HOT TOPICS SESSION 1st part

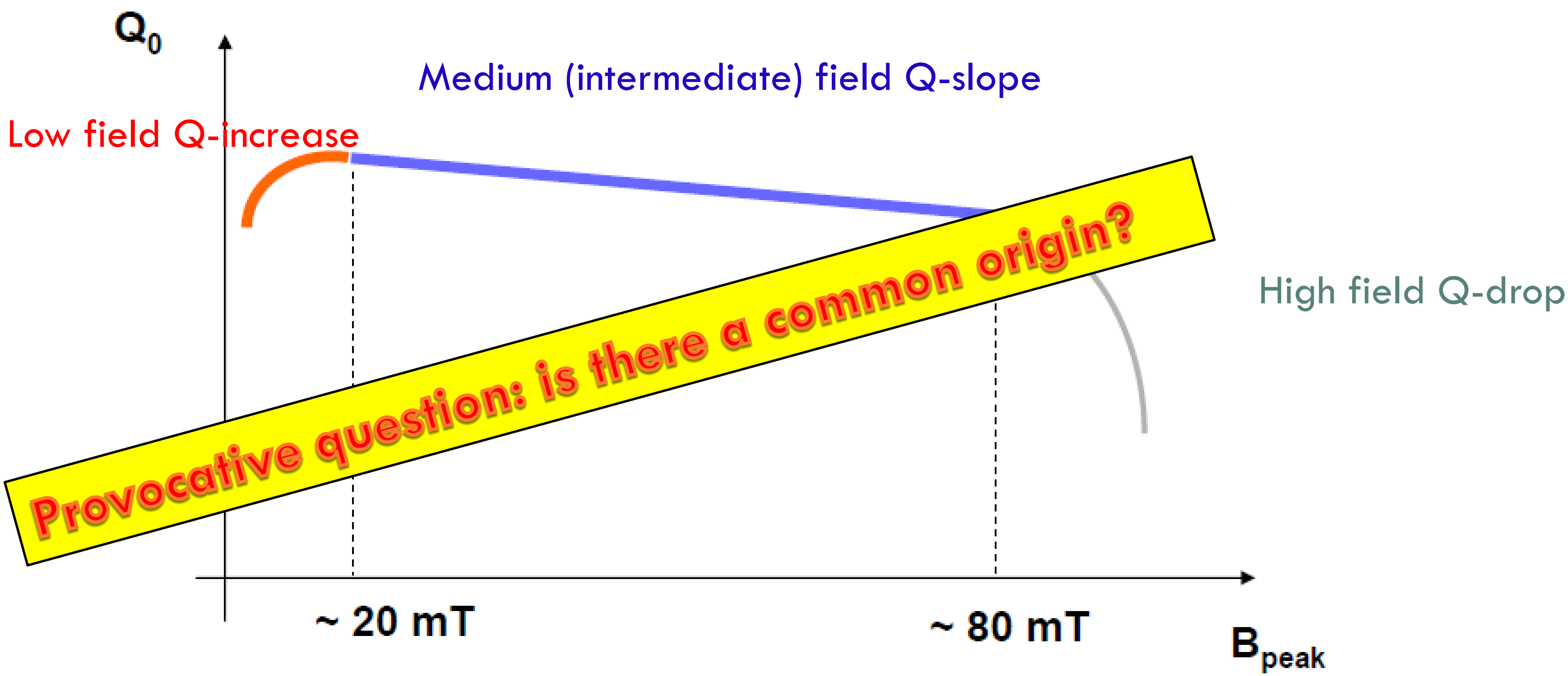
Medium field Q-slope and paths to high Q operation

1st part: Introduction

W. Weingarten / CERN

Disclaimer: no attempt made for a complete survey of original work

What are we talking about?



Incentive

Achieving larger gradients must be reciprocal to reducing the RF losses

Doubling the gradient => increasing Q by factor 4 and eliminating the medium and high field Q-slopes

Charge from International Program Committee

1. "In the final 15 minutes of the Mon., Tue., and Thur. sessions, just before lunch, the moderator will present **his view** of the current state of the particular topic. This 15 minute talk is intended to incite and provoke interest so a little bit of **controversy is welcomed**!
2. …
3. The moderator will also have **pre-arranged a set of conference attendees** who, in the 6 pm sessions, will present his or her viewpoint on the topic. These should not be full talks. However, the person may show a couple slides espousing a point of view. …"
4. …

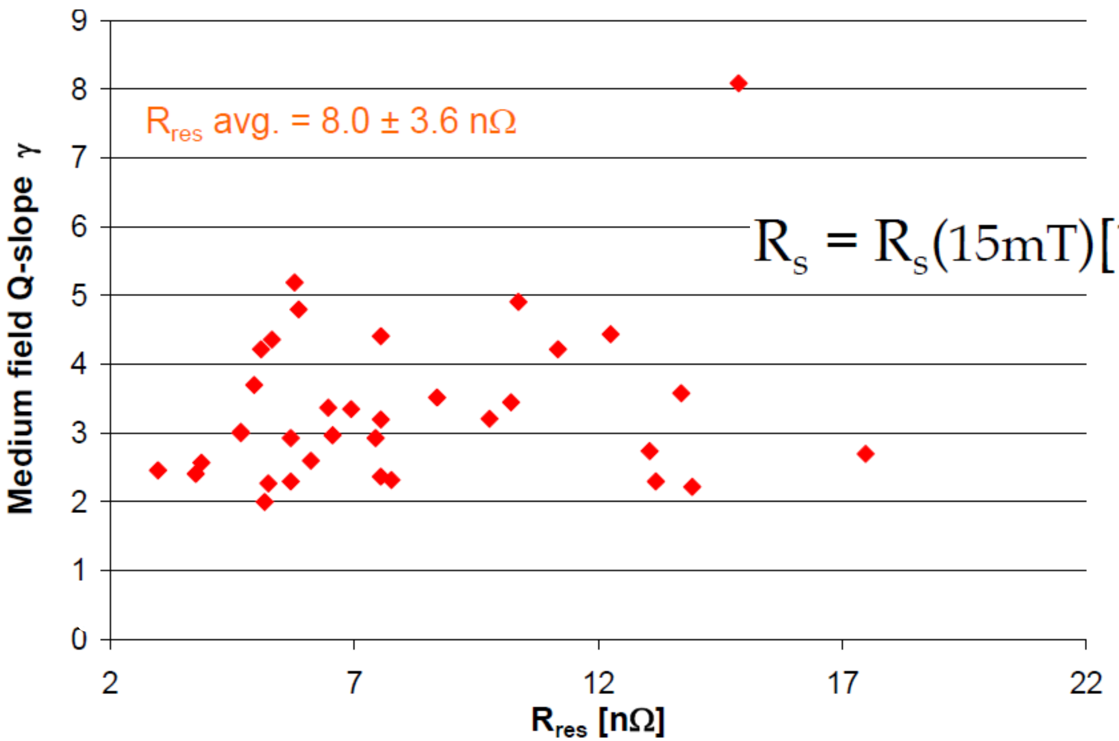
Experimental results on medium field Q-slope

- no correlation with residual resistance (#1 *)
- R_s factorizes into temperature dependent and field dependent part (#2 and #3)
- temperature dependent with threshold behavior (#4)
- pretty independent of baking, if not decreasing, for whatever previous treatment (#5)
- quadratic dependence of $R_{s,fd}$ on B (#6)
- magnetic field effect (#7)
- insensitive to HF rinsing (#8)
- also visible for heat flow parallel to surface (no temperature gradient across Nb wall) (#9)
- closely linked to surface conditions (#10)

fd = (magnetic) field dependent

*the numbers refer to the piece of evidence as collected in subsequent slides

medium field Q-slope #1
no correlation with residual resistance



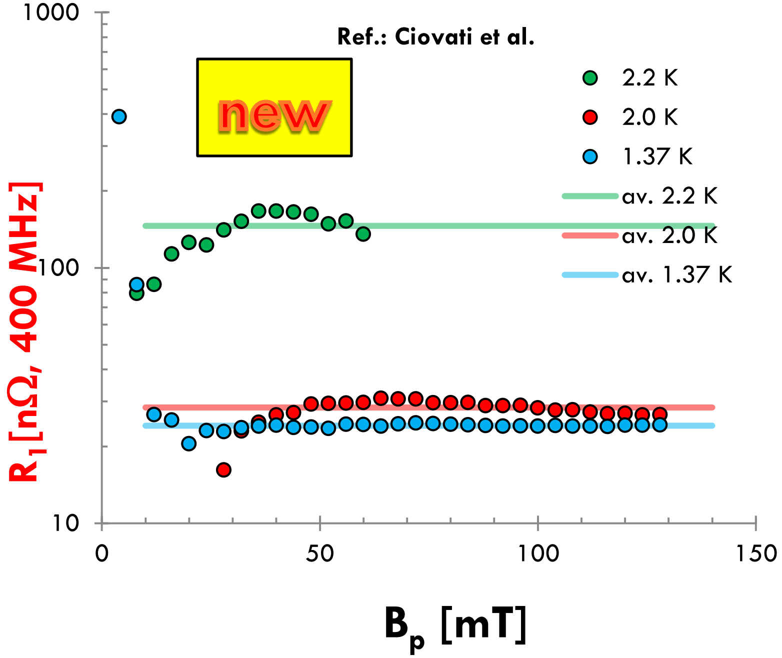
$$R_s = R_s(15mT)[1 + \gamma(B_p/B_c)^2]$$

G. Ciovati, Pushing the limits of RF superconductivity, Workshop Argonne 2004

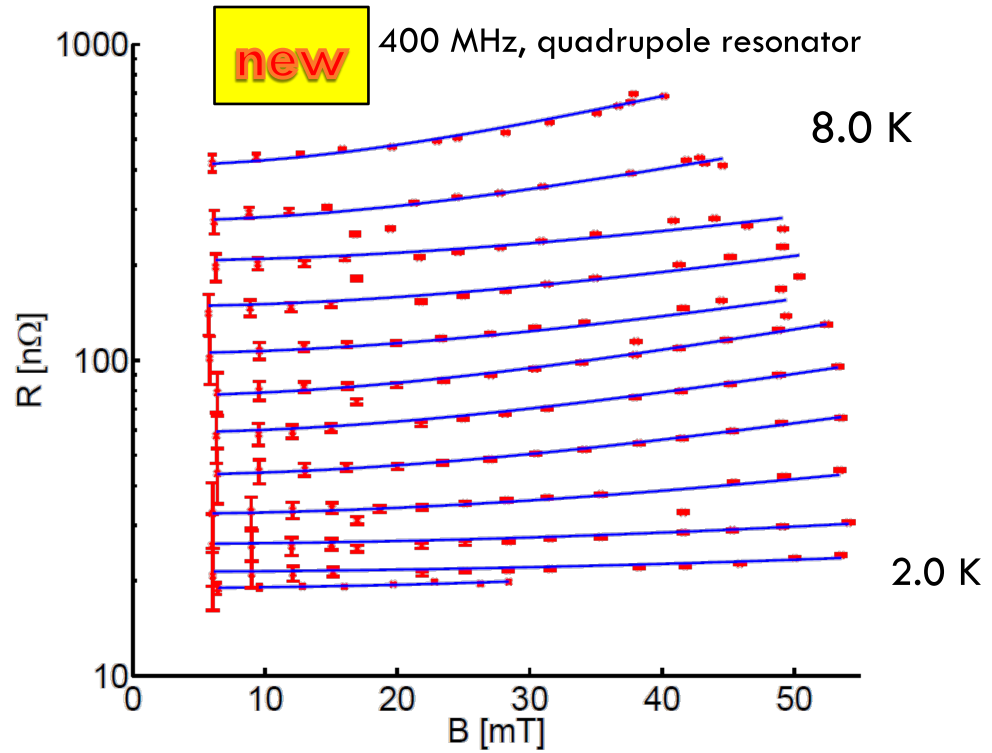
medium field Q-slope #2

factorization into temperature dependent and field dependent part

R_s-slope = [c + R_1 (T, ω)]· R_2(B)



