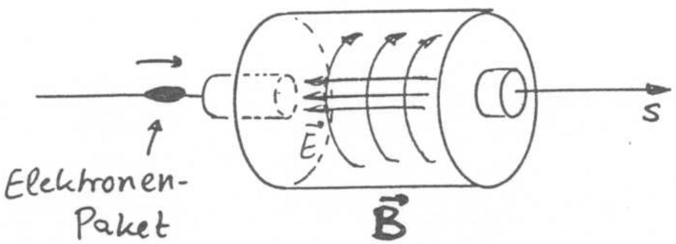
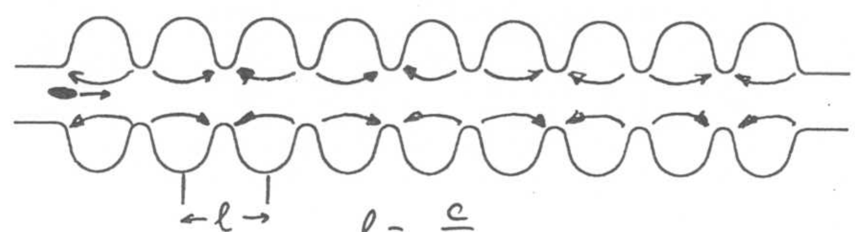
Supraleitende Resonatoren für TESLA

Peter Schmüser, Univ. Hamburg

Hohlraumresonatoren zur Teilchen-Beschleunigung.



der 9-zellige TESLA-Resonator



$l = \frac{c}{2f}$

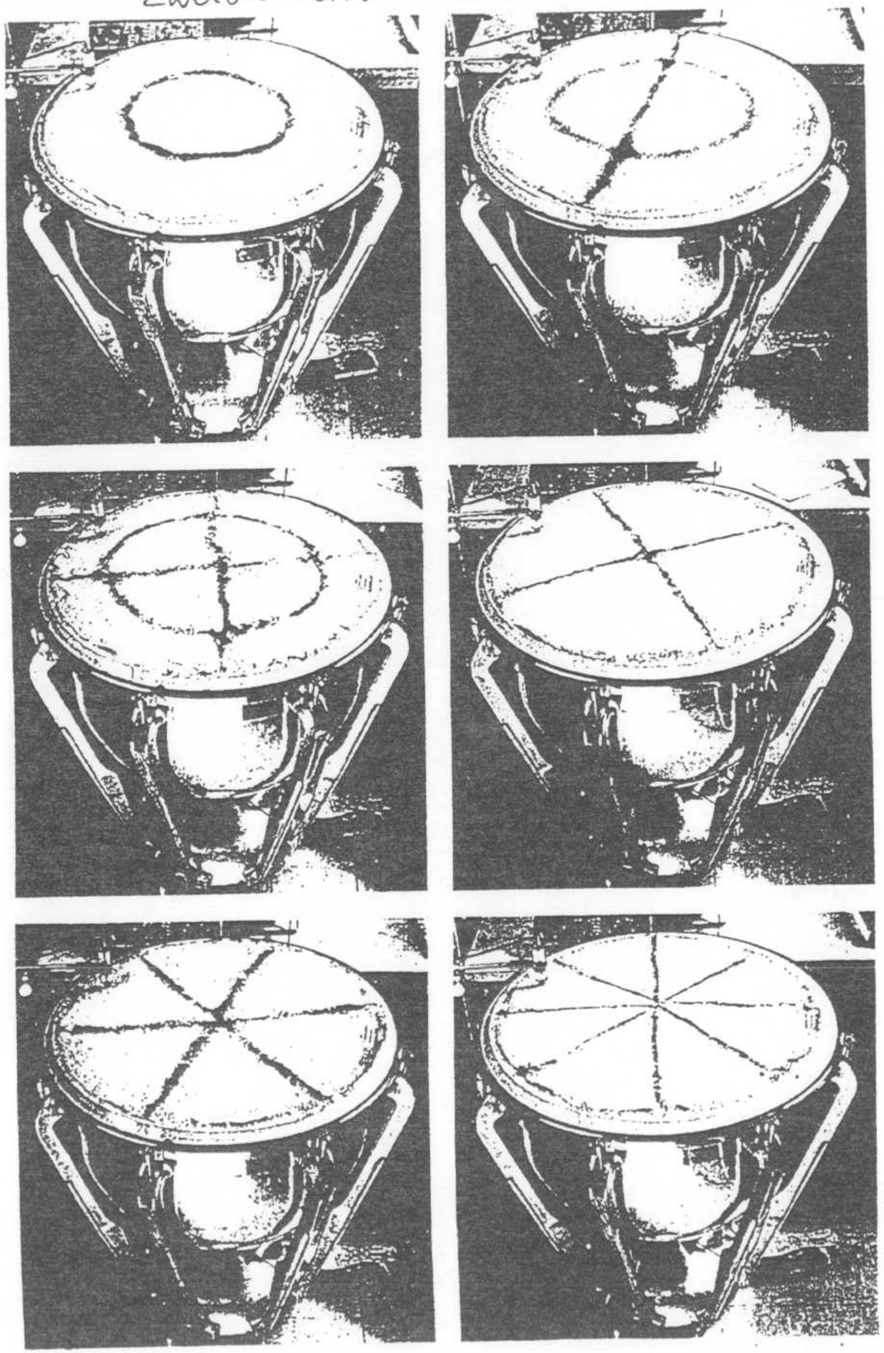
Resonanzfrequenz $f = 1.3$ GHz

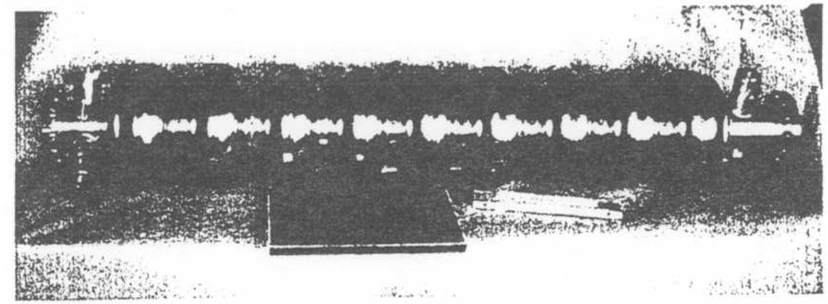
Material: supraleitendes Niob

gekühlt mit supraflüssigem Helium

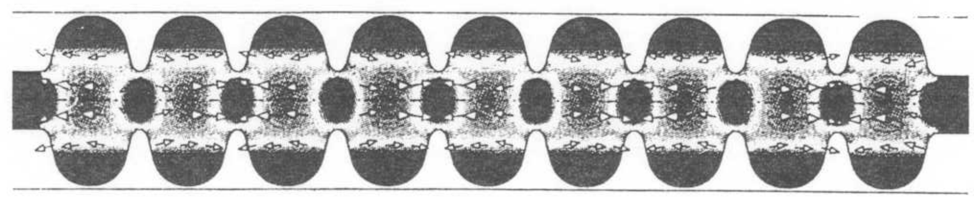
$T = 2$ Kelvin

zweidimensionale stehende Wellen

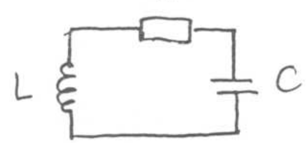




9-zelliger TESLA - Resonator
Cornell Univ (USA)
DESY, Univ Hamburg
Saclay (Frankreich)
INFN (Italien)



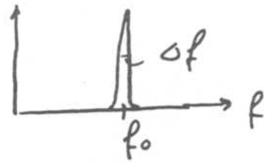
Frequenz 1,3 GHz
Temperatur 2 Kelvin (−271 °C)



R ≈ Oberflächenwiderstand
ca $10^{-8}\,\Omega$ in Niob bei 2 Kelvin

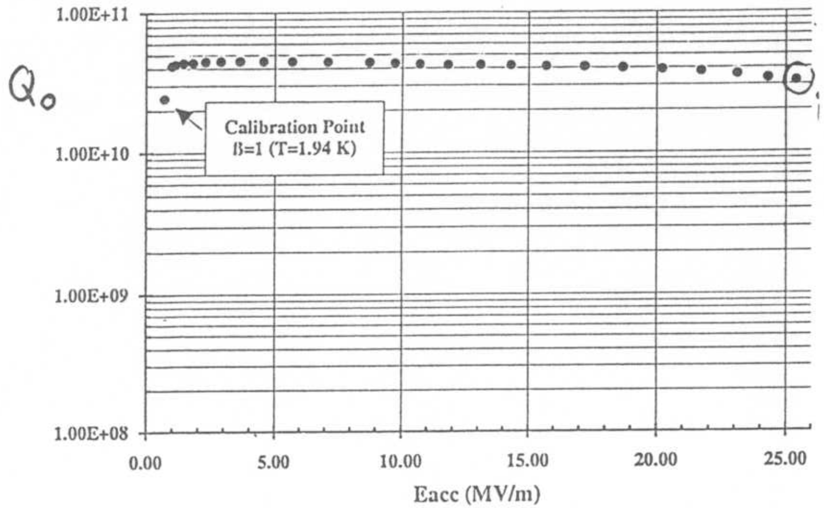
Warum supraleitende Kavitäten?

