High Field Q-slope: possible mechanisms

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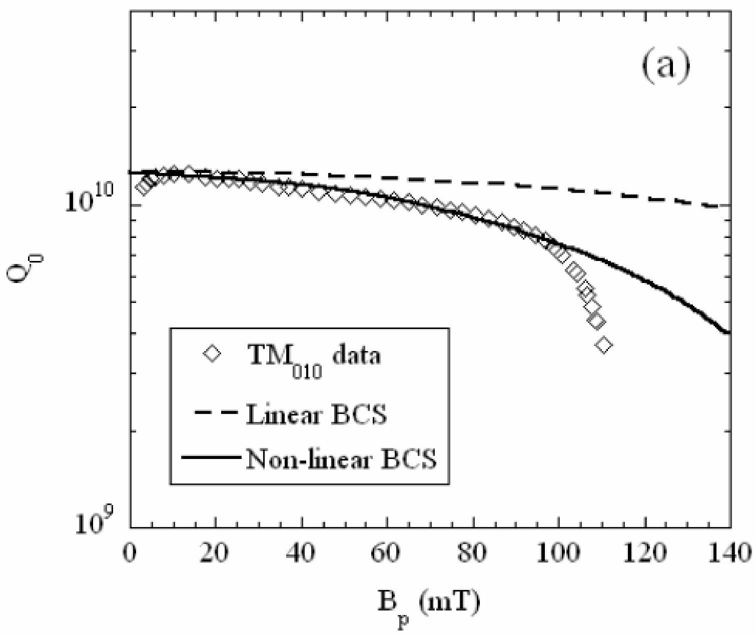
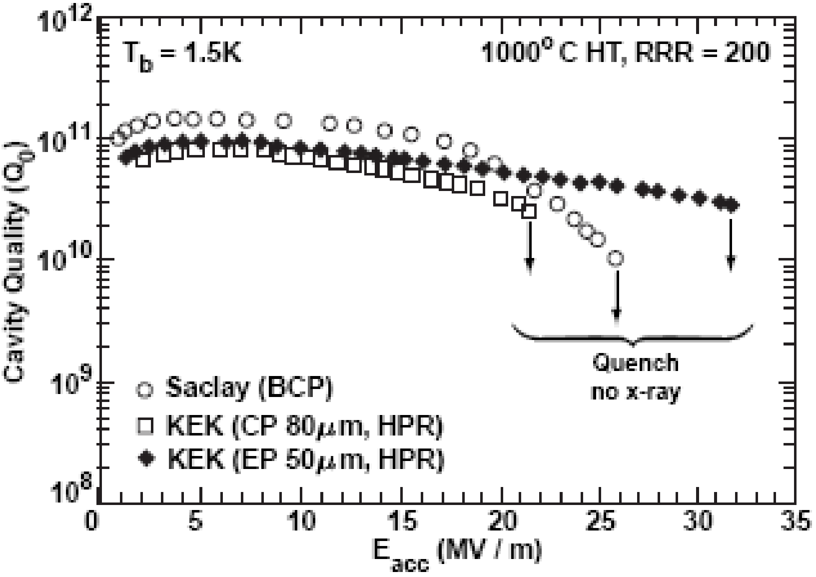
High field Q drop

- An obstacle towards achieving reproducibly high accelerating gradients is represented by ‘‘anomalous’’ losses when the peak surface magnetic field is above about 90 mT (theoretically it should be ~ the 200 mT of critical field)
- Those losses cause a sharp degradation of the cavity quality factor in the high field region, effect known as “Q drop”, a precipitous decrease in the cavity quality factor when exceeding 20-30 MV/m