W. Weingarten, ATS/Note/2011/019 TECH CERN



T. Junginger, this conference WEIOA04

medium field Q-slope #3 (Nb film on copper)

factorization into temperature dependent and field dependent part

C. Benvenuti et al. / Physica C 316 (1999) 153–188 165

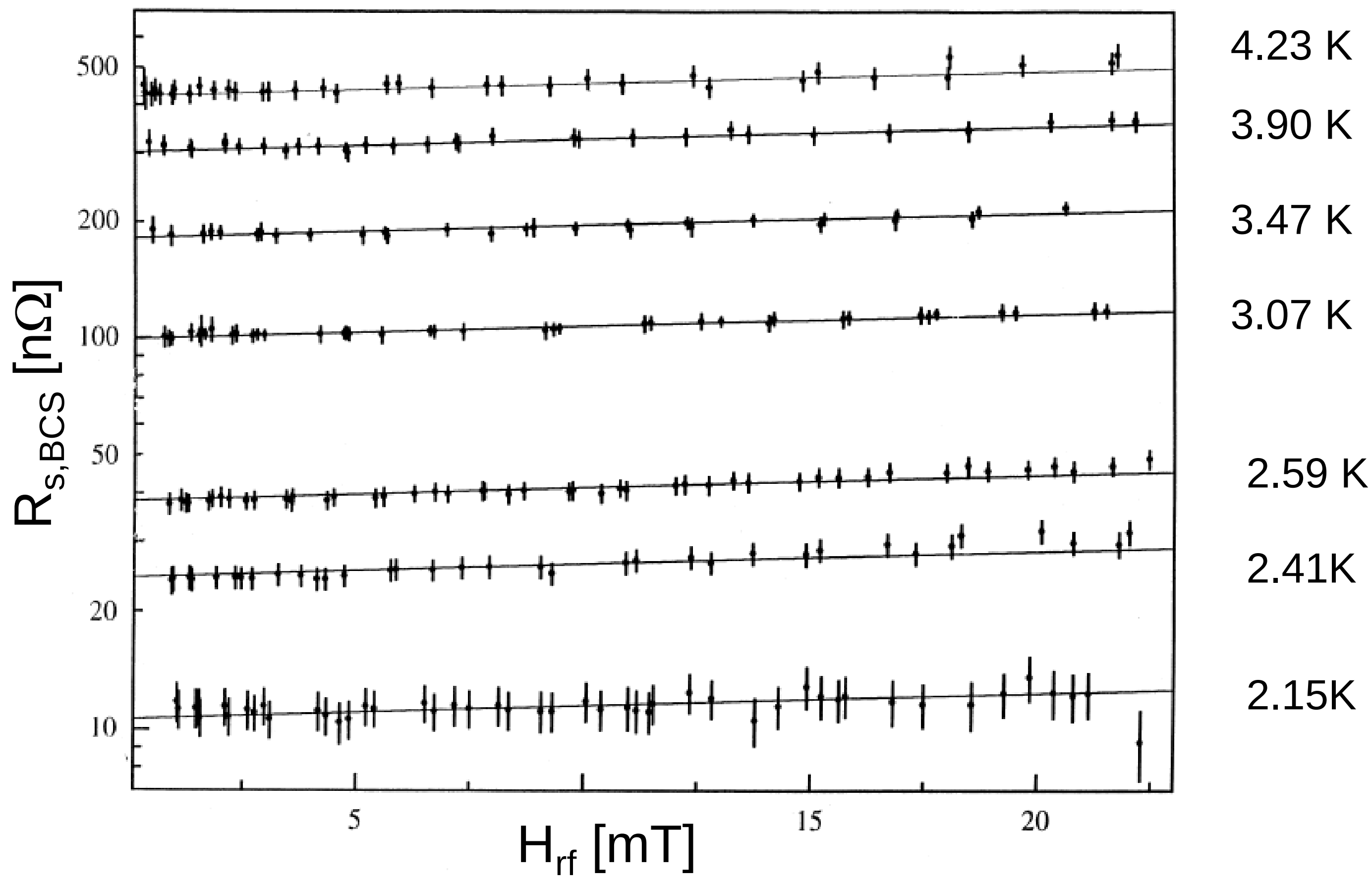
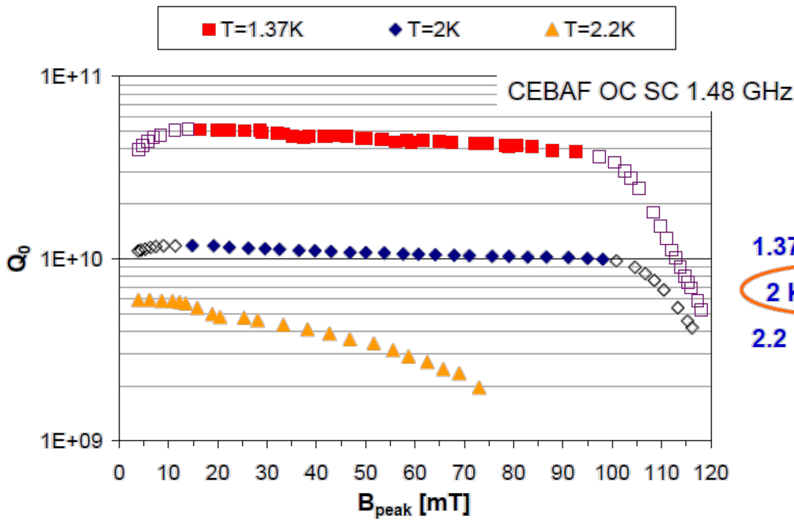


Fig. 8. Isothermal H_{rf} scans measured on a particular film. $R_{BCS}(T)$ is plotted as a function of H_{rf} for $T = 4.23$ K, 3.90 K, 3.47 K, 3.07 K, 2.59 K, 2.41 K and 2.15 K (from top to bottom). The lines represent the same H_{rf} dependence (up to a factor) for all values of T.

medium field Q-slope #4

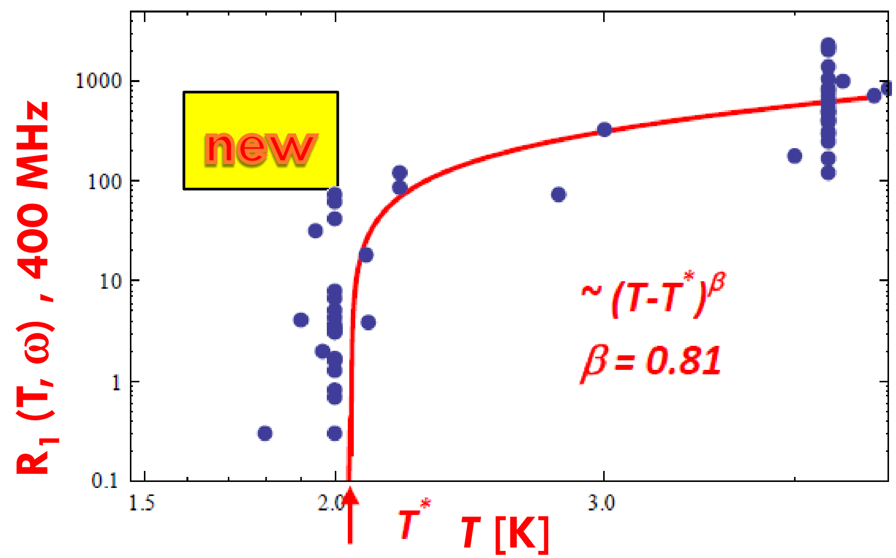
temperature dependent with threshold behavior

$$R_s = R_s(15mT)[1 + \gamma(B_p/B_c)^2]$$



	γ
1.37 K	1.85
2 K	0.94
2.2 K	13.7

$$R_s\text{-slope} = [c + R_1(T, \omega)] \cdot R_2(B)$$



Steep increase of slope between 2 and 2.2 K

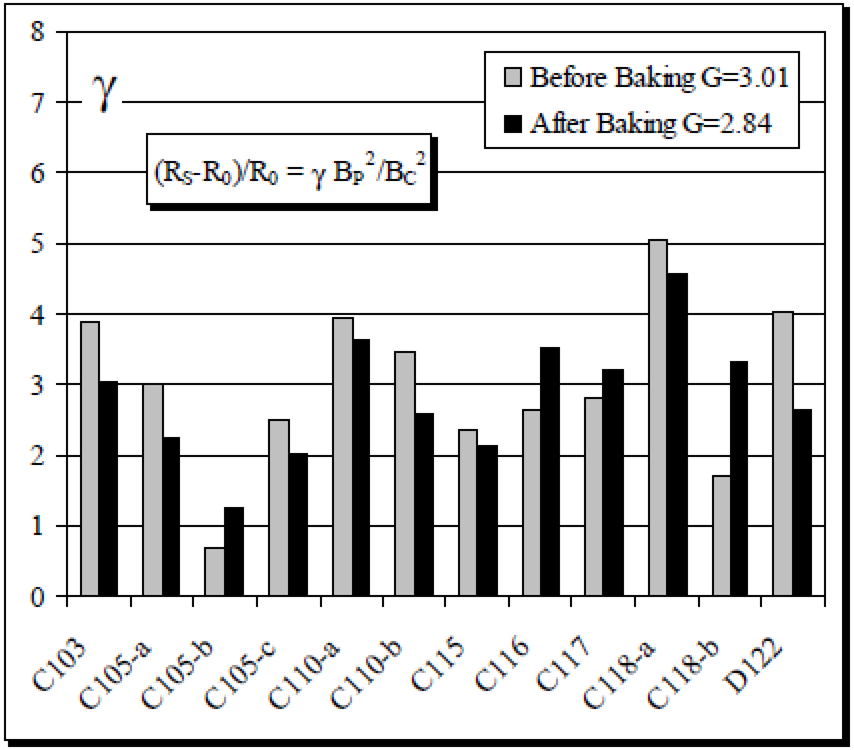
G. Ciovati, Review of frontier workshop, Argonne 2004

W. Weingarten, ATS/Note/2011/019 TECH CERN

medium field Q-slope #5

pretty independent of baking, if not decreasing, for whatever previous treatment

FIGURE 7. Gamma factor of the medium field Q-slope before and after UHV baking on BCP cavities, except for C103 and D122 (electropolishing) and for C110-b (air baking).



