Limits in cavity performance

Detlef Reschke

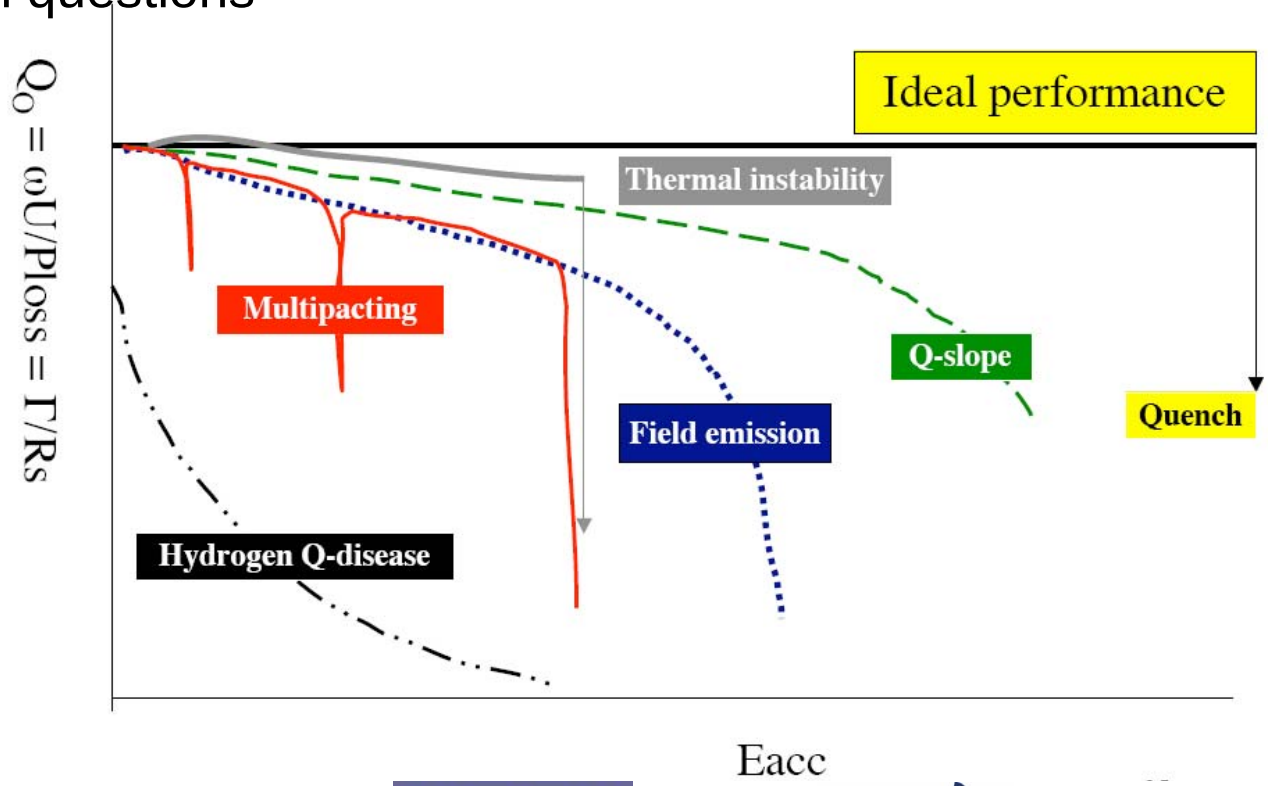
DESY

Tutorial, SRF 2007

- Introduction
- SCRF Basics (=> Tutorial 1b: Basic principles of RF Superconductivity, J. Knobloch)
- Limitations and anomalous loss mechanisms:
  - **Quench** (thermal local instability)
  - **Q-drop** (without field emission) + Q-slope (at medium field)
  - **Field emission**
  - **Multipacting**
  - Hydrogen Q-disease
  - Increased residual resistance

Introduction

- Outline:
  - physics of limitation
  - “tell-tales” and symptoms (rf, x-rays, T-maps, …)
  - cures
  - open questions

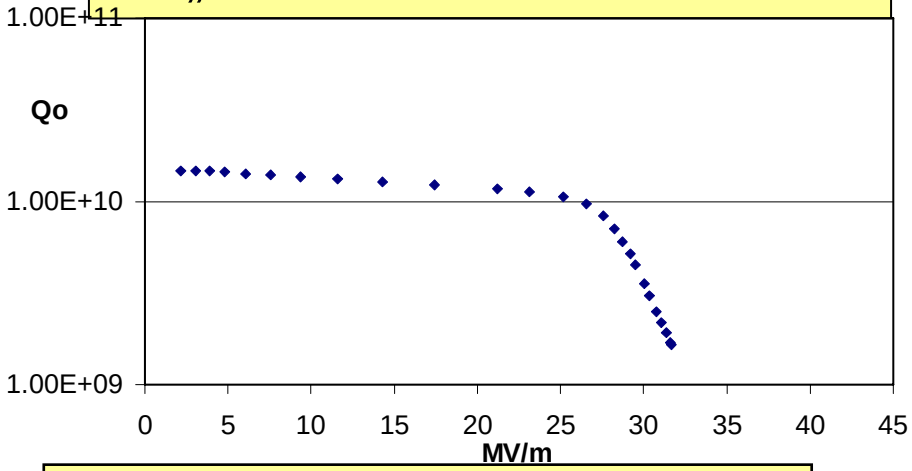


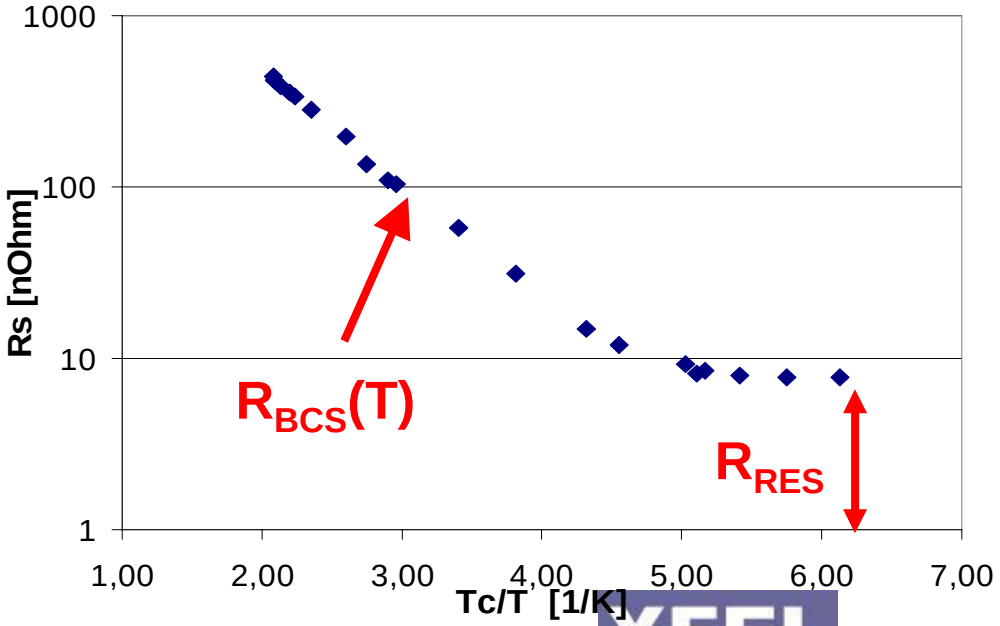
SCRF Basics: Surface Resistance $R_s(T)$

- SCRF: Surface resistance $R_s > 0$ for $T > 0K$!
- For Nb: $R_s(T, \omega, H) = (R_{BCS}(T, \omega) + R_{res}) + R_s(H)$

$$R_s = \frac{A}{T}\omega^2 e^{-\frac{\Delta}{k_B T_C}\frac{T_C}{T}} + R_{res}$$

e.g. „Q-slope w/o field emission“
=> „120C bake“ for EP-cavities





Geometry factor:

G = 270 Ohm

$$Q_o = \frac{G}{R_s}$$

Typical Quality factor:

$Q_0 \sim 2 \cdot 10^{10}$ at 2K

SCRF basics: Critical magnetic rf field

- RF field penetrates for less than 10^{-9} s
  => Delayed penetration in the fluxons (superheating) in case of no nucleation centers

Property	Experimental data [mT] at 4.2 K	Calculated field [mT] at 0 K	Calculated field [mT] at 2 K	E_{acc} [MV/m] at 2 K
B_{c1}	130	164	156	37
B_c	158	200	190	45
B_{sh}	190	240	230	54
B_{c2}	248	312	297	62

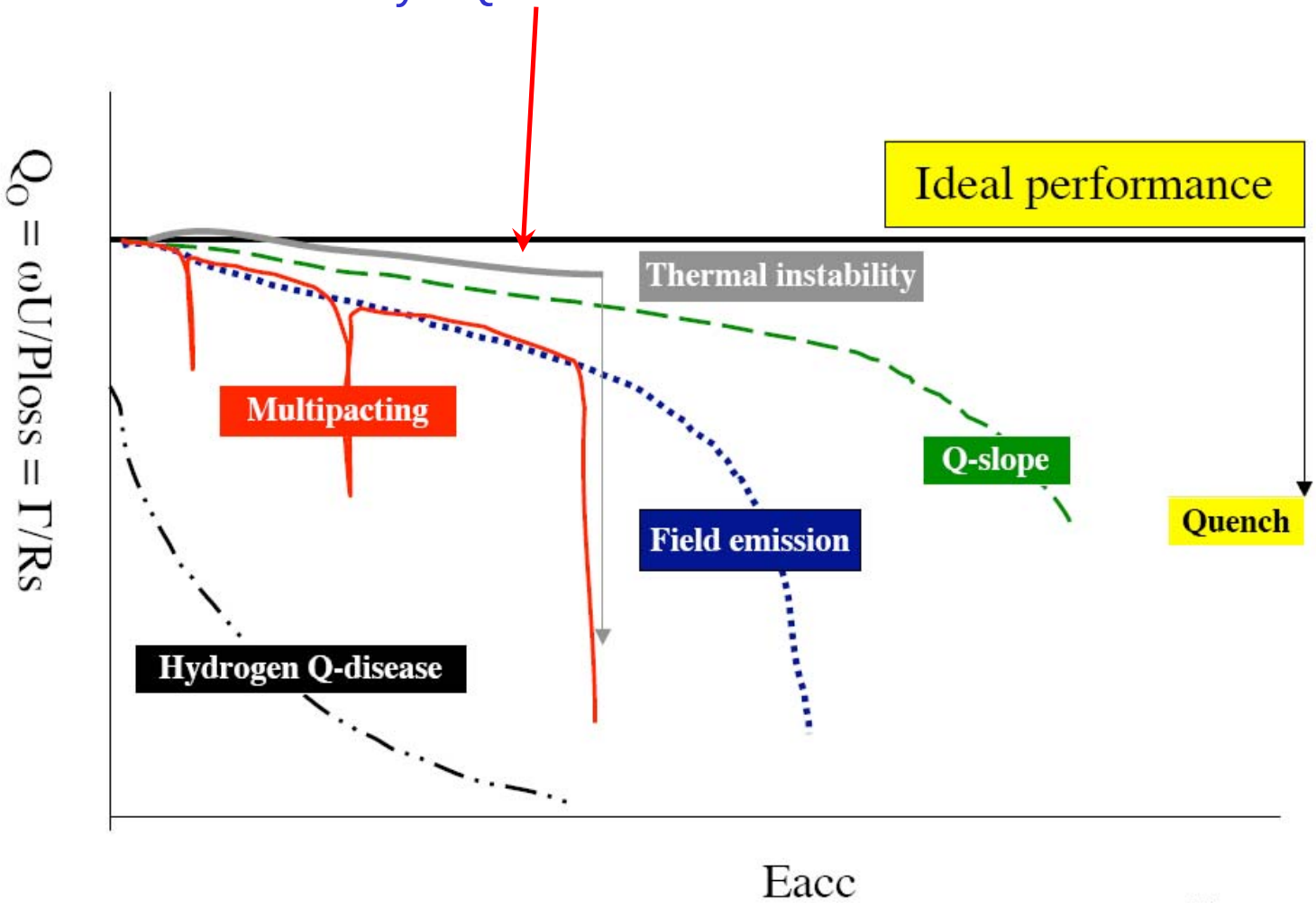
What is really the fundamental limit for RF cavities?

K. Saito, 2001: H_c^{rf} is 180 mT at <2K ! => end of discussion ???

- Experimental:
  - (180-190) mT typically achieved in single-cell cavities,
    but 209 mT at Cornell recently ! => new discussion necessary !!!
  - ~ 170 mT achieved in nine-cell cavities

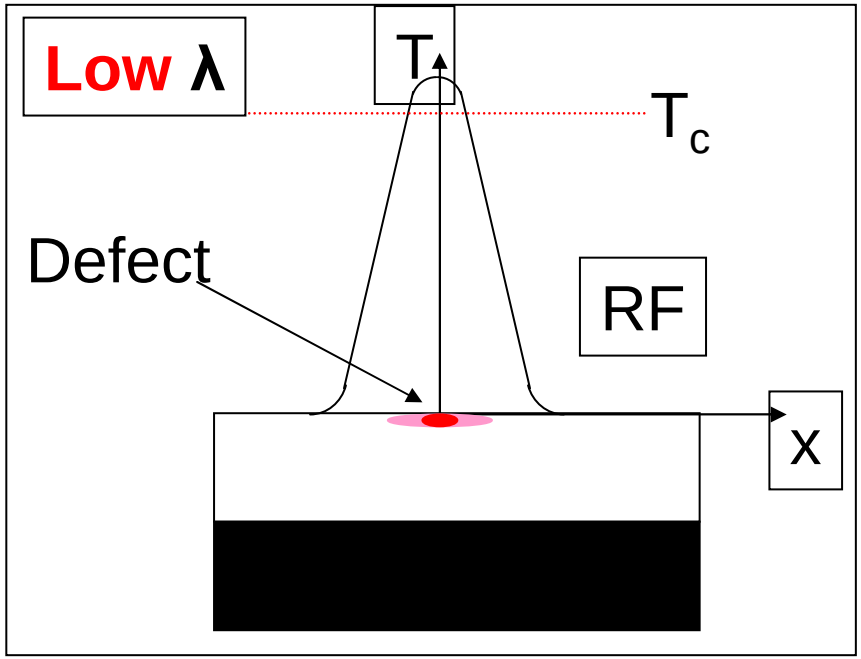
“Quench”

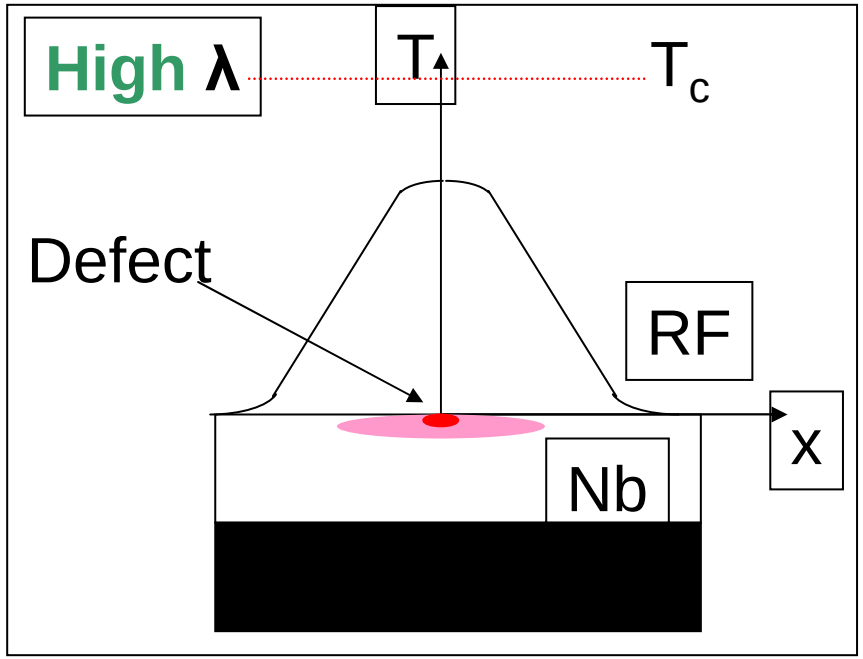
- Local thermal instability: “Quench”



“Quench”

- Localised effect $\Rightarrow$ surface defect has higher R_s
- T of part (or all) of surface exceeds T_c, dissipating all stored energy.
- Quench: surrounding material cannot transport the increased thermal load to the helium

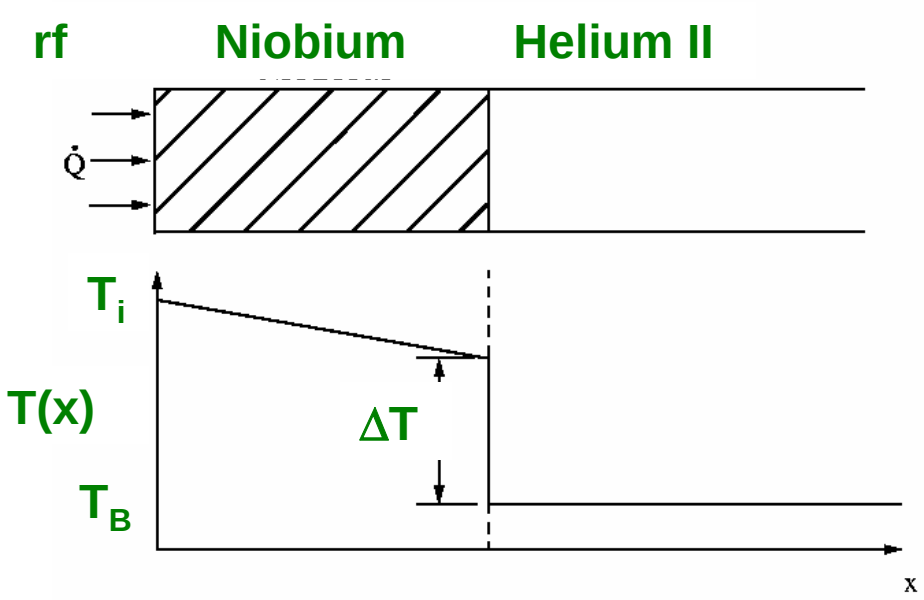




=> high purity Nb with high thermal conductivity

=> small + few defects

“Quench”: Mechanism



- The RF current produces heat
- Superconductors are bad thermal conductors:
  - Thermal conductivity
  - Kapitza Nb/He interface resistance
- A small normalconducting defect can produce a very large heating (Factor 10^6 surface resistance!)

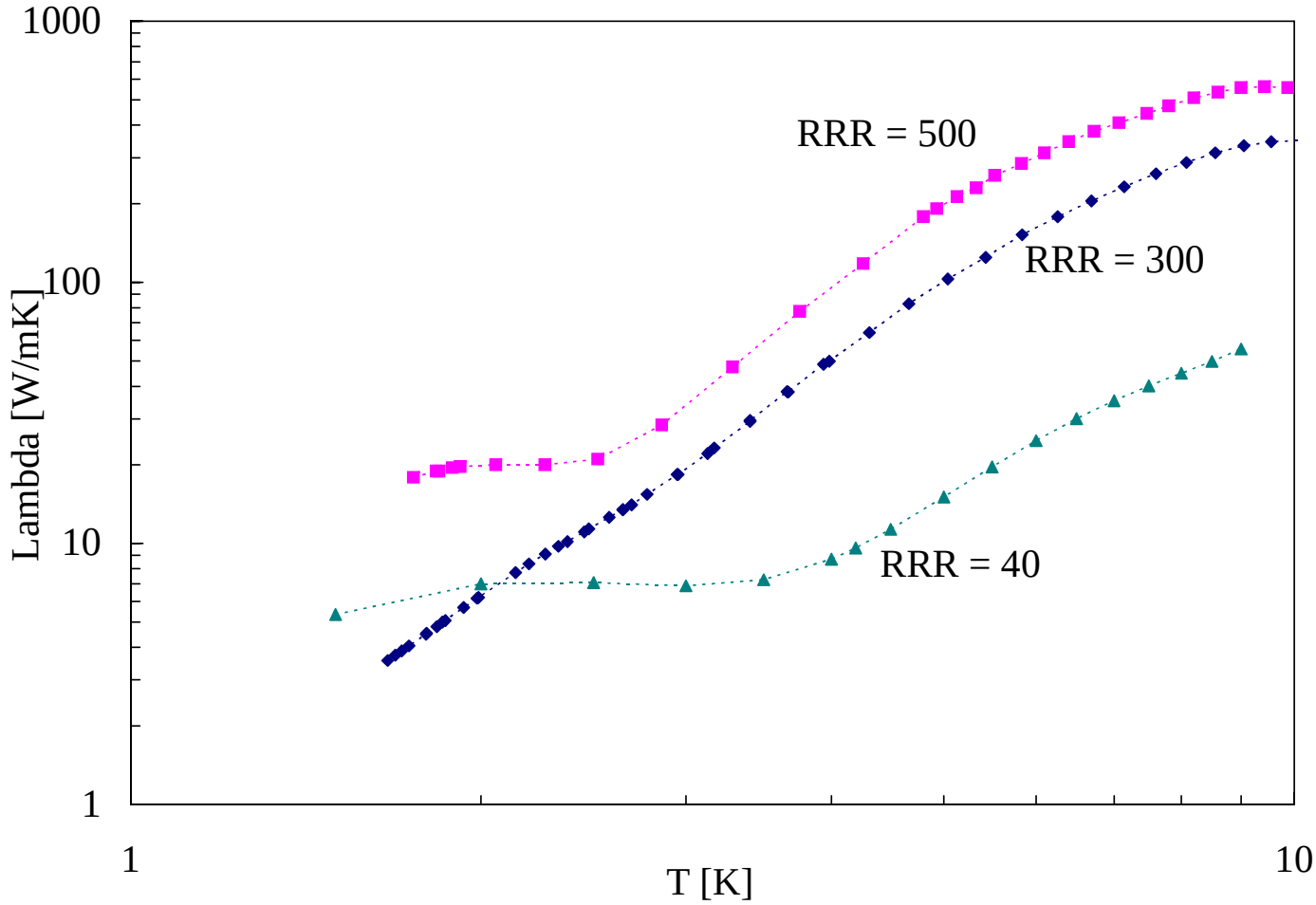
Temperature difference between inner surface and helium bath temperature (two dimensional case)**:**

$$T_\mathrm{i} - T_\mathrm{B} = \frac{\dot{Q}}{A}\left(\frac{d}{\lambda} + \frac{1}{h_\mathrm{k}}\right)$$

High thermal and Kapitza conductivity required !!

“Quench”: Thermal Conductivity

- Thermal conductivity: From “reactor grade” RRR = 40 to high purity RRR = 500



no discussion of high purity niobium fabrication!!

“Quench”: Thermal Conductivity and Defects

- Simplification of the differential equation gives for the quench field:

$$H_q = \sqrt{(4 \cdot \lambda \cdot (T_c - T_{bath}) / r_{def} \cdot R_{s,def})}$$

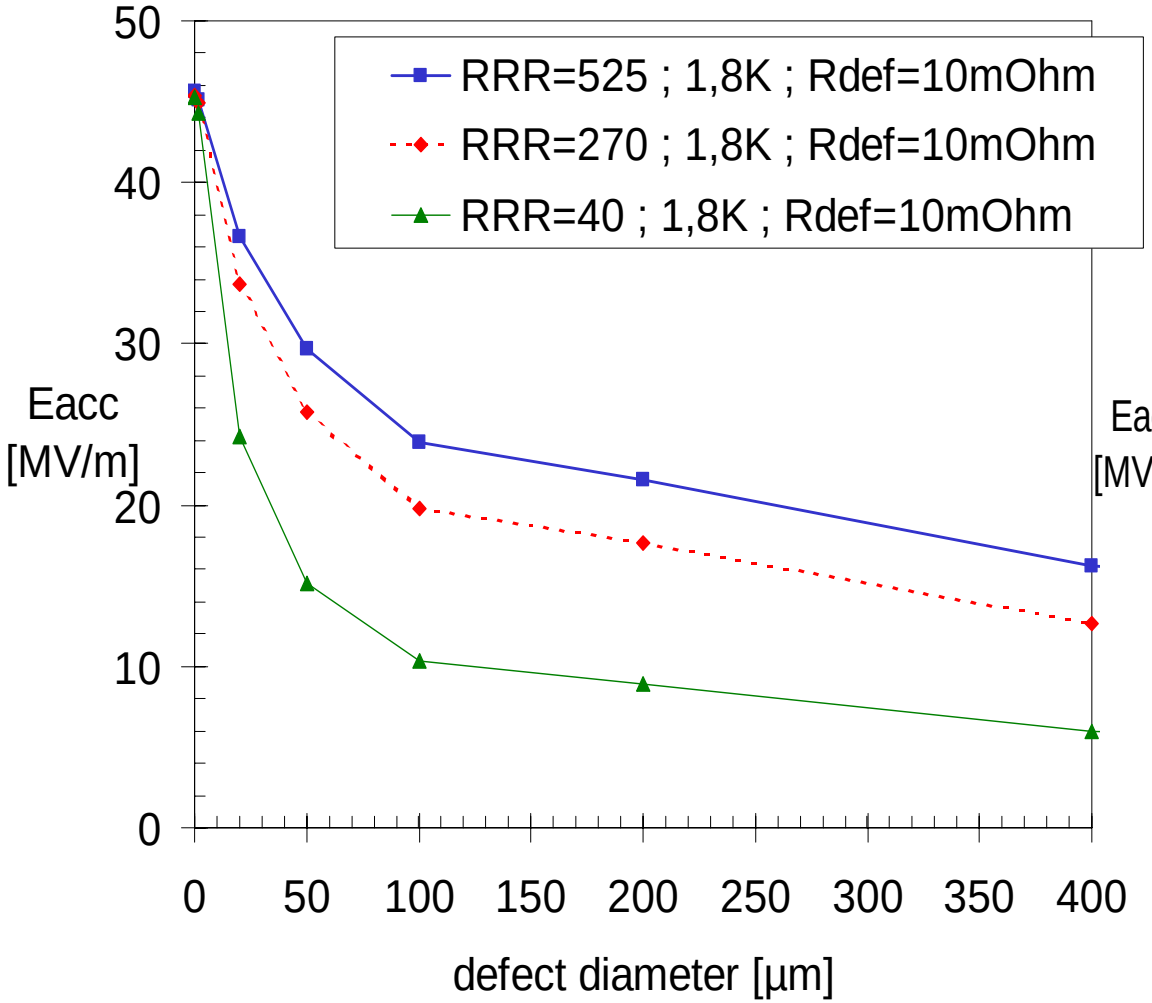
with: - averaged thermal conductivity λ
- r_{def} << d (thickness of Nb)
- no Kapitza conductivity
- no R_{BCS} and R_{res}
- T_c independent of H_{rf}

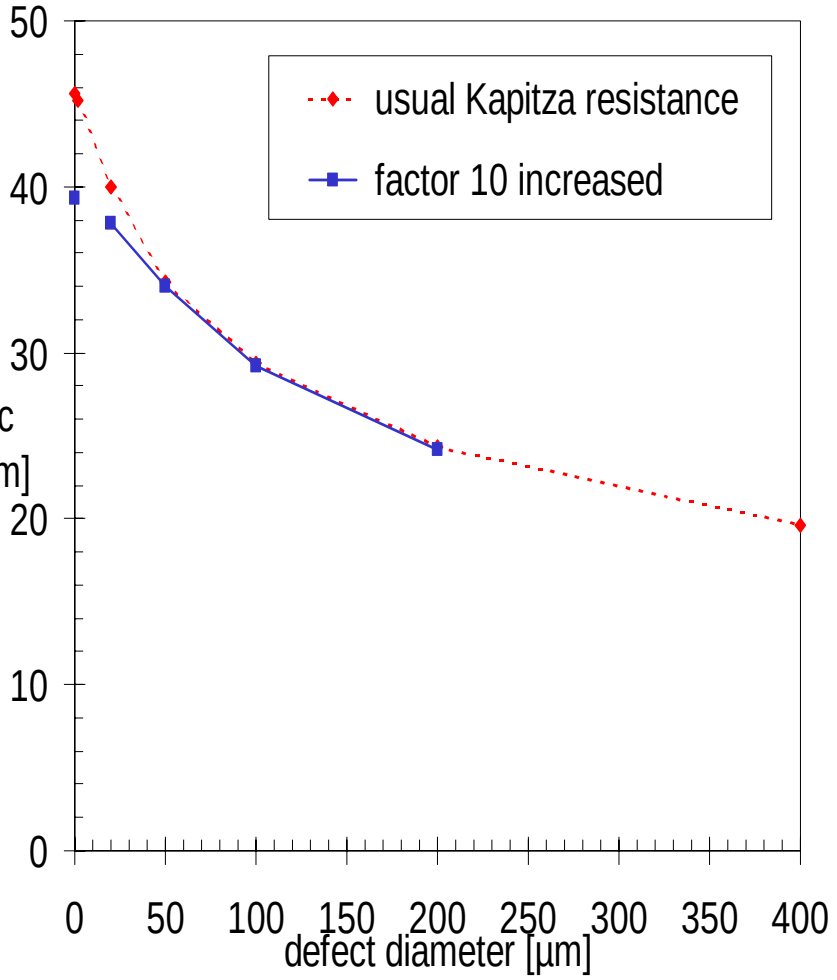
=> Defects (e.g. foreign material inclusions) have to be very small (Factor 10^{-6})

=> thermal conductivity of niobium has to be high
- pure Nb material free of ***“defects”***

e.g. for r_{def} = 50 µm, $R_{s,def}$ = 10 mΩ, λ = 75 W/mK => **H_q = 820 Oe**

„Quench“: Numerical thermal model calculations





Remark: H_q with **nearly no dependence of T_B** in superfluid Helium !

