Superconducting RF

University of Chicago
Physics 575
Accelerator Physics and Technology of Linear Colliders

Chapter 7

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Before we start…

- … a big thank you to Peter Schmüser for helping me to prepare the lecture.
- … another thank you to the colleagues from the TESLA collaboration and the field from superconducting RF cavities for the material provided
- … please check out the lecture notes for references. I tried to give a lot of primary and secondary literature
  - A good introduction into superconducting cavities is given in [Padamsee et al. 1998].
  - Short review articles are also available [Aune et al. 2000, Padamsee 2001].
- … let me inform you that this is a first-timer for me giving this type of lecture: Please comment on the stuff you didn't like – and on the things, which you like.

Outline of the lectures

- Theory first … (Lecture 1)
  - RF cavities (revisited – see also Juwen Wang)
    - A variety of SRF cavities in pictures
    - The Pillbox cavity
    - Acceleration of a bunched beam
  - Superconductivity basics
  - RF superconductivity
  - Limitations of superconducting RF (SRF) cavities
    - Diagnostic tools
    - Surface and material science
    - Defects
      - Thermal conductivity
    - Field emission
    - Multipacting
    - Increased surface resistance at high field

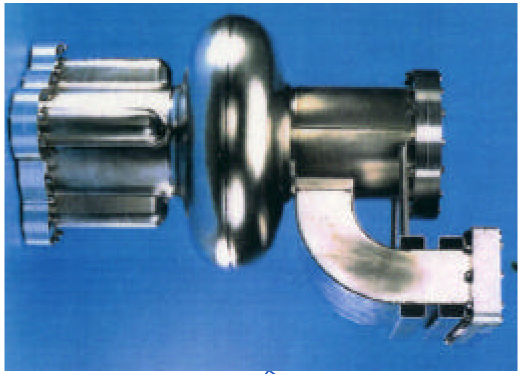
Outline (continued)

- Practical example: TESLA cavities (Lecture 2)
  - What is TESLA?
    - Goals for TESLA cavities
  - Choice of superconductor
  - Design of SRF cavities
  - Manufacturing issues
  - Surface preparation
  - Current state-of-the-art cavity performance
  - Higher gradients for TESLA-800
    - Electropolishing
    - ‘Superstructure’
  - Operating SRF cavities
    - Cryostats
    - RF Couplers
    - Low-level RF control

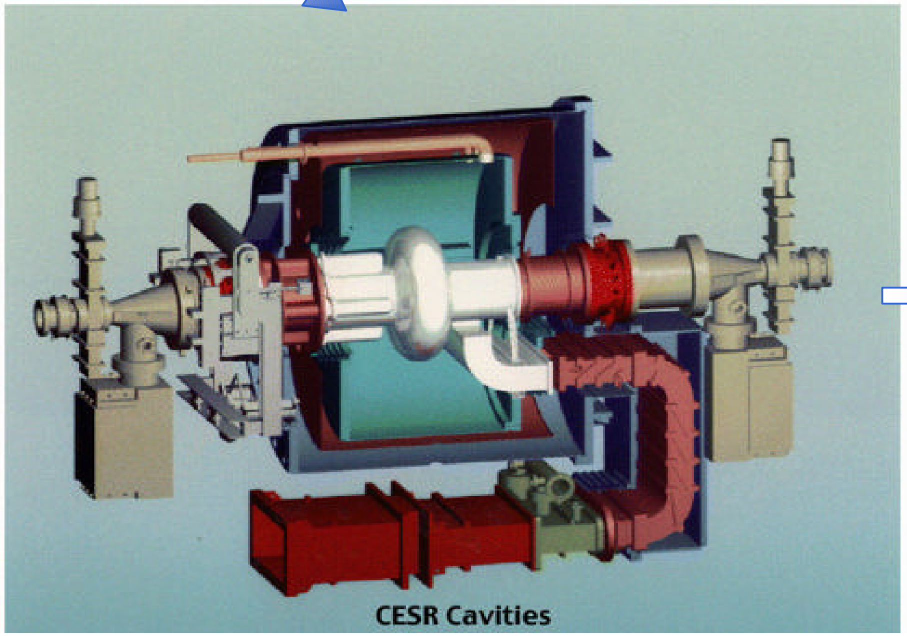
SRF cavities

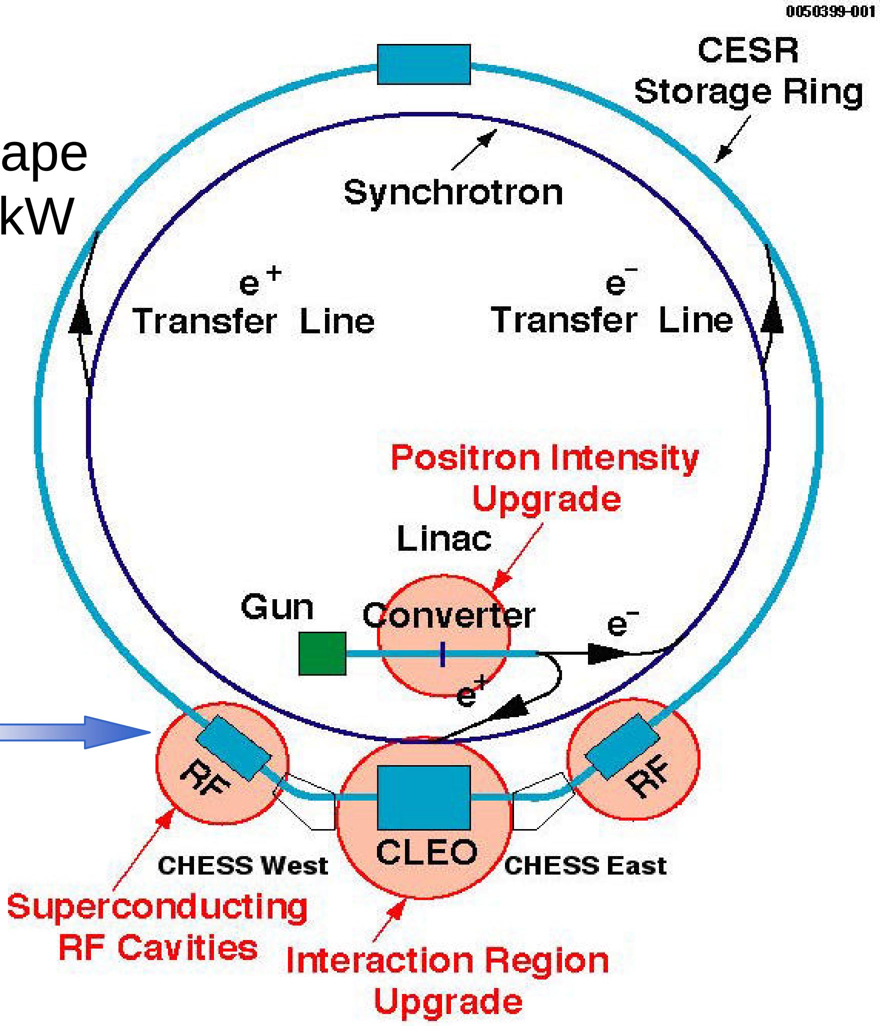
- What do they actually look like?
  - – Protons
  - – Ions
  - – Electrons
- Courtesy H. Padamsee

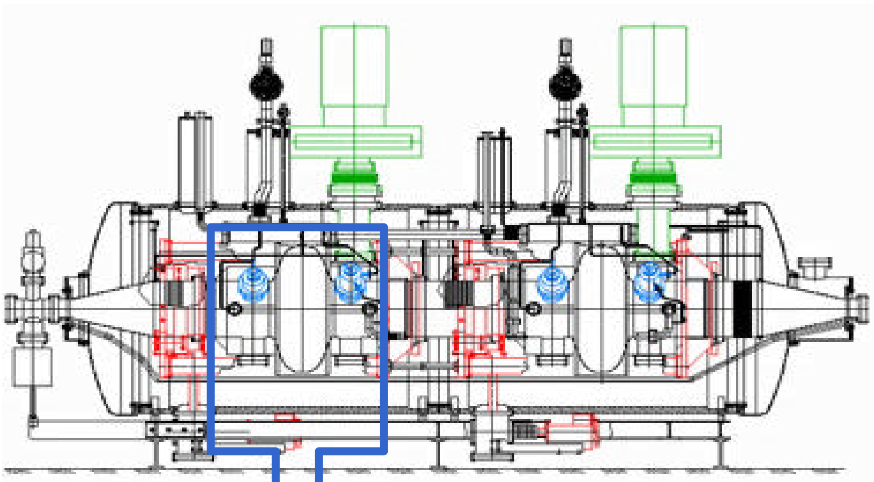
High luminosity rings (CESR)

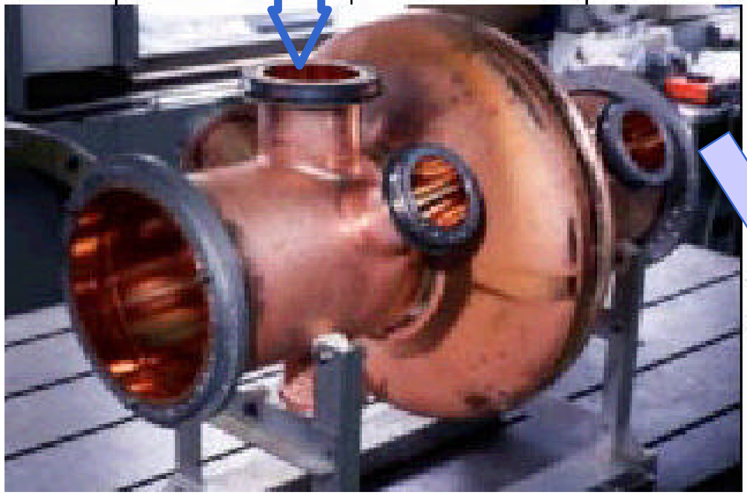


- Low Impedance Shape
- Beam Power > 270kW



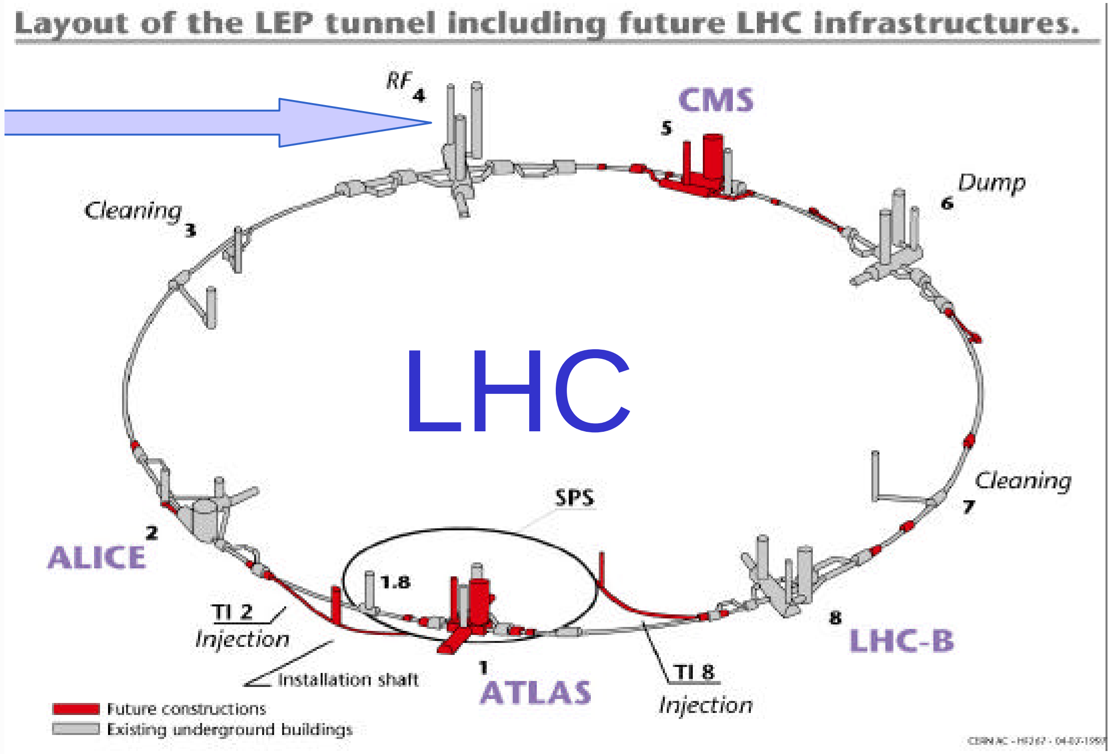


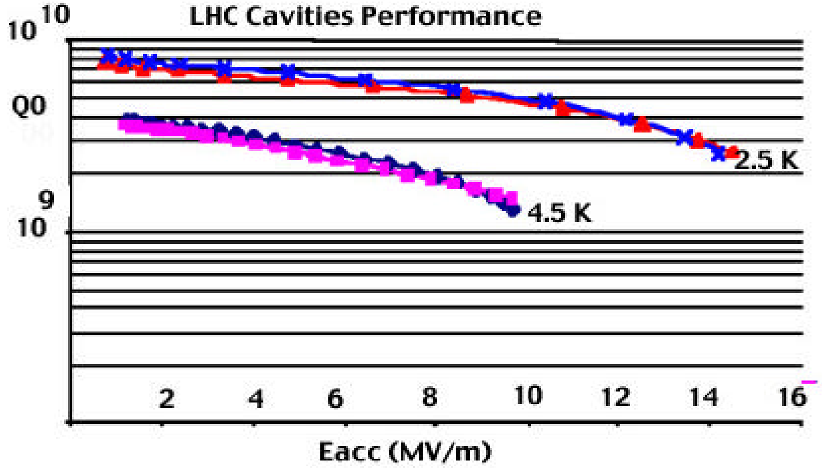




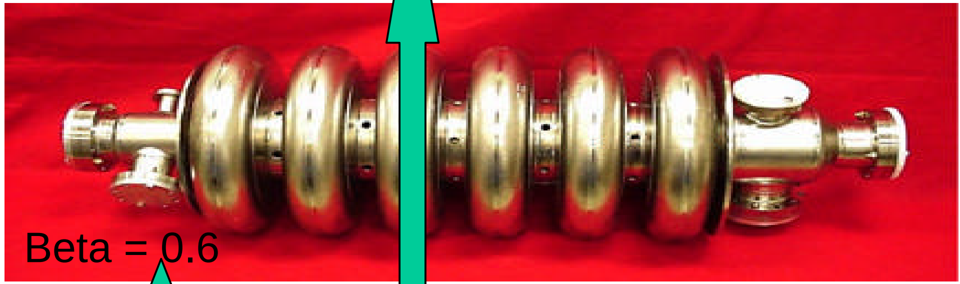
400 MHz

16 Nb/Cu Cavities

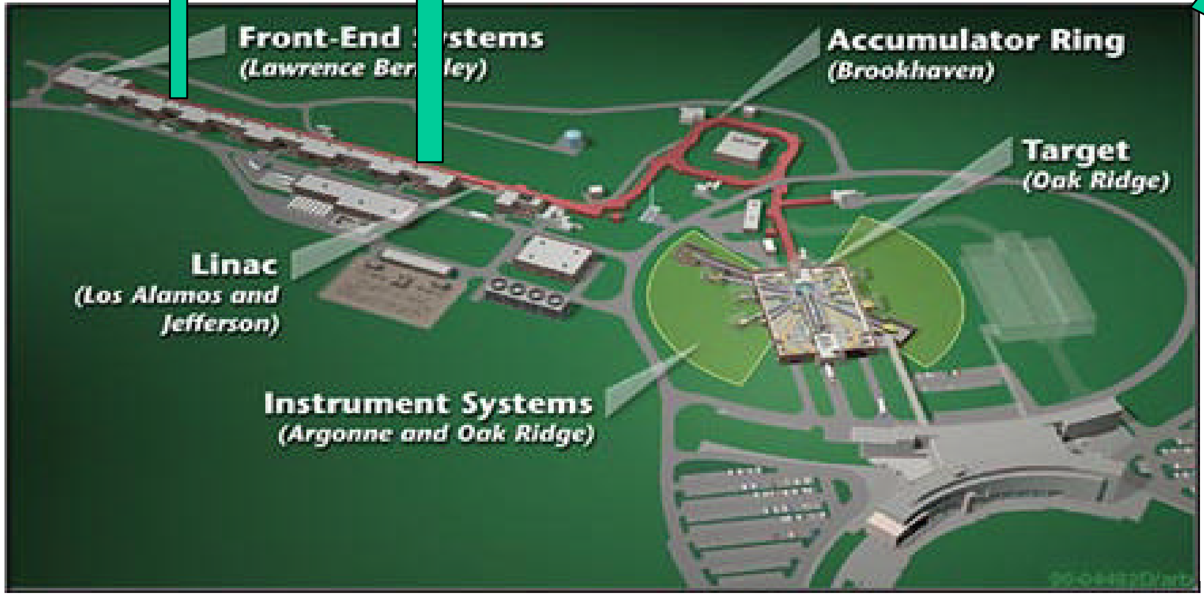

Layout of the LEP tunnel including future LHC infrastructures.

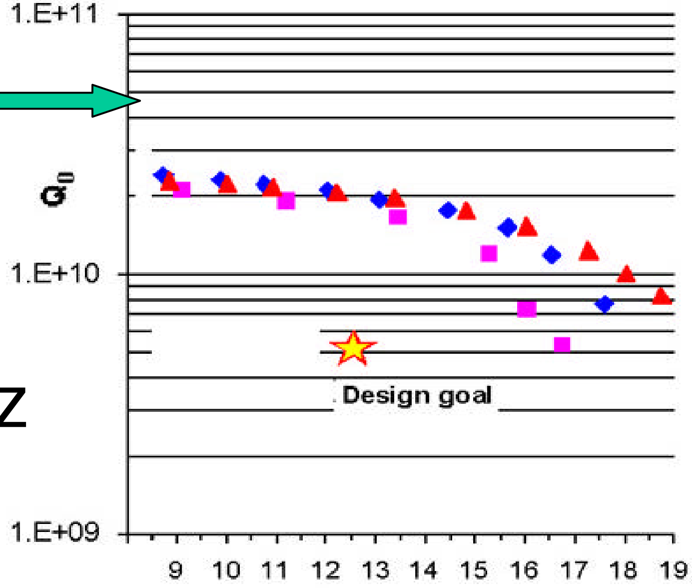


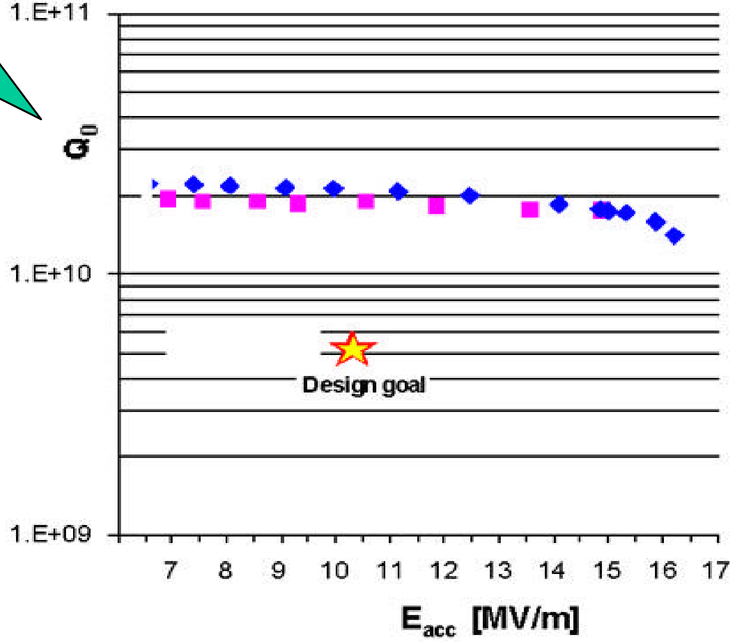
SNS (Spallation Neutron Source)



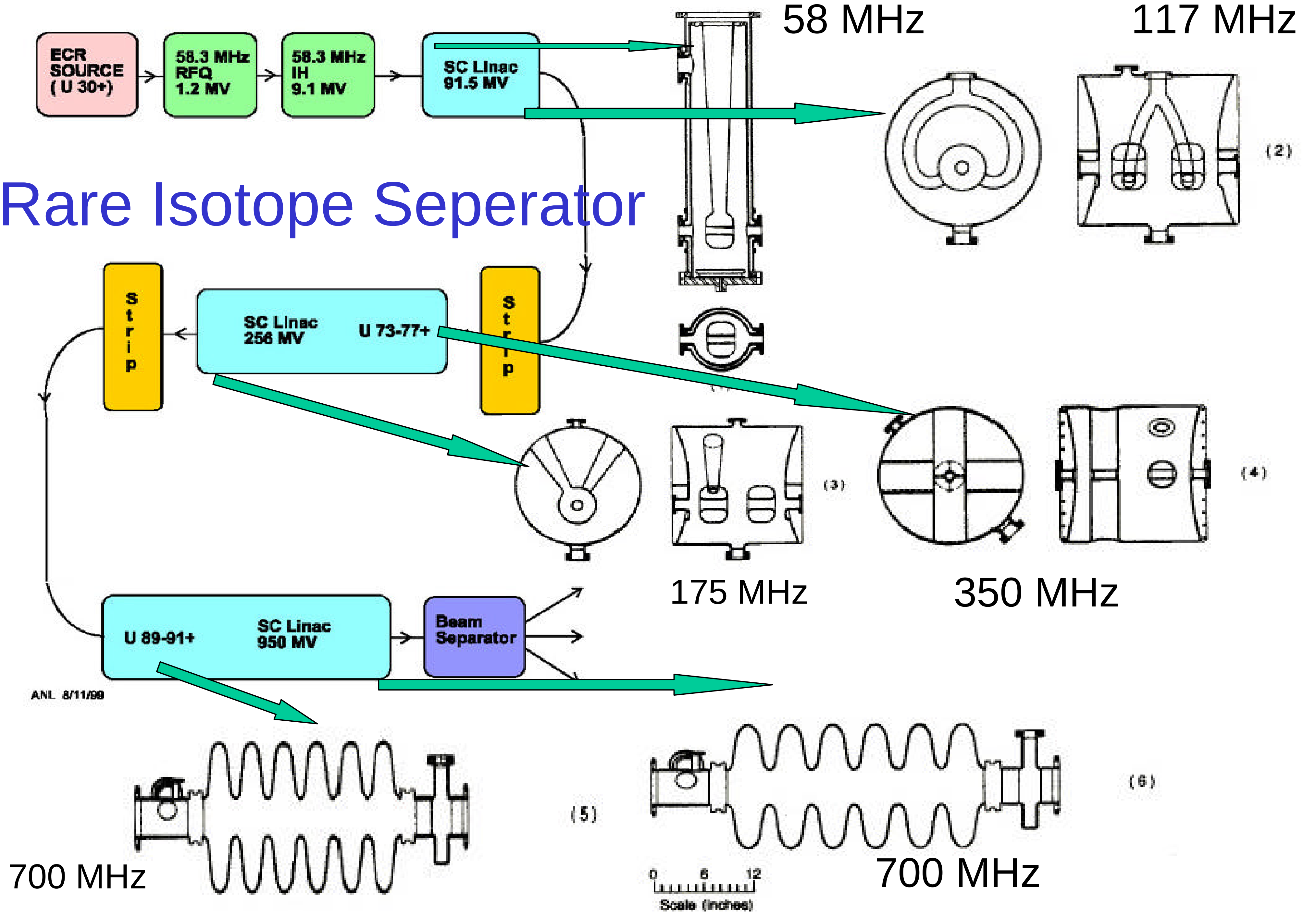
800 MHz







Rare Isotope Seperator



ECR SOURCE (U 30+)

58.3 MHz RFQ 1.2 MV

58.3 MHz IH 9.1 MV

SC Linac 91.5 MV

Strip

SC Linac 256 MV U 73-77+

Strip

U 89-91+ SC Linac 950 MV

Beam Separator

ANL 8/11/98

58 MHz

117 MHz

175 MHz

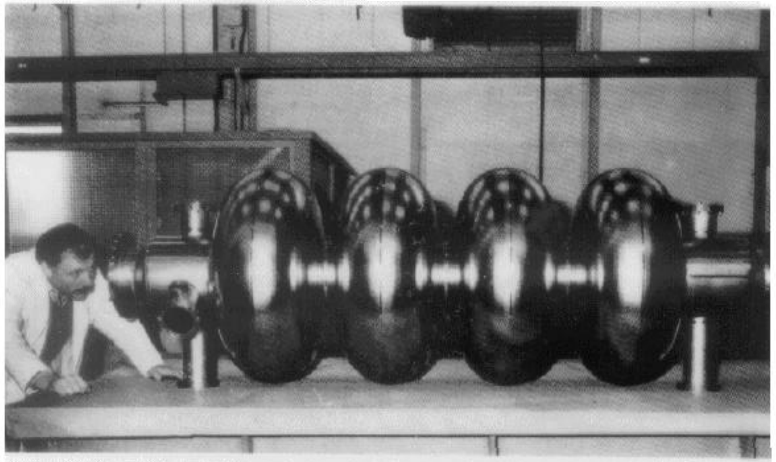
350 MHz

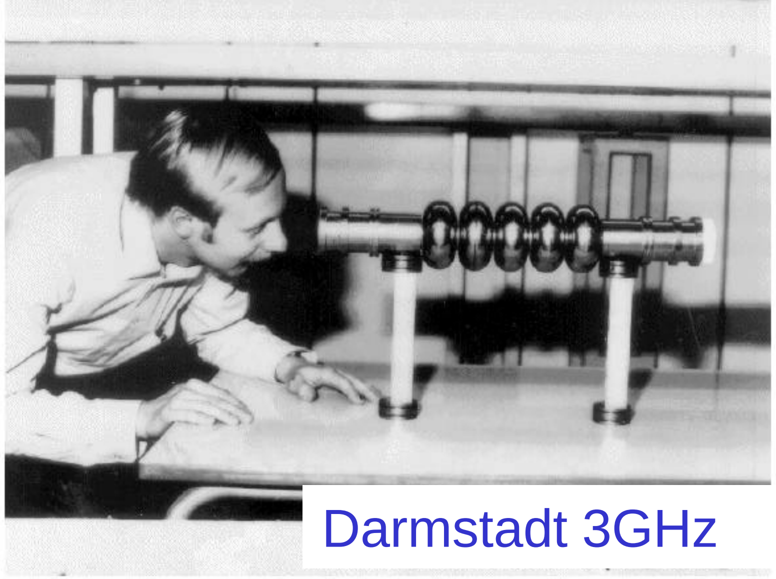
700 MHz

700 MHz

Niobium bulk cavities

CERN 350 MHz





Darmstadt 3GHz

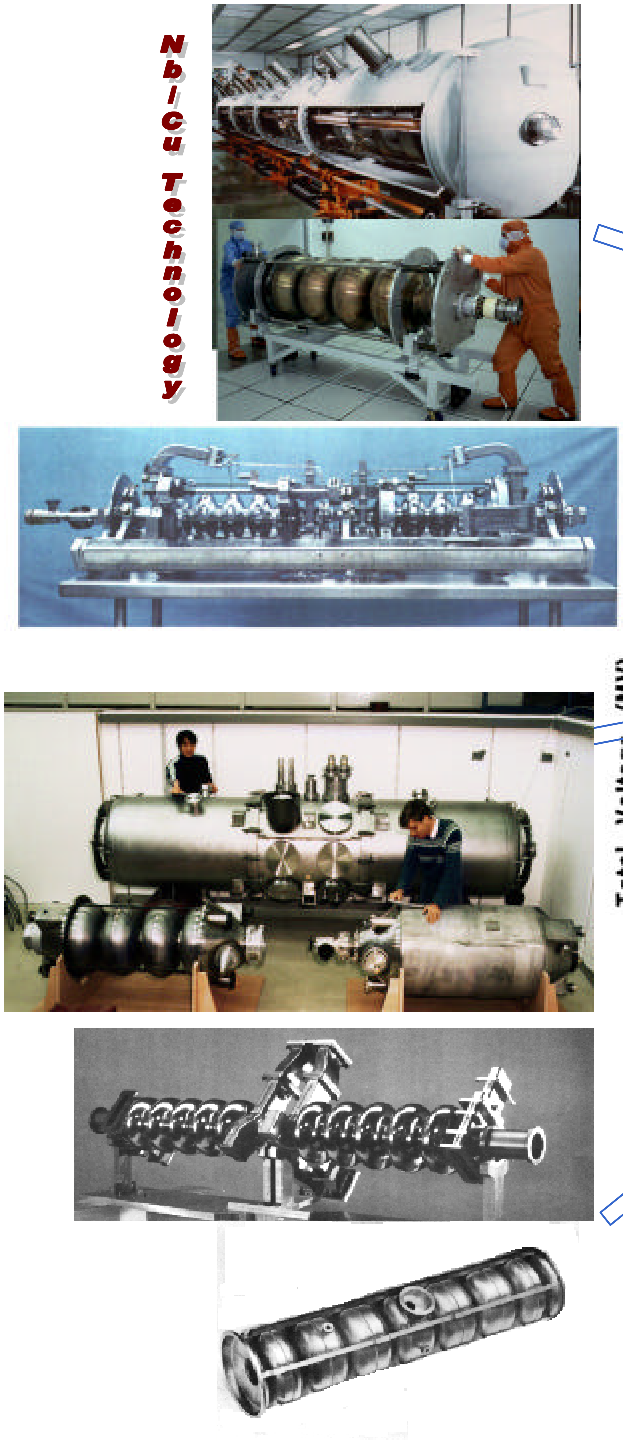
TESLA
1,3 GHz

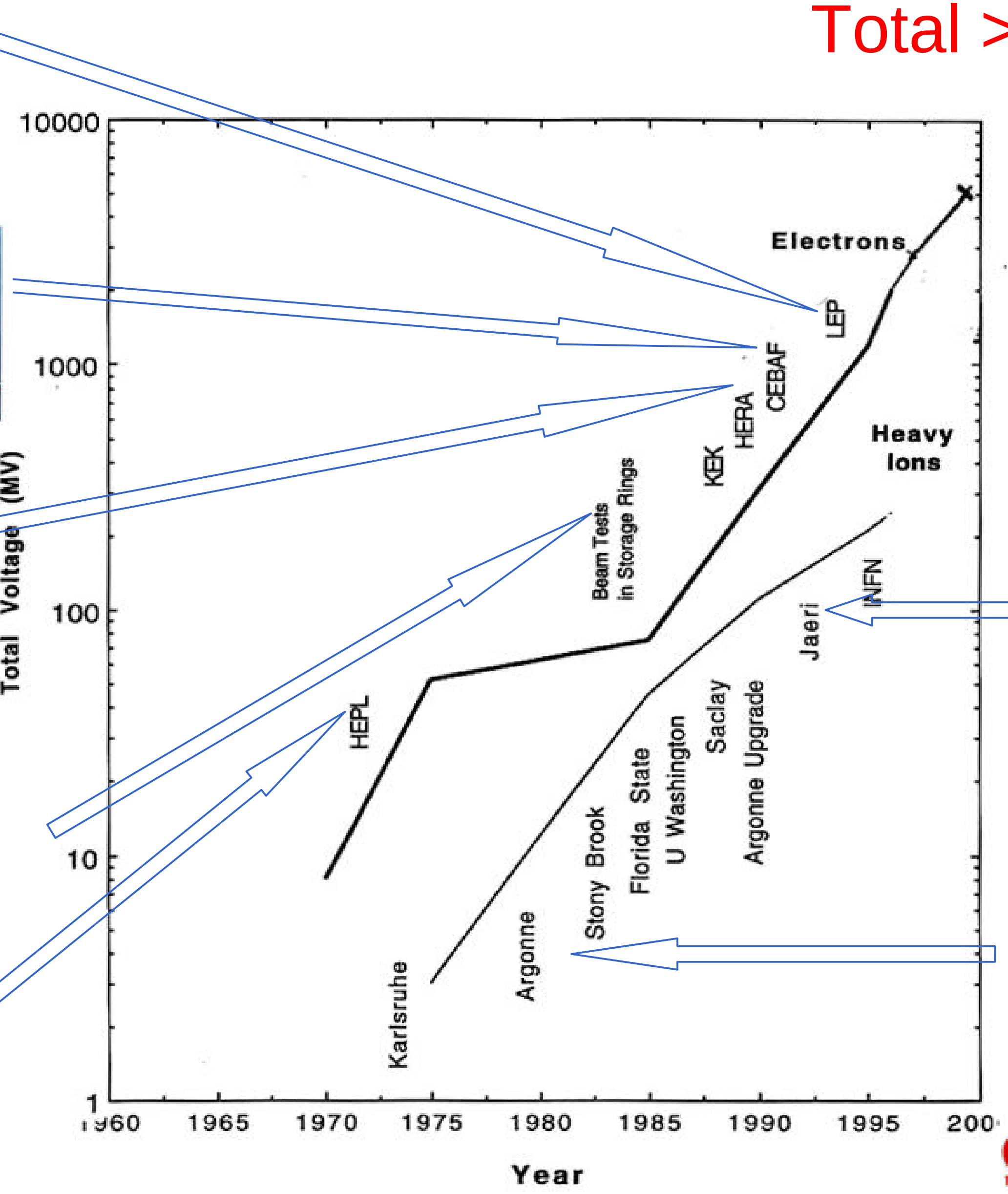
Livingston plot for SRF cavities

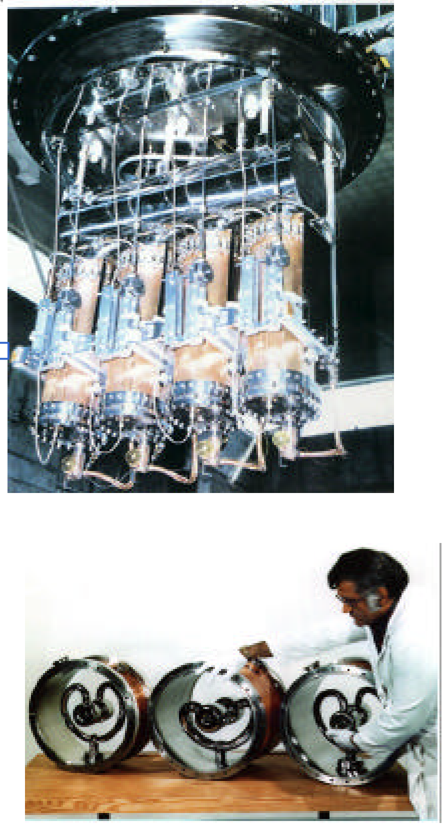
Courtesy H. Padamsee

Total >1000 meters

> 5 GV



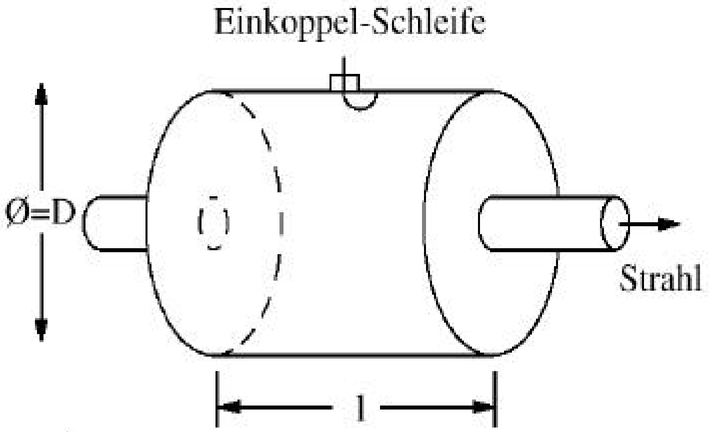




Outline of the lecture

- RF cavities
  - A variety of SRF cavities in pictures
  - The Pillbox cavity
  - Acceleration of a bunched beam
- Superconductivity basics
- RF superconductivity
- Limitations of superconducting RF (SRF) cavities

Properties of Cavities

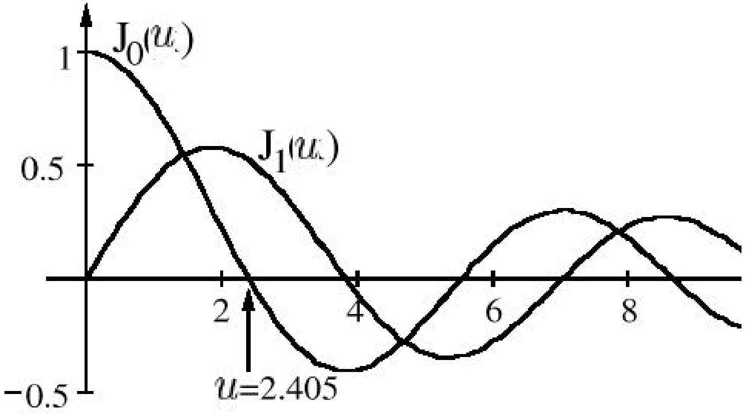


Example: cylindrically symetric cavity - Pillbox

$$\frac{\partial^2 E_s}{\partial r^2} + \frac{1}{r}\frac{\partial E_s}{\partial r} = \frac{1}{c^2}\frac{\partial^2 E_s}{\partial t^2}$$

$$E_s(r,t) = E(r)e^{i\omega t}$$ with $$u = \frac{\omega}{c} r$$

$$E(u) = E_0\, J_0(u)$$ J_0, J_1 Besselfunctions



Frequency: $$E\left(r = \frac{D}{2}\right) = 0$$ $$f = \frac{c \cdot 2.405}{\pi D}$$

Stored Energy: $$U = \frac{1}{2}\varepsilon_0\, E_0^2\, J_1^2(2.405)\, l\, \pi \left(\tfrac{D}{2}\right)^2$$

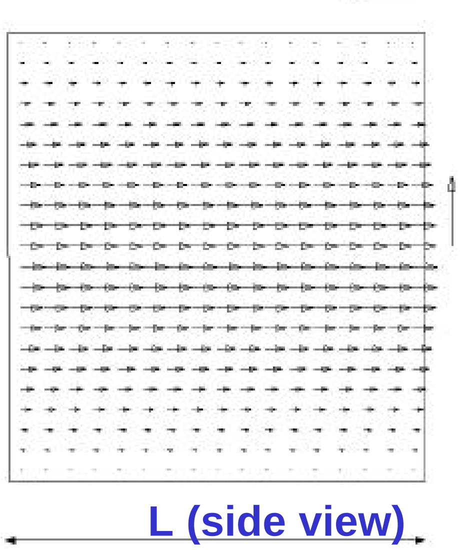
Dissipated power: $$P_{\mathrm{Ges}} = \frac{1}{2} R_{\mathrm{S}} \cdot \frac{\varepsilon_0}{\mu_0} \cdot E_0^2 \cdot \pi\, D\, l \cdot \left(1 + \frac{D}{2l}\right) J_1^2(2.405)$$

Quality factor: $$Q_0 = \omega \cdot \frac{U}{P_{\mathrm{Ges}}} = \frac{\mu_0\, c \cdot 2.405}{2\, R_{\mathrm{S}} \left(1 + \frac{D}{2l}\right)}$$

Geometry factor: $$G = \frac{\mu_0\, c \cdot 2.405}{2 + D/l}$$

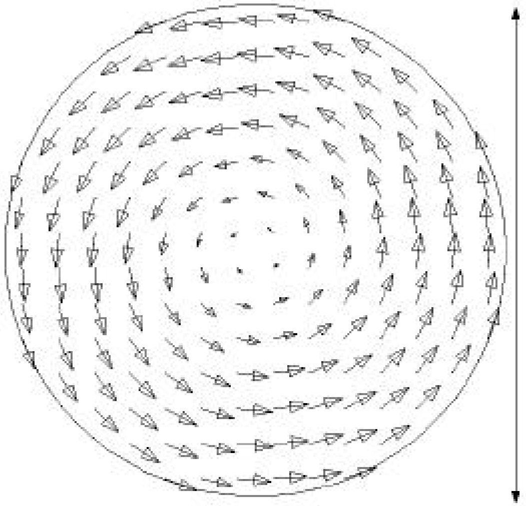
Field distributions in cavities

Electric Field (Pillbox):



TM010 : accelerating mode

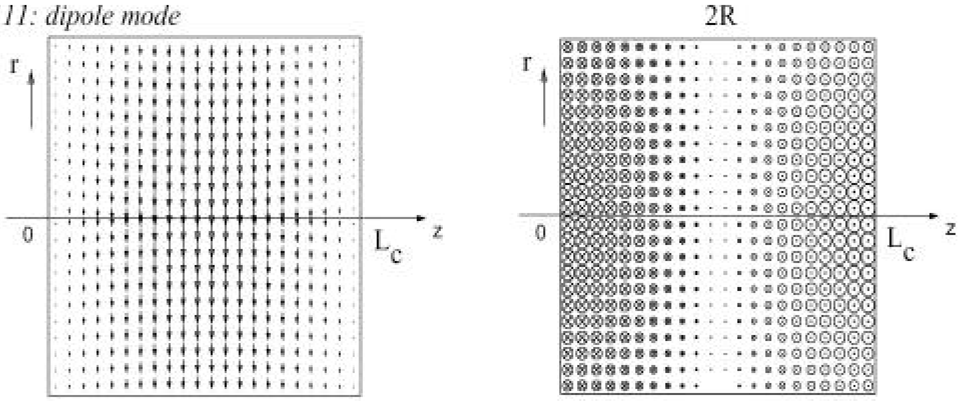
Magnetic Field :