Low, Medium, High Field Q-Slopes Change with Surface Treatments

Bernard Visentin

Workshop "Pushing the limits ...", Argonne 2004

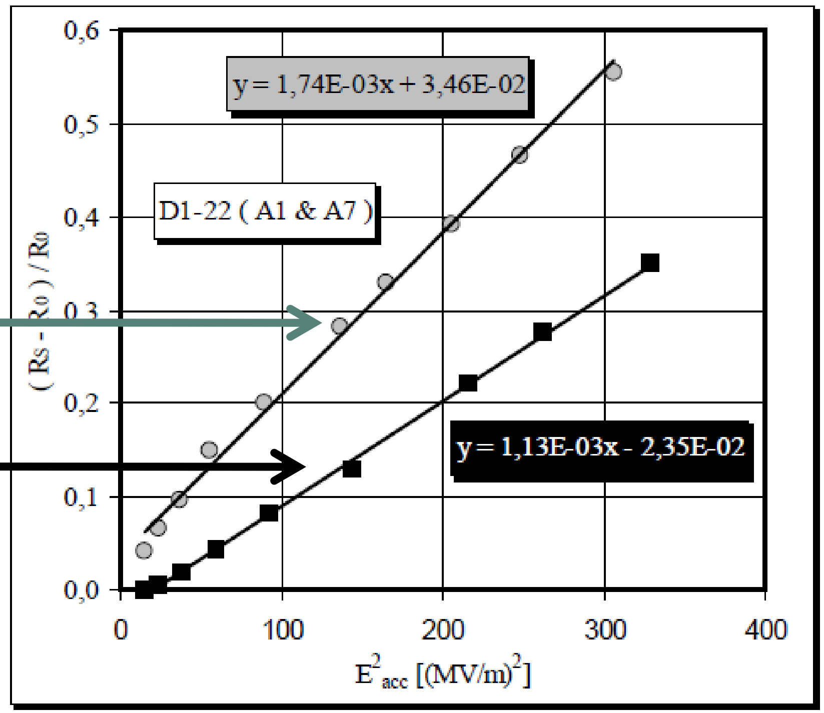
medium field Q-slope #6

quadratic dependence of $R_{s,fd}$ on B

fd = (magnetic) field dependent

before baking

after baking



Low, Medium, High Field Q-Slopes Change with Surface Treatments

Bernard Visentin

Workshop "Pushing the limits …", Argonne 2004

medium field Q-slope #7

magnetic field effect

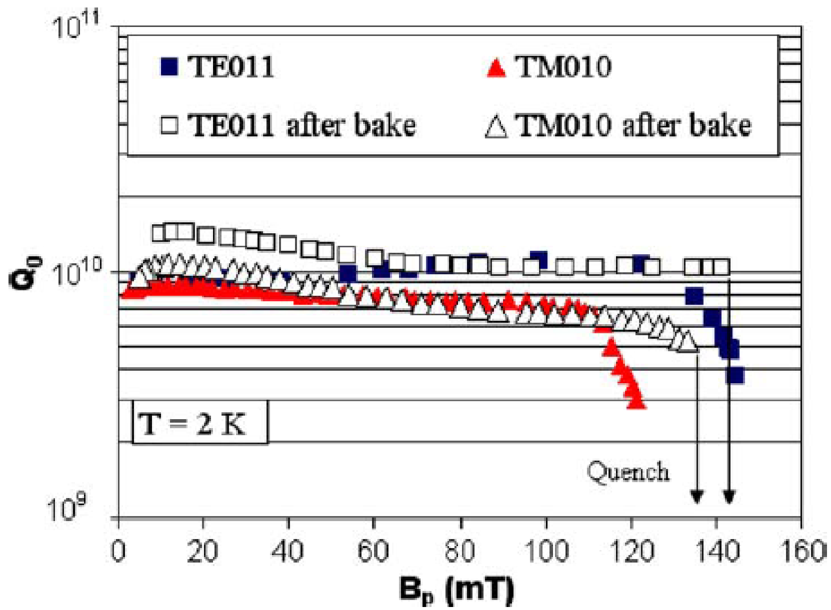
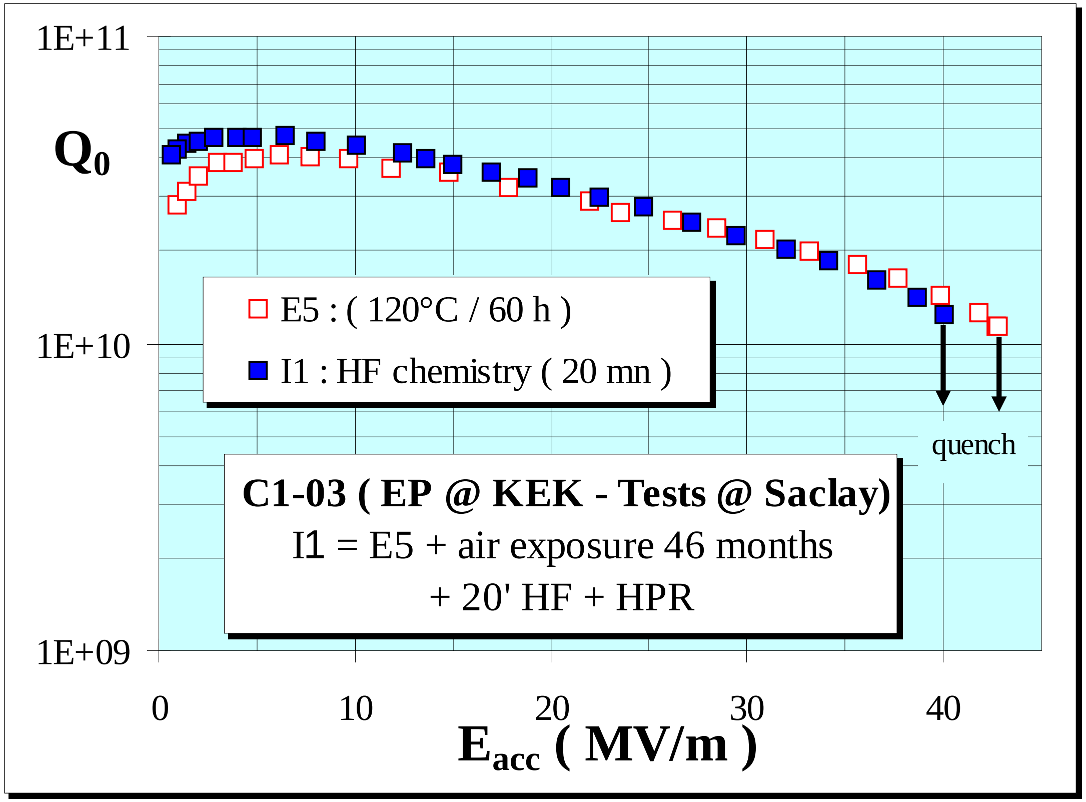


Fig. 8. Q_0 vs. B_p measured in the TM_{010} mode (1.47 GHz) and in the TE_{011} mode (2.82 GHz) of a post-purified single cell cavity before and after baking at 120 °C for 30 h [23].

G. Ciovati, Review of the frontier workshop and Q-slope results, Physica **C 441** (2006) 44.

medium field Q-slope #8

insensitive to HF rinsing

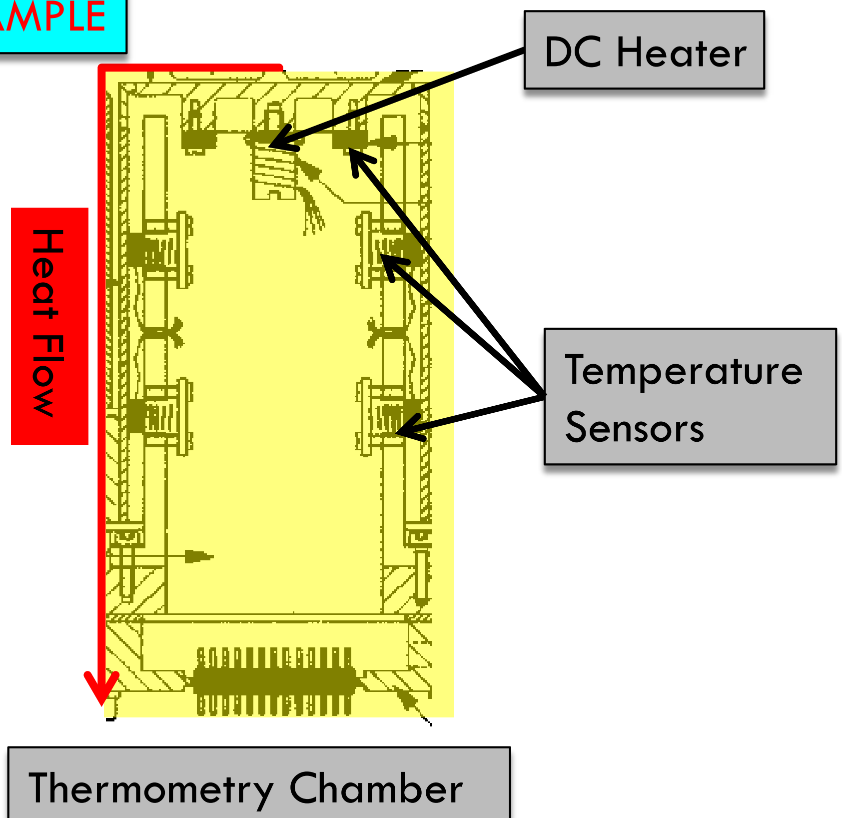


B. Visentin, International Workshop on Thin Films 2006, Legnaro (Italy), slide 17

medium field Q-slope #9

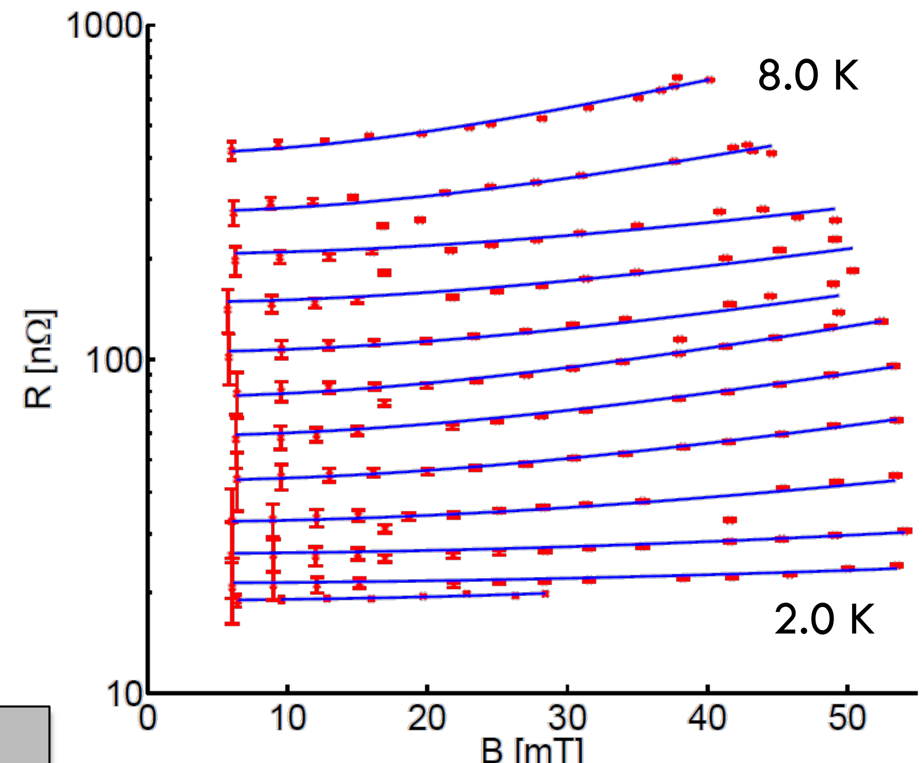
also visible for heat flow parallel to surface (no temperature gradient across cavity wall)