- sehr hohe Gütefaktoren



$$Q_0 = \frac{f_0}{\Delta f} > 10^{10}$$

Kupfer: Q_0 einige 10^4



25 Millionen eV auf 1 m Länge

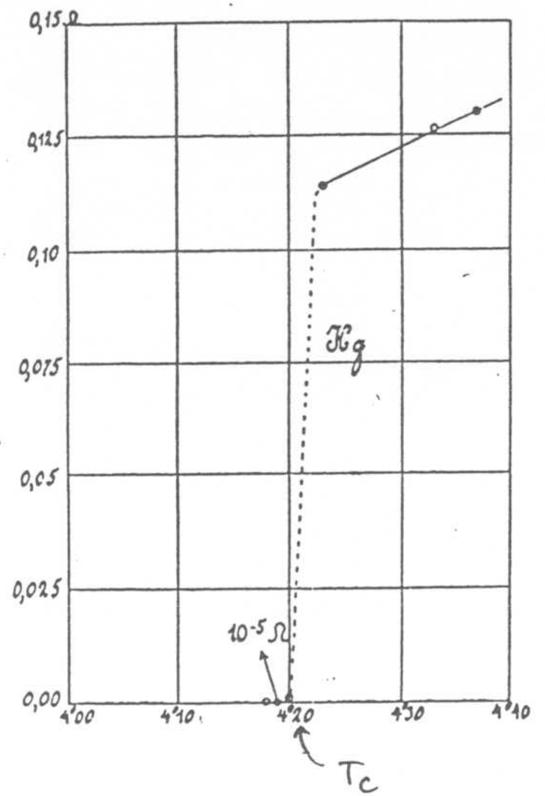
TESLA : Strahlstrom 8 mA

⇒ 200 kW Leistung pro Kavität wird auf Strahl übertragen
nur ca 20 - 40 W geht ins Helium

Cu: ≈ 200 kW auf Strahl
≈ 200 kW in das Cu → Kühlwasser

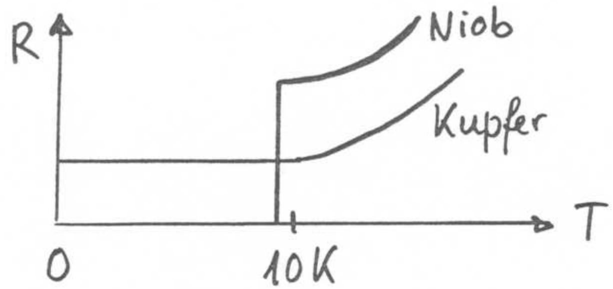
Die Entdeckung der Supraleitung

H. Kamerlingh Onnes, Leiden 1911



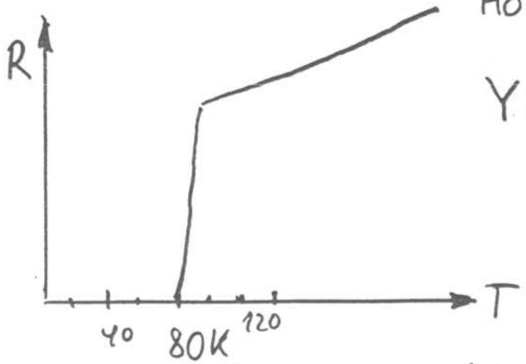
Widerstand von Quecksilber bei der Temperatur des flüssigen Heliums

Supraleitung findet man in vielen Metallen, aber die besten Normalleiter werden nicht supraleitend (Cu, Ag, Au)



Kritische Temperatur T_c

Al	1.14 K	Niob-Titan	9.2 K
Pb	7.9 K	Niob-Zinn	18 K
Nb	9.2 K		



Hoch-T_c-Supraleiter

$YBa_2Cu_3O_7$

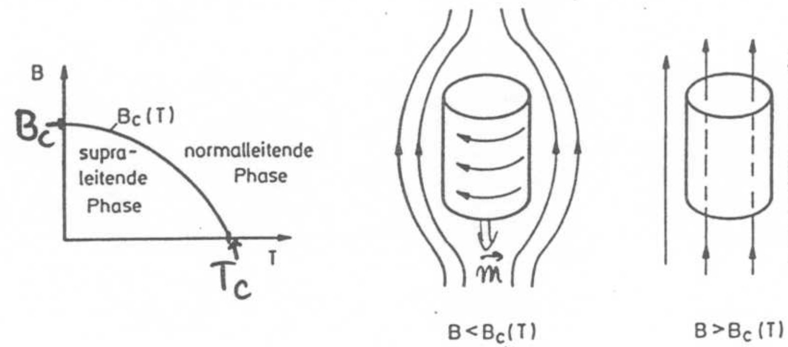
$T_c \approx 80\,K$
(flüssig N_2)

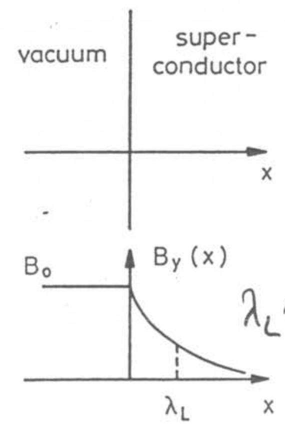
Dies sind keramische Materialien.
Zur Zeit für Magnete und Mikrowellen-Resonatoren nur bedingt geeignet.

Supraleiter im Magnetfeld

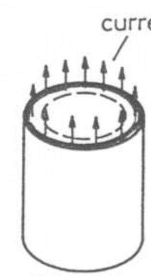
Typ I (reine Elemente): kein Magnetfeld im Innern

Meissner-Ochsenfeld-Effekt





$\lambda_L \approx 50\,nm$



Strom in Bleidraht

Bester Typ I-Supraleiter: Blei

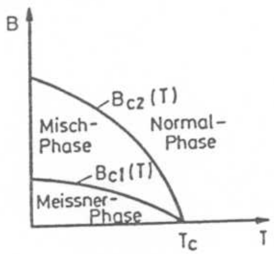
$T_c = 7.2\,K$, $B_c = 80\,mT$

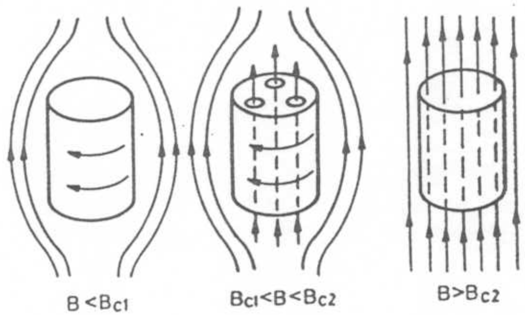
$\Rightarrow$ ungeeignet für Elektromagnete
mäßige Eignung für Mikrowellen

Typ II Niob, alle Legierungen

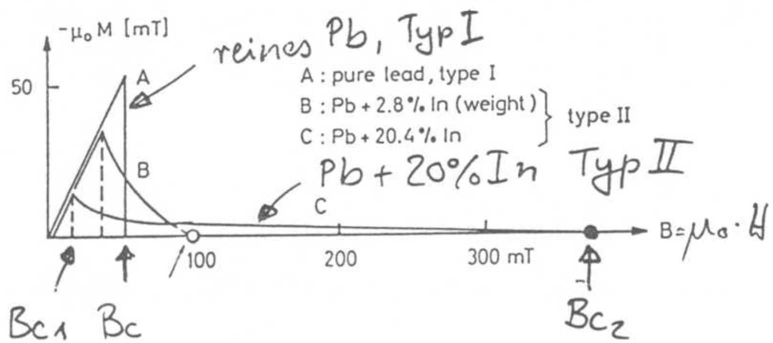
$0 \leq B \leq B_{c1}$ Meissner-Phase

$B_{c1} \leq B \leq B_{c2}$ Misch-Phase (Shubnikov)





$-\mu_0 M$ (Magnetisierung) Pb + In



Niob: $T_c = 9.2\,K$, $B_c^{th} \approx 200\,mT$

nicht für Magnete

ziemlich gut für HF-Resonatoren

Requirements on Superconductor:

general : high critical temper. T_c

(but not "High-T_c" ceramic S.C.)