“Quench”: Thermal Conductivity and RRR

- Thermal and electrical conductivity are linked
- RRR (residual resistivity ratio):

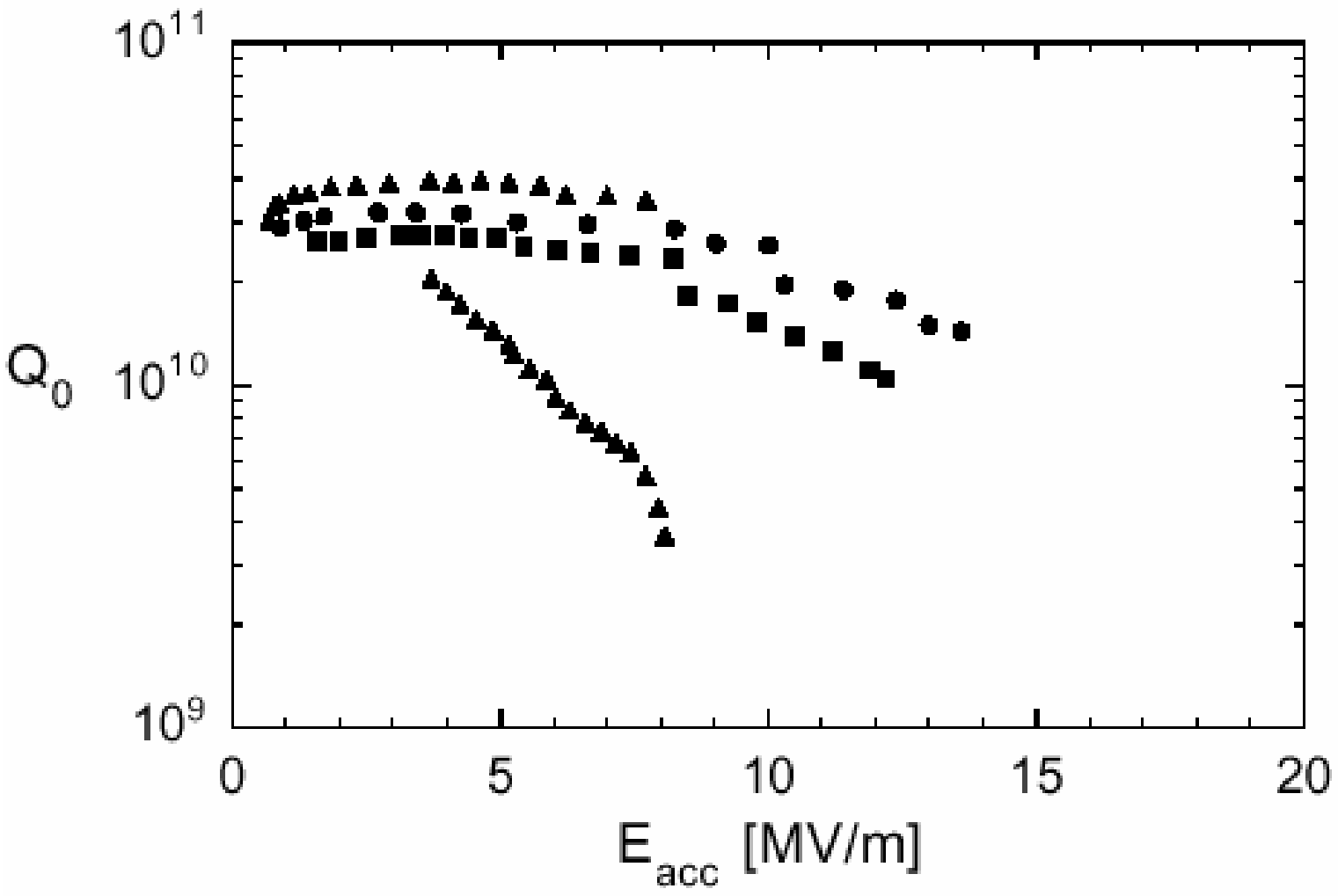
$$RRR = \frac{\rho_{nc}(300K)}{\rho_{nc}(4.2K)}$$

$$\approx 4 \cdot \lambda_{thermal}(4.2K)$$

as good rule of thumb

- RRR is given by amount of metallic (e.g. Ta) and gaseous (e.g. H, N, O) impurities
- Furthermore avoid all other impurities and defects from manufacturing
  => careful check of fabrication process
  => quality control by eddy current scanning technique

„Quench“: Examples of cavities with material defects

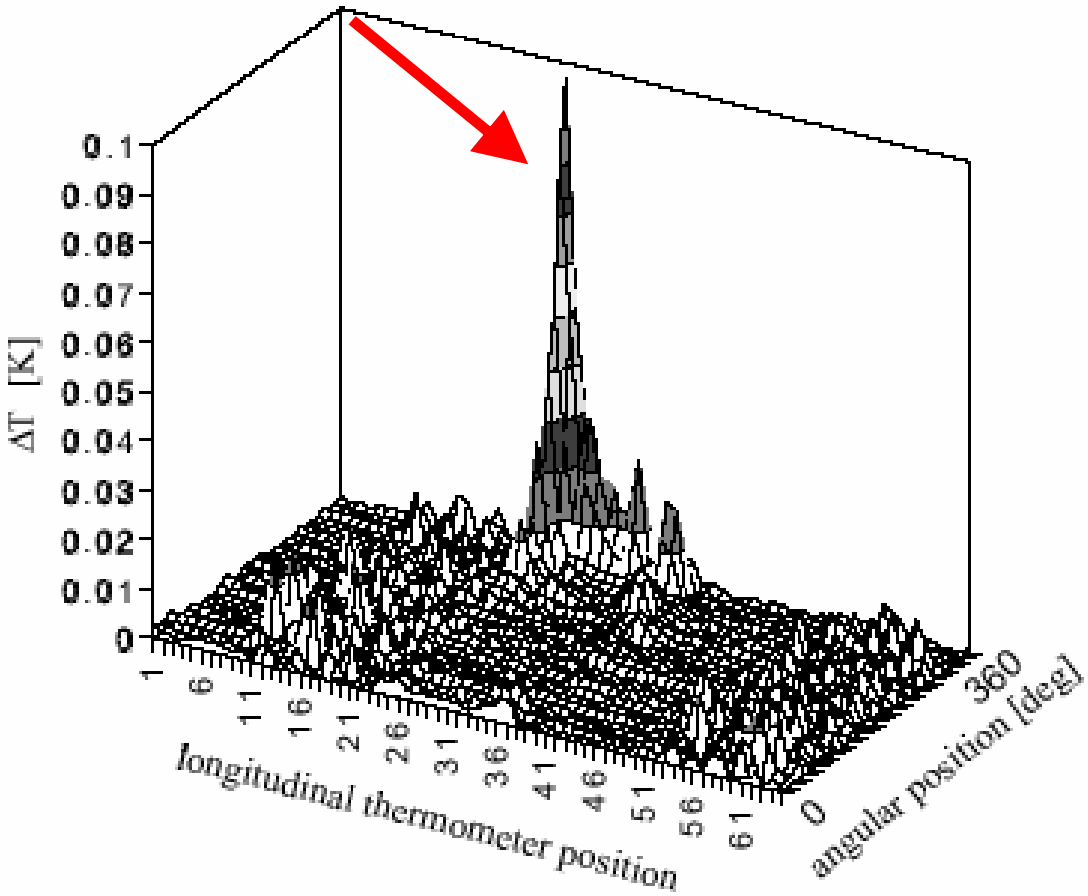


TTF first production series:

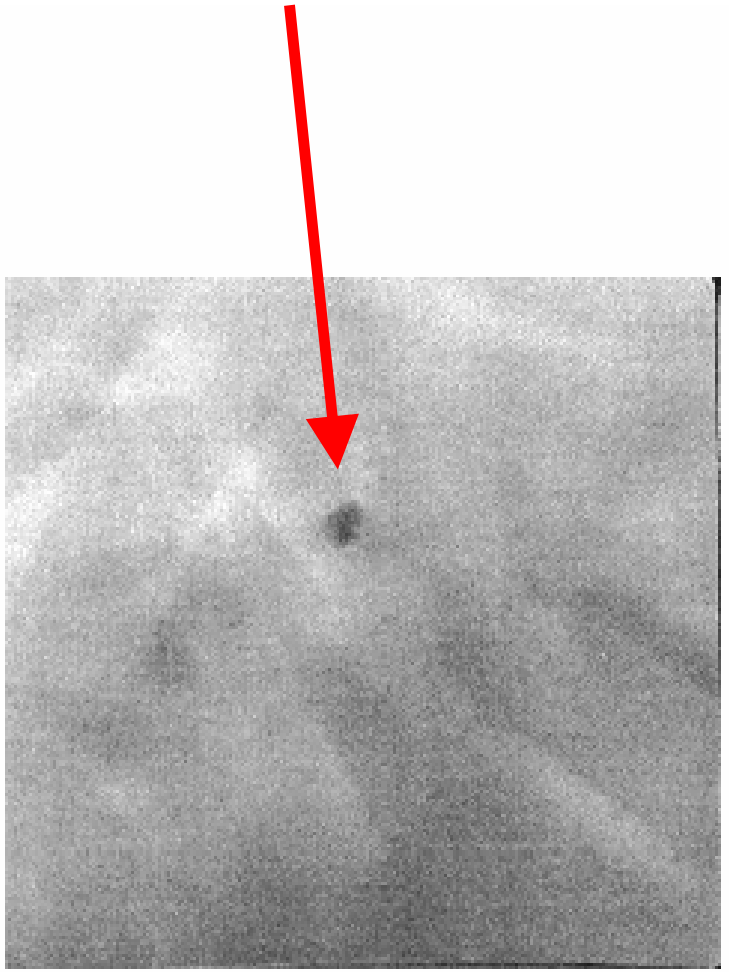
No eddy-current scanning was applied on the niobium sheets used in these cavities.

“Quench“: Example of a material defect

Heating on the outside surface measured with carbon resistors

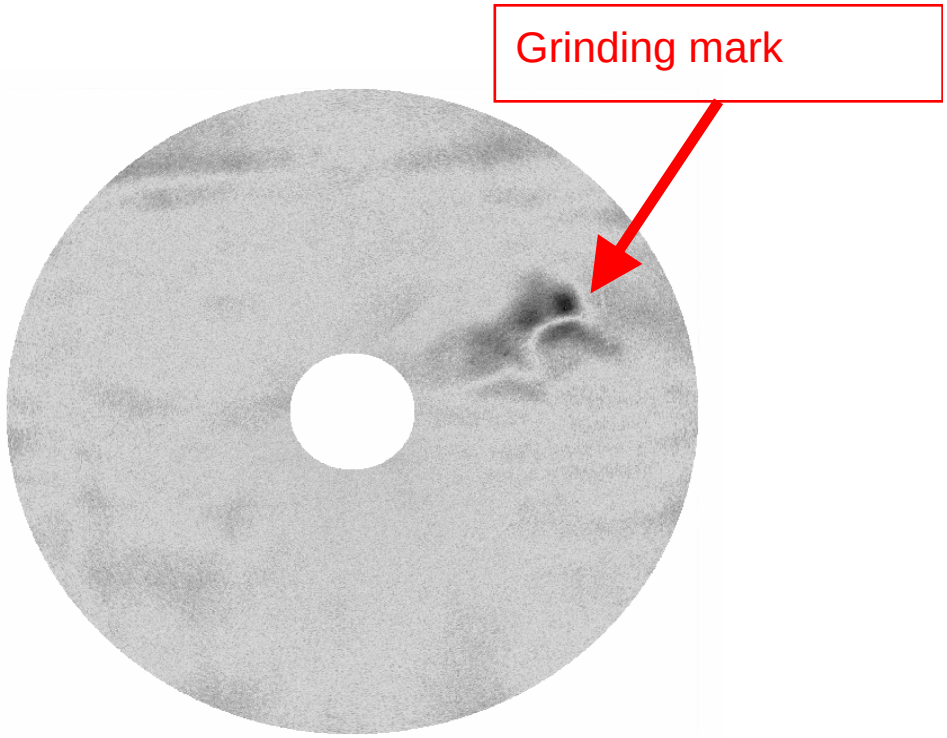


Defect found with X-ray technique: Tantalum



“Quench”: Eddy current scanning

Large tantalum inclusions (~200 µm) and places with irregular patterns from surface preparation (grinding)



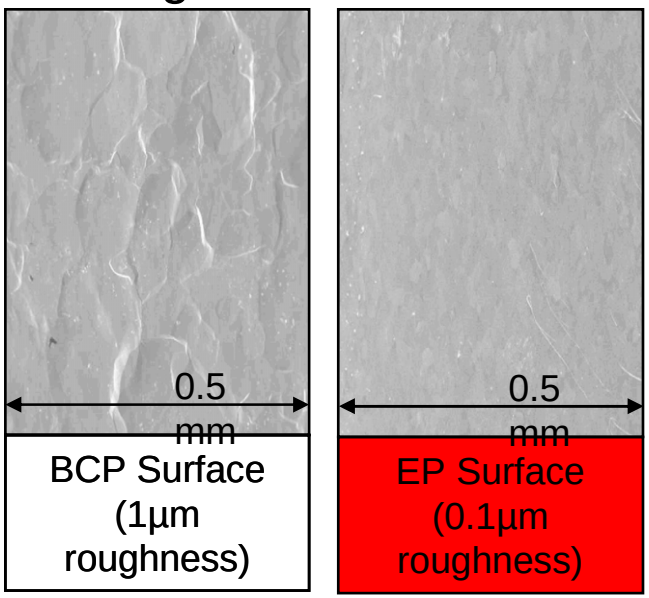
“Quench”: Nature of defects

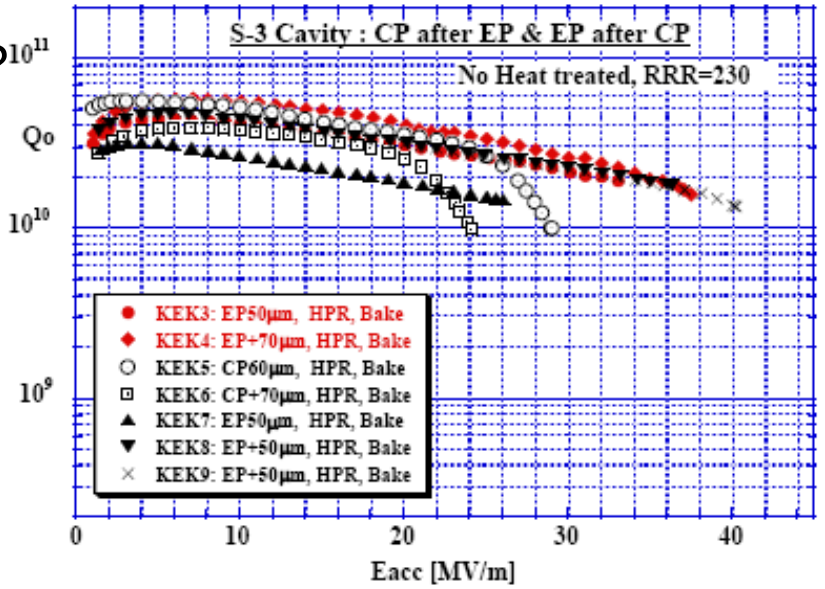
Attention!!

- avoid defects:
  - eddy-current scanning is sensitive to (100 – 200 µm) defects
  => good for app. 20MV/m
- nature of defects often unclear!!
  - How to find a < 50 µm defect on several cm^2 – surface ??
  - identified:
    foreign metal inclusions, delaminated regions, irregularities with sharp edges, pores, welding mistakes, …

“Quench”: Nature of defects II

- EP with higher H_q than BCP on same cavity?
  - surface roughness with field enhancement ?





  - chemical residues
  - grain boundaries

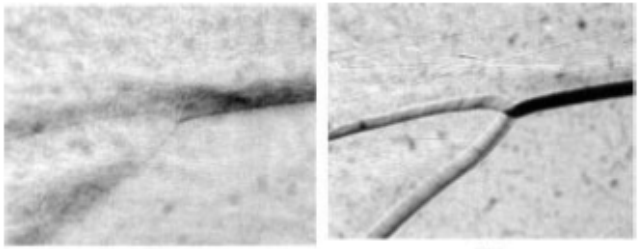
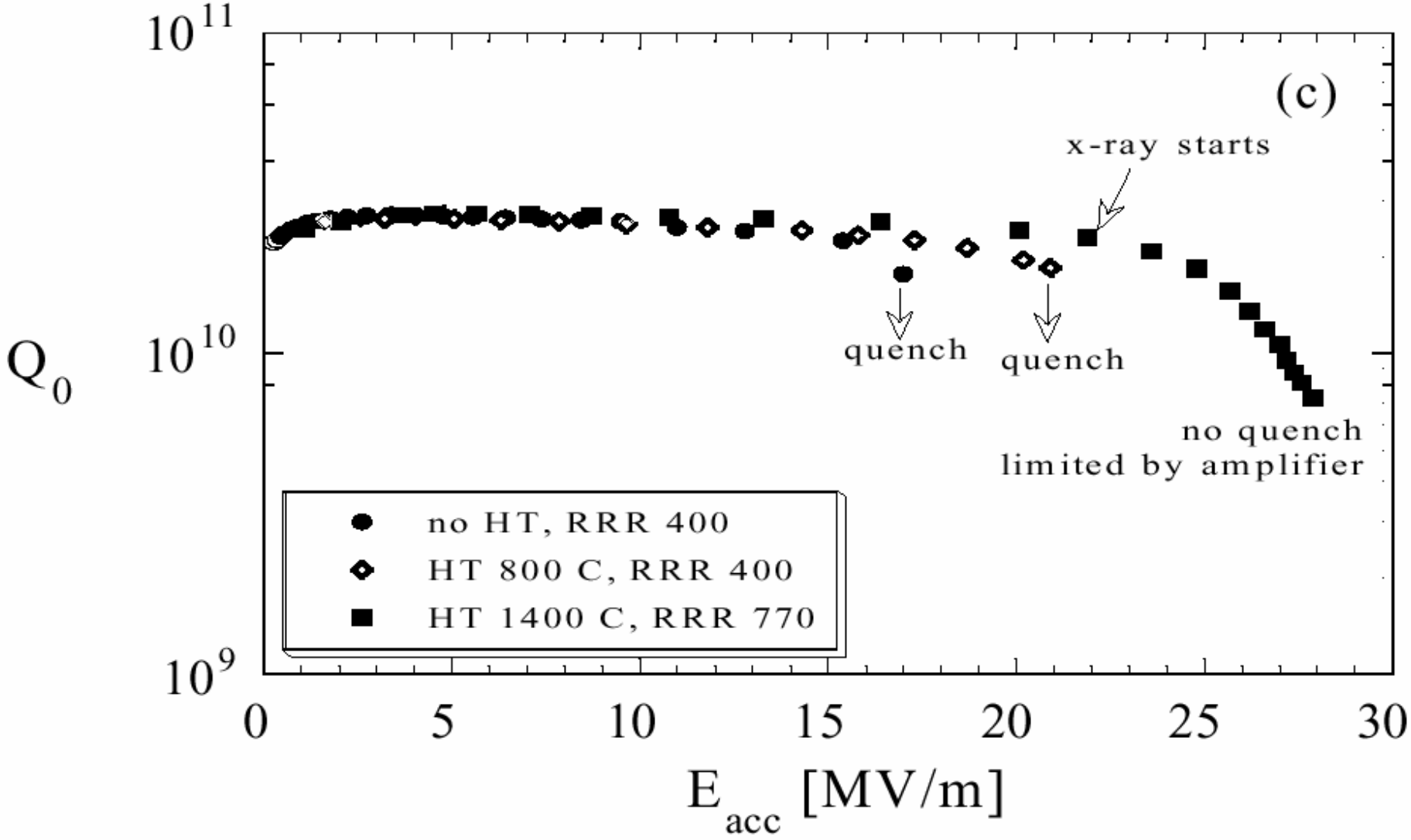


Figure 29. Expanded optical micrographs of grain boundaries in the welded regions. The typical grain size is 1 mm. (a) Electropolished to remove 100 µm, (b) after standard chemical polishing to remove 44 µm. Note that in (a) electropolishing still leaves a grain boundary step, although it is not as high, nor as sharp, as the step that results from standard chemical etching [23].

“Quench”: Benefit of the high temperature heat treatments



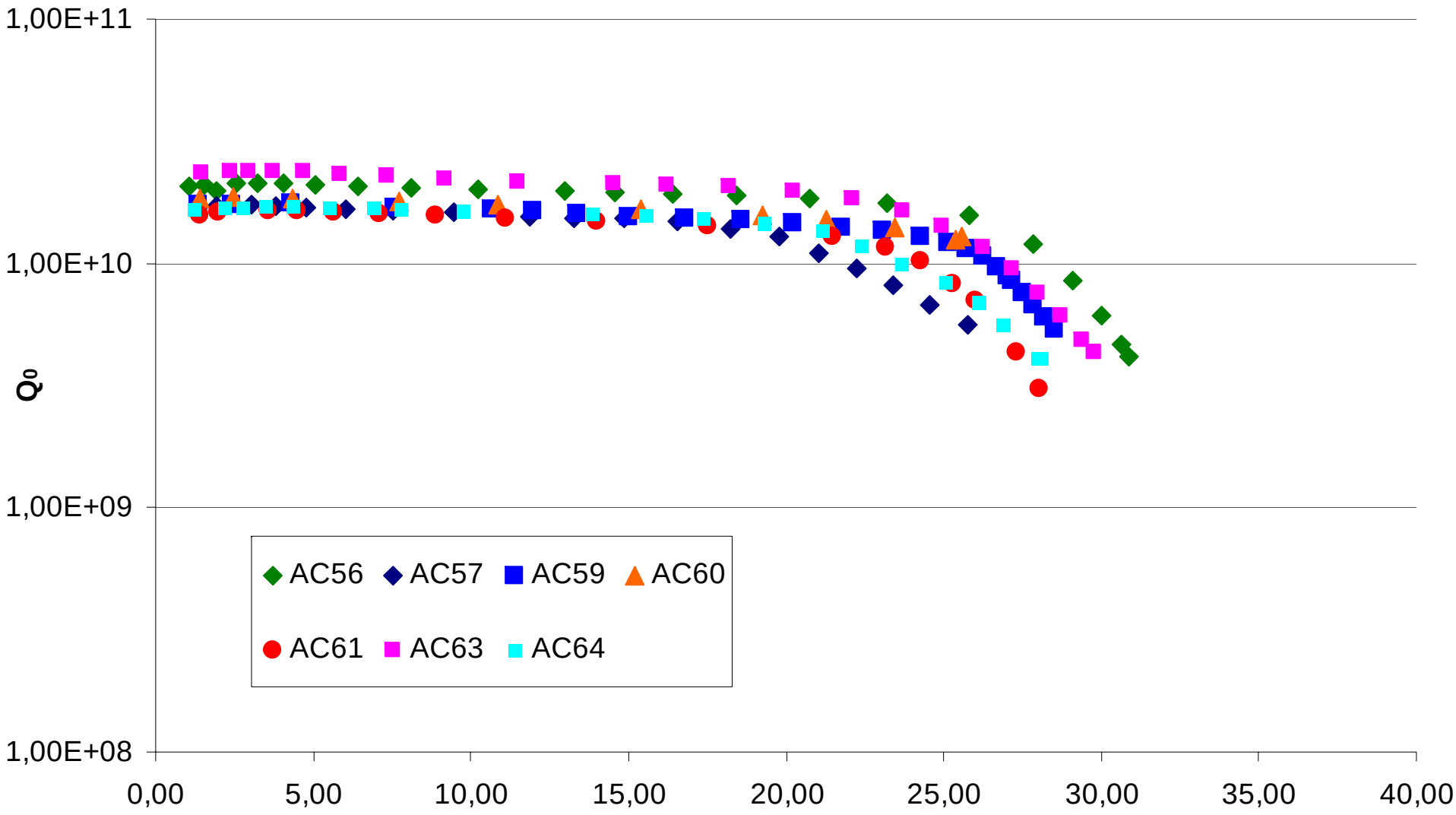
“Quench”: Post-purification

- Post-purification by solid-state gettering
- use Ti (or Y) as getter material => higher affinity for O, (N, C) than Nb
  - coating of cups or cavity with getter material at 1350 C (Ti) under UHV
  - diffusion of O from Nb to Ti until equilibrium