SAMPLE



RESULT

400 MHz, quadrupole resonator



T. Junginger, this conference WEIOA04

- Measured Temperature=Temperature on sample surface
- Precise calorimetric measurement technique

medium field Q-slope #10

closely linked to surface conditions

Nb/Cu

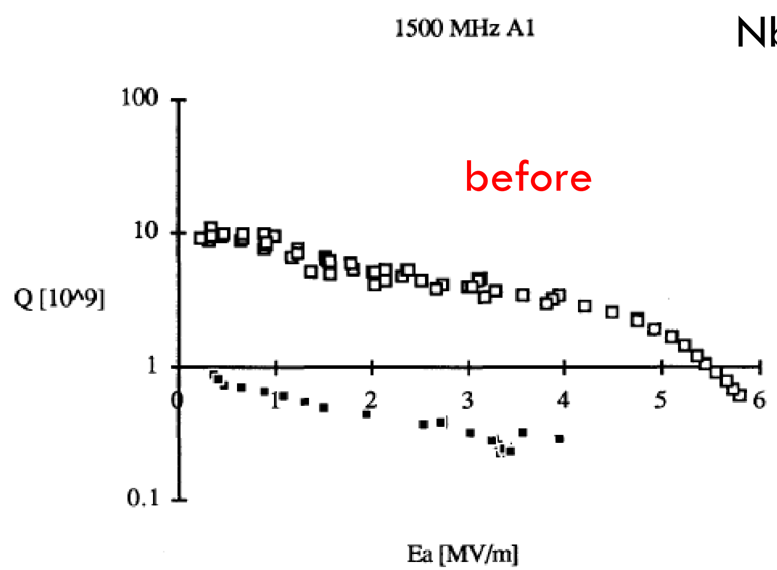


Fig. 2(a) Q value vs accelerating field for the fundamental mode at 4.2 K (lower) and 1.6 K (upper).

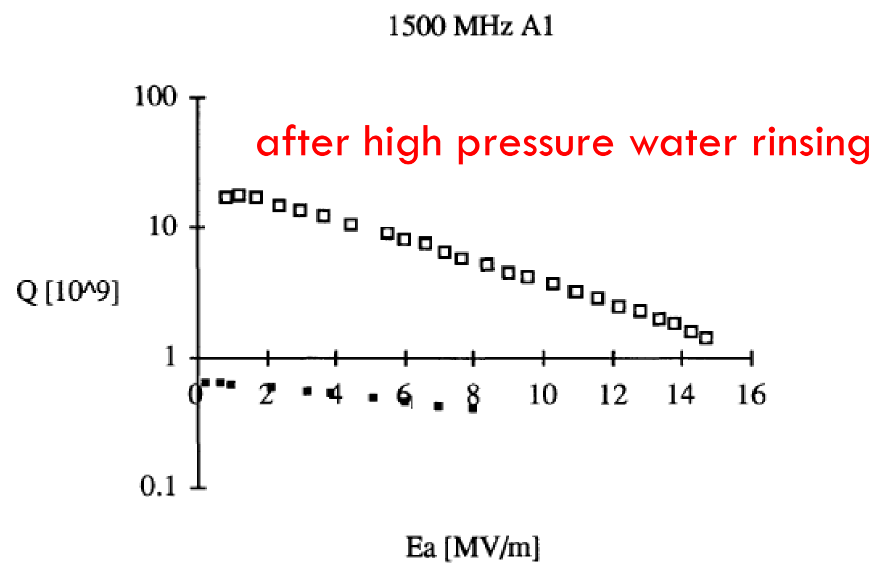


Fig. 2(b) Q value vs accelerating field for the fundamental mode at 1.6 K after high-pressure water rinsing at 4.2 K (lower) and 1.6 K (upper).

SUPERCONDUCTING NIOBIUM SPUTTER-COATED COPPER CAVITIES AT 1500 MHz

Ph. Bernard, D. Bloess, W. Hartung(*), C. Hauviller and W. Weingarten
CERN, Geneva, Switzerland

P. Bosland and J. Martignac
CEN Saclay, Gif-sur-Yvette, France

Proc. 5th Workshop RF Supercond. DESY Hamburg 1991

Current models for the Q-slope(s)

which I personally find

- **Magnetic field enhancement** at surface roughness features — **unplausible**
- **Interface tunnel exchange** (localized electrons are injected from the oxide layer into the sc metal assisted by electric field) — **unplausible**
- **Thermal feedback** via temperature dependent BCS contribution to surface resistance due to heat transport across cavity wall and interface to lHe — **unplausible**
- **Non-linear surface resistance** from current dependent energy gap — **unplausible**
- **Magnetic flux entry at B_{c1}** at favorable sites — **plausible**

More details in the discussion session at 6 pm

Thank you for your attention !

See you again at 6 p.m.

HOT TOPICS DISCUSSION 2nd part

Critical review of models against experiments

Outlook: paths to high Q operation

Current models for the Q-slope(s)

- **Magnetic field enhancement** at surface roughness features
- **Interface tunnel exchange** (localized electrons are injected from the oxide layer into the sc metal assisted by electric field)
- **Thermal feedback** via temperature dependent BCS contribution to surface resistance due to heat transport across cavity wall and interface to lHe
- **Non-linear surface resistance** from current dependent energy gap
- **Magnetic flux entry at B_{c1}** at favorable sites (such as screw dislocations)

Magnetic field enhancement model

Proceedings of the 1999 Workshop on RF Superconductivity, La Fonda Hotel, Santa Fe, New Mexico, USA

High-Field Q Slope in Superconducting Cavities Due to Magnetic Field Enhancement at Grain Boundaries

J. Knobloch*, R. L. Geng, M. Liepe†, and H. Padamsee
Floyd R. Newman Laboratory of Nuclear Studies
Cornell University, Ithaca, NY 14853
†DESY, Notkestrasse 85, D-22603 Hamburg

High-Field Q Slope

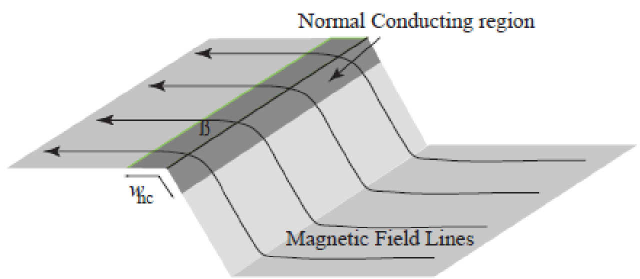
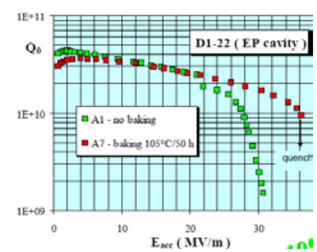
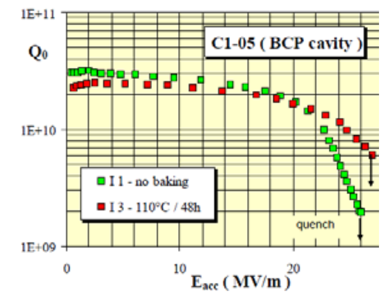


Figure 3: Schematic of a grain boundary that has quenched due to magnetic field enhancement at the grain boundary.

No difference EP and BCP treated cavities





Reproduction of high field Q-slope possible

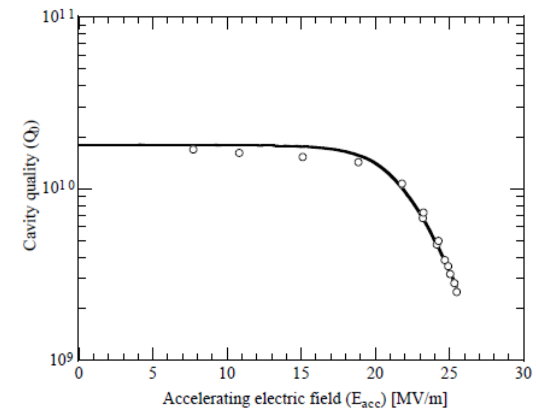


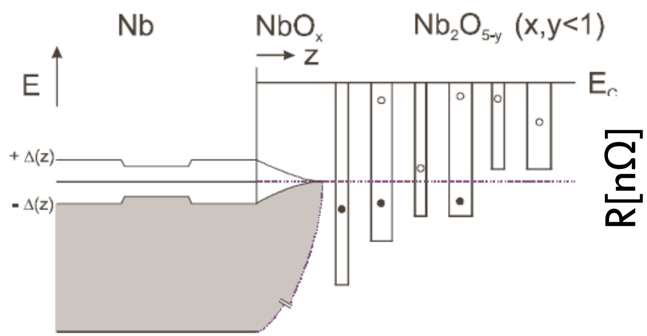
Figure 19: Comparison of the measured cavity quality (Test C) with that calculated by (25) using $H_{crit} = 1875$ Oe.

Interface tunnel exchange model

The 10th Workshop on RF Superconductivity, 2001, Tsukuba, Japan

MATERIAL SCIENCE OF Nb RF ACCELERATOR CAVITIES: WHERE DO WE STAND 2001?

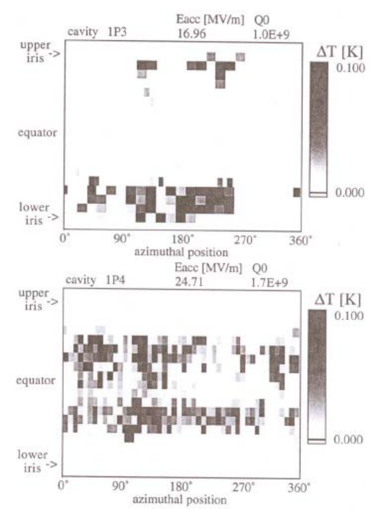
J. Halbritter



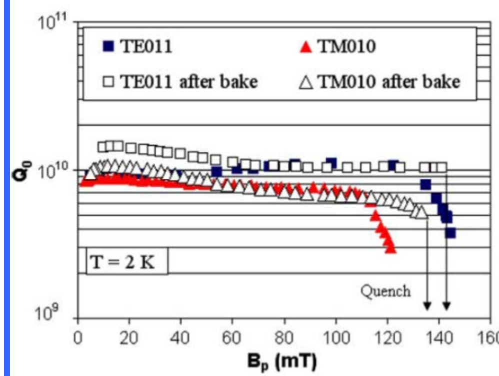
- Dissipation due to tunneling of sub-gap electrons via localised states at the Nb-NbO interface
- The effect is <u>driven by the surface electric field</u>
- In SC state the effect should be only observable above a threshold field
- Above the threshold the resistance should increase like

$$R(E^{\perp}) \propto e^{(-2\kappa\Delta\varepsilon_r / e\beta E^{\perp})}$$

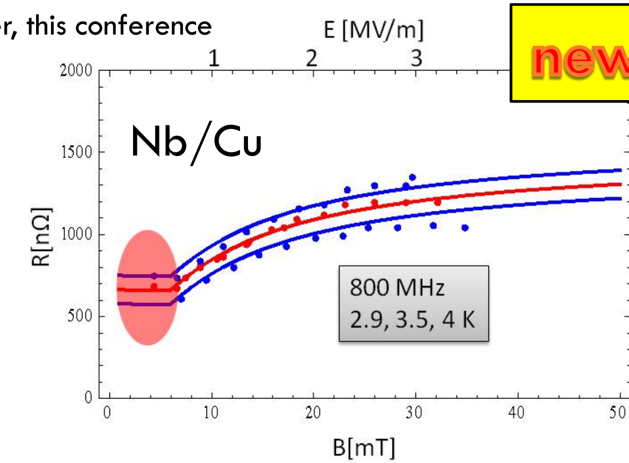
T-maps without e-loading



Similar results on TM_{010} and TE_{011} cavities



quadrupole resonator T. Junginger, this conference



new

Thermal feedback model

$$R = R_{\mathrm{BCS}}\left(1+\gamma\left(\frac{B_{\mathrm{p}}}{B_{\mathrm{c}}}\right)\right)^2$$