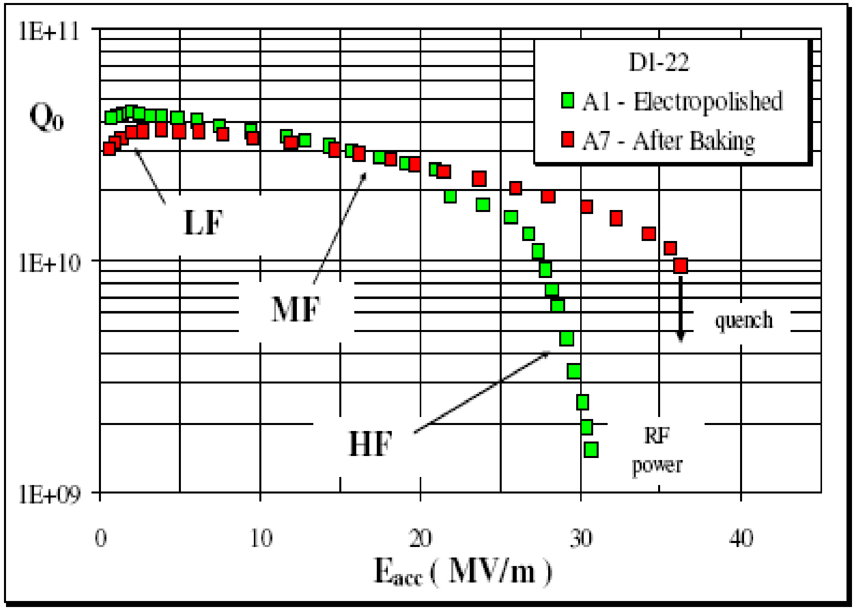


Historically

- Few years ago Q drop was considered a typical feature of BCP cavities, since at KEK electro polishing did not give significant Q drop
- The Q drop was therefore named ‘European headache’
- Later at CEA/Saclay it was discovered that baking at moderate temperatures (90-120°C) alleviated the problem
- It was later understood that a moderate temperature bake out was part of the Japanese electro polishing procedure
- However it has to be noted that baking effect is still more pronounced in in EP cavities, i.e. often small residual drop remains in the BCP cavities

Today

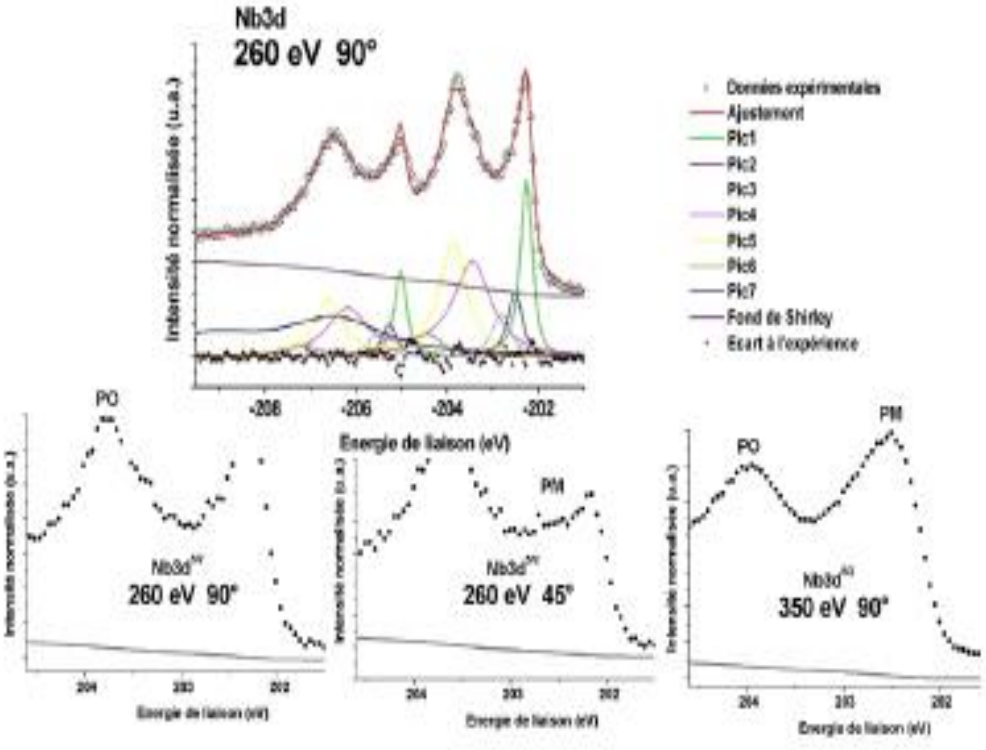
- While LF and MF models successfully explain the Q slope, the cause of this sudden increase in surface resistance at HF is yet unknown
- Several mechanisms were suggested so far as possible explanations of the effect, but they appear to be either not relevant to the high field behavior or can not explain some of the established experimental facts
- Mainly six models trying to explain the Q drop mechanism, somehow in agreement with some experimental fact and in disagreement with others

