The 12-th Workshop on RF Superconductivity,
Cornell University

Q-drop:
An analysis starting from elementary fundamental theory

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Work supported by the European Community Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme
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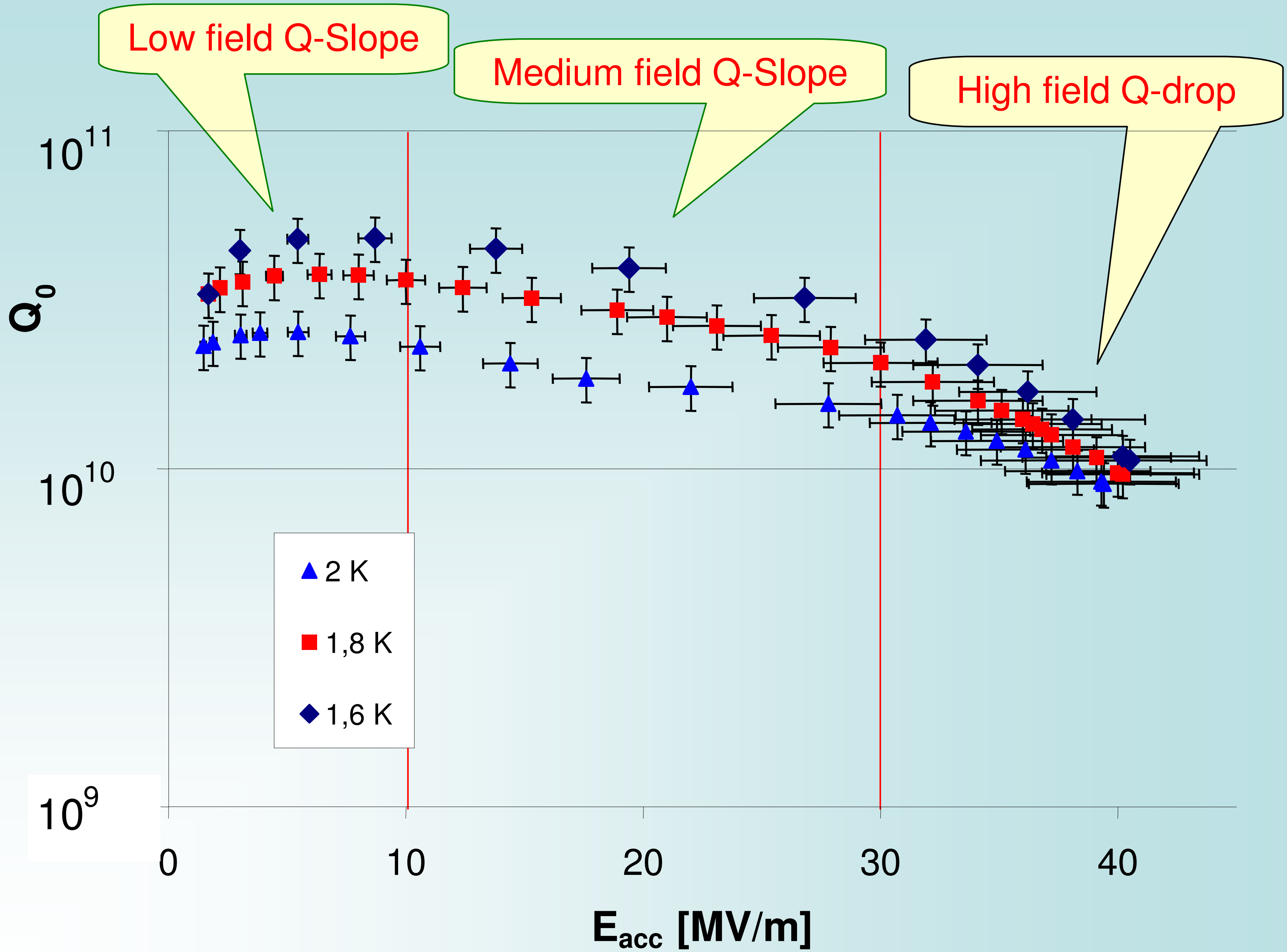
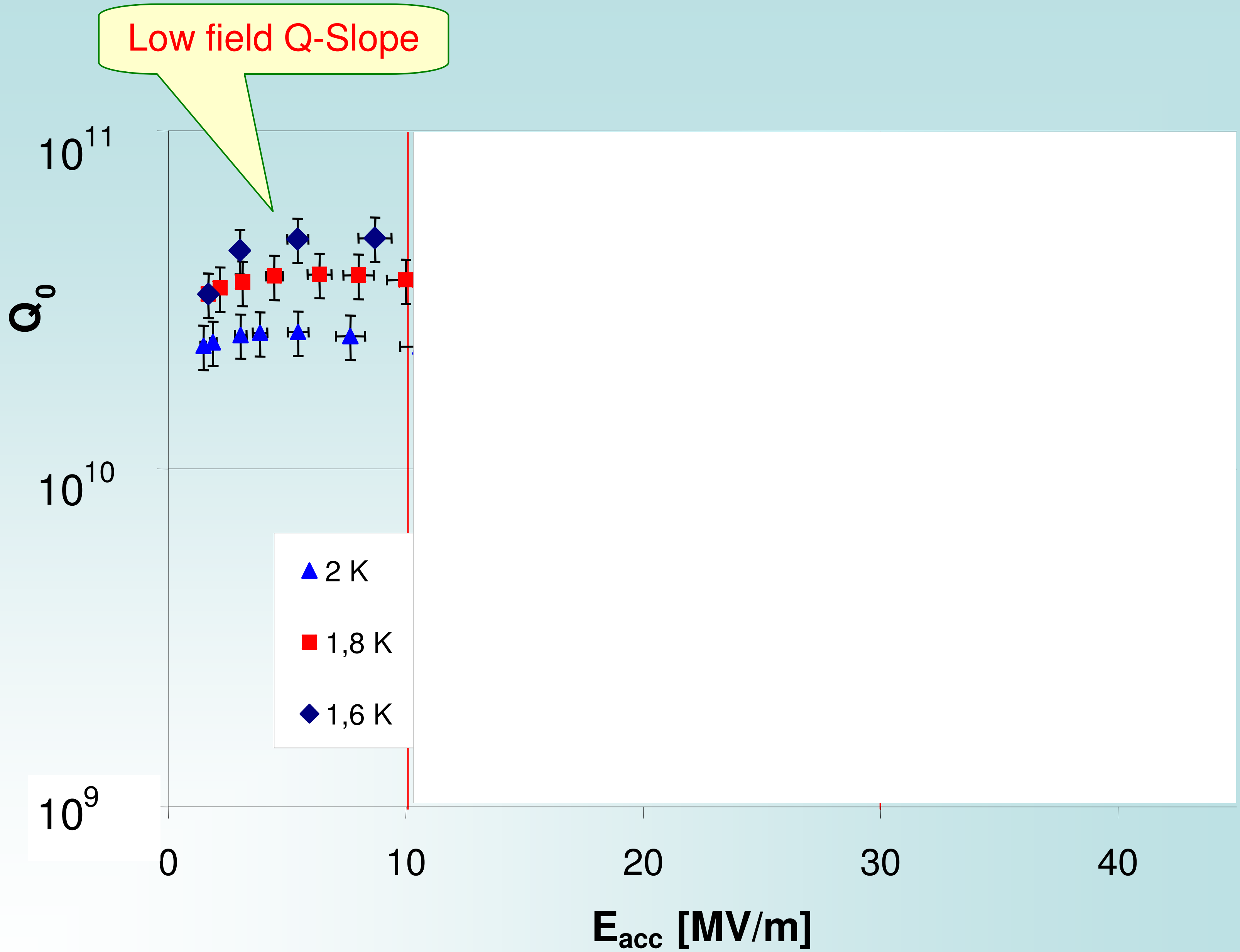


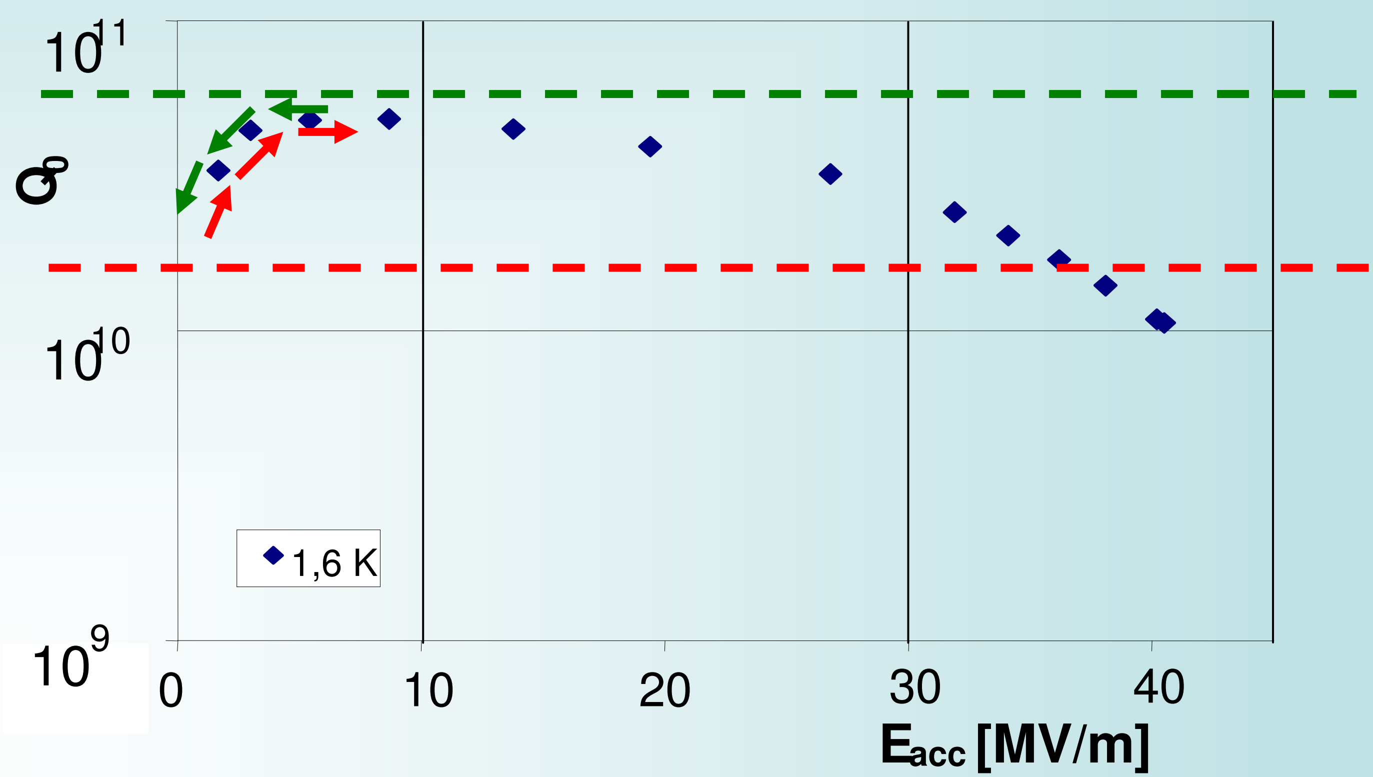
Best 9-cell cavity result (after electro-polishing) (Courtesy D. Proch)



Low field Q-Slope
Q_0
10^{11}
10^{10}
10^{9}
0
10
20
30
40
E_{acc} [MV/m]
2 K
1,8 K
1,6 K

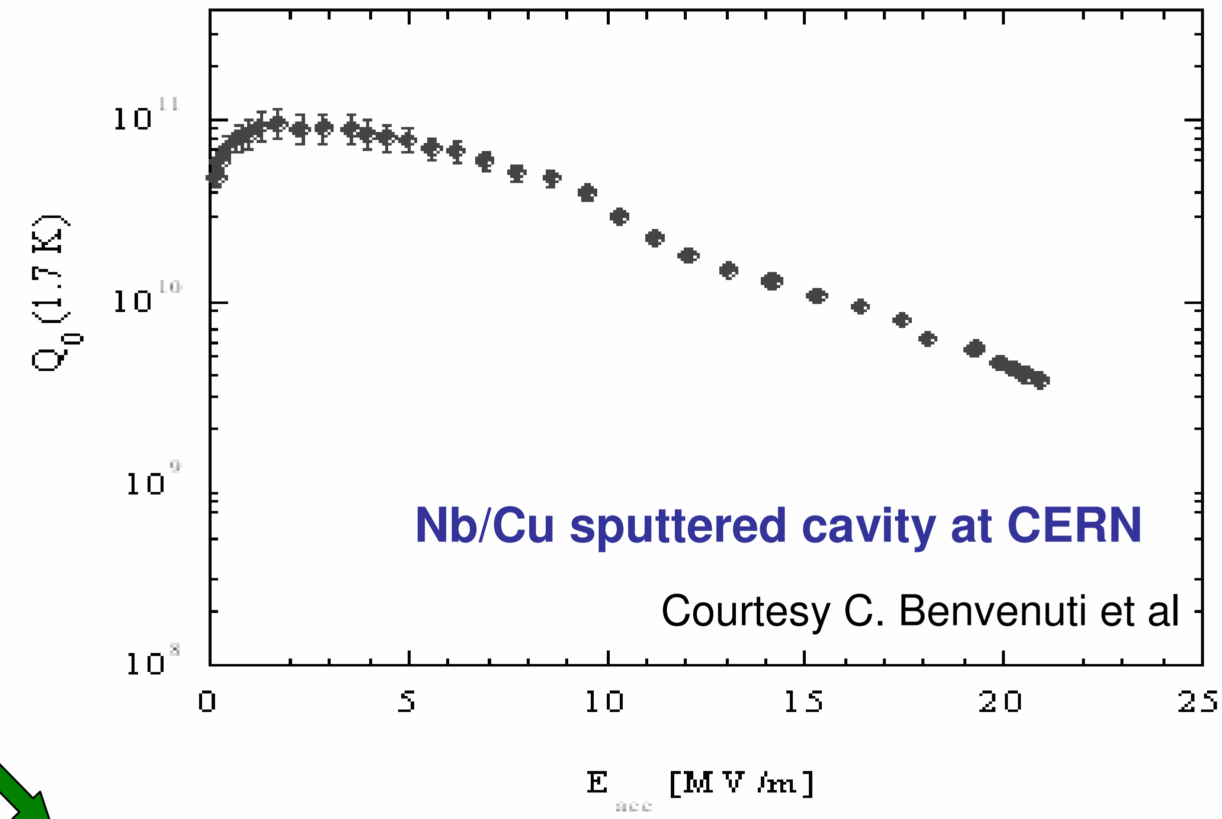
Questions:

- **Is the low-field Q-slope a calibration problem**?
- If not, which is its physical reason?
- and in such a case…..
  - ✓ Is something pulling up the Q ? **(if understood, it could be beneficial)**
  - ✓ The Q is originally higher, but for some reason at low field, it decays?