Systematic Trends for the Medium Field Q-Slope

J. Vines, Y. Xie, H. Padamsee

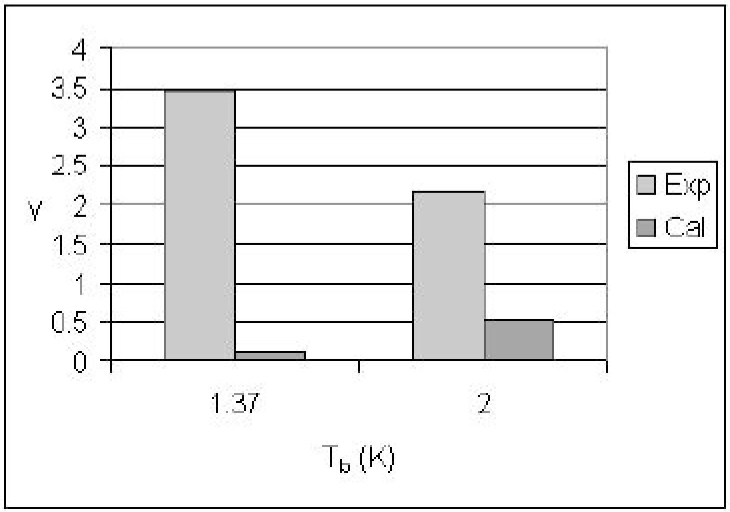
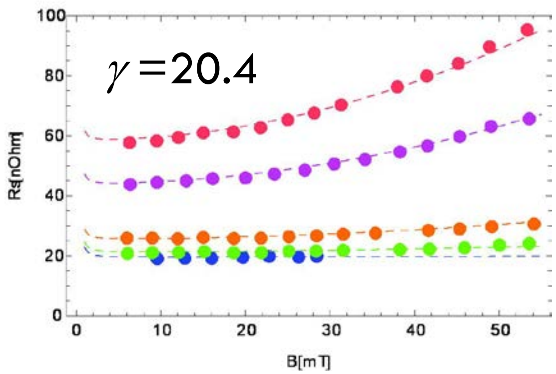


Figure 20: Comparison between data from a CEBAF cavity (light gray) and numerical simulation (dark gray).

"... significant disagreement between our thermal feedback model and experiment that needs to be addressed further"

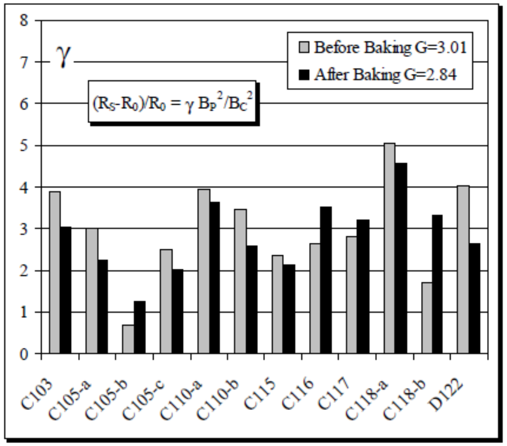
T. Junginger: quadrupole resonator

Nb bulk



Low, Medium, High Field Q-Slopes Change with Surface Treatments

Bernard Visentin



Non-linear surface resistance model

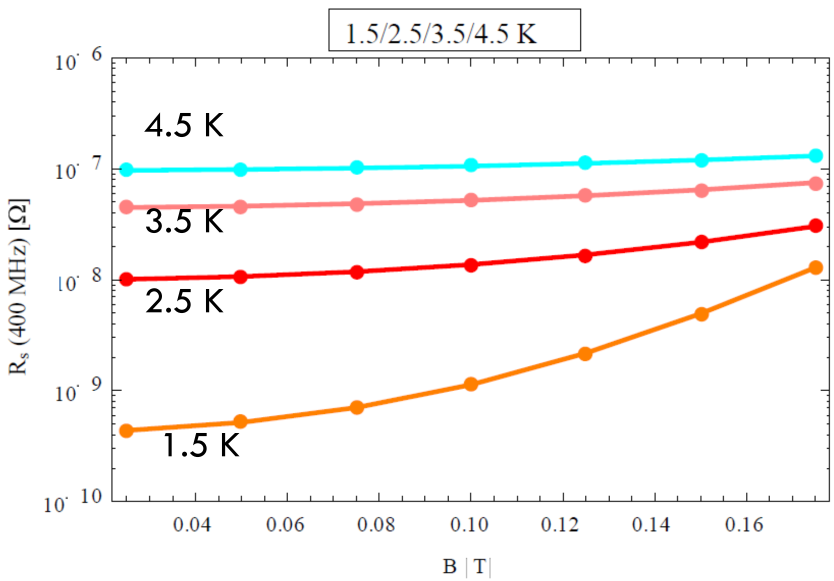
Physica C 441 (2006) 38–43

Multiscale mechanisms of SRF breakdown

A. Gurevich *

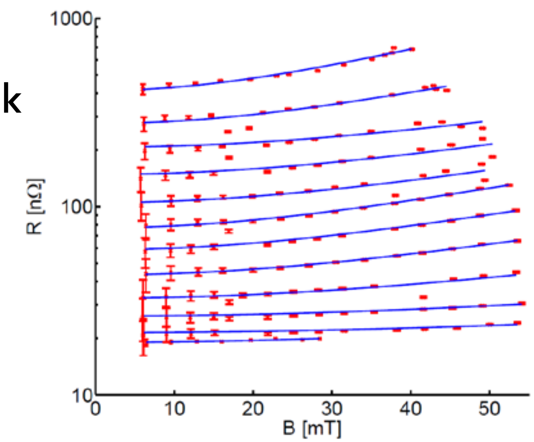
$$R_s = \frac{8R_{BCS}}{\pi\beta_0^2}\int_0^{\pi}\sinh^2\left(\frac{\beta_0}{2}\cos\tau\right)\tan^2\tau\,d\tau$$

$$\beta_0 = \frac{v_s p_F}{k_B T} = \frac{\pi}{2^{3/2}}\frac{H_0}{H_c}\frac{\Delta}{k_B T}$$



400 MHz, quadrupole resonator

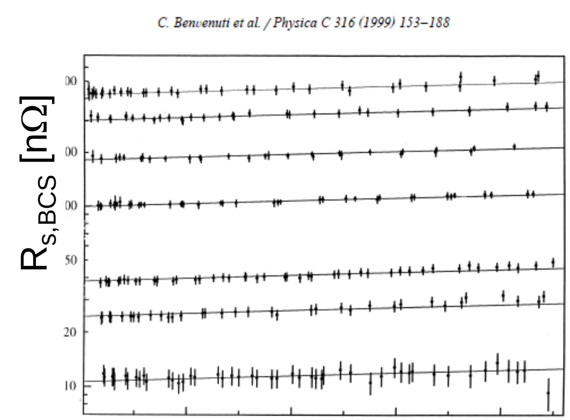
Nb bulk



8 K

2 K

1500 MHz, Nb/Cu cavity



4.23 K

2.15 K

H_{rf} [mT]

Magnetic flux entry at B_{c1} model 1

Most evident model, proposed since long by many authors

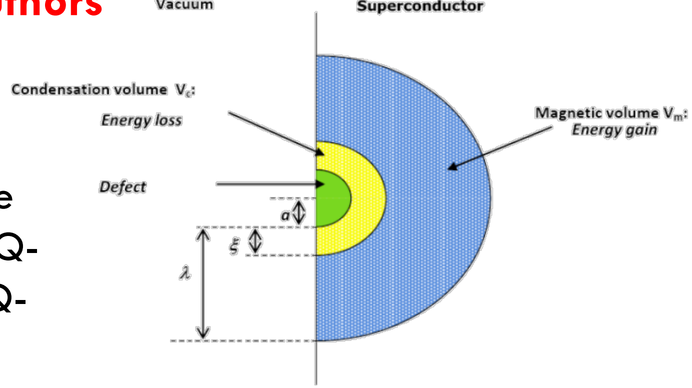


Figure 1: The superconductor loses energy inside the condensation volume V_c and gains energy inside the magnetic volume V_m.

quantitative relation for Q-slope and Q-drop

Q-slope/Q-drop

$$R_{s,fd}(\omega,T,B) \approx \left[\underbrace{R_{res1} + \mu_0^2 \cdot \omega^2 \cdot \Delta x^3 \cdot \sigma_{n0} \cdot \Theta(T-T^*) \cdot \left(\frac{T-T^*}{T_c-T^*}\right)^{\beta}}_{R_{s,fdt}} \cdot \underbrace{(-1)\left[\frac{1}{\kappa^2} + \frac{ln\left(1-\kappa^2\left(\frac{B}{B_c}\right)^2\right)}{\kappa^4\left(\frac{B}{B_c}\right)^2}\right]}_{R_{s,fdb}} \right]$$

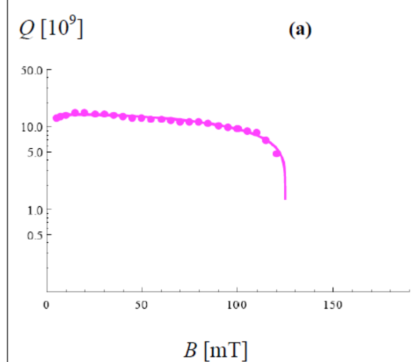
$$R_{res2} = const$$

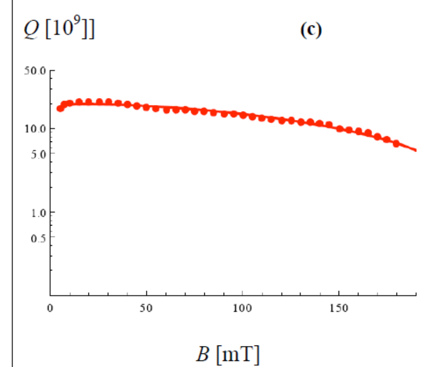
$$R_{res}(\omega) = \mu_0^2 \cdot \sigma_{n0} \cdot \omega^2 \cdot \lambda^2 \cdot \Delta y$$

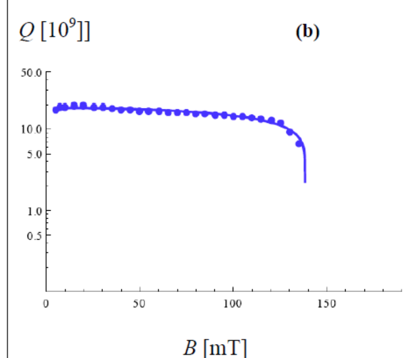
low field Q-increase

$$R_{s,Q-inc} \approx \frac{2 \cdot \omega \cdot L \cdot \mu_0^2}{\pi B^2}$$

Simulation (by percolation and proximity effect assisted flux entry);
data from G. Ciovati, Proc. SRF2009, Berlin,Germany







	(a) Baseline (EP)	(b) Heat treated	(c) 120°C/24h bake
Fitted parameters			
RRR	266	199	179
R_{res1} [nΩ]	35	15	26
L [pJ/m^2]	6	1	5
κ(surface)	1.5	1.3	0.9
Fix or derivative parameters			
β	1	1	1
λ/ξ (bulk)	1.1	1.1	1.1
R_{res2} [nΩ]	1.5	1.5	1.5
l [nm]	719	538	482
Δx [nm]	0.	0.	0.
Δy [nm]	0.	0.	0.