- 1) Increase of RRR = 250-300 to RRR = 500 – 700
  2) Homogenizing impurities

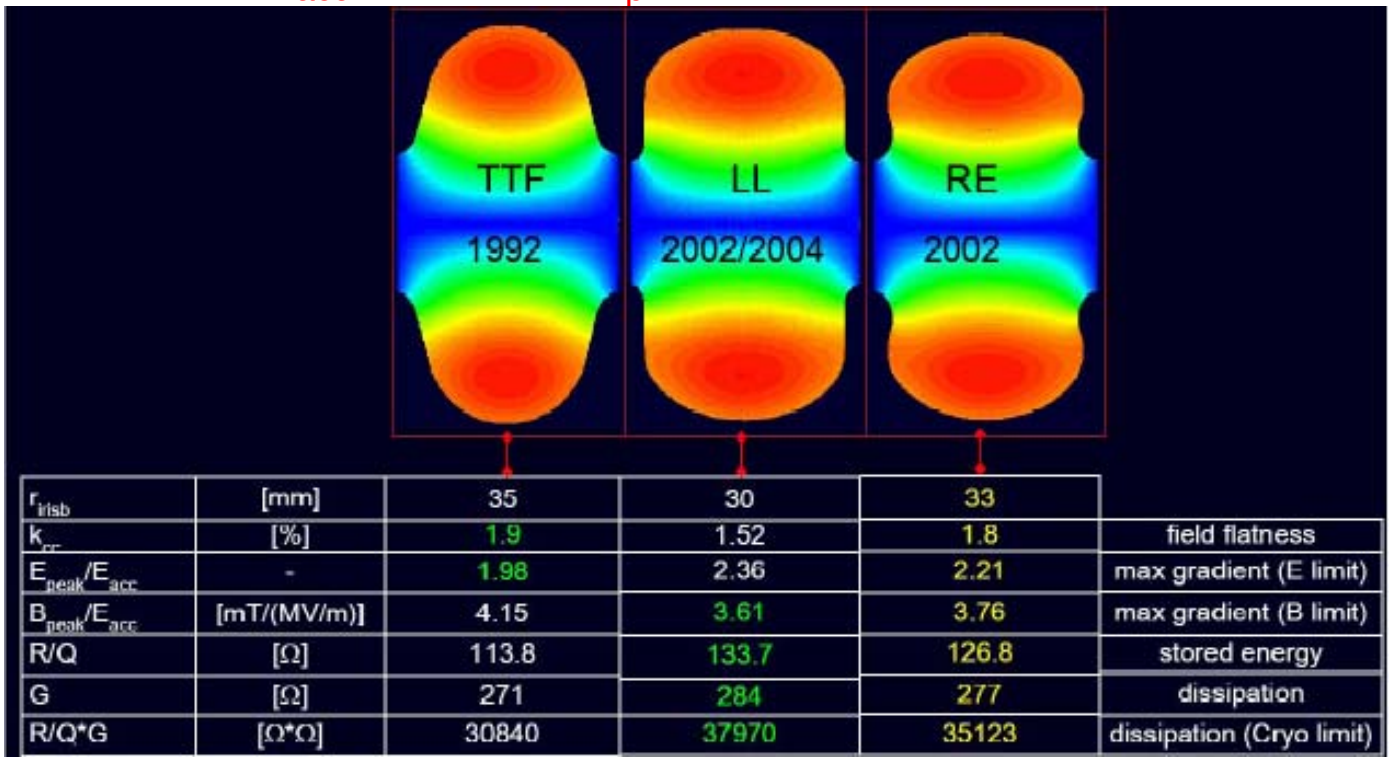
- Disadvantage 1: getter material needs to be etched/polished off
  - inside: up to 100µm diffusion of getter material along grain boundaries
  - outside: app. 50 µm removal to establish good heat transfer (Kapitza resistance)?
- Disadvantage 2: cavity becomes soft

„Quench“: Postpurified TTF cavities



“Quench”: Cavity shape

- Increased gradient E_{acc} for same H_p with modified cell shape:



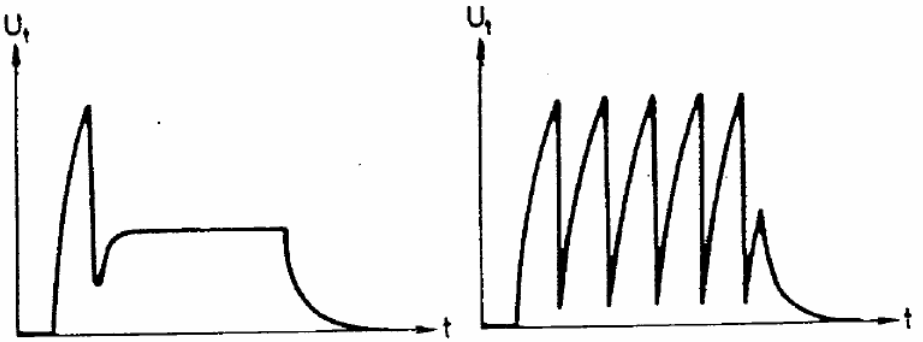
r_{irisb}	[mm]	35	30	33	
k_{cc}	[%]	1.9	1.52	1.8	field flatness
E_{peak}/E_{acc}	-	1.98	2.36	2.21	max gradient (E limit)
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76	max gradient (B limit)
R/Q	[Ω]	113.8	133.7	126.8	stored energy
G	[Ω]	271	284	277	dissipation
R/Q*G	[Ω*Ω]	30840	37970	35123	dissipation (Cryo limit)

- TESLA shape: Lower E_s + tilted iris area, but higher H_p/E_{acc} (~15%)
  => good wet cleaning, optimized for FE, stronger cell-to-cell coupling
- Low Loss : Lower H_p/E_{acc} , but reduced iris diameter + higher E_p/E_{acc}
- Reentrant : Compromise for rf parameters, but difficult cleaning

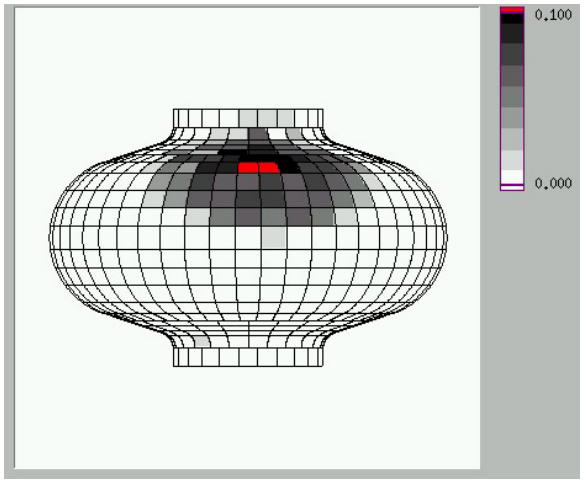
(courtesy of J. Sekutowicz)

“Quench”: Tell tales and symptoms

- rf-signal:
  - breakdown of transmitted power within ≈ms (thermal time constant)
  - often self-pulsing



- T-Mapping:
  - hot spot in surface area with high magnetic field
  - high ΔT during quench
  - precursor just below the quench ??



- No X-rays !!!

  => with x-rays life becomes more complicated (quench with FE present, FE induced quench, multipacting, …)

“Quench”: Open questions

- Is there a **superiority** of large grain /single crystal Nb for H_q ??
  - reduced effect of grain boundaries
  - smooth surface on large grains without EP
  - dependence on preparation ?

  => answer here at this workshop ???

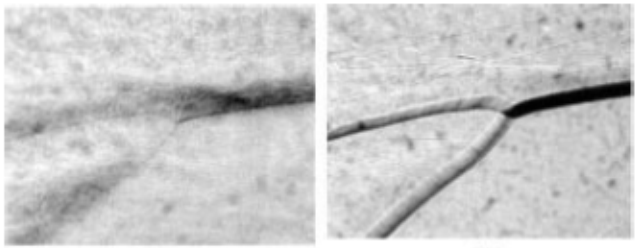


Figure 29. Expanded optical micrographs of grain boundaries in the welded regions. The typical grain size is 1 mm. (a) Electropolished to remove 100 μm, (b) after standard chemical polishing to remove 44 μm. Note that in (a) electropolishing still leaves a grain boundary step, although it is not as high, nor as sharp, as the step that results from standard chemical etching [23].

- Why gives EP higher quench fields?

  => discussion above !!!

- Complete modeling of quench properties and comparison to measurements

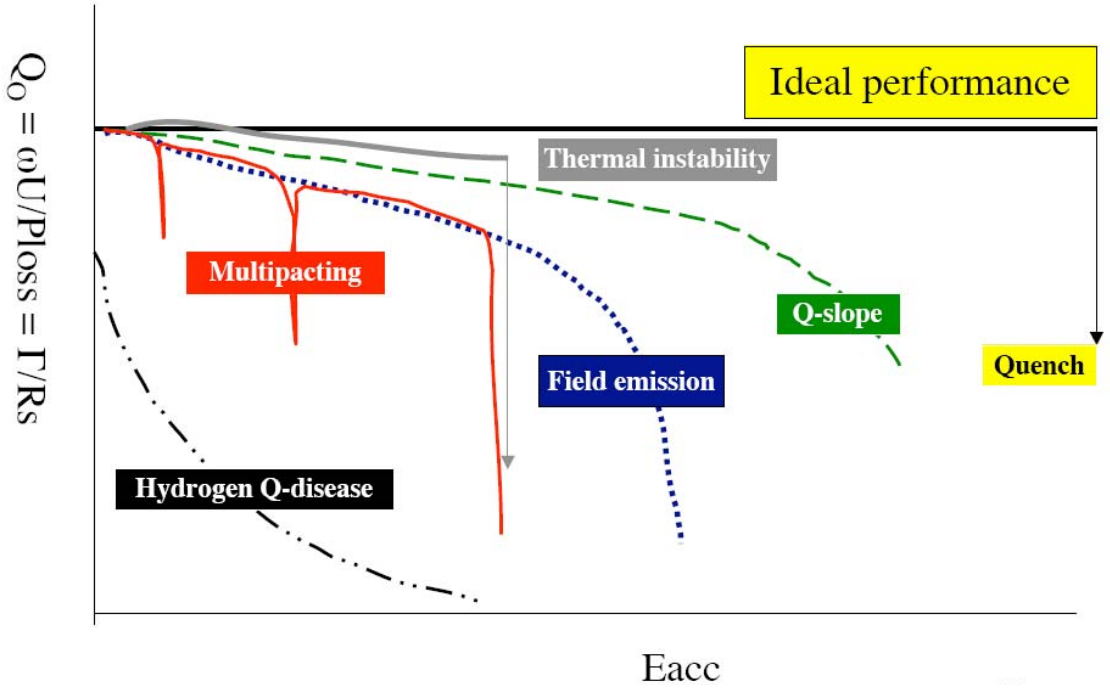
  e.g. Kapitza resistance; often missing precursor in T-maps; (medium field Q-slope); …

- Fundamental maximum magnetic field => H_{c1}, H_c, H_{sh} ???

“Q-drop” without field emission

- My problem or the solution?
  Excellent summaries given by
  - G. Ciovati, 12th Workshop on RF Superconductivity, Cornell, 2005
  - B. Visentin, International Workshop on Thin Films, Legnaro, 2006
  - V. Palmieri, 12th Workshop on RF Superconductivity, Cornell, 2005

- Different situation for
  i) thin films
  ii) bulk Nb

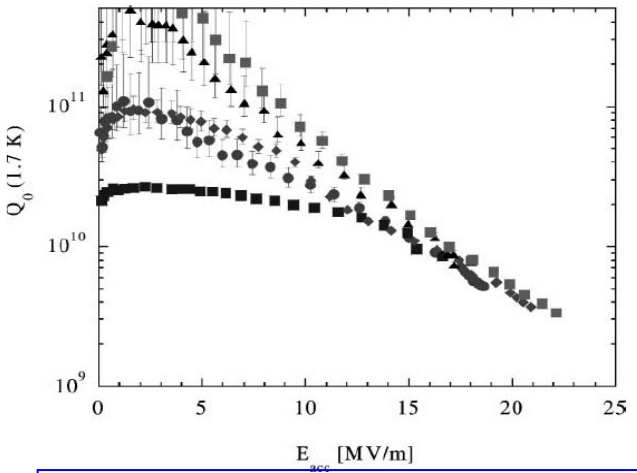


Thin Film Cavities & Q-Drop

dapnia
cea
saclay

Advantages to use Thin Film Technology for SRF Cavities :
Reduced Cost – New Superconducting Material (higher T_c & H_{sh})

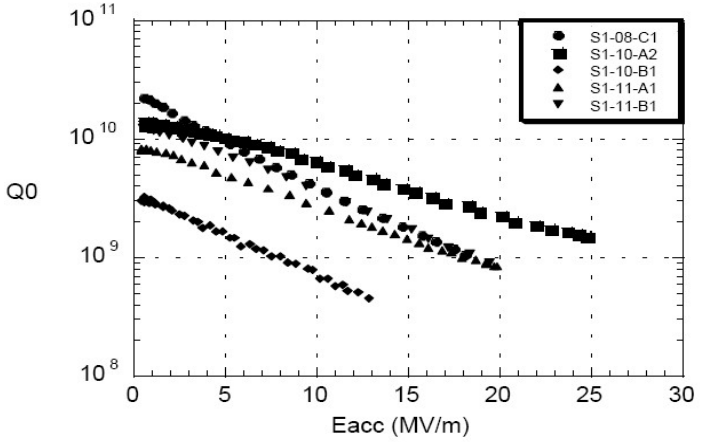
severe Q-drop limits High Gradient Performances E_{acc} < 25 MV/m



*CERN – **Nb** / Cu – 1.5 GHz*

Magnetron Sputtering in Kr

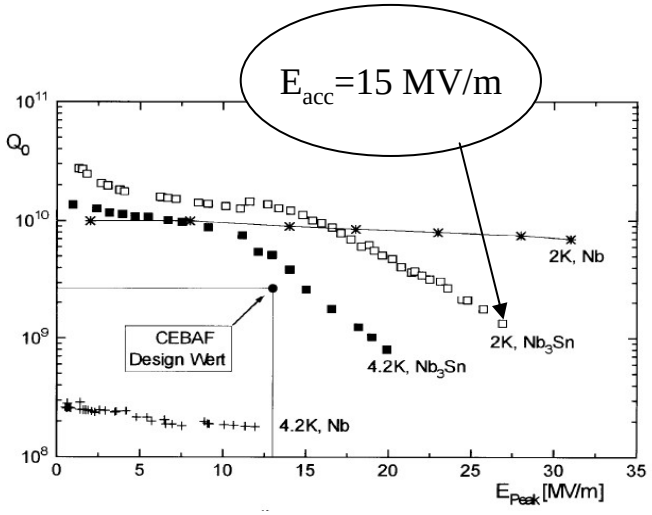
V. Arbet-Engels et al.- NIMA (2001)



*Saclay – **Nb** / Cu – 1.5 GHz*

Magnetron Sputtering in Ar

P. Bosland et al.- ASC (1998)



*Wuppertal – **Nb_3Sn** / Nb – 1.5 GHz*

Vapor Deposition Technique

G. Müller et al.- EPAC (1996)

(no field emission, no quench only RF power limitation)

Q-Drop Origin (Thin Film)

dapnia
cea
saclay

- Granular Superconductor Theory : Josephson fluxon penetration in weak links (grain boundaries → oxidized sputter island)
- Thermal resistance at superconductor-substrate interface
- Energy Gap dependence Δ(H)

V. Palmieri - SRF (2005)

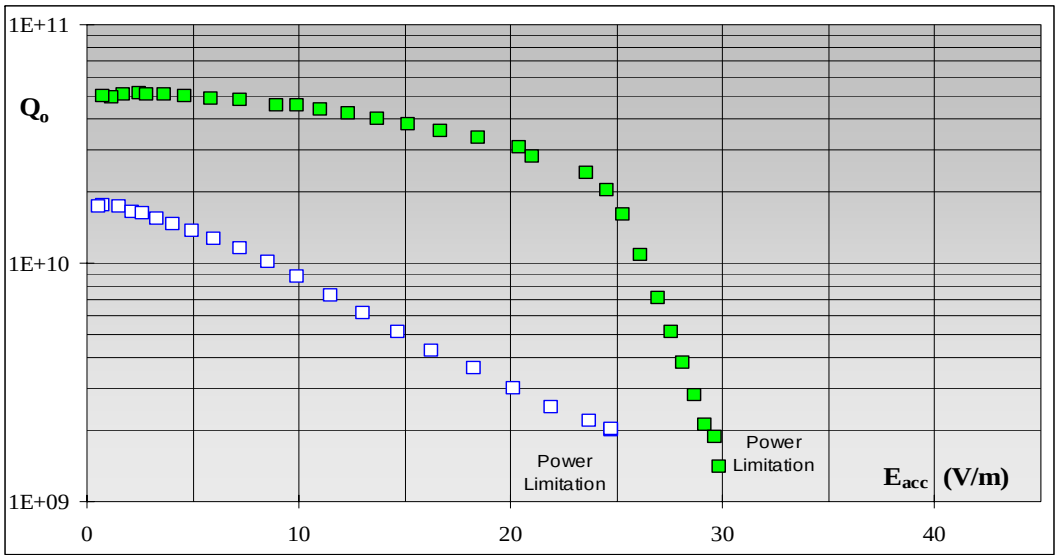
J. Halbritter - Workshop of the Eloisatron Project (1999)

B. Bonin - Supercond. Sci. Technol. 4,257 (1991)

- Not a fundamental limitation : improve cleanness during process (substrate, sputtering,…)

V. Arbet - Engels et al.- NIMA (2001)

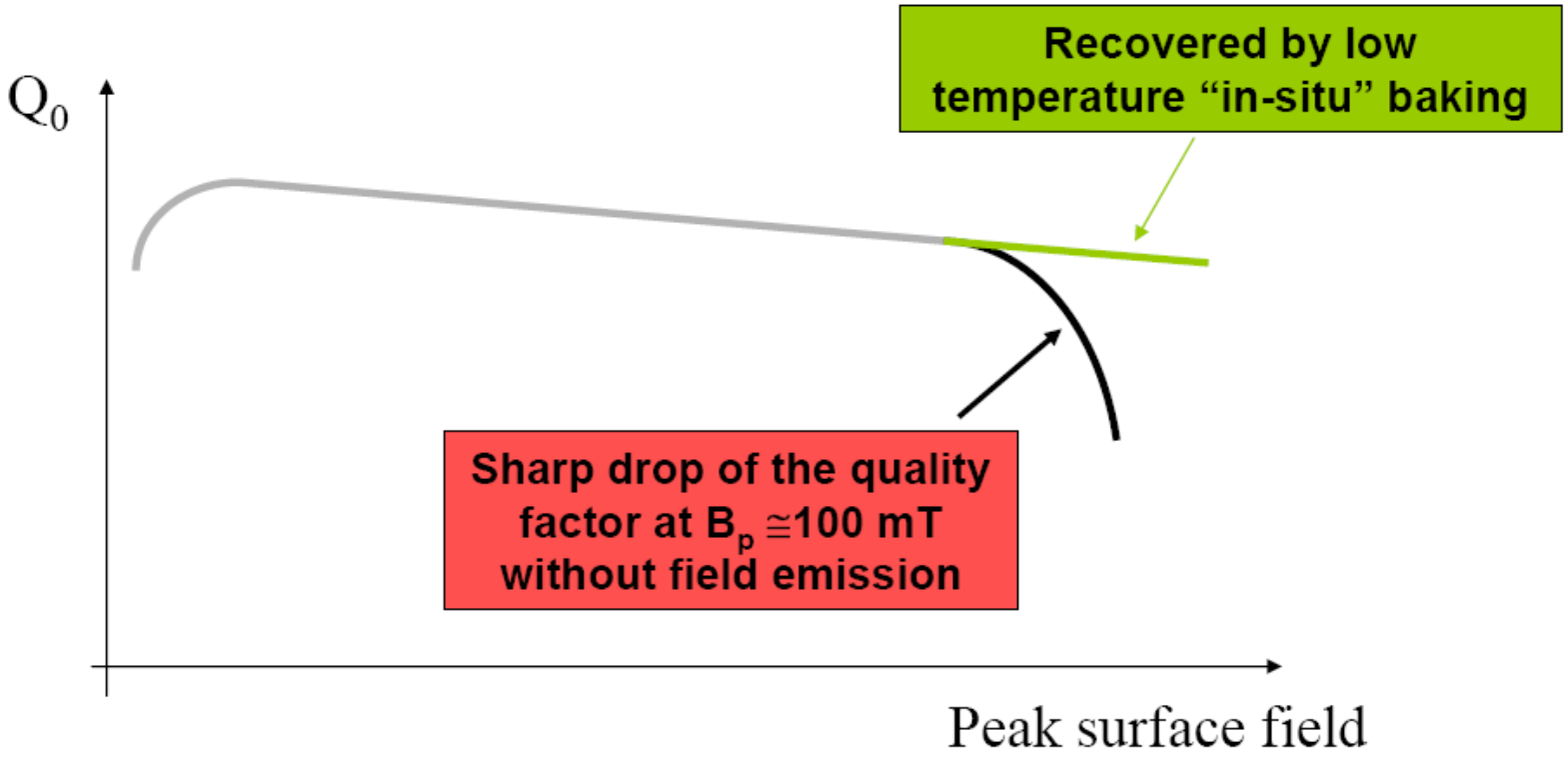
not enough data on Thin Film Cavities



Hope to clear up the Thin Film issue ???

Q-drop of bulk niobium cavities

- For bulk Nb cavities:

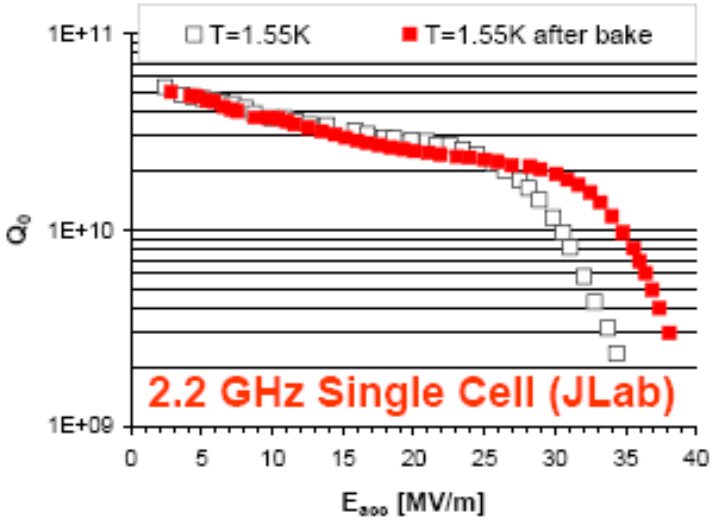


Preparation dependence: BCP

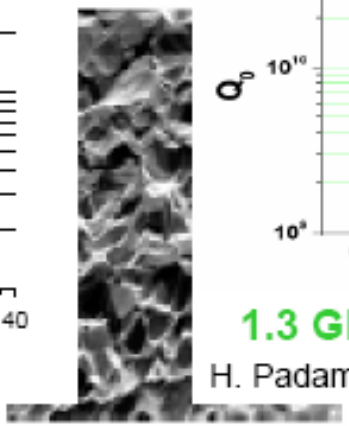
- G. Giovati:

BCP treated cavities (1)

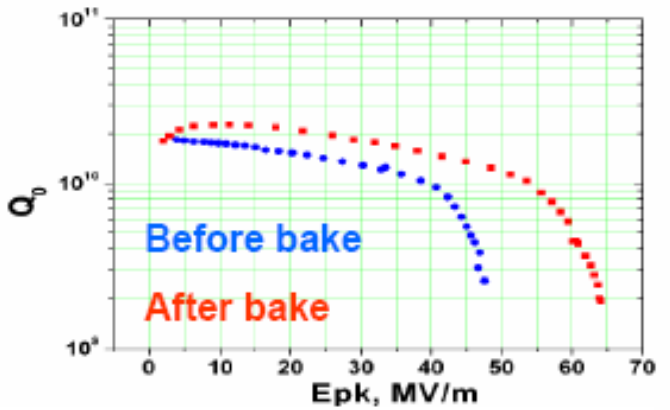
- Fine grain (~ 50μm), rough surface (5-10μm)



P. Kneisel *et al.*-PAC 05-TPPT076



R.L. Geng *et al.*-SRF 99-TUP021



1.3 GHz Single Cell (Cornell)

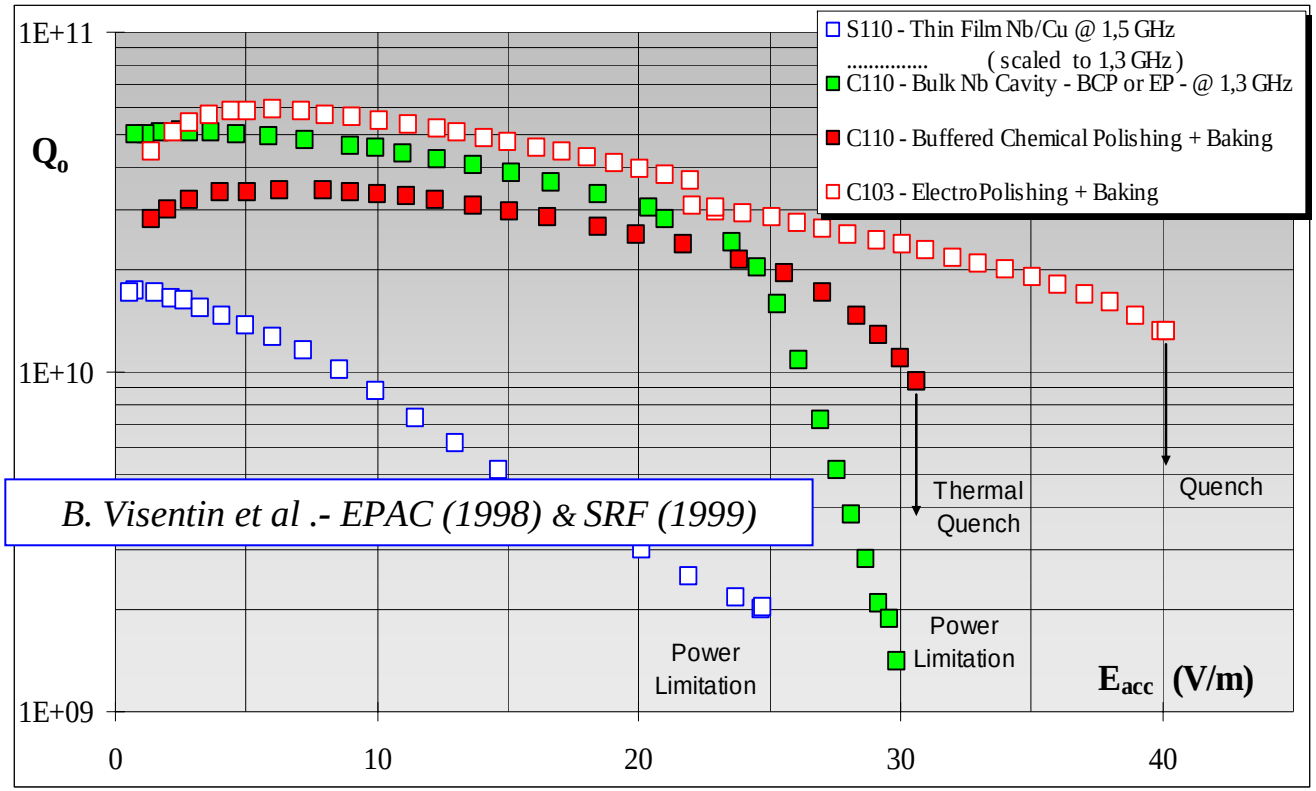
H. Padamsee *et al.*-Frontier Workshop-p. 291

Q-drop STILL PRESENT after baking

Preparation dependence: Contradiction for BCP !

- B. Visentin: **Contradiction !!!**

It can be cured by baking : limitations in Q_0 and E_{acc} can be exceeded



Baking: Universal treatment

fine, large, single crystal, clad, shape, w /wo annealing @ 800C or 1350C

EP or BCP chemistry

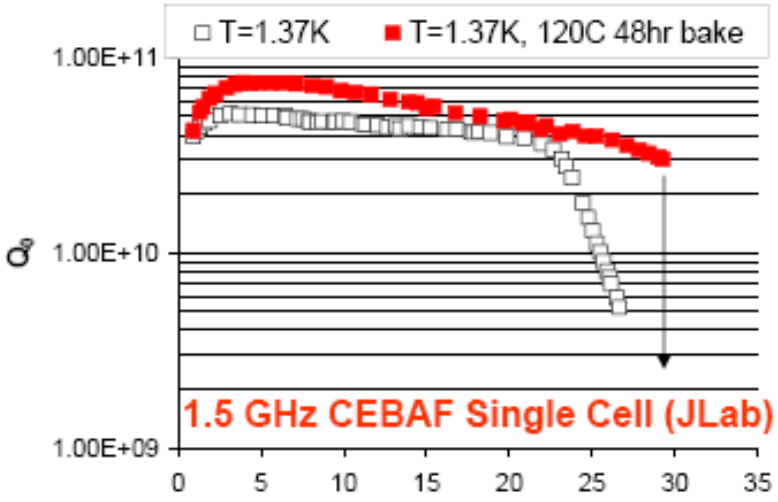
Check of world wide data base necessary !!! (More data available: TTF??)