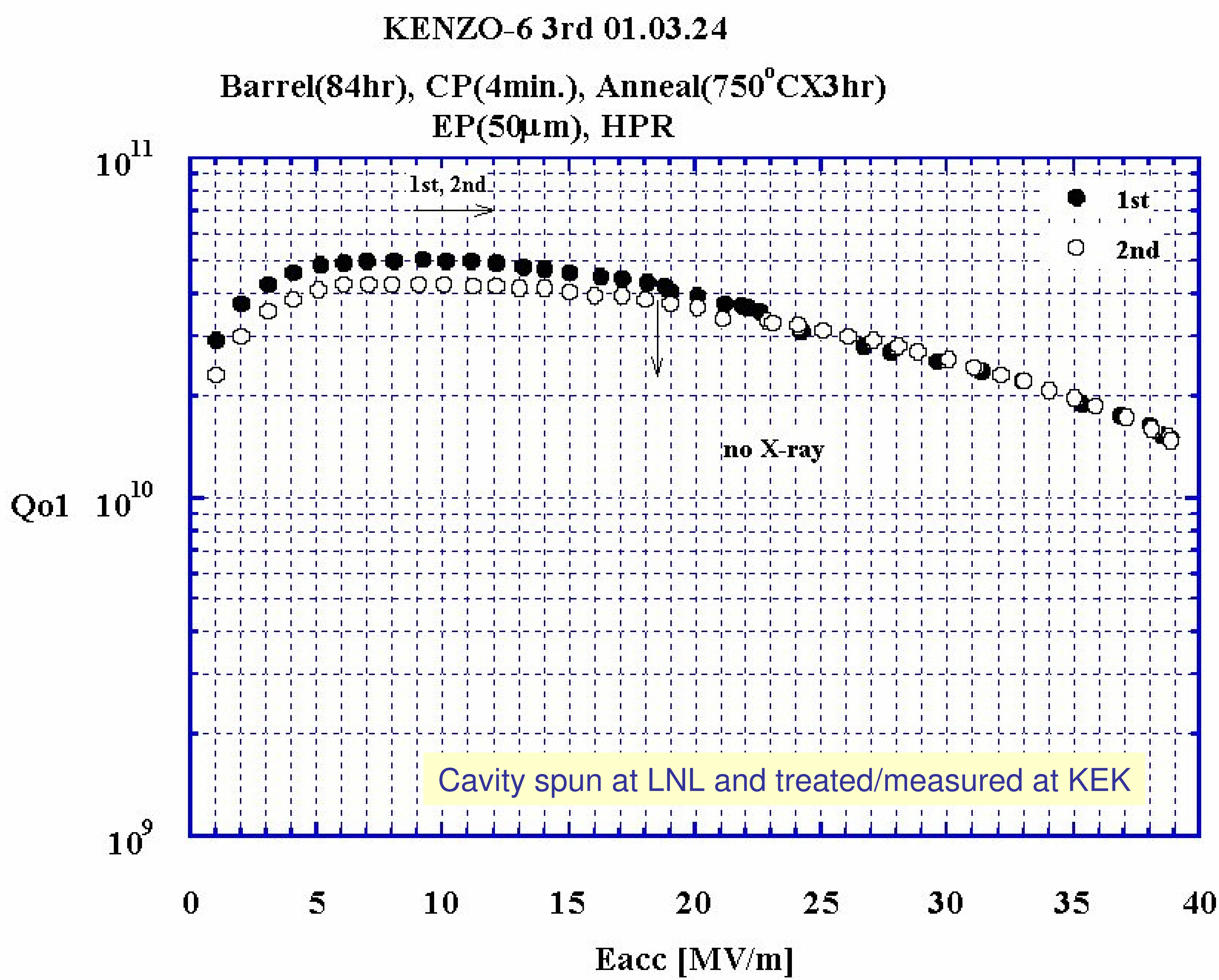
Before Abano/Santa fè Workshops (1997/1999):

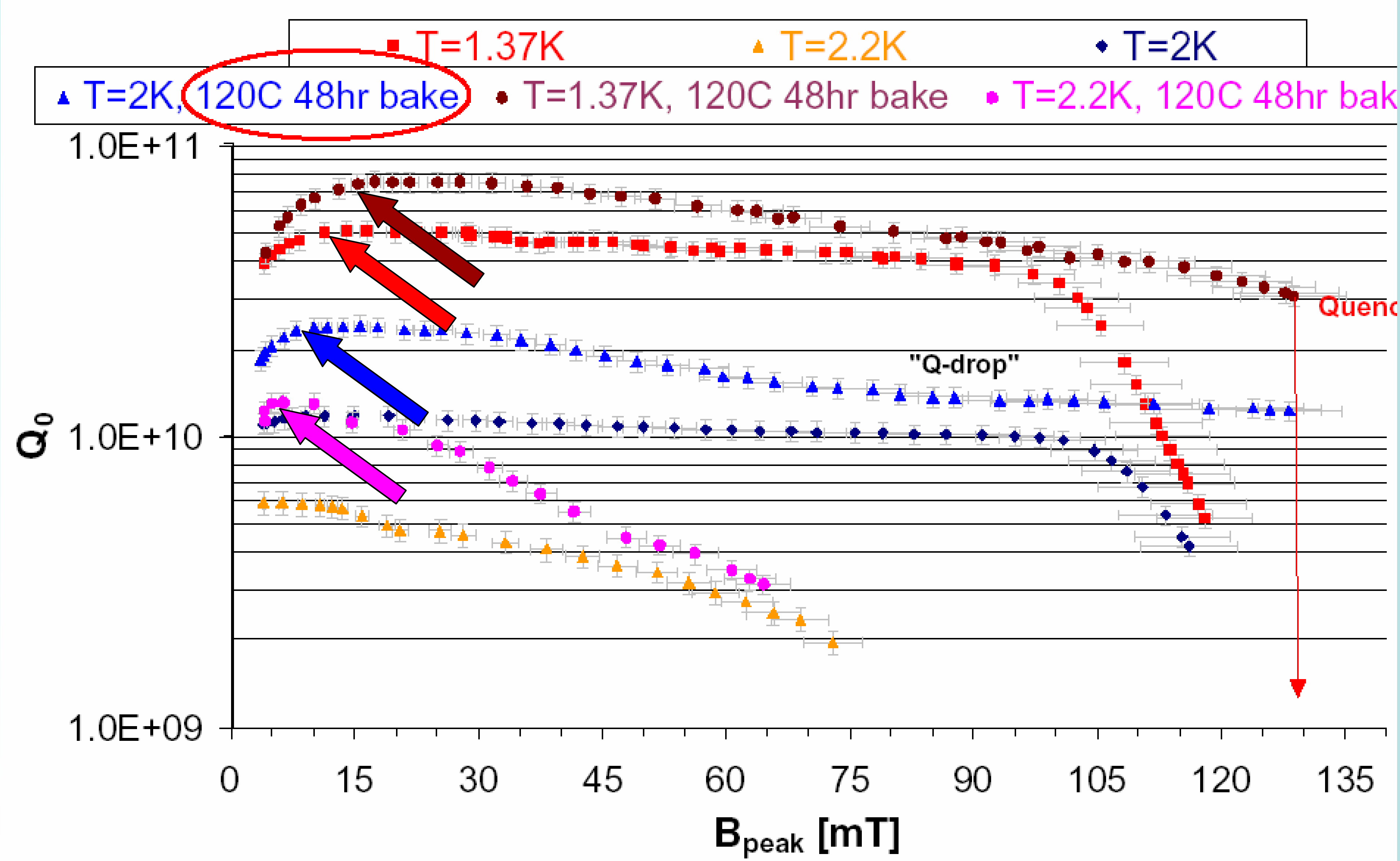
the low field Q-slope was reported only for Nb/Cu cavities



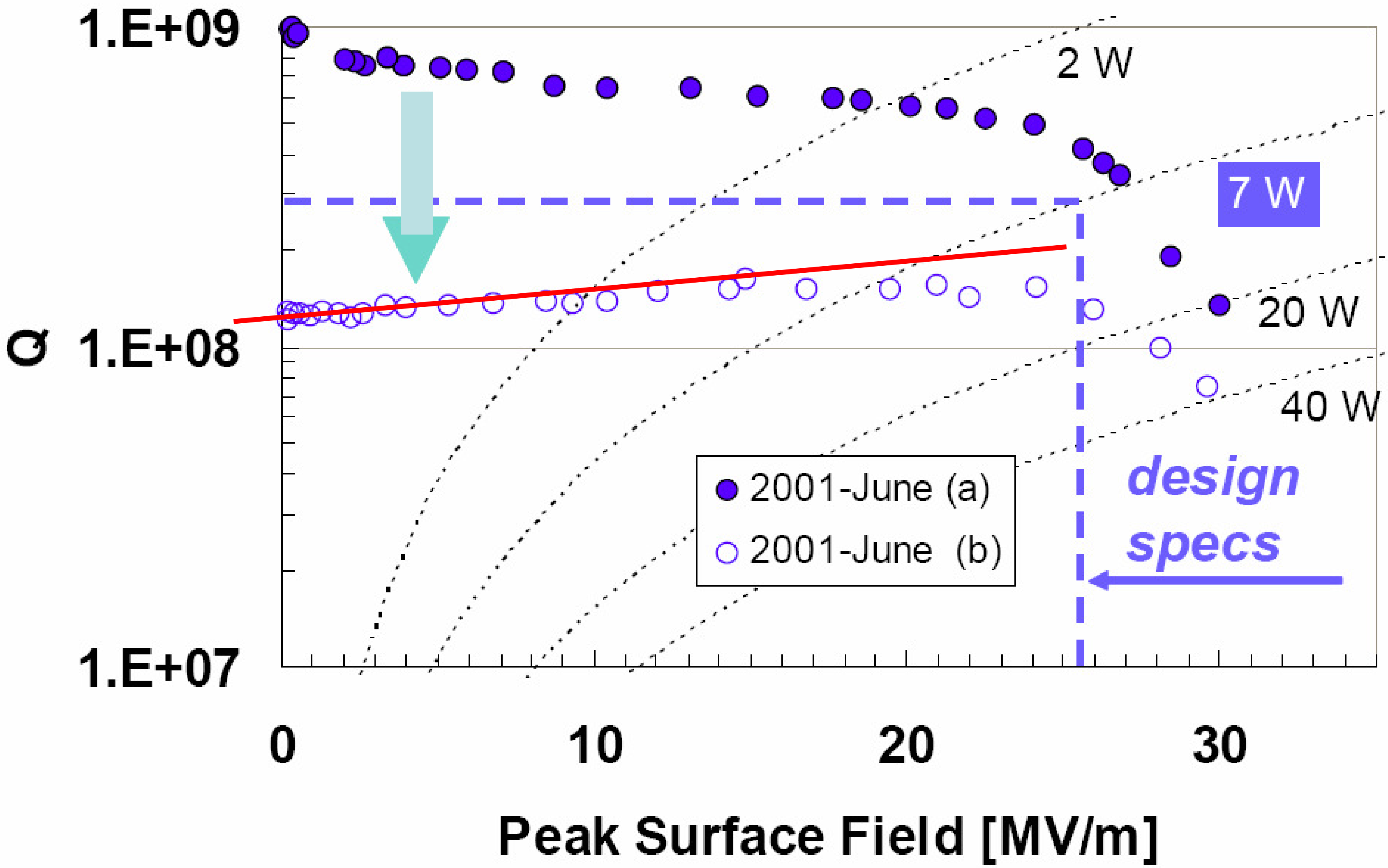
Since first cavities were baked in the cryostat at ~150°C for ~48 hours

the low field Q-slope was also reported for bulk Nb cavities


KENZO-6 3rd 01.03.24
Barrel(84hr), CP(4min.), Anneal(750°CX3hr)
EP(50µm), HPR
1st, 2nd
1st
2nd
no X-ray
Cavity spun at LNL and treated/measured at KEK
Qo1
Eacc [MV/m]