Figure 7: Typical comparison of measured and fitted individual data: The Q (B) curves were obtained for a 1300 MHz single cell cavity at 2.0 K made of fine grain niobium.

Magnetic flux entry at B_{c1} model 2

$$R_{s,fd}(\omega,T,B)\approx\left(\underbrace{R_{res1}+\mu_0^2\cdot\omega^2\cdot\Delta x^3\cdot\sigma_{n0}\cdot\Theta\left(T-T^*\right)\cdot\left(\frac{T-T^*}{T_c-T^*}\right)^{\beta}}_{R_{s,fdt}}\right)\underbrace{\cdot(-1)\left[\frac{1}{\kappa^2}+\frac{ln\left(1-\kappa^2\left(\frac{B}{B_c}\right)^2\right)}{\kappa^4\left(\frac{B}{B_c}\right)^2}\right]}_{R_{s,fdb}}$$

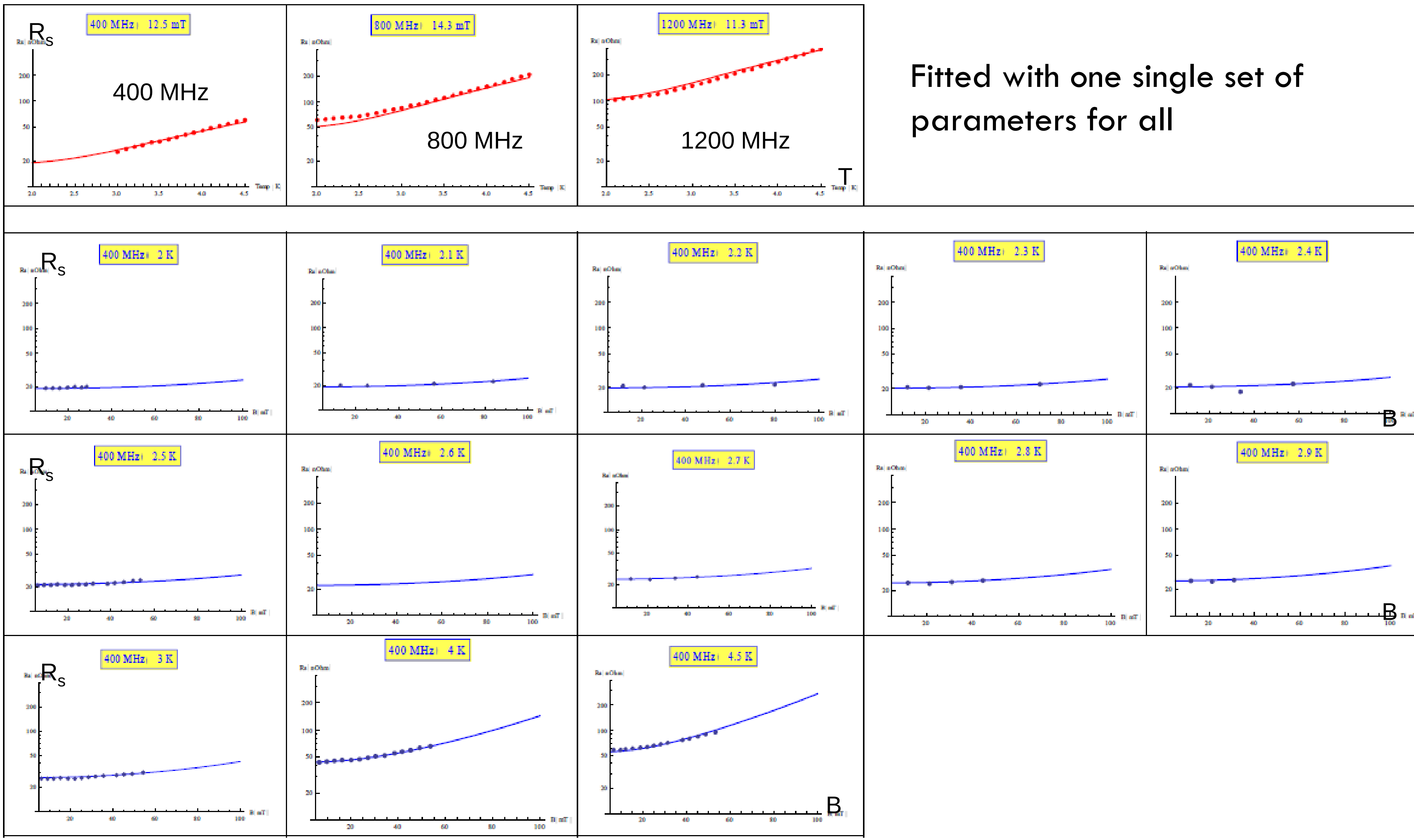
is equivalent to infinite series like this

singularity at $B = B_c/\kappa \approx B_{c1}$

$$R_{s,fd}(\omega,T,B)\approx\left(\underbrace{R_{res1}+\mu_0^2\cdot\omega^2\cdot\Delta x^3\cdot\sigma_{n0}\cdot\Theta\left(T-T^*\right)\cdot\left(\frac{T-T^*}{T_c-T^*}\right)^{\beta}}_{R_{s,fdt}}\right)\underbrace{\cdot\frac{1}{\kappa^2}\cdot\left(\frac{\left(\frac{\kappa B}{B_c(T)}\right)^2}{2}+\frac{\left(\frac{\kappa B}{B_c(T)}\right)^4}{3}+\ldots\right)}_{R_{s,fdb}}$$

Magnetic flux entry at B_{c1} model 3

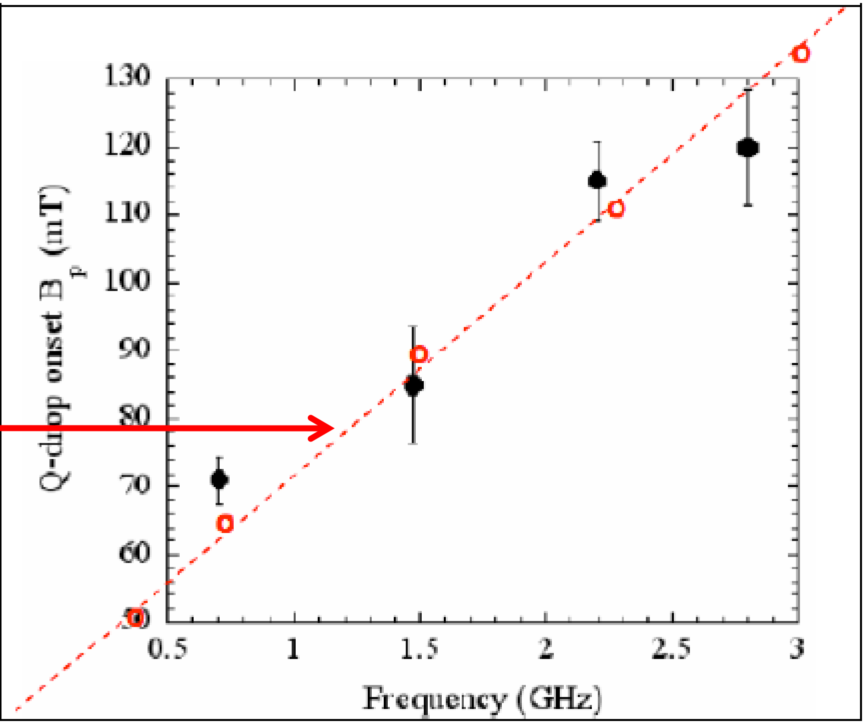
Quadrupole resonator at CERN (T. Junginger/W. Weingarten)



Fitted with one single set of parameters for all

RRR→42 Δx→157nm Δy→15nm R_{res1}→27 nΩ R_{res2}→8.1nΩ β→2.8

Magnetic flux entry at B_{c1} model 4



fit with magnetic flux entry model

Figure 6: Q-drop onset field measured at different frequencies. The data point at 2.82 GHz was measured in the TE_{011} mode (from ref. 52).

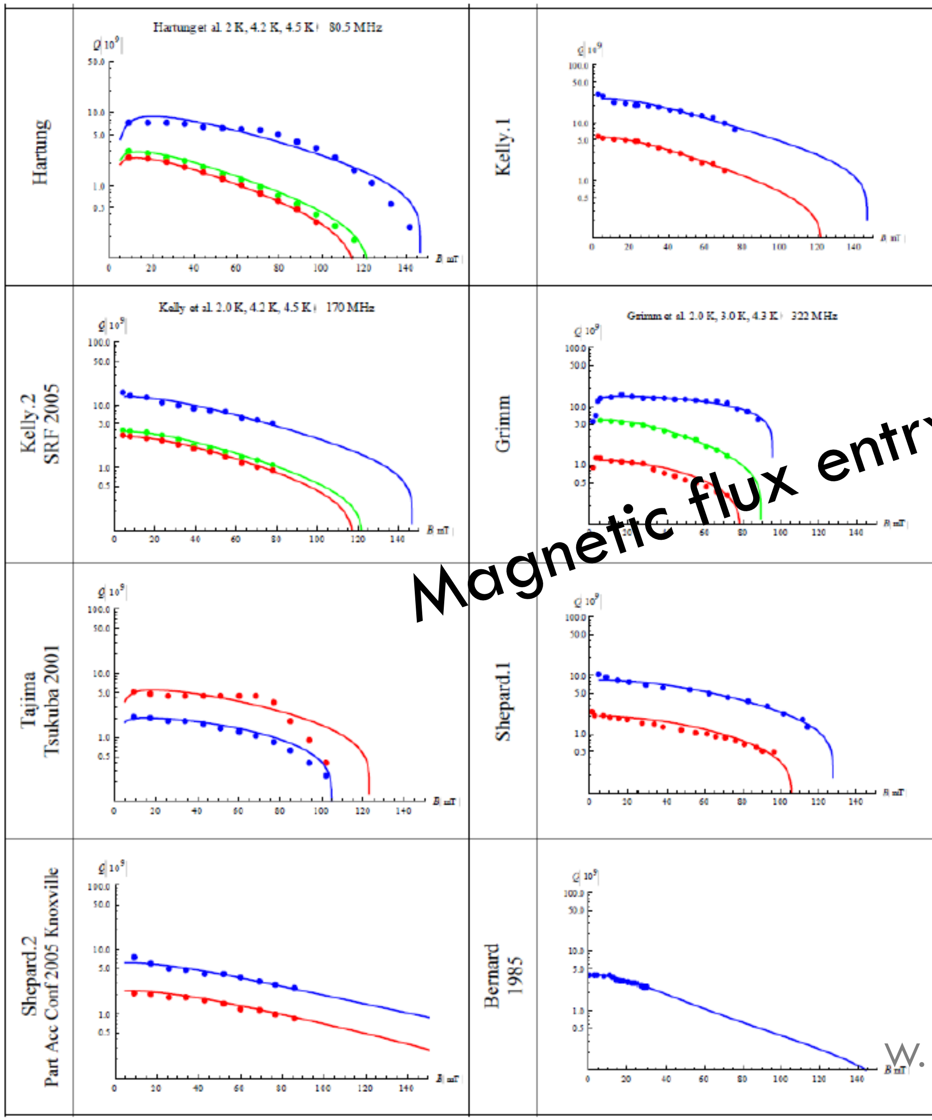
G. Ciovati, Journal Applied Physics 96 (2004) 1591