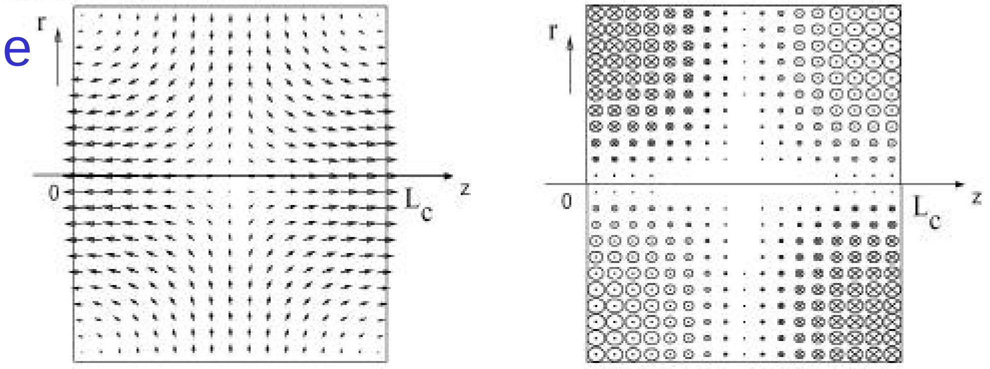
D (front view)

Other modes : e.g. deflecting modes

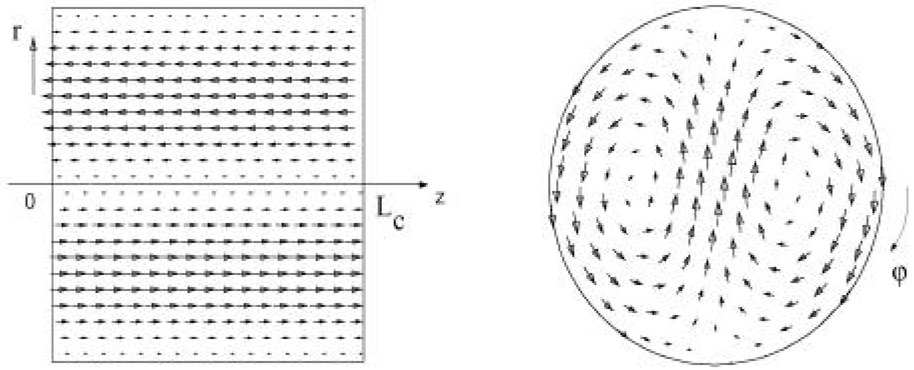
TE111: dipole mode



TM011: monopole mode

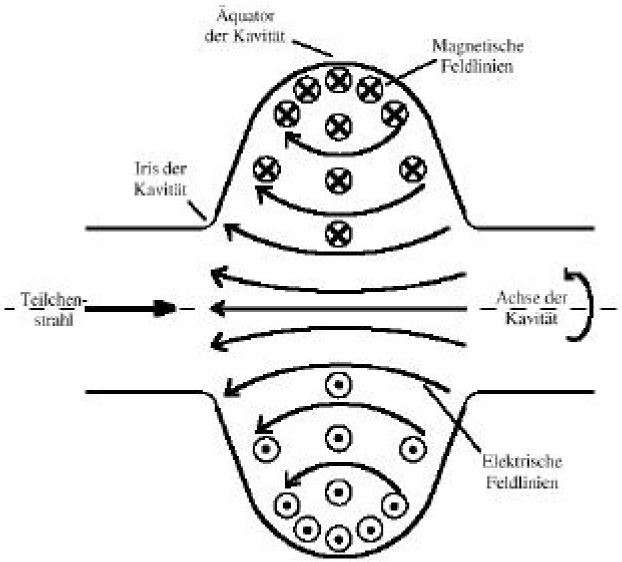


TM110: dipole mode



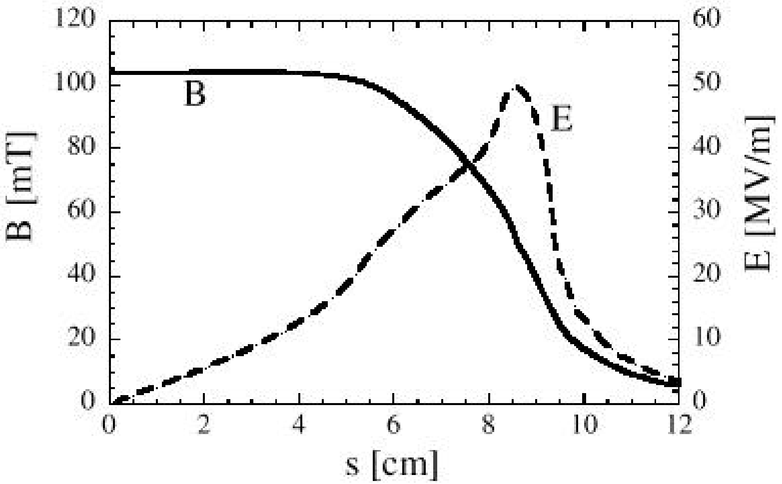
Field distributions in cavities

Elliptical cavity:



Numerical solution for surface fields:

Þ

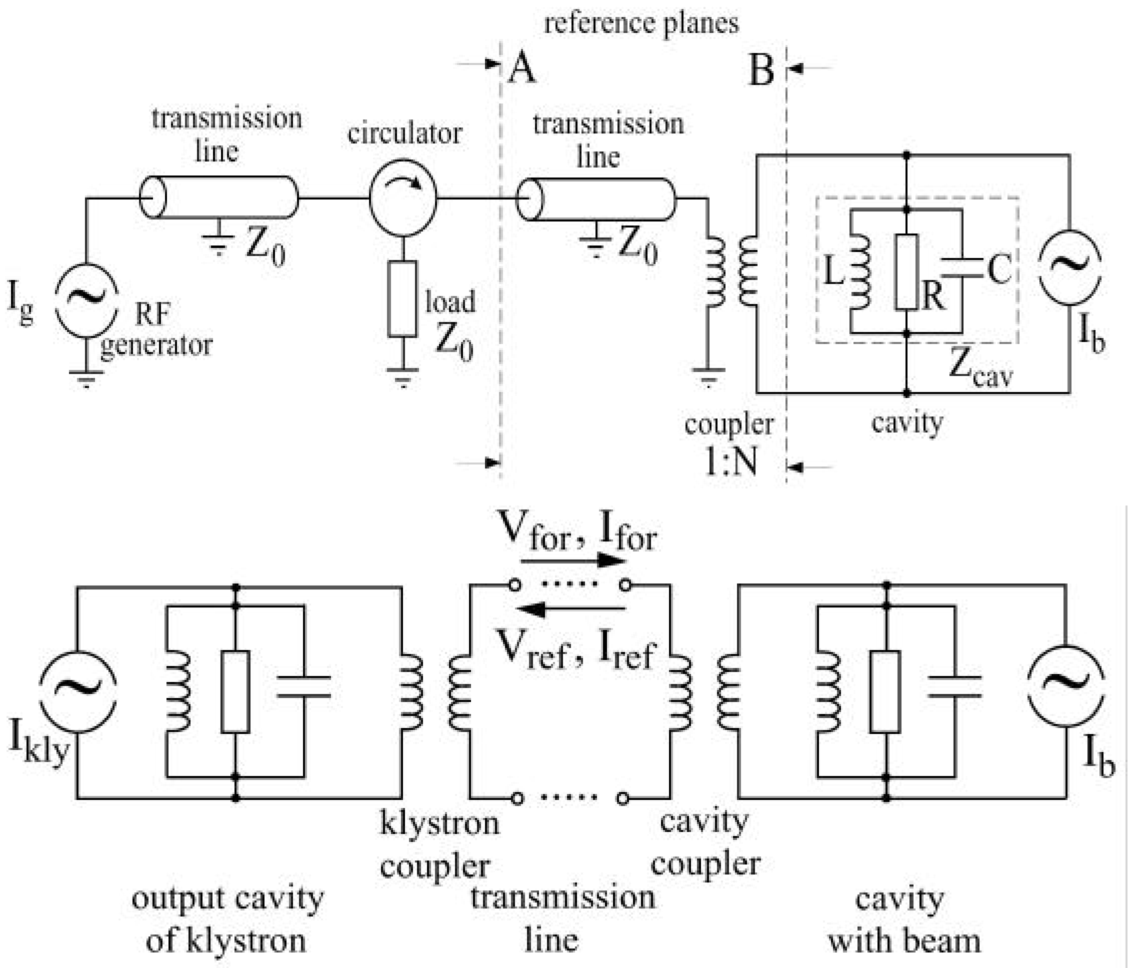


Relations for the surface fields to acclerating gradient:

E_{peak}/E_{acc} = 1,98 **minimize this to reduce field emission**

Þ **B_{peak}/E_{acc} = 4,17 [mT]/[MV/m]** **minimize because of maximum critical field of the superconductor**

Equivalent circuit of generator-cavity-beam system



- Cavity is a resonance circuit
- R is called the shunt impedance, this is **NOT** R_{surf} !
- Coupler is like a transformer (1:N, N>>1)

Equivalent circuit formulas

Cavity quality factor:

$$Q_0 = \frac{R_0}{\omega_0 L} \quad \text{with} \quad \omega_0 = 1/\sqrt{LC}$$

Coupler (external) quality factor:

$$Q_{ext} = \frac{R_{ext}}{\omega_0 L}$$

Loaded quality factor:

$$Q_{load} = \frac{R_{load}}{\omega_0 L}, \qquad \frac{1}{Q_{load}} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$$

Decay time :

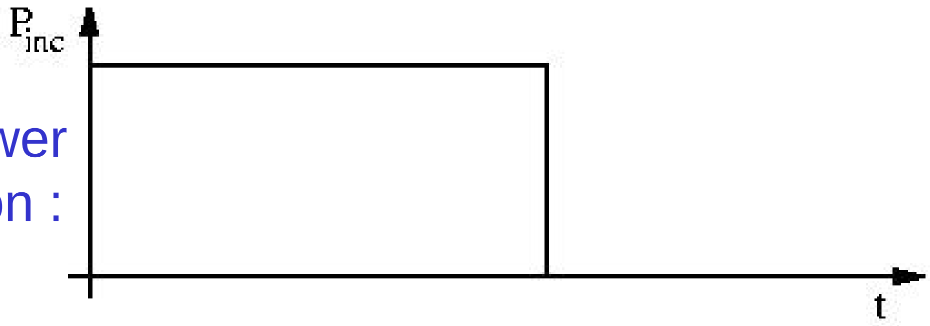
$$\tau = \frac{2Q_{load}}{\omega_0}$$

Coupling factor :

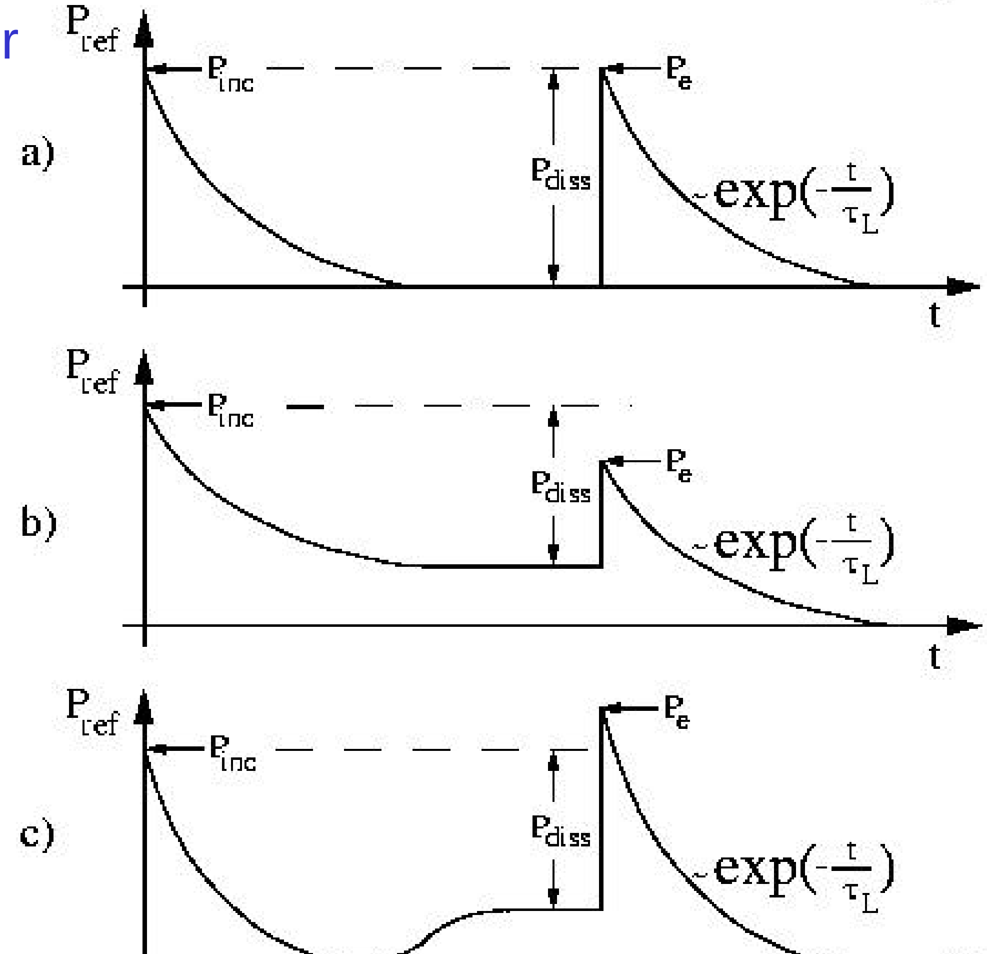
$$\beta_c = \frac{Q_0}{Q_{ext}}$$

Acceleration of a bunched beam

Incident power from Klystron :



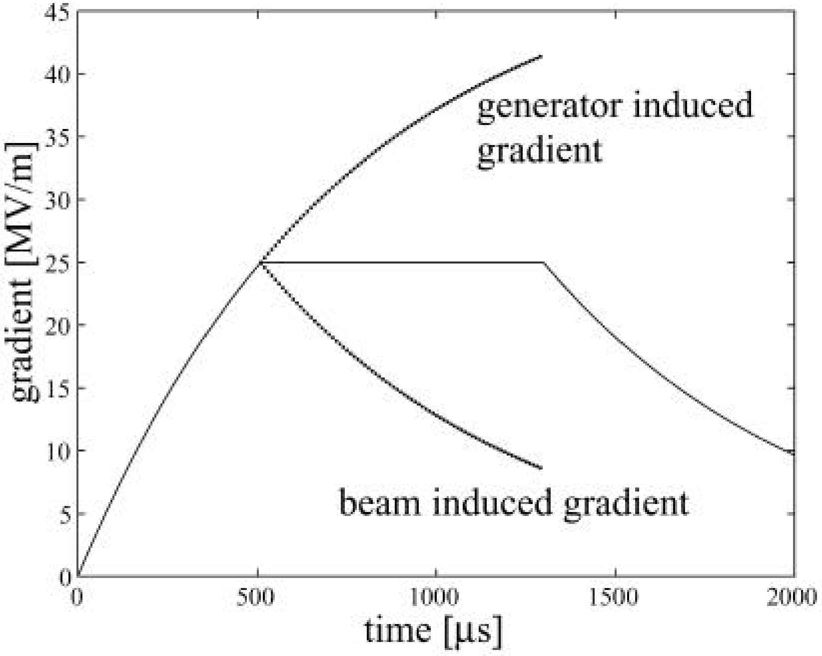
Reflected power to Klystron :



β = 1

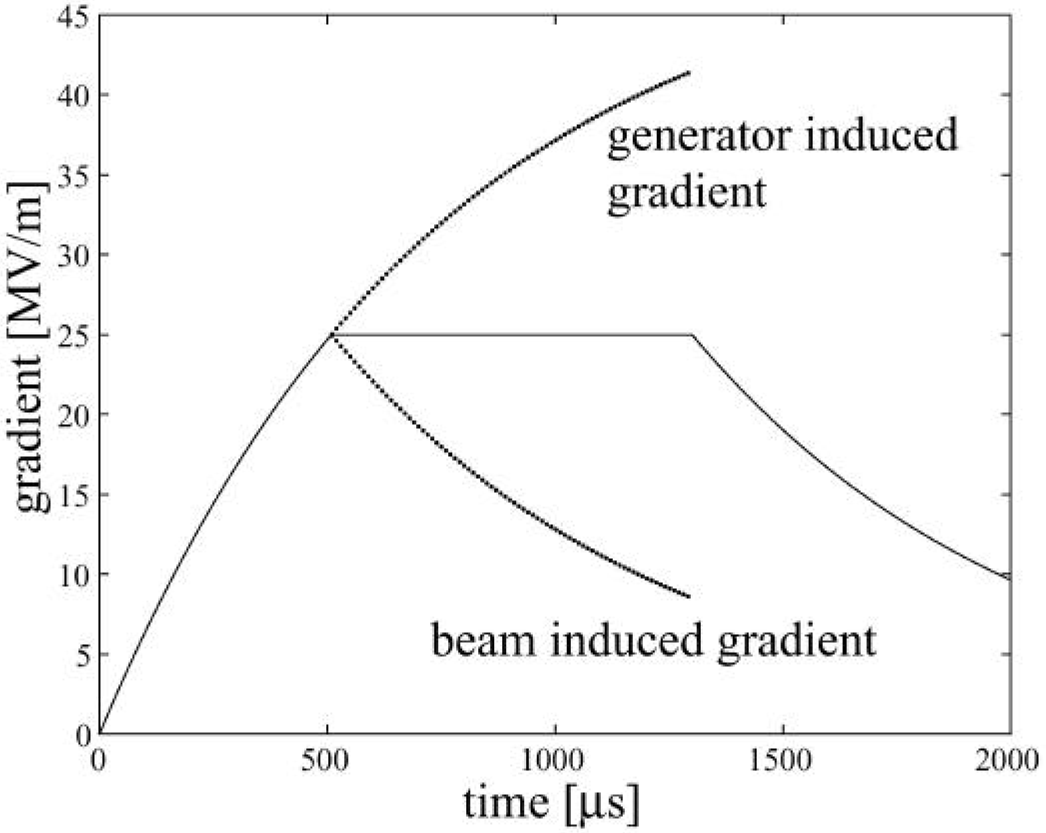
β < 1

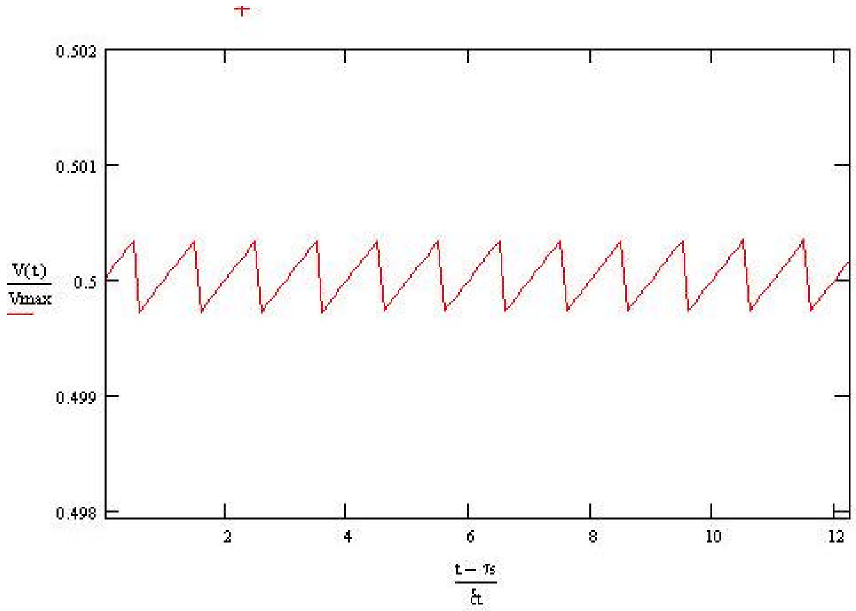
β> 1



For beam operation

Acceleration of a bunched beam (see MathCAD example)



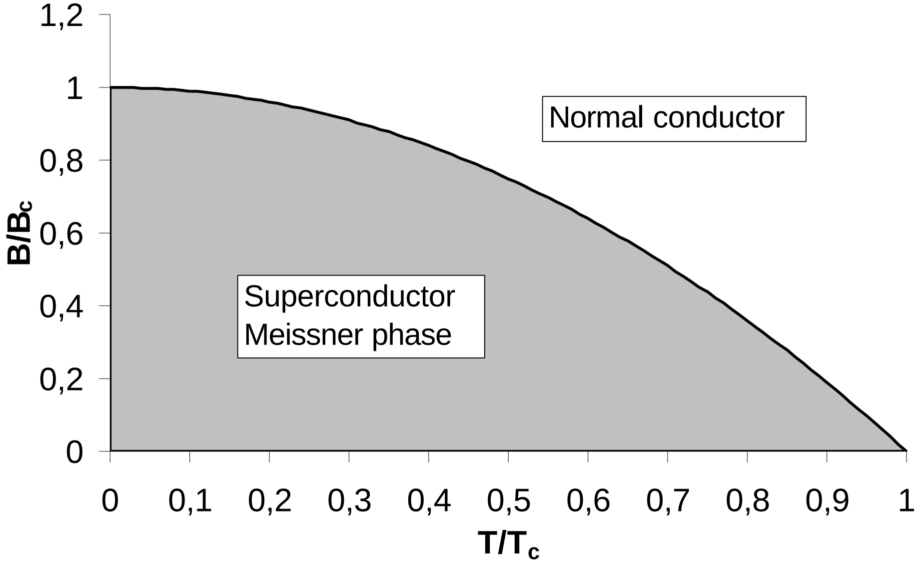


- Let's see what happens, when the Q_{ext} is wrong…

Outline of the lecture

- RF cavities
- Superconductivity basics
- RF superconductivity
- Limitations of superconducting RF (SRF) cavities

Superconductors in magnetic fields (Type I)



$$G_n - G_s = \frac{1}{2\mu_0} B_c^2$$

Temperature dependence:

$$B_c(T) = B_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

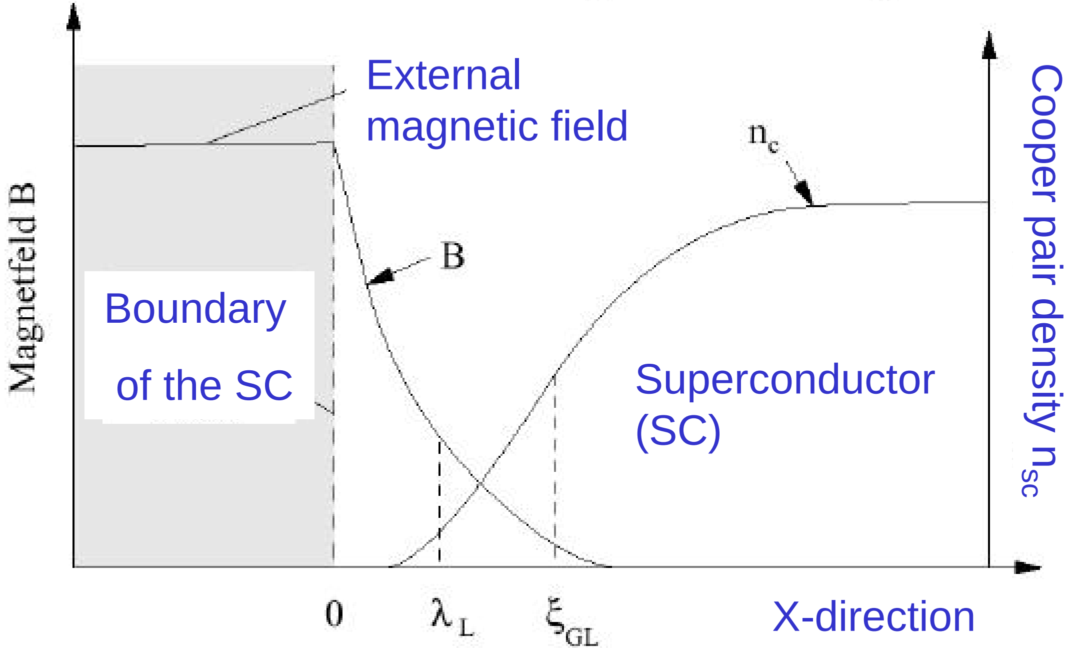
Penetration depth:

$$B(x) = B(0)e^{-\frac{x}{\lambda_L}} \qquad \lambda_L = \sqrt{\frac{m}{\mu_0 n_s c^2}}$$

$$\lambda_L(T) = \lambda(0)\left(1 - \left(\frac{T}{T_c}\right)^4\right)^{-\frac{1}{2}}$$

Coherence length:

$$\xi_0 = \frac{\hbar v_F}{\Delta}$$



External magnetic field

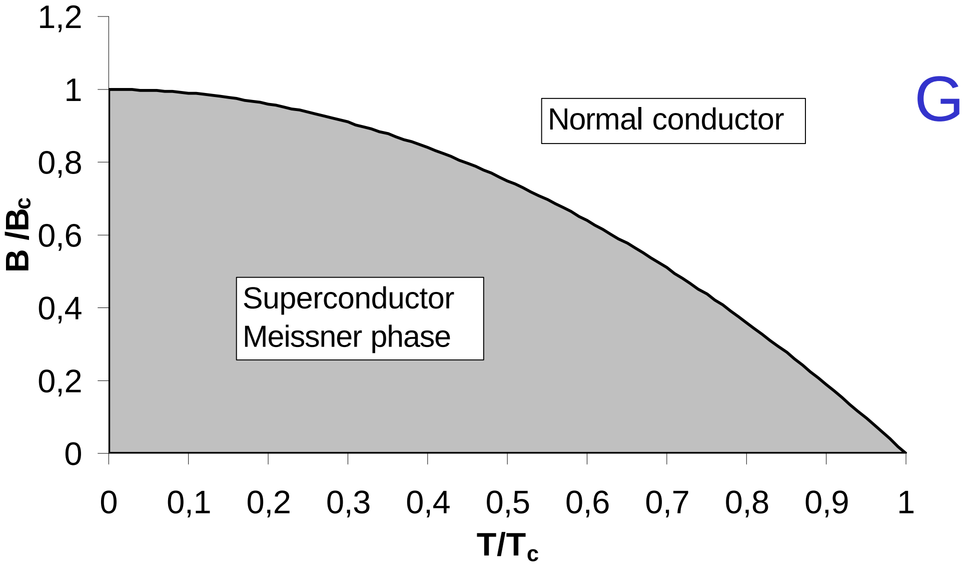
Boundary of the SC

Superconductor (SC)

Cooper pair density n$_{SC}$

X-direction

Superconductors in magnetic fields (Typ II)

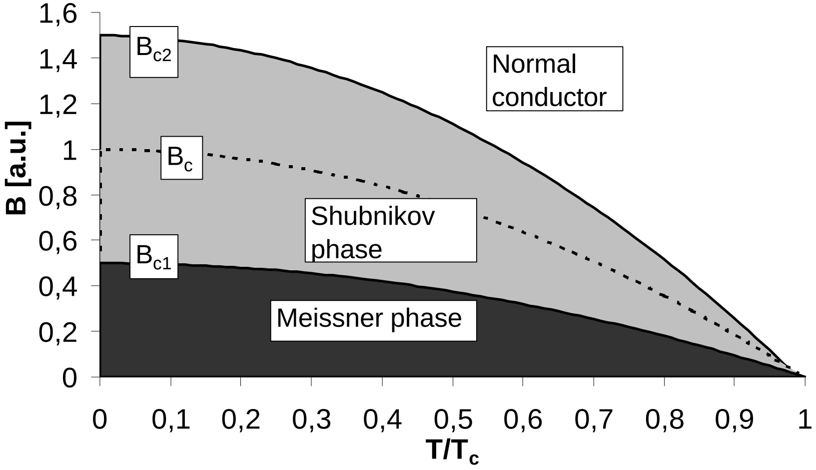


Ginzburg-Landau-Parameter:

$$\kappa = \frac{\lambda_L}{\xi_0}$$

Type I: $\kappa < \frac{1}{\sqrt{2}}$

Type II: $\kappa > \frac{1}{\sqrt{2}}$



Flux penetration into a superconductor

Electron holography is used to make magnetic fluxons visible (Tonomura et al.)

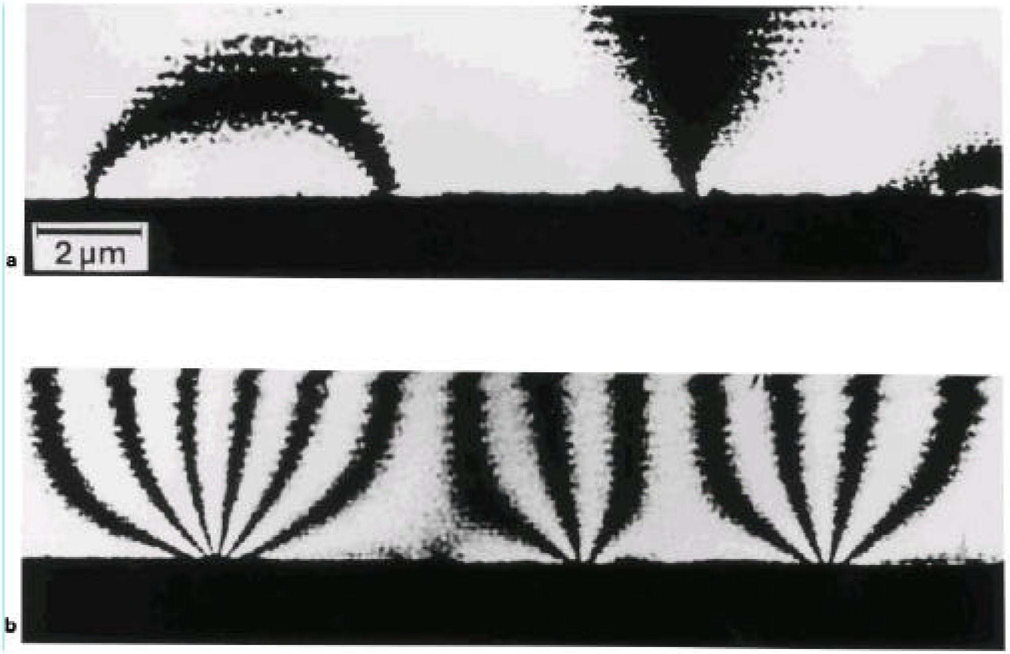


Fig. 6. Interference micrographs of magnetic lines of force penetrating superconducting Pb films: (a) film thickness 0·2 μm; (b) film thickness 1·0 μm.

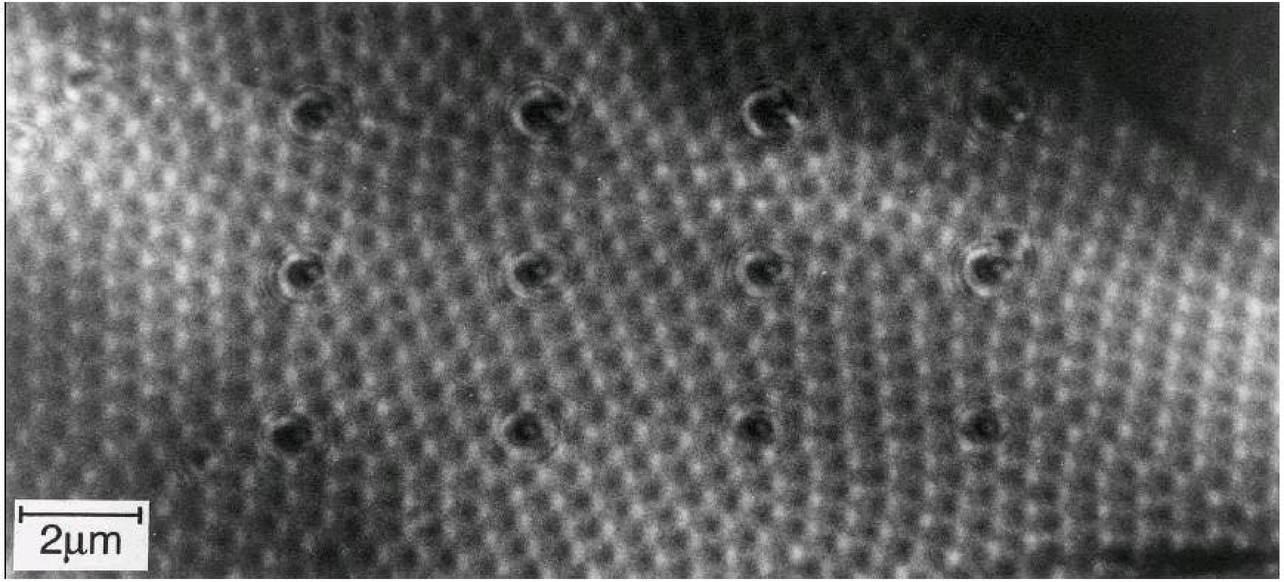


Fig. 16. Vortex configuration near black defects ($T = 7{\cdot}5$ K, $H = 75$ gauss).

Fluxons stick to defects !

This is good for magnets, but bad for cavities (check homework).

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

Critical magnetic field for the RF case

- RF field at 1,3 GHz is on for less than 10^{-9} s
- If there are no nucleation centers (surface defects...) the penetration of the magnetic field can be delayed. Superheating!

Superheating fields:

$$\begin{aligned} B_{sh} &= 0.75 B_c \quad && \text{for} \quad \kappa \gg 1 \\ B_{sh} &= 1.2 B_c && \text{for} \quad \kappa \approx 1 \\ B_{sh} &= \frac{1}{\sqrt{\kappa}} B_c && \text{for} \quad \kappa \ll 1 \end{aligned}$$

Niobium properties:

Critical temperature T_c	9.2 K
Coherence length ξ_0	39 nm
London penetration depth λ_L	30 nm
GL parameter κ	0.8

Þ Theoretical accelerating field limits

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?

Outline of the lecture

- RF cavities
- Superconductivity basics
- RF superconductivity
- Limitations of superconducting RF (SRF) cavities

RF superconductivity

The superconducting Cooper pairs have inertia. Therefore the unpaired normalconducting ‘feel’ also a part of the electromagnetic RF (ac) fields.

Þ Superconductors have for temperatures T>0 K a surface resistance!

Electric conductivity and Surface resistance

Normalconducting electrons:

$$n \propto \exp(-E_g/k_B T)$$

$$j_n = \sigma_n E_0 exp(-i\omega t)$$

Superconducting electrons:

$$m_c \dot{v}_c = -2eE_0 exp(-i\omega t) \quad \Rightarrow \quad j_c = i\frac{n_c 4e^2}{m_c \omega} E_0 exp(-i\omega t)$$

Combine both nc and sc electrons:

Ohm's Law: $$j = j_n + j_c = \sigma E_0 exp(-i\omega t)$$

Electric conductivity:

$$\sigma = \sigma_n + i\sigma_c \quad \text{with} \quad \sigma_c = \frac{n_c 4e^2}{m_c \omega}$$

Electric conductivity and Surface resistance

Surface resistance (analogous to skin depth):

$$R_{surf} = Re\left(\frac{1}{\sigma\lambda_L}\right) = \frac{1}{\lambda_L} \cdot \frac{\sigma_n}{\sigma_n^2 + \sigma_c^2}$$

Surface resistance for superconductors in BCS theory:

$$R_{\mathrm{BCS}} = \frac{C}{T} f^2 \, \sigma_n \, \Lambda^3 \, \exp(-1.76 \, T_c/T)$$

Effective penetration depth: $\Lambda = \lambda_L \sqrt{1 + \xi_0/\ell}$

- Resistance depends
  - strongly on the temperature, we need 2 K
  - quadratically on frequency: Limit for 3 GHz would be 30 MV/m.
  - on the mean free path, what purity do we need?

Surface resistance R_s

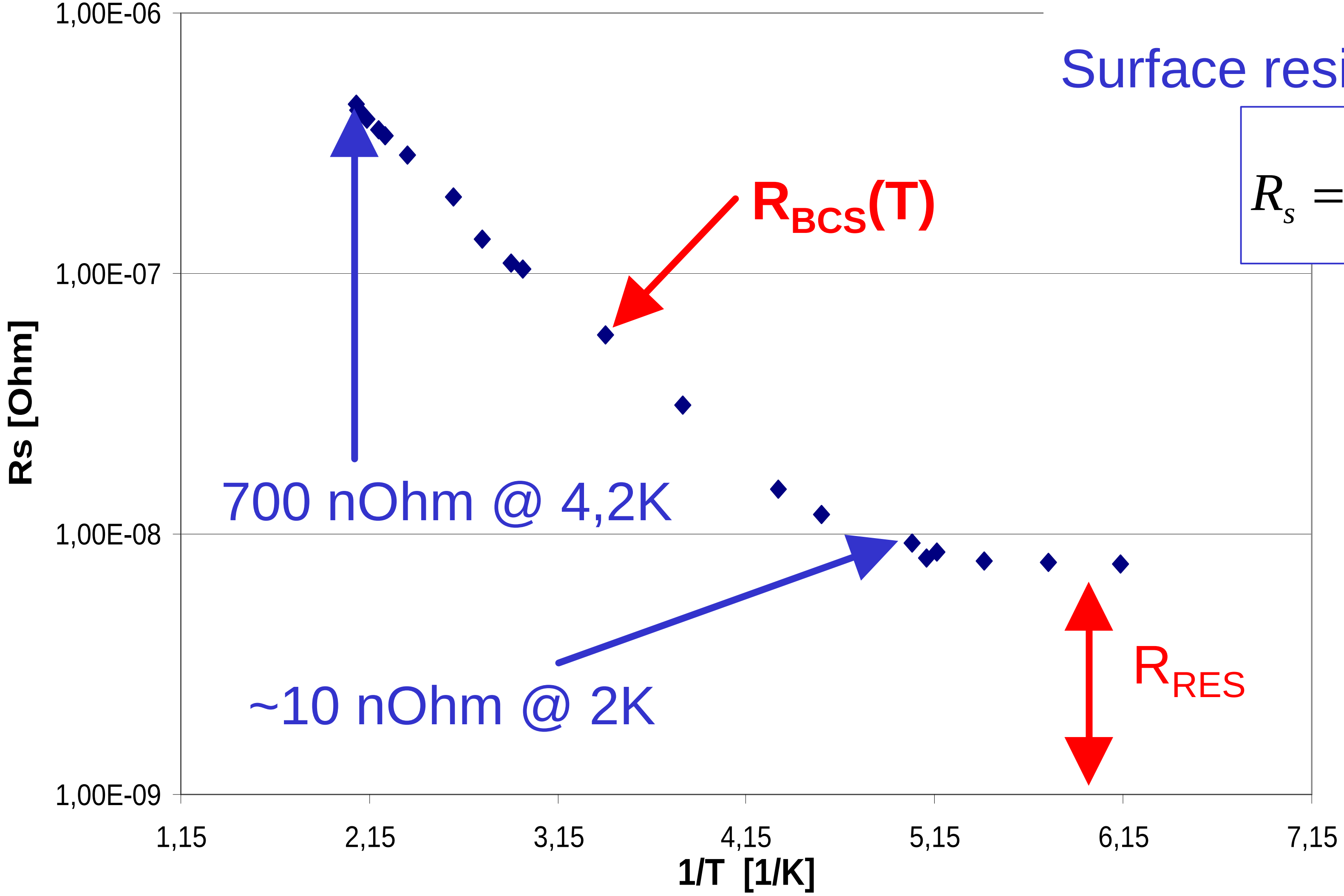
Geometry factor:

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

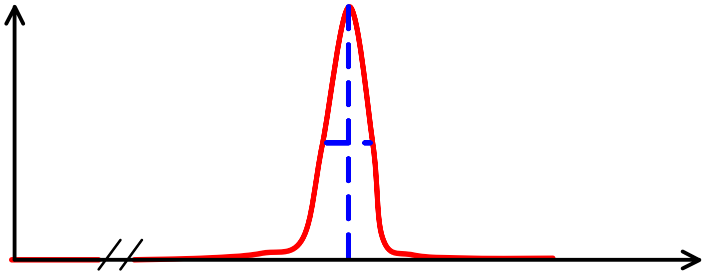
G = 270 Ohm

Surface resistance:

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



Cavities for TESLA -RF surface resistance



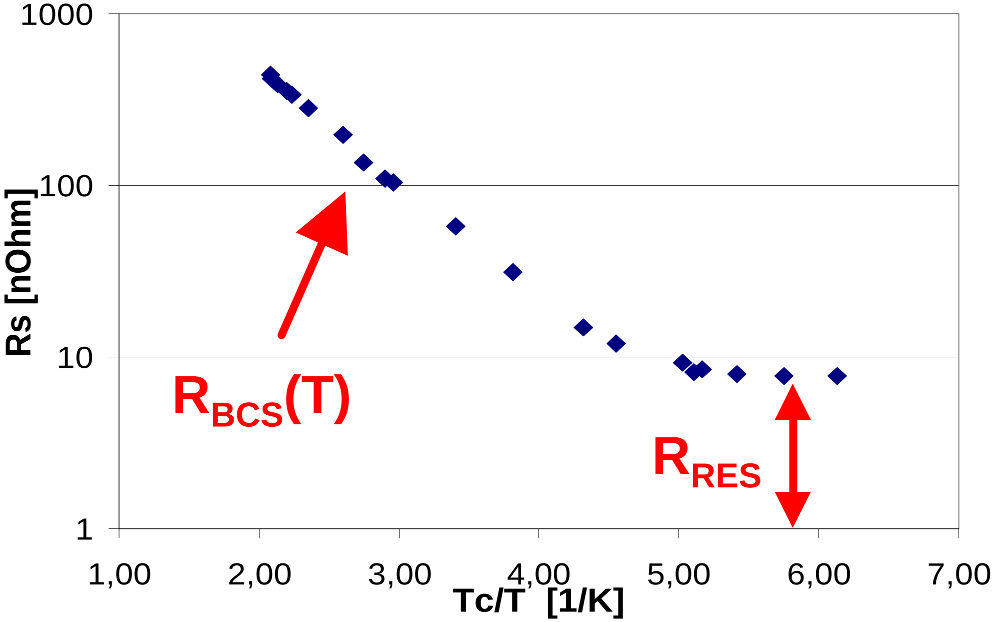
$$f_o = 1.300.000.000\,\mathrm{Hz}$$

Quality factor:

$$Q_o = \frac{f}{\Delta f} = \frac{270\ \mathrm{Ohm}}{R_S}$$

RF surface resistance:

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



‘Natural’ Bandwidth:

$\Delta f \approx 0{,}1$ Hz

$\Rightarrow$ **$Q_0 \approx 10^{10}$**

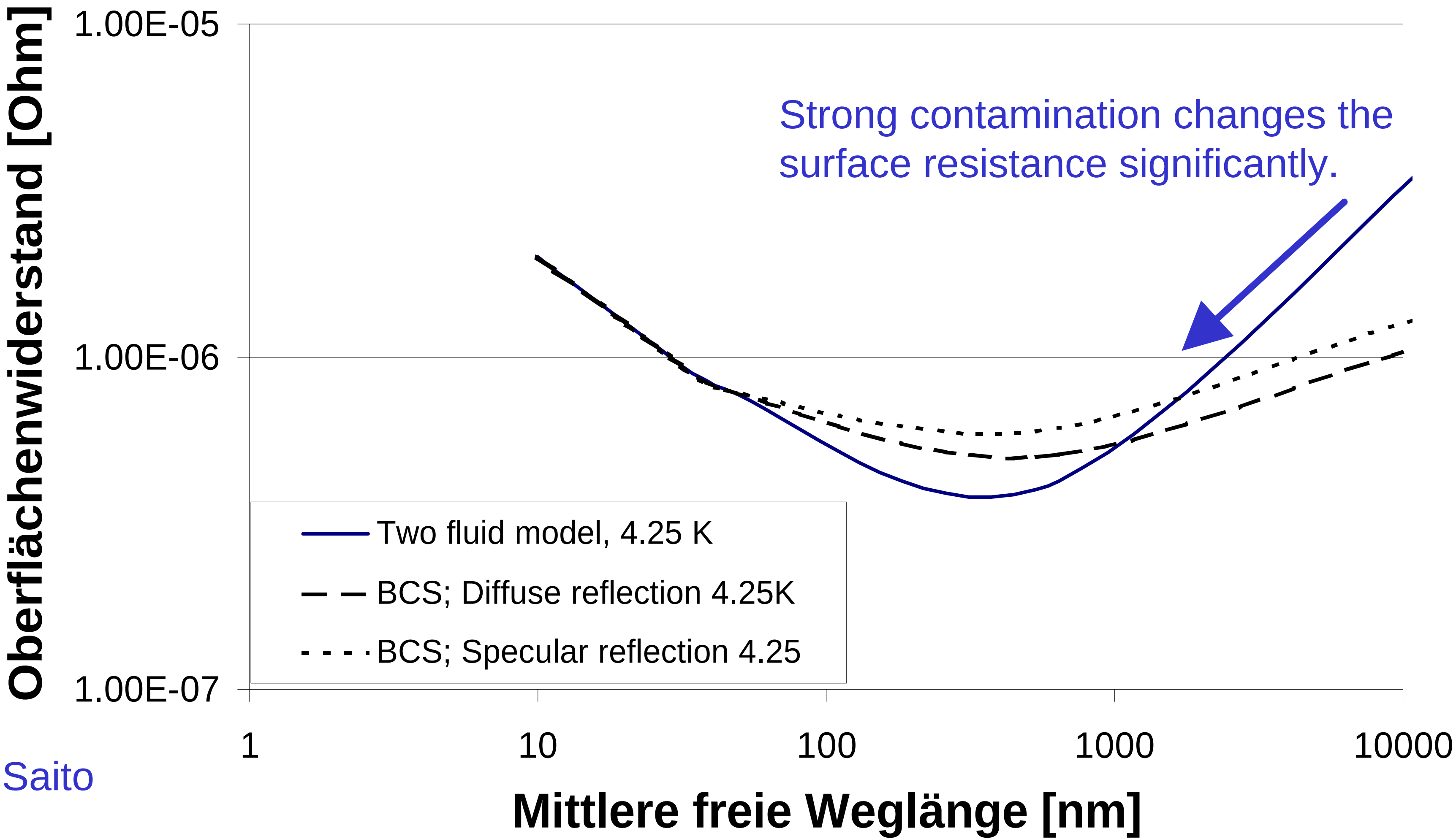
Line width with main coupler

$\Delta f \approx 300$ Hz

$\Rightarrow$ **$Q_0 \approx 10^{6}$**

Surface resistance and mean free path

In the two-fluid model: $R_{BCS}(\ell) \propto \left(1+\frac{\xi_0}{\ell}\right)^{\frac{3}{2}} \cdot \ell$



Strong contamination changes the surface resistance significantly.