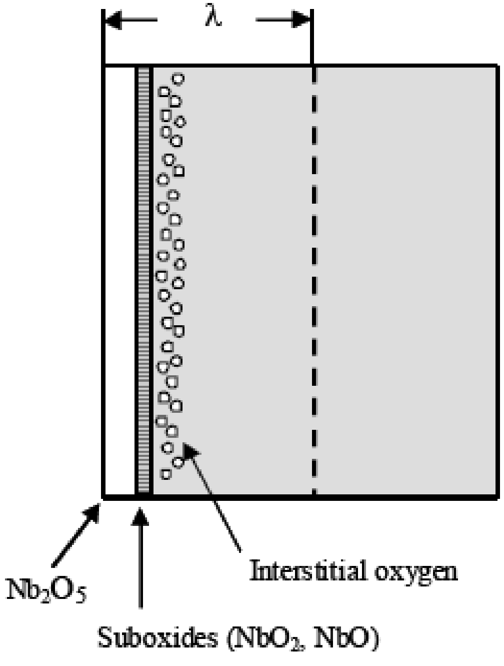


	Q-Slope Fit	Q-Slope before baking (EP = BCP)	Q-Slope Improvem' after baking	Q-Slope after baking (EP < BCP)	No change after 4 y. air exposure	Exceptional Results (BCP)	Q-Slope unchanged after HF chemistry	T_{bath} Q-slope after baking	Quench EP > BCP	BCP Quench unchanged after baking	Argum' Validity	Fund^al Disagreem' Exper. ≠ Theory
Magnetic Field Enhancem'	Y simulat. code	~~N~~ $\beta_m \neq$ $R_{ES}^3 \neq$	Y R_{ES}^3 ↑	Y lower β_m	-	N high β_m	-	-	Y lower β_m	N R_{ES}^3 ↑	Y	D_1
Interface Tunnel Exchange	Y E'	N $\beta_f \neq$	Y Nb_2O_{5-y} ↓	Y lower β_f	N Nb_2O_{5-y} ↑	N high β_f	~~N~~ ~~new Nb_2O_{5-y}~~	~~N~~ ~~improv'~~	-	-	Y	D_2
Thermal Feedback	Y parabolic	Y = thermal properties	Y R_{BCS}↓ R_{res}↑	N = therm. proprties	-	-	-	-	-	-	N C coeff.'	-
Magnetic Field Dependence of Δ	Y expon^tial	N $B_{rf}^X \neq$	Y B_{rf}^5 ↑	Y higher B_{rf}^3	-	-	-	-	-	-	~~N~~ ~~thin film~~	D_1
Segregation of Impurities	?	N segregation ≠	N only O diffusion	Y surface ≠	-	Y good cleaning	N chemistry	-	-	-	Y	-
Bad S.C. Layer Interstitial Oxygen $Nb_{6-x}O$	?	Y NC layer	Y O diffusion	N	N interstitial re-appears	-	~~N~~ ~~new bad layer~~	-	Y higher B_{rf}^3	N B_{rf}↓	Y	D_1

Weak superconducting layer model

As we saw yesterday, UV-ray photon spectroscopy shows that the two first layers of the niobium metal on the surface right underneath the oxide, are heavily charged in oxygen dissolved atoms