Individual fits to the collective data

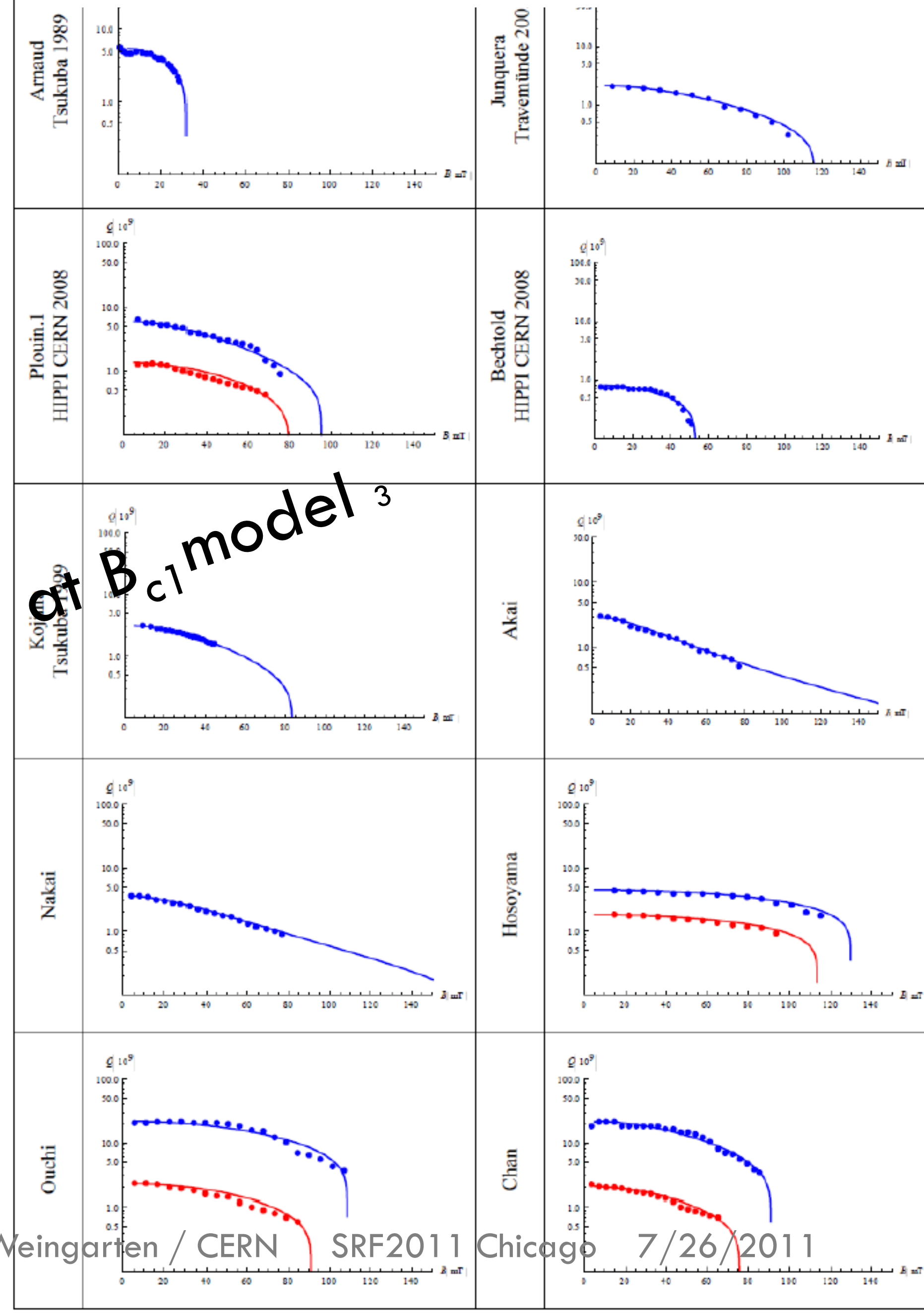
Author/Fitting curve Q(B_p)

Nb bulk

Reference: W. Weingarten TTC meeting Paris 2009

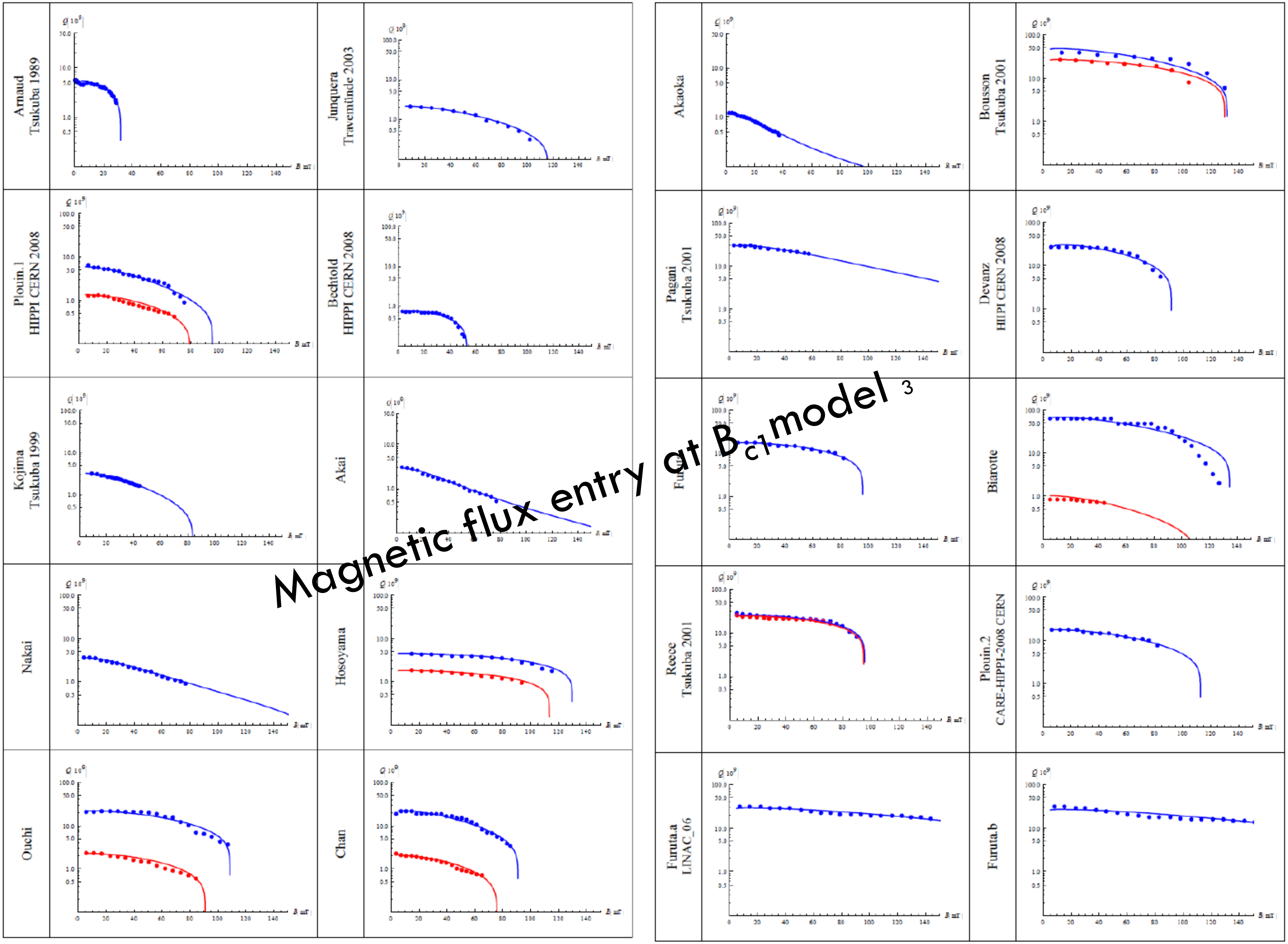


Fitted with one single set of parameters per test

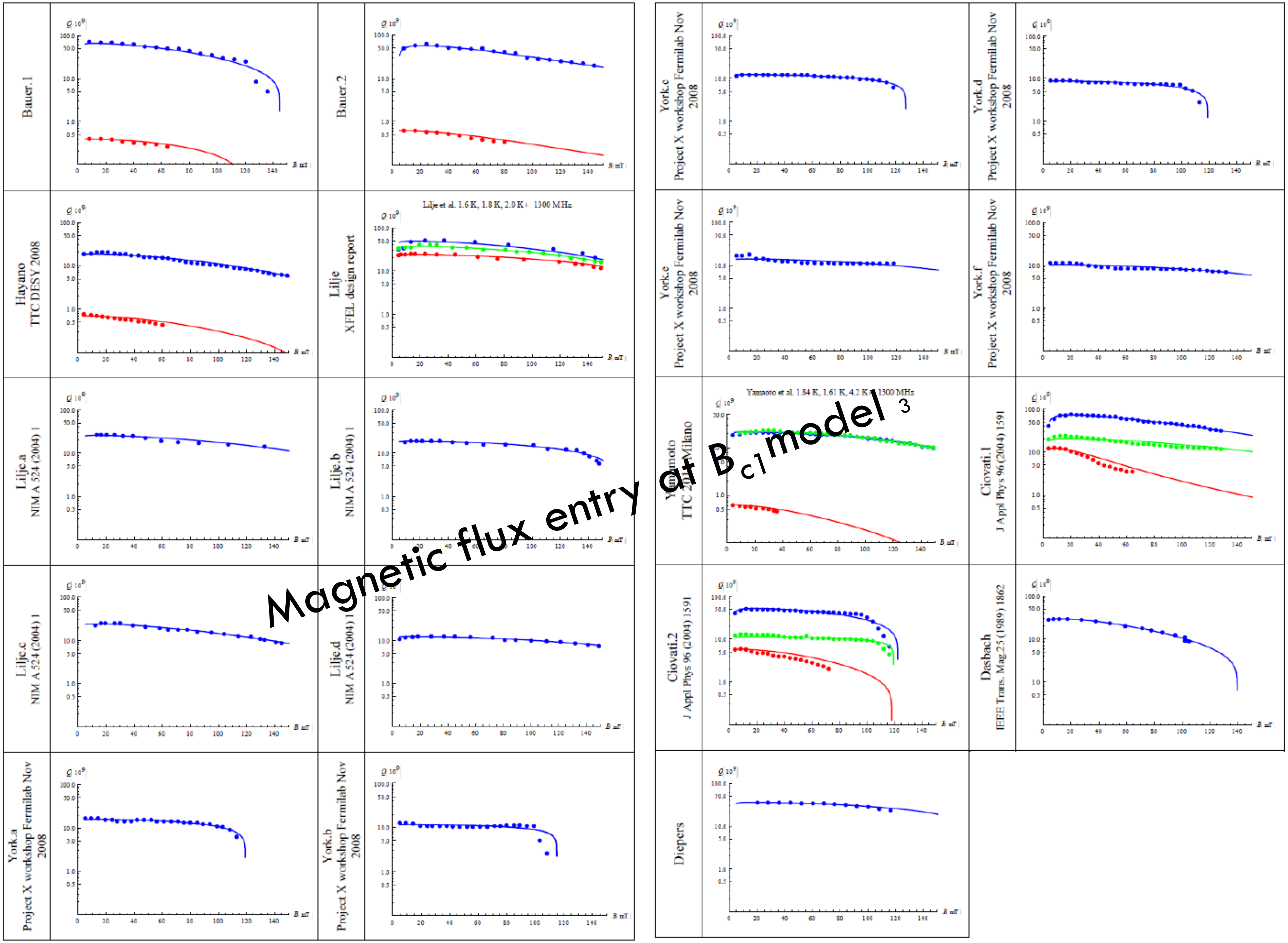


Magnetic flux entry at B_{c1} model 3

Magnetic flux entry at B_{c1} model 3



Magnetic flux entry at B_{c1} model 3



How do the previous models fit to the experimental results on the medium field Q-slope? **My personal view**