<u>Accelerator magnets</u>

B_c large $\Rightarrow$ only type II, alloys

strong flux pinning $\Rightarrow$ lattice defects etc

$\Rightarrow$ need "dirty" superconductor

NbTi $T_c = 9.2\,K$, $B_{c2} \approx 14\,T$

very ductile, easily extruded with Cu

the "Standard conductor"

Nb_3Sn $T_c = 18\,K$, $B_{c2} \approx 20\,T$

brittle material, difficult to use in accelerator magnets

<u>Microwave cavities</u>

high heat conductivity, no flux pinning

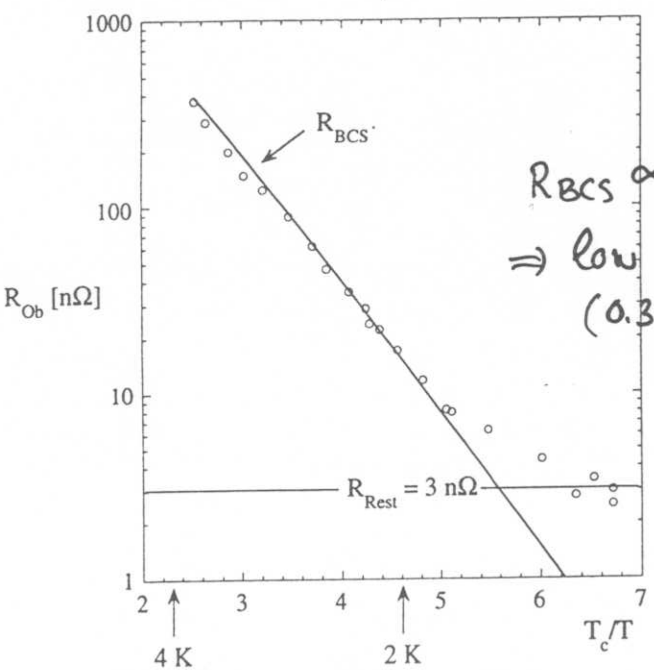
$\Rightarrow$ need very pure superconductor

Pb $T_c = 7.2\,K$ $B_c = 80\,mT$

Nb $T_c = 9.2\,K$ $B_c^{th} = 200\,mT$

Niobium surface resistance

TESLA 9-cell cavity
$f \approx 1.3$ GHz



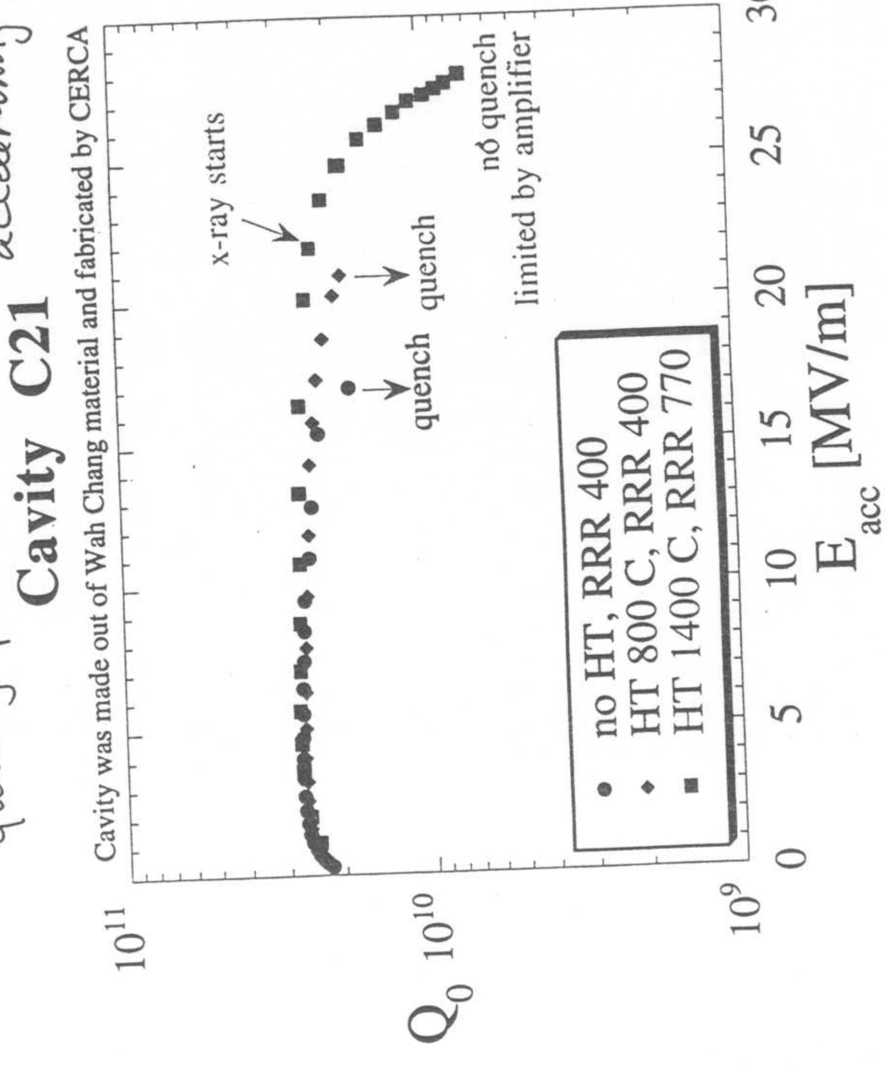
$R_{BCS} \propto f^2$
⇒ low frequency
(0.35 – 3 GHz)

$3\,n\Omega \;\hat{=}\; Q_0 = 10^{11}$

$$R_{BCS} \propto f^2 \exp\left(-1.76\,\frac{T_c}{T}\right)$$

Power dissipation in London penetration layer $\lambda_L \approx 30$ nm

quality factor as a function of accelerating field

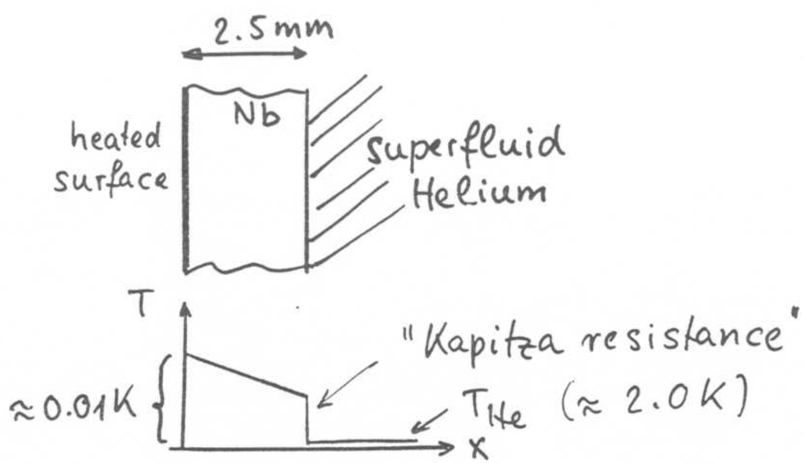


residual resistivity ratio

$$RRR = \frac{R(300K)}{R(10K)}$$

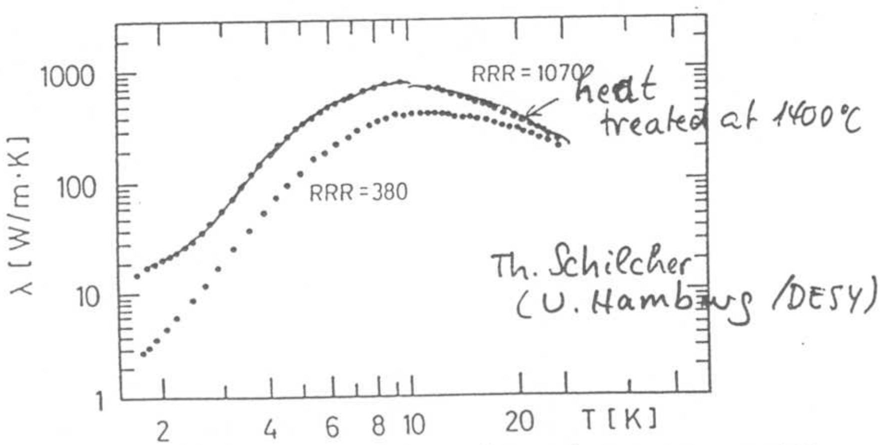
good measure of purity

Heat transfer to liquid He



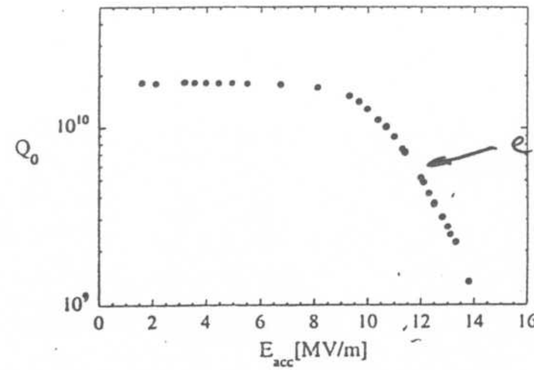
Much stronger heating due to small normal-conducting defects