Courtesy G. Ciovati



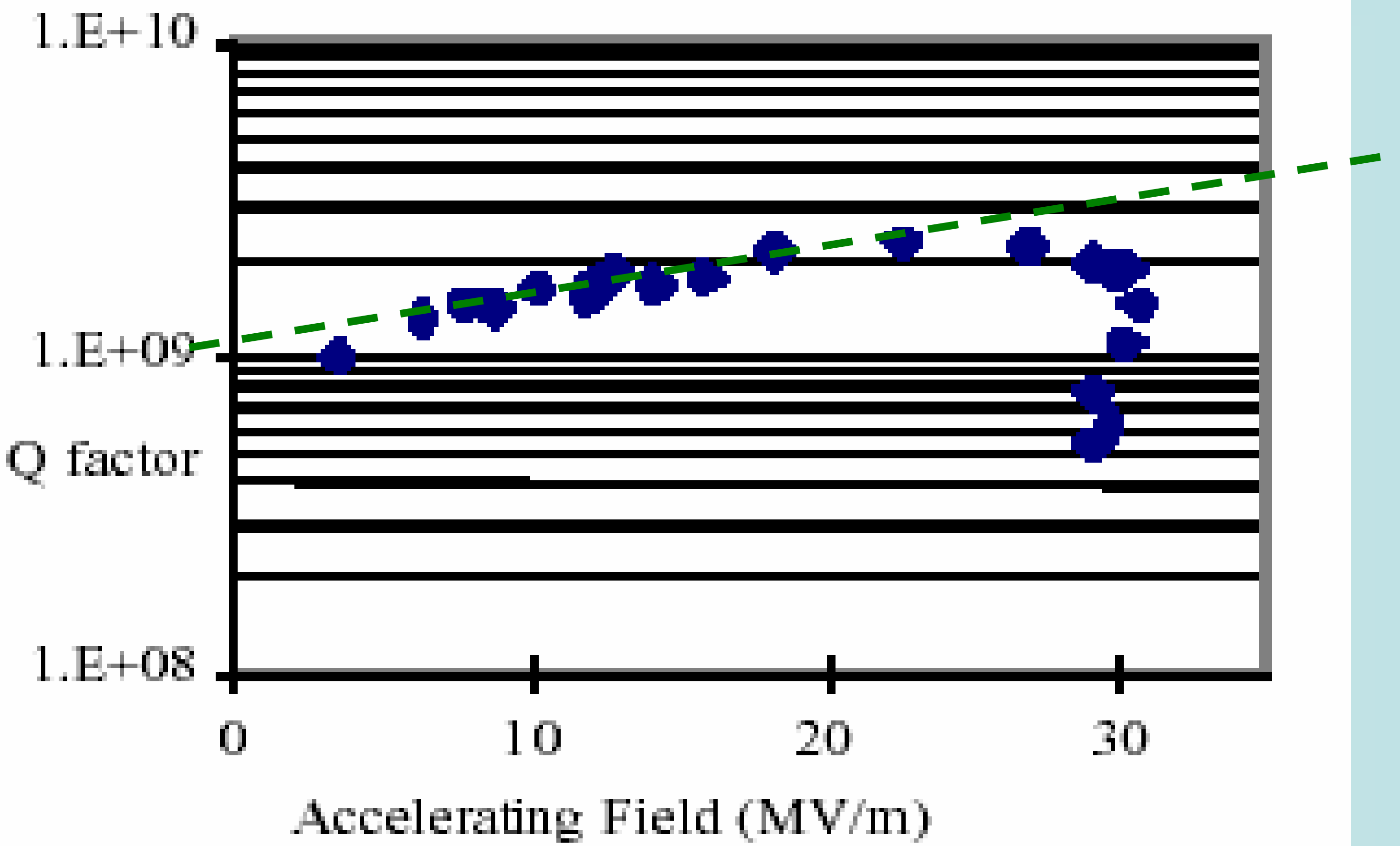
(Courtesy G. Bisoffi)

ACTIONS

- <u>Plasma discharge</u>: sputtering of Cu and stainless steel layer in a high-j region of tens of cm^2 in SRFQ2
- Chemical Polishing would have taken months
- 3M – Scotch Brite **lapping followed by HPWR** (2 weeks)

Presented at the 9-th RF Superconductivity Workshop, Santa Fè, NM, 1999

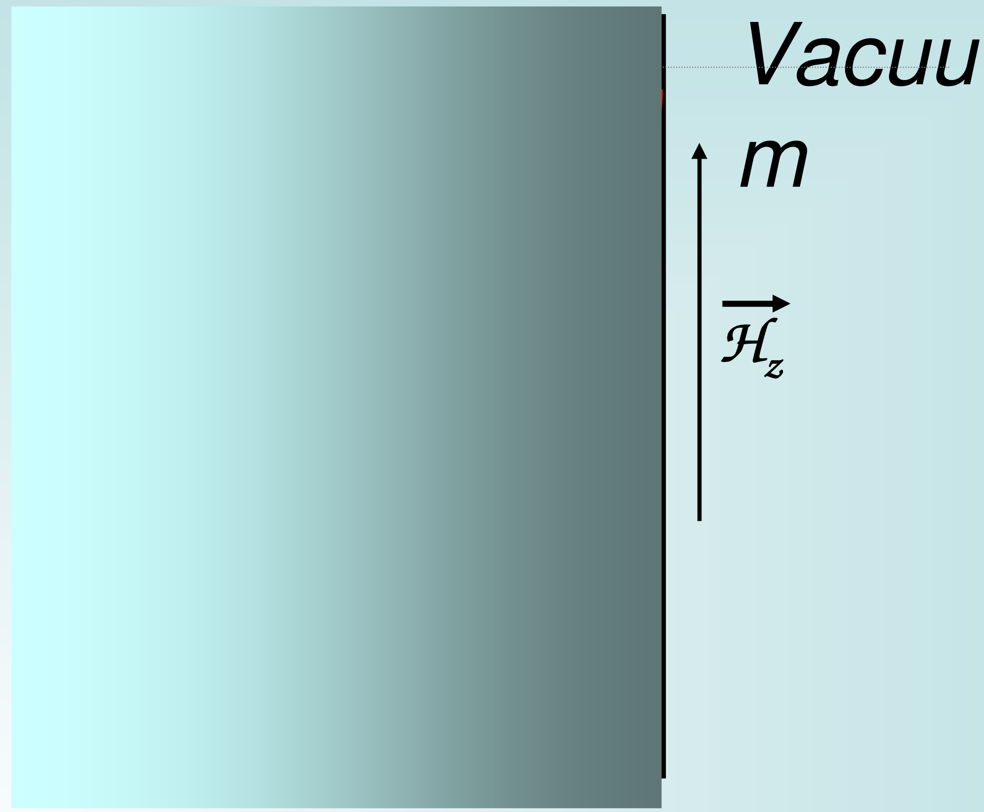
Renzo Parodi - **RF SUPERCONDUCTIVITY AT INFN_GENOA**



Typical plot of Q_o vs E_{acc} for cavities treated by **Dry Oxidation of the surface** after a medium temperature annealing

Let us suppose that:

on **bulk niobium (SC 2)** we put an overlayer of **a different superconductor (SC 1)**

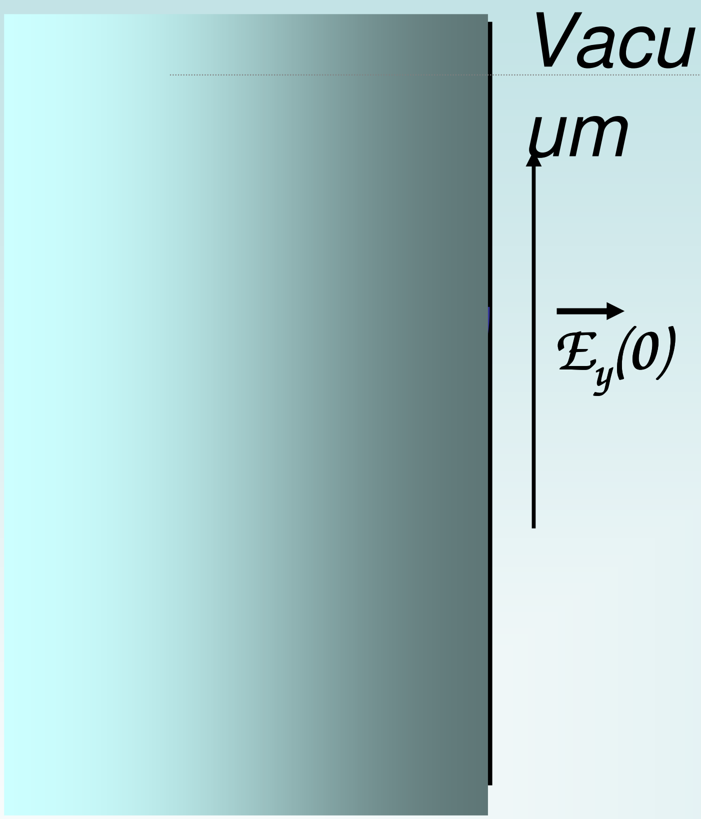


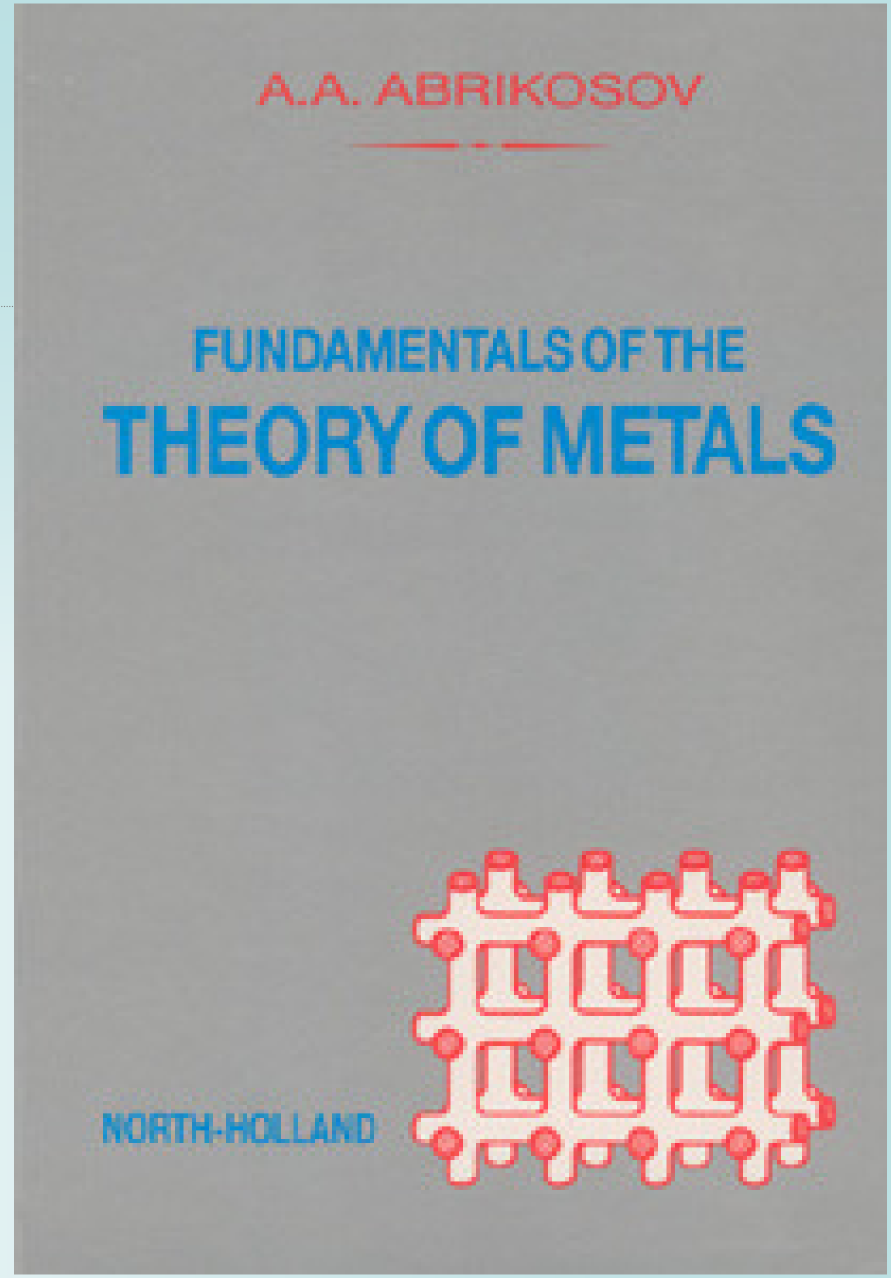
λ_2 is the penetration depth of the SC 2

a is the tickness of the SC 1

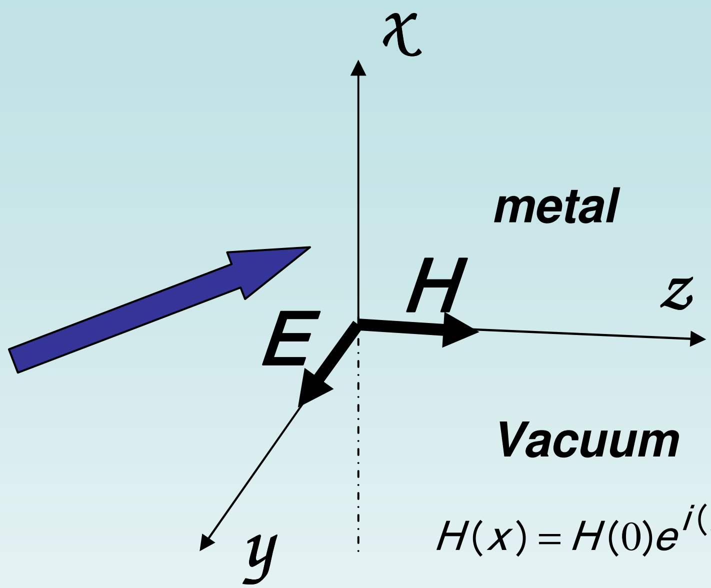
λ_1 is the penetration depth of the SC 1