Preparation dependence: BCP ctd.

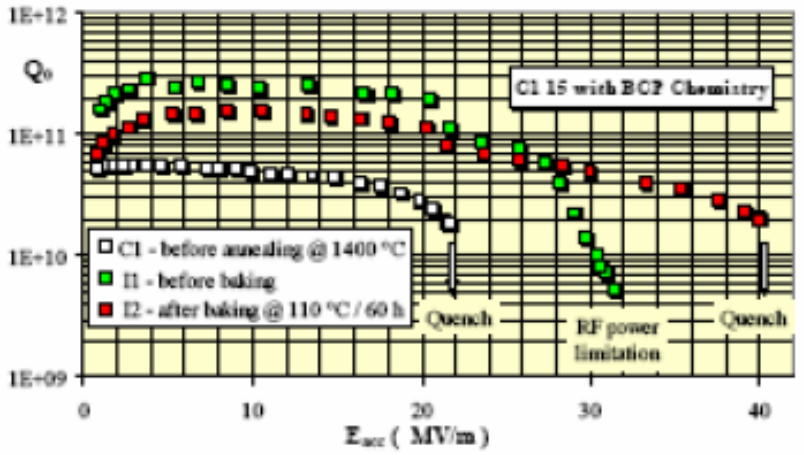
- G. Giovati:

BCP treated cavities (2)

- Larger grains (1-5mm) by post-purification, rough surface (5-10μm)



G. Ciovati-*J. Appl. Phys.* 96, p. 1591 (2004)



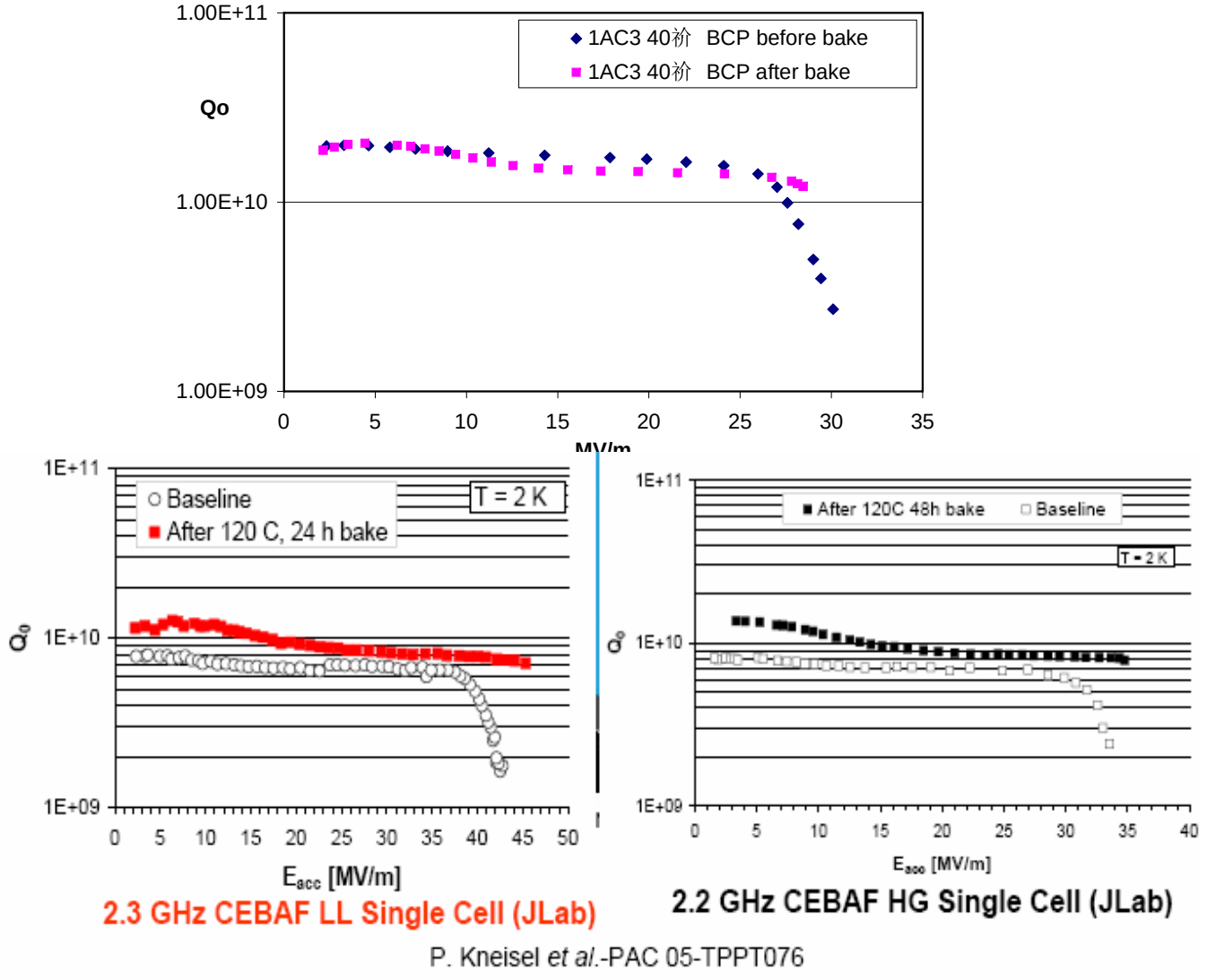
1.3 GHz Single Cell (Saclay)

B. Visentin *et al.*-EPAC 02-THPDO013

Q-drop RECOVERS after baking

Preparation dependence: BCP + large grain

- Q-drop **recovers** for **BCP treated large grain + single crystal cavities !!**

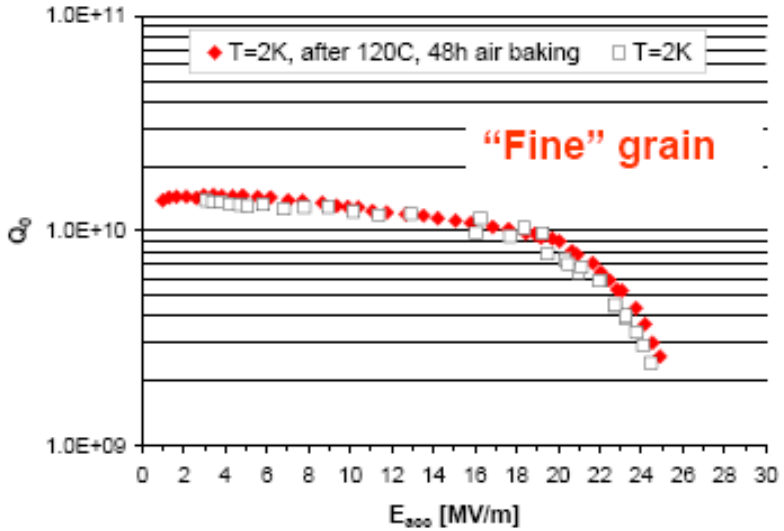


P. Kneisel *et al.*-PAC 05-TPPT076

Preparation dependence: BCP + Air bake

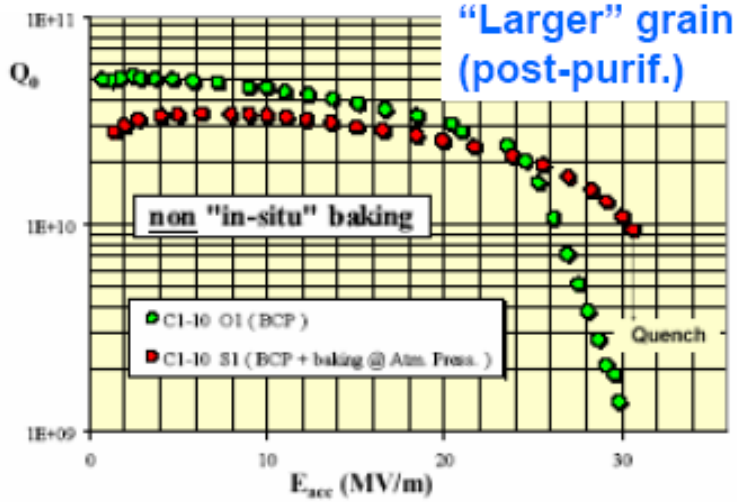
- G. Giovati: BCP treated cavities (3)

"Air" baking



1.5 GHz CEBAF Single Cell (JLab)

G. Ciovati, unpublished



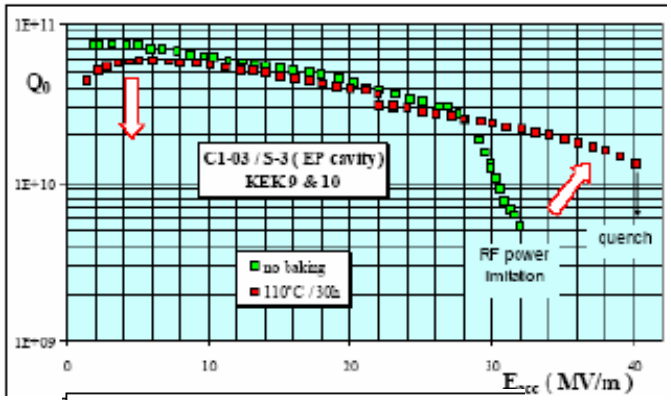
1.3 GHz Single Cell (Saclay)

B. Visentin *et al.*-SRF 03-MOP19

- **Reduced Q-drop improvement**
- **Higher residual resistance**

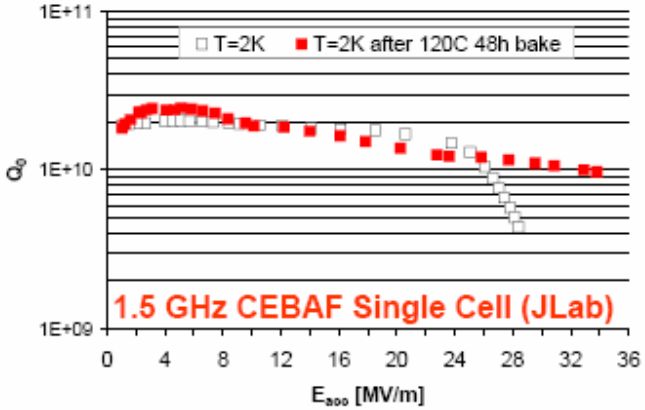
Preparation dependence: EP

- Q-drop **recovers** for **all EP treated Nb bulk cavities !!**
  => fine / large grain; 800 C / 1400 C annealing

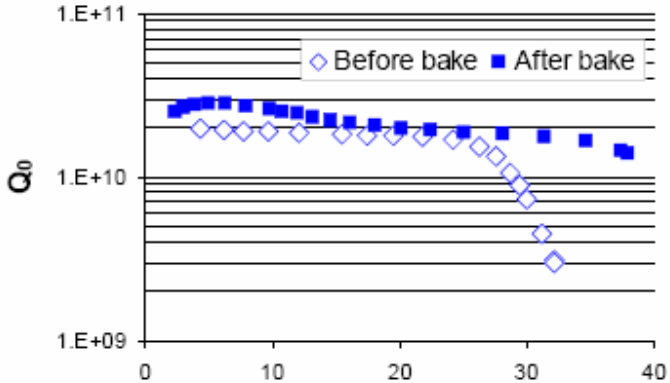


1.3 GHz Single Cell (Saclay)

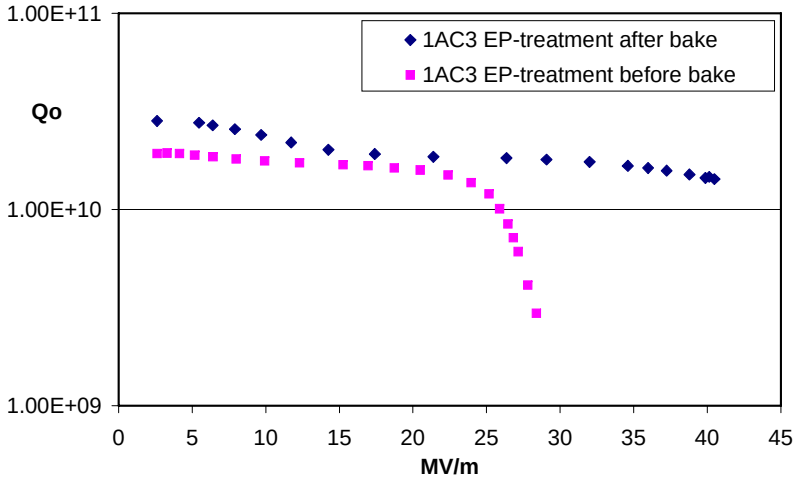
B. Visentin *et al.*-SRF 03-TUO01



G. Ciovati, J. Mammosser, unppublished

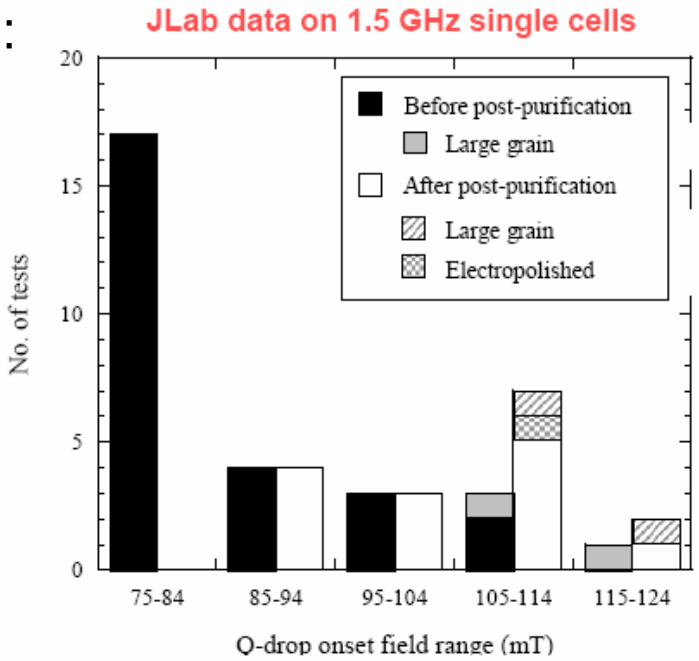


L. Lilje -EPAC 04- WEAOCH03



Preparation dependence: Summary

- Q-drop is common to BCP, EP, fine + large grain Nb, single crystal Nb
- The onset of Q-drop is higher for lower density of grain boundaries:
  G. Giovati:



Comparison with Cornell, DESY and Saclay data necessary !!!

- **Contradiction on effect of bake for fine grain Nb!!**
- Bake cures Q-drop on **all** EP-treated and LG + SC BCP cavities
  => effect of grain boundary density??
- “Air” baking less effective than “UHV” bake

What is “bake”??

- Standard recipe:

T = 110 – 125 C for 1 - 2 days UHV- conditions

=> fully assembled cavity after cleanroom treatment

- Alternatives:

  i) higher temperature

  T = 135 – 150 C for 3 – 12 h still UHV-conditions

=> still fully assembled cavity required

  ii) open bake at air (Saclay) or nitrogen (DESY)

  open bake in air:

  T = 110 C for < 60h (3h)

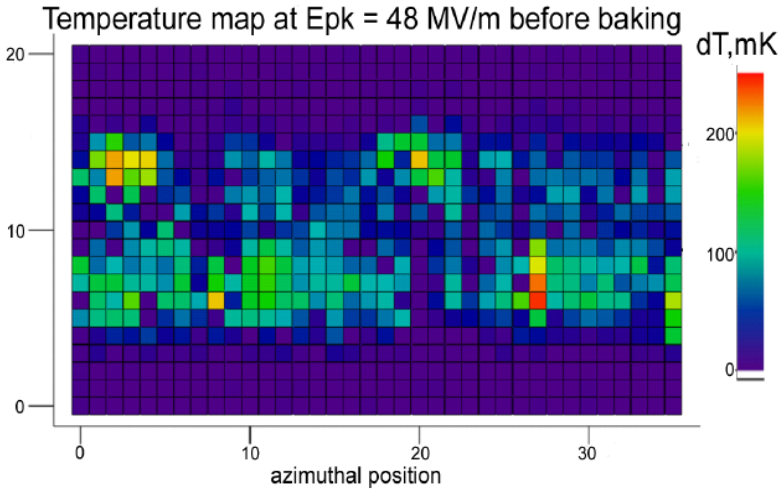
=> open air / nitrogen baking well adapted to cavity mass production

=> more experiments necessary !!

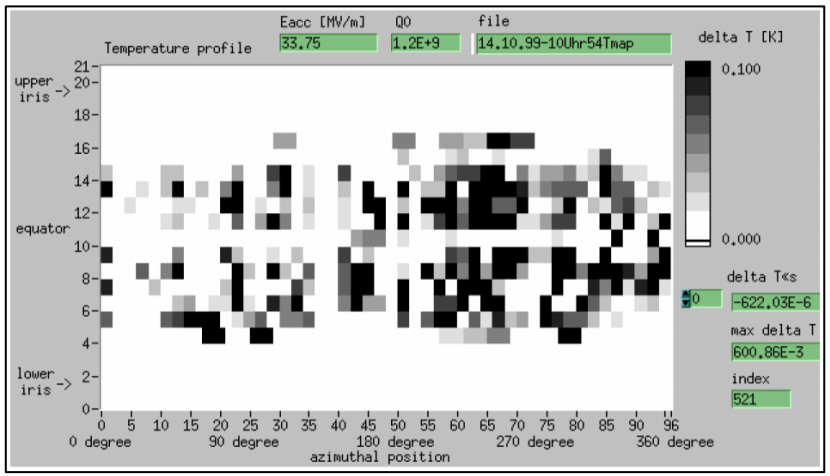
Temperature maps before bake

- Wide distributed loss areas or “hot spots” ?

  A) **Fine grain**:



G. Eremeev, H. Padamsee - EPAC (2006)



L. Lilje - SRF (1999)

=> Fine grain shows widely distributed (homogeneous ??) losses in the equator region

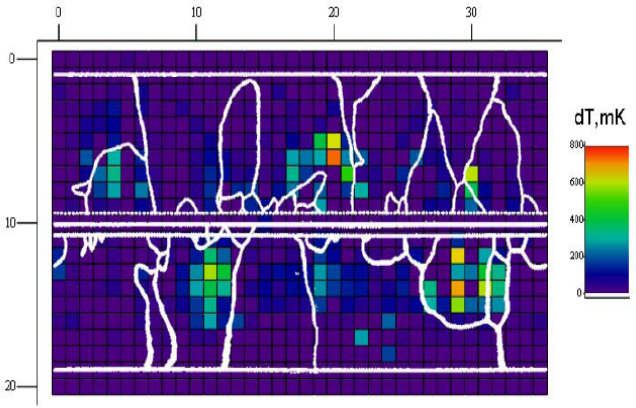
=> effect of magnetic (not electric) field

(confirmed by separate TE_{011} – cavity experiments)

Temperature maps before bake II

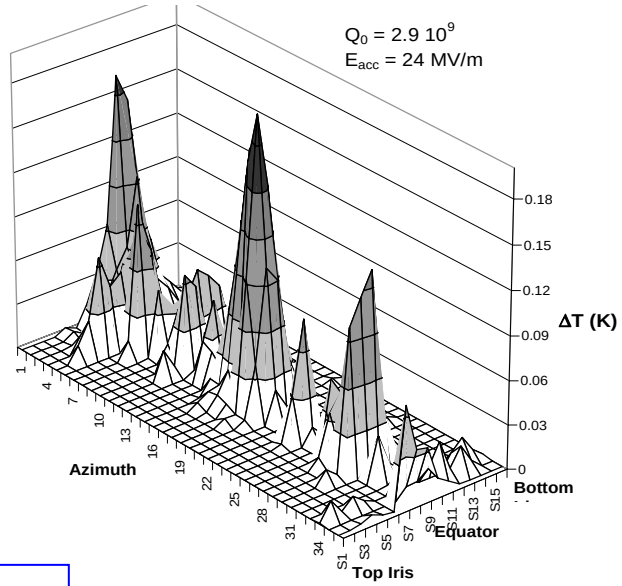
- Wide distributed loss areas or “hot spots” ?

B) **Large grain**:

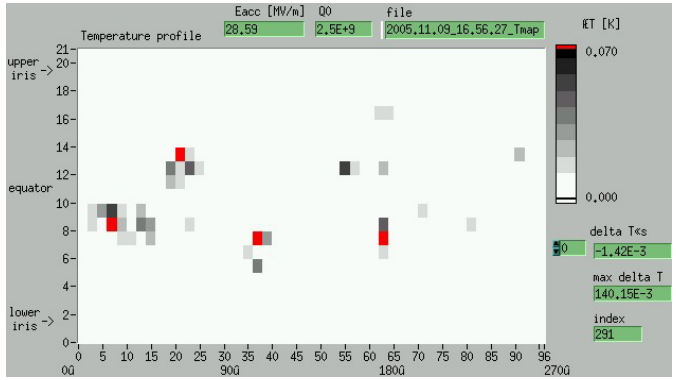


Large grain (G.B.= white lines)

G. Eremeev, H. Padamsee - EPAC (2006)



G. Ciovati - LINAC (2006)

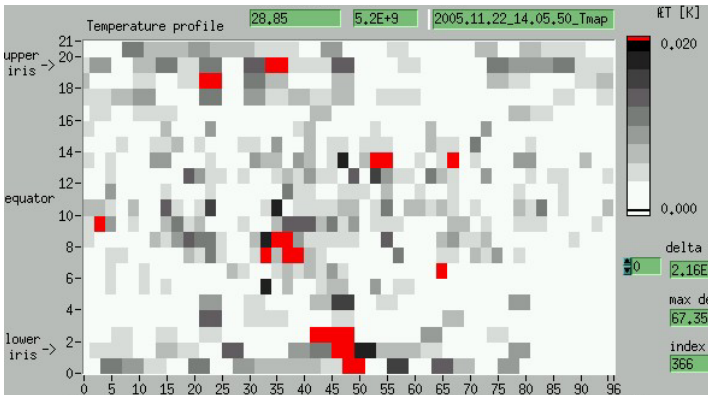


D. Reschke

=> Many experiments show “hot spots“, but there are exceptions:

=> no correlation with grain boundaries

=> magnetic field effect

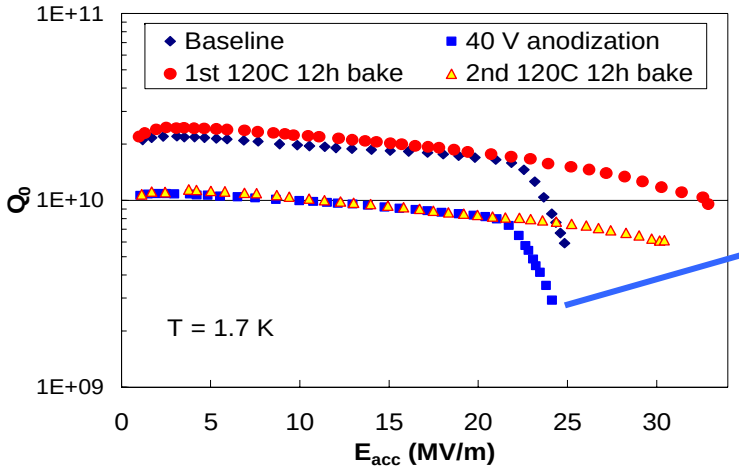


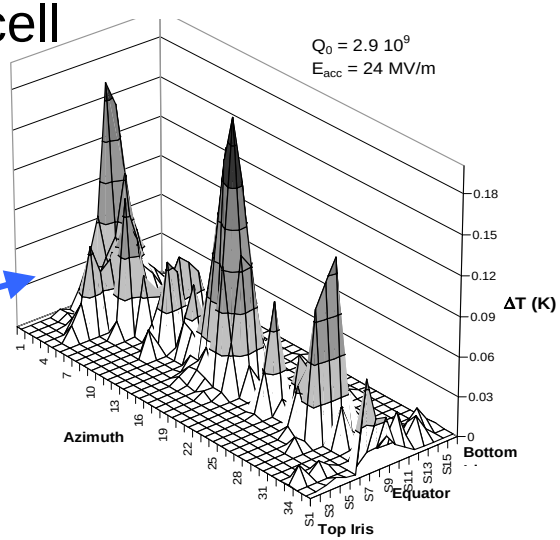
D. Reschke

Q-drop: Effect of anodization

- **Contradictory** results for anodization (=increase the thickness of oxide):

G. Ciovati: **Large grain** single cell





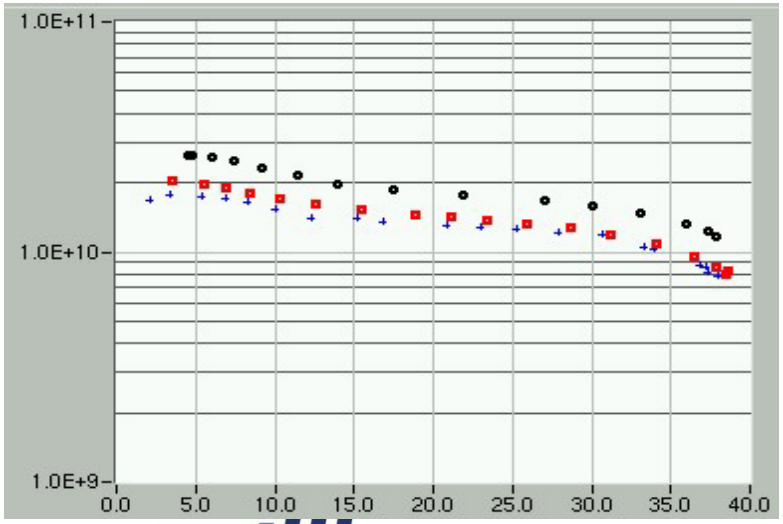
Hot spots (large grain cavity)

Reduced after baking

Q-slope restored by 40 V anodization

D. Reschke: **Fine grain EP** single cell

=> no Q-slope after 30V anodization

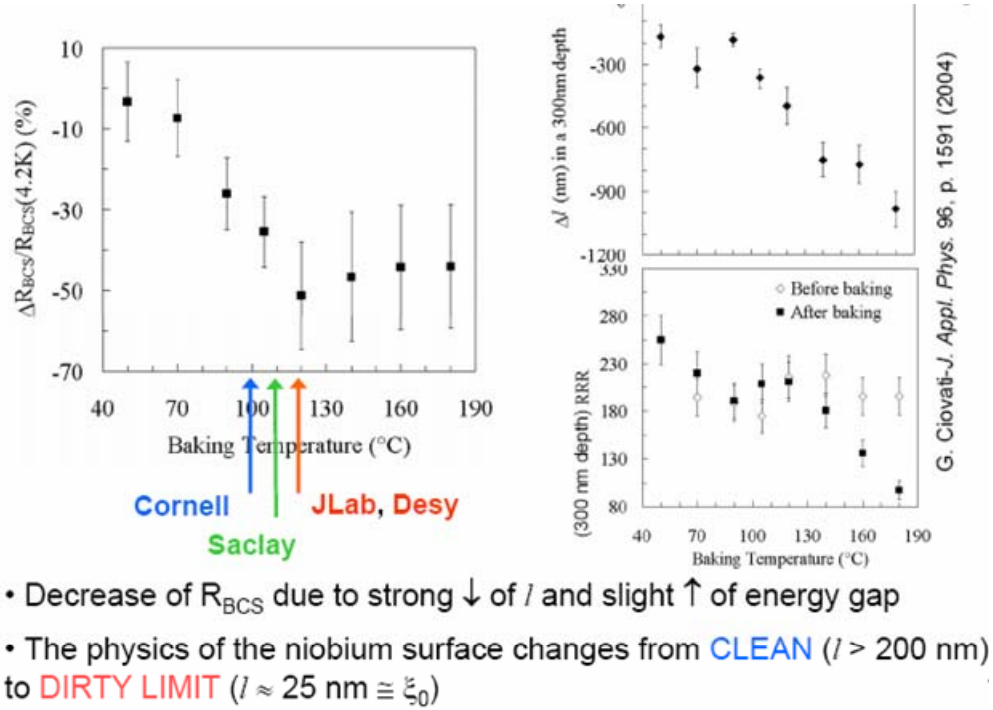


black: after EP + bake
red: + anodizing
blue: + add. bake
T = 2K

Q-drop: other experimental observations

- Benefit of bake is maintained
  - after long air exposure (several years)
  - high pressure water rinsing
- Oxipolishing (> 60nm) is required to restart Q-drop
  (=> contradiction to Cornell experiments??)
- BCS surface resistance decreases after bake => reduction of mean free path