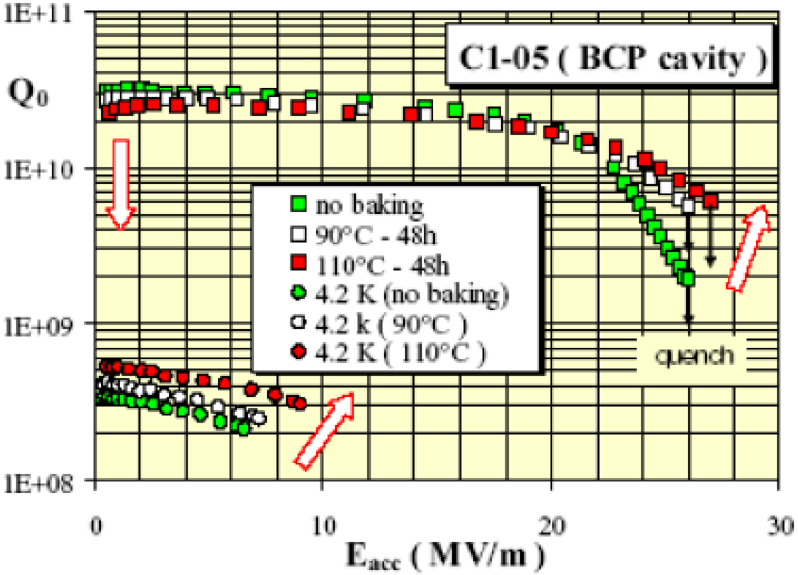


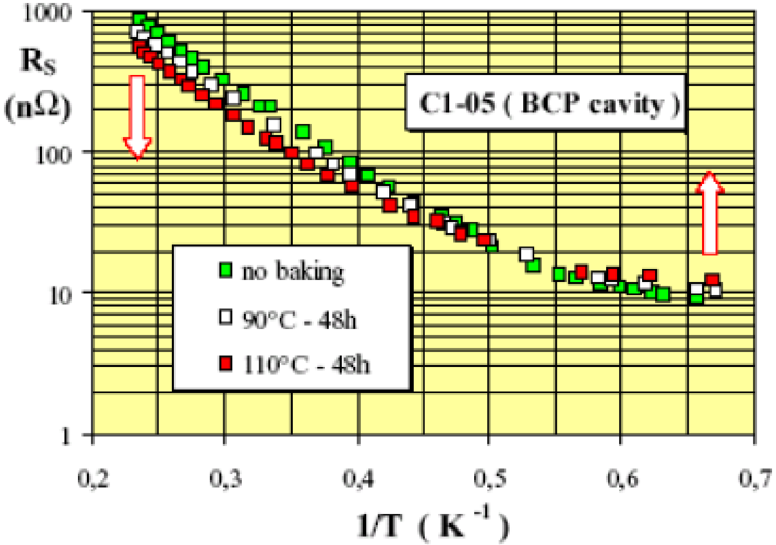
Weak superconducting layer model

- “Two-superconductor model”, high purity bulk niobium covered by a thin (~2nm) layer of contaminated Nb
- This heavily degraded layer thickness is much smaller than the coherence length → the proximity effect makes Cooper pairs survive even in the bad layer
- However, the weak layer, as a result of the contamination, has a **lower critical field $H_c < H_{c_{Nb}}$ which causes the Q-drop**

Where weak layer models (seem to) succeed: low T baking

- We know that a standard cure for the Q-drop is a heat treatment for 48 hrs at 120°C
- Recently Visentin showed that Q drop can also be cured at 145°C for 3 hrs
- We observe Q drop removal, a reduction in the BCS resistance and an increase in the residual resistance



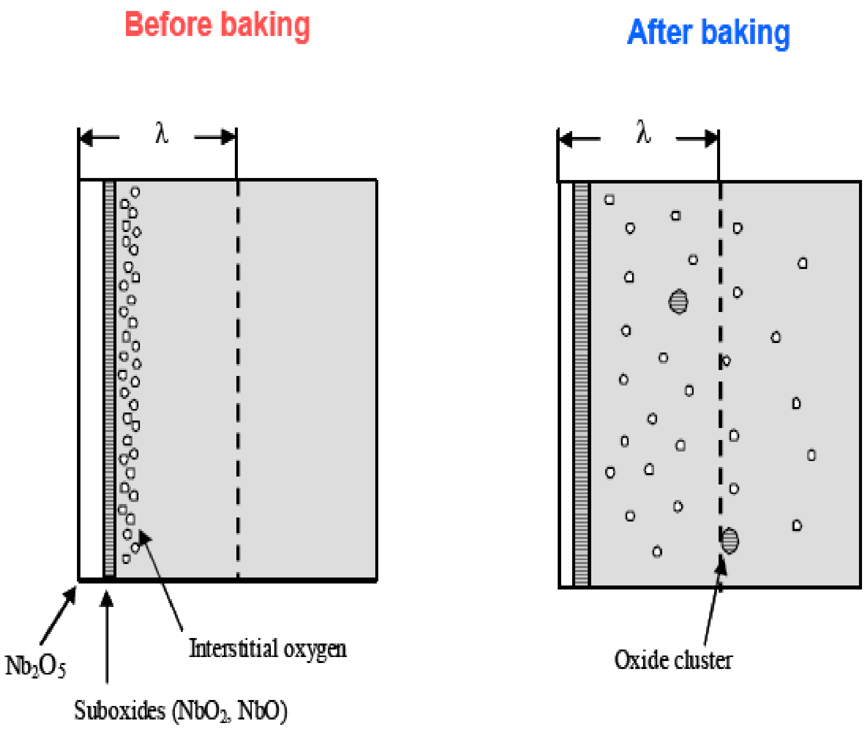


Where weak layer models (seem to) succeed: low T baking

‘Intuitively’ works well:

- Diffusion process: improvement and saturation, as observed in the cure
- With heat treatment weak layer starts to diffuse into the pure Nb, dissolving into the bulk
- Therefore the layer is now ‘cleaner’ and has an higher critical field → Q drop is cured
- Also, both curing baking procedures (3hrs-145°C and 48hrs-120°C) result in the same oxygen profile in the Nb surface, as calculated from diffusion models, which we will examine next

{However, now the impurity content is distributed into the ‘purer’ bulk → the surface resistance should increase, in disagreement with experimental data (not the only disagreement, as we will see in few slides)}



Diffusion models – G. Ciovati

- Estimate of the concentration profile of interstitial oxygen in niobium after baking by solving the diffusion equation in one dimension
- Usually two approaches:

1. Oxide layer is considered an infinite source of oxygen, so that the concentration at the niobium-oxide interface is always equal to the solubility limit
2. The oxygen contribution from the oxide layer is neglected and the concentration at the niobium-oxide interface decreases for longer baking time and higher temperatures

Diffusion models – G. Ciovati

- Improved model where is taken into account both contributions from the interstitial oxygen initially present at the niobium-oxide interface and from the decomposition of the natural niobium pentoxide layer
- Consider the two sources separately and then add the solutions
- First let's look at the Nb_2O_5 decomposition term:

$$\frac{\partial c(x,t)}{\partial t} = D(T)\frac{\partial^2 c(x,t)}{\partial x^2}$$

$$\mathrm{Nb_2O_5} \rightarrow \mathrm{NbO_2} \rightarrow \mathrm{NbO}$$

$$\frac{\partial u(x,t)}{\partial t} = D(T)\frac{\partial^2 u(x,t)}{\partial x^2} + q(x,t,T)$$

$$q(x,t,T) = u_0 k(T) e^{-k(T)t}\delta(x)$$

- *U* represents the oxygen concentration, *q* is the source term, in which the exponential time dependence is due to the first-order reduction kinetic

- The source is concentrated at the niobium-oxide interface at *x*=0

- *u*0 is the total amount of oxygen per unit area from the Nb2O5 decomposition

Diffusion models – G. Ciovati

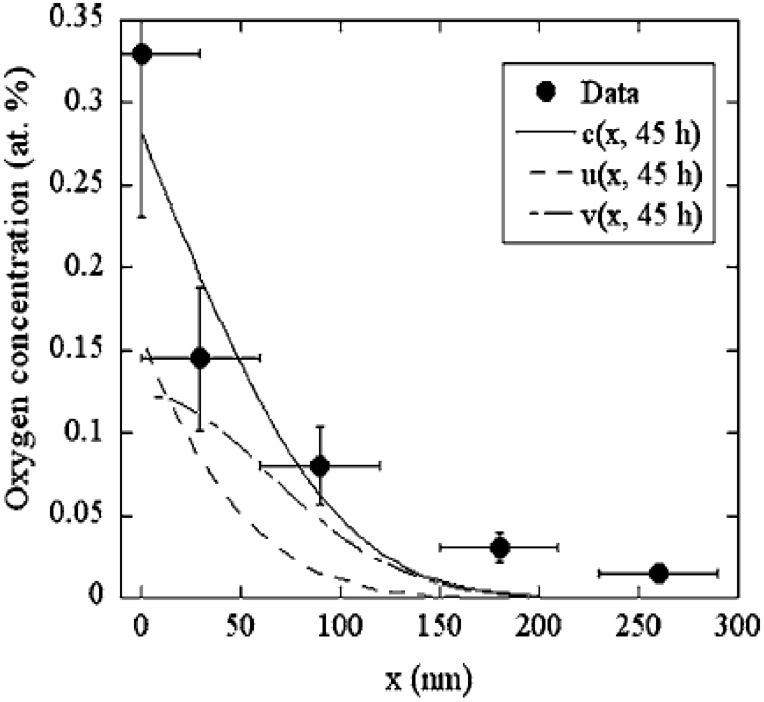
Besides the diffusion of oxygen generated by the dissociation of the oxide layer, the diffusion of the interstitial oxygen initially present at the niobium-oxide interface needs to be considered. The diffusion equation for the oxygen concentration *V(x, t)* is given by:

$$\frac{\partial v(x,t)}{\partial t} = D(T)\frac{\partial^2 v(x,t)}{\partial x^2}, \quad v(x,0) = v_0\delta(x)$$

