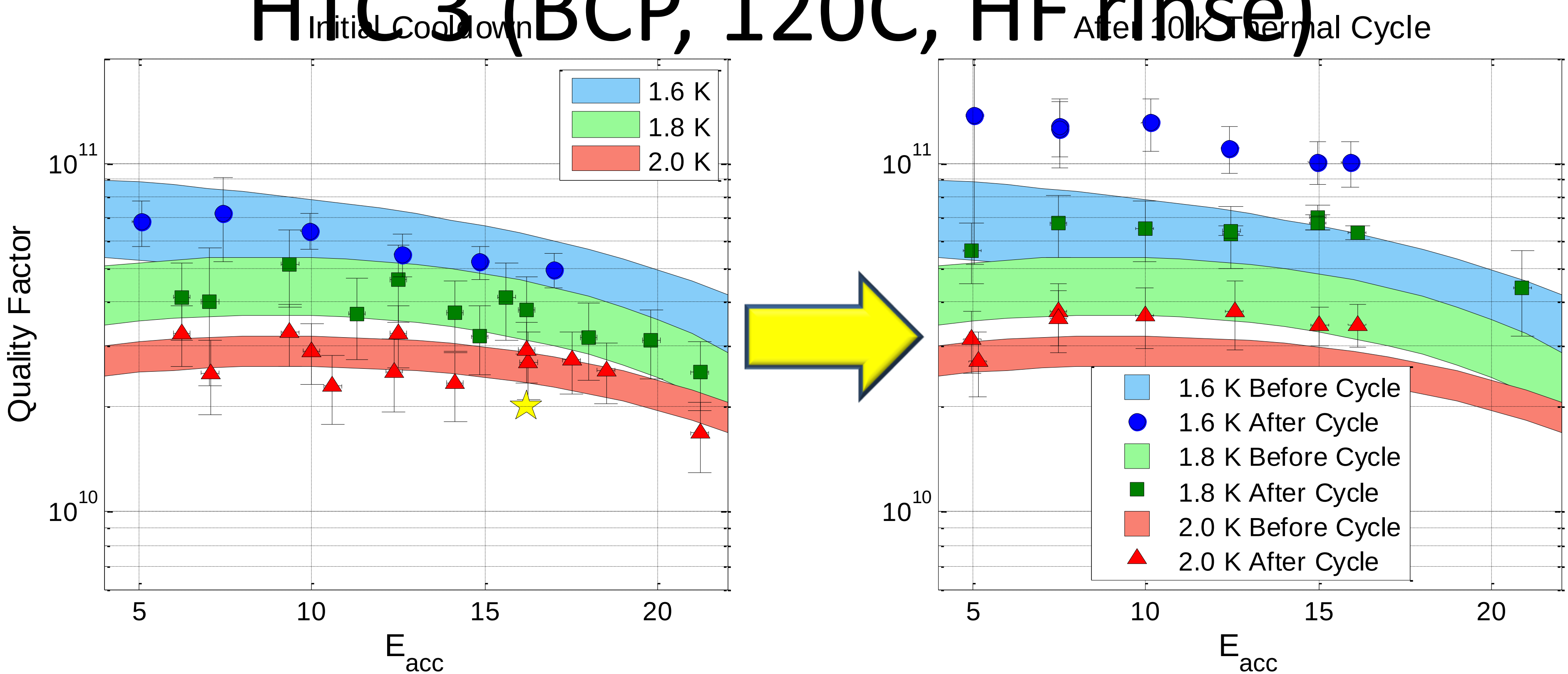


# HTC 1 (@1.8K)




- **Higher $Q_0$ in cryomodule than in vertical test!**
- Difference: residual resistance

# HTC 3 (BCP, 120C, HF rinse)




**Initial Cooldown at 16.2 MV/m**

Q(2.0 K) = 2.5 x $10^{10}$

Q(1.8 K) = 3.5 x $10^{10}$

Q(1.6 K) = 5.0 x $10^{10}$

**10 K thermal cycle at 16.2 MV/m**

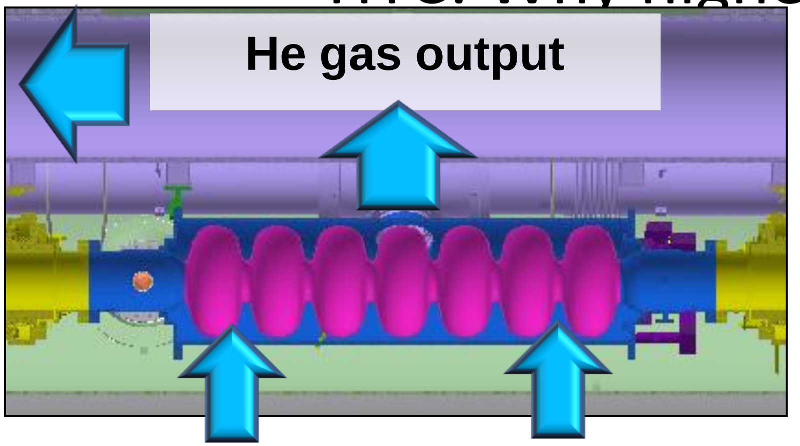
**Q(2.0 K) = 3.5 x $10^{10}$**

**Q(1.8 K) = 6.0 x $10^{10}$**

**Q(1.6 K) = 10.0 x $10^{10}$**

More details: See Nick Valles' poster MOP071 and Ralf's talk on Friday
HZB thermal cycling work: TUIOA01

# HTC: Why higher $Q_0$ than in Vertical Test?




- Excellent magnetic shielding (two layers)
- Very small thermal gradients across cavity during cool down
  - Cavity temperature gradient ~0.2 K
  - Cool down rate through $T_c$: ~ 0.4 K/hr

6 Cernox temperature sensors mounted on top and bottom of end cells and center cell