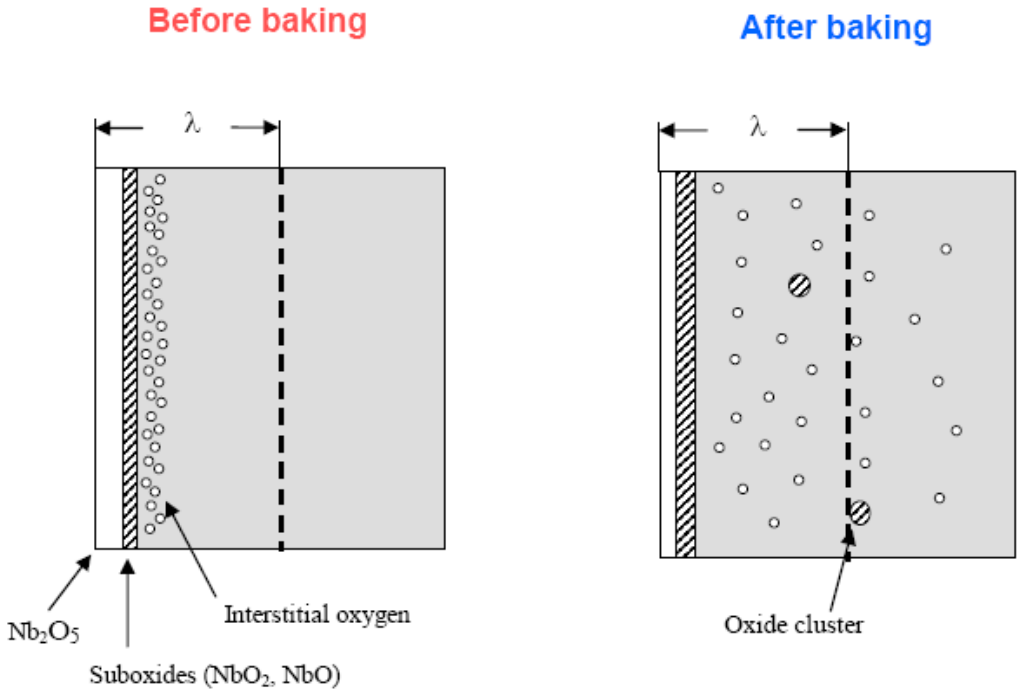
G. Giovati:



- Decrease of R_{BCS} due to strong ↓ of l and slight ↑ of energy gap
- The physics of the niobium surface changes from CLEAN (l > 200 nm) to DIRTY LIMIT ($l \approx 25$ nm $\cong \xi_0$)

Q-drop: Sample experiments

- Schematic of the Nb surface:
  (courtesy of G. Giovati)



- Surface analysis by SIMS, XPS etc.
  - natural oxide Nb_2O_5 decomposes into sub-oxides (NbO, NbO_2)
  + thinner Nb_2O_5 layer
  - diffusion of oxygen in the rf penetration depth (=> modification of R_{BCS})
- Magneto-optical measurements:
  - evidence of flux penetration along grain boundaries

High Field Q-Drop (6 theories)

dapnia

cea

saclay

- Diffusion (O, Imp.) : “ Interface Tunnel Exchange ”
  “ Bad Superconducting Layer ”
  “ Granular Superconductivity ”
- Surface Roughness : “ Magnetic Field Enhancement ”
- High Field (T, H_{peak}) : “ Thermal Feedback ”
  “ Energy Gap Dependence Δ (H) ”

Theories / Experiments Confrontation

dapnia

cea

saclay

B. Visentin - SRF (2003) – updated at Argonne Workshop (2004)

	Q-Slope Fit	Q-Slope before baking (EP = BCP)	Q-Slope Improvem^{t} after baking	Q-Slope after baking (EP < BCP)	No change after 4 y. air exposure	Exceptional Results (BCP)	Q-Slope unchanged after HF chemistry	TE_{011} Q-slope after baking	Quench EP > BCP	BCP Quench unchanged after baking	Argum^{t} Validity	Fund^{al} Disagreem^{t} Exper. ≠ Theory
Magnetic Field Enhancem^{t}	Y simulat. code	~~N~~ $\beta_m \neq$ $B_{C2}{}^{S} \neq$	Y $B_{C2}{}^{S}\uparrow$	Y lower β_m	-	N high β_m	-	-	Y lower β_m	N $B_{C2}{}^{S}\uparrow$	Y	D_1
Interface Tunnel Exchange	Y E^{S}	N $\beta^* \neq$	Y $Nb_2O_{5-y}\downarrow$	Y lower β^*	N $Nb_2O_{5-y}\uparrow$	N high β^*	~~N~~ new Nb_2O_{5-y}	~~N~~ improv^{t}	-	-	Y	D_2
Thermal Feedback	Y parabolic	Y ≅ thermal properties	Y $R_{BCS}\downarrow$ $R_{res}\uparrow$	N ≅ therm. propties	-	-	-	-	-	-	N C coeff.^{t}	-
Magnetic Field Dependence of Δ	Y expon^{tial}	N $B_{C2}{}^{S} \neq$	Y $B_{C2}{}^{S}\uparrow$	Y higher $B_{C2}{}^{S}$	-	-	-	-	-	-	~~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 $Nb_{4-6}O$	?	Y NC layer	Y O diffusion	N	N interstitial re-appears	-	~~N~~ new bad layer	-	Y higher $B_{C2}{}^{S}$	N $B_{C2}\downarrow$	Y	D_1

Y / **N** = theory in **agreement** / **contradiction** with experimental observation **N+**

/ = undisputable disagreement with experiment

Q-drop: Summary

- Q-drop is driven by magnetic surface field

- Bake cures Q-drop for all EP-treated cavities
- Bake cures Q-drop for Large-grain + single-crystal BCP-treated cavities
  but inconsistent results for fine grain BCP-treated cavities

=> Density of grain boundaries:
Dependence of onset field of Q-drop and effect of baking ?

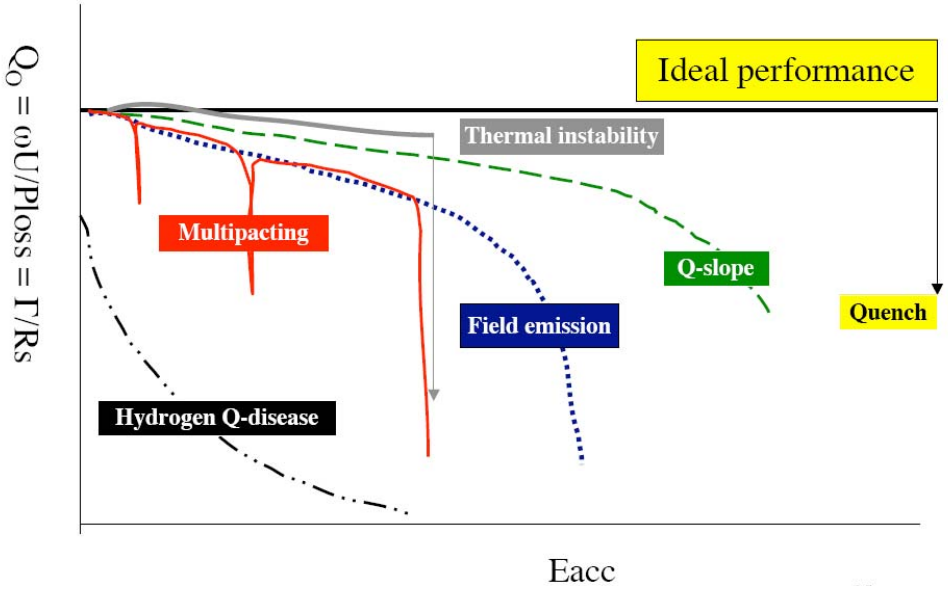
- Baking increases the oxygen concentration within the rf penetration depth

Q-drop: Open questions

- Role of **oxygen ??**
- Is there any role of hydrogen?
- Experimental check of flux penetration in cavities?
- Is there one consistent model for the explanation of Q-drop and the effect of baking in bulk Nb ?
  => this workshop ???

“Medium field” Q-slope

- Experimental:
  - Nearly (!) all bulk Nb cavities show a Q-slope (factor 2 – 5 Q-reduction to low field)
  - linear / quadratic field dependence (depending on Lab and cavity)
  - Q-slope is present after EP & BCP & bake & no-bake
- Consequence:
  - no hard limit (☺)
  - **BUT:** Cryogenic load increases => increased cost or limited operational acceleration gradient



“Medium field” Q-slope: Models

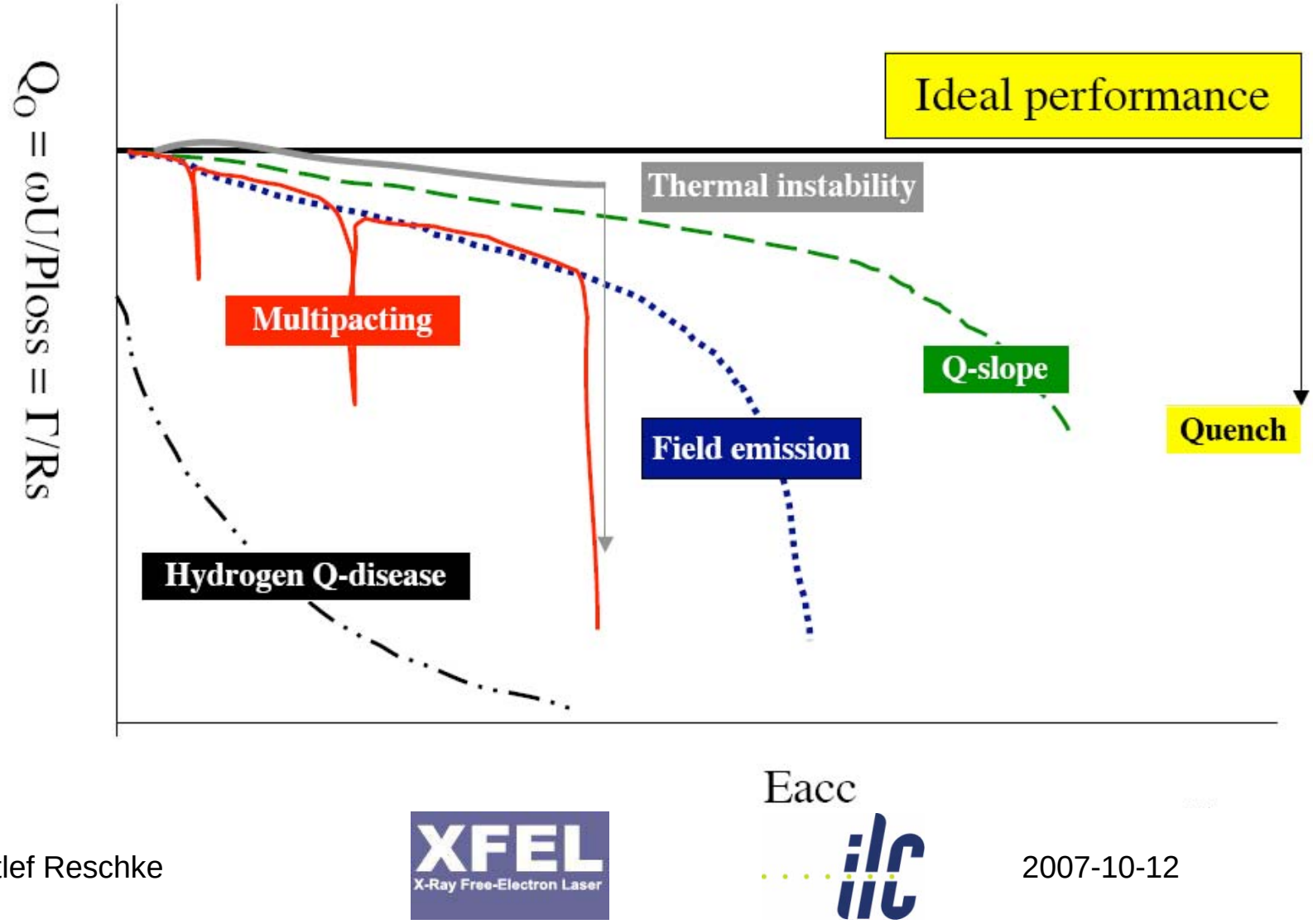
- linear dependence by hysteretic losses due to Josephson fluxons in weak links (=> grain boundaries)
  => check on single-crystal cavities necessary
- Quadratic dependence:
  i) Halbritter model (SRF 2001)
  ii) Thermal feedback model:

  i) intrinsic heating of $R_{BCS} + R_{res}$ not sufficient for “standard” parameters for thermal conductivity and Kapitza conductance (ok with reduced Kapitza)

  ii) non linear correction for rf pair breaking by A. Gurevich
  - better fit of experimental data (P. Bauer, SRF 2005)
  => new results at this workshop ??

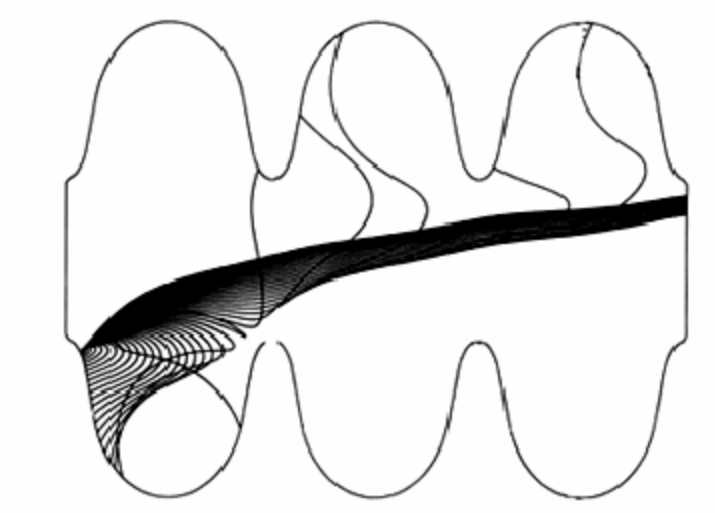
Field emission

- Field emission:



Field emission: Introduction

- **Major limitation of the last years in multi-cell cavities**, especially in beam operation:

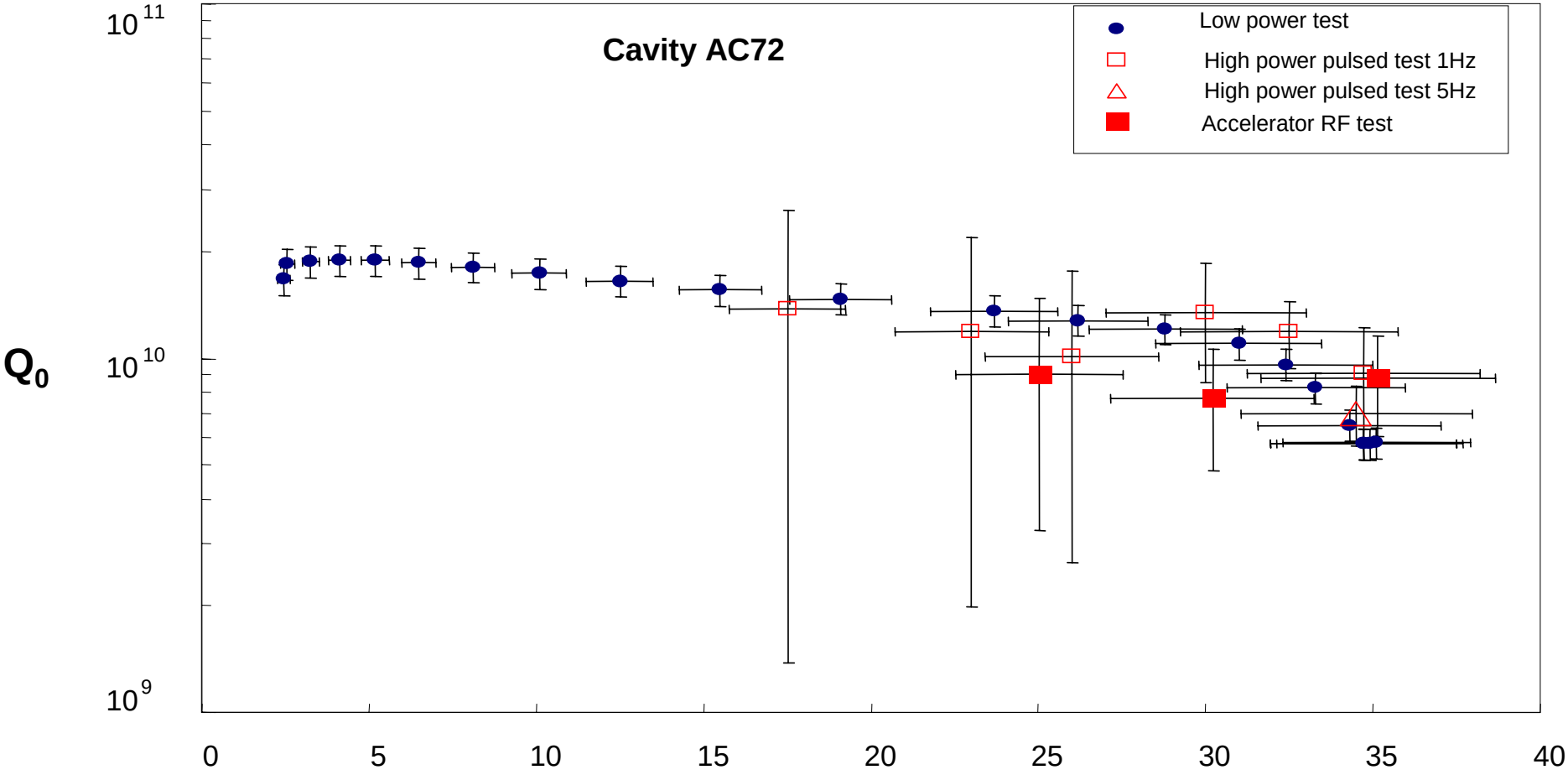


- **Field Emission!!**

- Typical (good) onset of field emission at 1.3 GHz
  - single-cell cavities: $E_{acc,onset} > 30$ MV/m
  - multi-cell cavities (vertical + horizontal): **$E_{acc,onset} \approx$ (20 - 25) MV/m**
- But:

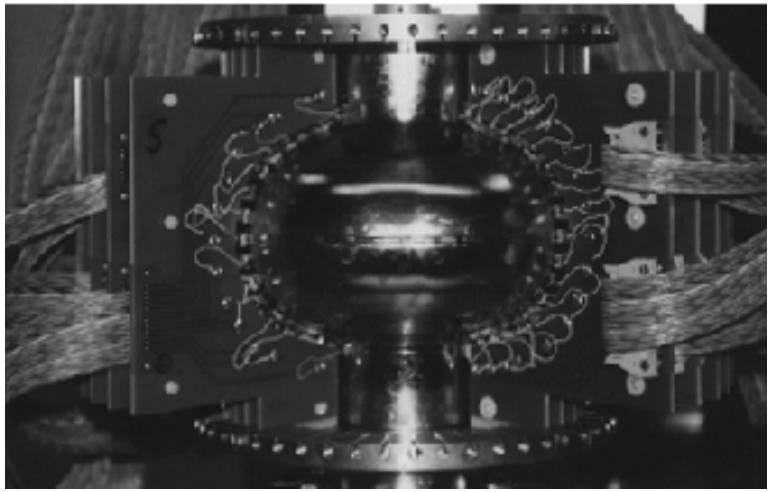
High gradient cavity operation

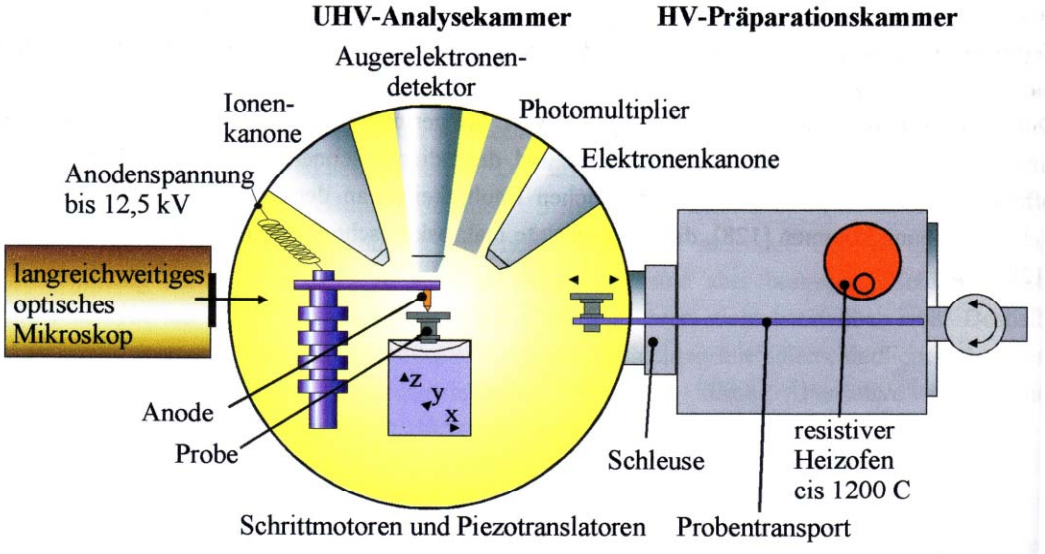
- 35 MV/m without field emission in e^- - beam operation is possible !!

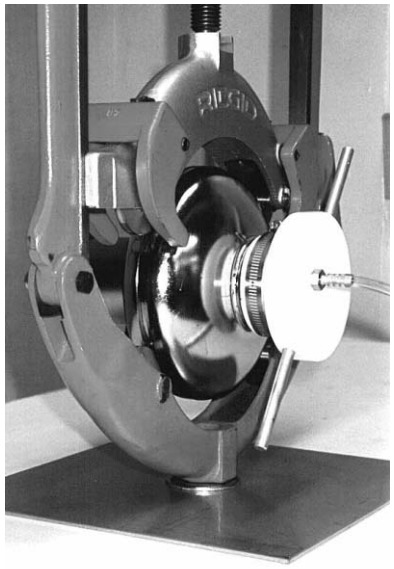


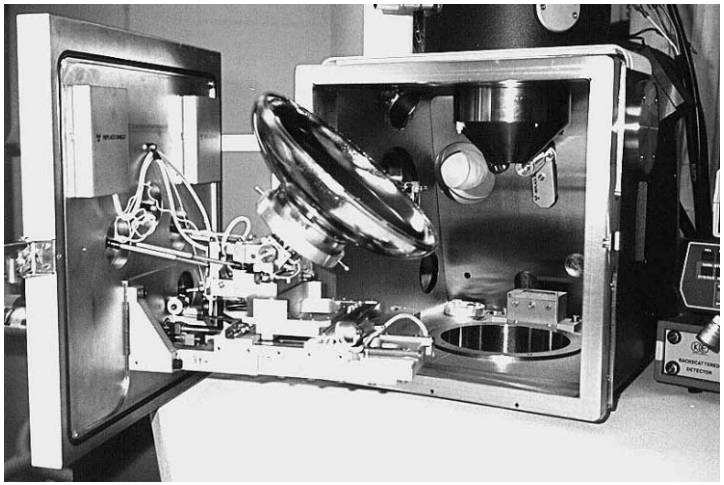
Field emission: Instruments

- Some tools developed for field emission investigation







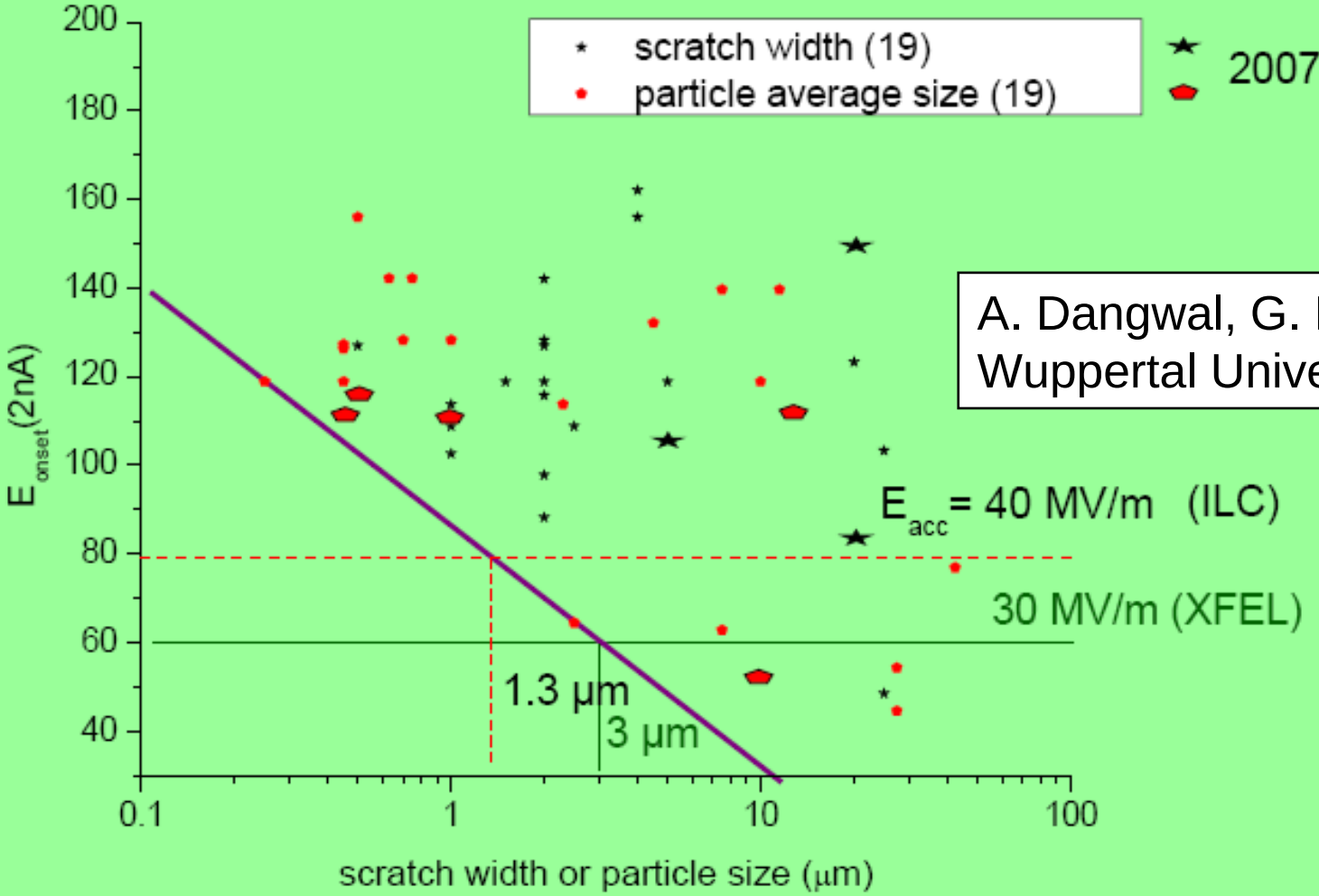


Field emission: Experimental observations

- Metallic (conducting) particles of irregular shape; typical size: 0,5 - 20 µm
- Only 5% - 10% of the particles emit