Only one Superconductor:
No overlayer





THE ELECTROMAGNETIC RESPONSE OF A METAL



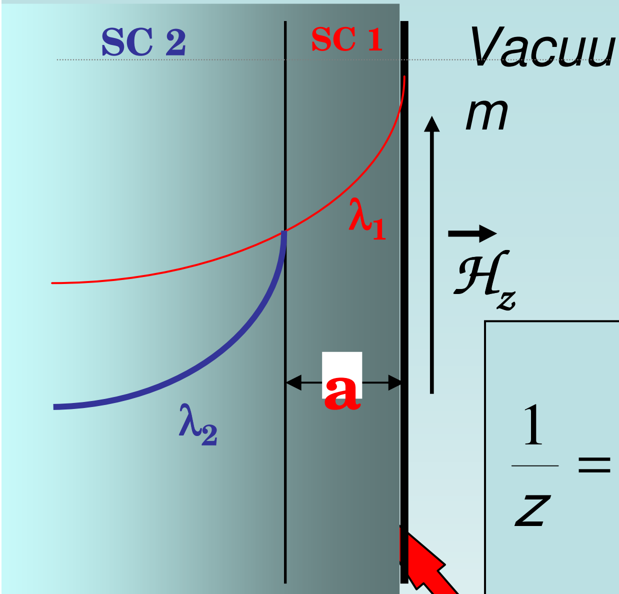
$$H(x) = H(0)e^{i(kx-\omega t)}$$

For a semi-infinite conductor that **fills the** $+x$ **half-space** and has a **plane surface at** $x = 0$

the **Surface Impedance** is defined as:

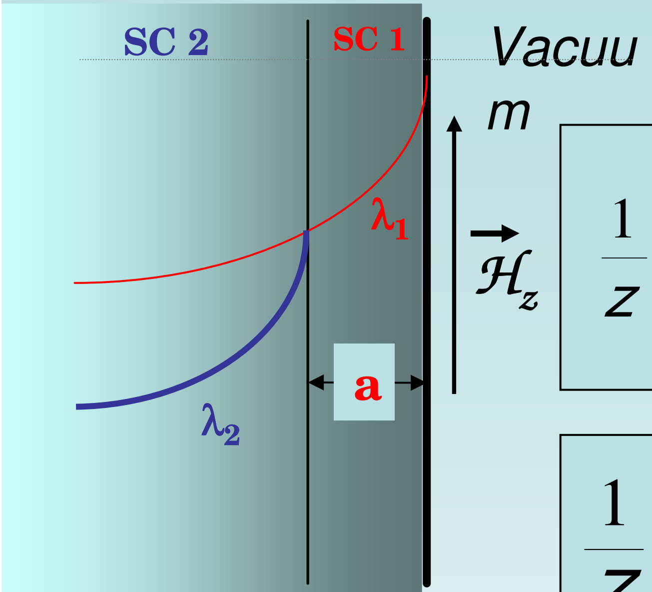
$$Z \equiv \frac{E_y(0)}{\int_0^\infty J_y(x)dx} = \frac{4\pi}{c}\frac{E_y(0)}{H_z(0)}$$

Two Superconductors:
SC 2 + SC 1



$$\frac{1}{z} = \frac{\int_0^a J(x)dx + \int_a^\infty J(x)dx}{E_y(0)} = -\frac{c}{4\pi}\left\{\frac{H'_z|_0^a + H''_z|_a^\infty}{E_y(0)}\right\}$$

$$H_z(x) = \begin{cases} X \le a; & H'_z(x) = H'_z(0)\, e^{-\frac{x}{\lambda 1}} \\ X = a; & H'_z(a) = H'_z(0)\, e^{-\frac{a}{\lambda 1}} \\ X \ge a; & H''_z(x) = H''_z(a)\, e^{-\frac{(x-a)}{\lambda 2}} = \\ & = H''_z(0)\, e^{-\frac{a}{\lambda 1}} e^{-\frac{(x-a)}{\lambda 2}} \end{cases}$$

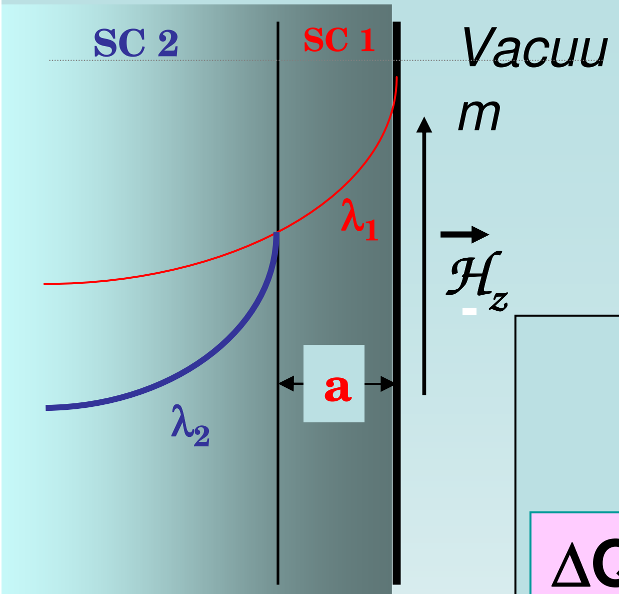


$$\frac{1}{z} = \frac{\int_0^a J(x)dx + \int_a^\infty J(x)dx}{E_y(0)} = -\frac{c}{4\pi}\left\{\frac{H_z^{I}|_0^a + H_z^{II}|_a^\infty}{E_y(0)}\right\}$$

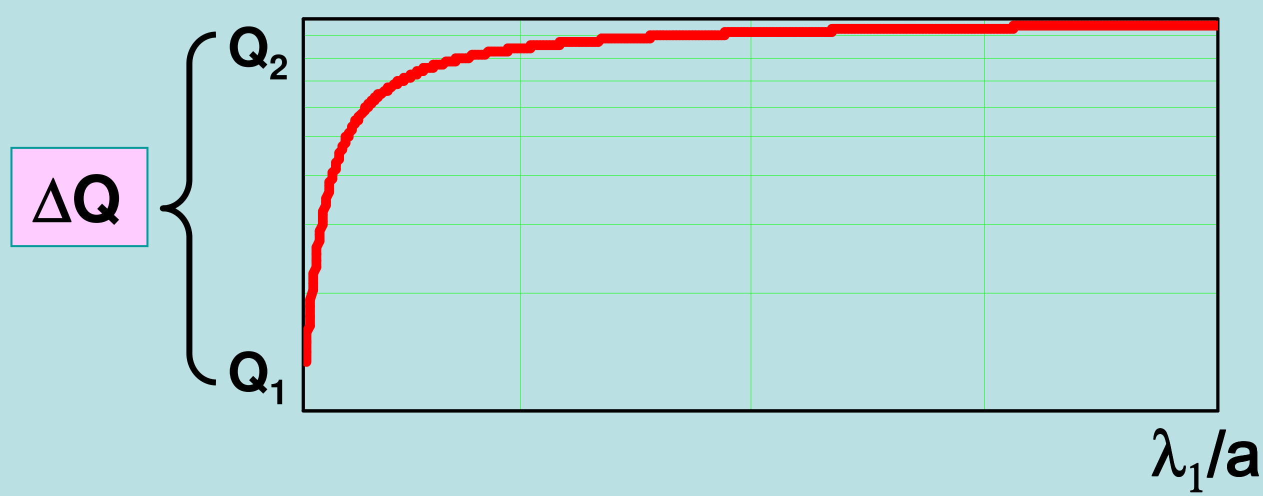
$$\frac{1}{Z} = -\frac{c}{4\pi}\cdot\frac{H_z^{I}(0)}{E_y(0)}\cdot\left(1-e^{-a/\lambda_1}\right) + \frac{c}{4\pi}\cdot\frac{H_z^{II}(0)}{E_y(0)}e^{-a/\lambda_1}$$

$$\frac{1}{Z} = \frac{1}{Z_1}\cdot\left(1-e^{-a/\lambda_1}\right) + \frac{1}{Z_2}e^{-a/\lambda_1}$$

$$Q = Q_1\left(1-e^{-a/\lambda 1}\right) + Q_2 e^{-a/\lambda 1}$$

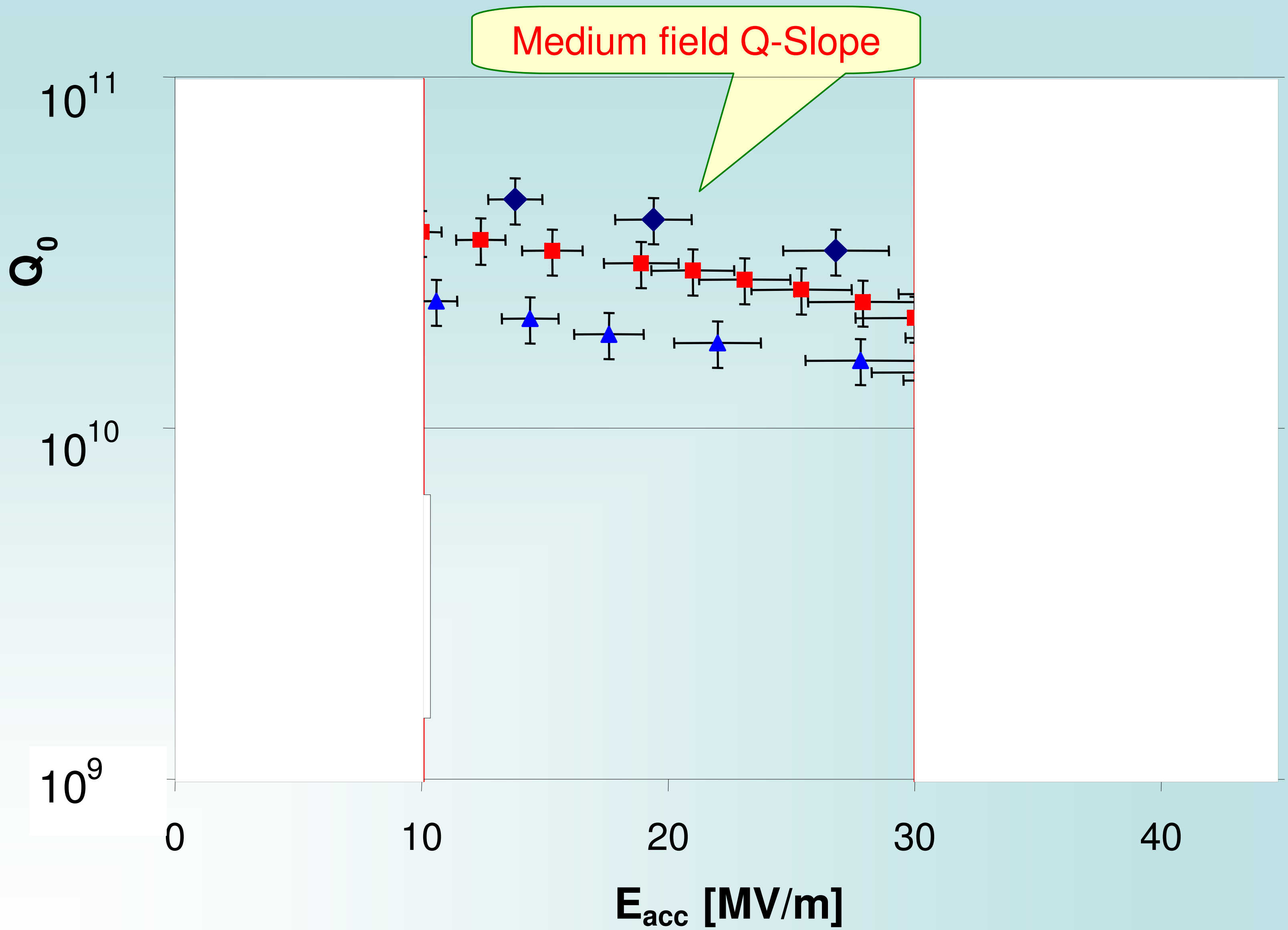


For a “2 Superconductor system”