area of defect $< 10^{-6}$ area of cavity



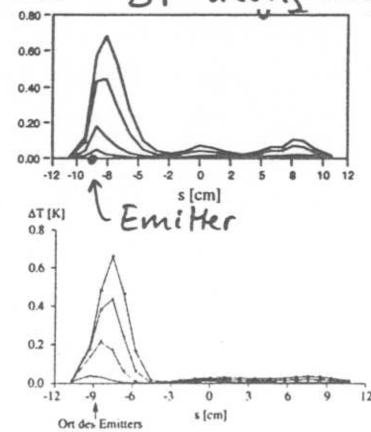
heat conductivity of very pure Nb

Field emission of electrons



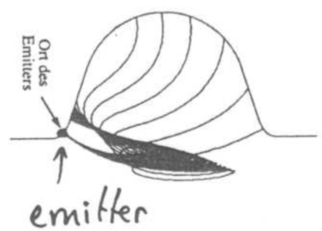
exponential decay of quality factor

ΔT along meridian



← measurement

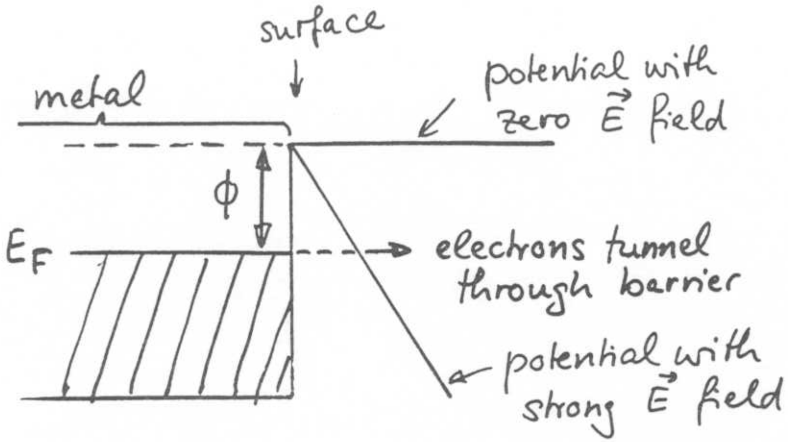
← simulation



computed trajectories (for various rf phases)

What is field emission?

Extraction of electrons from a metal via the quantum mechanical tunnel effect



current density given by Fowler-Nordheim equation

$$j(E) = \frac{A}{\phi} \, (\beta_{FN} \cdot E)^2 \, \exp\left(- \frac{B \cdot \phi^{3/2}}{\beta_{FN} \cdot E}\right)$$

ϕ work function of metal

β_{FN} : empirical field enhancement factor

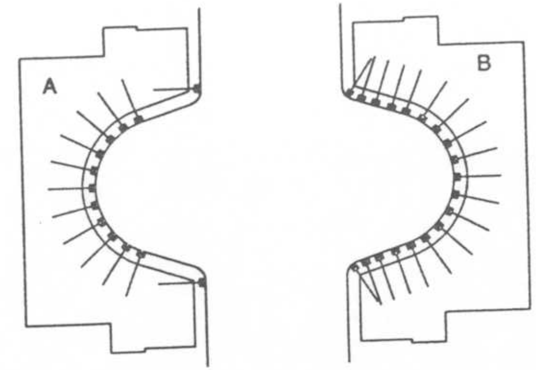
flat surface : expect field emission only at extremely large electric field (10 GV/m)

observation in cavities: field emission starts often at $\gtrsim 20$ MV/m

$\beta_{FN} \gtrsim 100$ needed

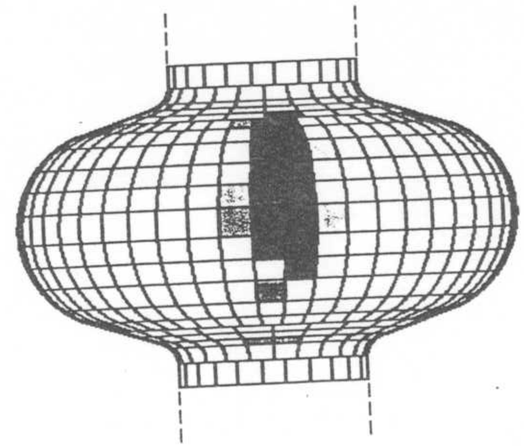
Temperatur-Karten der Kavitäten

Dissertation M. Pekeler

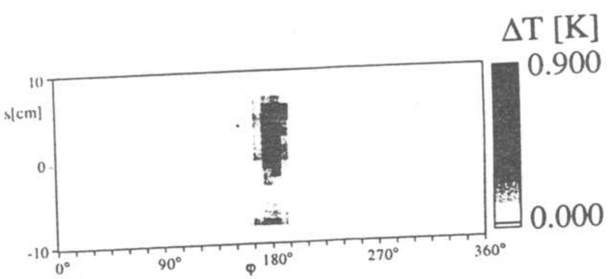


Allen-Bradley Kohleschicht-Widerstände

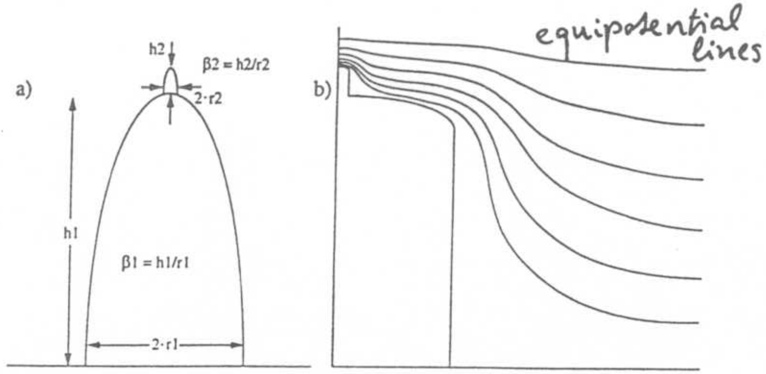
100 Ω	300 K
1000 Ω	4.2 K
≈ 10000 Ω bei 2 K	



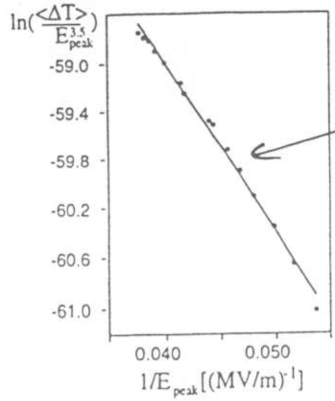
temperature mapping of cavity to find "hot spots"



tip on tip - model : $\beta_{FN} = \beta_1 \cdot \beta_2$



"Fowler - Nordheim" plot



fit yields $\beta_{FN} \approx 300$

Destruction of field emitters by high peak power (HPP) processing (several 100 kW for ≈ 100μs)