Correlation between FE onset field and defect size ?

based on FE measurements and SEM analysis of 38 field emitters



A. Dangwal, G. Müller
Wuppertal University

Evidence for correlation ⇒ fast FE quality control by defect size

Field emission: Experimental observations

- Metallic (conducting) particles of irregular shape; typical size: 0,5 - 20 µm
- Only 5% - 10% of the particles emit
- hydrocarbon contamination of the vacuum system

- Modified Fowler-Nordheim's law :

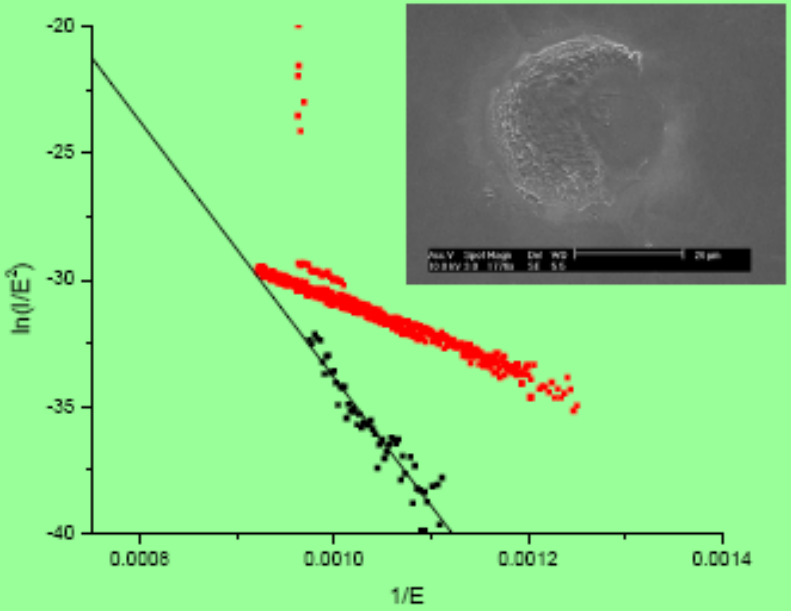
$$I \propto A_{FN} \cdot (\beta_{FN} E)^2 / \Phi \cdot \exp\left(- \frac{C\,\Phi^{3/2}}{\beta_{FN}\,E}\right)$$

- typical β-values between 50 and 500 for srf cavities

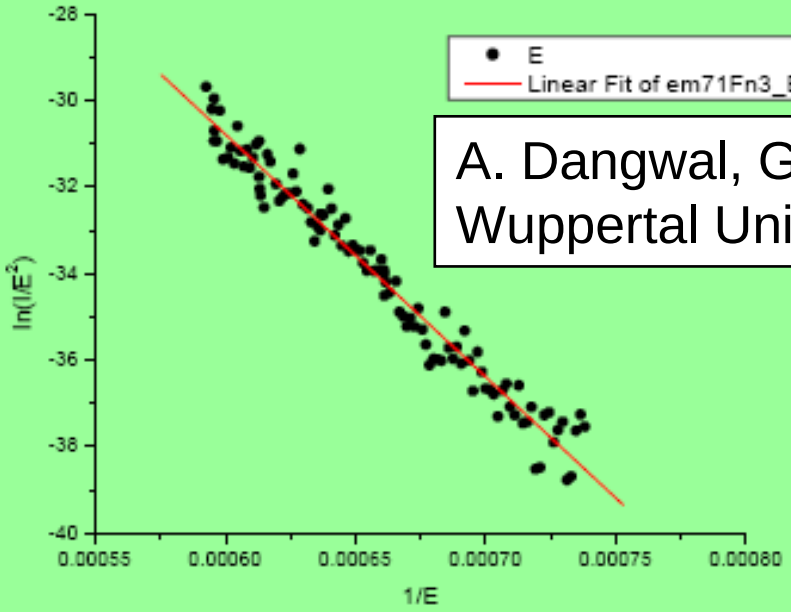
Intrinsic FE of SCNb in defect-free sample areas

measured with W-tip anodes of $\varnothing_a$ = 5-10 µm at U = 5000 V and Δz > 1 µm

SCNb4, (111) orientation



SCNb7, (100) orientation



A. Dangwal, G. Müller
Wuppertal University

Initially intrinsic field emission of Nb
with slope $\beta = 1 \Rightarrow \Phi = 3.8$ eV

creation of an emitter at ~ 1000 MV/m
by a microdischarge $\Rightarrow$ crater in Nb

Intrinsic field emission of Nb
slope $\beta = 1 \Rightarrow \Phi = 4$ eV

$\Rightarrow$ SCNb samples reveal anisotropy of work function Φ

Field emission: Experimental observations

- Metallic (conducting) particles of irregular shape; typical size: 0,5 - 20 µm
- Only 5% - 10% of the particles emit
- hydrocarbon contamination of the vacuum system

- Modified Fowler-Nordheim's law :

$$I \propto A_{FN} \cdot (\beta_{FN} E)^2 / \Phi \cdot \exp\left(- \frac{C\,\Phi^{3/2}}{\beta_{FN}\,E}\right)$$

- typical β-values between 50 and 500 for srf cavities
- A_{FN} (FN emission area) not directly correlated to physical size of emitter

- No substantial difference in rf and dc behaviour

Field emission: model

- Protrusion-on-protrusion model explains the experimental observations
- Modifications of A_{FN} and β by adsorbed gases and oxide layers
- Activation of emitters between 200C and 800C by modification of the boundary layer

  $\rightarrow$ influence of 120C bake-out ??

  => Poster of A. Dangwal et al.

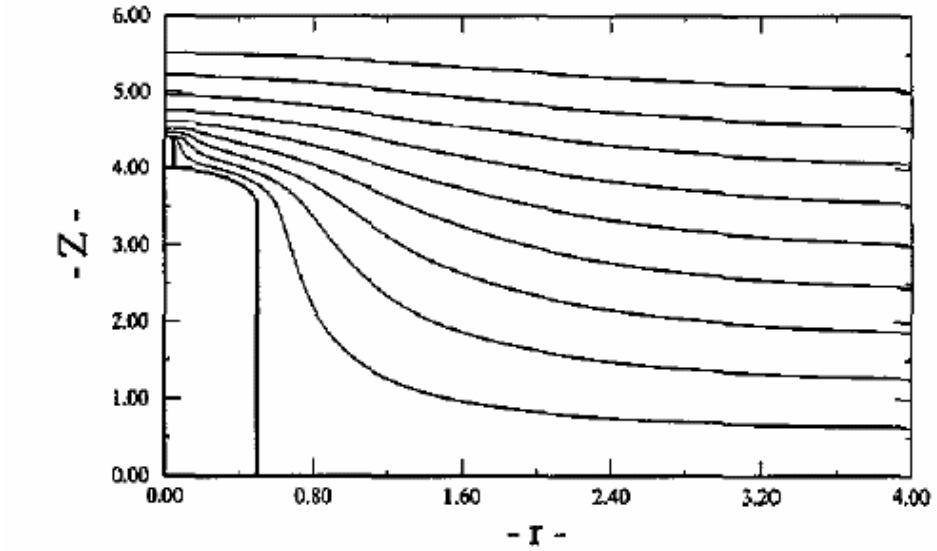


Figure 12. Calculated equipotentials for two superposed hemispherically capped cylindrical projections.

Present picture of field emission

- Quality of final cleaning & dustfree assembly is crucial for field emission free cavities
  → perfect cleaning of cavity + all auxiliaries
  → dustfree assembly
  → pumping & venting without recontamination (particles, hydrocarbons)
  → documentation
- No intrinsic limitation of Nb in a well-fabricated and well-prepared cavity
- surface conditions are poorly known compared to semi-conductor's:
  - No investigations of the sensitive inner cavity surface possible !
  - samples → very valuable, but bad statistics
  - cutting of cavities → continue Cornell experiments
  - imprint technique (CEA Saclay) → surface morphology
- no review of contamination and cleaning mechanisms
  see P. Kneisel, B. Lewis, SRF workshop 1995

Open questions and “to do’s”

- Personal view of open questions and “to do”-list:
  - check of particles and water quality of HPR supply water
  - practical approach needed, how to judge about the quality of final cleaning
    (e.g.: - Is particle counting of drain water useful?
    - New clever ideas for sample experiments?)
  - simplify procedure and components with respect to cleanroom work
  - cavity cleaning option before module assembly necessary ?

  - optimal surface treatment with respect to field emission
    (BCP vs. EP; Which acid mixture?; HPR parameters => comparison of P. Michelato; control of cleanroom assembly procedures; …)

  - influence of “120C bake-out” on field emission?? (experiments at Wuppertal University
- **More ???**

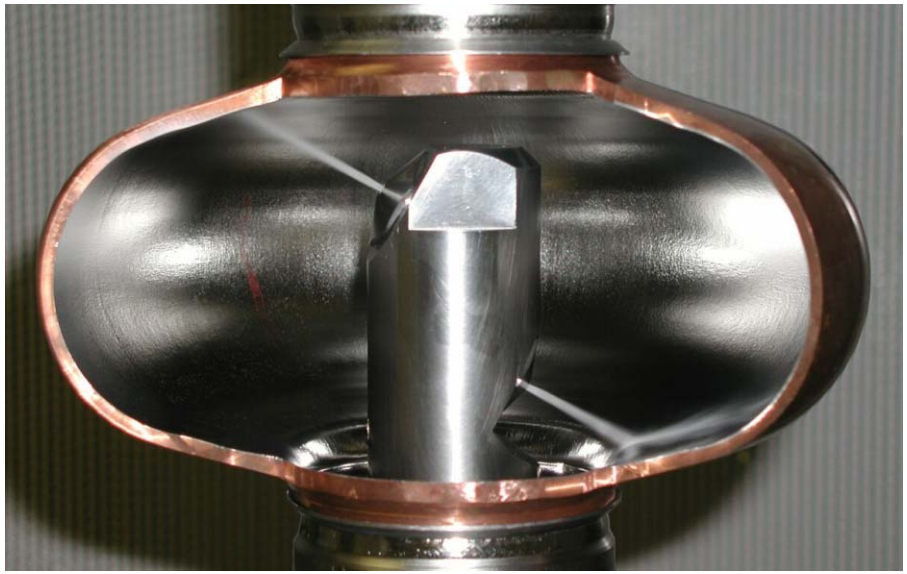
Chances of improvements ??

- Improvements of present procedures
  - hot water rinsing after chemistry ?? => (better solubility, better drying)
  - improved high pressure rinsing systems (=> P. Michelato)
    (no moving parts inside cavity; defined + well-known power of jet, higher pressure; different jet shape; rinsing of longer units possible?)
  - drying + venting procedures? (=> Poster of K. Zapfe et al.)
  - welding of flanges
    (connecting cavities to a “super-structure”; e^- beam or Laser welding)
  - ????

Alternative Cleaning Approaches

- Megasonic Rinsing (K. Saito et al.??)
  - effective cleaning of sub-micron particles
  - development necessary:
    - better transmission of power ⇒ (small) oscillator inside cavity
    - transportation of particles ⇒ high flow rate
- Dry-Ice Cleaning
  - effective cleaning of sub-micron particles and film contamination
  - horizontal cleaning option

  => Poster D. Reschke et al.



- Others:

  Laser, Plasma, UV light,
  hot steam etc.

  ⇒ no activities ??!

Field emission: Tell tales and symptoms

- rf-signal:

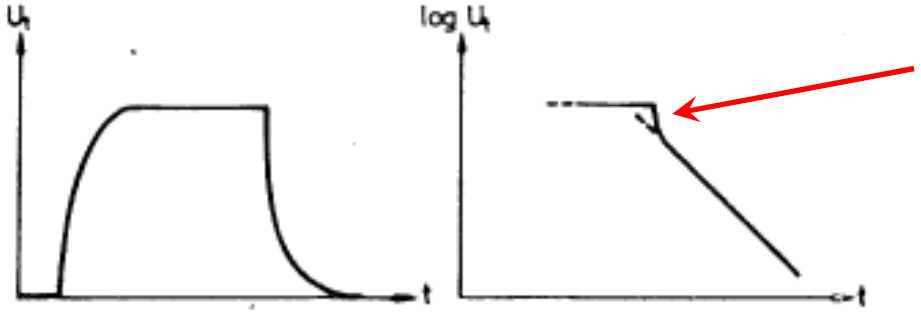


Fig. 5a Fig 5b

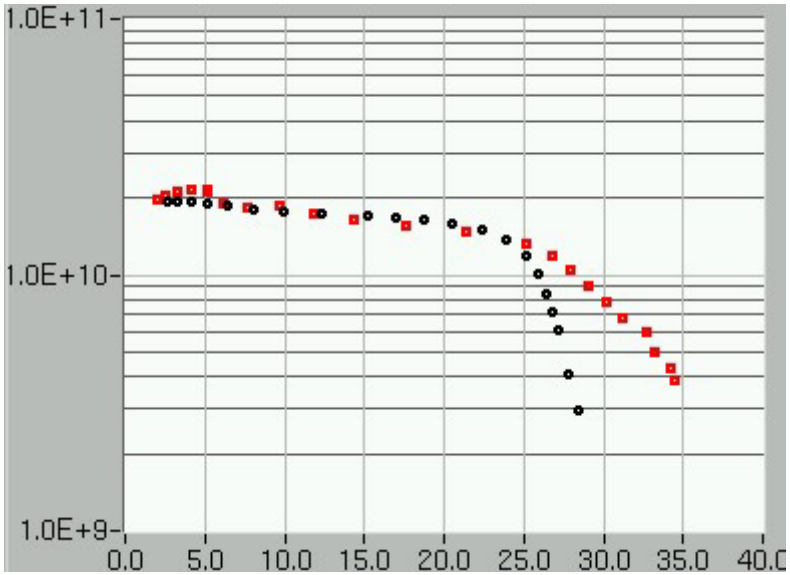
$U_t(t)$ and log $U_t(t)$ from a cavity with field emission loading

marker in log $P_{trans}(t)$

- Exponential X-ray increase according to Fowler Nordheim's law

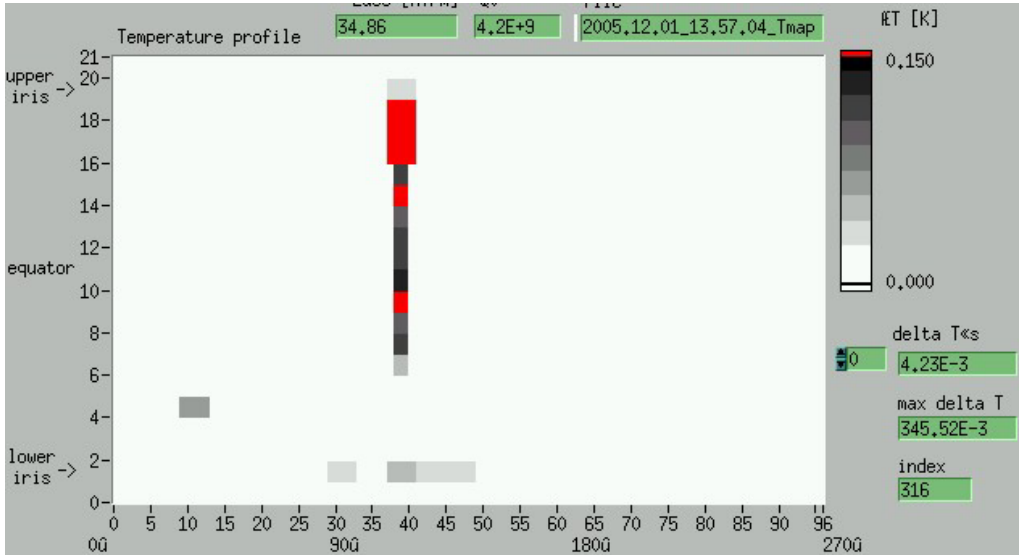
+ Q(E)-curve:

  Typical decrease of Q-value



Field emission: Tell tales and symptoms II

- T-Mapping:



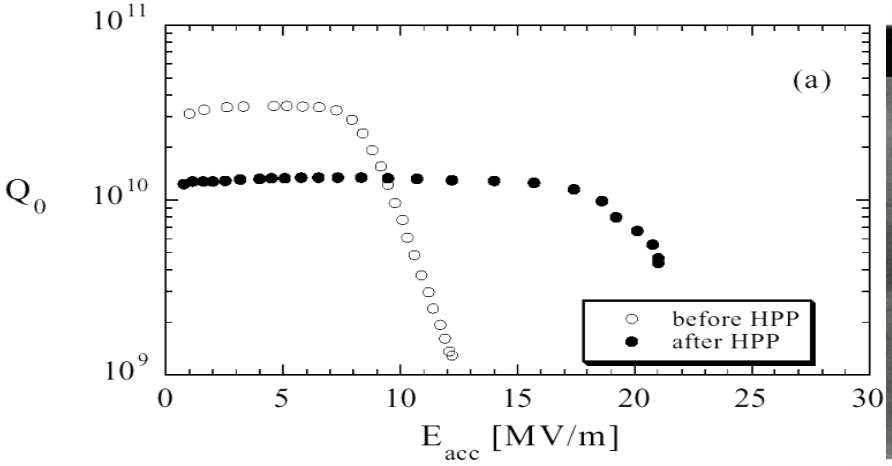
2-D T-map of a field emission loaded cavity

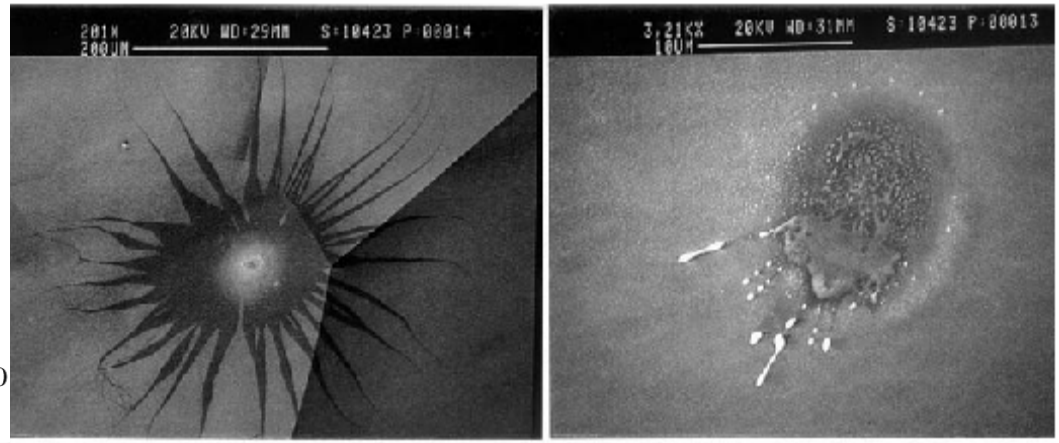
> 90% of electron energy transferred into heat

- Electron probes: measurement of dc current at rf probes
- Higher order modes excited by field emission
- X-ray mapping: mapping system with x-ray sensitive sensors (e.g. photo diodes
- X-ray spectroscopy: Bremsstrahlung spectrum gives highest energy of e^-
- X-ray films

Field emission removal: processing

- Processing of emitters (“conditioning”) possible
  - i) rf and helium proc. with moderate rf power and cw-like operation
  - ii) high peak power processing with high rf power and short pulses
- Helium processing: i) modification of the adsorbed gases (≈ seconds)
  ii) explosive destruction (≈ subseconds; rare)
- High peak power processing (HPP): local melting leads to formation of a plasma and finally to the explosion of the emitter (model by J. Knobloch)
  → “star bursts” (Lichtenberg figures) caused by the plasma





Processing in multicell cavities

- HPP on 5- and 9-cell structures in vertical tests:
  improvement from (10-15) MV/m to (20-28) MV/m,
  but often reduced Q-value
- Typically E_{acc}(pulsed) ≈ 2x E_{acc}(processed)

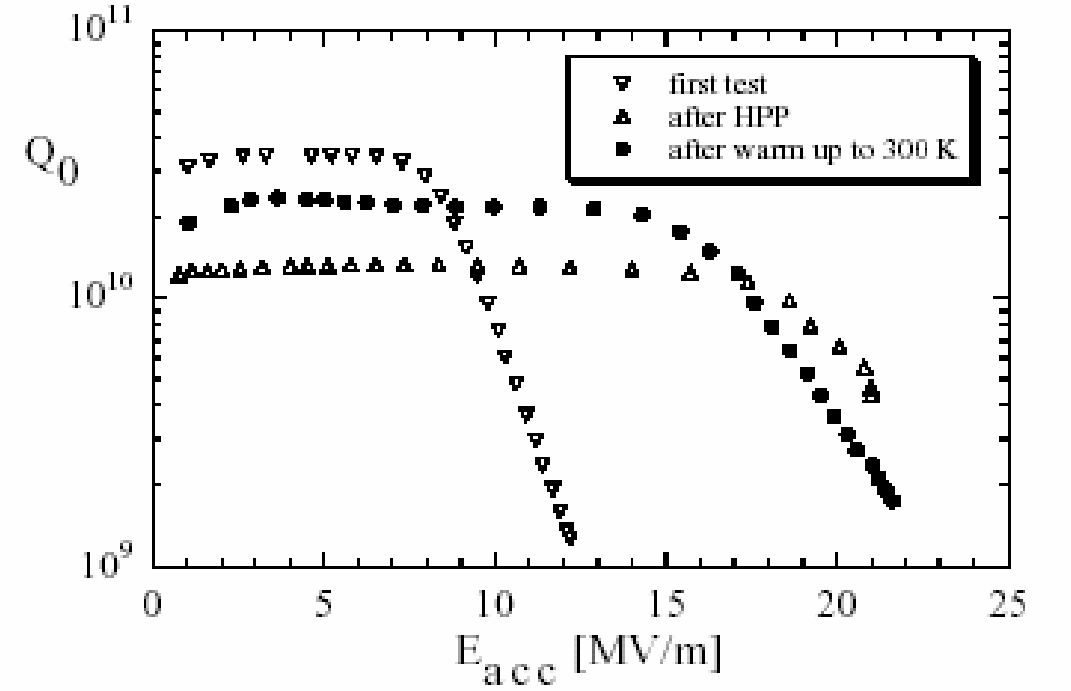
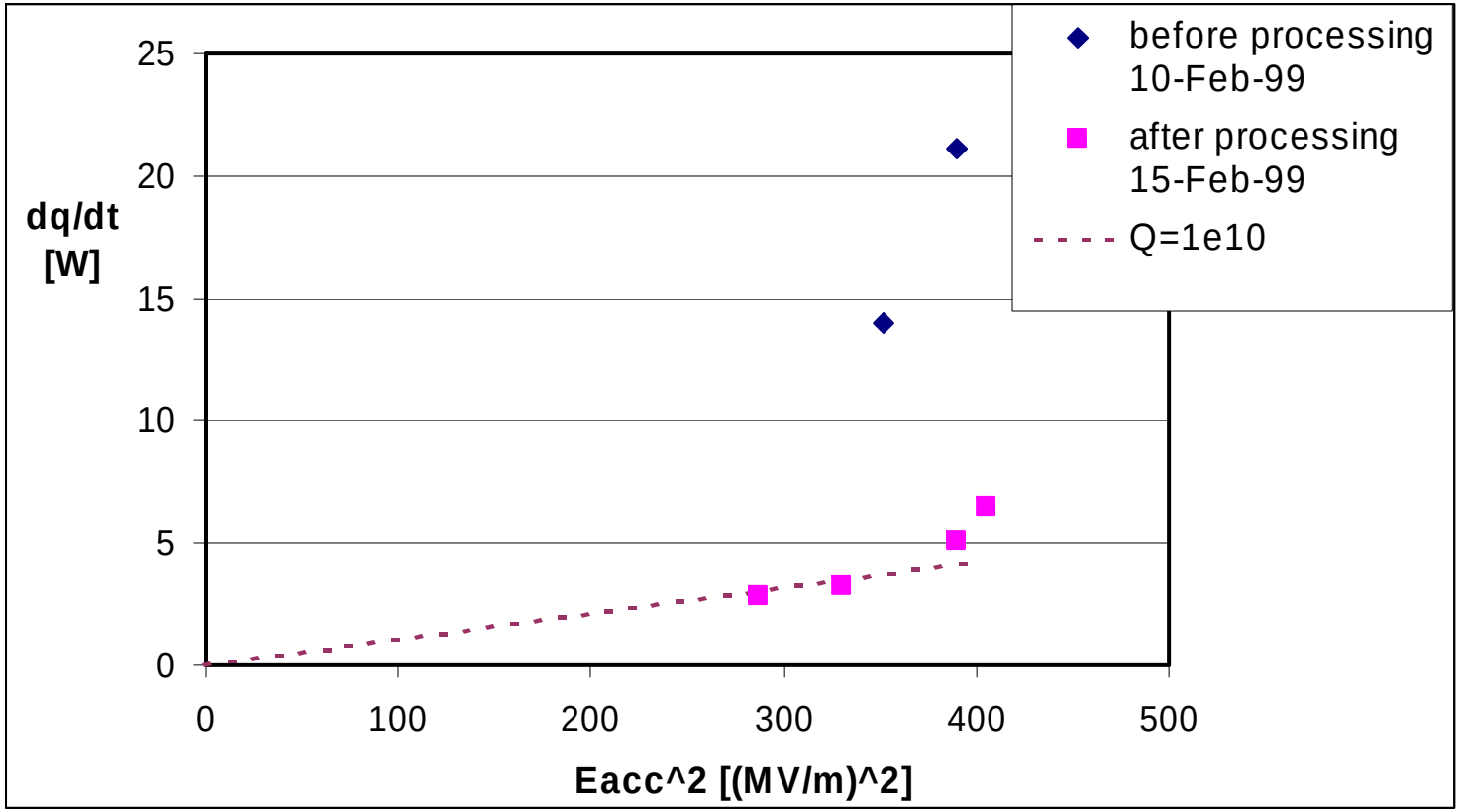


Fig. 2: Cavity C19 before and after HPP. The Q_0 recovered partially after warm up to room temperature.

Processing in accelerator structures: TTF

- Processing of module 2 in linac successful (Feb 1999)
  (operation limited by power coupler above 19 MV/m)



Processing at high gradients ?