Model	Remarks	My personal view
Magnetic field enhancement	• possibly relevant for Q-drop	**unplausible** because of • similarity for BCP and EP treated cavities
Interface tunnel exchange	possibly relevant • for low field Q-***decrease*** and • losses in el. field regions (signal on T-maps)	**unplausible** because of • similar results on TM_{010} and TE_{011} cavities
Thermal feedback		**unplausible**, because • simulations yield too small effect (γ <1) in contradiction with experiments • Q-slope also visible on quadrupole resonator sample test results with heat flow parallel to surface (no T-gradient across cavity wall)
Non-linear surface resistance		**unplausible** because of • no clear factorisation of Q-slope into T and B dependent part
Magnetic flux entry at B_{c1}	•B-dependent part fairly well described analytically, •T-dependent part, however, could have many origins (percolation, proximity, field enhancement, …)	**plausible,** because the model (in its percolation format) describes the Q-dependencies of the surface resistance altogether (low field Q-increase/Q-slope/Q-drop)

Paths to high Q-operation 1

- There is a continuous quest for **lower RF losses** compared to niobium. Alternatively, but closely linked to that, the operation of accelerating structures at 4.5 K instead in super-fluid helium at 2K would be possible.
- Candidates to get around this issue are the **"classical" high T_c superconductors**, NbN and Nb_3Sn. These alternate materials have already been proven to possess Q-values larger than niobium, however only at low gradient; the reason is probably their relatively complicated phase diagram;

Paths to high Q-operation 2

- An **R&D program** would consist in preparing samples and evaluating their performance under RF exposure again in a **host cavity**.
- Coating can be done by **thermal diffusion** of tin into niobium in a dedicated furnace or by **co-deposition** of niobium and tin.
- The study can extend to "**multi-layers**" of a thin film of, say, niobium, Nb_3Sn or NbN*).

*) A. Gurevich, Enhancement of RF breakdown field of superconductors by multilayer coating, Appl. Phys. Letts. **88**, 012511 (2006)

Paths to high Q-operation 3
Nb_3Sn/Nb

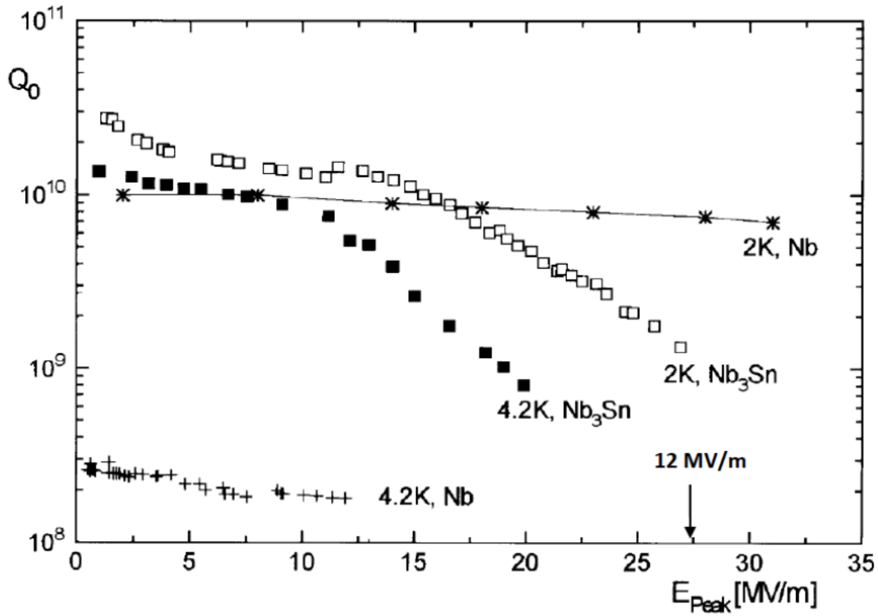
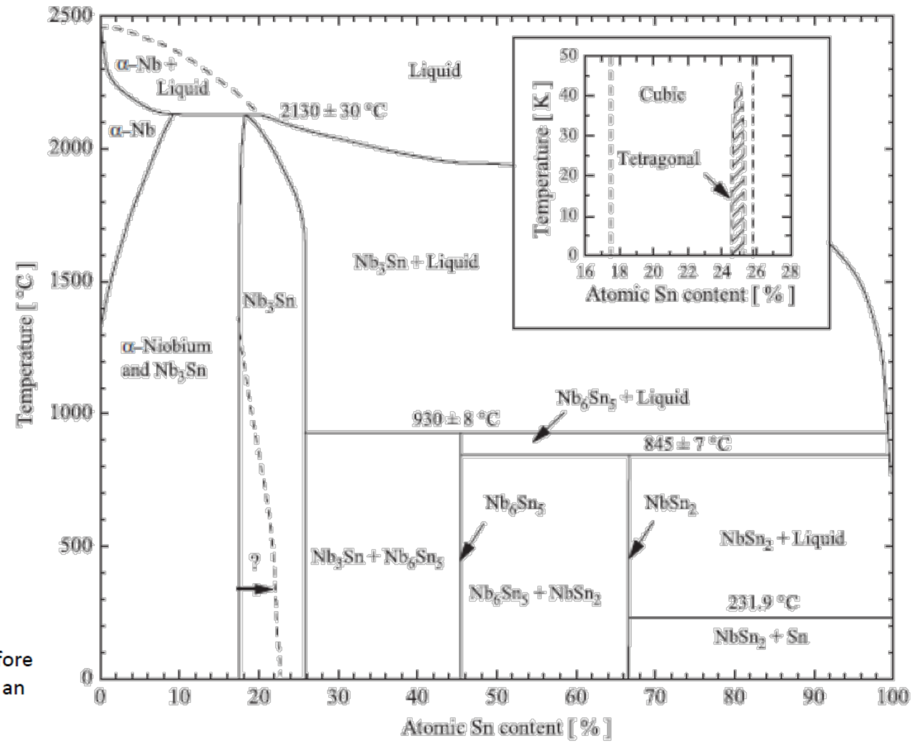


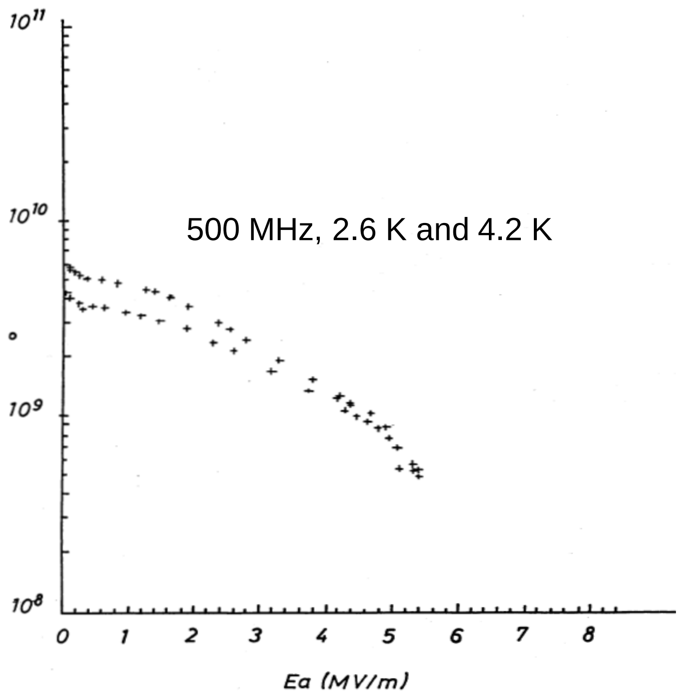
Figure 8: Electric peak field dependence of Q-value of a single-cell 1.5 GHz cavity as measured before (Nb) and after Nb_3Sn coating at 2 and 4.2 K. The electrical peak field of 27 MV/m corresponds to an accelerating gradient of 12 MV/m[28].



G. Müller, P. Kneisel, D. Mansen, H. Piel, J. Pouryamout, and R.W. Röth , Proc. of the 5th EPAC, London, p. 2085 (1996).

A. Godeke, A review of the properties of Nb_3Sn and their variation with A15 composition, morphology and strain state, Supercond. Sci. Technol. **19** (2006) R68–R80.

Paths to high Q-operation 4
NbTiN/Cu



C. Benvenuti et al., Proc. 4th Workshop RF Superconductivity 1989, KEK, Tsukuba (Japan), p. 869.

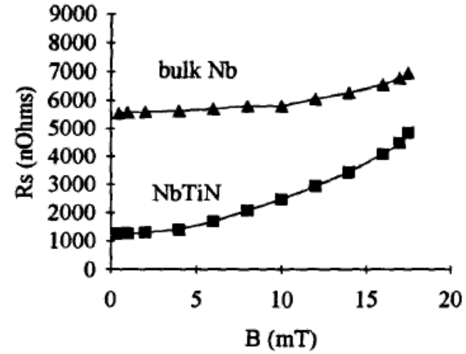


Fig 2: Surface resistance of the D29 $(Nb_{0.55}Ti_{0.45})N$ / Cu film at 4 GHz and 4.2 K.

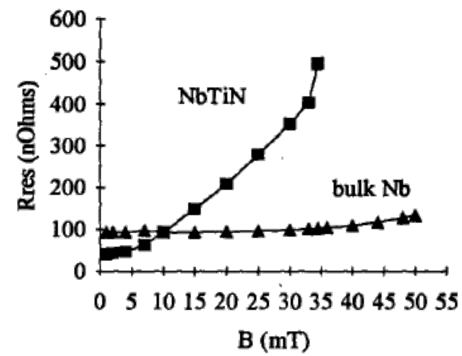


Fig 3: Residual surface resistance of the D29 $(Nb_{0.55}Ti_{0.45})N$ / Cu film at 4 GHz and 1.6 K.

P. Bosland et al., NbTiN thin films for RF application, 6th Workshop RF Superconductivity, Newport News 1993

Thank you for your attention!

Let us now enter into a lively discussion