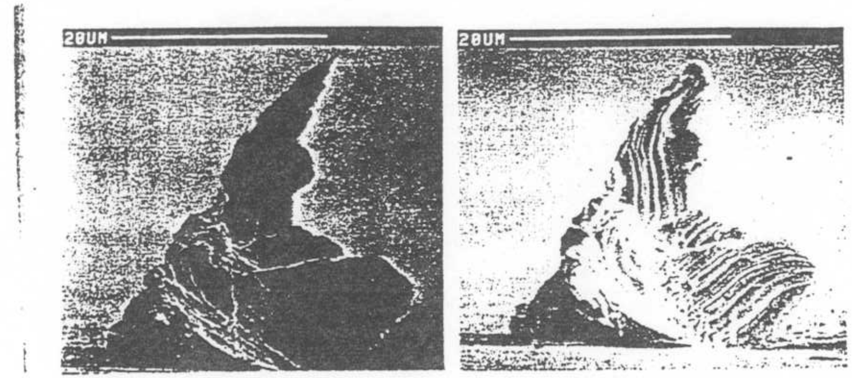
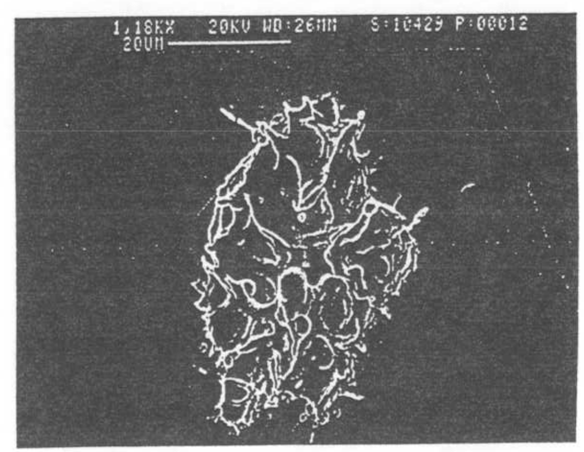
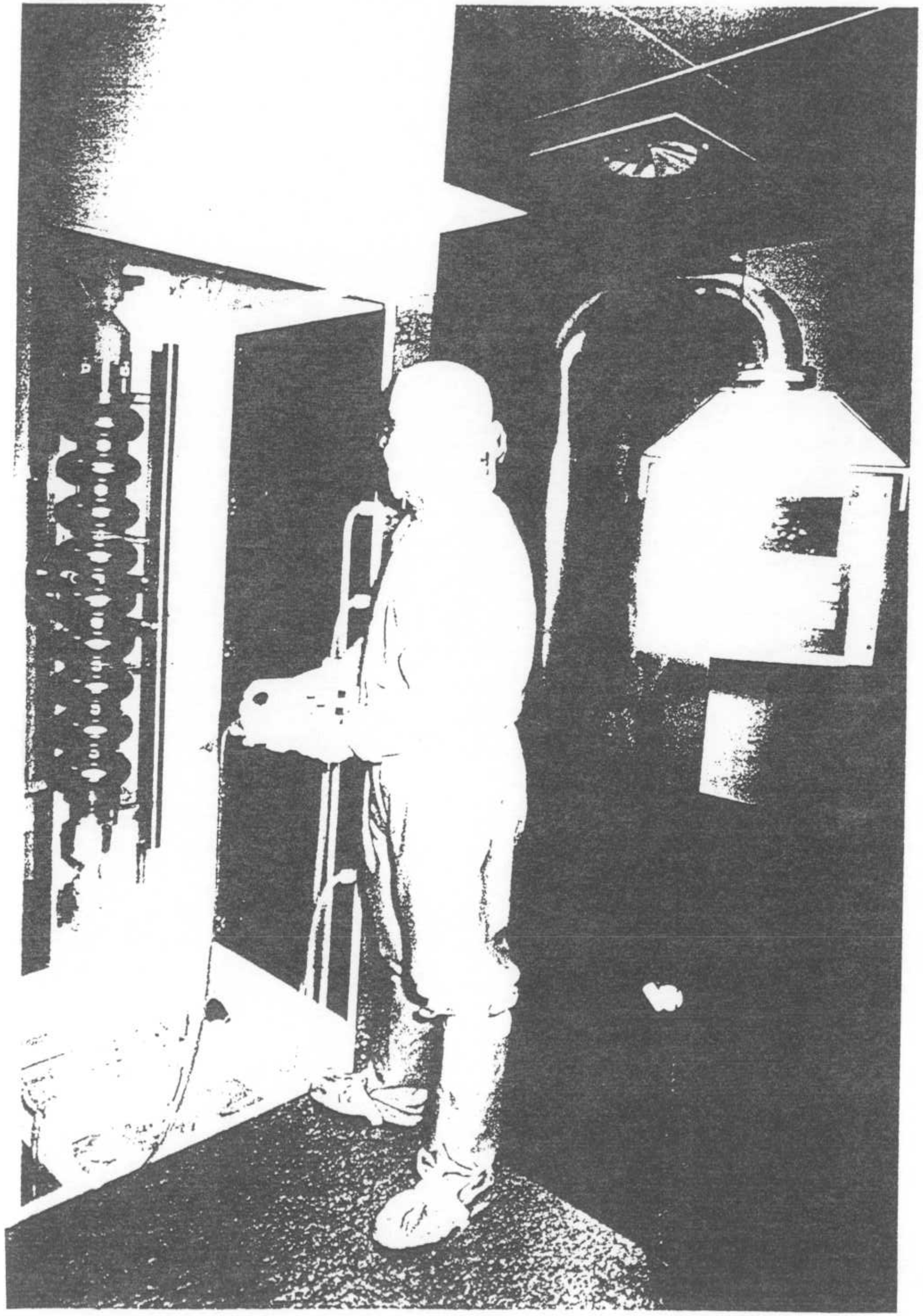


Fig. 6 Microphotograph of an emitting site: a) before emission; b) after emission. Note the apex melting.