- HPP for gradients above 30 MV/m in 1.3GHz nine-cell structures?
- → No experience?!
- → Very high power necessary (coupler performance)

	pulse length [µsec]		
Eacc [MV/m]	200	400	500
40	2,45 MW	0,79 MW	0,57 MW
60	5,5 MW	1,77 MW	1,28 MW
80	9,77 MW	3,15 MW	2,28 MW

for $Q_L = 3 \cdot 10^6$ (by D. Kostin, DESY)

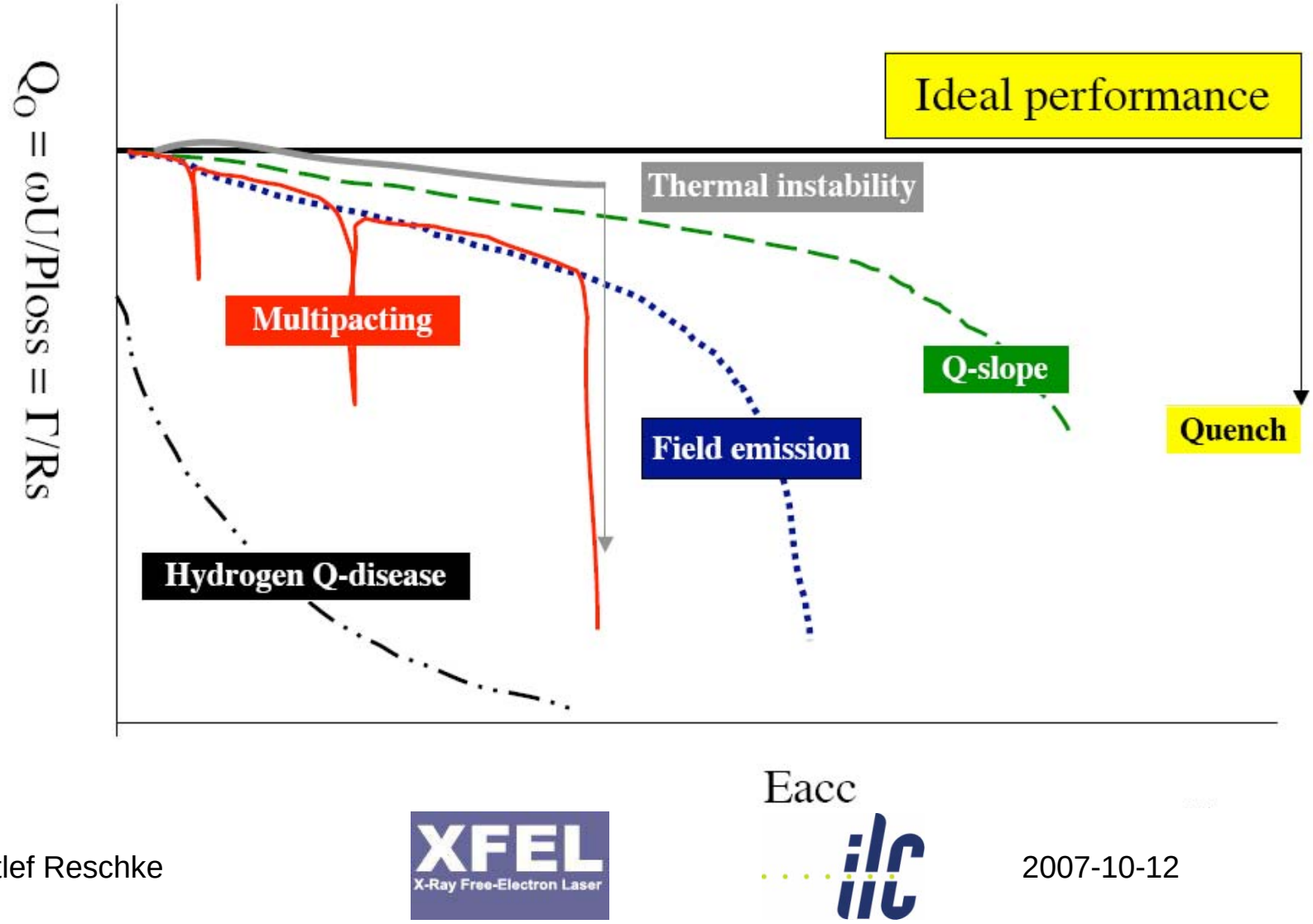
Field emission: Summary

- Precent picture of field emission not complete, but well substantiated
- Standard cleaning and assembly procedures allow high quality cavity performance, but:
  Field emission (= dark current) is still the main limitation, if usable gradients above 20 MV/m in multi-cell accelerator cavities are required
- Further improvements of standard techniques, quality control and development of alternative approaches necessary!

- Processing is only a repair tool for accelerator application

Multipacting

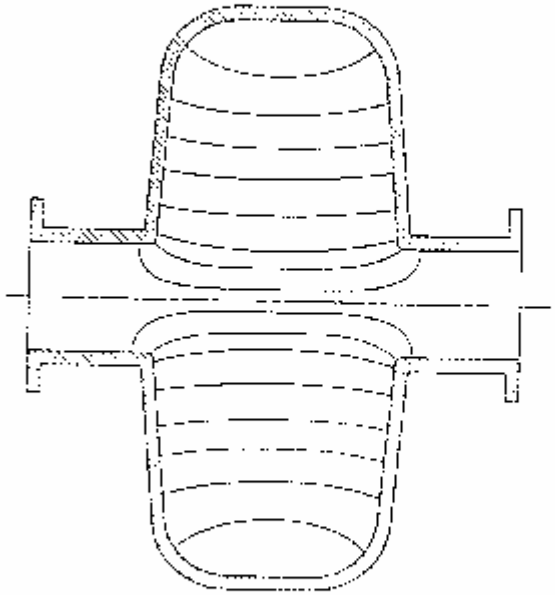
- Multiple impact of electrons:



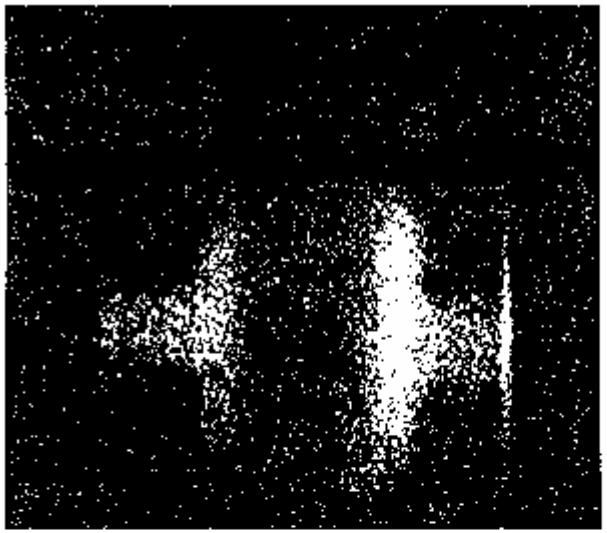
Multipacting: overview

- ‘Multiple Impact‘ of electrons
- Electrons
  - are omnipresent in cavities (from field emitters for example)
  - are accelerated in the RF field
  - hit the surface
  - can produce more electrons
  (depending on the secondary electron emission coefficient)
- Resonance condition depends on frequency, rf-phase, cavity geometry, surface conditions (adsorbed gases => water !!),
- If in resonance (same place, same RF field phase), they produce an avalanche
  => breakdown of rf-field (like a quench !!!)
  => MP is sometimes processable (depending on type and order)

S-Band TM010 Resonator
Stanford, late 1960-ies

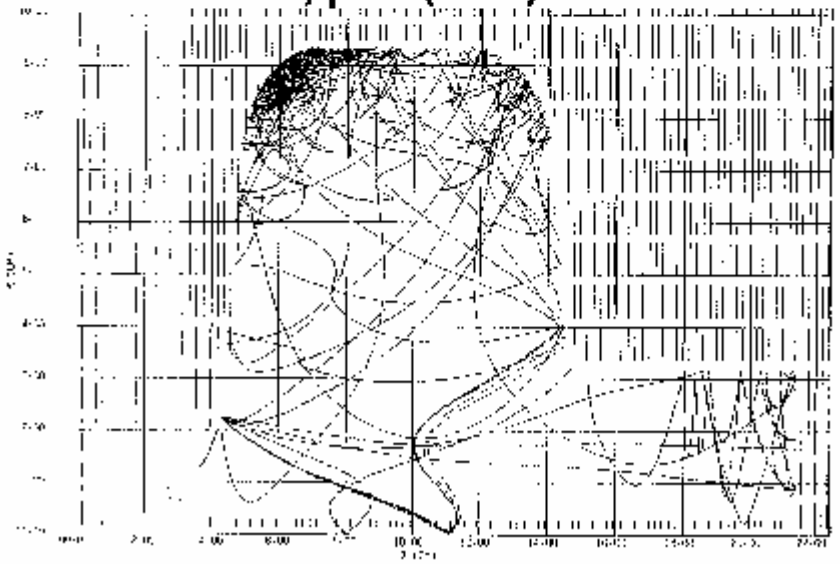


this is the standard geometry for about 15 years;
unfortunately the cylindrical geometry is favourable for electron multipacting



X-ray mapping

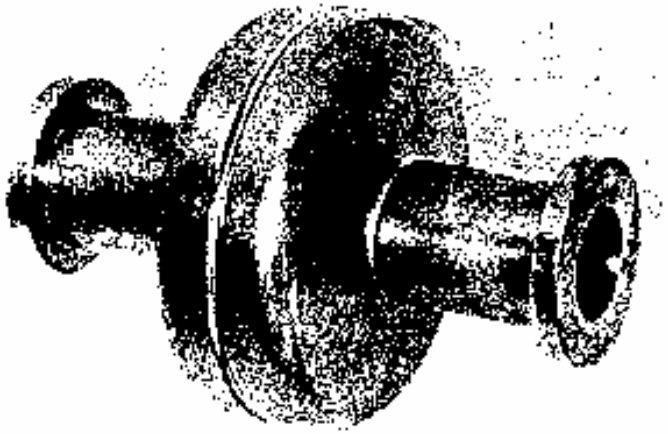
I.Ben-Zvi, J.F. Crawford and J.P. Turneaure
Eletron Multipacting in cavities
1973 PAC Conf., p.54 (1973).



Simulated electron trajectories

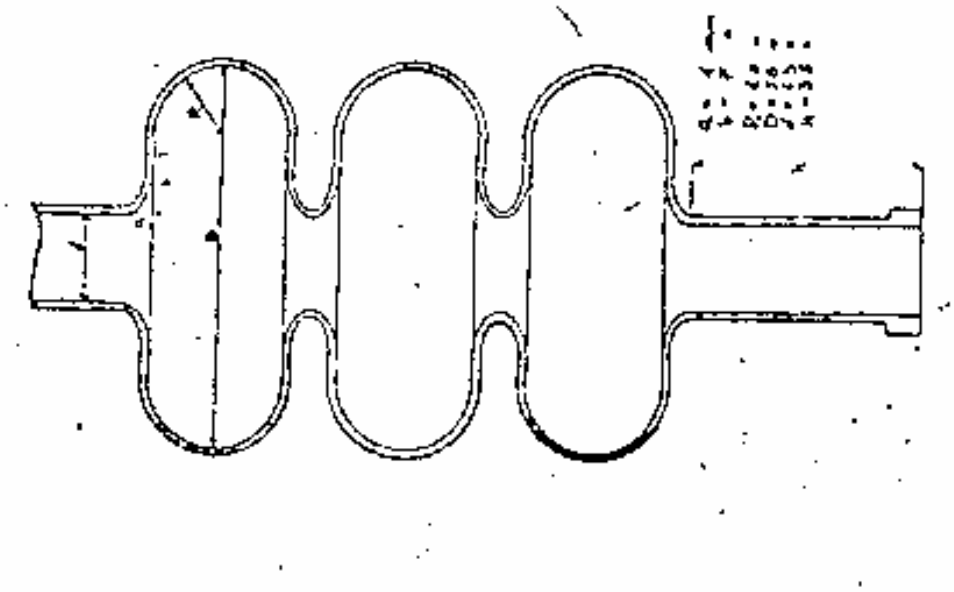
Avoid Multipacting by spherical cavity shape

S-band TM010 Resonator
Stanford
the standard geometry
until about 1980



about 3 MV/m

C-band Structure
Genoa, about 1980
the first spherical geometry
realized because of easier manufacturing

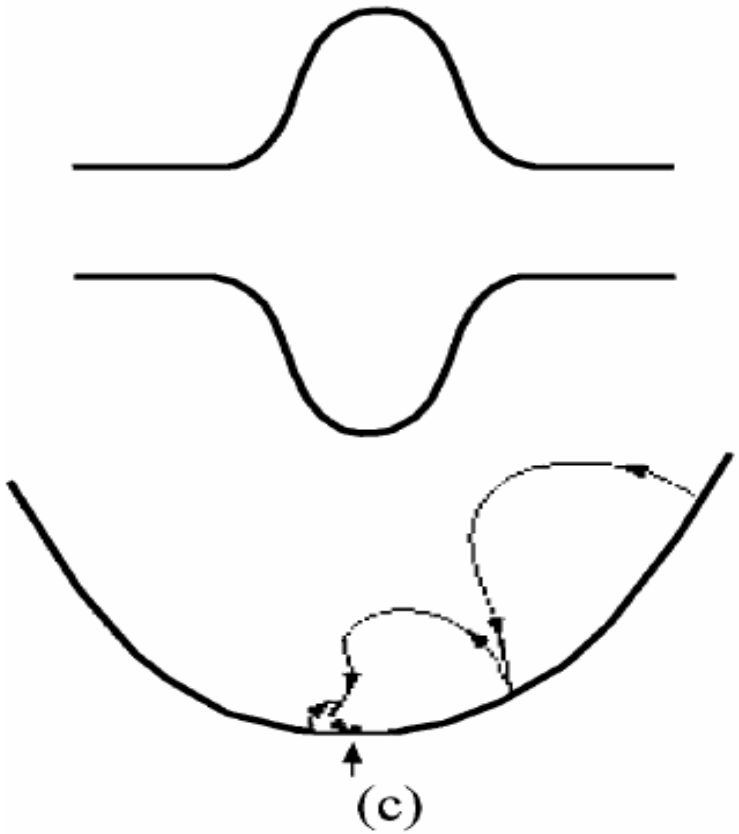


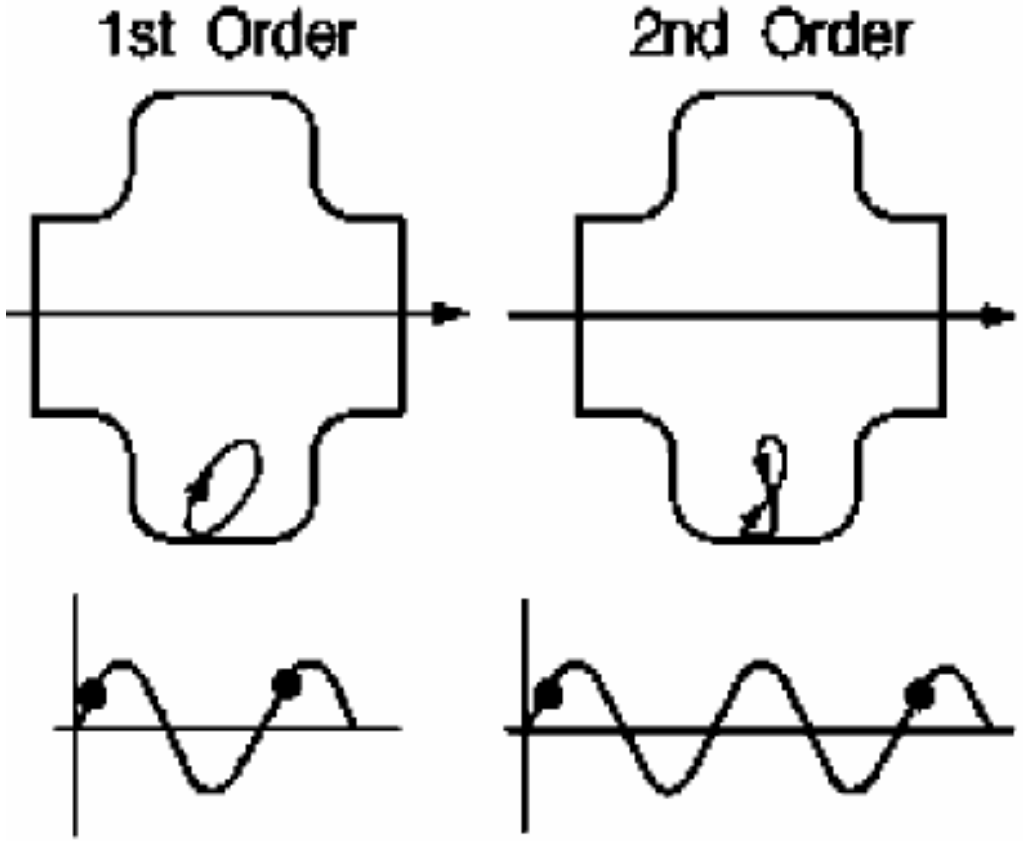
8 MV/m !!!

calculated in thesis of U. Klein

Multipacting in pill box cavities

In a cavity with a nearly pill-box-like shape, electrons can multiply in the region shown (one-surface multipacting)



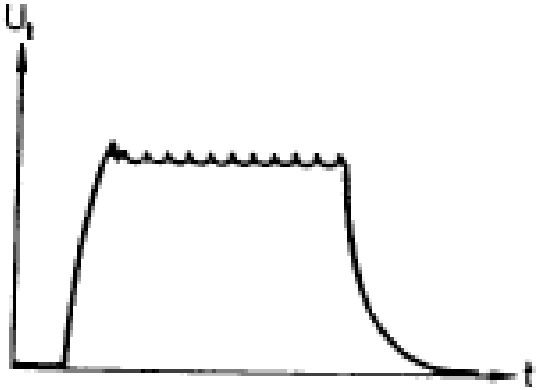


When the cavity shape is rounded, the electrons drift to the zero-field region at the equator. Here the electric field is so low that the secondary cannot gain enough energy to regenerate (only two-point MP possible)

Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), 28 –51

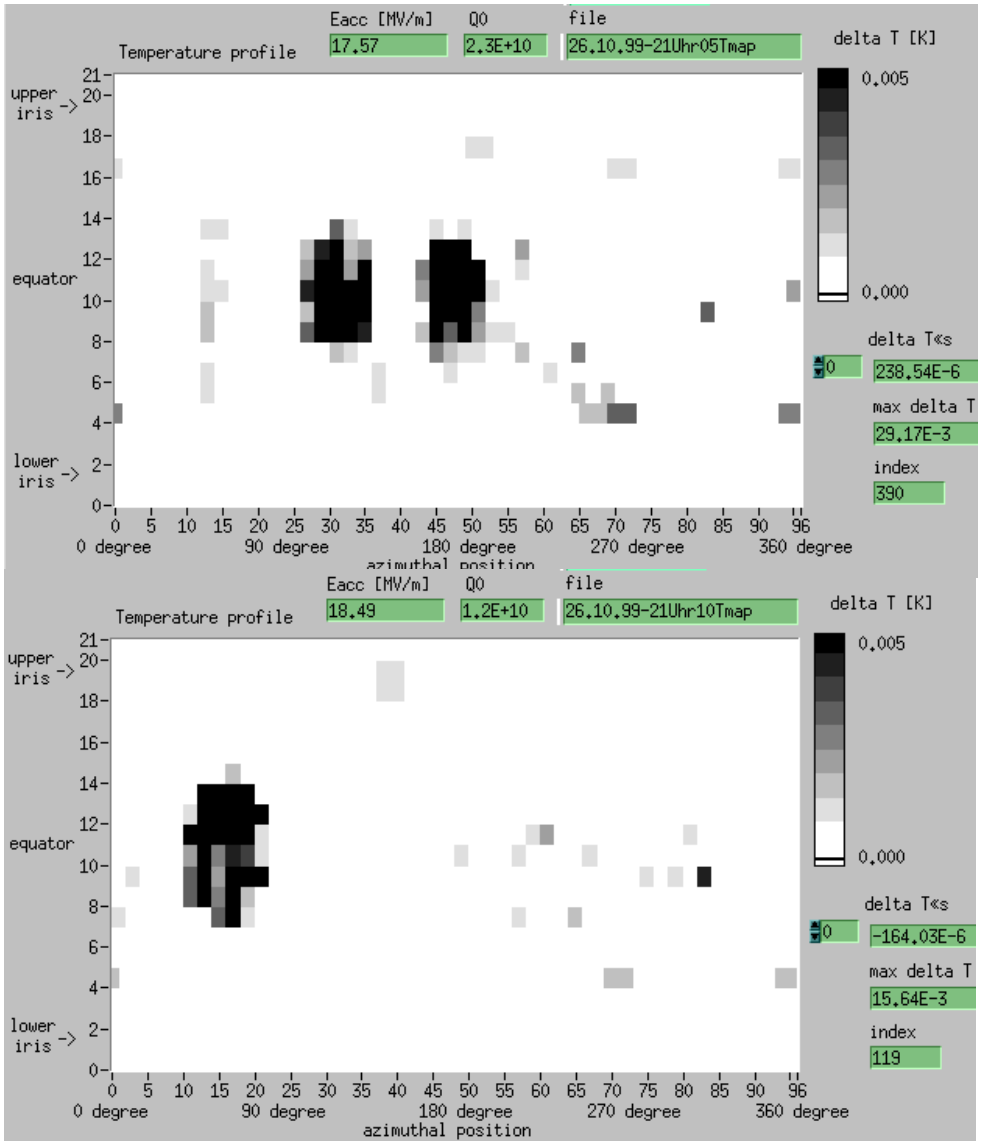
Multipacting: Tell tales and symptoms

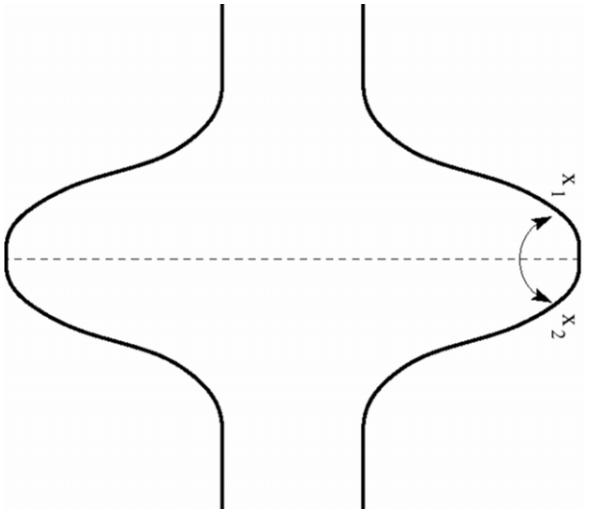
- rf-signal of transmitted power:
  - no increase of P_{trans} for enhanced forward power (left); jump in P_{trans} for partially processed MP (right)



- often breakdowns of rf field (like quench) during processing
- X-ray detectors and electron pickups are also showing activity (in the moment of breakdown!!!)
- Processing takes seconds to hours (one-surface MP nearly no processing; two-surface MP good processing)
- Re-processing after warm-up to room temperature necessary
- Higher order modes excitated

Multipacting: Temperature mapping





- Heating moves along the equator

Hydrogen Q-disease

- History
  - first detected at HERA- and S-Dalinac cavities beginning of 1990's
  - systematic investigations in different Labs (Saclay, Wuppertal, DESY,…)
- Experimental
  - dramatic reduction of Q_0 and field after slow cooldown or parking at ~ (70 – 170) K for hours ("100K-effect")
  - after fast cooldown no Q-disease
  - only in cavities of high RRR Nb
  - sensitive to BCP / EP conditions
  - grinding / cutting in presence of water causes Q-disease
  - annealing at > 600C in UHV cures Q-disease

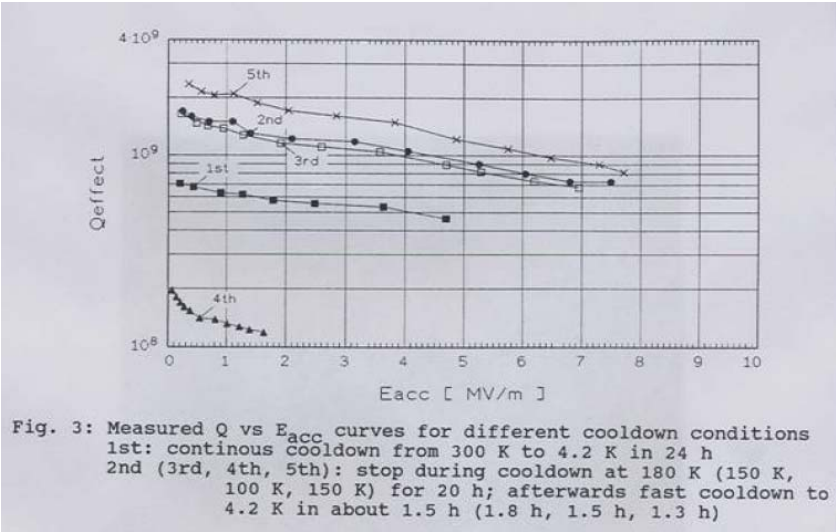


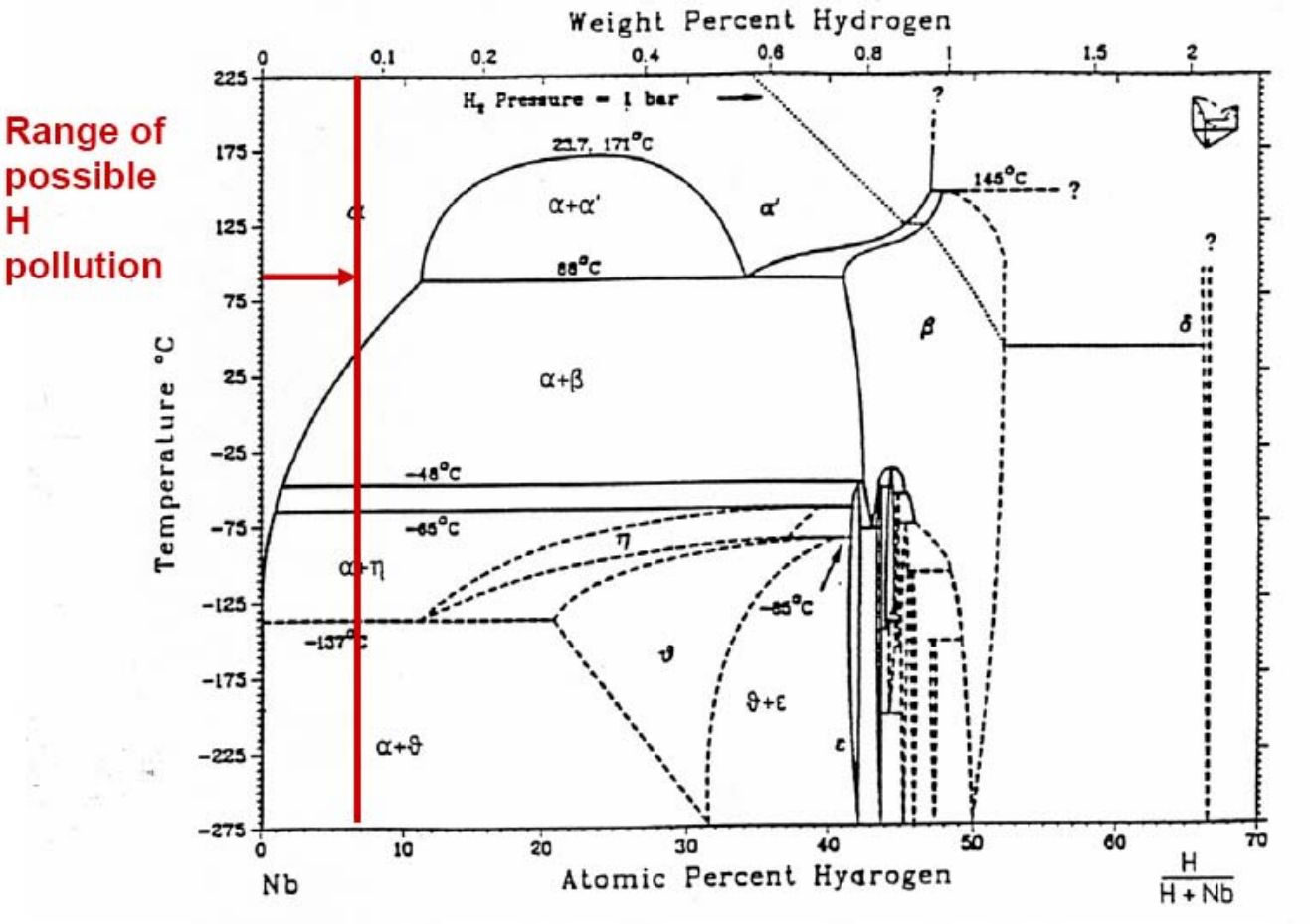
Fig. 3: Measured Q vs E_{acc} curves for different cooldown conditions
1st: continous cooldown from 300 K to 4.2 K in 24 h
2nd (3rd, 4th, 5th): stop during cooldown at 180 K (150 K, 100 K, 150 K) for 20 h; afterwards fast cooldown to 4.2 K in about 1.5 h (1.8 h, 1.5 h, 1.3 h)

Hydrogen Q-disease: mechanism

- Mechanism (courtesy of D. Proch)
  - Hydrogen can move freely in Nb at room temperature as interstitial impurity
  - There is a phase transition to NbH_x around 130K
  - NbH_x has a slightly larger lattice constant as compared to pure Nb
    - NbH_x will settle at lattice distortions or at the surface
      - Around 130 K NbH_x will migrate to the surface and produce RF losses (it is a normal conductor)
      - At very low temperatures NbH_x will not move any more
  - Cure against H-disease
    - Fast cool down (typical condition at vertical test with dewar cooling
    - Degassing of Nb at temperatures around 800°C (or higher)

Hydrogen Q-disease: mechanism

- Nb-H phase diagram



Avoid Q-disease

- Use of cooled (< 20C) BCP acid
- Removal of H during EP by venting and protection with cloth
- No grinding / cutting / EDM with water
- Annealing at > 600C

- Improved analysis and understanding of EP electrolyte
  => more investigations + effort necessary

- BUT:
  rare cases of Q-disease found instead of above precautions

  => explanations at this workshop ??