Kneisel, Saito

Surface resistance and electric conductivity

Normalconductor (Copper): $R_s = \frac{1}{s d}$ At 1 GHz: $s = 1\, mm$

$R_s = 4\, m\Omega$

Superconductor (Niob):

$$j = j_n + j_s = (s_n - i s_s)E$$

$$Z_s = R_s + iX_s$$

σ_n Conductivity of normal electrons,
σ_s Cooperpairs

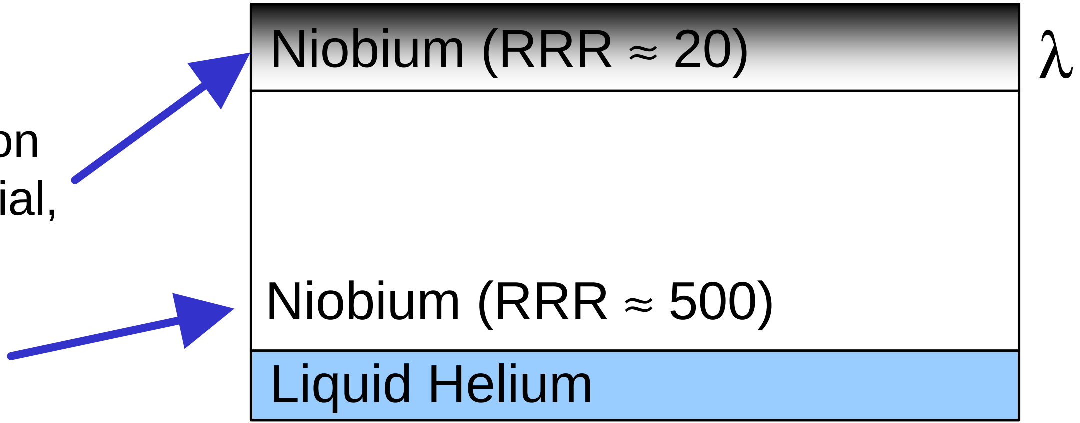
$$s_s >> s_n$$

$$R_s = \mathrm{Re}(Z_s) \propto s_1$$

$$\propto l$$

Mean free path

Þ Ideal superconductor for RF applicaton
1. Layer: slightly contaminated material,
small surface resistance
2. Layer: very pure metal,
high thermal conductivity



Residual surface resistance

- Is not fully theoretically understood, but depends strongly on:
  - Surface contamination
    - Gas layers
    - Dust
  - Lattice imperfections
  - External magnetic field. Remember:

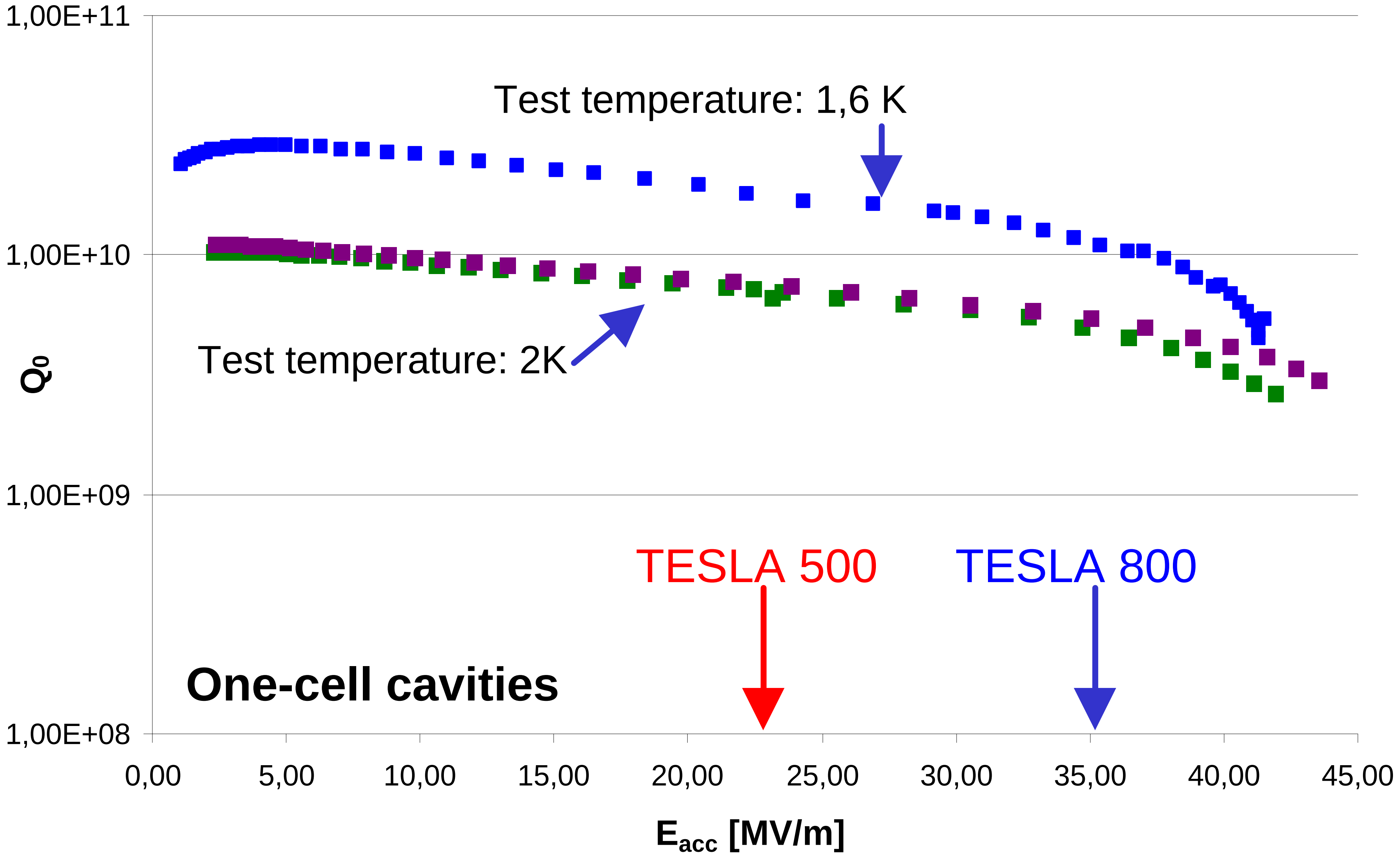
$$R_{fl} = \eta \frac{B_{ext}}{B_{c2}} R_{surf,nc}$$

  - We have to shield sc cavities from magnetic fields to have a low surface resistance!
  - Typically: R_{res} = 5 nOhm
  - Lowest: R_{res} = 1-2 nOhm

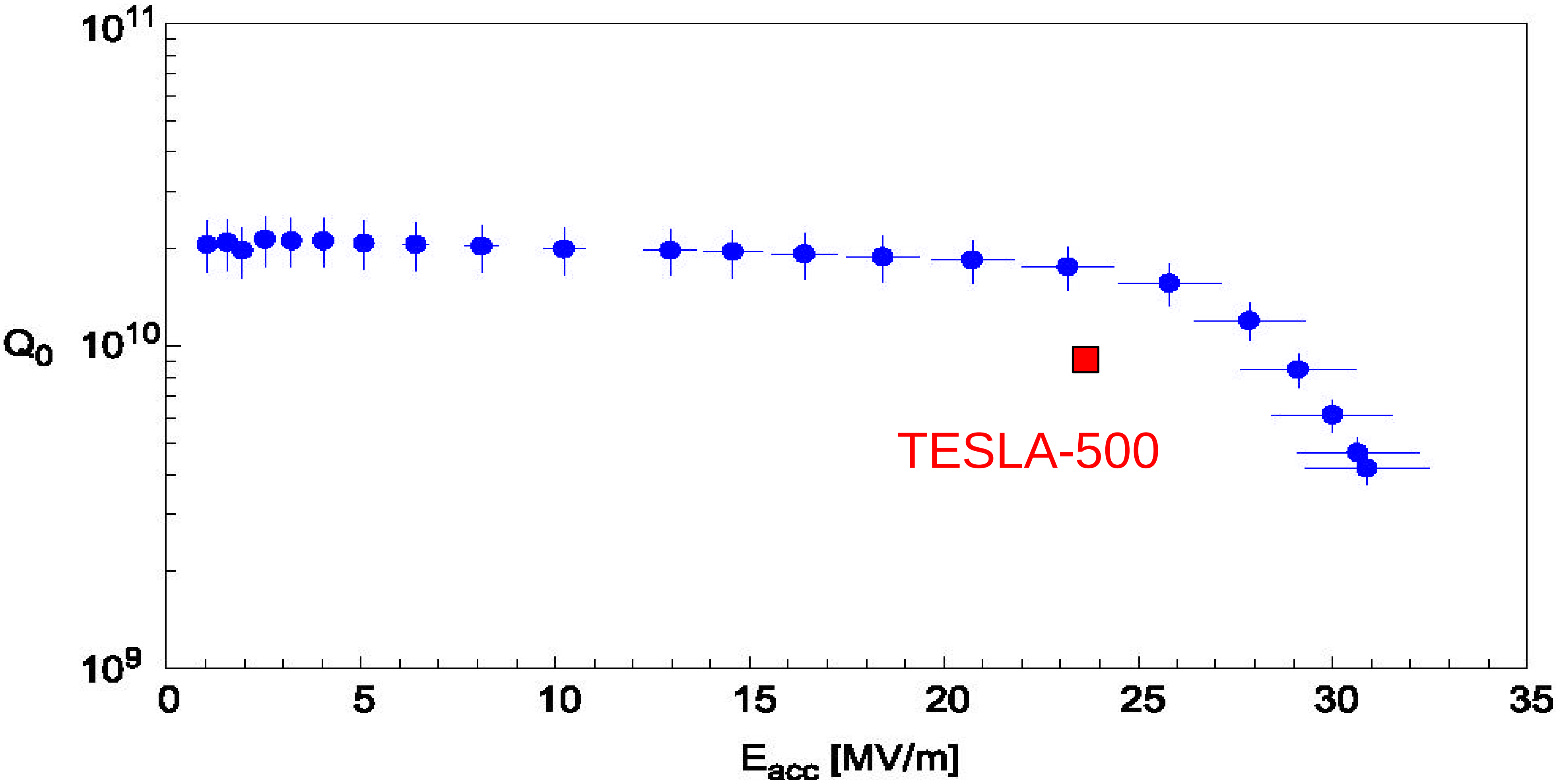
Surface resistance and accelerating gradient

- One usually measures the $Q(E_{acc})$ curve:
  - $Q_0 \sim (1/ R_{surf})$
  - Quality factor will tell you how much you have to pay for the cooling power
  - Depends on the acclerating gradient e.g. field emission
  - Helps to understand the loss mechanisms especially is supported by temperature mapping

Surface resistance and accelerating gradient



Example for an excitation curve of a TESLA cavitiy



Specification:

E_{acc} = 23,4 MV/m @ $Q_0 = 1 \cdot 10^{10}$ for TESLA-500
E_{acc} = 35 MV/m @ $Q_0 = 5 \cdot 10^{9}$ for TESLA-800

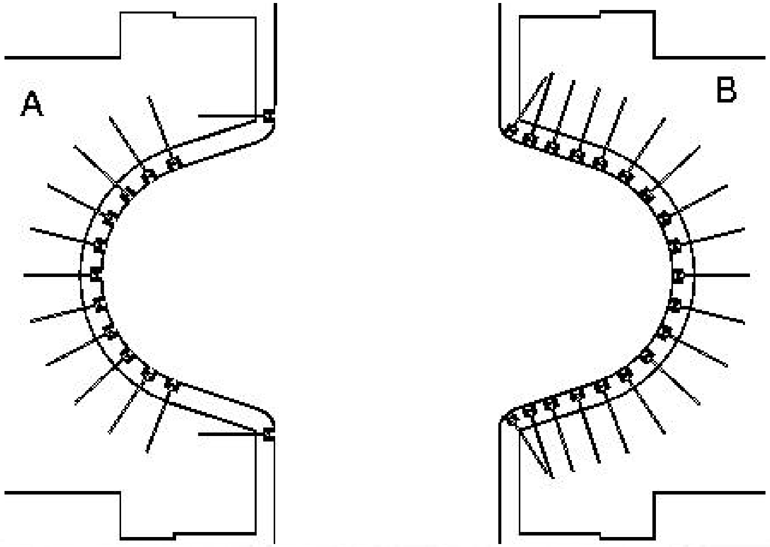
Temperature mapping system

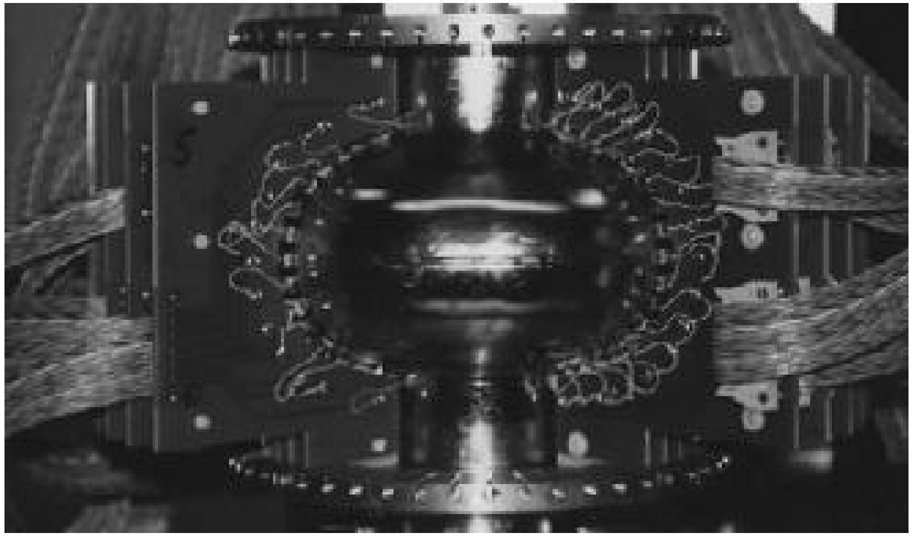
Temperature mapping is a very important tool to understand the loss mechanisms in superconducting cavities.

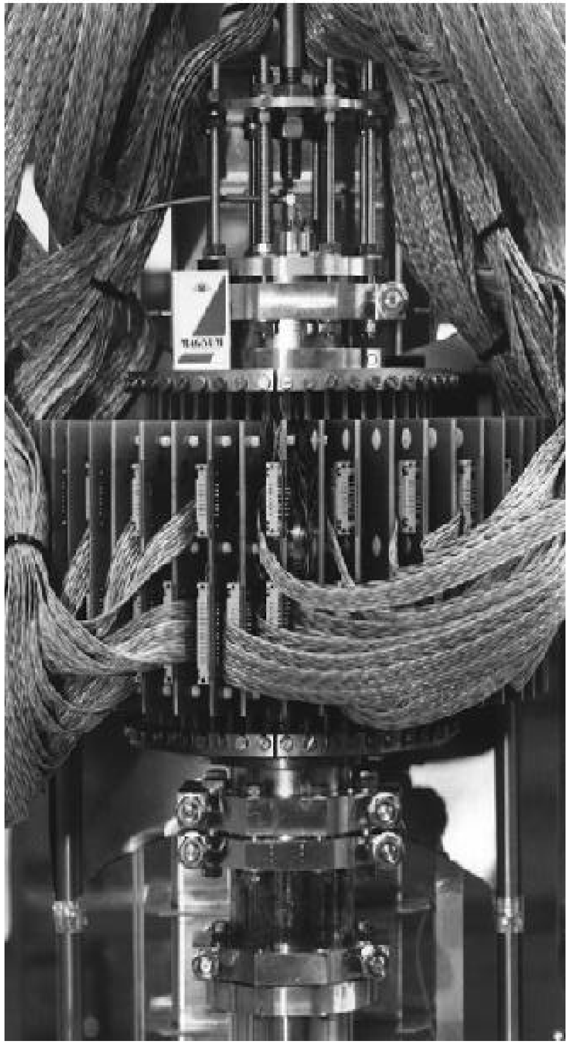
All loss mechanisms have typical signatures:

-local heating for local defects, multipacting and field emission

- global heating like in the case of high field enhanced surface resistance







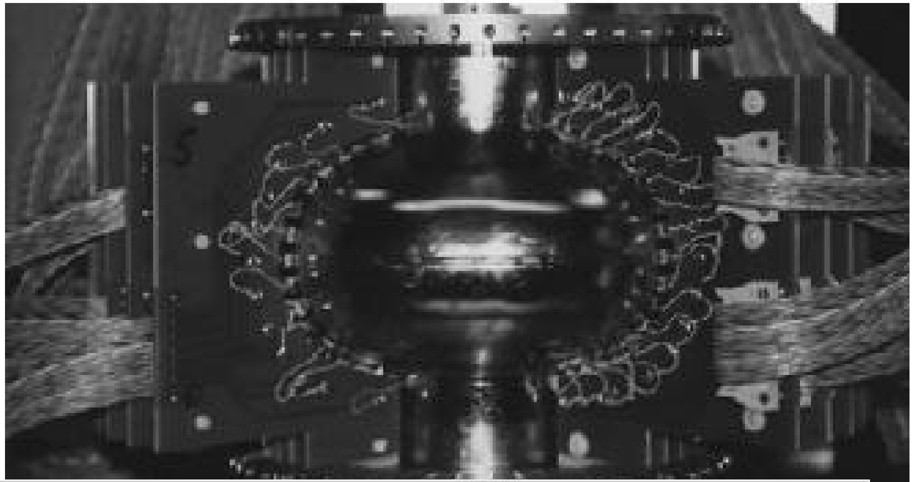
Temperature mapping system

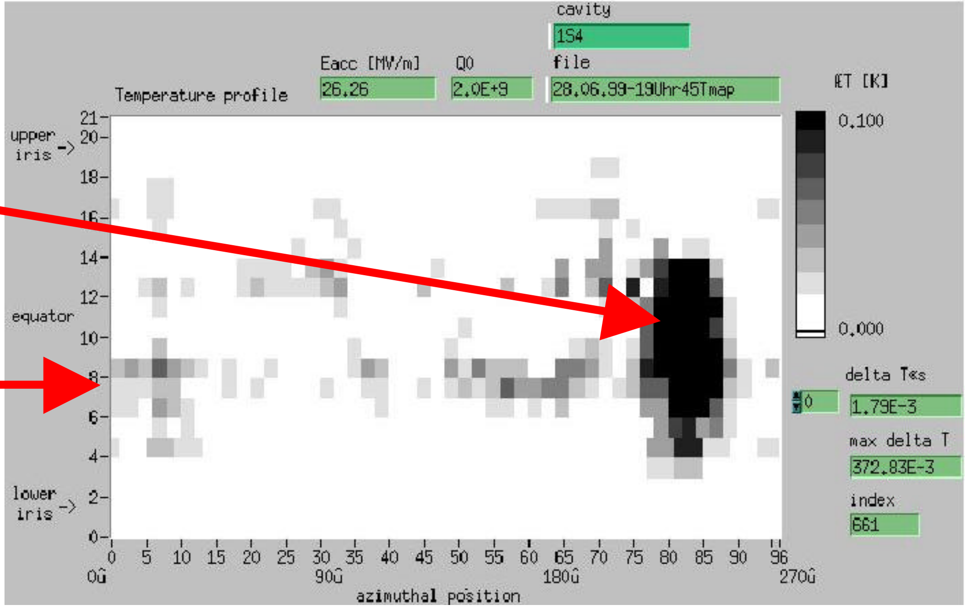
Example of a
Temperature mapping:

-the picture shows a Mercator projection of a single-cell cavity

-strong localised heating spot on the equator

-another band of heating around the equator in the high magnetic field (high current) region





cavity 1S4

Eacc [MV/m] 26.26

Q0 2.0E+9

file 28.06.99-19Uhr45Tmap

delta T«s 1.79E-3

max delta T 372.83E-3

index 661

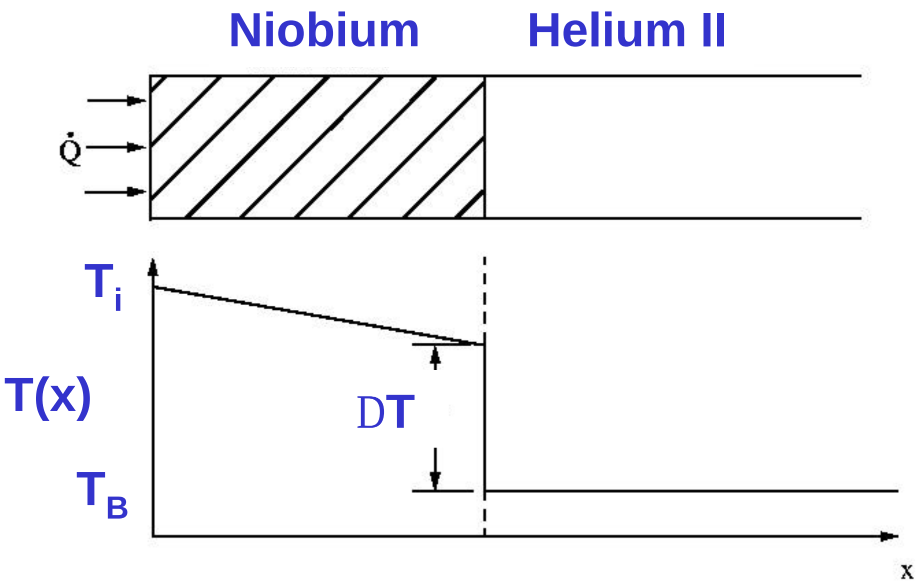
Outline of the lecture

- RF cavities
- Superconductivity basics
- RF superconductivity
- Limitations of SRF cavities

Limitations of SRF cavities

- Surface and material science
- Defects - Thermal conductivity
- Field emission
- Multipacting
- Increased surface resistance at high field

Thermal Conductivity and Defects



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

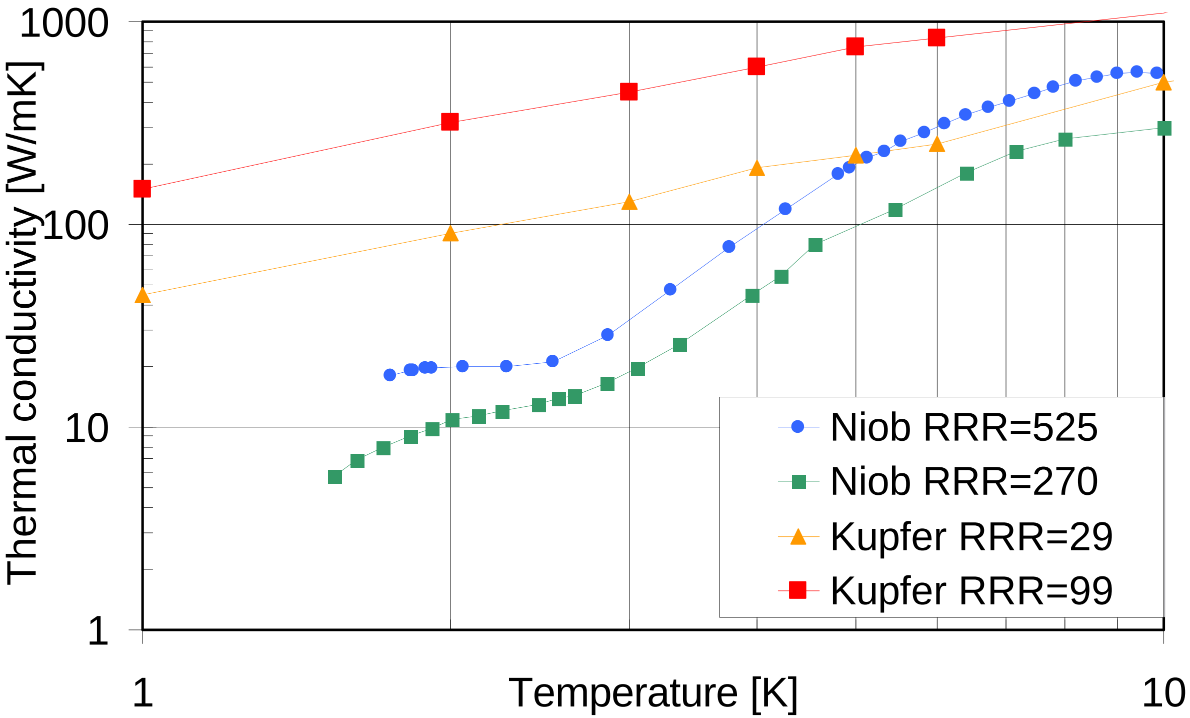
Temperature difference between inner surface and helium bath temperature:

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

Thermal and Kapitza conductivity

Thermal Conductivity and Defects

- Defects (e.g. foreign material inclusions) have to be very small (Factor 10^{-6})
- The thermal conductivity of niobium has to be high
  - ⇒ Very pure material
  - ⇒ This means a high RRR (residual resistivity ratio)



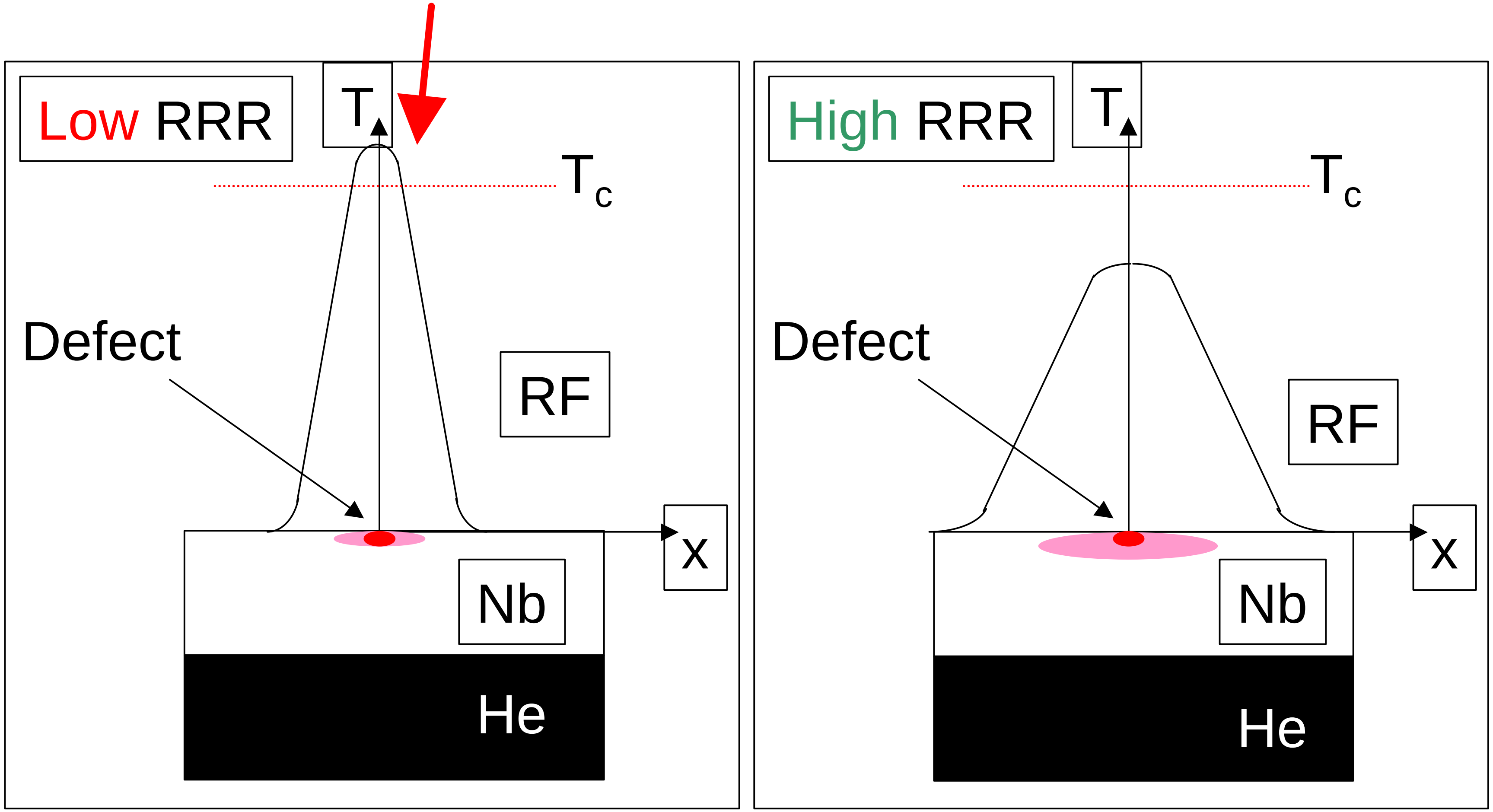
$$RRR = \frac{\rho_{nc}(300K)}{\rho_{nc}(4.2K)}$$

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

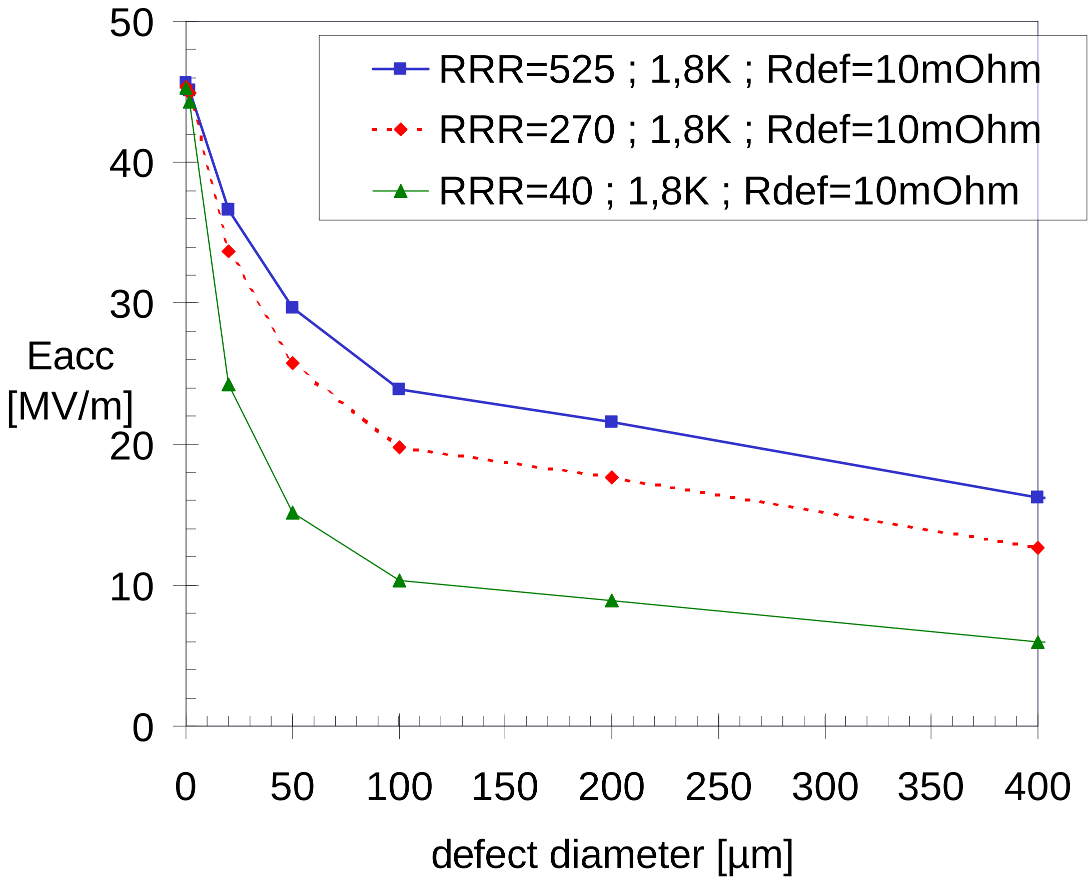
Rule of thumb

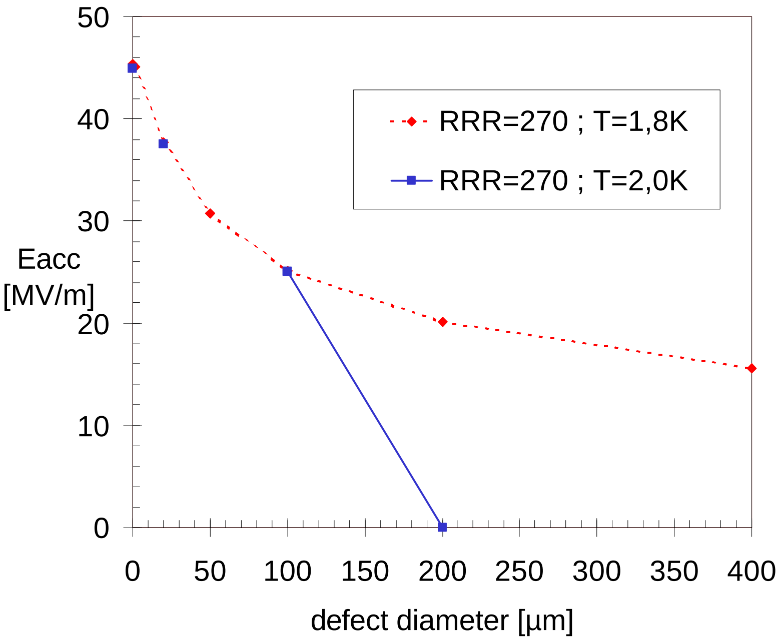
Stabilising normalconducting defects

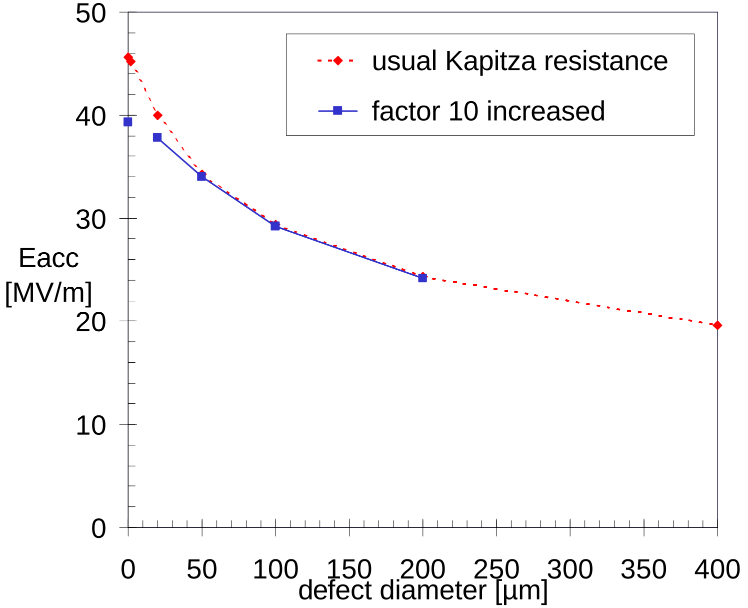
Thermal breakdown = QUENCH!