B. Bonin (Saclay) : melting of a sharp tip by HPP

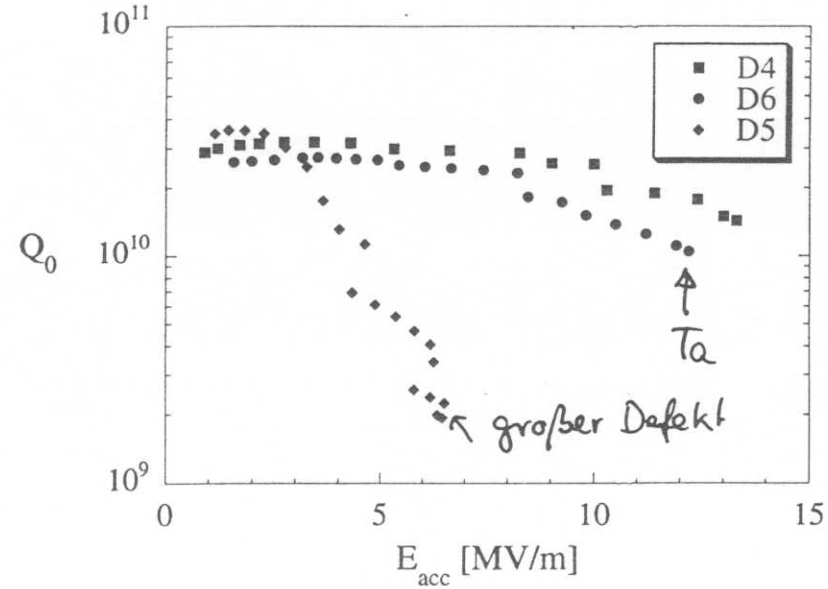


D. Moffat (Cornell): remnant of an exploded emitter clean-room treatment



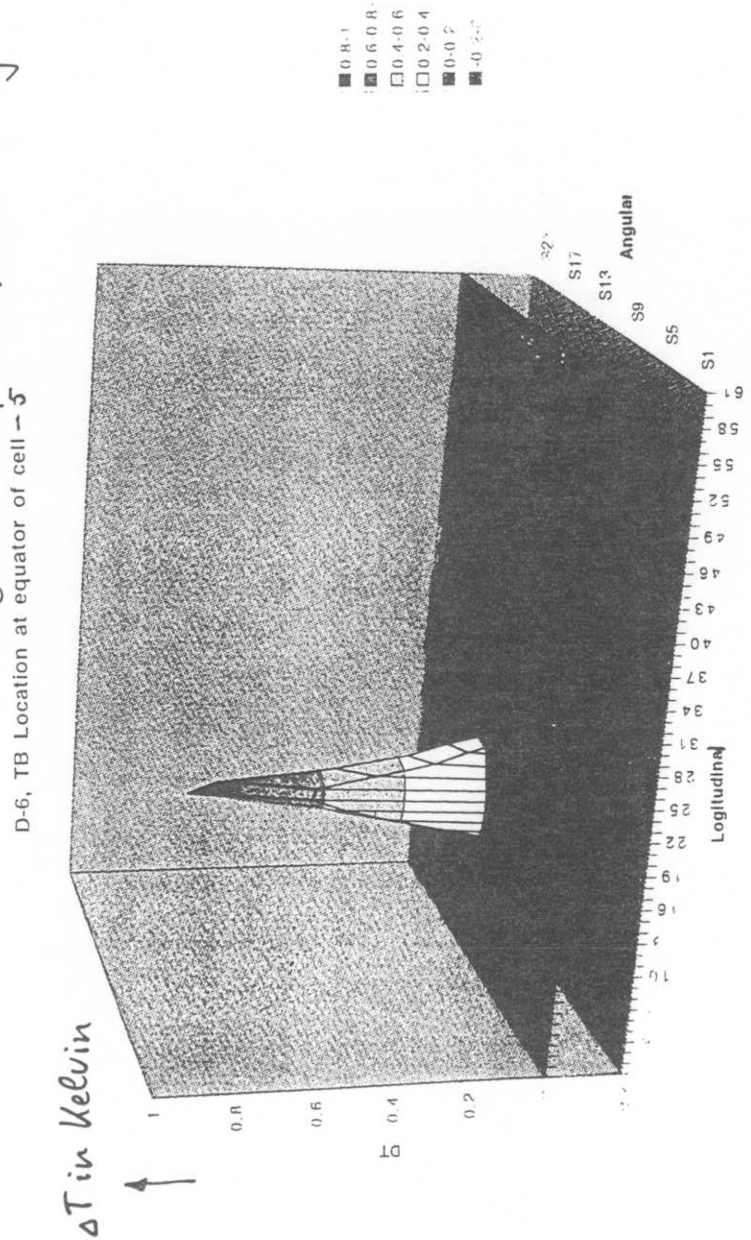
Cavities with niobium defects

Sudden Q degradation without field emission

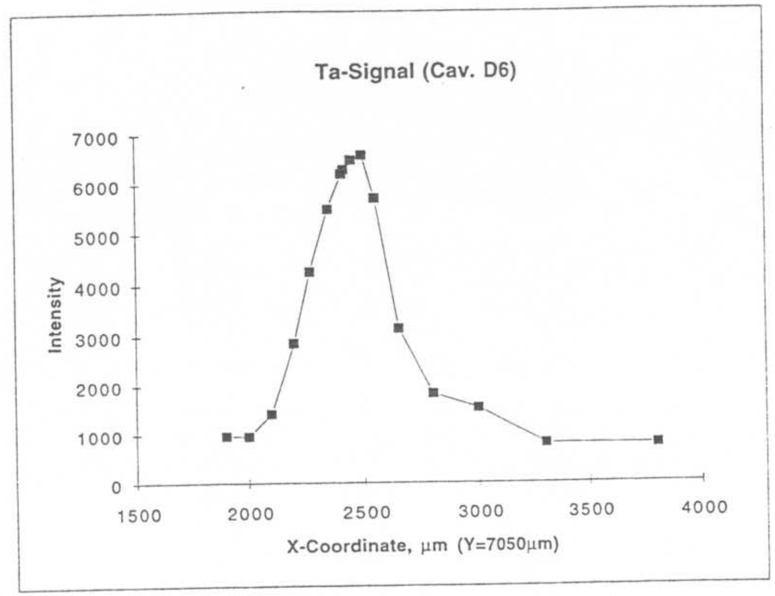


observed in 3 nine-cell cavities of the first production series for the TESLA Test Facility

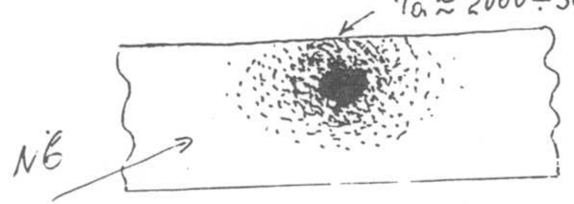
Temperature map at the Outer surface of the cavity

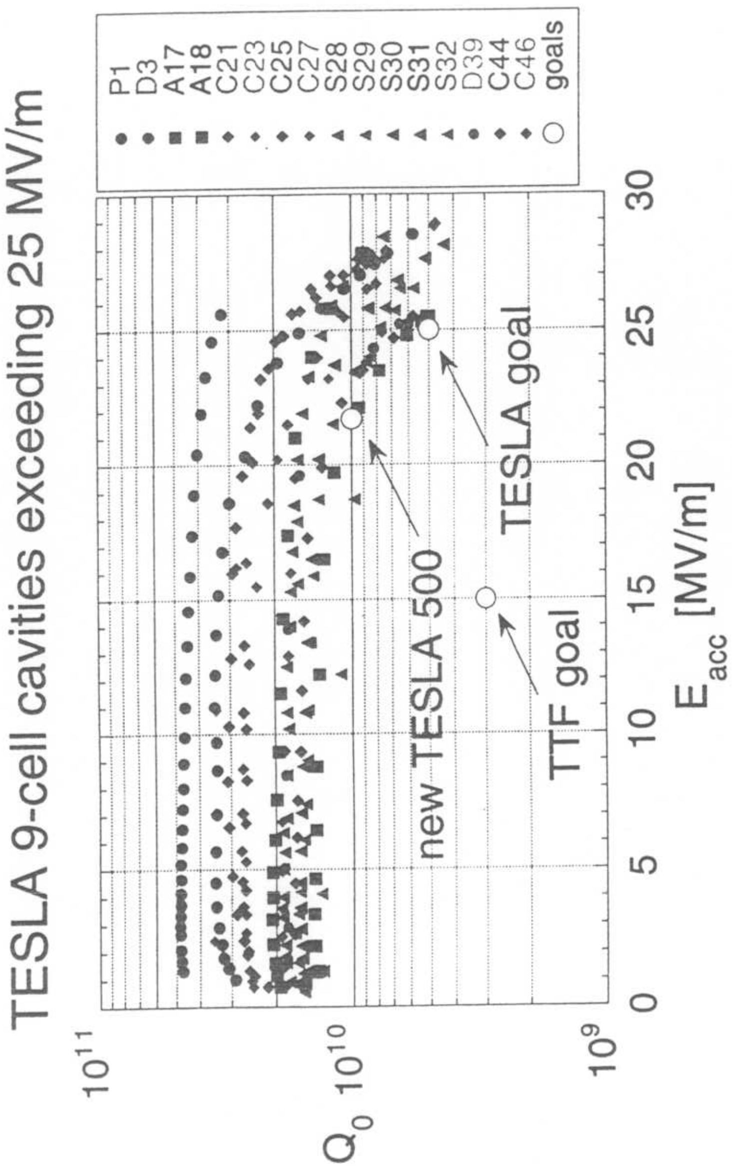


Identification of tantalum grain by means of X ray fluorescence at Hasylab



Spot size (X-direct.) ≅ 1 mm
Spot size (Y-direct.) ≅ 0,5 mm





All cavities are closed off in the class 10 cleanroom area by all metal sealed flanges or valves before leaving the cleanroom for further tests and installations. Also all components directly attached to the cavities like power input couplers, higher order mode couplers or pickup electrodes are carefully cleaned in the cleanroom area and are mounted to the cavities inside the class 10 area. For the venting of pumped cavities an ultra clean Argon gas system is used.

For RF-tests there are two vertical test dewars [8] and one horizontal test stand [9]. RF-power is either supplied by a 400 Watt cw generator or a 5 MW klystron plus modulator [10] for pulsed operation or peak power processing [11].

Relevant information on all cavities concerning treatment steps and test results are collected in an Oracle database [21]. A comprehensive description of the cavity treatment and the results can be found in [22].

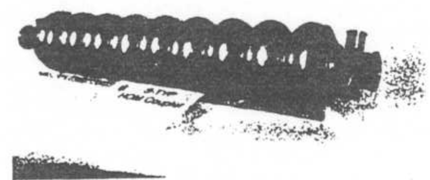


Figure 2: A 9-cell cavity.

3 RESULTS ON 9-CELL CAVITIES

The cavities (fig. 2) are fabricated from RRR 300 niobium sheets by deep drawing and by electron beam welding. Up to now 55 TESLA 9-cell cavities have been delivered by 4 European manufacturers: a first series of 28 in 1994, a second series of 27 in 1997.

Already in the first series the strict observance of clean treatment showed success by reaching gradients of 25 MV/m at Q values above $5 \cdot 10^9$ on several cavities However, there was also a number of cavities that performed much worse. The reasons for this poorer performance were traced back to either unproper preparation of the cavity dump bells before welding or by inclusions of normalconducting grains in the niobium.