$$Q = Q_1\left(1 - e^{-a/\lambda 1}\right) + Q_2 e^{-a/\lambda 1} = Q_1 + (Q_2 - Q_1)e^{-a/\lambda 1}$$

$$= Q_1 + \Delta Q \cdot e^{-a/\lambda 1}$$



Medium field Q-Slope
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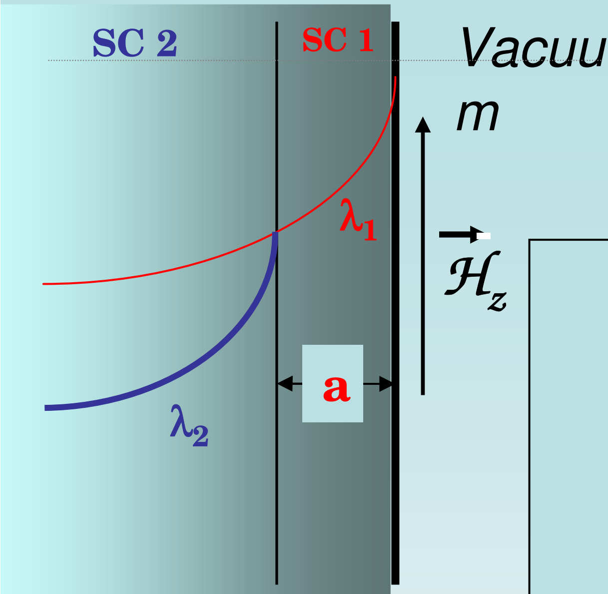
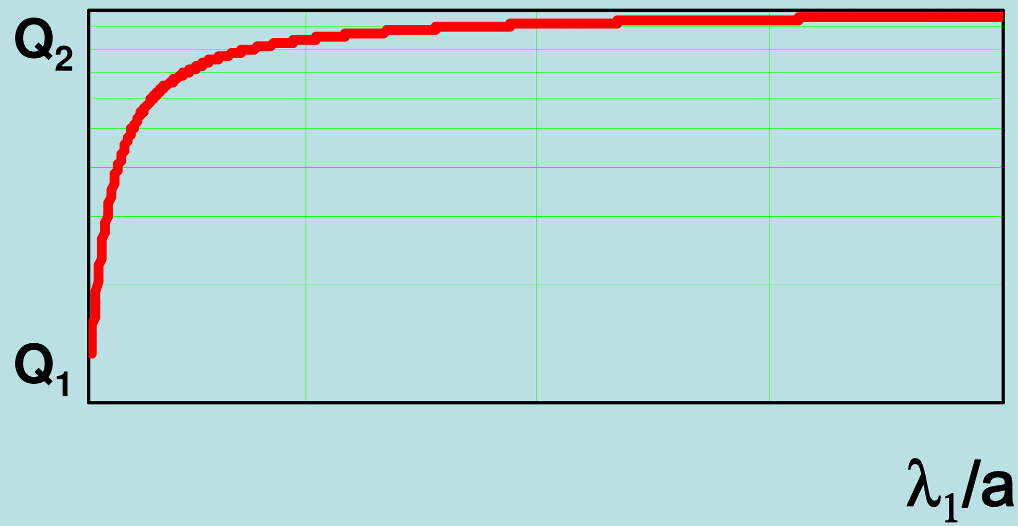


$$Q = Q_1 + (Q_2 - Q_1)e^{-a/\lambda_1}$$

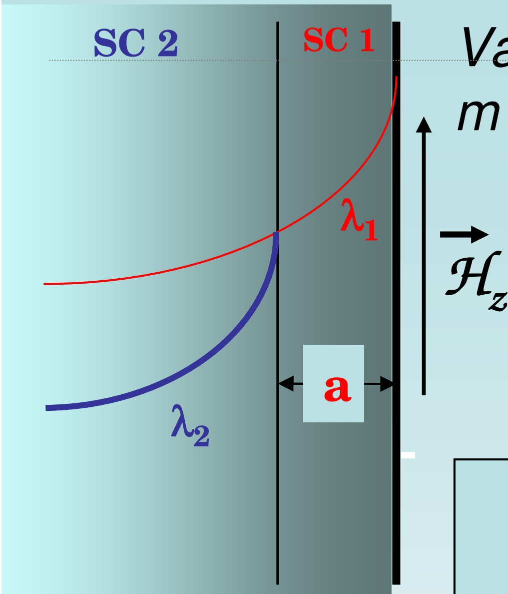


An hypotesis:

Gap and Penetration depth depends on magnetic field

$$\Delta(B) = \Delta_0 - kB$$

$$\lambda(B) = \lambda_0 + \left.\frac{\partial \lambda}{\partial B}\right|_0 B + \ldots \cong \lambda_0 + \alpha B$$

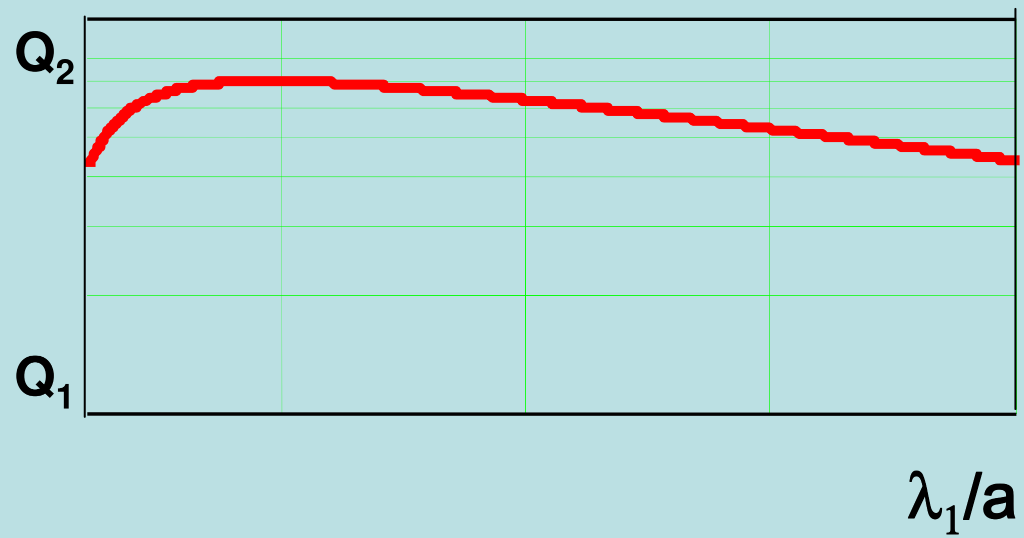


$$\Delta(b) = \Delta_0 - kb$$

$$b = B / B_c$$

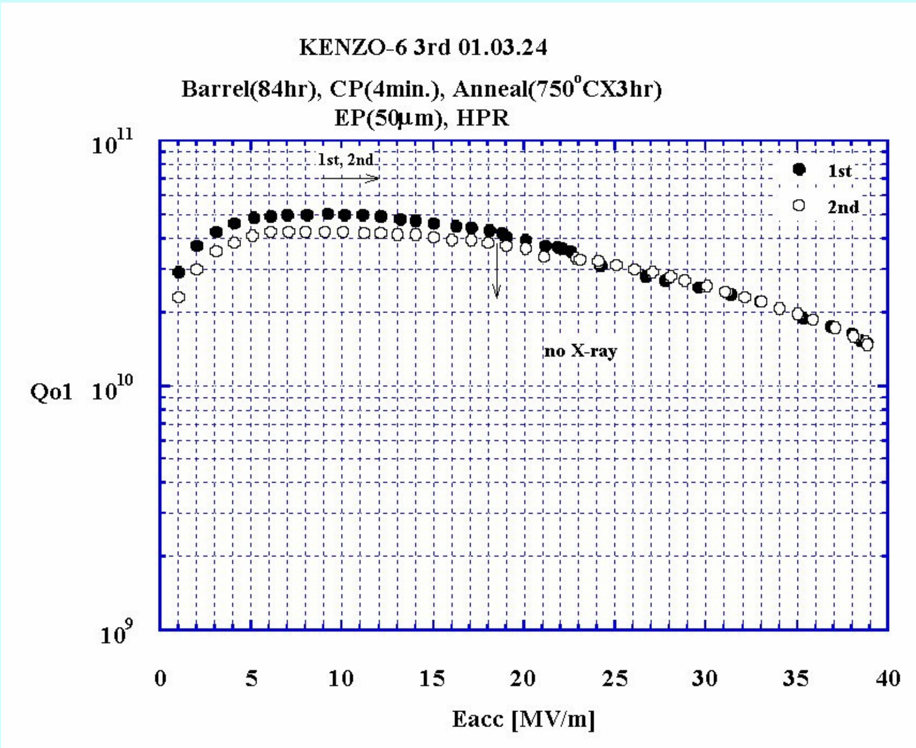
$$Q_2 = Q_{0,2}\, e^{-k_2 b}$$

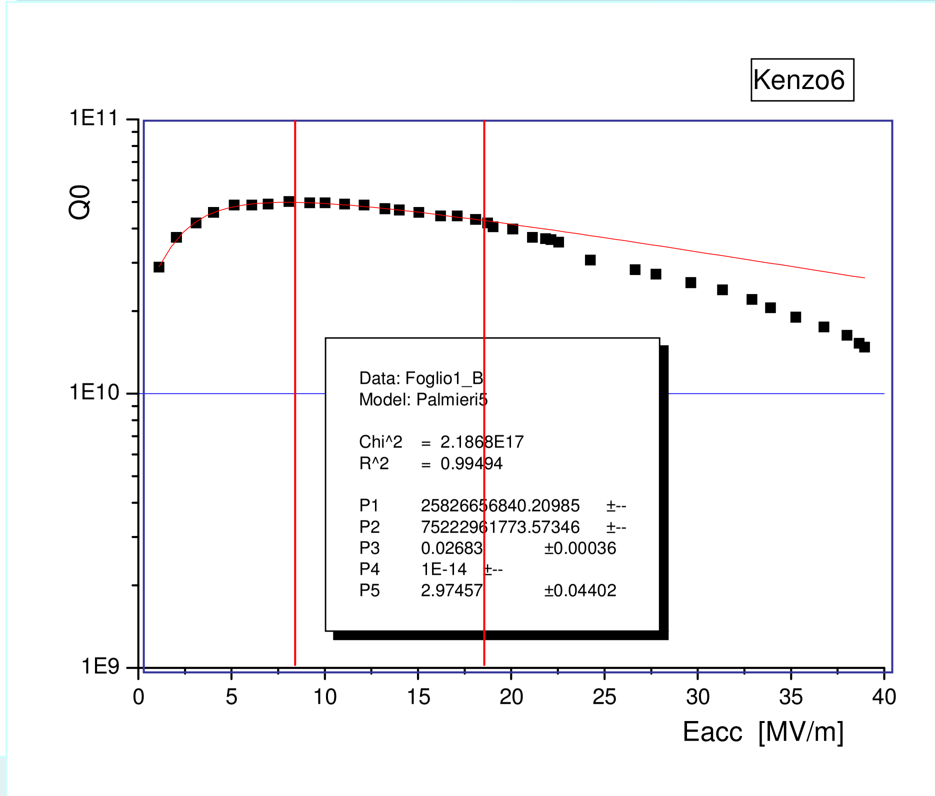
$$\lambda(b) \cong \lambda_0 + \alpha b$$