Numerical thermal model calculations

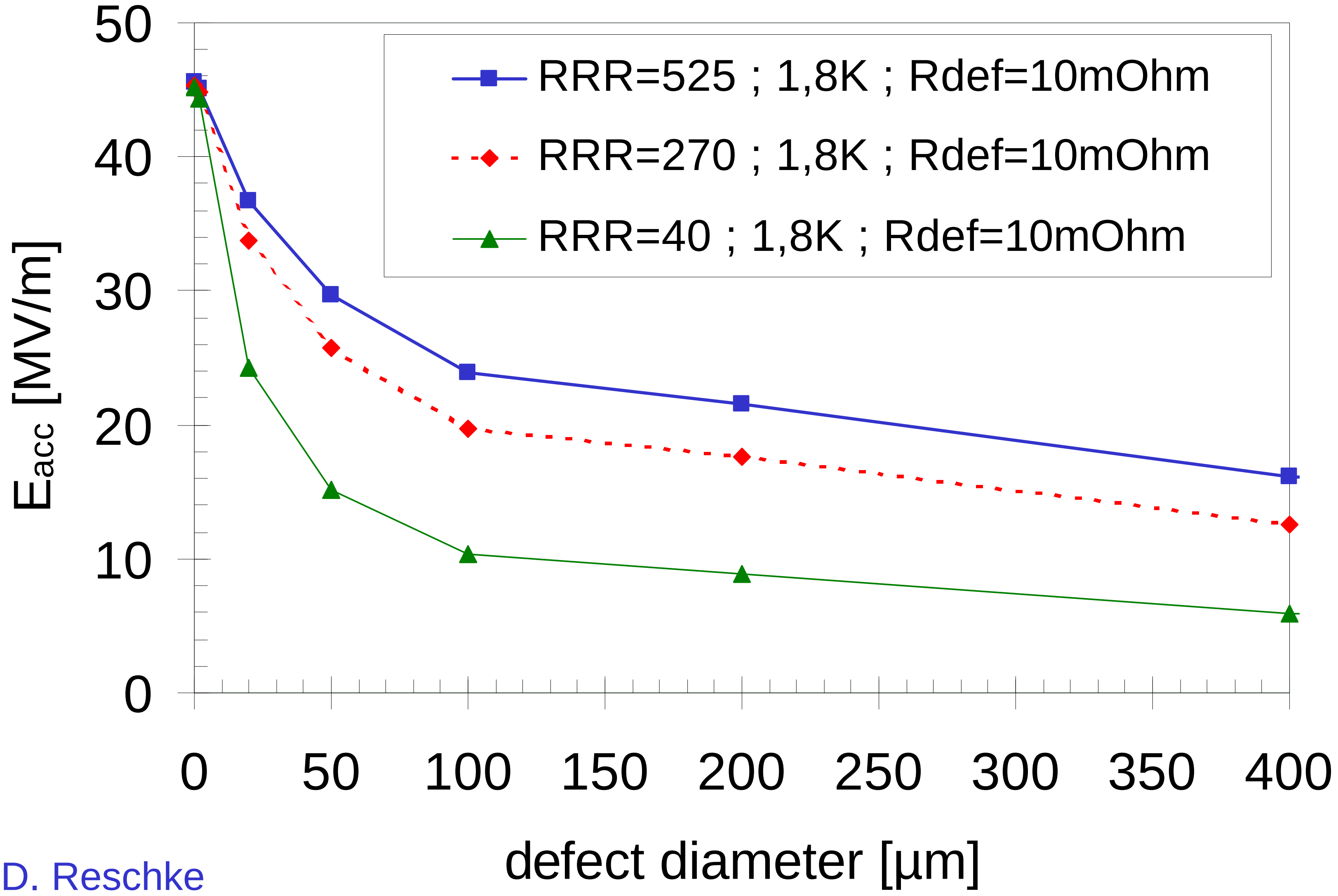






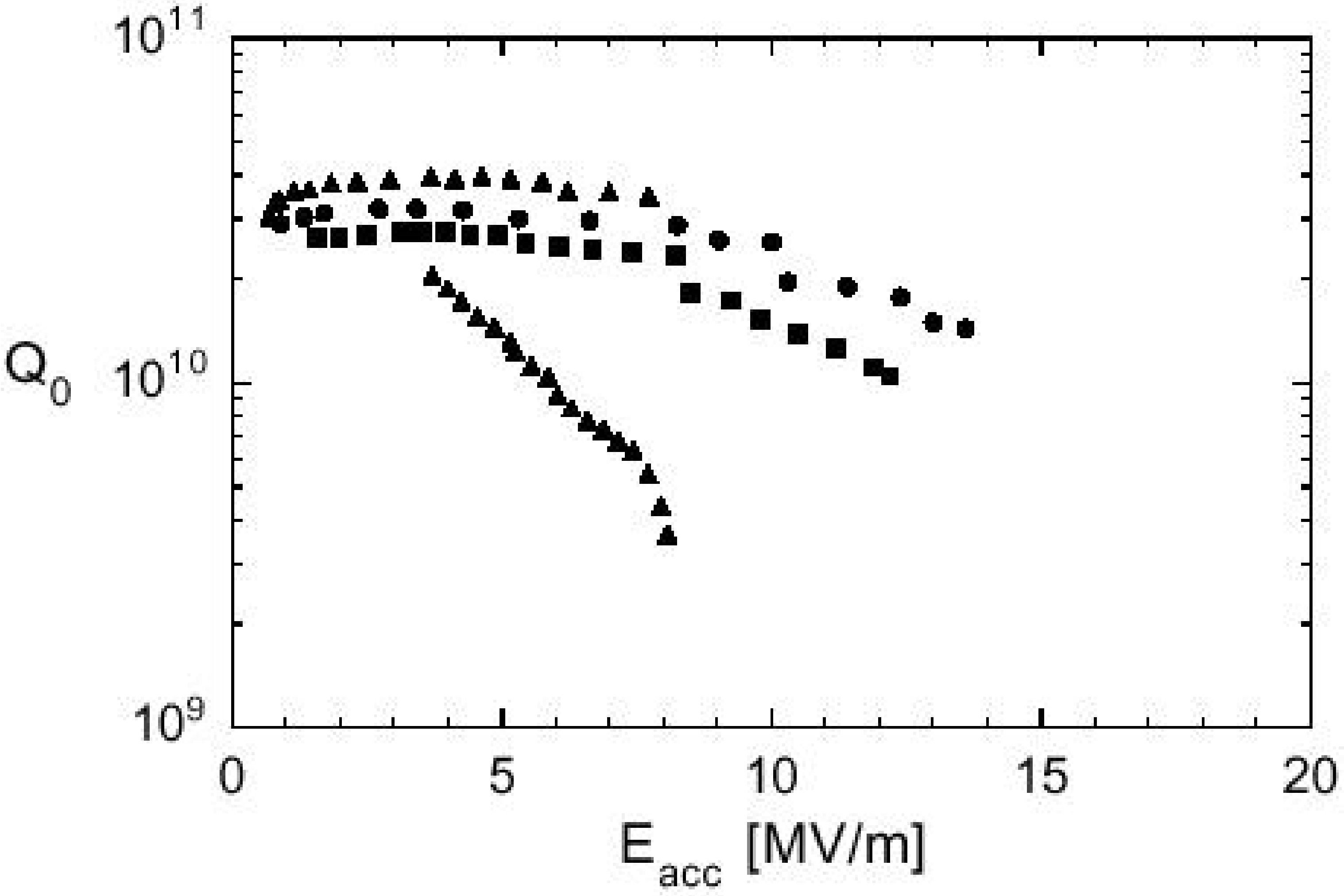
D. Reschke

Numerical thermal models



D. Reschke

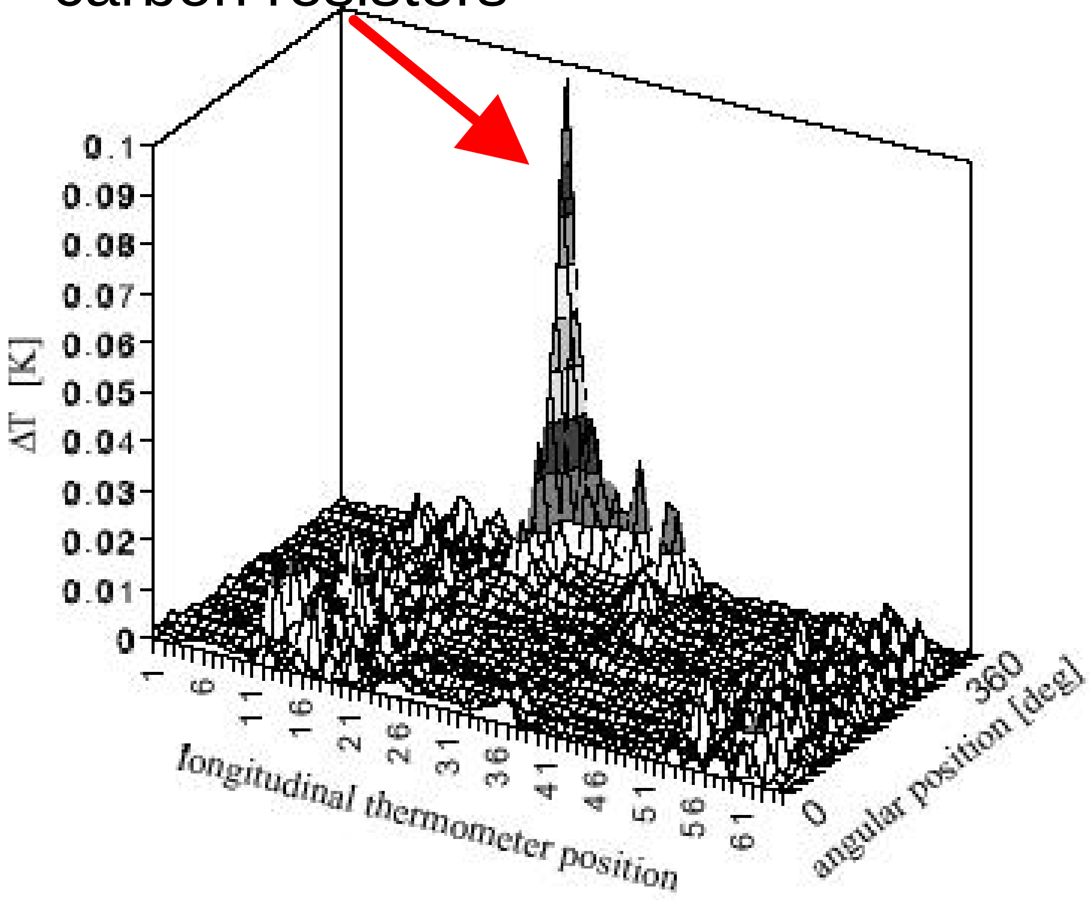
Examples of cavities with material defects



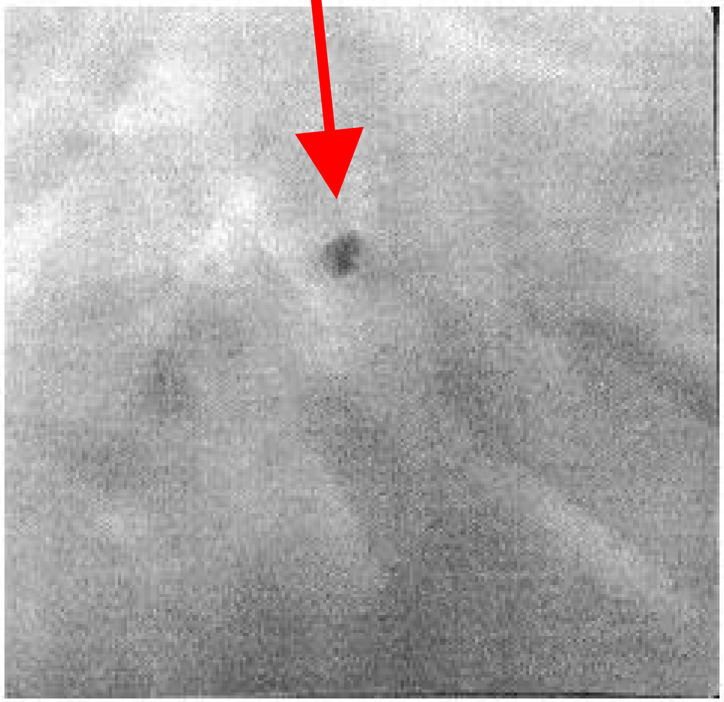
No eddy-current scanning was applied on the niobium sheets used in these cavities from the first production series.

Example of a material defect

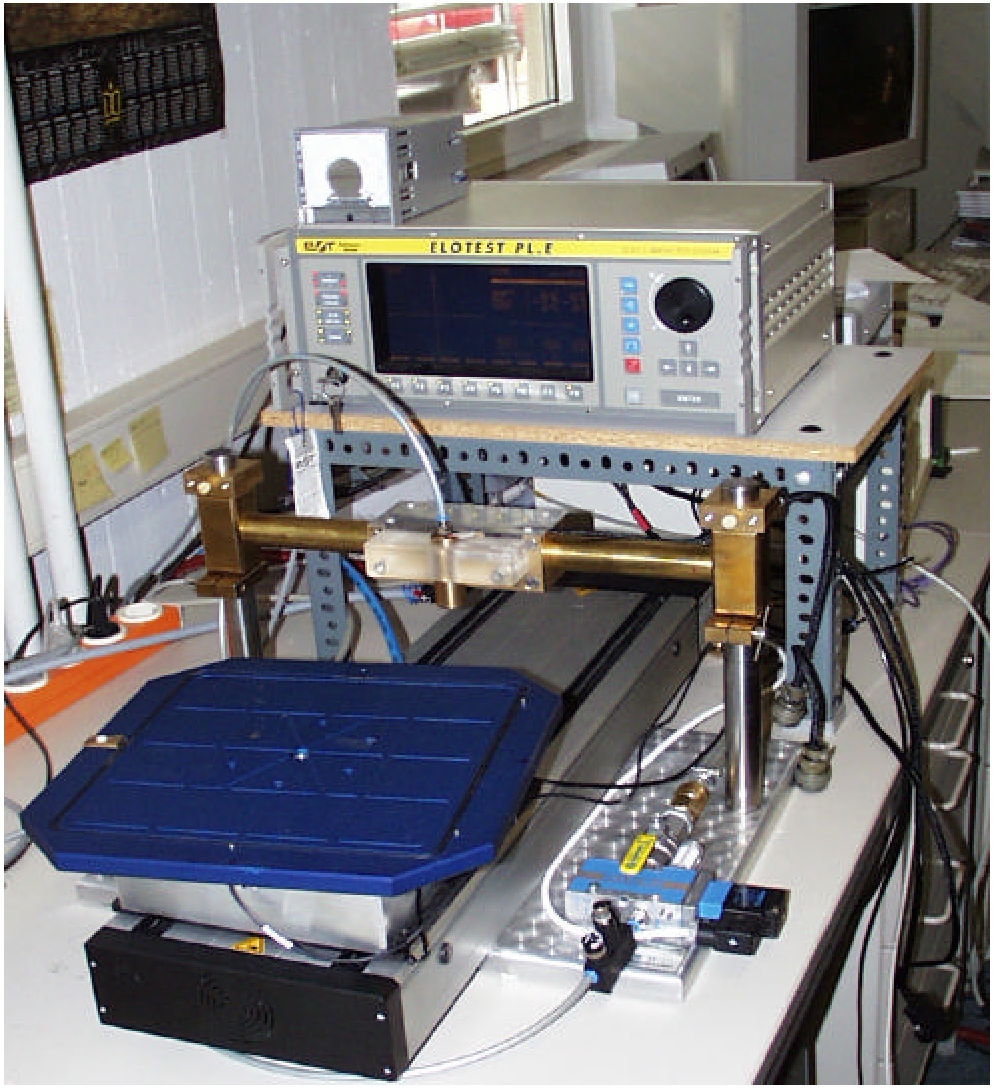
Heating on the outside surface measured with carbon resistors



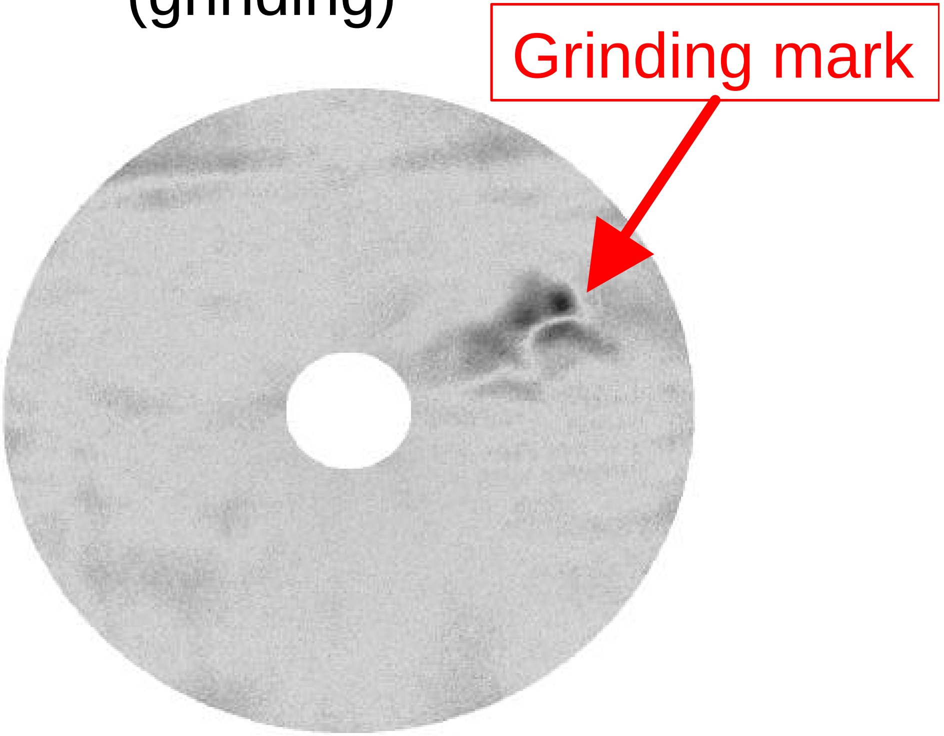
Defect found with X-ray technique: Tantalum



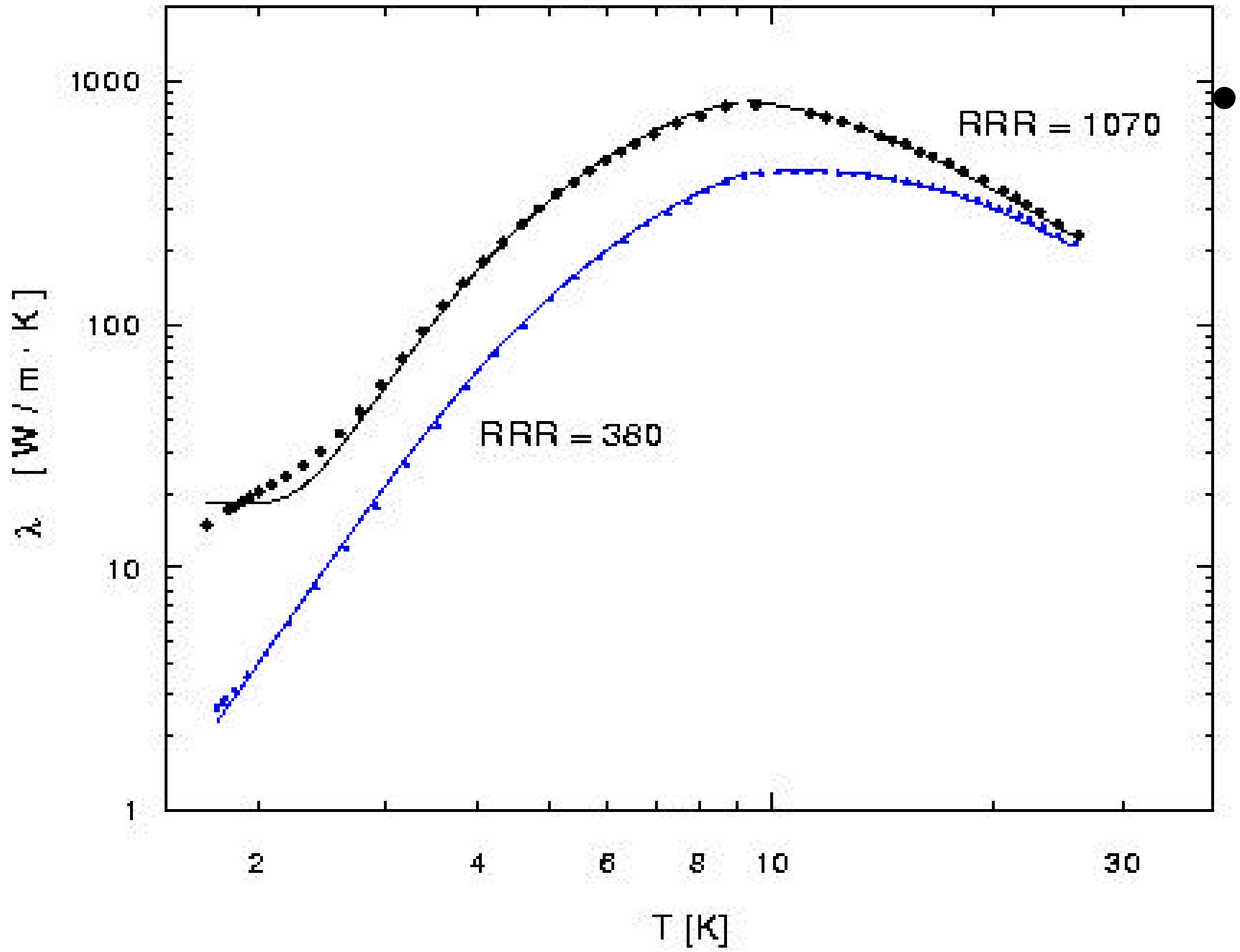
Eddy current scanning



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

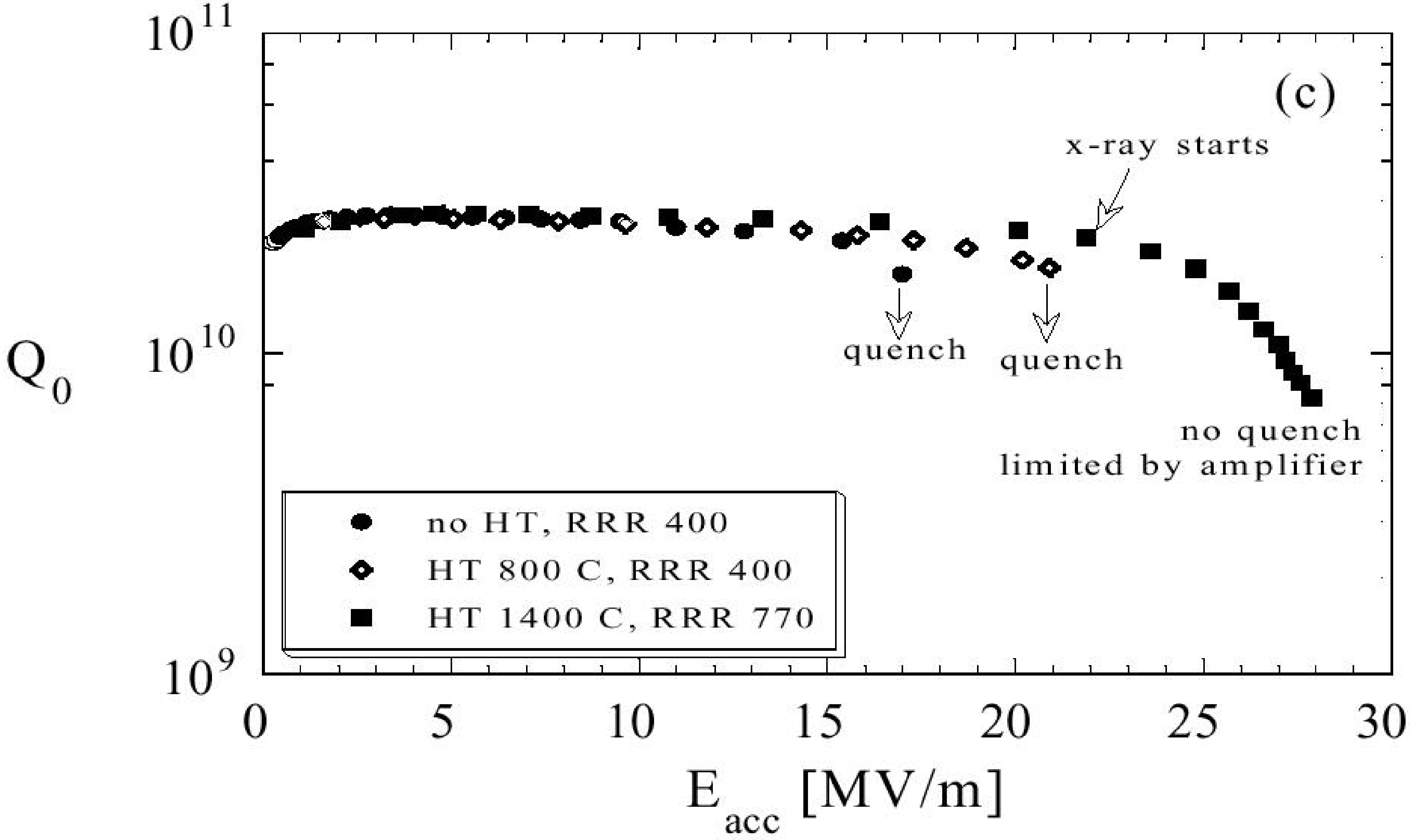

Grinding mark

Thermal conductivity of Niobium



- Higher thermal conductivity means:
  - better to stabilise defects
  - higher niobium quality

Benefit of the high temperature heat treatments

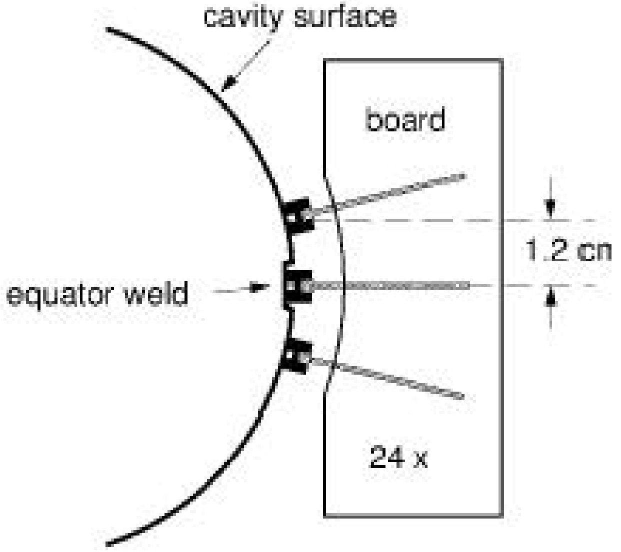


Thermal Breakdown

- Temperature of part (or all) of surface exceeds T_c, dissipating all stored energy.
- Localised effect ⇒ surface defect has higher R_s.
- Quench occurs when surrounding material cannot transport the increased thermal load to the helium.
- Possible solution: High RRR ⇒ less defects or higher purity.

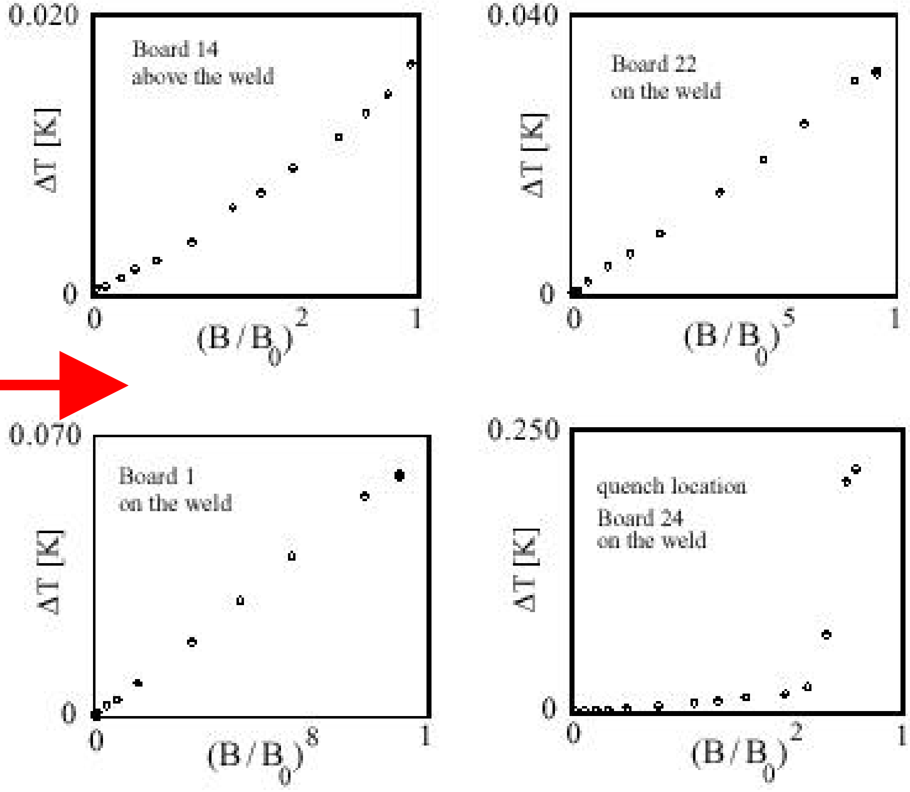
Imperfect equator welds

Temperature mapping of the equator region

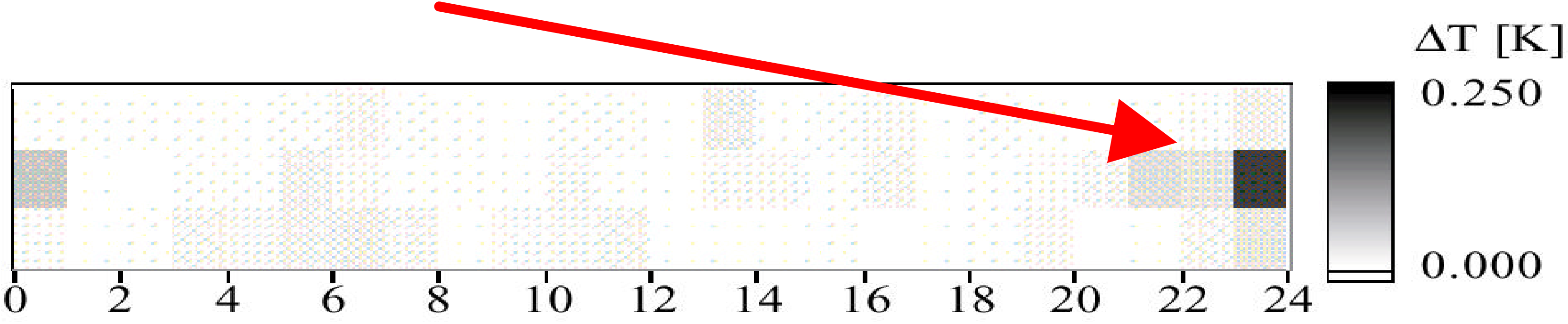


Thermometer response:

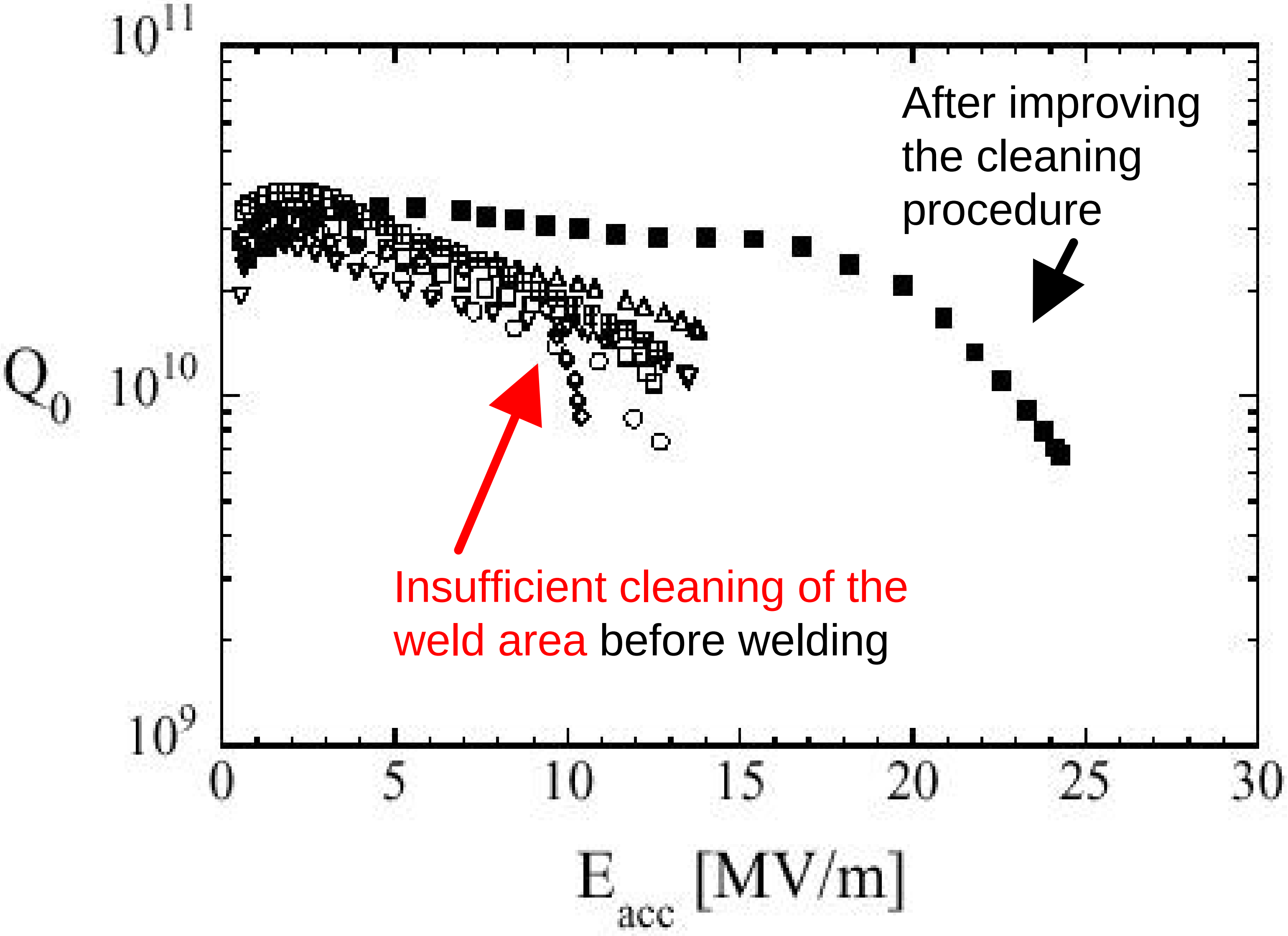
$\Delta T \sim B^2 - B^8$



Heating on the equator



Imperfect equator welds



After improving the cleaning procedure

Insufficient cleaning of the weld area before welding

By now four manufacturers have qualified to produce reliably high performing cavities.

Field Emission

- Primary limitation over past 5-10 years
- Emission of e^- from cavity surface in presence of high surface E-fields
- Emitted e^- impacts elsewhere on cavity surface, heating the surface and increase R_s
- Limits the achievable E_{acc} in cavity

- Very clean surface preparation and handling are needed
- For a detailed theory see [Padamsee et al 1998]

Distribution of Maximum Operational SRF Cavity Gradients in CEBAF by Type of Limitation

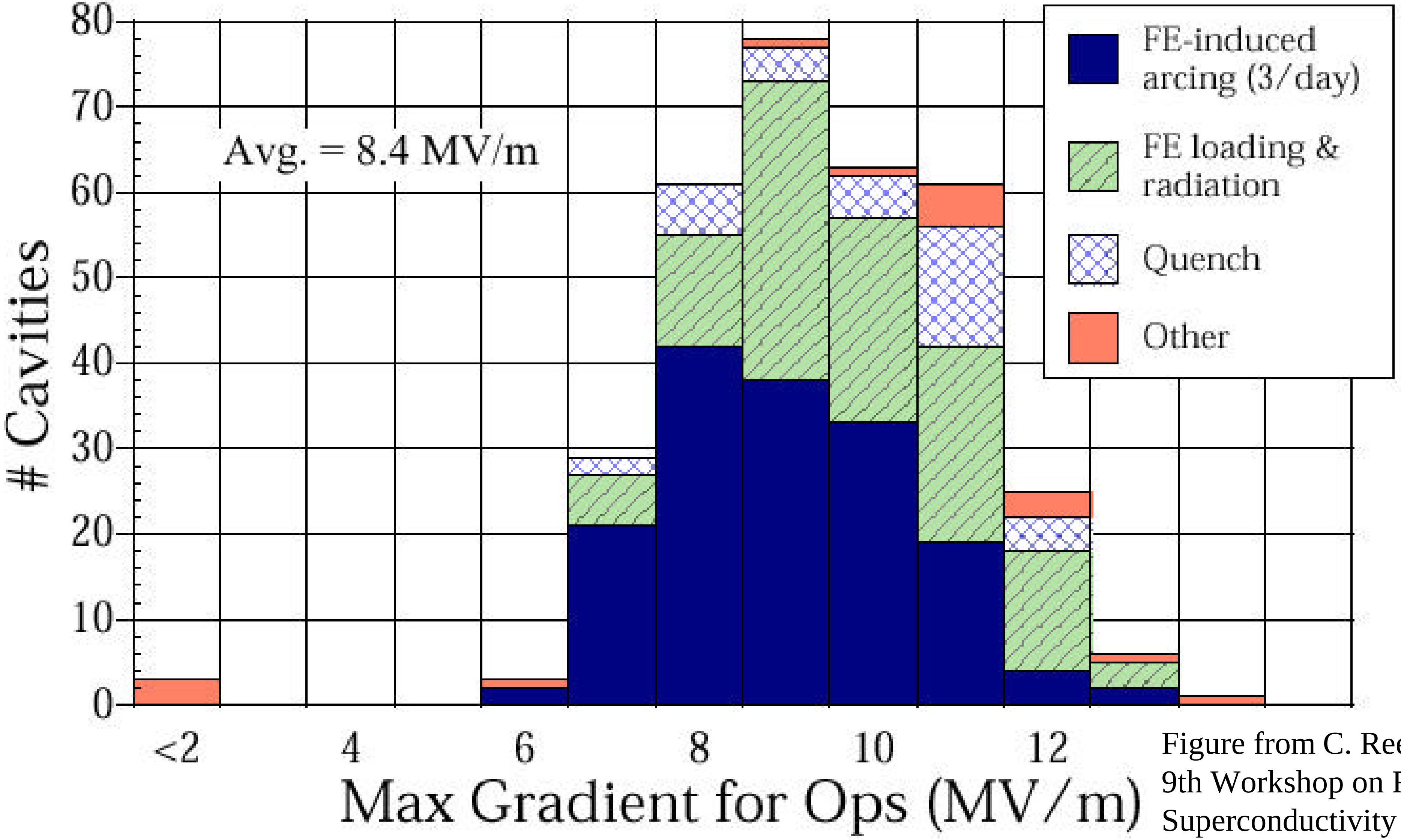
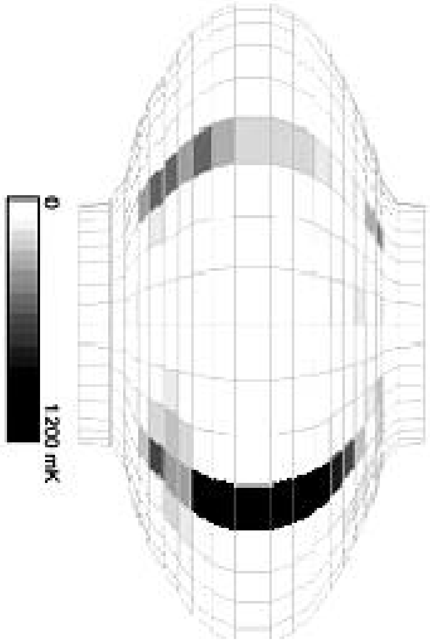


Figure from C. Reece, 9th Workshop on RF Superconductivity

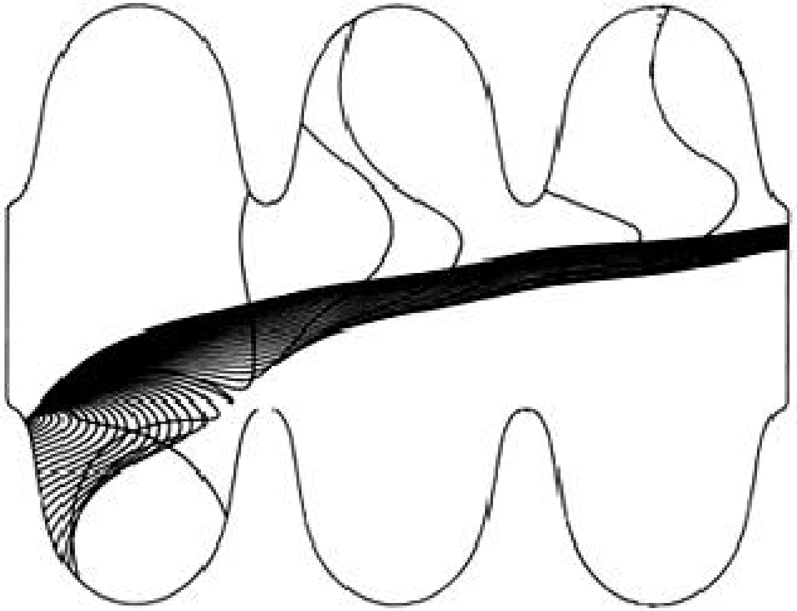
Field Emission

Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51

Particle causing field emission



Temperature map of a field emitter

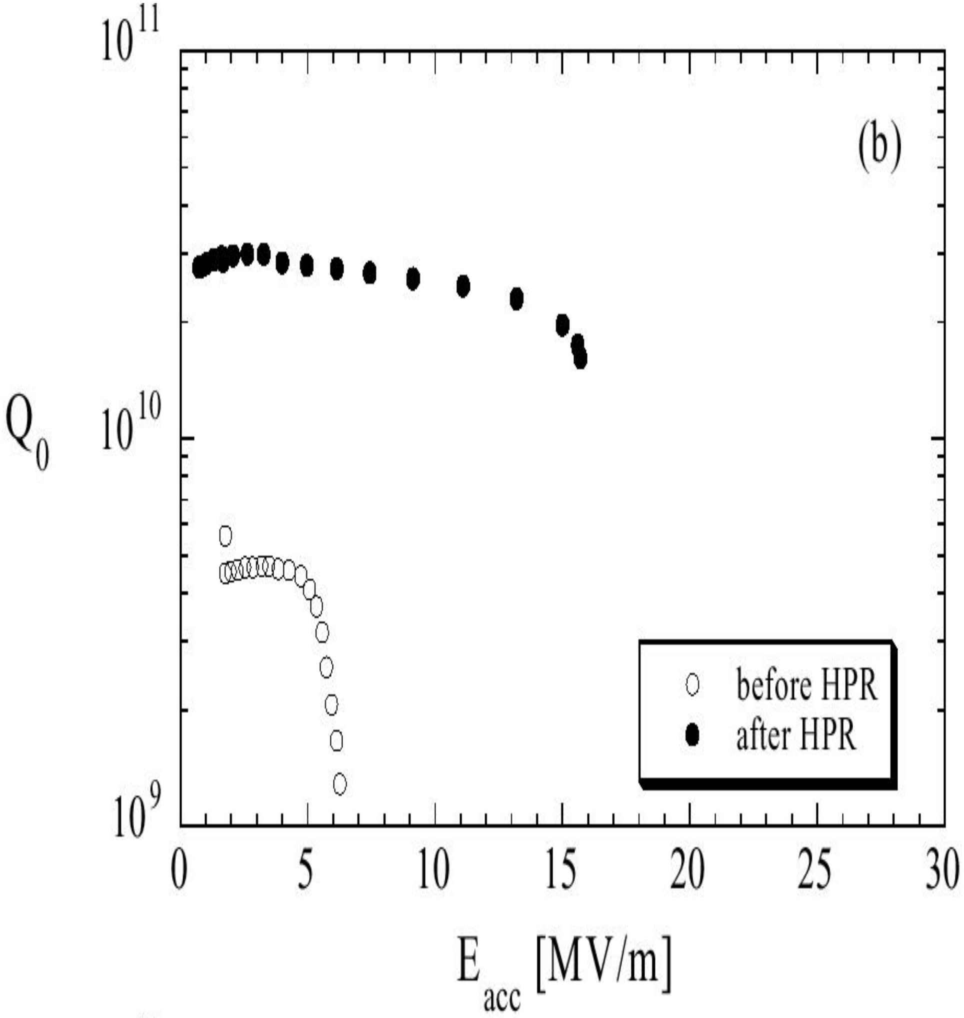


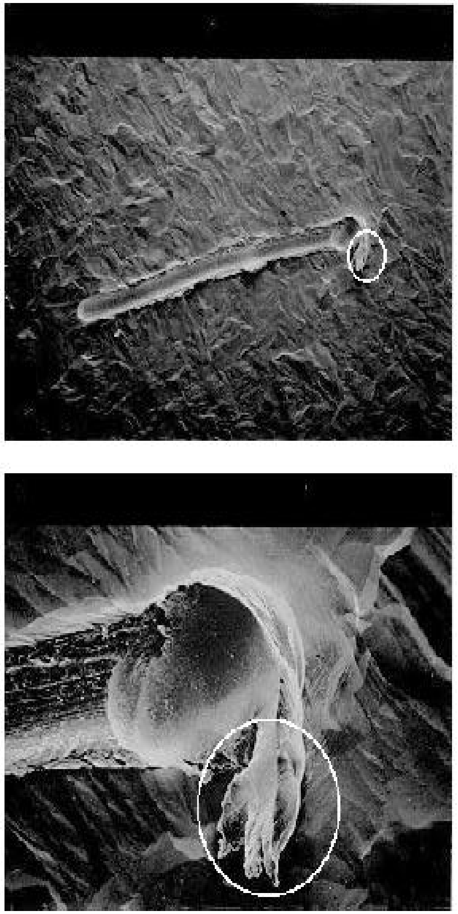
Simulation of electron trajectories in a cavity

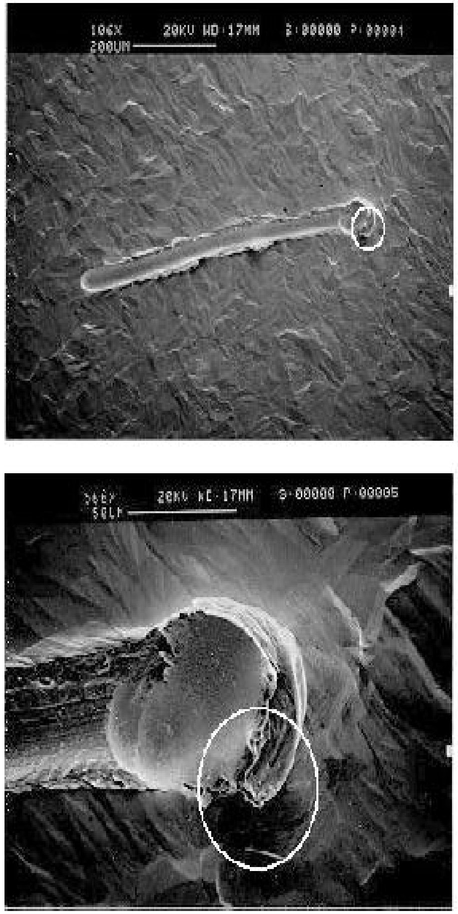
High pressure ultra-pure water rinsing

Ultra-pure water (18 MΩ, partice filter <0.4 µm) is sprayed with 100 bar on the niobium surface. This removes particles very efficiently.