For the second series, proper weld preparation was assured and all niobium sheets were scanned by an eddy current method to exclude sheets containing inclusions from cavity production [12]. The success of these measures can be seen in fig. 3 where the average

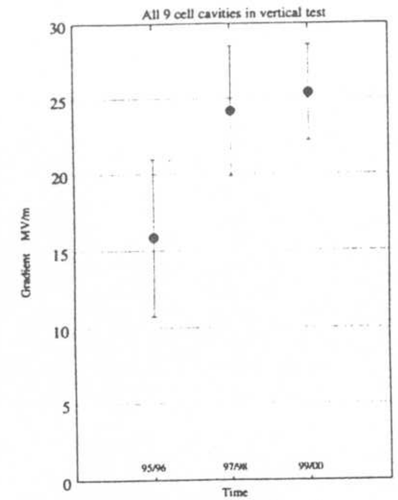


Figure 3: Average gradient of all 9-cell cavities measured in vertical tests during the past 5 years.

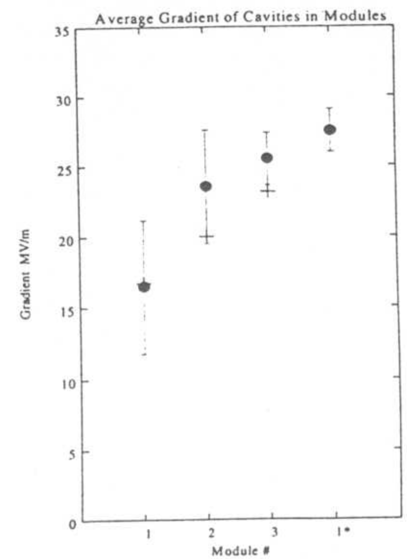
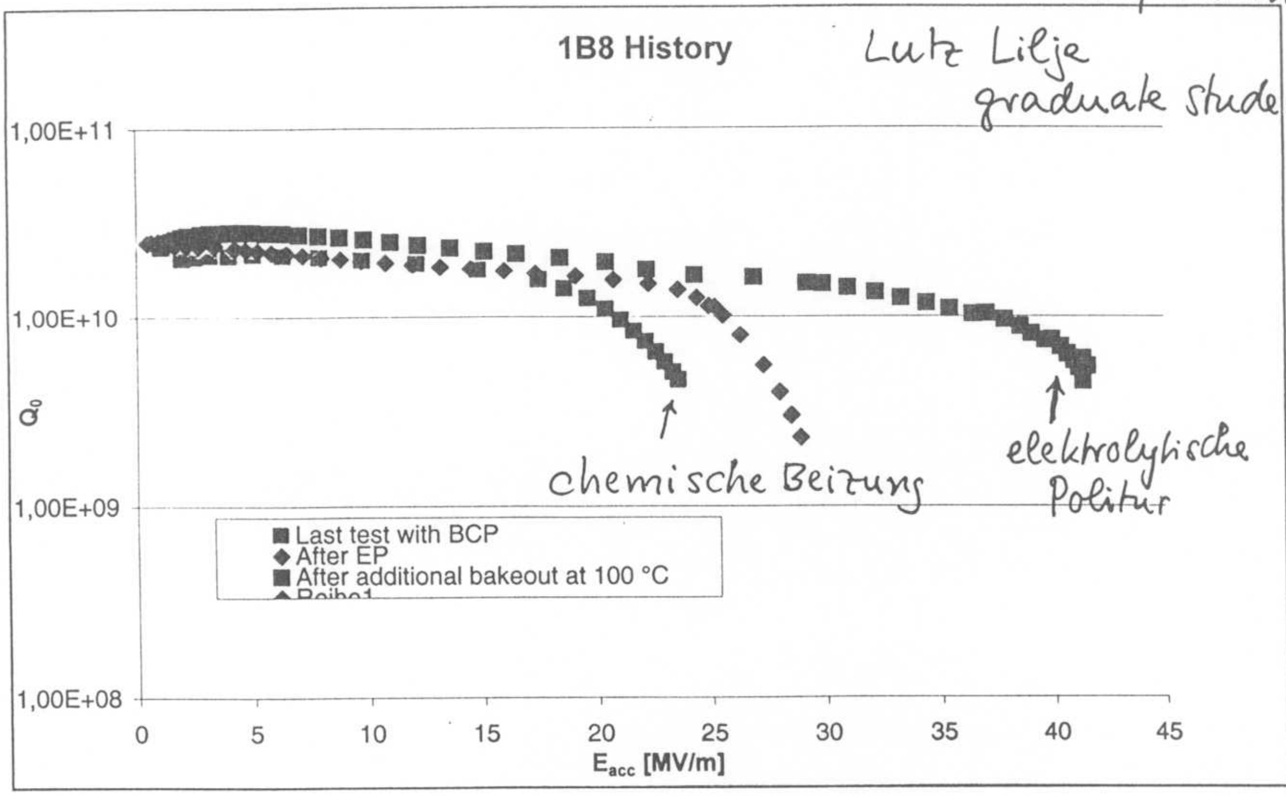


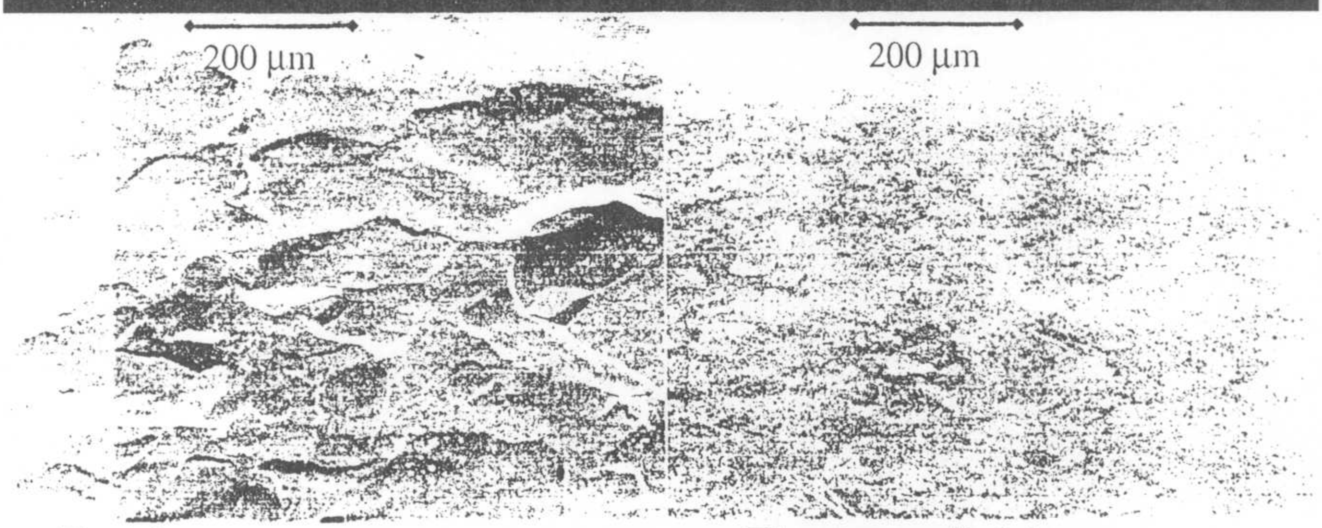
Figure 4: Average gradient, as measured in vertical tests, of the 9-cell cavities assembled into accelerator modules. Crosses indicate the gradients obtained in the module.