$$Q = Q_1 + (Q_2 - Q_1)\, e^{-a/\lambda 1}$$

$$Q = Q_1 + (Q_2 e^{-k_2 b} - Q_1) e^{-\frac{a}{(\lambda 1 + \alpha b)}}$$





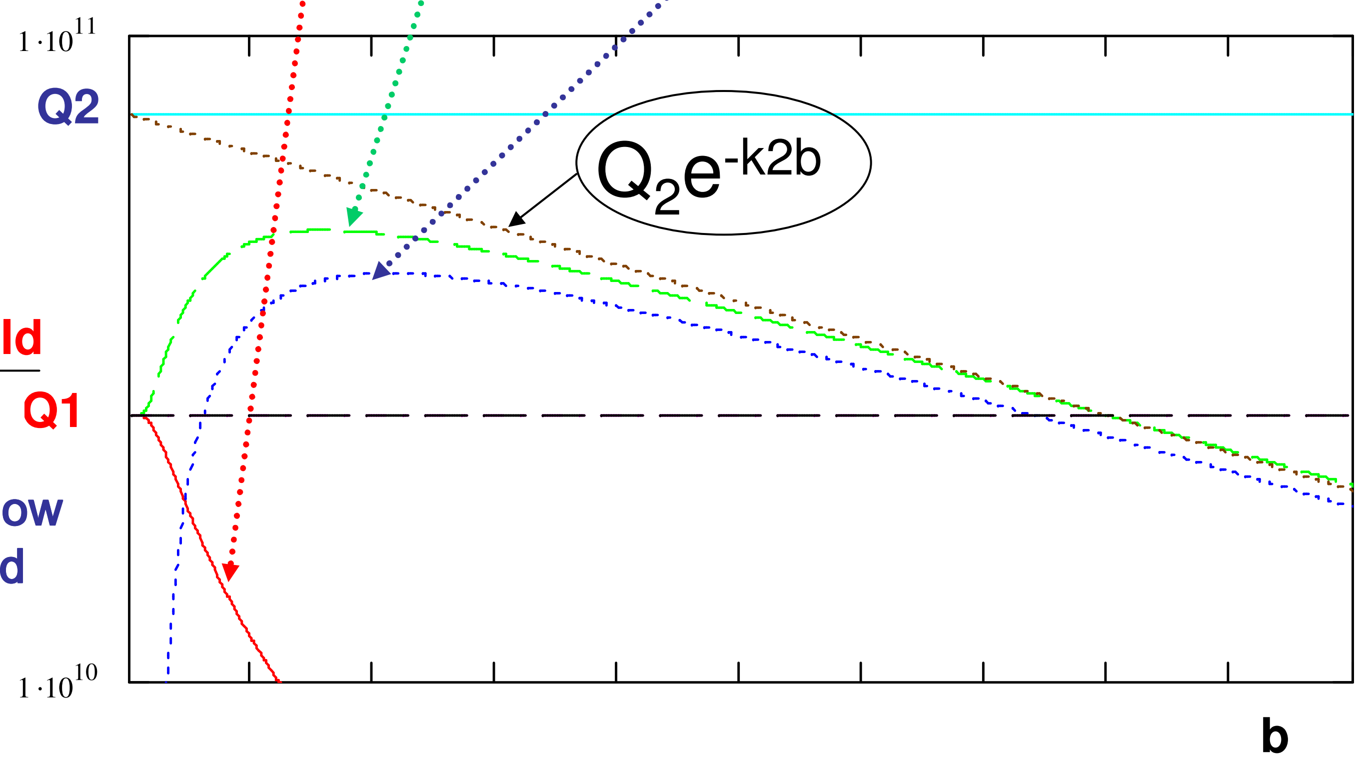
$$Q = Q_1 + (Q_2 e^{-k_2 b} - Q_1) e^{-\frac{a}{(\lambda 1 + \alpha b)}} =$$

$$= Q_1 * \left(1 - e^{-\frac{a}{(\lambda 1 + \alpha b)}}\right) + Q_2 * e^{-k_2 b} e^{-\frac{a}{(\lambda 1 + \alpha b)}}$$

Why Q increases with field?

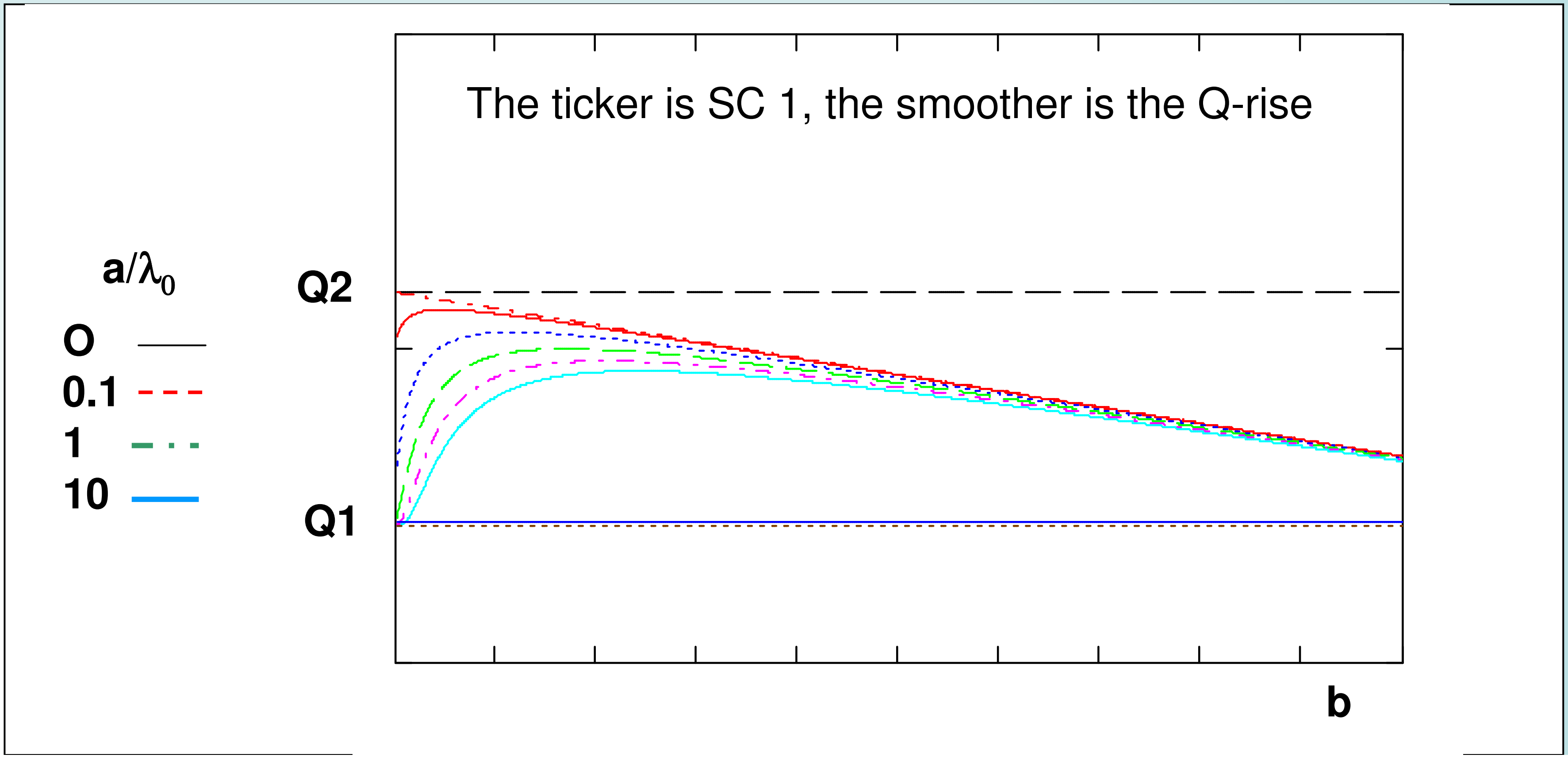
The more λ1 increases vs field

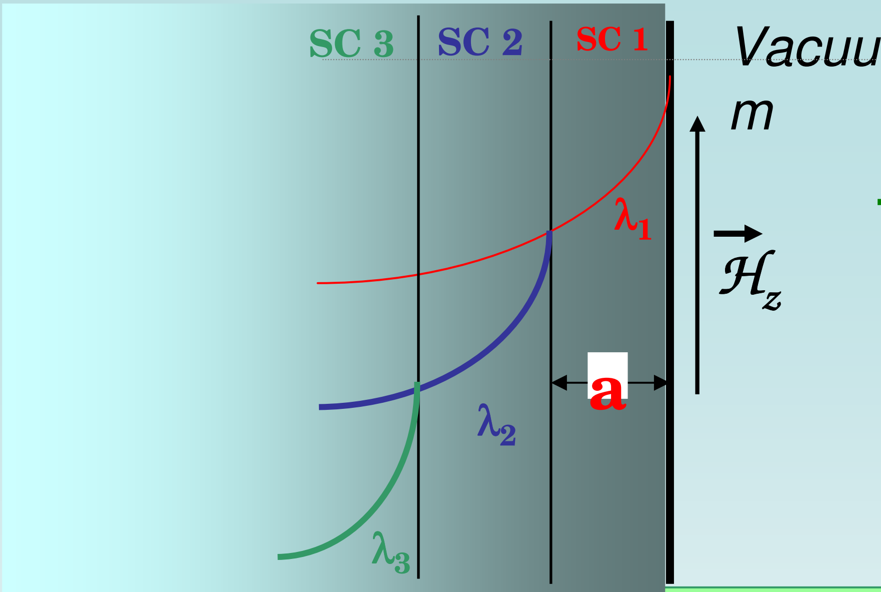
The more SC2 (low losses) is involved



$$Q = Q_1 + (Q_2 e^{-k_2 b} - Q_1) e^{-\frac{a}{(\lambda 1 + \alpha b)}} =$$

$$= Q_1 * \left(1 - e^{-\frac{a}{(\lambda 1 + \alpha b)}}\right) + Q_2 * e^{-k_2 b} e^{-\frac{a}{(\lambda 1 + \alpha b)}}$$





Three Superconductors:
SC 3 + SC 2 + SC 1

$$\frac{1}{\lambda} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

$$Q = Q_1 + (Q_2 - Q_1)e^{-a/\lambda 1} + (Q_3 - Q_2)e^{-a/\lambda 1 - a/\lambda 2}$$

Generalization to **n** layers: SC n + SC n-1 +…+ SC 2 + SC 1

$$\lim_{\substack{a \to 0 \\ n \to \infty}} Q = Q_1 + \sum_{i=1}^{n-1}(Q_{i+1} - Q_i)e^{-a \sum_{J=1}^{i} \frac{1}{\lambda j}} = \int_0^\infty \frac{dQ(x)}{dx} e^{-\int_0^x \frac{1}{\lambda(\bar{x})} d\bar{x}} dx$$

$$\Delta(B) = \Delta_0 - kB$$

?

$$\Delta = \Delta_0 - p_f v_s$$

I.I. Kulik, V. Palmieri, "THEORY OF DEGRADATION AND NON LINEAR EFFECTS IN Nb-COATED SUPERCONDUCTING CAVITIES", **Proceedings of the Eight Workshop on RF Supercoductivity, Abano, Italy, October 1997, V. Palmieri, A. Lombardi eds. Special Issue of Particle Accelerators, Vol. 60,(1998)p.257-264**

The Ginzburg-Landau result

$$\cancel{\Delta = \Delta_0 (1 - H^2/H_c^2)}$$

does not apply!!!

$$\cancel{\Delta = \Delta_0 (1 - H^2/H_C^2)}$$

This formula has done a lot of damage to our community for the understanding of the Q-Slope

R.H. White and M. Tinkham, Magnetic-Field Dependence of Microwave Absorbtion and Energy gap in Superconducting Films, **Phys Rev, vol 136, 1A, (1964), p. A203**

"…..The qualitative features of Δ/Δ_0 dependences like $(1 - h^2)$ and $(1-h^2)^{1/2}$ arevery different from those of the experimental absorption curves reported here …. due to the disagreement between these results and previous theory and experiment, it must be concluded that the above procedure for determining an effective energy gap parameter as a function of H is too naive."

Y. Nambu, S.F. Tuan, Phys, Rev. Lett. 11, 119 (1963); Phys.Rev.133, A1, (1964)

"…Electrons moving parallel to the surface play a special role: since the magnetic filed will confine such an electron and the one with which it is paired to opposite surfaces of the film, they contribute little to the superconductivity pairing energy…"

This relation goes back to first principles

$$\Delta = \Delta_0 - p_f v_s$$

It means to take into account the supercurrent!

If for Superconducting Magnets the fundamental and indipendent parameters are 3: $\mathbf{T_c}$, $\mathbf{H_c}$ and $\mathbf{J_c}$, …..

why for Superconducting cavities, JC disappeared?

Is 40 MV/m (1600 G) a field not strong enough?

REVIEWS OF MODERN PHYSICS VOLUME 34, NUMBER 4 OCTOBER 1962

Critical Fields and Currents in Superconductors*

JOHN BARDEEN

UNIVERSITY OF ILLINOIS, Urbana, Illinois

… **II. THERMODYNAMIC RELATIONS**

To discuss the thermodynamics of a superconductor in a magnetic field or with current flow, it is most convenient to take the external field H and the superfluid velocity $\mathbf{v}_s$ as independent variables. ……

The displacement of the pairs causes an increase in free energy of the system which may be expressed simply in terms of $\mathbf{J}_s$……

APPENDIX B. DIRECT CALCULATION OF CHANGE OF GAP WITH CURRENT

... In the low temperature limit, there are no excitations formed and thus no change in D until the velocity vs reaches the value for which it is favorable to form pairs of excitations, corresponding to transfer of an electron from one side of the Fermi sea to the other. This criterion is (depairing condition)

$$\frac{1}{2}m\left({}^{p_f}\!/_{m}+v_s\right)^2-\frac{1}{2}m\left({}^{p_f}\!/_{m}-v_s\right)^2>2\Delta \qquad \text{or} \qquad p_f>2\Delta$$

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CONTENTS

This, of course, does *not* violate the sum rule, because under these conditions there is a great deal of absorption for $\hbar\omega < 2\Delta$ because of the existence of the thermally excited quasiparticles. This prevents a simple estimate of the annihilated area of the sort (3–45), and thus makes a more detailed calculation necessary. Even so, the limit (6–38) can be simply interpreted by noting that for $kT \gg \Delta$, only a fraction $\sim (\Delta/kT)$ of the normal absorption is by electrons lying in the region that is affected by the opening of the gap. This accounts qualitatively for the factor of (Δ/kT) which distinguishes (6–38) from (6–37).