High Pressure Water Rinsing

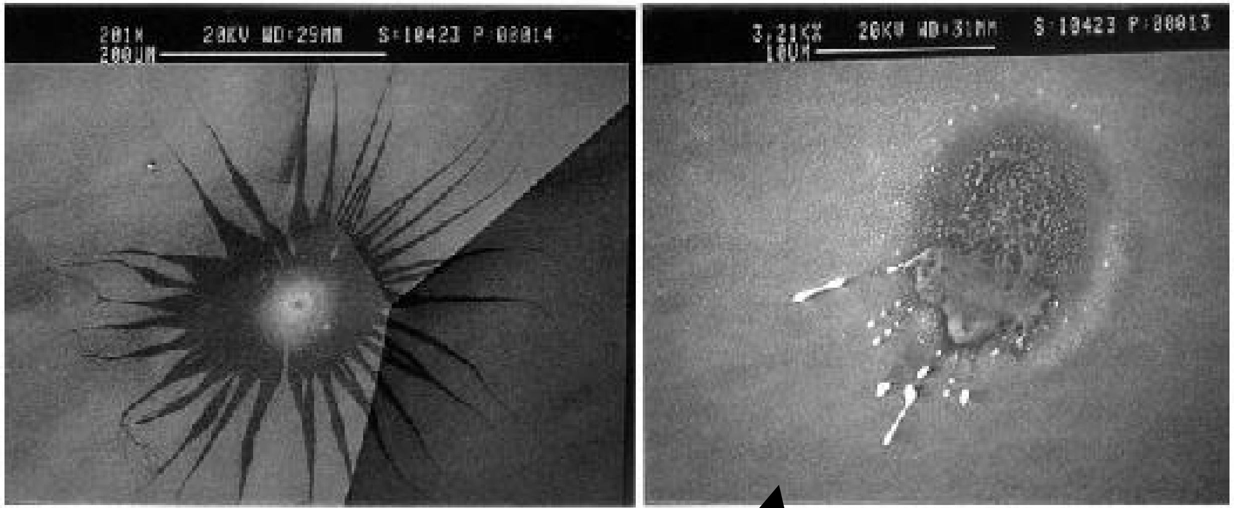



Before HPWR


After HPWR

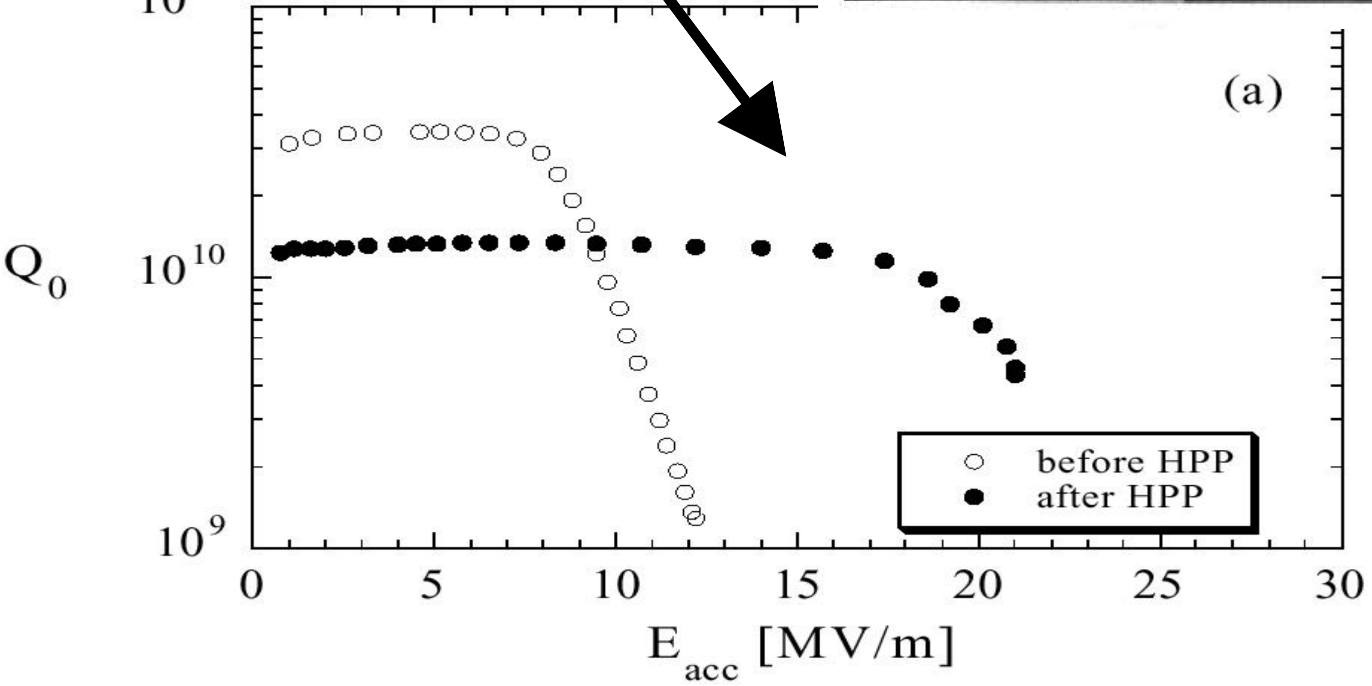
High Power Conditioning

In some cases applying high RF power to the cavity can cause the destruction of field emitters and improve the cavity performance

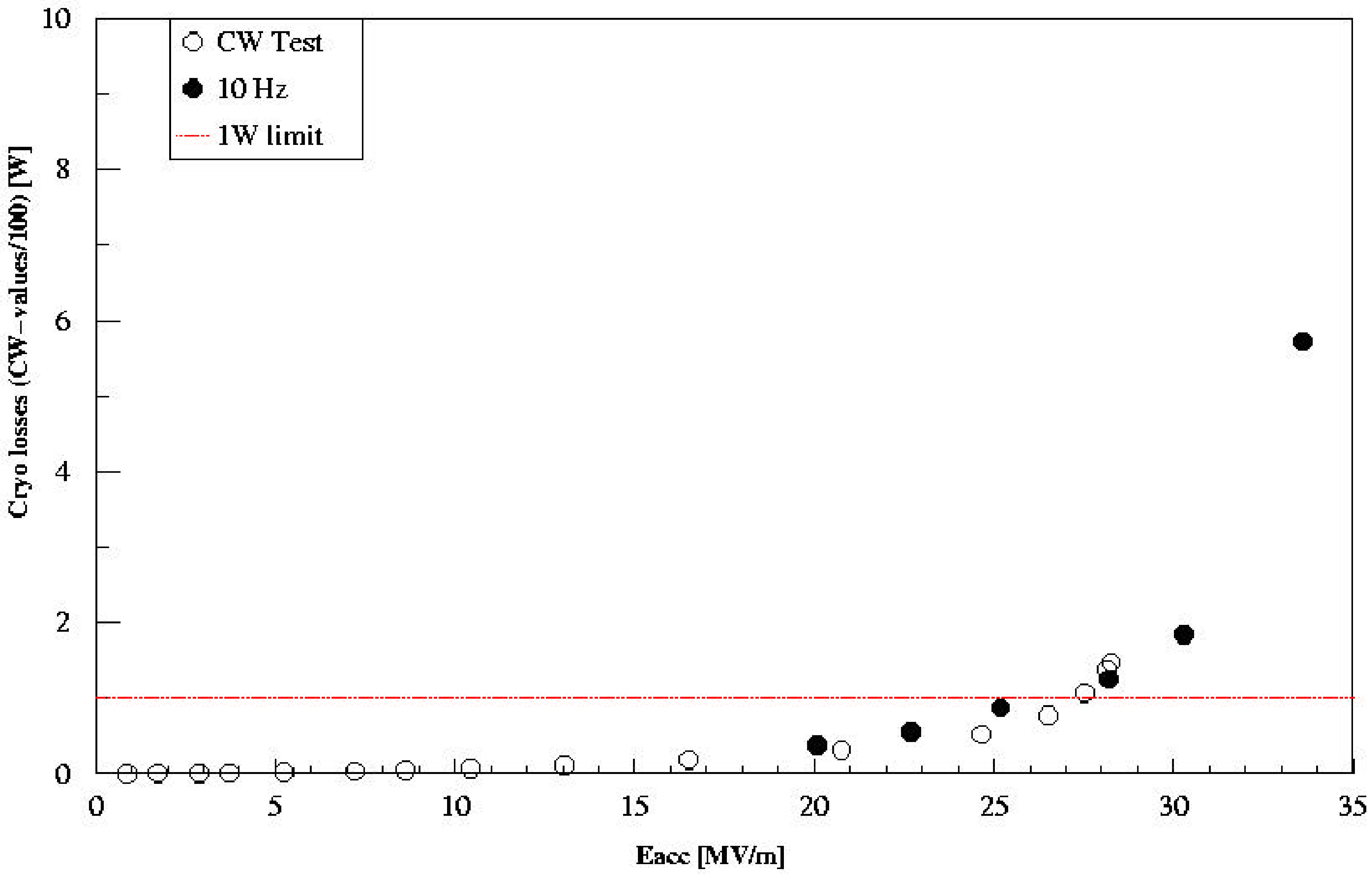


SEM pictures of molten particle after application of high RF power

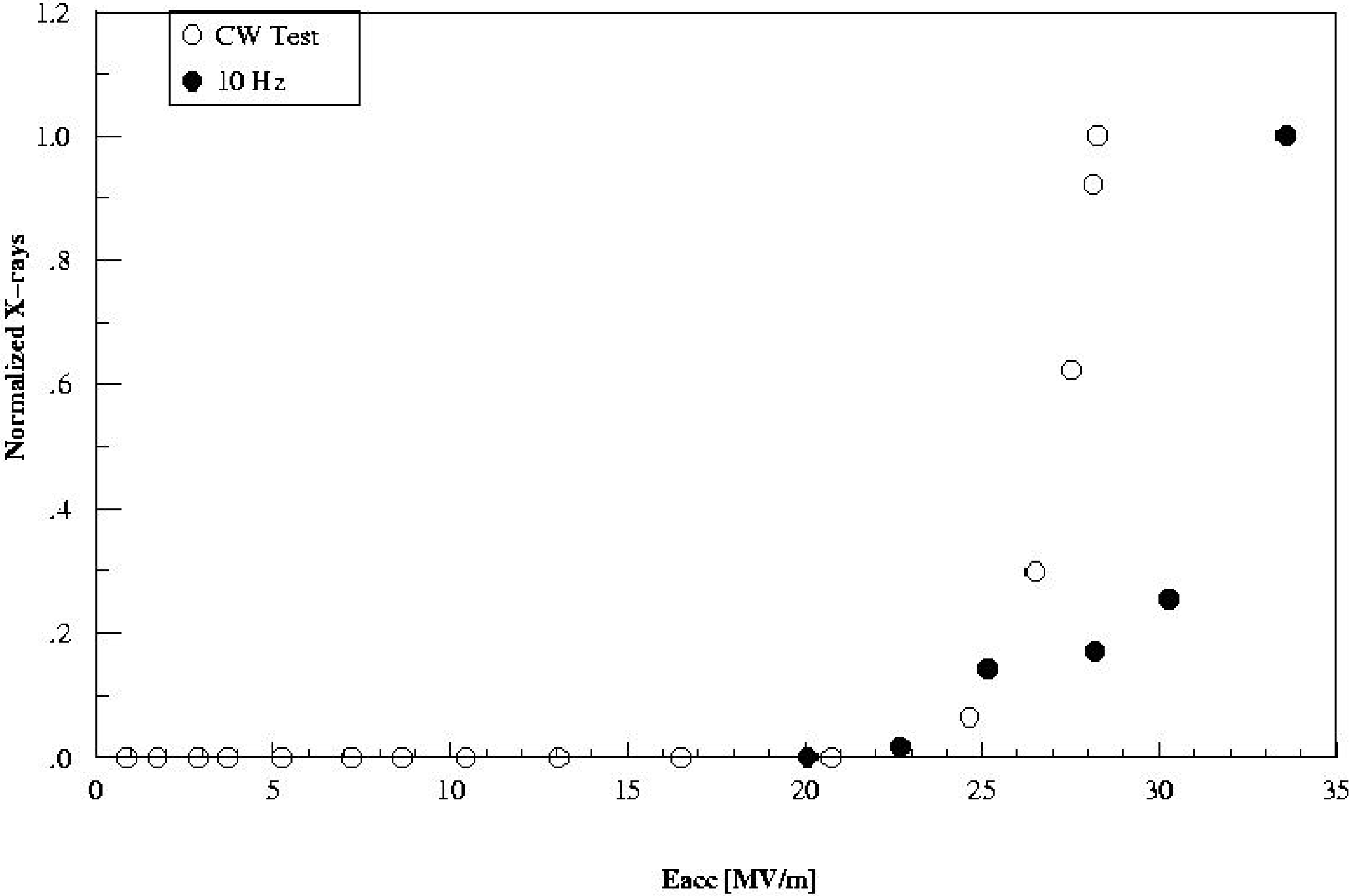
SEM Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51



Module 4 Cavity



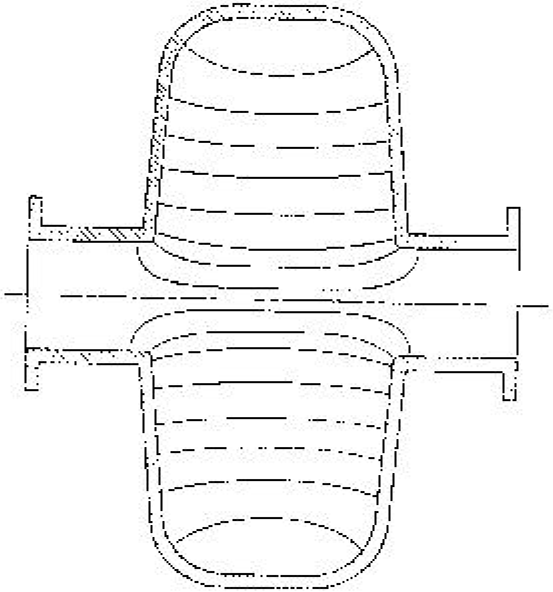
Module 4 Cavity X-rays



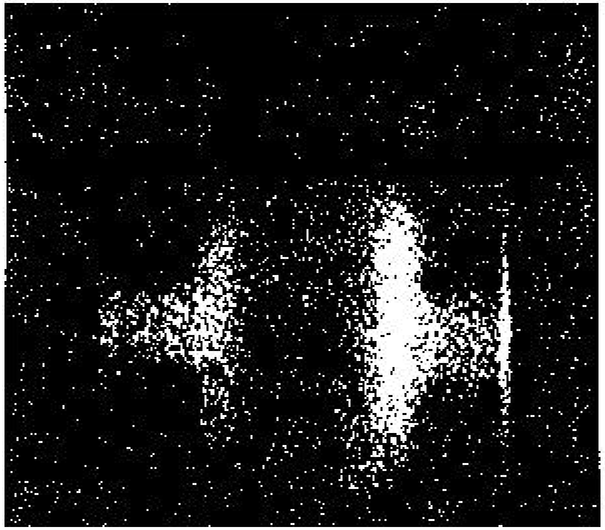
Multipacting

- ‘Multiple Impacting‘
- Electrons
  - Are omnipresent in cavities (from field emitters for example)
  - Are acclerated in the RF field
  - hit the surface
  - can free other electrons, depending on the secondary electron emission coefficient
- If in resonance (same place, same RF field phase), they produce an avalanche.

S-Band TM010 Resonator
Stanford, late 1960-ies

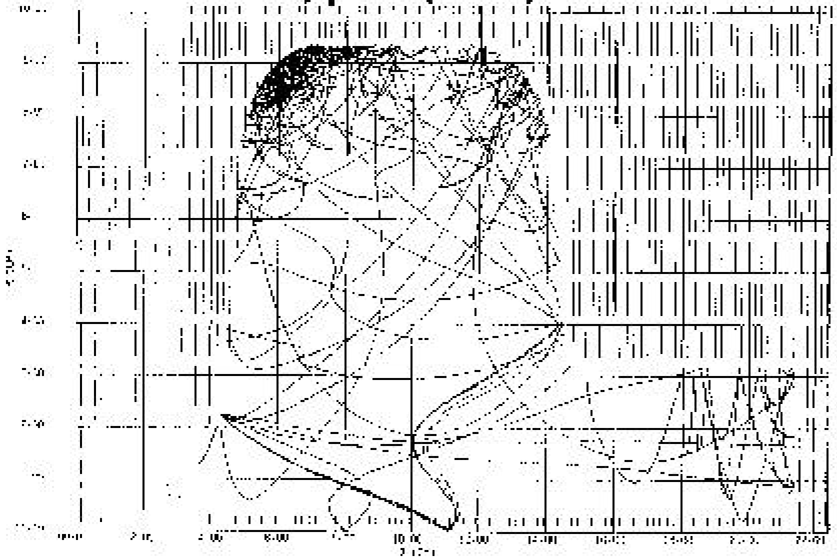


this is the standard geometry for about 15 years; unfortunately the cylindrical geometry is favourable for electron multipacting



X-ray mapping

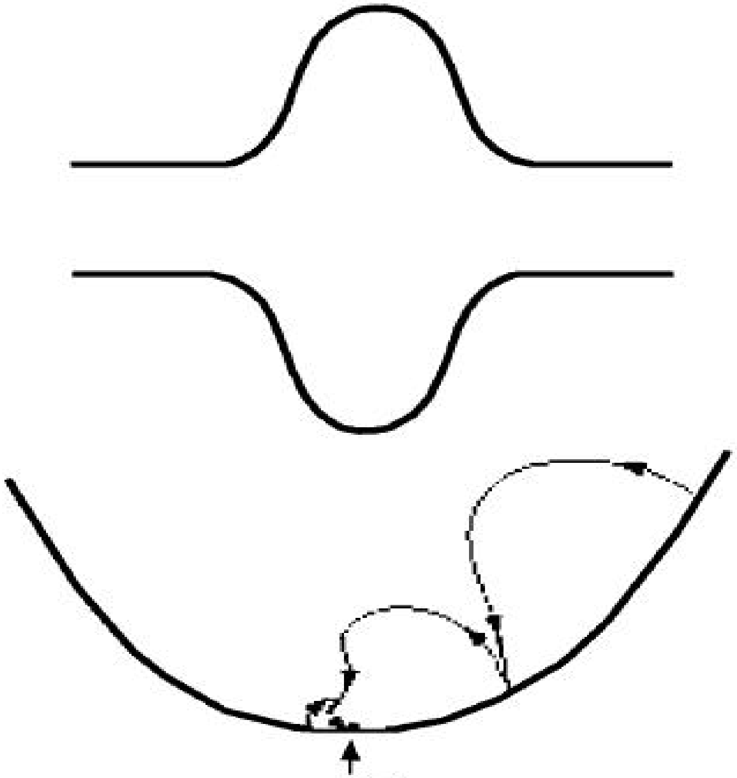
I.Ben-Zvi, J.F. Crawford and J.P. Turneaure
Eletron Multipacting in cavities
1973 PAC Conf., p.54 (1973).



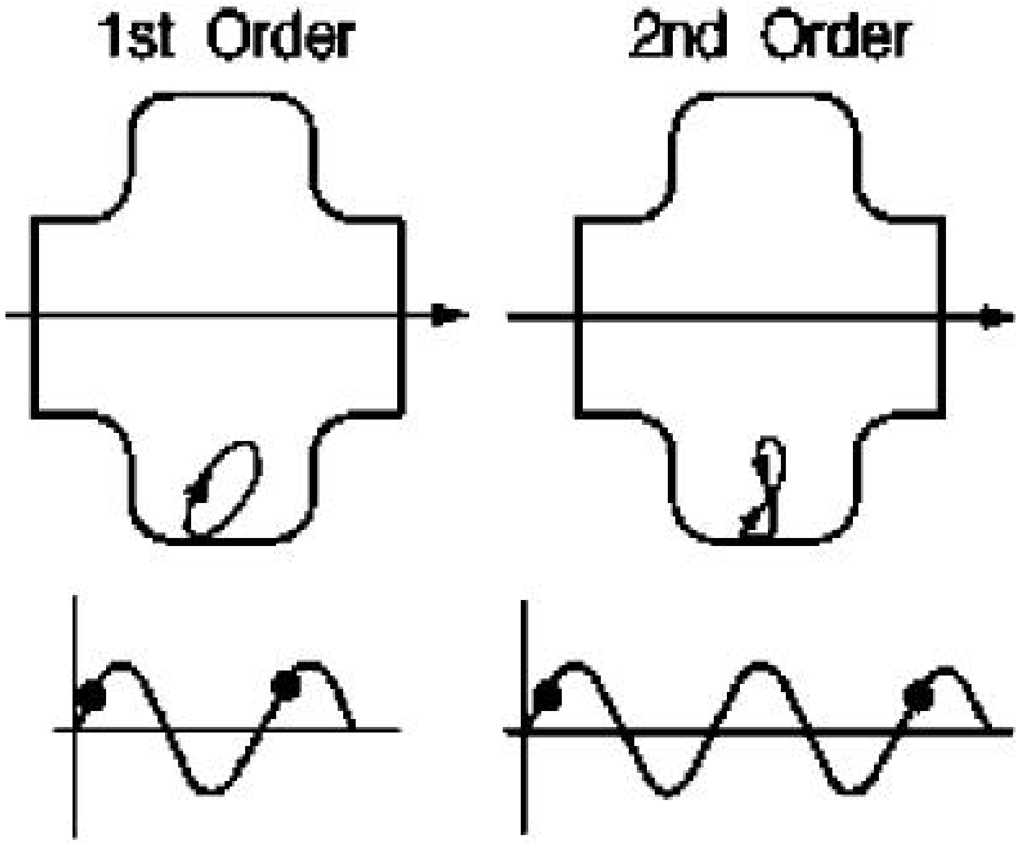
Simulated electron trajectories

Multipacting in superconducting cavities

In a cavity with a nearly pill-box-like shape, electrons can multiply in the region shown.

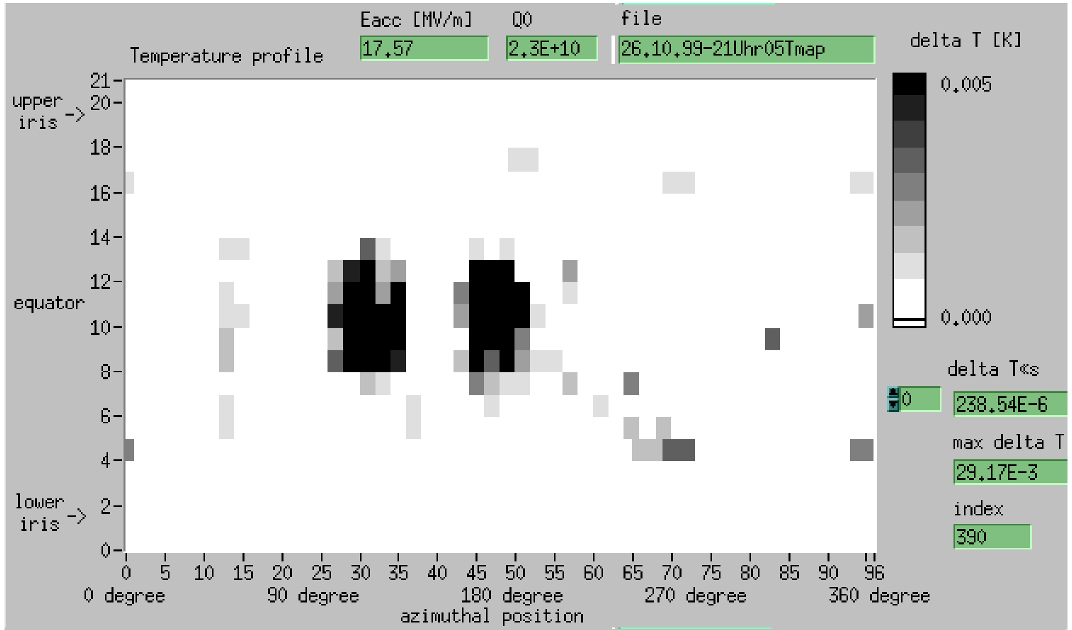


(c)

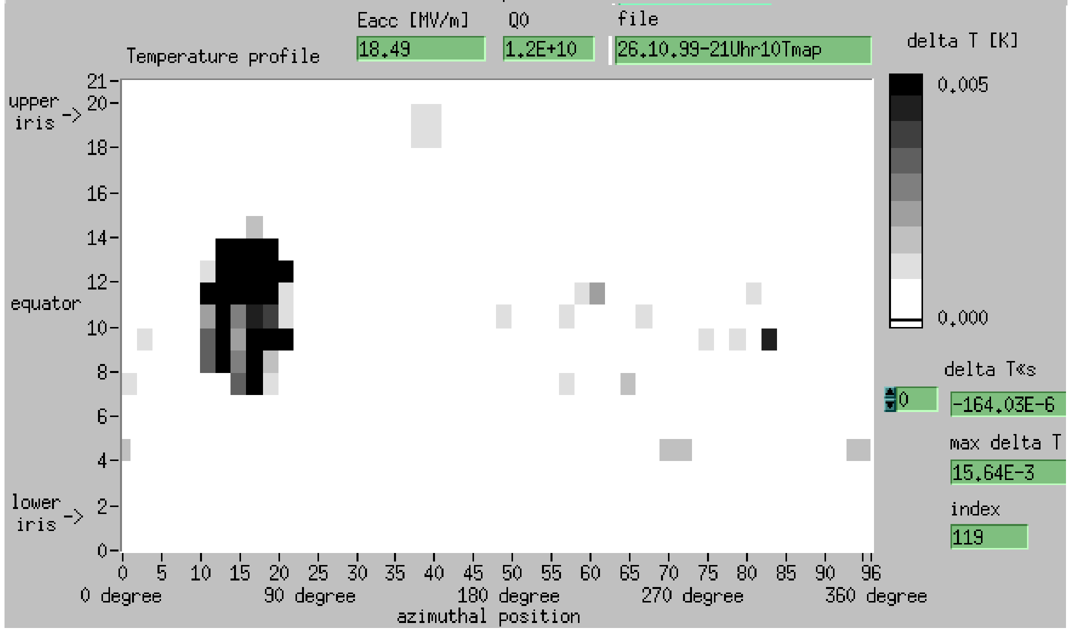


When the cavity shape is rounded, the electrons drift to the zero-field region at the equator. Here the electric field is so low that the secondary cannot gain enough energy to regenerate.

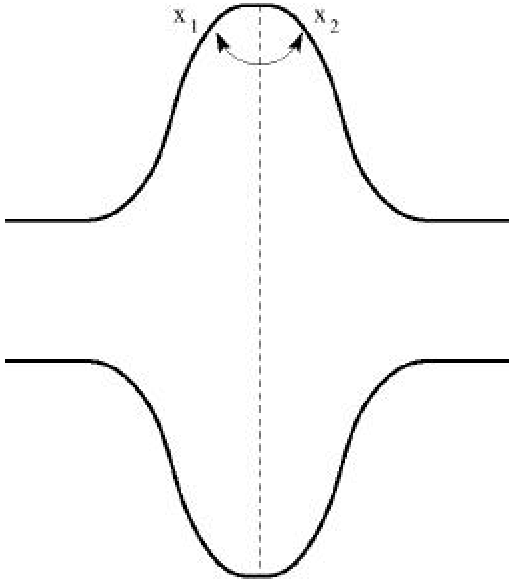
Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51



Eacc [MV/m] 17.57
Q0 2.3E+10
file 26.10.99-21Uhr05Tmap
delta T«s 0 238.54E-6
max delta T 29.17E-3
index 390



Eacc [MV/m] 18.49
Q0 1.2E+10
file 26.10.99-21Uhr10Tmap
delta T«s 0 -164.03E-6
max delta T 15.64E-3
index 119



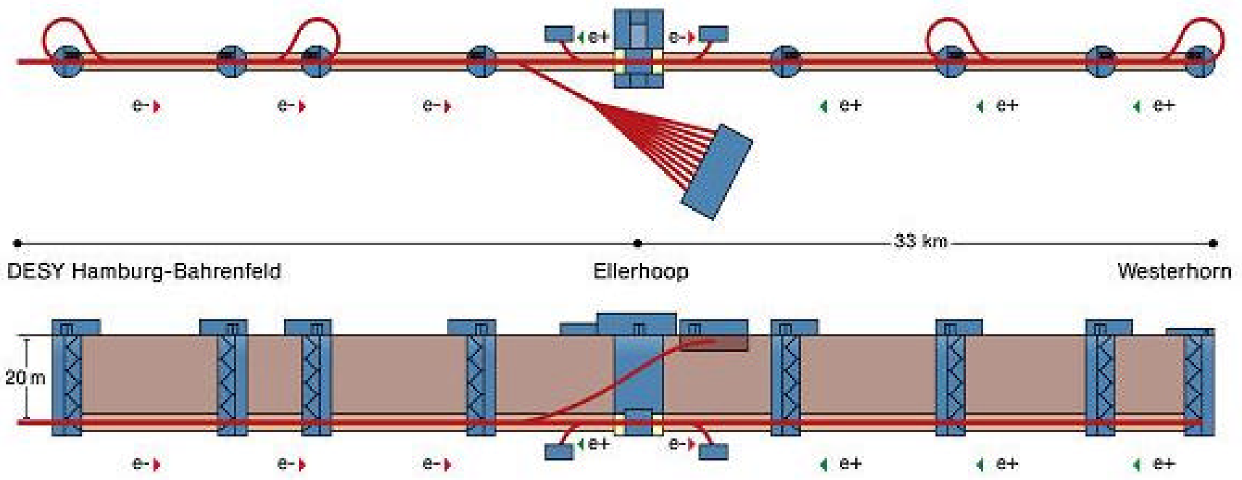
Multipacting: Temperature mapping

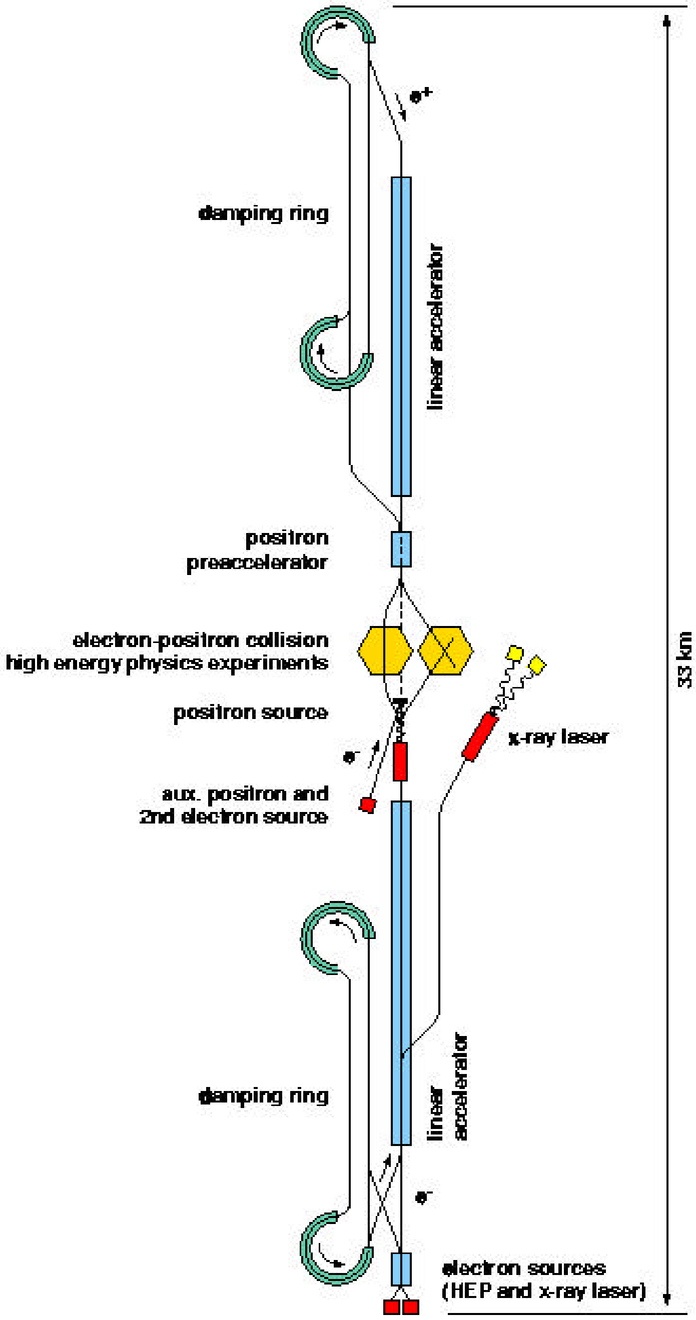
- Heating moves along the equator
- X-ray detectors and electron pickups are also showing activity
- Processing takes a few minutes

Outline (Lecture 2)

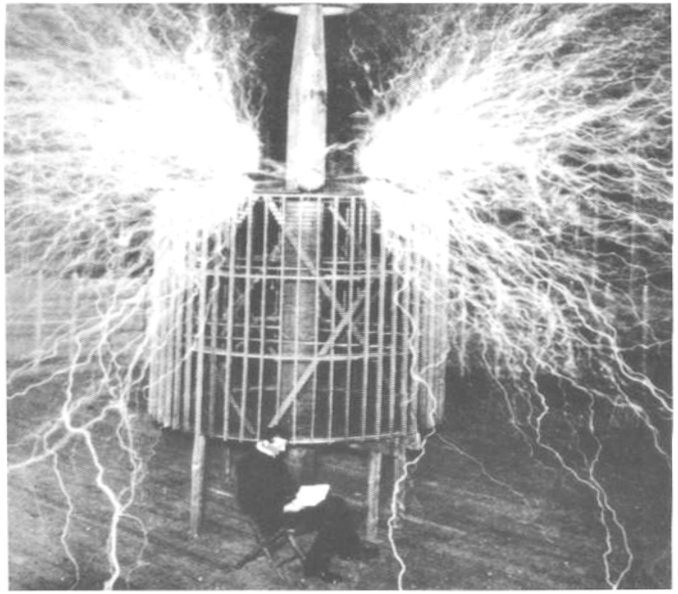
- Practical example: TESLA cavities
  - What is TESLA?
    - Goals for TESLA cavities
  - Choice of superconductor
  - Design of SRF cavities
  - Manufacturing issues
  - Surface preparation
  - Current state-of-the-art cavity performance
  - Higher gradients for TESLA-800
    - Electropolishing
    - ‘Superstructure’
  - Operating SRF cavities
    - Cryostats
    - RF Couplers
    - Low-level RF control