Increased Residual Resistance

- No full understanding, but many sources identified!
- Surface contamination
  - Particles
  - Adsorbed gases especially hydro carbons (polluted vacuum systems + pumps)
- Lossy oxides
  - contribution < 1nΩ for well-prepared cavities
- External magnetic field
  - Frozen-in-flux during cool down results in increased losses of ~ 3-5 nΩ/µT in GHz- cavities according to

$$R_{fl} = \eta \frac{B_{ext}}{B_{c2}} R_{surf,nc}$$

  => For $Q_0 > 10^{10}$ static magnetic field < 2 µT

  => cryoperm shield necessary

Thanks !

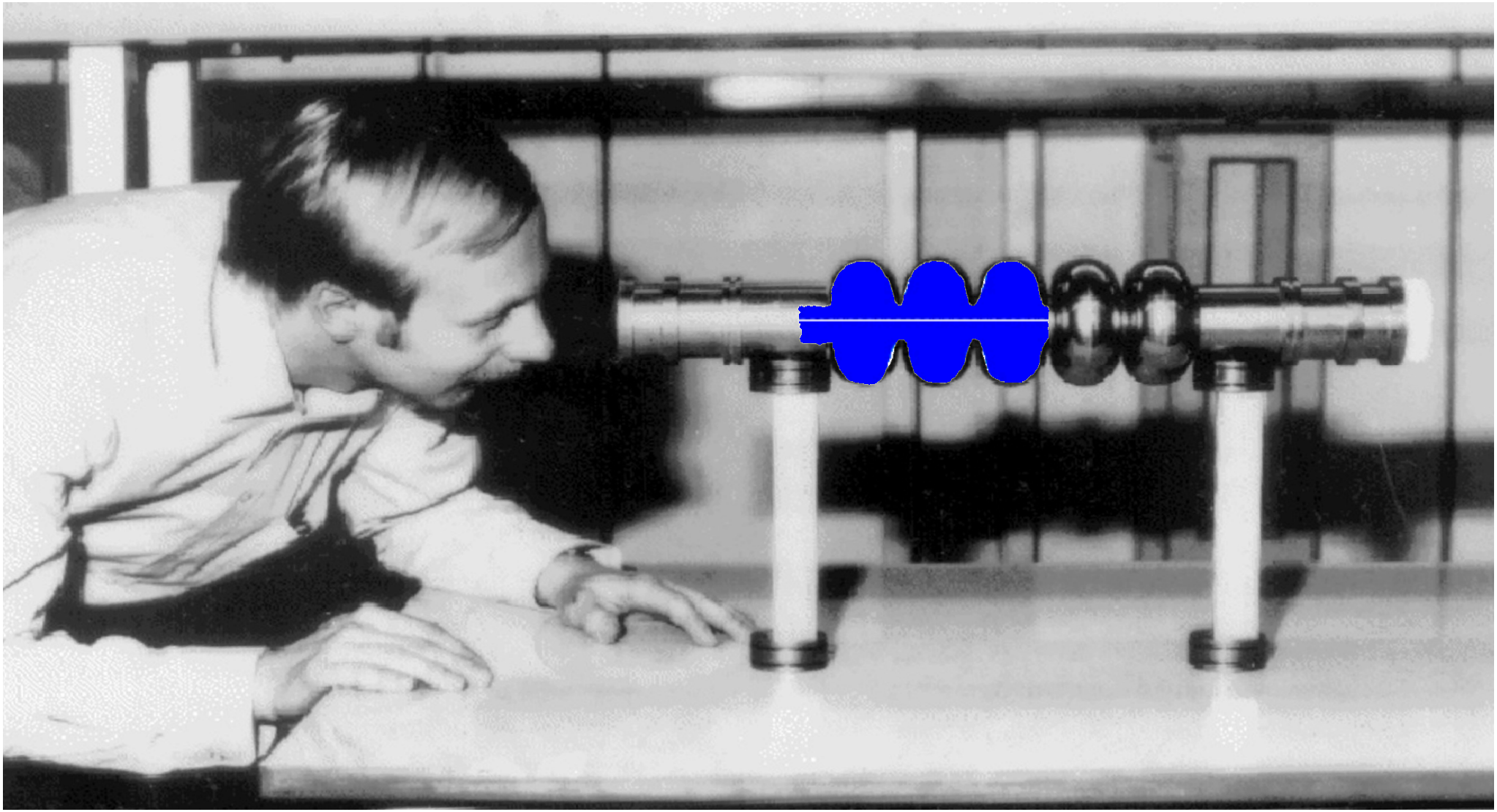
- **Thanks to all colleagues who provided me information, especially:**

  Gianluigi Ciovati, Arti Dangwal-Pandey, Andre Gössel, Eiji Kako, Denis Kostin, Lutz Lilje, Günter Müller, Hasan Padamsee, Enzo Palmieri, Dieter Proch, Kenji Saito, Bernhard Visentin, Hans Weise

Some Literature

- In general:
  - Proceedings of the SRF Workshops
  - H.Padamsee, J.Knobloch, T.Hays, RF Superconductivity f. Accelerators, 1998 (=> new edition available?)
  - Overview articles e.g. H. Padamsee, Supercond. Sci. Technol., 14 (2001)
- Field emission + cleaning specific:
  - E. Ciapala et al., SRF Workshop 2001
  - W. Kern ed., Handbook of Semiconductor Cleaning Technology, 1993
  - P. Kneisel,B. Lewis, SRF Workshop, 1995
  - P. Kneisel, Contamination Workshop Jlab, 1997
  - D.L. Tolliver, Handbook of Contamination Control in Microelectronics, 1988
- Q-drop:
  - G. Ciovati, 12th Workshop on RF Superconductivity, Cornell, 2005
  - B. Visentin, International Workshop on Thin Films, Legnaro, 2006
  - V. Palmieri, 12th Workshop on RF Superconductivity, Cornell, 2005

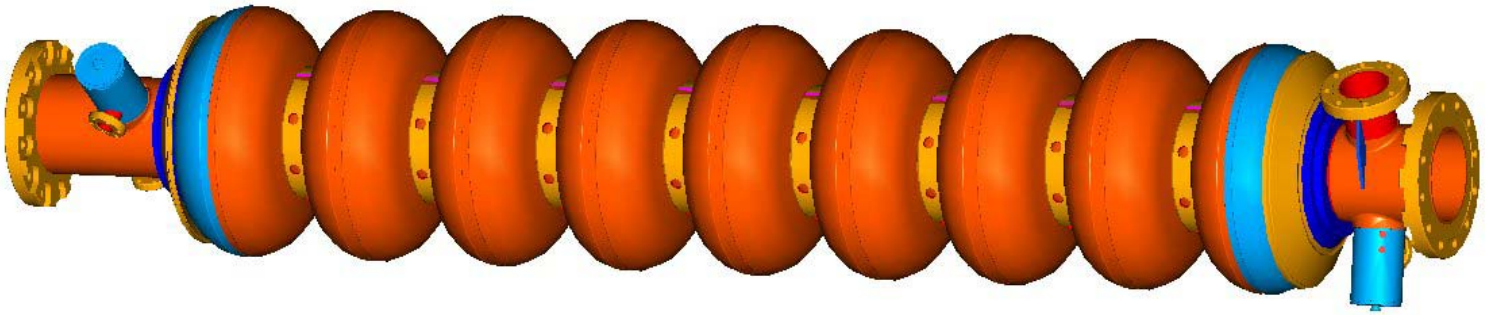
The end !!



(courtesy of H. Weise)

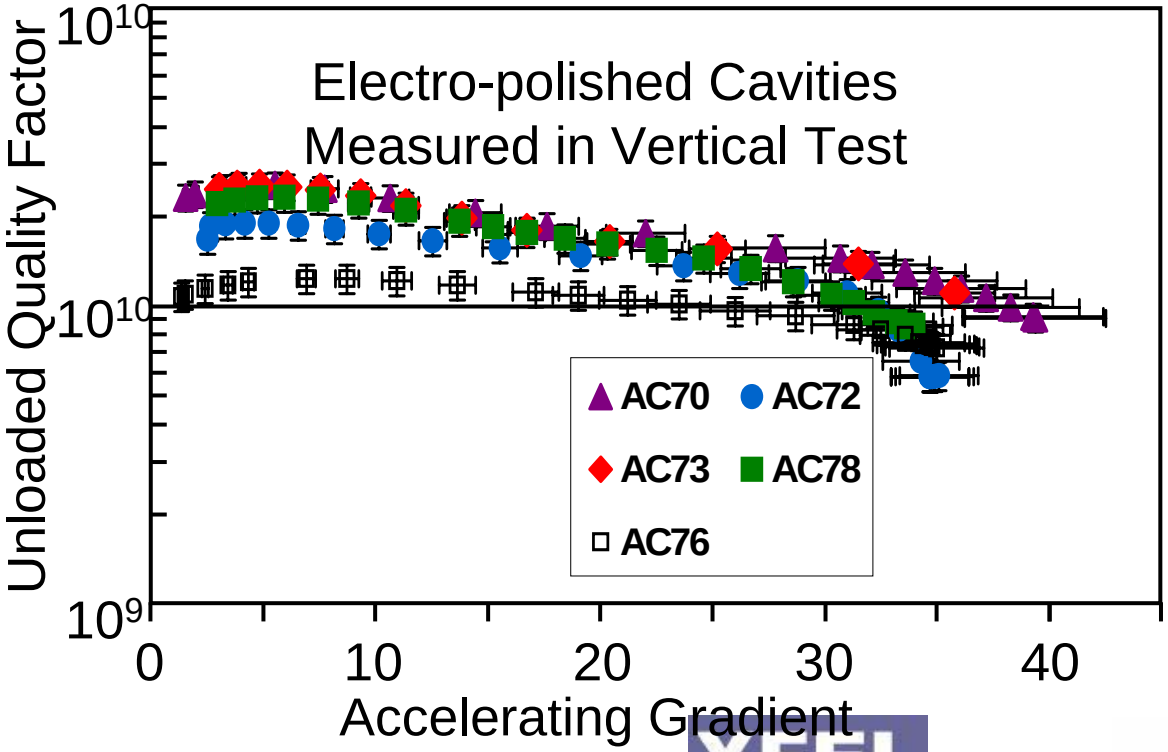
Addendum:

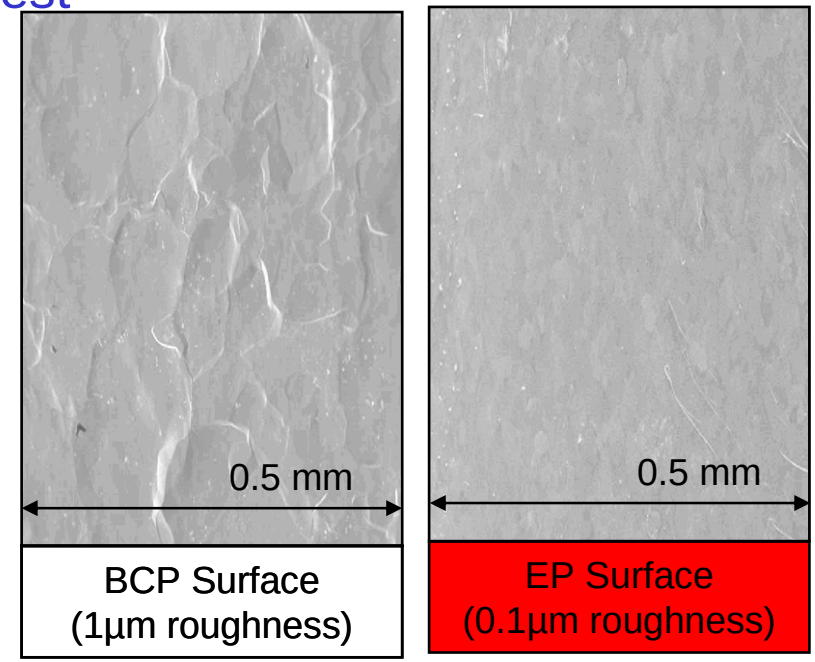
- Additional transparencies for explanation!



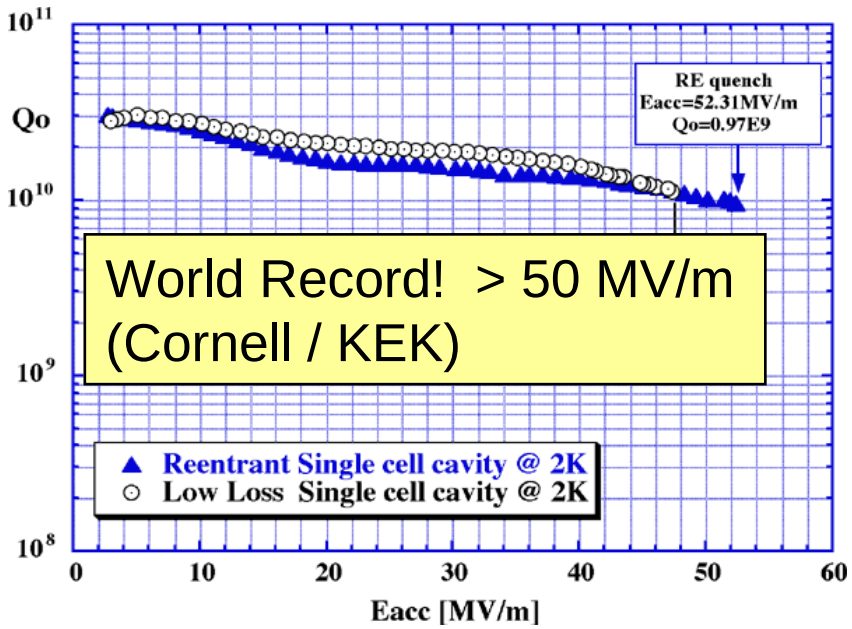
Cavity preparation

- BCD cavity preparation scheme:
  - Cleaning after fabrication, entrance-check + 1. tuning
  - Electropolishing (EP) of (120-150) µm for removal of damage layer
  - 800C firing for mechanical stress release & H-degassing
  - Electropolishing for final preparation (20-50)µm
  - HPR + Assembly + Vertical acceptance test

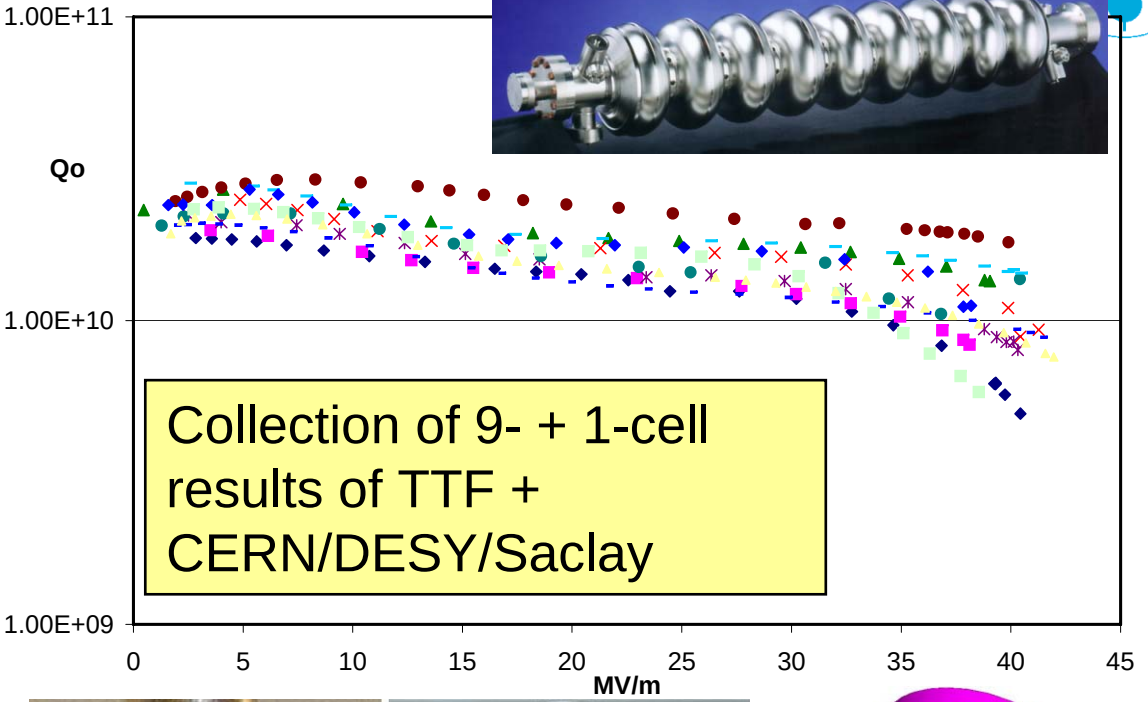




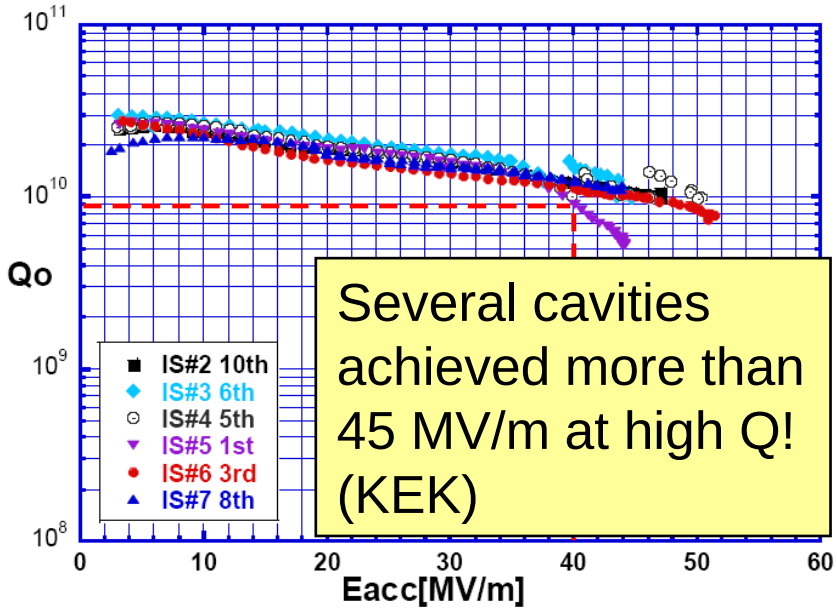
Some results



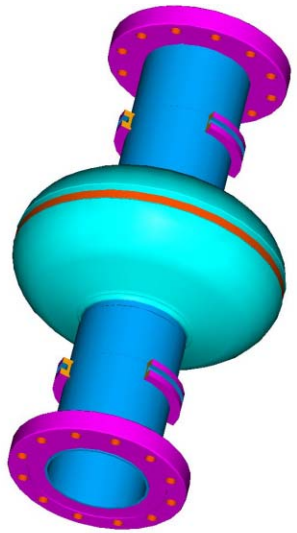
World Record! > 50 MV/m (Cornell / KEK)



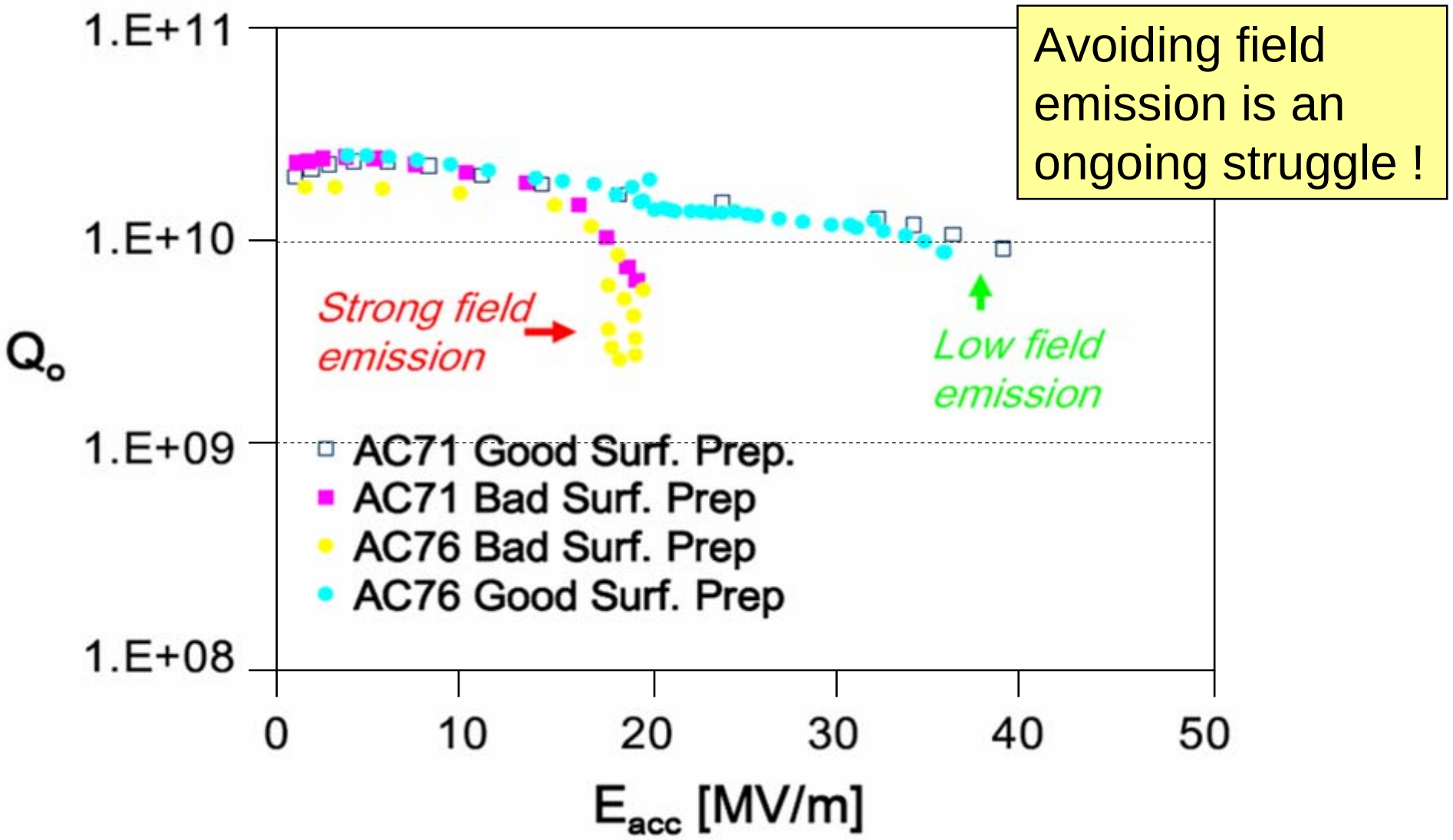
Collection of 9- + 1-cell results of TTF + CERN/DESY/Saclay



Several cavities achieved more than 45 MV/m at high Q! (KEK)



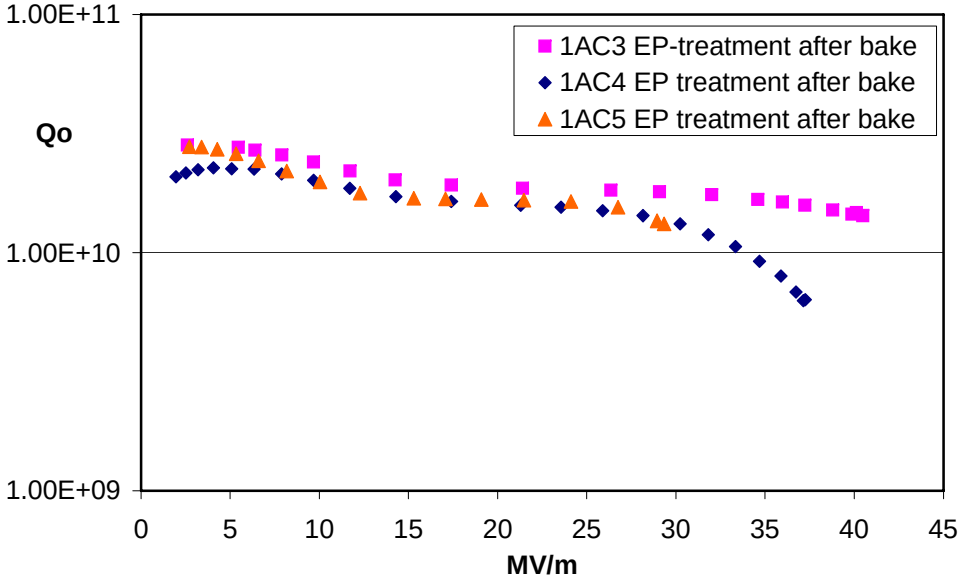
But Work needed: Reproducibility in Preparation

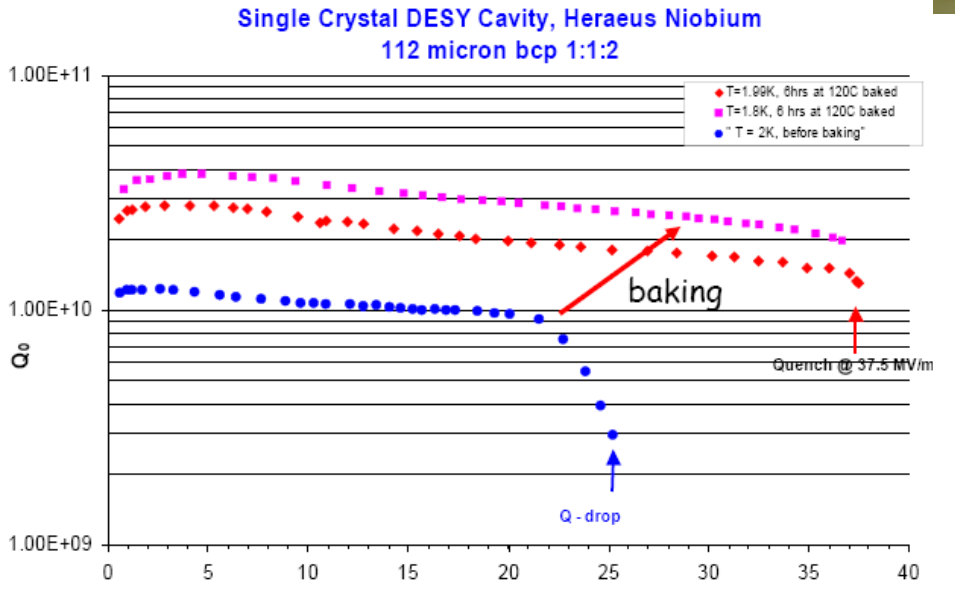


Avoiding field emission is an ongoing struggle !

ACD: Large-grain + mono-crystal cavities

- Activities on large-grain + single-crystal single-cell cavities at JLab, KEK, DESY, …
- 3 nine-cell cavities at DESY after BCP treatment only: E_{acc} = 28 MV/m





Q(Eacc) curve after only 80 µm BCP and in situ baking 120°C for 12 hrs.

Detlef Reschke