Penetration depths

Given a theoretical expression for $I(\omega, R, T)$ or equivalently $K(\omega, q, T)$ based on the microscopic theory, the calculation of penetration depths proceeds exactly as outlined in III-*B*. The expressions (3–27) and (3–28) are used to compute λ for the cases of specular and diffuse reflection of the electrons at the surface. Because $J(R, T)$ defined by (6–28) is so similar to e^{-R/ξ_0}, $K_{BCS}(q) \approx K_p(q)$, and calculations of the penetration depth with BCS lead to results that are almost identical with those of the Pippard theory.

The most interesting feature is that BCS predicts a definite temperature dependence for λ, which is similar to that, $(1 - t^4)^{-\frac{1}{2}}$, of the Gorter–Casimir–London theory, but which differs significantly. In particular, if one plots λ *vs* $y = (1 - t^4)^{-1/2}$, which leads to a straight line in the GCL theory, one finds a good straight line above about $y = 2\,(T/T_c \approx 0.9)$ where most of the variation of λ occurs, but an increased slope as $y \to 1\,(T/T_c \to 0)$. Since for years the result $\lambda \sim (1 - t^4)^{-\frac{1}{2}}$ had been accepted as describing the experimental results very well, this new prediction has been carefully tested. Results are somewhat conflicting, but on pure metals the evidence favors the BCS prediction. (See, for example, Schawlow and Devlin, Phys. Rev. *113*, 120 (1959).) With alloys where $l < \xi_0$, the situation is less clear. Recent experiments by Pippard and co-workers seem to be fit better by the old theory, but the reason for this is not known since the old theory has no microscopic foundation.

D. Persistent Currents

Consider the BCS ground state at $T = 0$. Now imagine that a uniform electric field is momentarily applied. In this case, the wavefunction will evolve in time with each k-value changing as

$$k(t) = k(0) + \frac{e}{\hbar}\int_0^t E(t)dt \qquad (6\text{—}39)$$

Thus the entire Fermi sphere, modified by the BCS $h(k)$ near the surface, is displaced in k-space. In particular, the pair $k\uparrow$, $-k\downarrow$ evolves into the pair

$$(k + q)\uparrow, \qquad (-k + q)\downarrow \qquad (6\text{—}40)$$

where $q = (e/\hbar)\int_0^t E(t)dt$. Now, as noted in conjunction with the BCS reduced interaction (4–8), we can perfectly well use these displaced pairs as the basis for the wavefunction, because the scattering operator simply conserves momentum, and all these pairs have the same momentum $2q$. However, the kinetic energy of the electrons is increased. For each pair

$$2\frac{\hbar^2k^2}{2m} \to \frac{\hbar^2}{2m}(\vec{k} + \vec{q})^2 + \frac{\hbar^2}{2m}(-\vec{k} + \vec{q})^2 = 2\frac{\hbar^2}{2m}(k^2 + q^2) \qquad (6\text{—}41)$$

Thus, summed over the sphere, there is an increase in energy of

$$\Delta KE = 2\,\frac{n}{2}\,\frac{\hbar^2q^2}{2m} = \frac{1}{2}\,nmv_s^2 \qquad (6\text{—}42)$$

which is just the classical value for n per electrons/unit volume moving with velocity $v_s = \hbar q/m$. Evidently, if this increase in kinetic energy exceeds the condensation energy $(H_0^2/8\pi)$, the current would be unstable, and the system would be expected to go normal to stop the current. Otherwise, this displaced state might be expected to be stable, describing a persistent current of density

$$J_s = nev_s \qquad (6\text{—}43)$$

Before this conclusion is established, however, one must consider possible excitations. Even at $T = 0$, it might be energetically favorable to create a pair of γ-quasiparticles. The most favorable case would be to create partial holes on the "leading" edge of the Fermi sphere and partial electrons on the "trailing" edge. This costs 2Δ in binding energy, but the decrease in kinetic energy is

$$\tfrac{1}{2}\,m(v_0 + v_s)^2 - \tfrac{1}{2}\,m(v_0 - v_s)^2 = 2mv_0v_s = 2\,|p_F|\,v_s$$

Thus, the superconducting state becomes unstable against pair creation when

$$2\,|p_F|\,v_s < 2\Delta$$

of when

$$v_s > \frac{\Delta}{|p_F|} \qquad (6\text{—}44)$$

For the simple free electron model, this criterion is slightly more restrictive than that based on (6–42). In fact, (6–44) yields

$$v_{crit} = \frac{H_0}{\sqrt{6\pi mn}} \qquad (6\text{—}45)$$

whereas (6–42) yields $\sqrt{3/2}$ times this value.

If the current is held below these critical values, it should be stable against catastrophic collapse. The question remains whether the phonons present at any finite temperature cannot slowly bring the current to zero. In the normal state, they certainly would do so, the mechanism being the scattering of electrons out of the high energy side of the displaced Fermi sphere and into the holes on the low energy side. But in a superconductor it costs an energy $\approx 2\Delta$ to

Applied Superconductivity

by *Vernon* L. Newhouse, Ph.D.
General Electric Research Laboratory
Schenectady, New York

John *Wiley & Sons,* Inc., New York · London · Sydney

this book. A more detailed account of the microscopic theory, and of its applications to various phenomena of superconductivity, is given in the review by Bardeen and Schrieffer (1961), and in the book by Lynton (1962).

11.3 Calculation of the Electron Depairing Velocity

By using the BCS model it is possible in a straightforward manner[24] to deduce the destruction of superconductivity by a critical current density. The argument runs as follows.

In a metal the conduction electrons are in motion even at absolute zero since they occupy states of finite kinetic energy. When carrying a current, the conduction electrons assume a net velocity in the current direction. In a normal metal any of these electrons can be scattered to unoccupied velocity states by interacting with an oscillating lattice ion or a lattice irregularity. If the electron is scattered to a lower velocity, it loses kinetic energy to the lattice, which appears as heat. It is this scattering of current-carrying electrons to lower velocities, accompanied by energy transfer to the lattice, that gives rise to the ohmic resistivity of the normal state.

In the superconducting state, current is carried by electrons paired with a binding energy 2Δ. Electron scattering to a different velocity state must be accompanied by electron de-pairing that results in an increase 2Δ in the potential energy of the electrons. It is shown in the following paragraphs that for electron velocities below a critical value, the maximum decrease in electron kinetic energy that can be achieved by scattering to a lower velocity is outweighed by the increase in electron potential energy due to de-pairing. Under these circumstances, the conduction electrons cannot lose energy to the lattice by scattering, so that the ohmic resistance is zero. The current-induced phase transition takes place when the current density becomes so large that the electron velocity exceeds the critical value for de-pairing.

In Chapter 1 it was pointed out that the critical current in a bulk superconductor is that which produces a surface field H_c. This suggests that the critical field rather than the critical current is fundamental in causing the phase transition. The above reasoning shows that the opposite is the case. In fact, it is found that the critical field corresponds to that which induces a screening current of critical density in the surface of a superconductor; and it is shown in Chapter 4 that the critical field of a thin film is therefore inversely proportional to its thickness and rises indefinitely as the film thickness is reduced. Clearly, therefore, it is the critical current density rather than the critical field that is fundamental in both the current and field-induced superconducting transition.

[24] Bogoliubov et al. (1958).

The critical velocity for electron de-pairing will be calculated at $T = 0$ and for the case of a film much thinner than the penetration depth, so that any current carried by the film can be assumed to be uniformly distributed throughout its thickness. It is convenient to use the representation shown in Figure 3.9a. Every point in this diagram represents a particular velocity state that can be occupied by no more than two electrons (of opposite spin). At absolute zero all the momentum states within the "Fermi

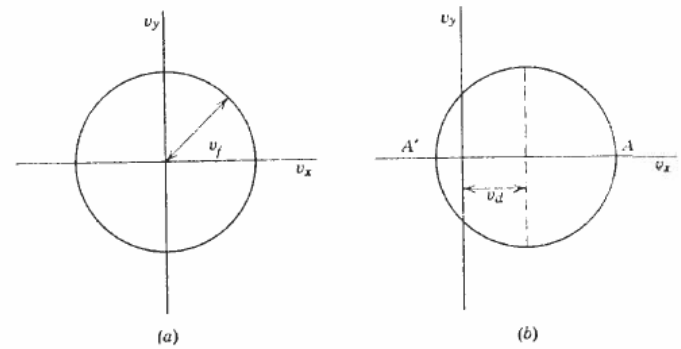


Fig. 3.9 Distribution of the conduction electrons among velocity states. (*a*) Zero net current. (*b*) Current density $J = nev_d$.

sphere" of radius v_f are occupied, and all those outside the sphere are unoccupied. In other words, at absolute zero all the electrons have velocities equal or less than $|v_f|$.

The so-called Fermi energy corresponding to the maximum velocity is $E_f = \frac{1}{2}mv_f^2$ where m is the effective electron mass. In the superconducting state the maximum energy of the electrons is reduced to $E_f' = E_f - \Delta$. $\Delta \ll E_f$, so that the effect of the energy gap on the Fermi energy can be neglected in this calculation.

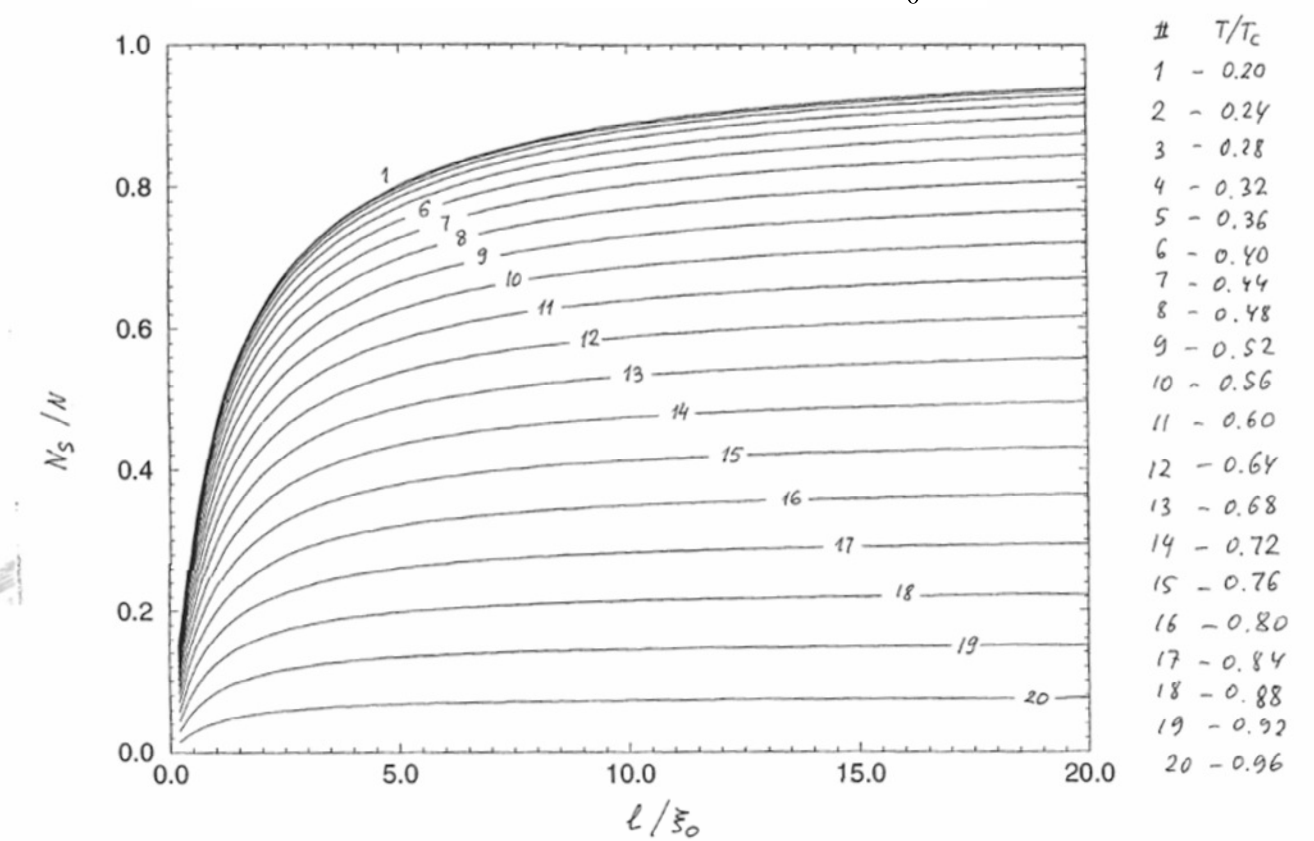
For each electron of a virtual pair having velocity v, the kinetic energy will be reduced by the binding energy Δ, so that the total energy per electron is $E = \frac{1}{2}mv^2 - \Delta$. Assume an electron current of density J flowing through the lattice. This will be associated with a mean electron drift velocity v_d so that $J = env_d$. If J is along the x axis, the Fermi sphere will be displaced a distance v_d along this axis (Fig. 3.9b). In the normal metal, some of the electrons moving through the lattice will be scattered to unoccupied states of lower velocity giving up energy to the lattice.