Layout of TESLA

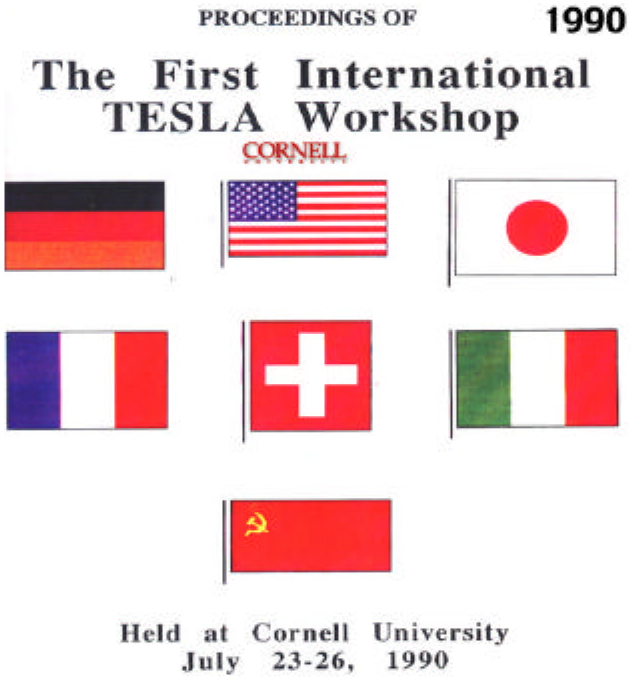




Lutz Lilje DESY



Tesla, the scientist



PROCEEDINGS OF 1990

The First International
TESLA Workshop

CORNELL

Held at Cornell University
July 23-26, 1990

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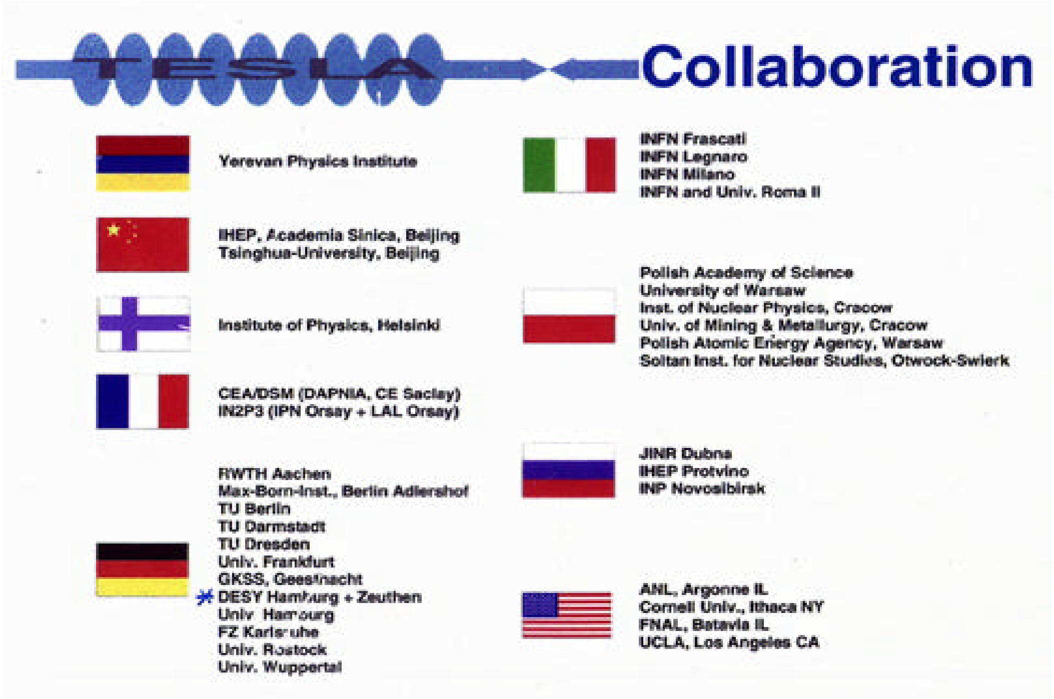


TESLA Collaboration

Yerevan Physics Institute

IHEP, Academia Sinica, Beijing
Tsinghua-University, Beijing

Institute of Physics, Helsinki

CEA/DSM (DAPNIA, CE Saclay)
IN2P3 (IPN Orsay + LAL Orsay)

RWTH Aachen
Max-Born-Inst., Berlin Adlershof
TU Berlin
TU Darmstadt
TU Dresden
Univ. Frankfurt
GKSS, Geesthacht
* DESY Hamburg + Zeuthen
Univ. Hamburg
FZ Karlsruhe
Univ. Rostock
Univ. Wuppertal

INFN Frascati
INFN Legnaro
INFN Milano
INFN and Univ. Roma II

Polish Academy of Science
University of Warsaw
Inst. of Nuclear Physics, Cracow
Univ. of Mining & Metallurgy, Cracow
Polish Atomic Energy Agency, Warsaw
Soltan Inst. for Nuclear Studies, Otwock-Swierk

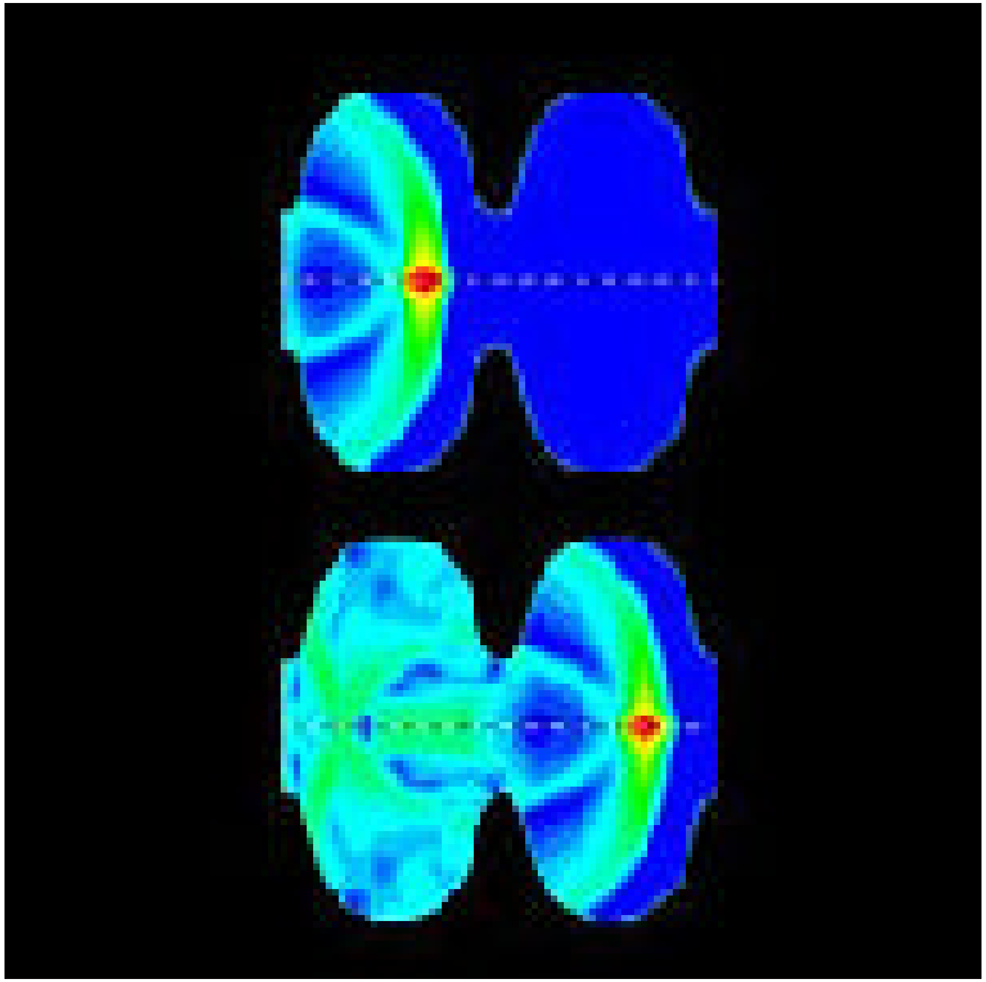
JINR Dubna
IHEP Protvino
INP Novosibirsk

ANL, Argonne IL
Cornell Univ., Ithaca NY
FNAL, Batavia IL
UCLA, Los Angeles CA

Main Advantages of TESLA

- SC Cavity => Fill slowly
  Drastic Reduction of Peak RF Power
- SC => Low Frequency Affordable =>
  Drastically Lower Wake fields
- Flexible beam parameters to
  high luminosity

Wakefields

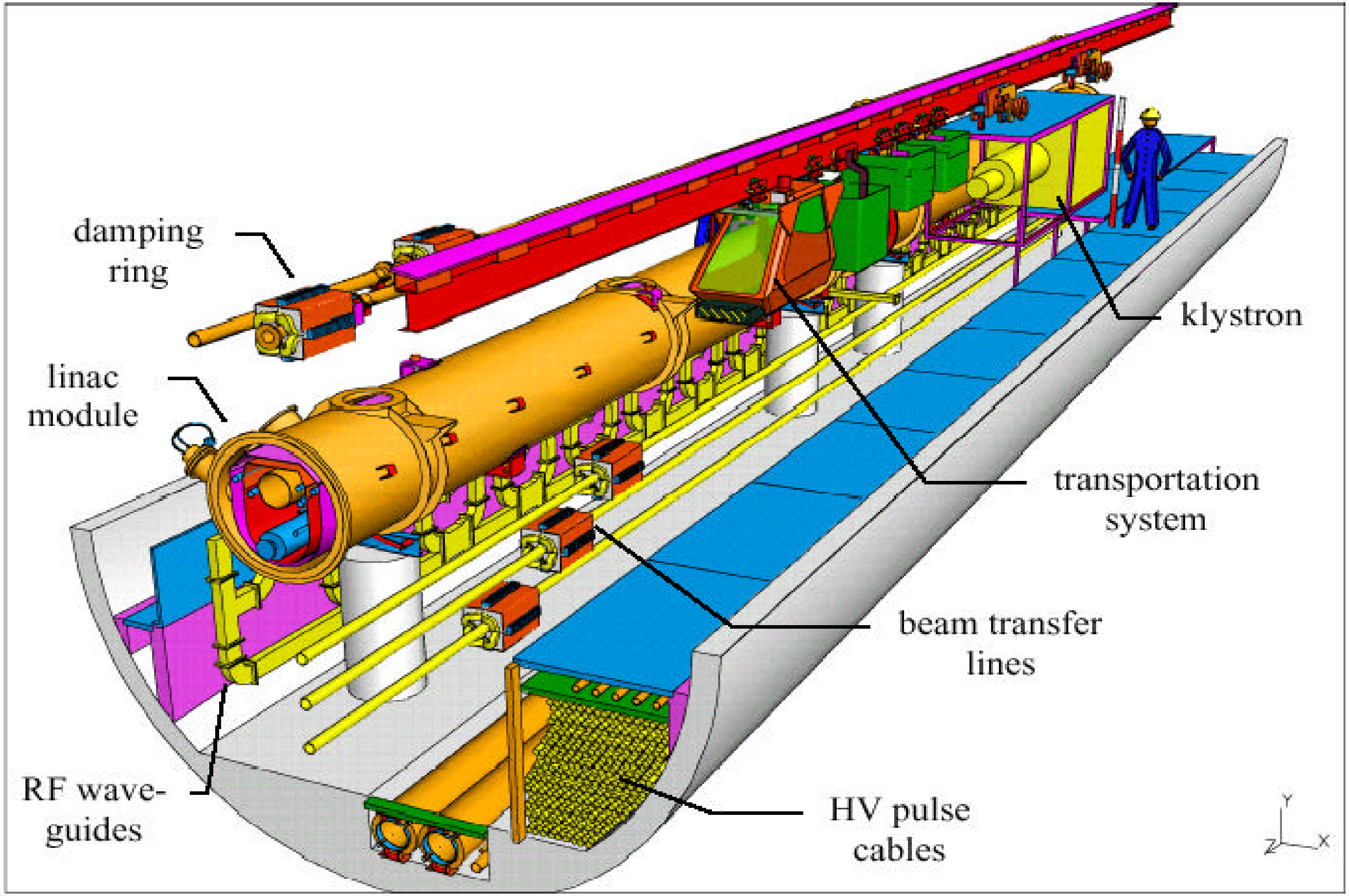


$$W_z \sim a^{-2} \sim \omega^2$$

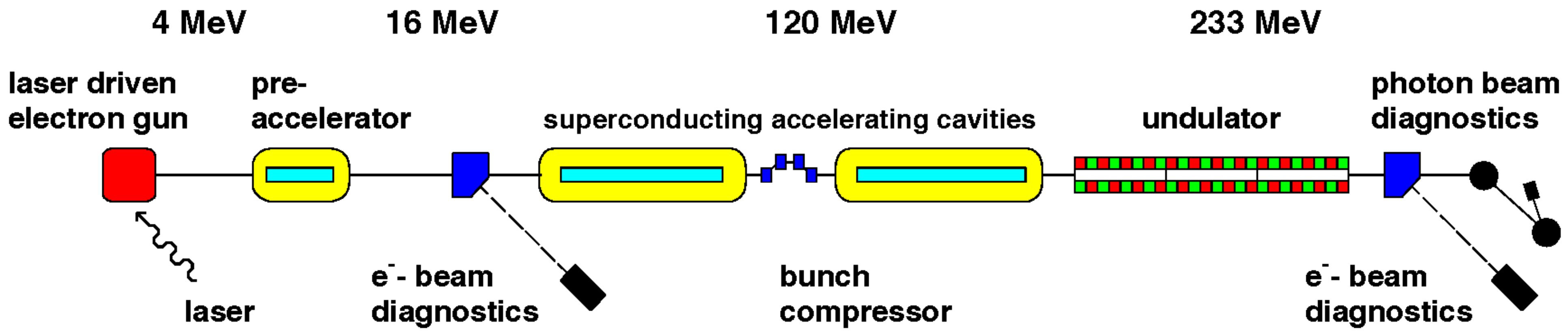
$$W_\perp \sim a^{-3} \sim \omega^3$$

a = Iris diameter

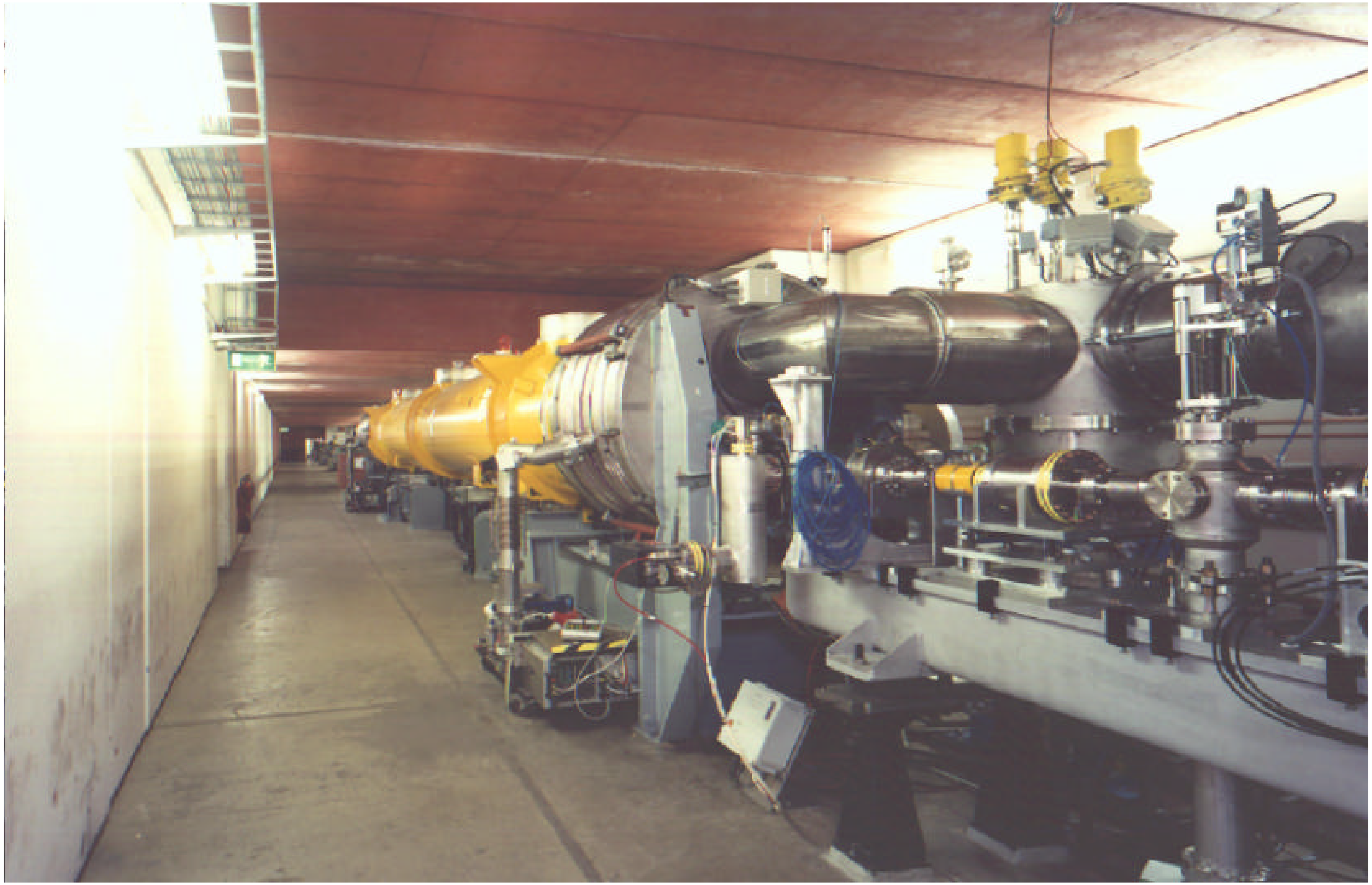
View of the TESLA Tunnel



TESLA Test Facility Linac



TESLA Test Facility Linac



SASE FEL bei TTF - Undulator

TESLA Cavities

Goals for TESLA cavities

Specifications:

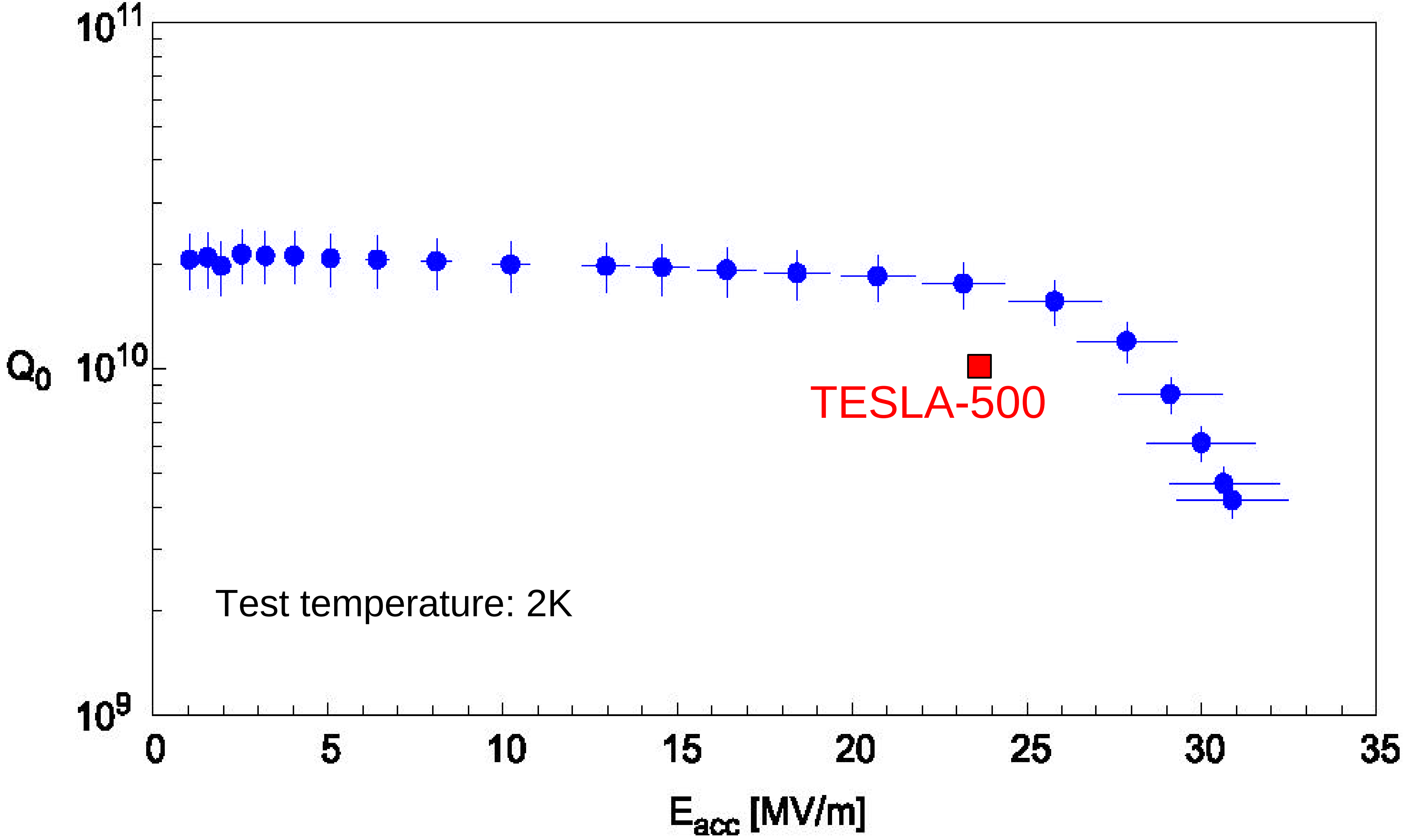
E_{acc} = 23,4 MV/m @ $Q_0 = 1 \cdot 10^{10}$ for TESLA-500

E_{acc} = 35 MV/m @ $Q_0 = 5 \cdot 10^{9}$ for TESLA-800

Theoretical limit: $E_{acc} \sim$ 45-50 MV/m

RF magnetic field exceeds critical field of niobium

Continuous wave test of TESLA cavity



Outline

- Example: TESLA cavities
  - What is TESLA?
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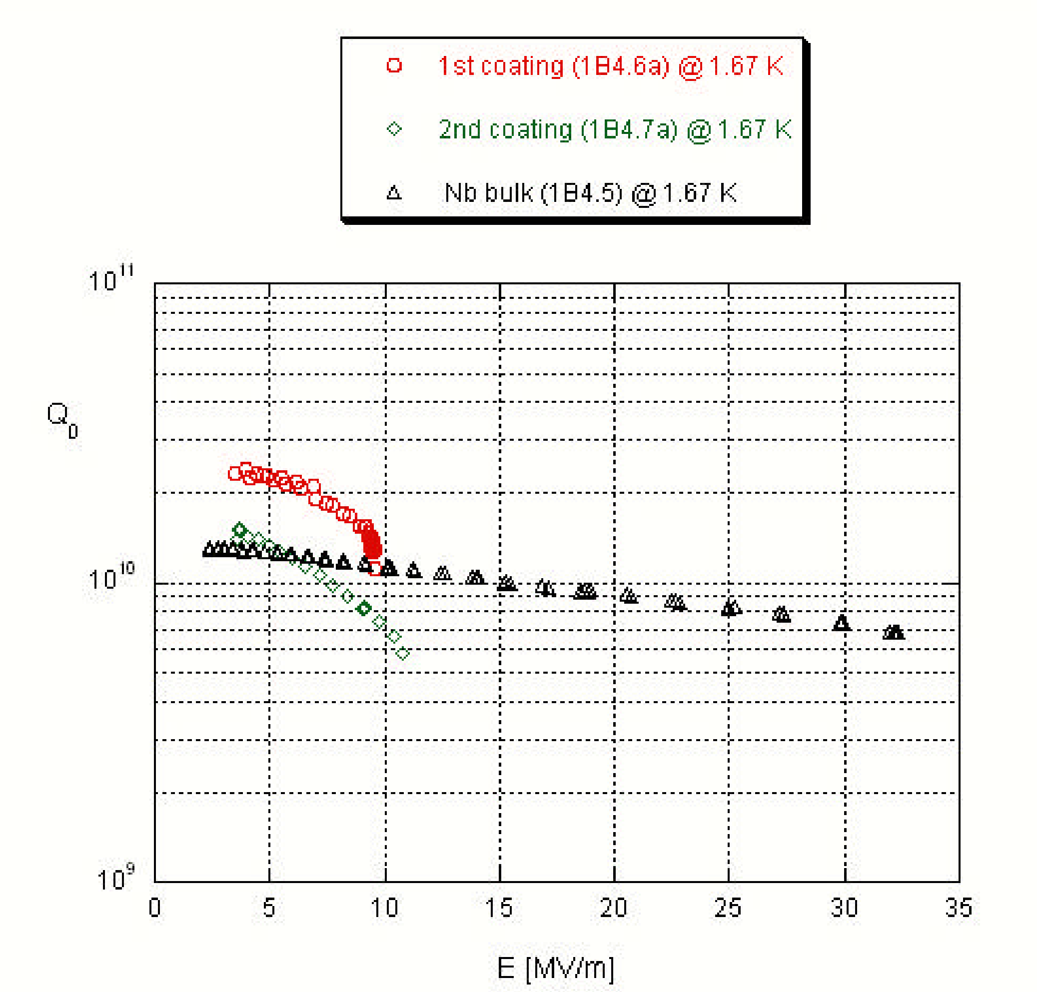
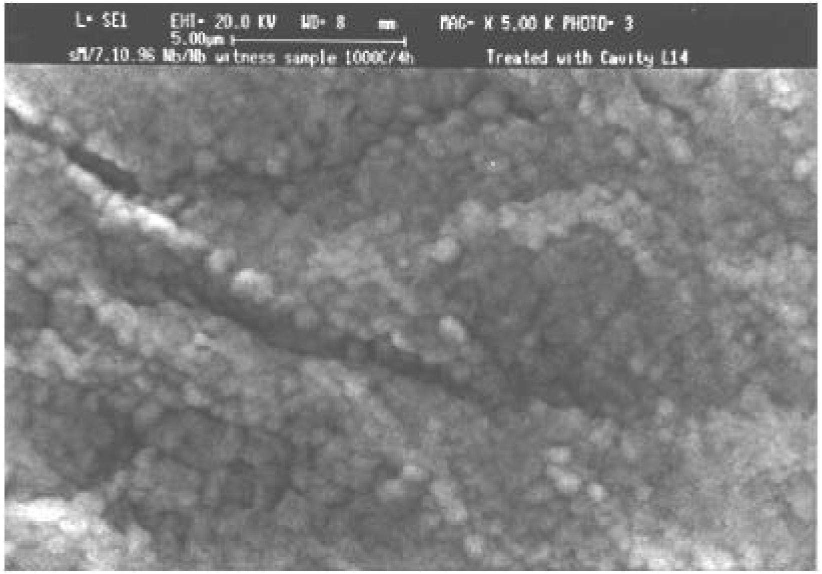
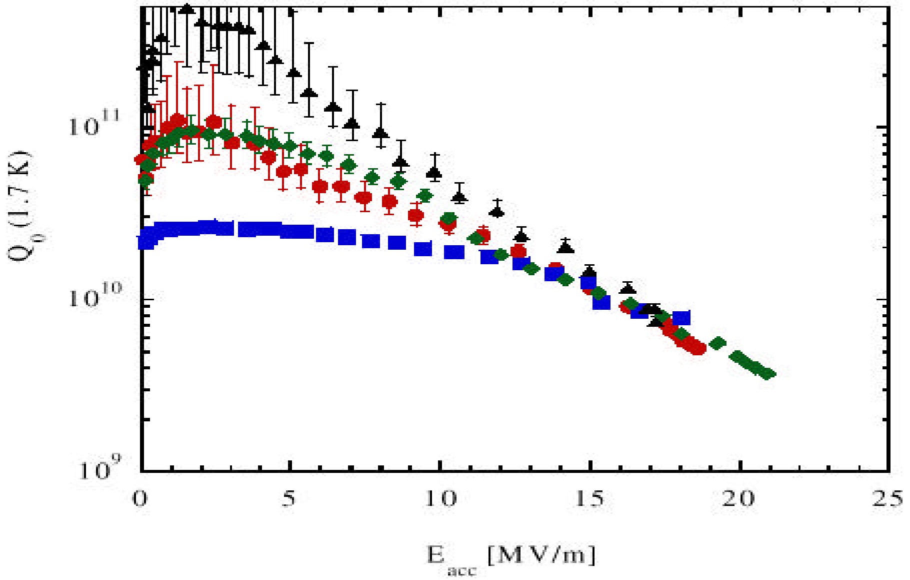
  - Design of SRF cavities
  - Manufacturing issues
  - Surface preparation
  - Current state-of-the-art cavity performance
  - Higher gradients for TESLA-800
  - Operating SRF cavities

Gesputterte Niobfilme



Niob auf Niob (Benvenuti et al.)

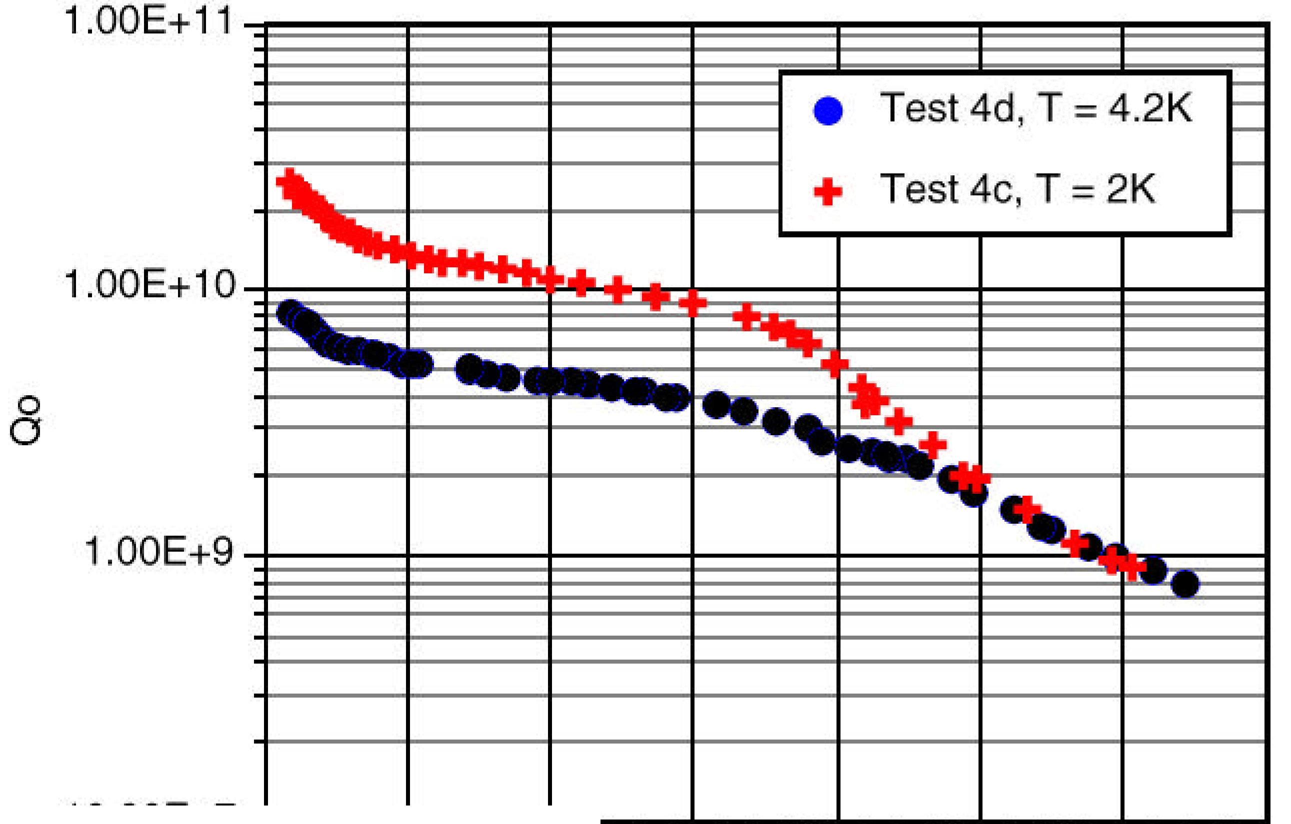




Niob auf Kupfer (Benvenuti et al.)

Nb_3Sn

Universität Wuppertal



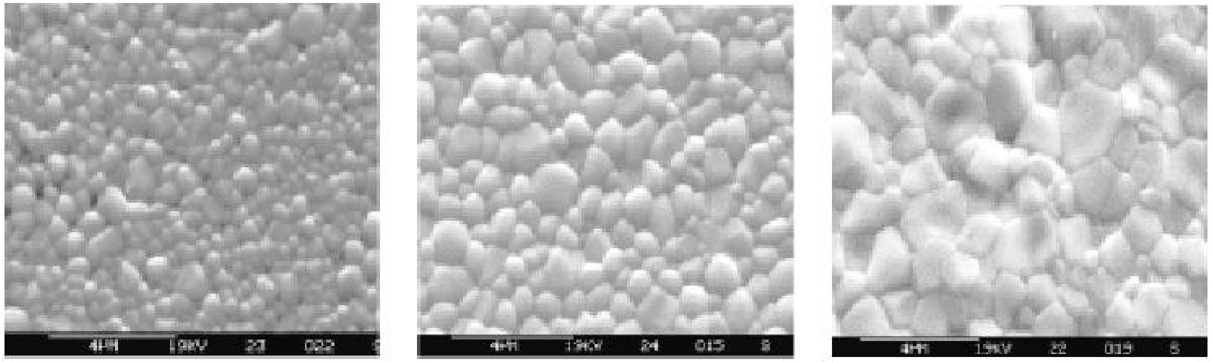
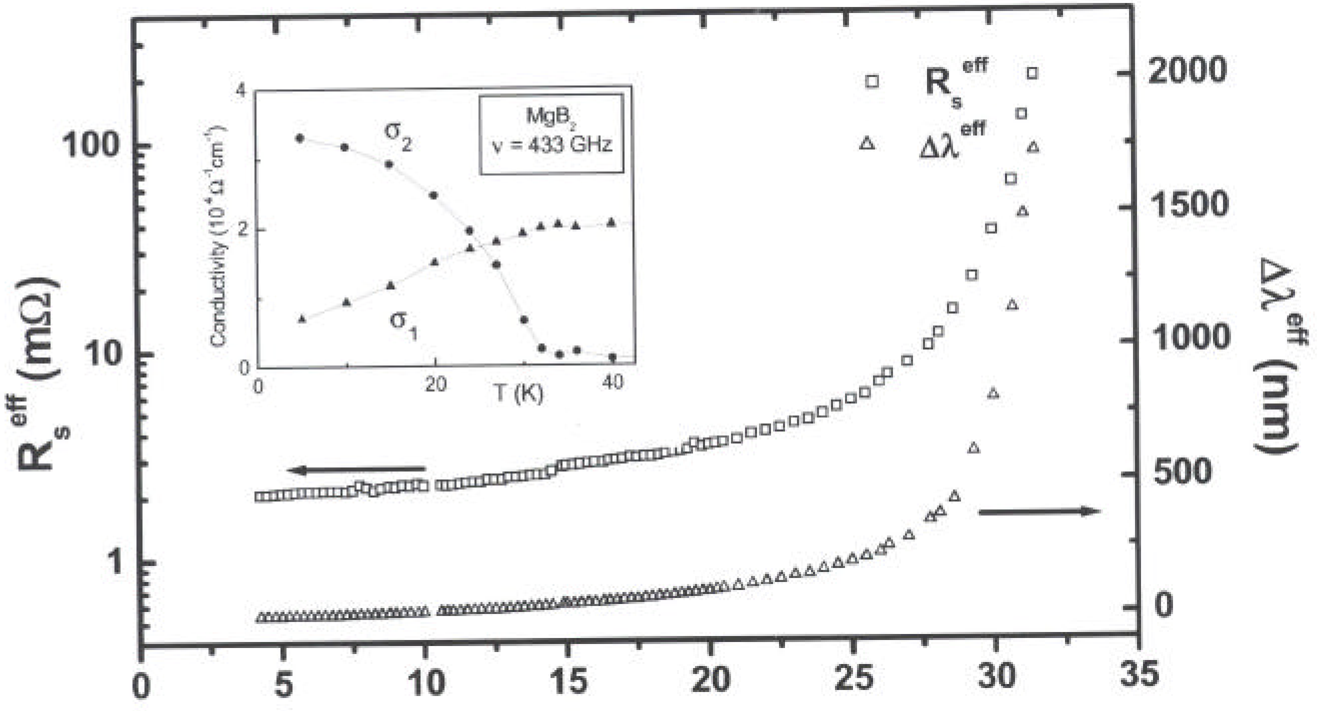


Fig. 1:
SEM pictures of three Nb_3Sn films: d_{film} = 0.6µm (left), 1.2µm (middle), 2.1µm (right).

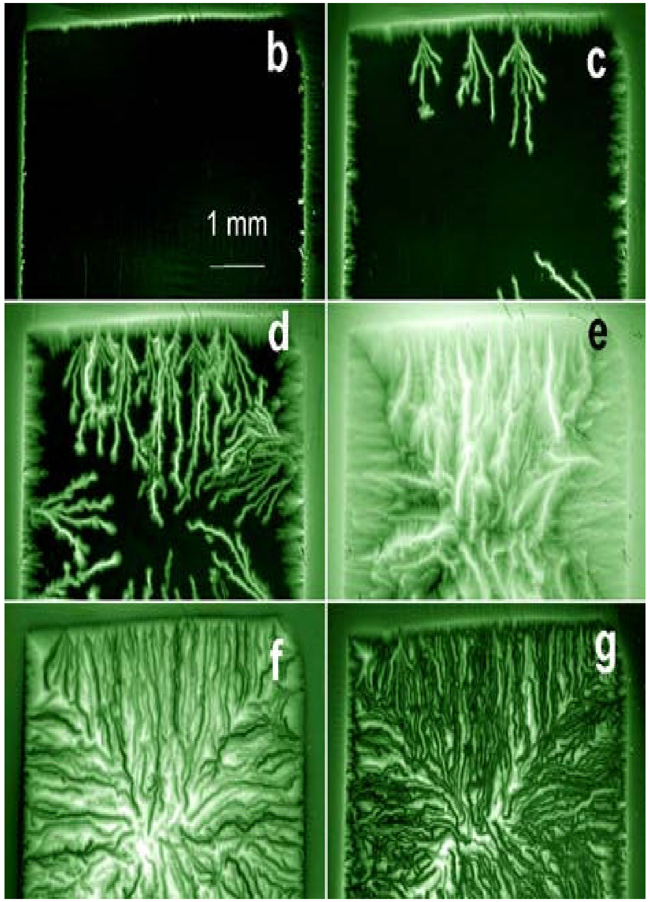
Magnesiumdiborid: MgB_2

Thin films

Fig. 1 (top) and Fig. 2 (bottom)



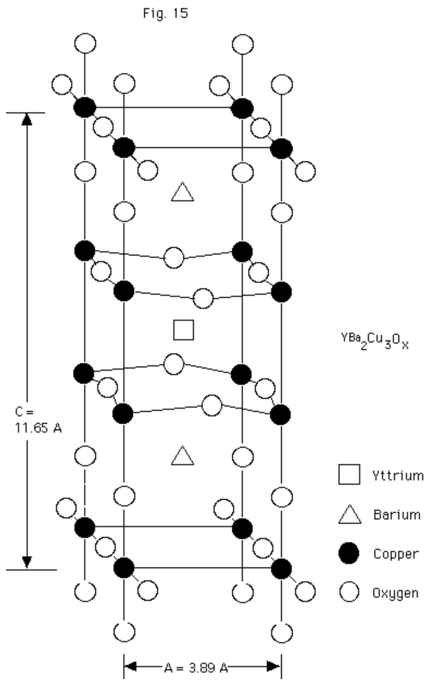
Palmieri, INFN

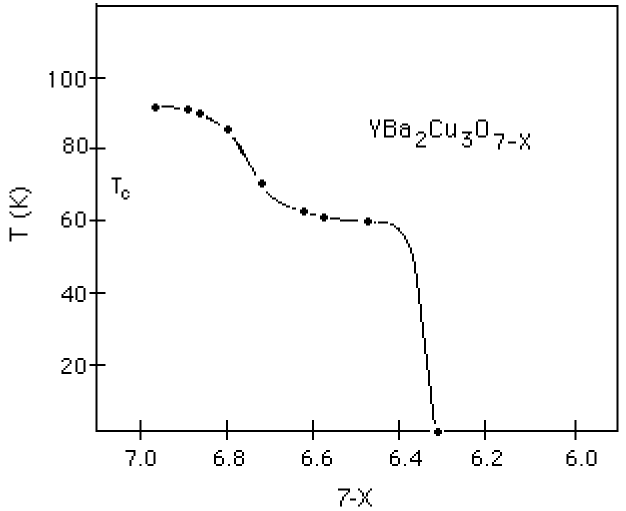


T.H. Johansen et al.

YBCO

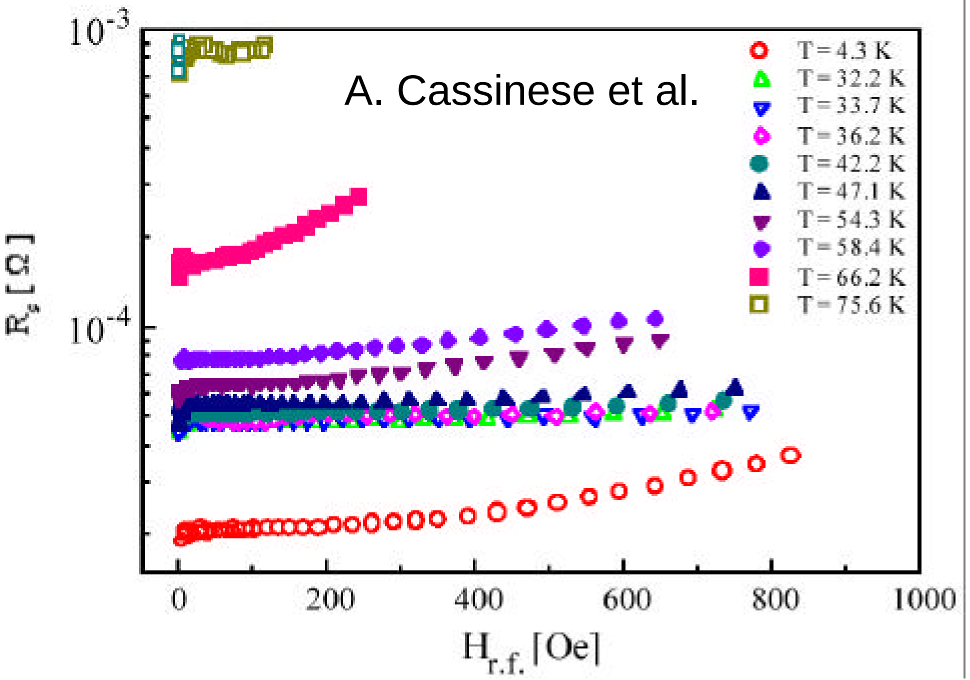
Thin films





T_c as a function of oxygen content in $YBa_2Cu_3O_{7-x}$

T.H. Johansen et al.