Solutions:

$$u(x,t) = \frac{u_0}{\sqrt{\pi D(T)}}\int_0^t \frac{k(T)e^{-k(T)s}}{\sqrt{t-s}} e^{-x^2/[4D(T)(t-s)]}ds$$

$$v(x,t) = \frac{v_0}{\sqrt{\pi D(T)t}} e^{-x^2/[4D(T)t]}$$



However:

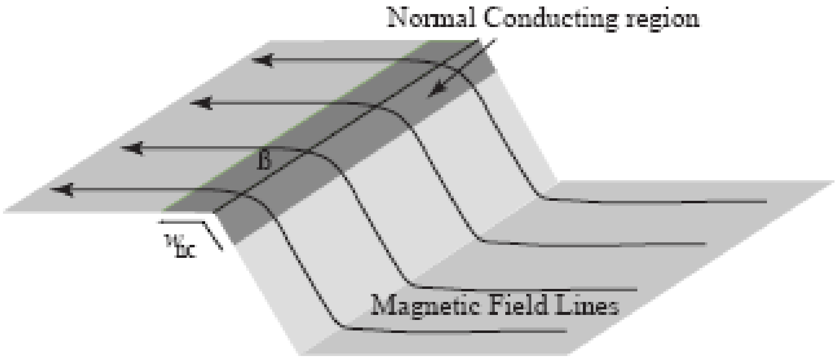
- Due to the lack of accurate quantitative data on the total oxygen contribution from the oxide layer the oxygen concentration at the niobium-oxide interface *u*0 is a not so good ‘estimate’
- No experimental evidence that the pentoxide diffuses
- Recently proved (Antoine) that diffusion happens towards the surface and not into the bulk

More contradictions to weak layer models

- Visentin also points out that in his HF treatment experiment the Nb oxide interface was completely re-built after dissolution of the oxide in HF, and with it the oxide-rich few nm thick layer on top of the bulk
- Q-drop though is not restored after the treatment, suggesting therefore that oxygen layers do not play a role in the Q drop mechanism

Magnetic field enhancement model

- Q slope can be explained by any surface resistance contribution with a strong field dependence
- One such contribution is the one proposed by Knobloch: field enhancement at the sharp edges of grains
- Especially BCP surfaces are rougher and characterized by sharp grain-edges – result of variation in the etching rate for different crystal orientations and preferential etching at the grain boundaries
- Localized quenching of grain edges occurs when enhanced fields reach the critical field



Magnetic field enhancement model

- Knobloch calculates the Q-drop from an estimate of the total needed length of the quenched grain edges for a certain Q reduction, then checks if it’s realistic
- Rnc is the surface resistance of normal conducting niobium and w_{nc} is the width of the region of the grain boundary that is in the normal state
- To estimate the total length Lnc of normal conducting grain boundaries needed to explain a Q0 reduction from 2 $*10^{10}$ to 5 $*10^{9}$ at Eacc = 30 MV/m, w_{nc} is chosen 1 μm

$$\frac{L_{\mathrm{nc}} w_{\mathrm{nc}} R_{\mathrm{nc}} H_{\mathrm{crit}}^2}{A_{\mathrm{cav}} R_{\mathrm{s}} H^2} = \frac{2 \times 10^{10}}{5 \times 10^{9}} = 4 \quad \Longrightarrow \quad L_{\mathrm{nc}} = 4 \frac{A_{\mathrm{cav}} R_{\mathrm{s}}}{w_{\mathrm{nc}} R_{\mathrm{nc}}} \left(\frac{H}{H_{\mathrm{crit}}} \right)^2$$

Magnetic field enhancement model

Computing for a 2-cell TESLA cavity → **L=2.3 m**

Given that the average grain is about 50 µm (= lgb) wide, there are roughly Acav/l^{2}gb ~ 6 *10^{7} grains with a **total grain boundary length of 6200 m**. Hence only a small fraction of all grains need be normal conducting to explain the Q slope