The scattering process involving the greatest loss of velocity and therefore the greatest loss of energy to the lattice is one in which an electron at

$$R_{BCS} \approx e^{-\frac{\Delta}{kT}} = e^{-\frac{\Delta_0}{kT}+\frac{p_f v_s}{kT}}$$

$$\frac{p_f v_s}{kT} = \frac{B * \lambda_0 * e * v_F}{KT} \left(\frac{n}{n_s}\right)^{1/2}$$

$$\frac{p_f v_s}{kT} = \frac{B * \lambda_0 * e * v_F}{KT} \left(\cot gh \frac{\ell}{\xi_0}\right)^{1/2}$$



$$\frac{p_f v_s}{kT} = \frac{B * \lambda_0 * e * v_F}{KT} (\cot gh \frac{\ell}{\xi_0})^{1/2}$$

The parasitic term $P_f V_s$ is neglectable at high value of $\frac{\ell}{\xi_0}$ the pure bulk Nb case

It becomes important at low $\frac{\ell}{\xi_0}$

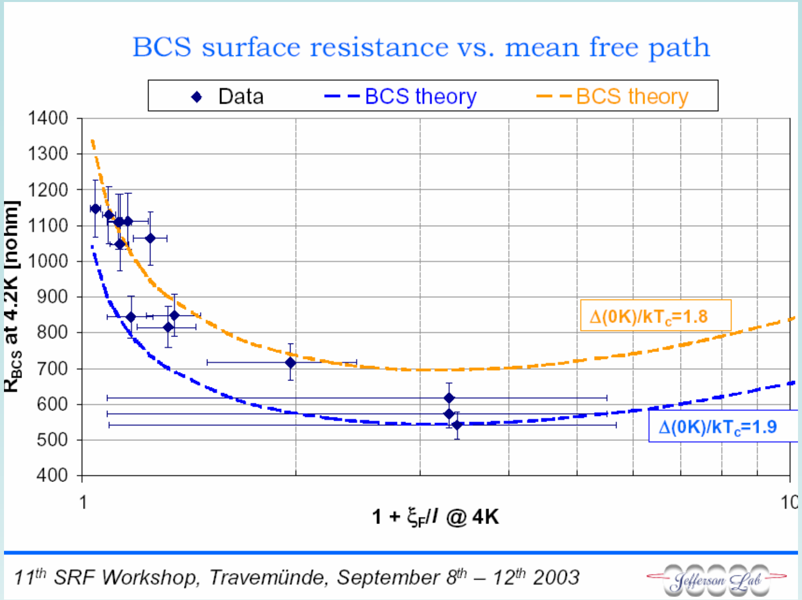
- thin film case
- contaminated surface after low temp baking

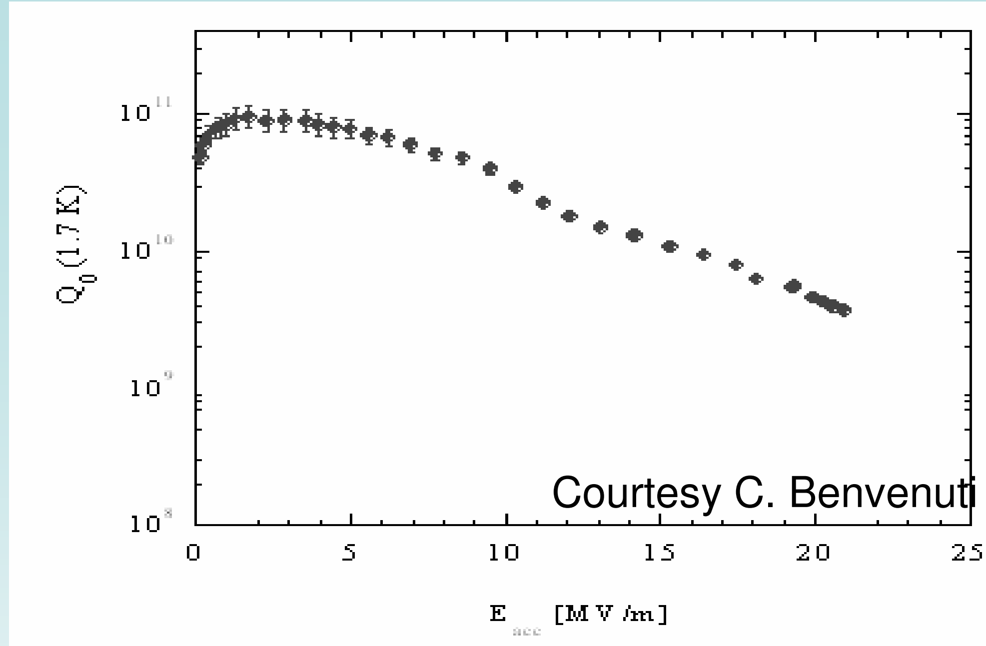
$$\Delta = \Delta_0 - p_f v_s$$

$$p_f v_s = B * \lambda_0 * e * v_F (\cot gh \frac{\ell}{\xi_0})^{1/2}$$

$$\xi_0 = \frac{\hbar * v_f}{\pi * \Delta}$$

This will affect λ_0 and $\mathbf{B_c}$





Courtesy C. Benvenuti et a

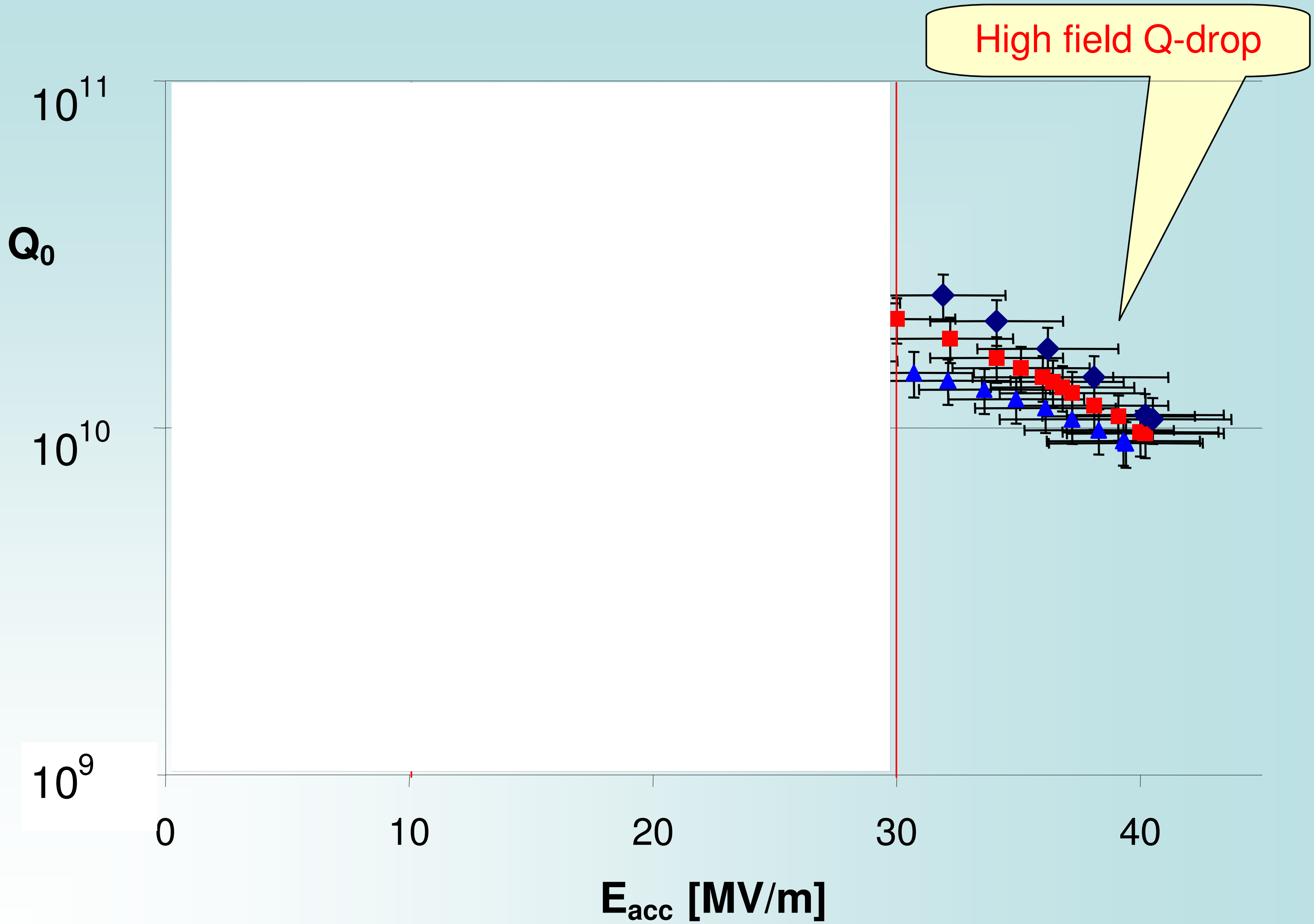
$$\frac{\ell}{\xi_0}$$

Is a key parameter; low values give:

- high Q

- higher slope

For film coated cavities there is no hope to get rid of the slope, unless RRR is increased, but in this case Q values will be lower than the actual

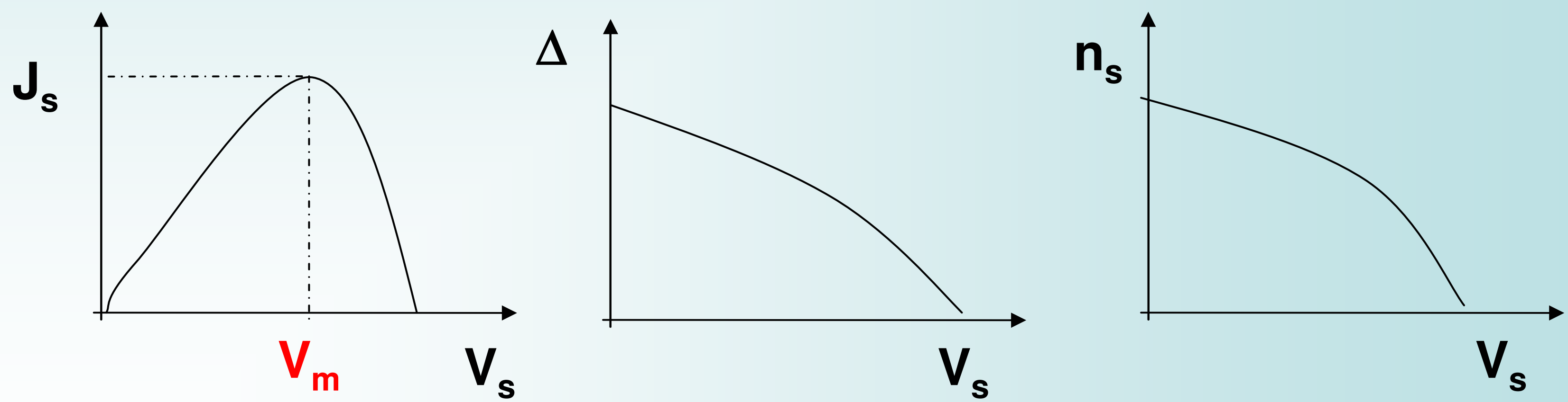

High field Q-drop
10^{11}
Q_0
10^{10}
10^{9}
0
10
20
30
40
E_{acc} [MV/m]

In local electrodynamics of superconductivity, $j = j_1 + j_2$

Where J_1 is the Meissner current $j_1 = n_s e v_s (1 - \frac{v_s^2}{v_c^2})$

At small supercurrent $j_1 = n_s e v_s$

but at larger V_s, GL theory foresees a deparing effect by the current



Over V_m the superconducting state become unstable

Conclusions:

- *Low field* - The hypotesis of an overlayer explains the Q rise

$$Q = Q_1(1 - e^{-a/\lambda 1}) + Q_2 e^{-a/\lambda 1}$$

- *Medium field* – The gap decrease linearly vs field

$$\Delta = \Delta 0 - p_f v_s$$

This effect is neglectable for high $\frac{\ell}{\xi_0}$ but is felt when $\frac{\ell}{\xi_0}$ is reduced

Film coated cavities: no hope to get rid of the slope, unless RRR is increased, but in this case Q values will be lower than the actual

- *High field* – The gap closes at V_C, but j_s start decreasing at $V_m < V_c$. Between V_m and V_C, there is instability