A. Cassinese et al.

Specification of the niobium sheet material for the TESLA cavities

Impurity content in ppm (wt)			
Ta	≤ 500	H	≤ 2
W	≤ 70	N	≤ 10
Ti	≤ 50	O	≤ 10
Fe	≤ 30	C	≤ 10
Mo	≤ 50		
Ni	≤ 30		

Tantalum is most important substitutional impurity.

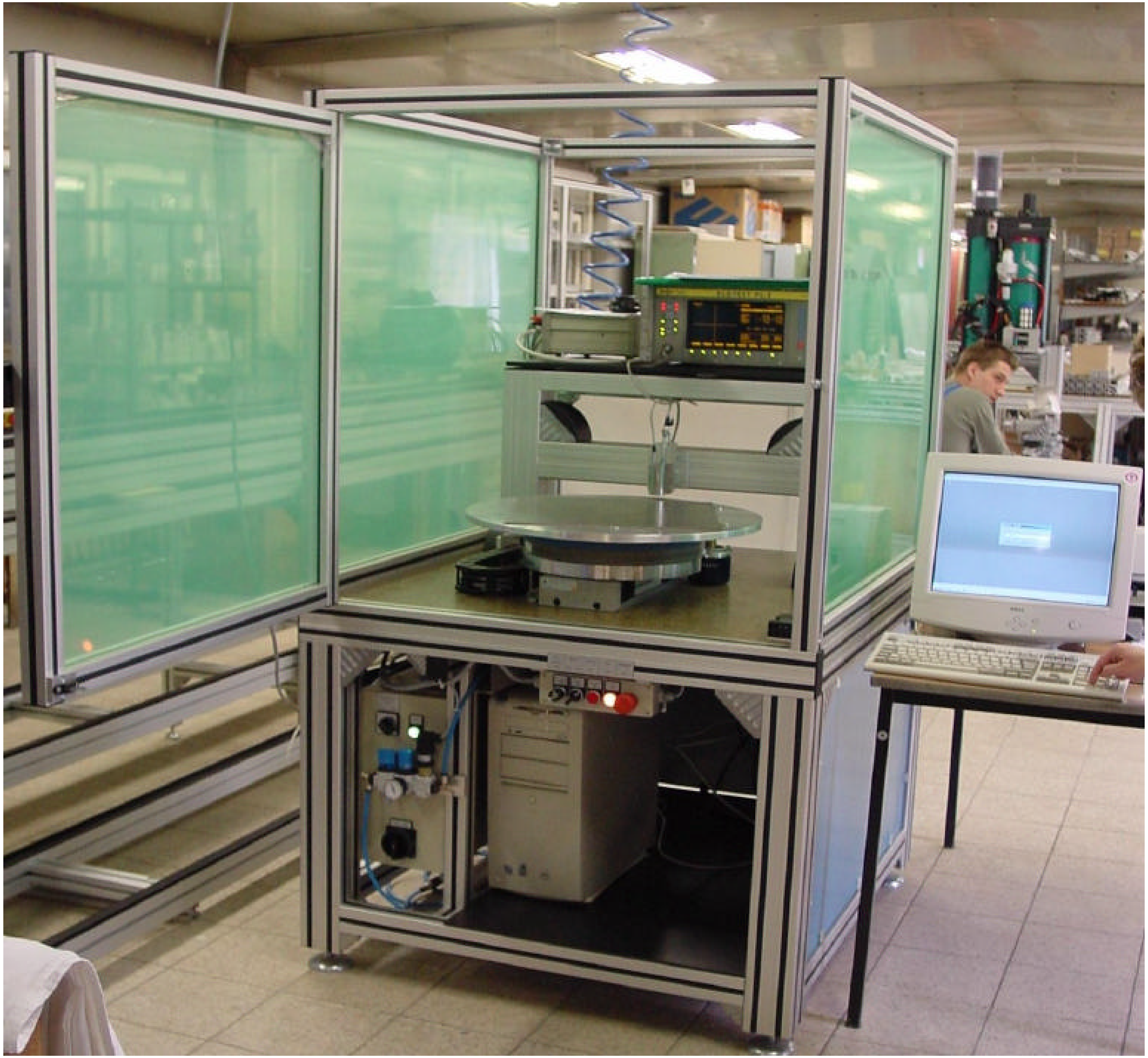
Oxygen and hydrogen are the most important interstitials.

The niobium grain size is very important to have good forming properties .

Mechanical Properties	
Residual resistivity ratio RRR	≥ 300
grain size	$\approx 50\ \mu$m
yield strength	> 50 MPa
tensile strength	> 100 MPa
elongation at break	30 %
Vickers hardness HV 10	≤ 50

Quality control of Nb for cavities

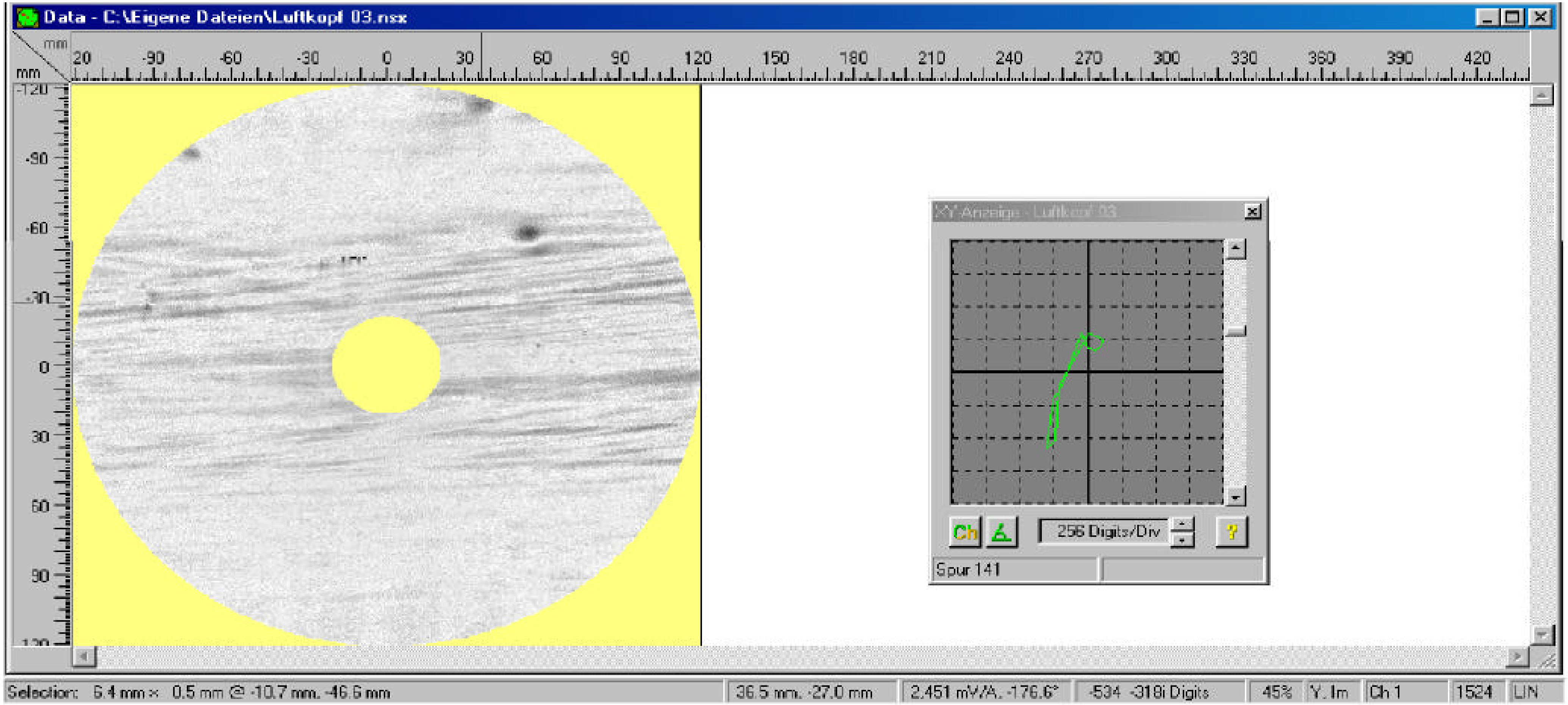
- **Eddy current** scanning of all sheets
  - measures change of electric resistance
  - 0.5mm depth, 40 µm defect dia. sensitivity
  - rejection rate of sheets about 5 %
- **SQUID scanning** under development
- Some **special investigations** on demand
  - x-ray radiography (defect visualization)
  - x-ray fluorescence (defect element determination)
  - neutron activation (Ta distribution)



Eddy current scanner for Niobium sheets

25.02.02

Result of eddy current scanning a Nb disc, dia. 265 mm

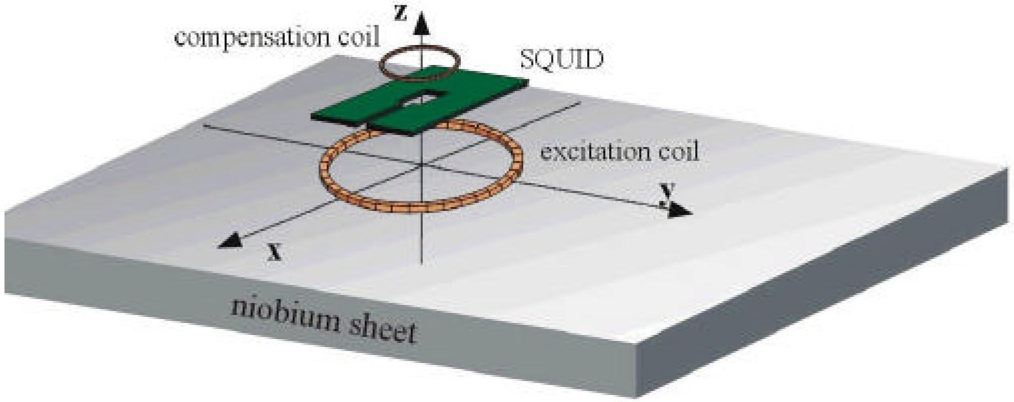


Spur 141

Selection: 6.4 mm × 0.5 mm @ -10.7 mm, -46.6 mm | 36.5 mm, -27.0 mm | 2.451 mV/A, -176.6° | -534 -318i Digits | 45% | Y, Im | Ch 1 | 1524 | LIN

Global view, rolling marks
and defect areas can be seen

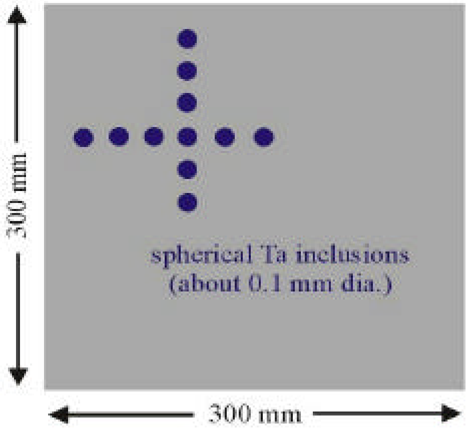
Real and imaginary part
of conductivity at defect,
typical Fe signal

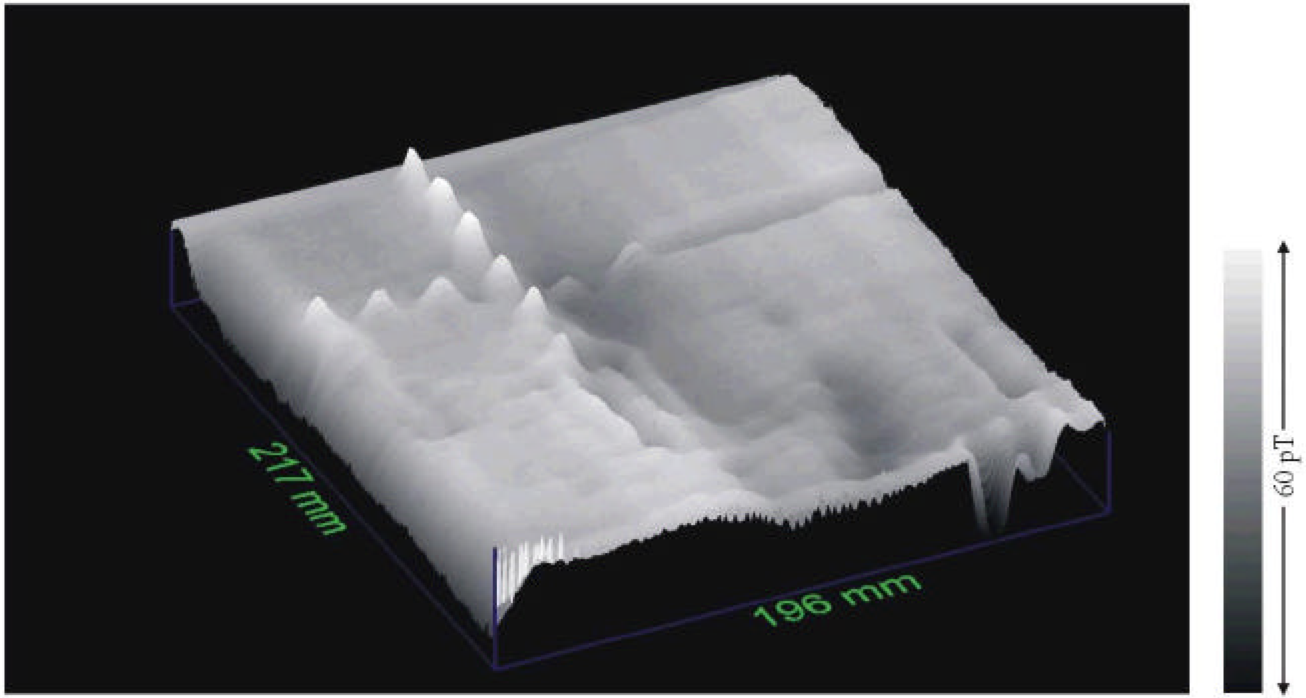


Principal arrangement of SQUID scanning

Measured response from the back side of the sheet

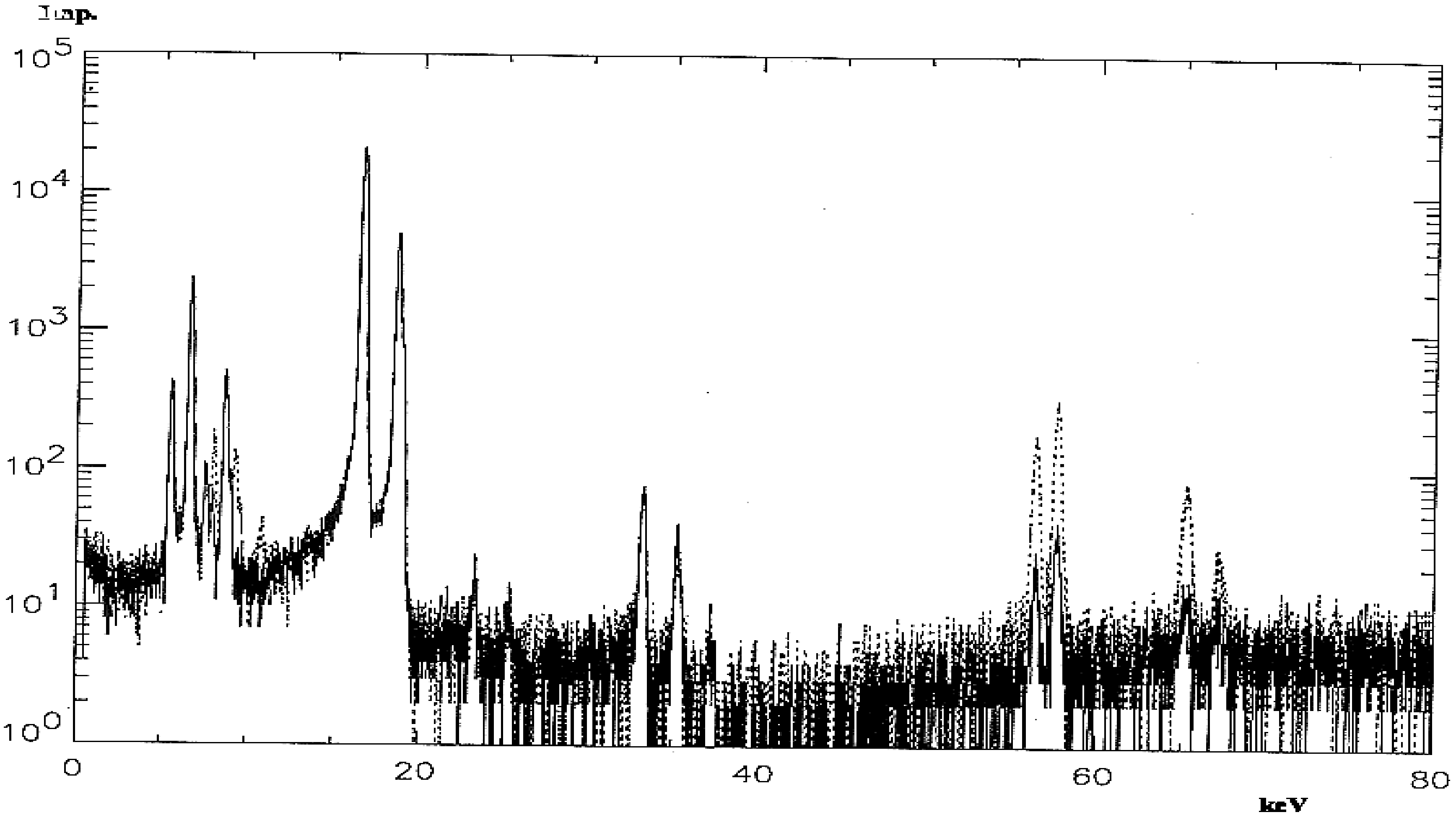
Nb test sheet with .1mm Ta inclusions





Two-dimensional distribution of eddy-current field above the niobium test sample, measured from the back side of the sample. The excitation coil had 30 turns and a diamter of 3 mm; the excitation frequency was 10 kHz. The reference phase of the lock-in amplifier was chosen such that the lift-off effect was minimized.

Analyzing the same defect by synchrotron radiation fluorescence.



Full line is spectrum of Nb next to the defect, dotted line is K-line of Ta at the defect region

Outline

- Example: TESLA cavities
  - What is TESLA?
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  - Higher gradients for TESLA-800
  - Operating SRF cavities

Basis of the TESLA cavities: Where did it all start?

- TESLA cavities are similar in the layout to the succesful CEBAF cavities, which have shown performance above the specified 5 MV/m
- Proposals for further improvements came from several labs:
  - Cornell University
  - CEA Saclay
  - Wuppertal University
  - CERN
  - etc.

CEBAF Cavity Pair Assembly

CEBAF (Jefferson LAB)

from C.E. Reece, Operating Experience With Superconducting Cavities at Jefferson Lab, 8th RF Superconductivity Workshop, Padua, Italy, to be published.

- is in full operation
- is delivering beam at 4.4 GeV / 115 μA
- is using 330 s.c. cavities operated at 1497 MHz / 2 K

- has grouped the cavities in pairs (2 cavities)
  and units (4 pairs)
- operates each cavity with its own 5 kW klystron
- reaches an average usable gradient of 7.5 MV/m
  an accelerating gradient spread of 5 MV/m FWHM
  an average quench limit of 13 MV/m !!!

- has a stable and reliable cavity operation
- could support higher energies (5.6 GeV)

- is going to increase the usable gradient by in-situ He processing
- is developing an upgrade (J.R. Delayen, this conference)

Distribution of Maximum Operational SRF Cavity Gradients in CEBAF by Type of Limitation

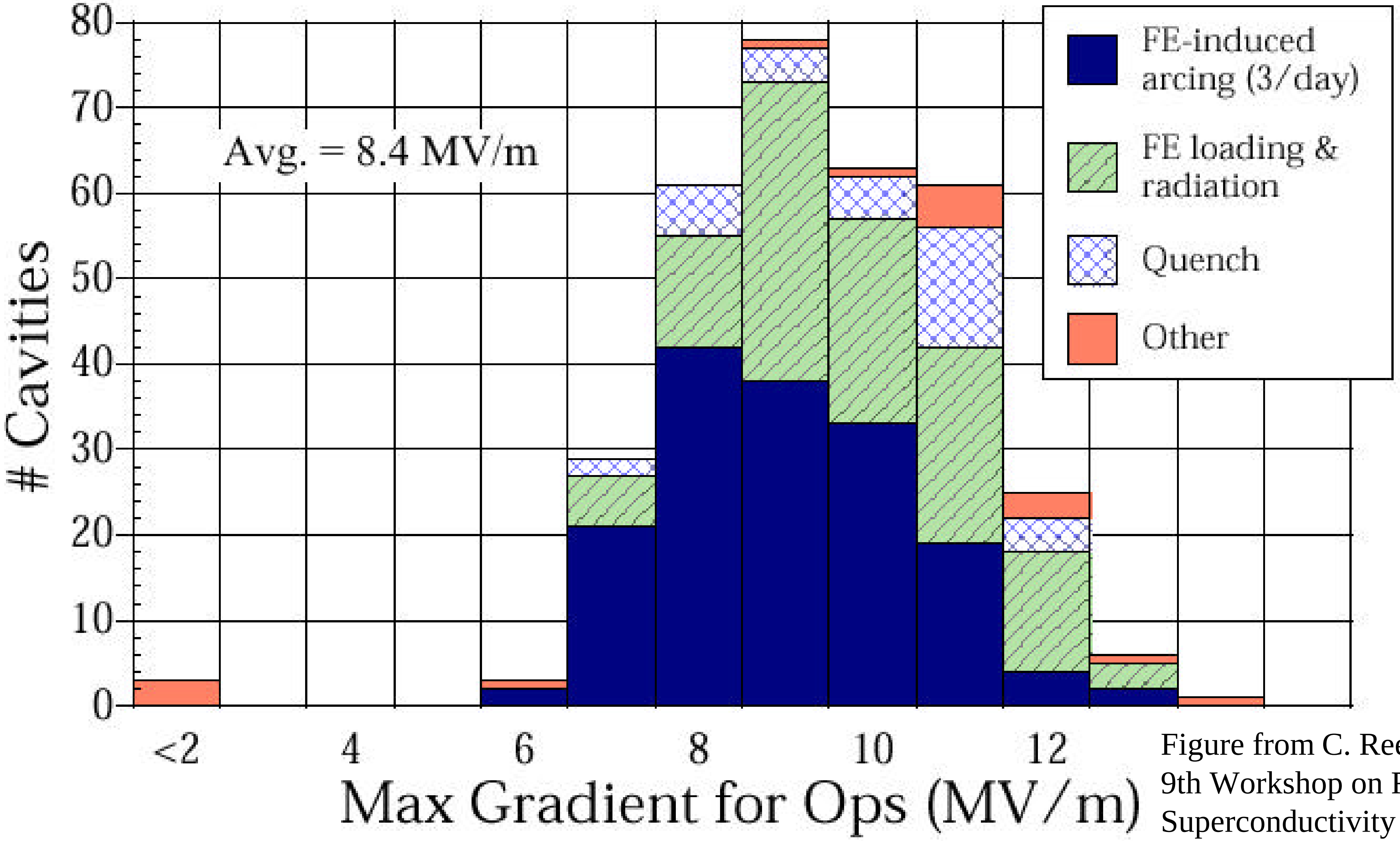
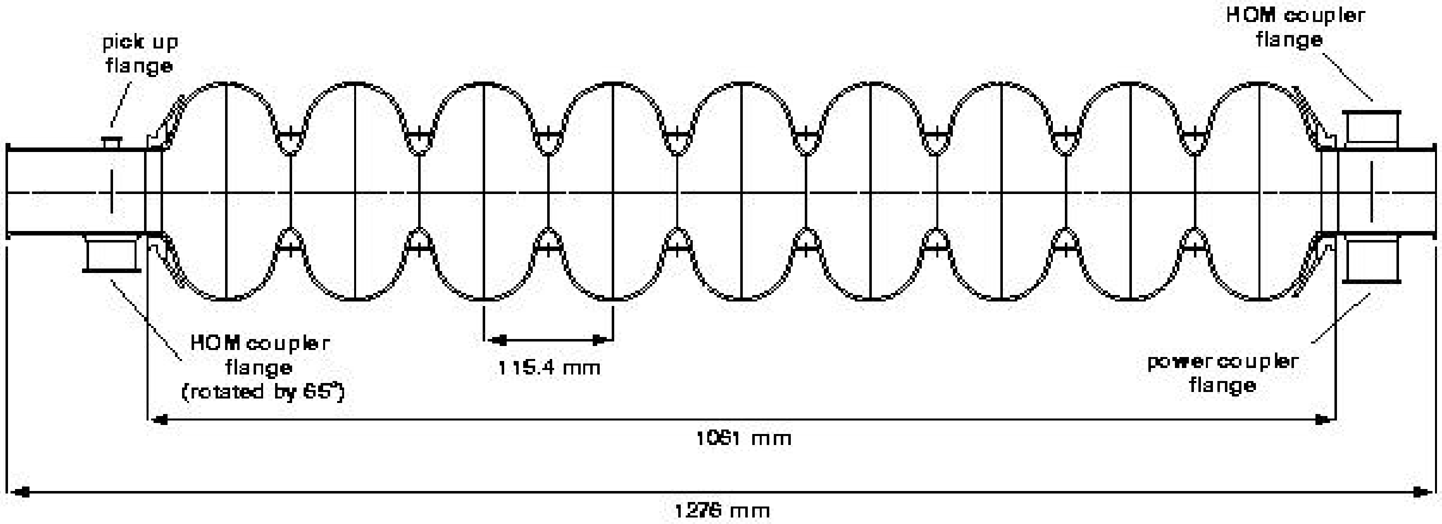


Figure from C. Reece, 9th Workshop on RF Superconductivity

TESLA cavity (9-cell)



type of accelerating structure	standing wave
accelerating mode	TM0 π mode
fundamental frequency	1300 MHz
design gradient E_{acc} (TTF)	15 MV/m
design gradient E_{acc} (TESLA)	25 MV/m
unloaded quality factor Q_0 (TTF)	$> 3 \times 10^9$
unloaded quality factor Q_0 (TESLA)	$> 5 \times 10^9$
shunt impedance R / Q	1036 Ω
E_{peak} / E_{acc}	2.0
B_{peak} / E_{acc}	4.26 mT / (MV/m)
cavity bandwidth at $Q_0 = 3 \times 10^6$	430 Hz

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  - Operating SRF cavities

Production and preparation of TESLA cavities

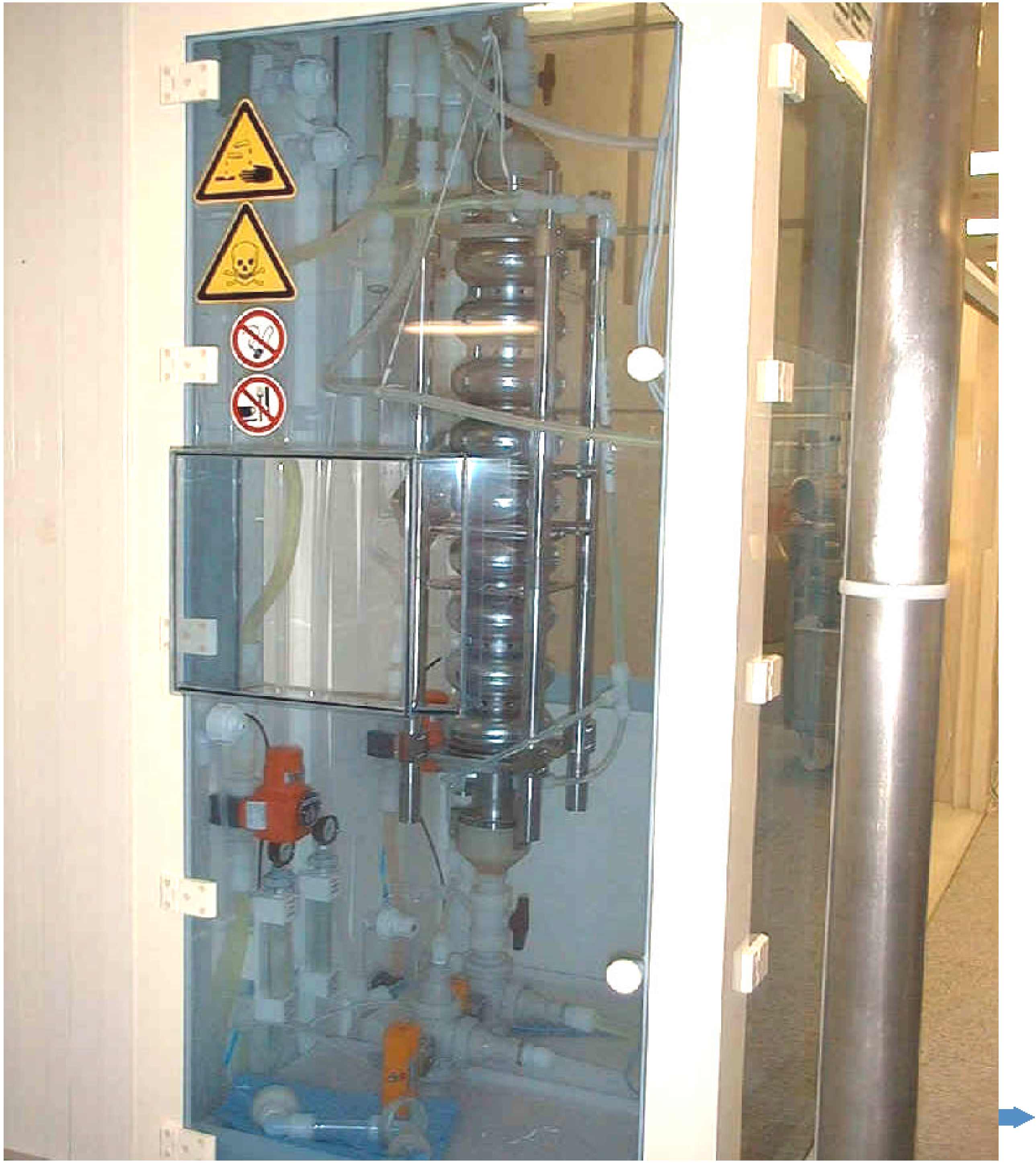
- Niobium sheets (RRR=300) are subjected to eddy-current scanning to avoid foreign material inclusions like tantalum and iron

- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification

- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)

- Chemical etching to remove damage layer and titanium getter layer
- High pressure water rinsing as final treatment to avoid particle contamination

Standard Cavity Production (EB welding)



Surface preparation

Chemical etching of the inner surface (100μm) by closed pumping circuit. Acid cooled to 9°C.

Detailed preparation sequence for niobium cavities

- removal of the damage layer by chemical etching
- 2 hours heat treatment at 800 C - remove hydrogen and stress anneal
- 4 hours heat treatment at 1400 C with titanium getter for higher thermal conductivity to stabilize defects
- removal of the titanium layer by chemical etching
- field flatness tuning
- final 20 µm removal from the inner surface by etching
- high pressure rinsing (HPR) with ultrapure water
- drying by laminar flow in a class 10 cleanroom
- assembly of all flanges, leak-check
- 2 times HPR, drying by laminar flow and assembly
- of the input antenna with high external Q

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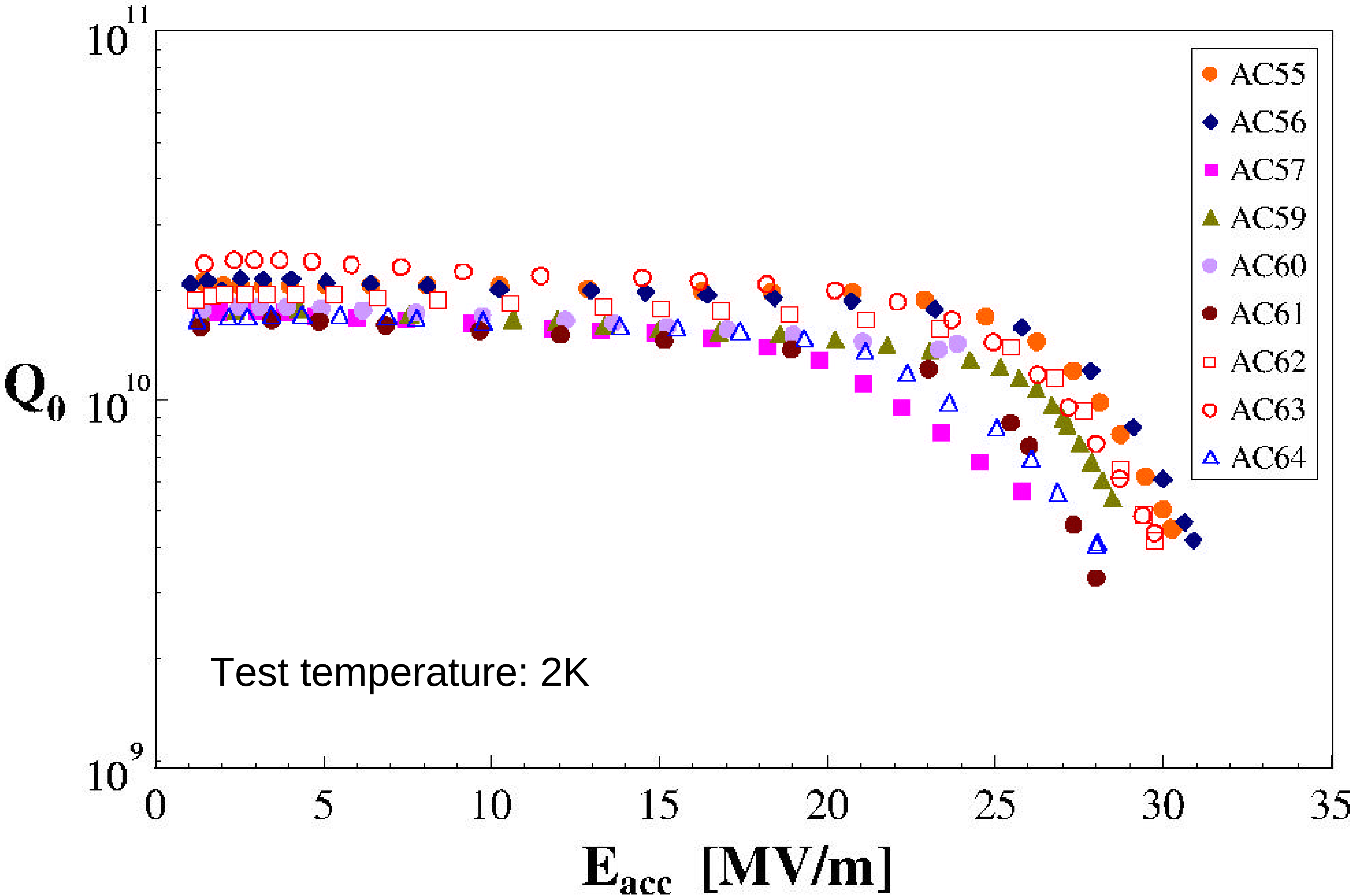
Latest production of TESLA-type nine-cell cavities

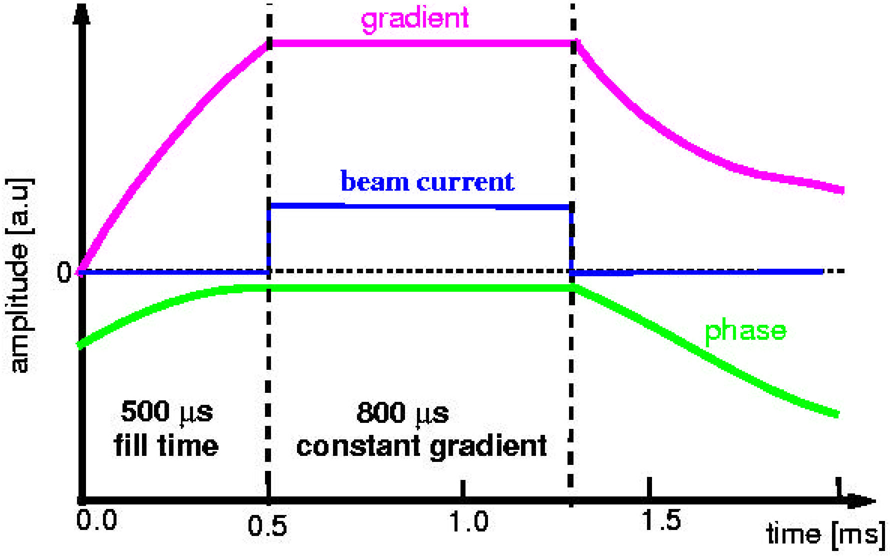


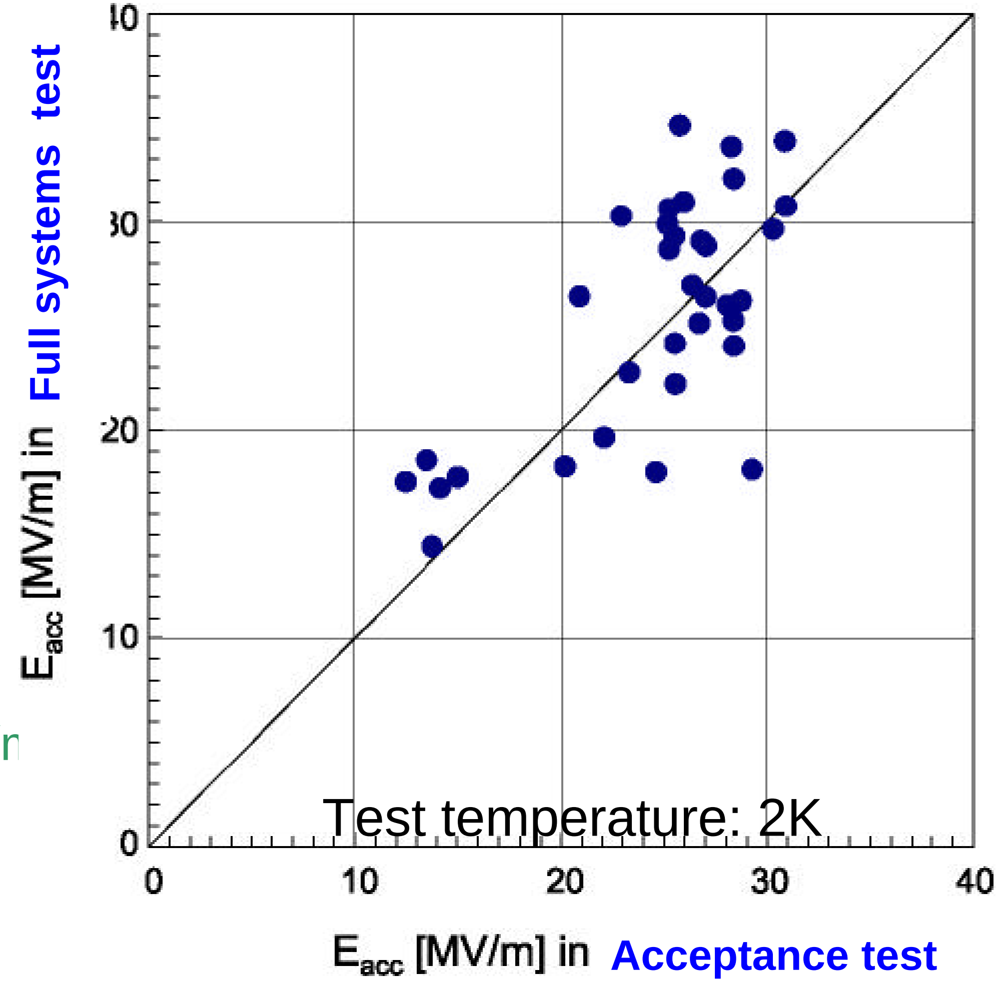
Acceptance test vs. Full systems test

- Acceptance test
  - Continuous wave measurement (ca. 5 hours) with high Q antenna
  - Conservative evaluation:
    - take the gradient where the **Q_0 ³ 10^{10}**

    ⇒ far below the breakdown field of the cavity
- Full systems test with main power coupler
  - pulsed test with:
    - 500 µs rise time
    - 800 µs flat-top
    - 10 Hz repetition rate
- Good agreement between both test methods