CERN / DESY / Saclay / KEK cooperation



02.12.99 Lutz Lilje DESY -FDET-

Niobium surfaces

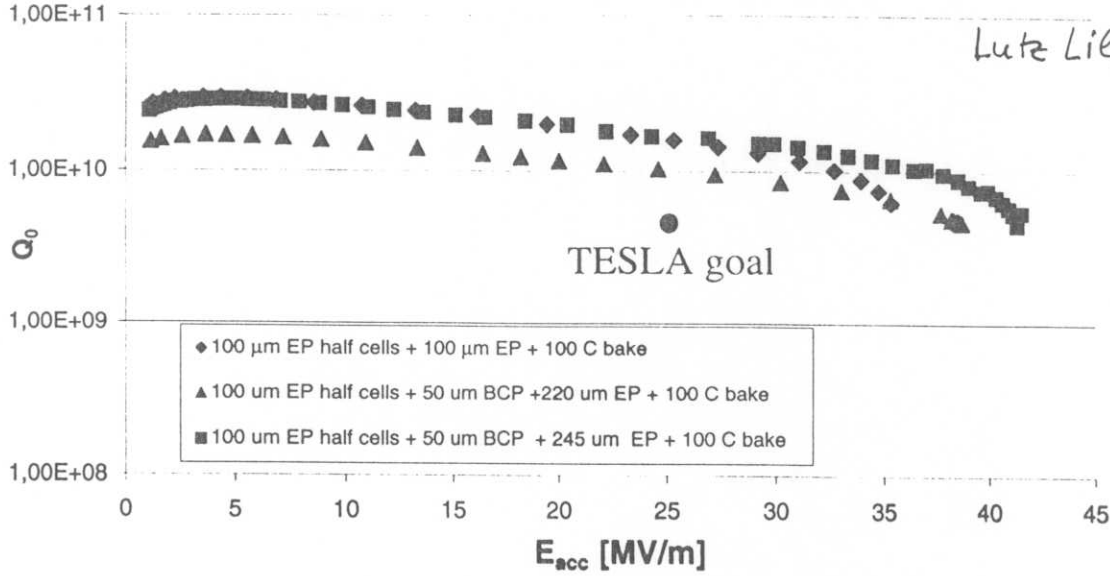


- Etching (Buffered chemical polish)
  - HF, HNO_3, H_3PO_4
- Electropolishing

Electropolished 1-cell 1.3 GHz cavities

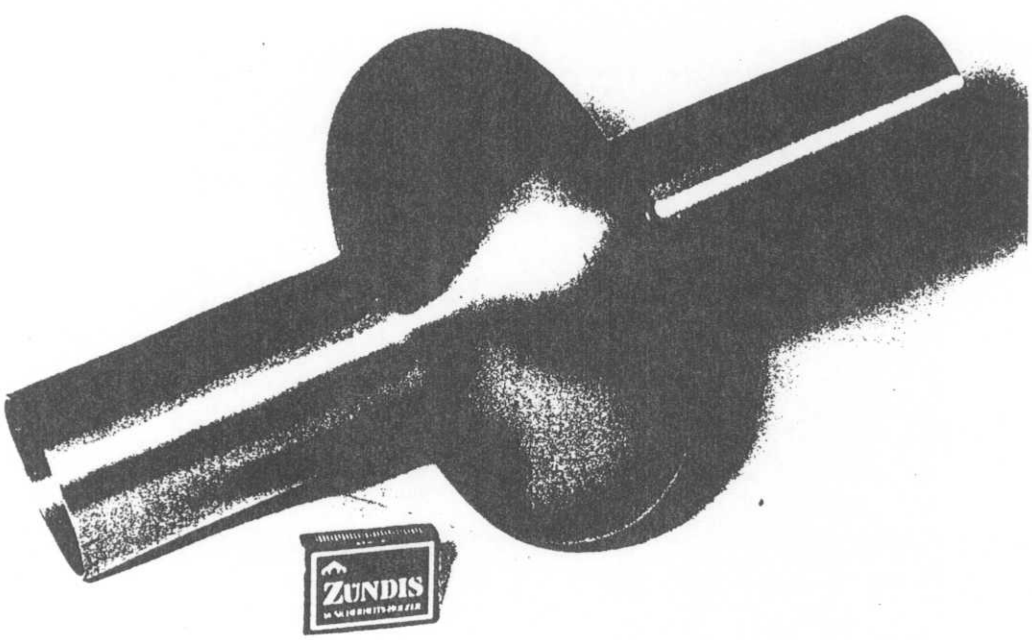
- EP done at CERN, measurements at CEA, CERN, KEK at DESY
- KEK-style electropolishing used for 1-cell cavities

Lutz Lilje (U. HH)

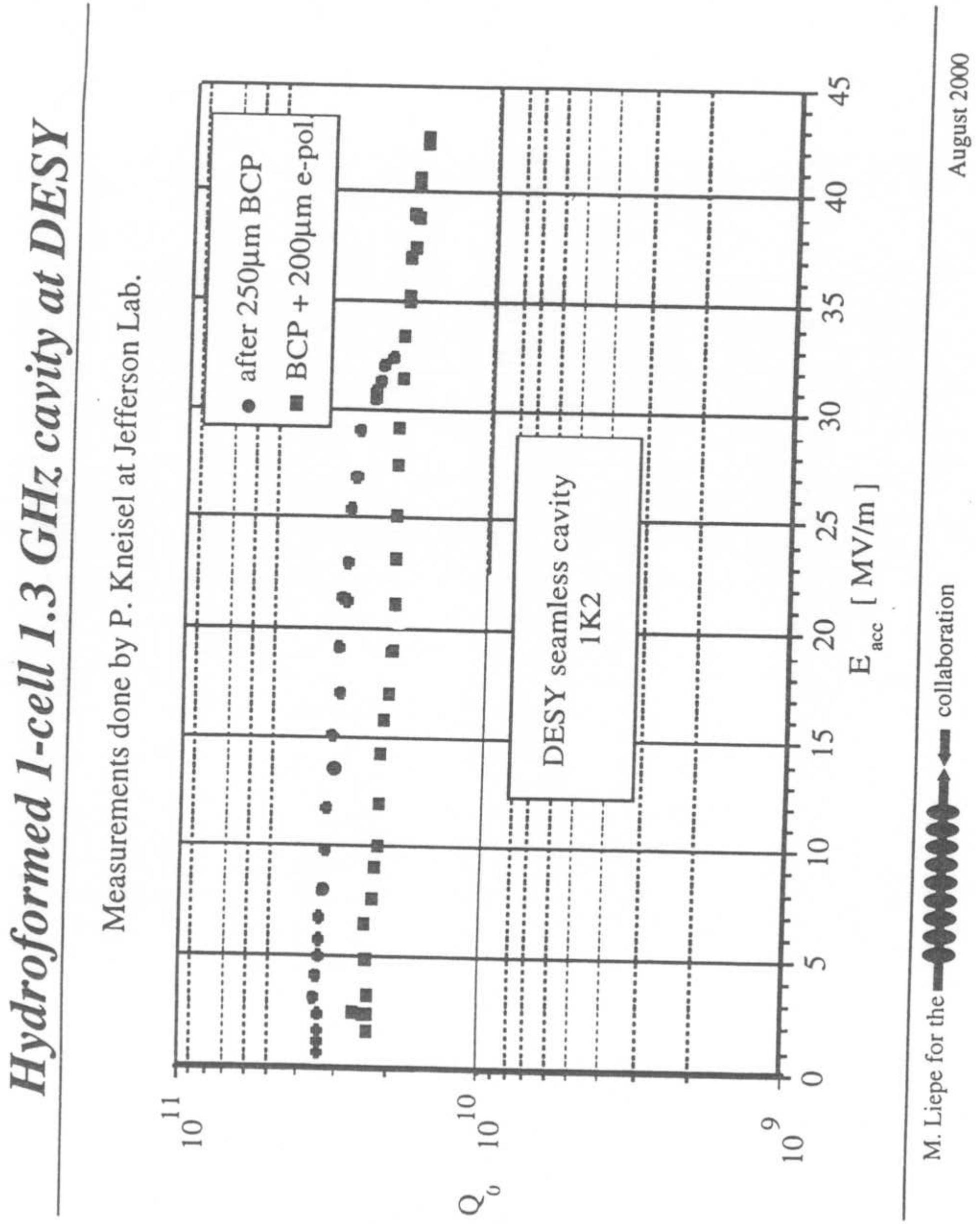


⇒ electropolishing of 9-cell cavities

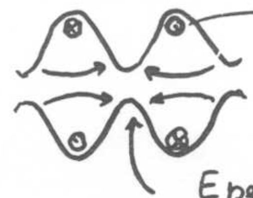
V. Palmieri, Legnaro, Italia



Seamless cavity, made by spinning



Performance limit of cavity?



$B_{peak} / E_{acc} \approx 4\,mT/(MV/m)$ at equator $\Rightarrow$ thermal breakdown

$E_{peak} \approx 2\, E_{acc}$ at iris
$\Rightarrow$ danger of field emission

Superconductivity breaks down if the rf magnetic field exceeds the critical field of the superconductor.

Complication in case of niobium:
type II superconductor with 3 critical fields: B_{c1}, $B_c^{th.}$, B_{c2}

Conservative estimate:
$B < B_{c1}$ ($\approx 160\,mT$ at $2K$)
$\Rightarrow E_{acc}$ max. $\lessapprox 40\,MV/m$

Probably some "superheating" possible up to $B_c^{th} \approx 190\,mT \;\hat{=}\; 48\,MV/m$

Flux penetration into the s.c. must be avoided since this leads to hysteresis and losses.