βm*H = H$_{\text{crit,}}$ βm ~ Bcrit/Bslopestart ~ 1.6

$$\frac{L_{\text{nc}} w_{\text{nc}} R_{\text{nc}} H_{\text{crit}}^2}{A_{\text{cav}} R_{\text{s}} H^2} = \frac{2 \times 10^{10}}{5 \times 10^{9}} = 4 \quad \Longrightarrow \quad L_{\text{nc}} = 4 \frac{A_{\text{cav}} R_{\text{s}}}{w_{\text{nc}} R_{\text{nc}}} \left(\frac{H}{H_{\text{crit}}} \right)^2$$

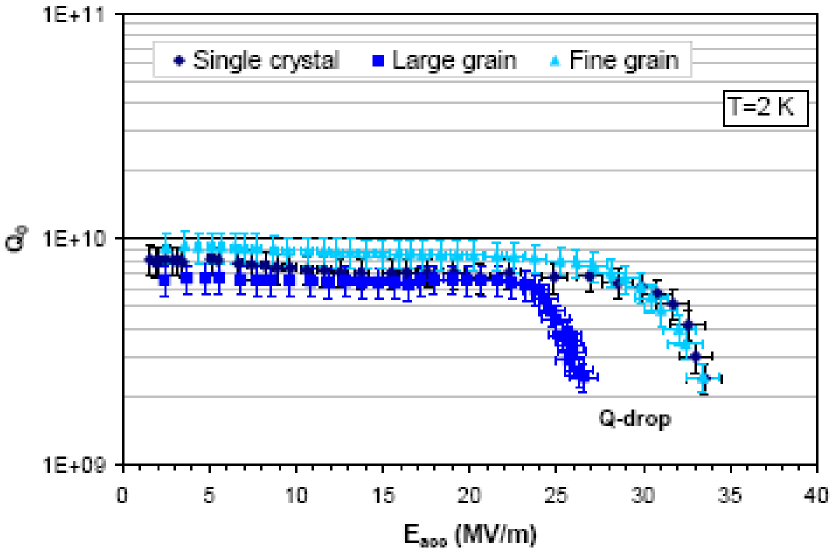
Magnetic field enhancement model

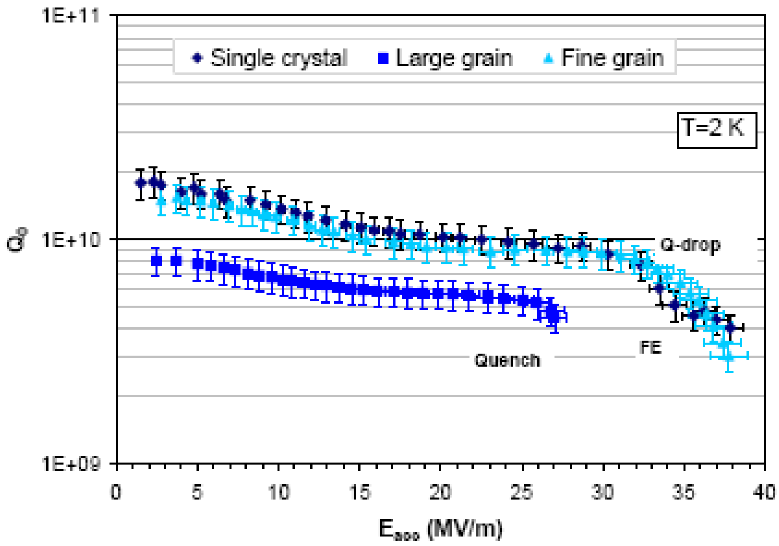
- The strength of the field enhancement model is that it naturally explains the difference between BCP and EP cavities, as a result of a difference in surface roughness
- Low T bake is though difficult to explain since the bake does not appear to modify the surface roughness
- It could be an ‘additional’ Q drop mechanism present in BCP cavities and not removed by the bake

→ could be an ‘additional’ model to the 2 SC model discussed before

Magnetic field enhancement model

- The fact the Q drop before baking is similar in EP and BCP cavities though, seems to completely contradict the field enhancement model
- Moreover experimental data of Q slopes for different grain sized cavities does not show evidence of improvement reducing the length of the boundaries





Conclusions

- Many different models, each of which is in agreement with some experimental data but in disagreement with some other
- Need, therefore, of further experimental and theoretical investigation