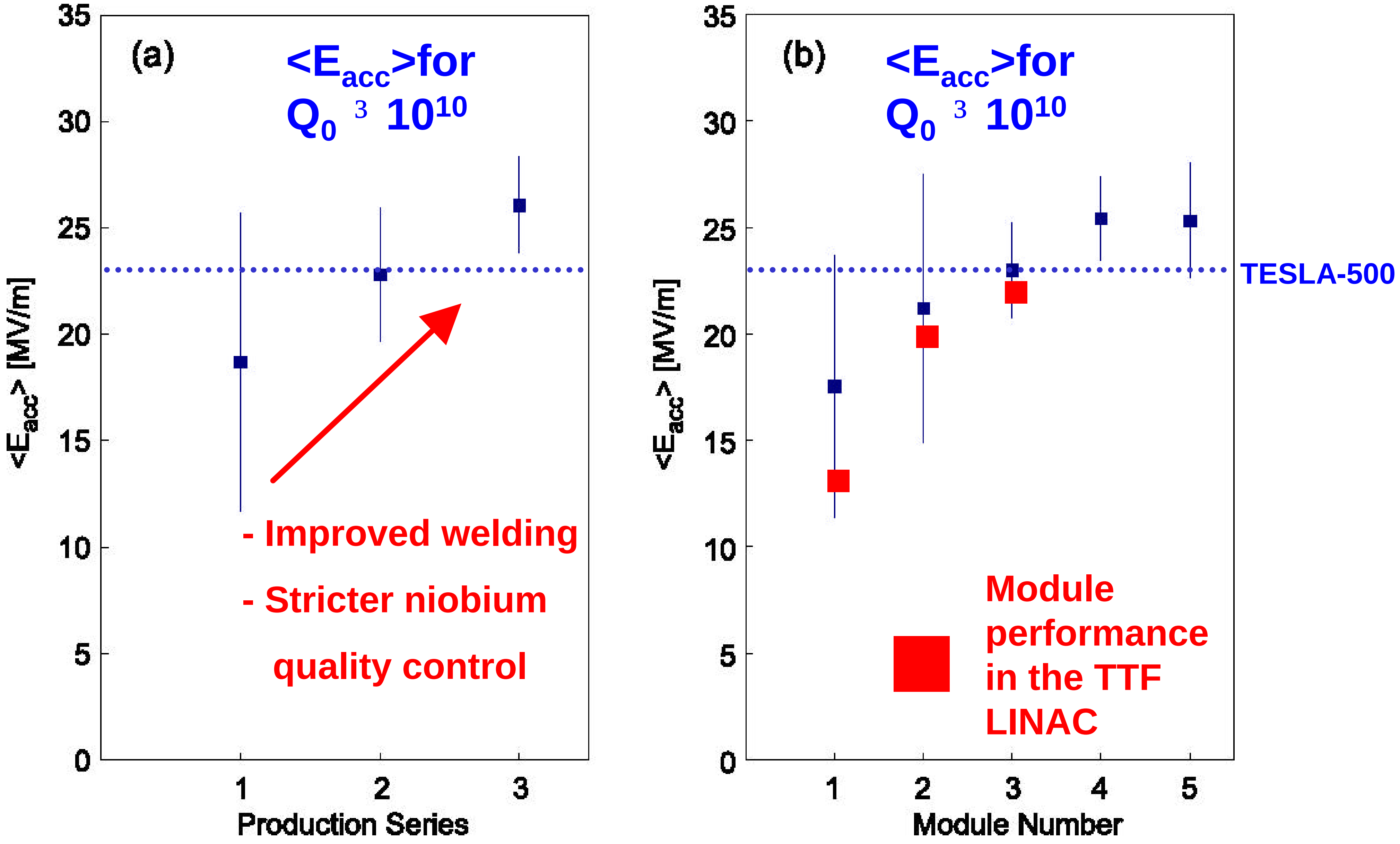
Acceptance test vs. full systems test





- Several cavities sustain more than 30 MV/r in pulsed measurement
- Results scatter around $E_{acc, cw} = E_{acc, pulse}$
- Prediction of the cavity behaviour in the LINAC is possible

Results of cavity productions



Lutz Lilje DESY

TESLA

25.02.02

Modules in the TTF LINAC

- Averages of accelerating gradients taken - not optimised for single cavity performance
- Predicted gradient from cw measurement agrees well with module performance
- Total operation time of sc cavities is about 8000 hours
- High gradient operation at 20 and 22 MV/m in the 2 modules about 700 hours
    - Reason: FEL people want lower gradient
- Installed in the LINAC
    - no third production cavities yet -> in 2002
    - no third production couplers yet -> in 2002

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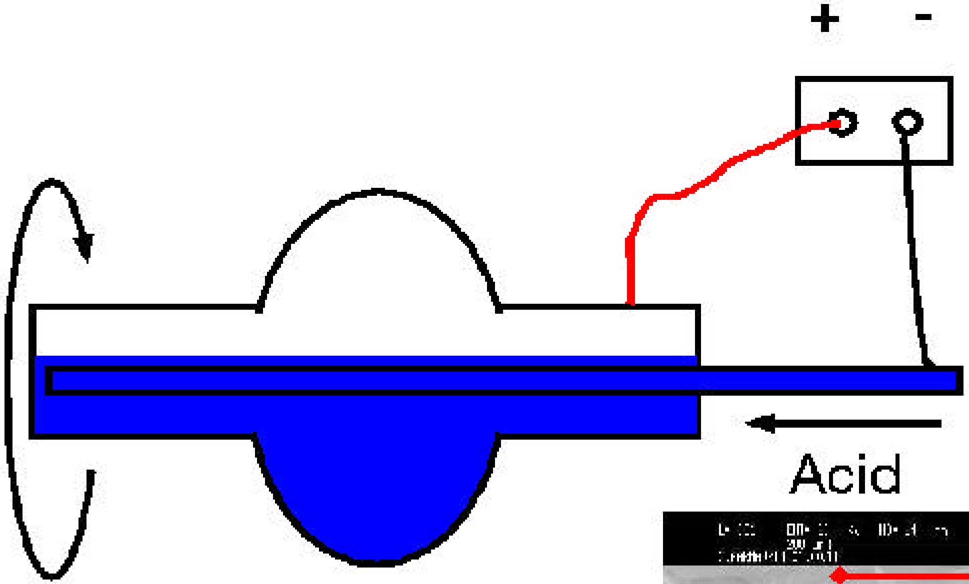
  - Higher gradients for TESLA-800
    - Electropolishing
    - Alternative manufacturing techniques
    - ‘Superstructure’
  - Operating SRF cavities

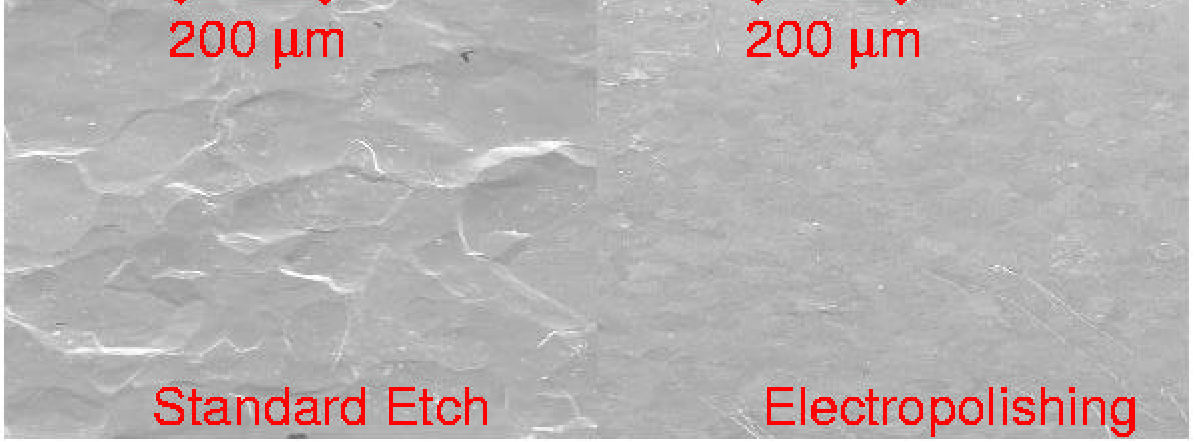
Electropolishing: The way to highest gradients

- Benefits of electrolytic polishing (EP):
  - bright and smooth surface
  - more than 40 MV/m achieved in several 1.3 GHz 1-cell cavities
  - suppression of field emission
  - 1400°C heat treatment seems to be unnecessary
  - works also for very different manufacturing techniques (see later)

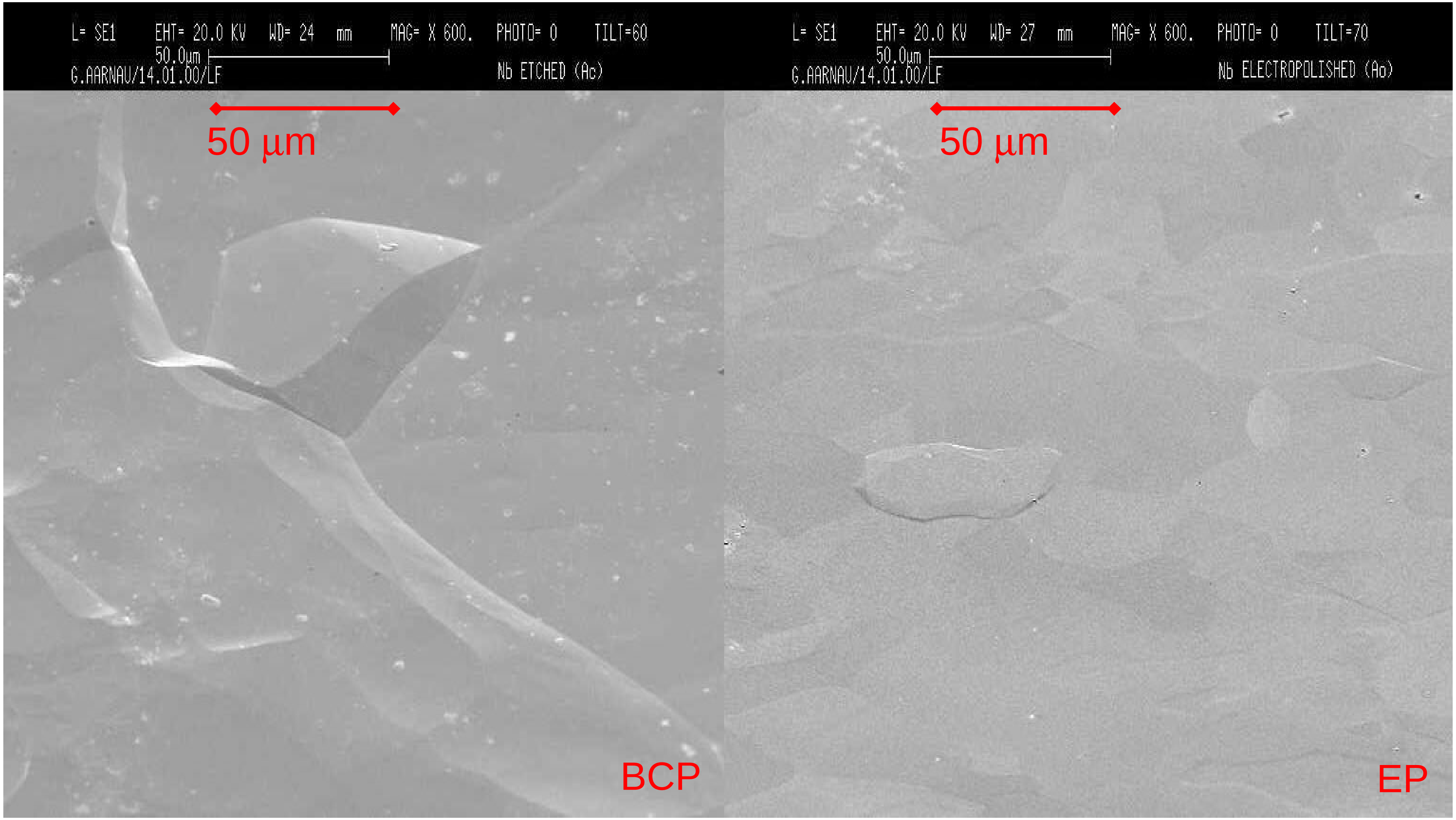
Electropolishing of 1-cell cavities
(Scheme)



- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 µm/min removal of material



Niobium surfaces

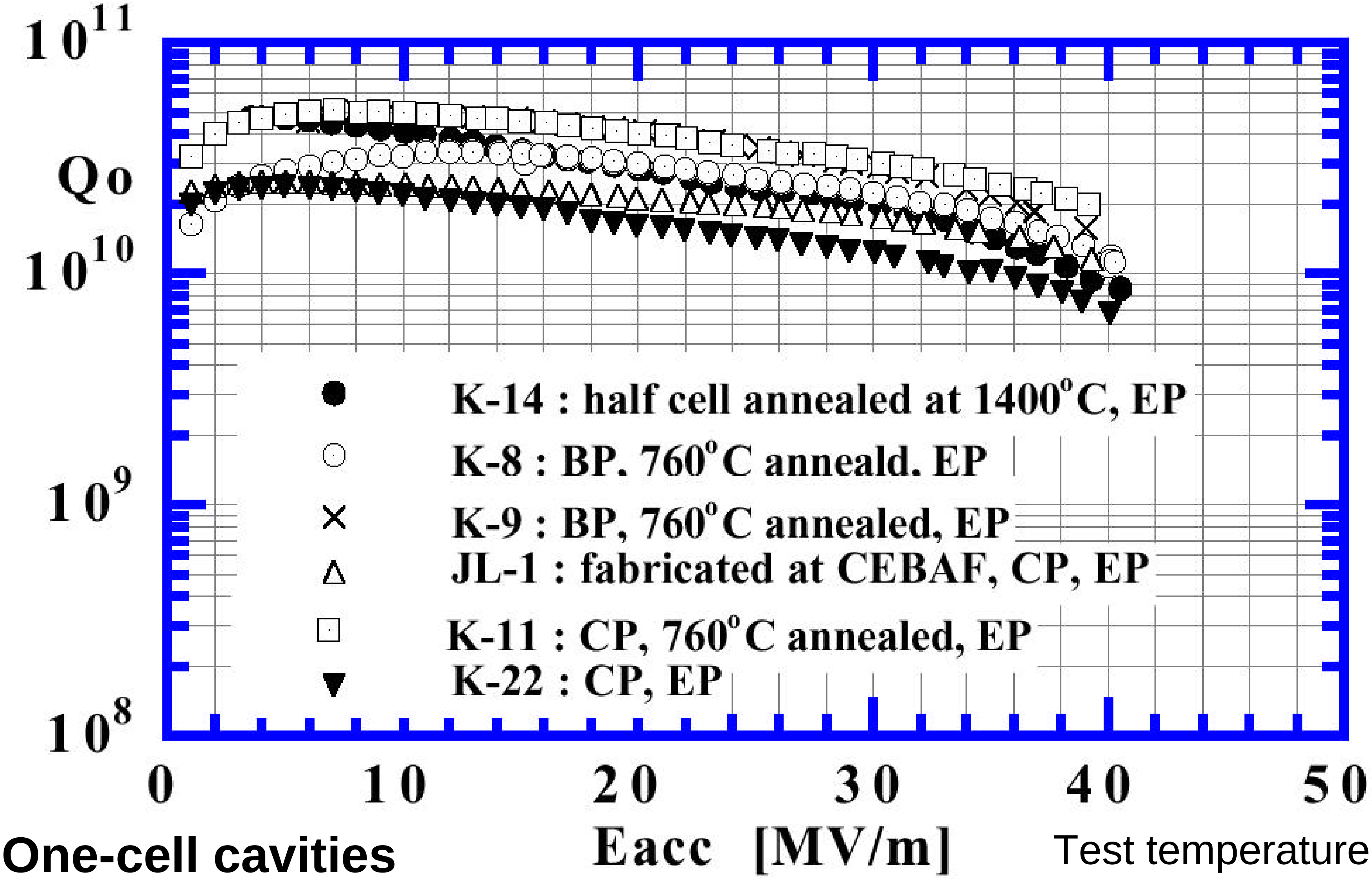


Niobium chemistry

- Oxidation
  - Electropolishing:
    - $2\ Nb + 5\ SO_4^{--} + 5\ H_2O \rightarrow Nb_2O_5 + 10\ H^+ + 5SO_4^{--} + 10\ e^-$
  - Chemical etching:
    - $2\ Nb + 5\ NO_3^- \rightarrow Nb_2O_5 + 5\ NO_2^{\ -}$
  - Anodizing:
    - $2\ Nb + 5\ OH^- \rightarrow Nb_2O_5 + 5\ H^+ + 10\ e^-$
- Complex forming
    - $Nb_2O_5 + 6\ HF \rightarrow H_2NbOF_5 + NbO_2 \bullet 0.5\ H_2O + 1.5\ H_20$
    - $NbO_2 \bullet 0.5\ H_2O + 4\ HF \rightarrow H_2NbF_5 + 1.5\ H_2O$

KEK results for electropolished niobium cavities

K. Saito et al. KEK 1998/1999

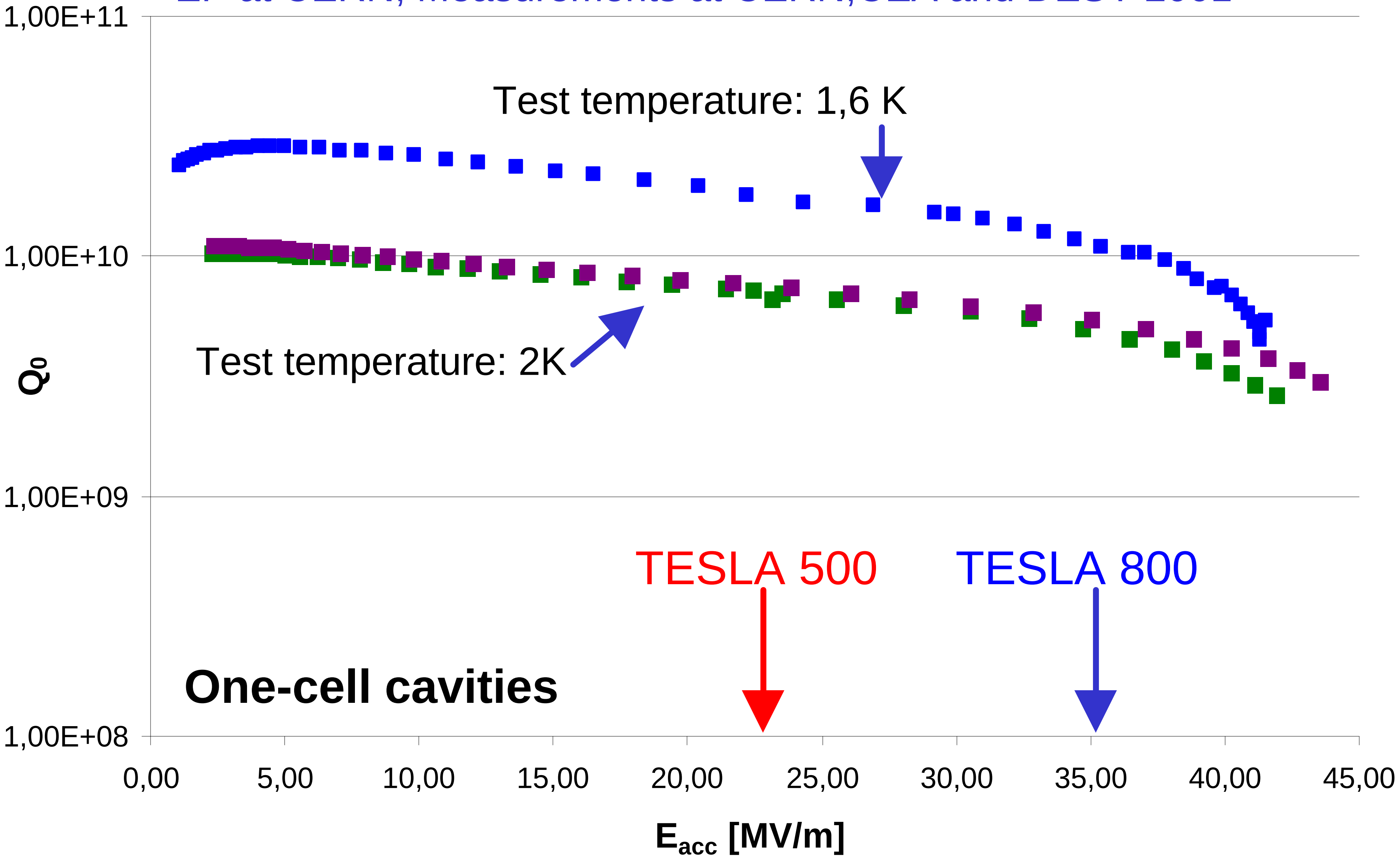


One-cell cavities

Test temperature: 1,6 K

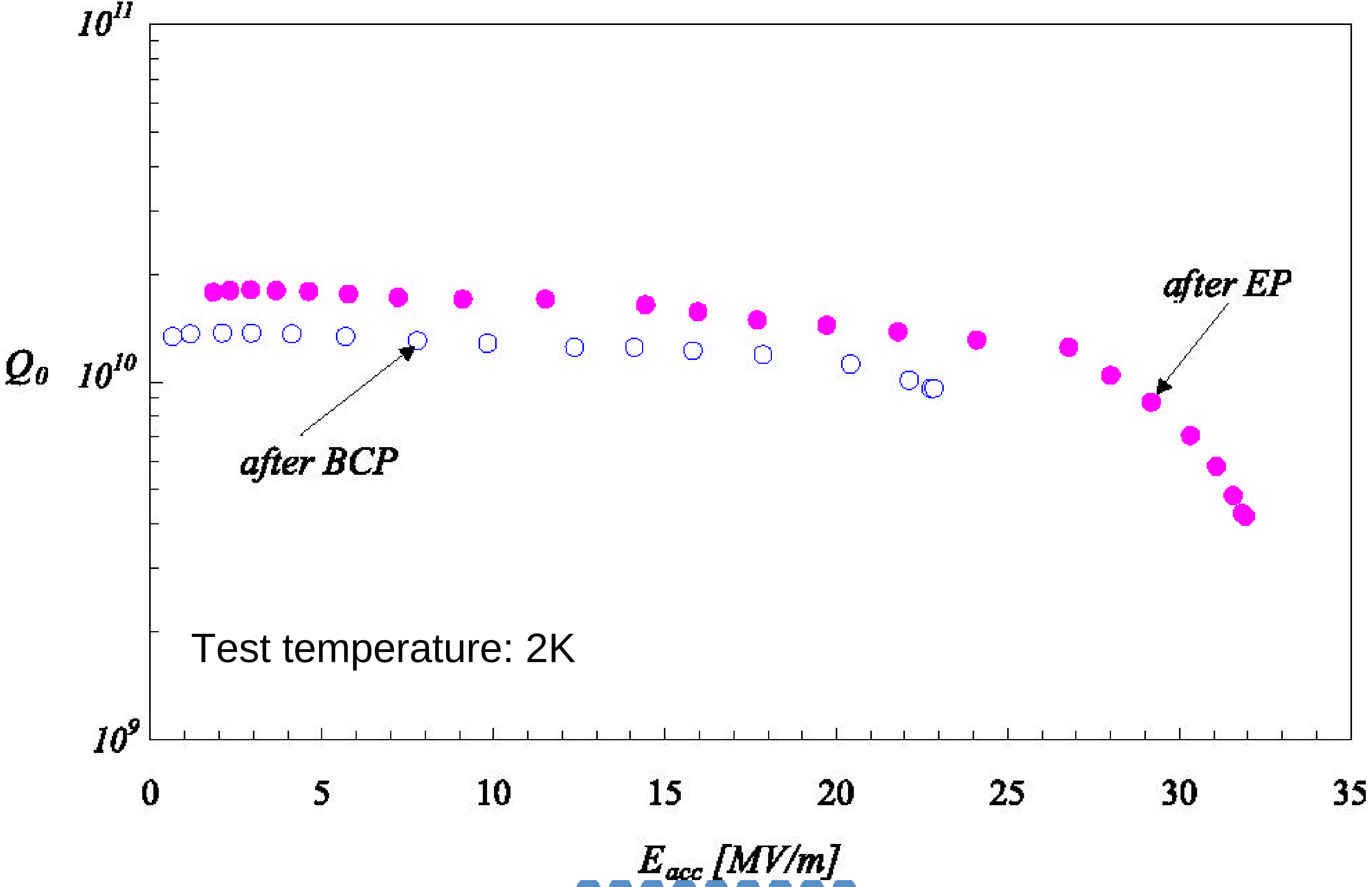
Electropolished cavities

EP at CERN, Measurements at CERN,CEA and DESY 2001



Electropolished TESLA nine-cell cavity

EP at Nomura Plating and KEK, Test at DESY

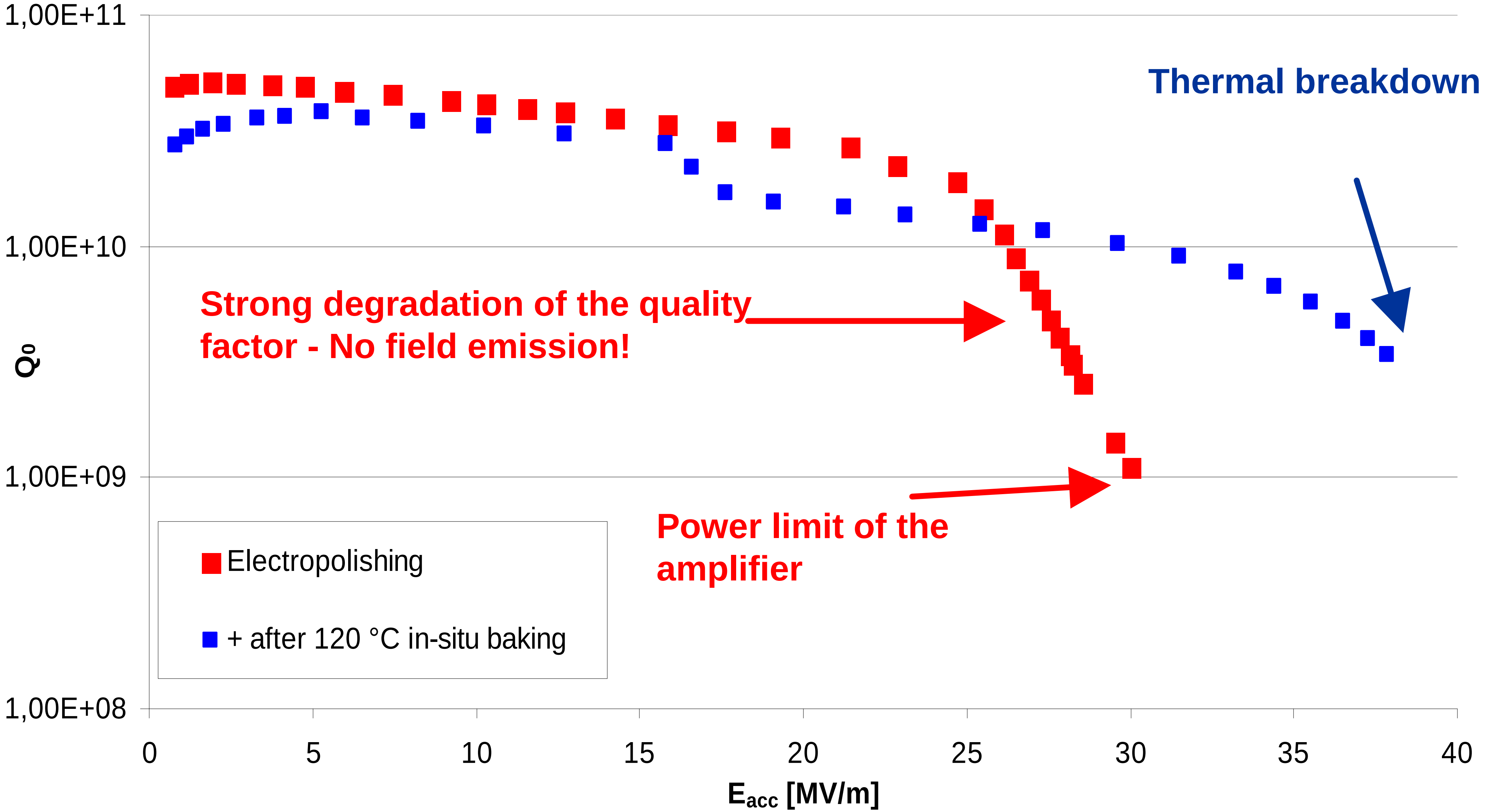


Test temperature: 2K

In-situ Baking

- Heating of the cavity to 100 - 120 °C
- Duration: ca. 40 hours
- Pressure below 10^{-6} mbar
- Inert gas atmosphere on the outside

Improvement by ‘In-situ’ baking

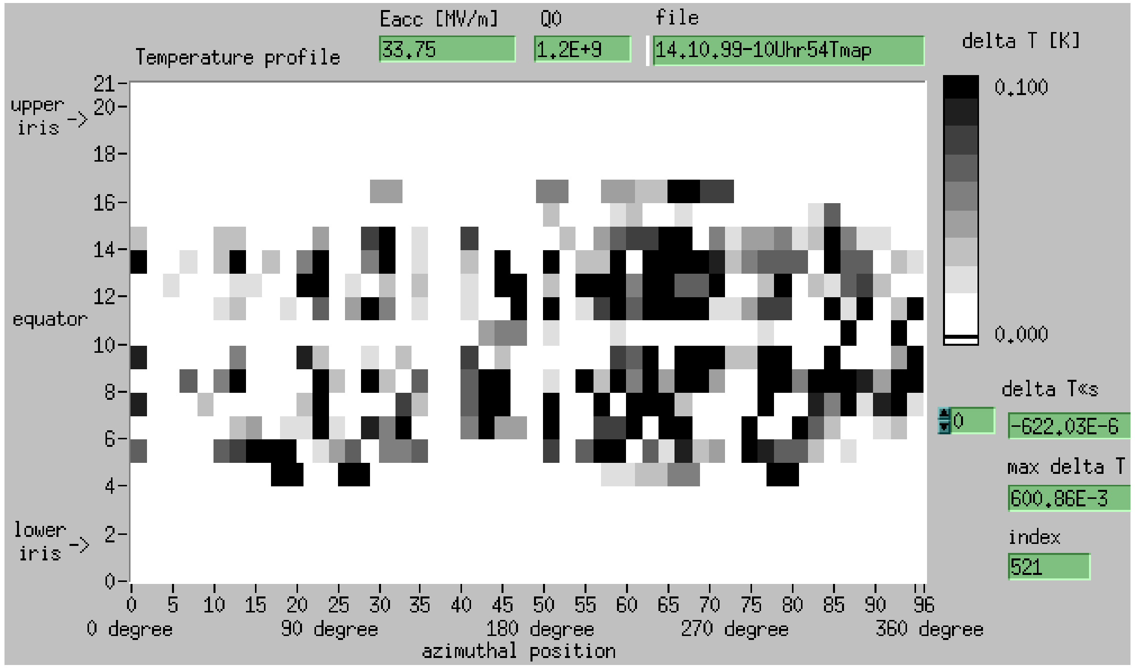


Thermal breakdown

Strong degradation of the quality factor - No field emission!

Power limit of the amplifier

Temperature mapping at 33MV/m



Temperature profile

Eacc [MV/m] 33.75

Q0 1.2E+9

file 14.10.99-10Uhr54Tmap

delta T [K]

delta T<s -622.03E-6

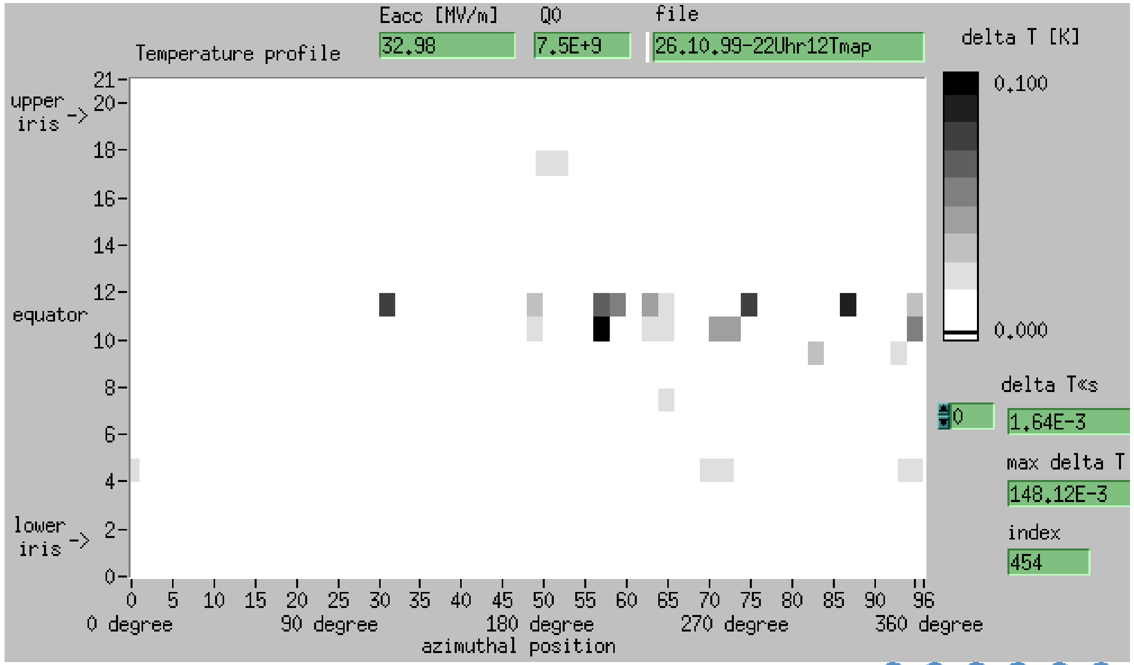
max delta T 600.86E-3

index 521

... before in-situ bakeout at 120°C

⇒ Large area in the high magnetic field region of the cavity heats up

⇒ Global effect



Temperature profile

Eacc [MV/m] 32.98

Q0 7.5E+9

file 26.10.99-22Uhr12Tmap

delta T [K]

delta T<s 1.64E-3

max delta T 148.12E-3

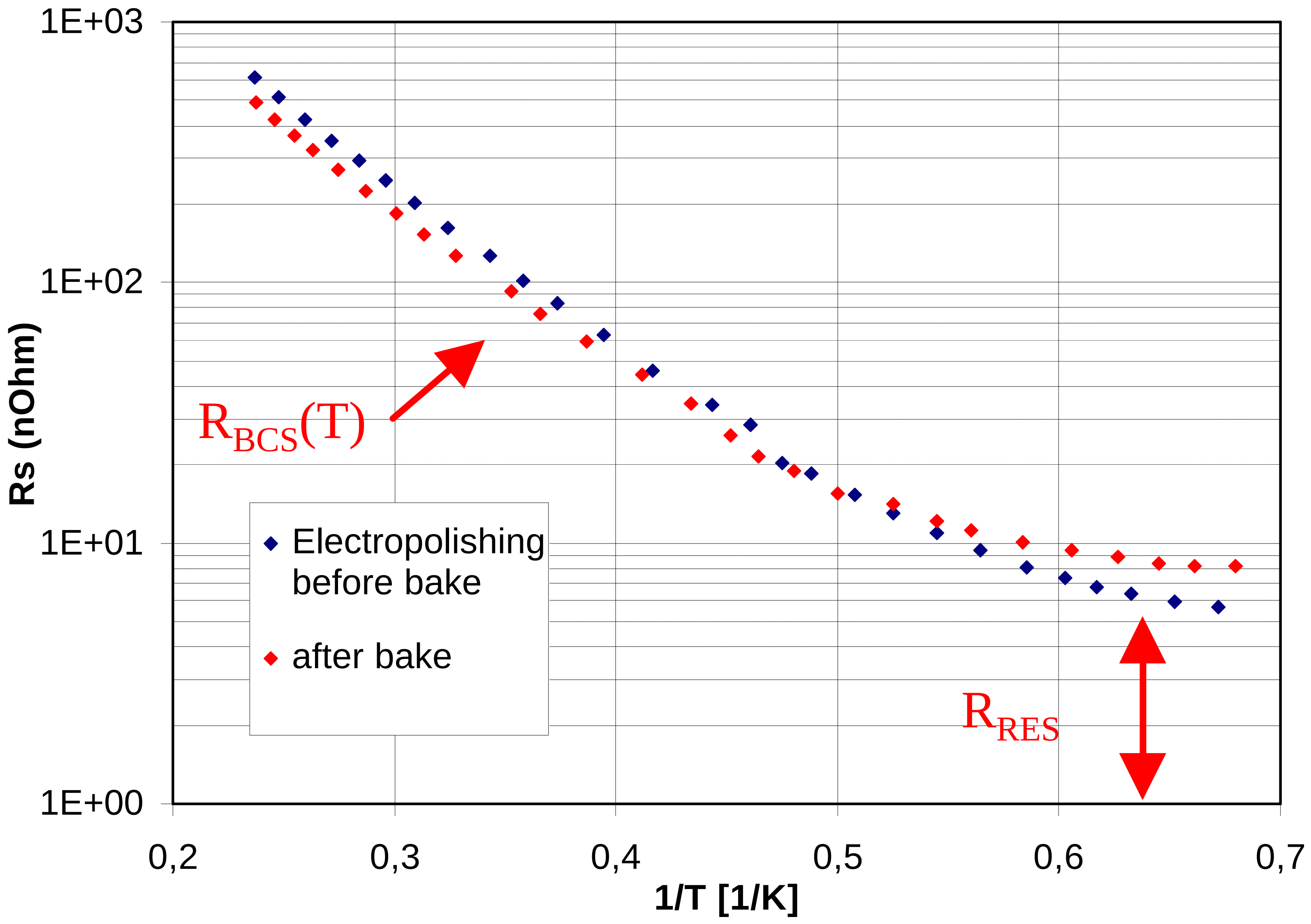
index 454

... after in-situ bakeout at 120°C

⇒ Heating of the equator welding

⇒ Change of the surface properties of the niobium

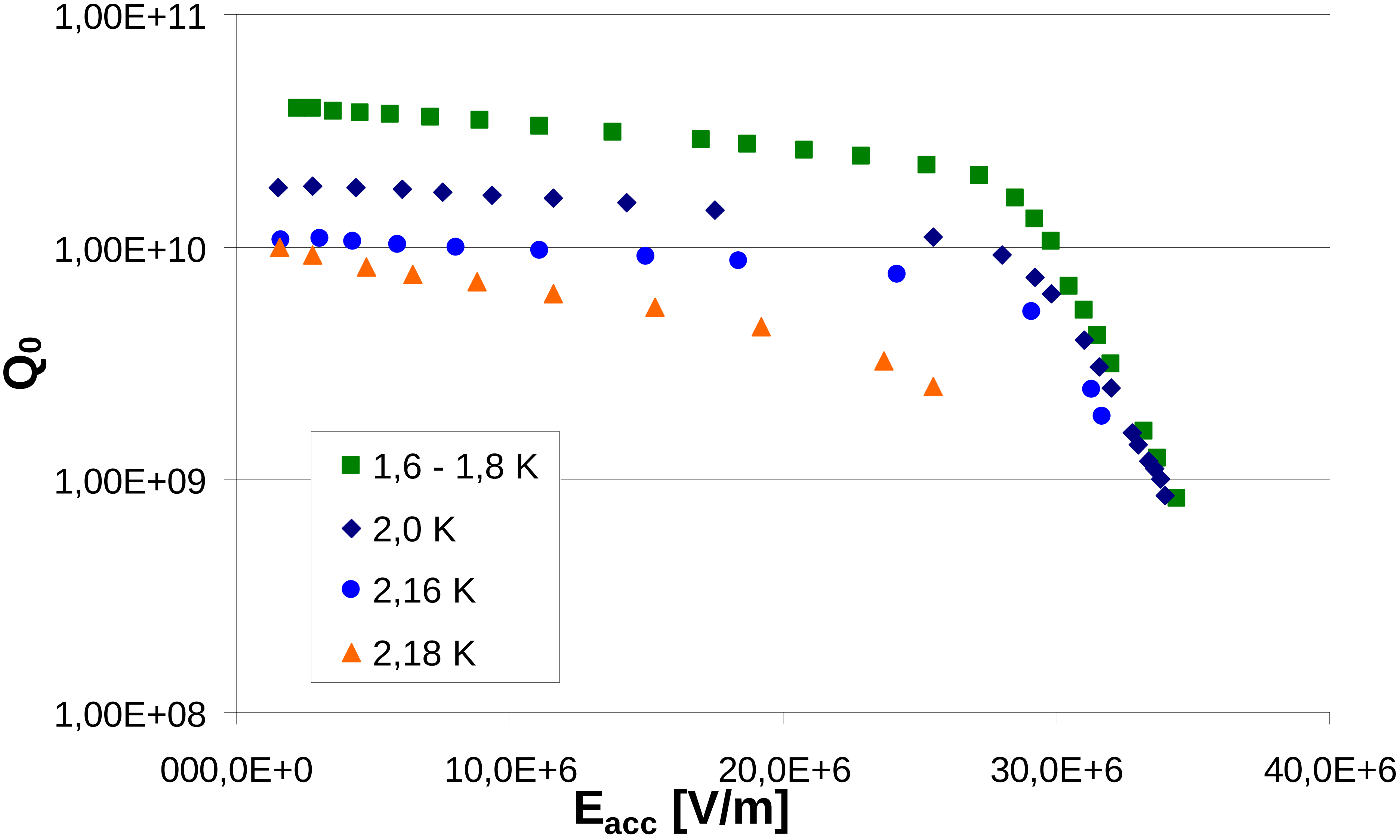
Surface resistance R_s



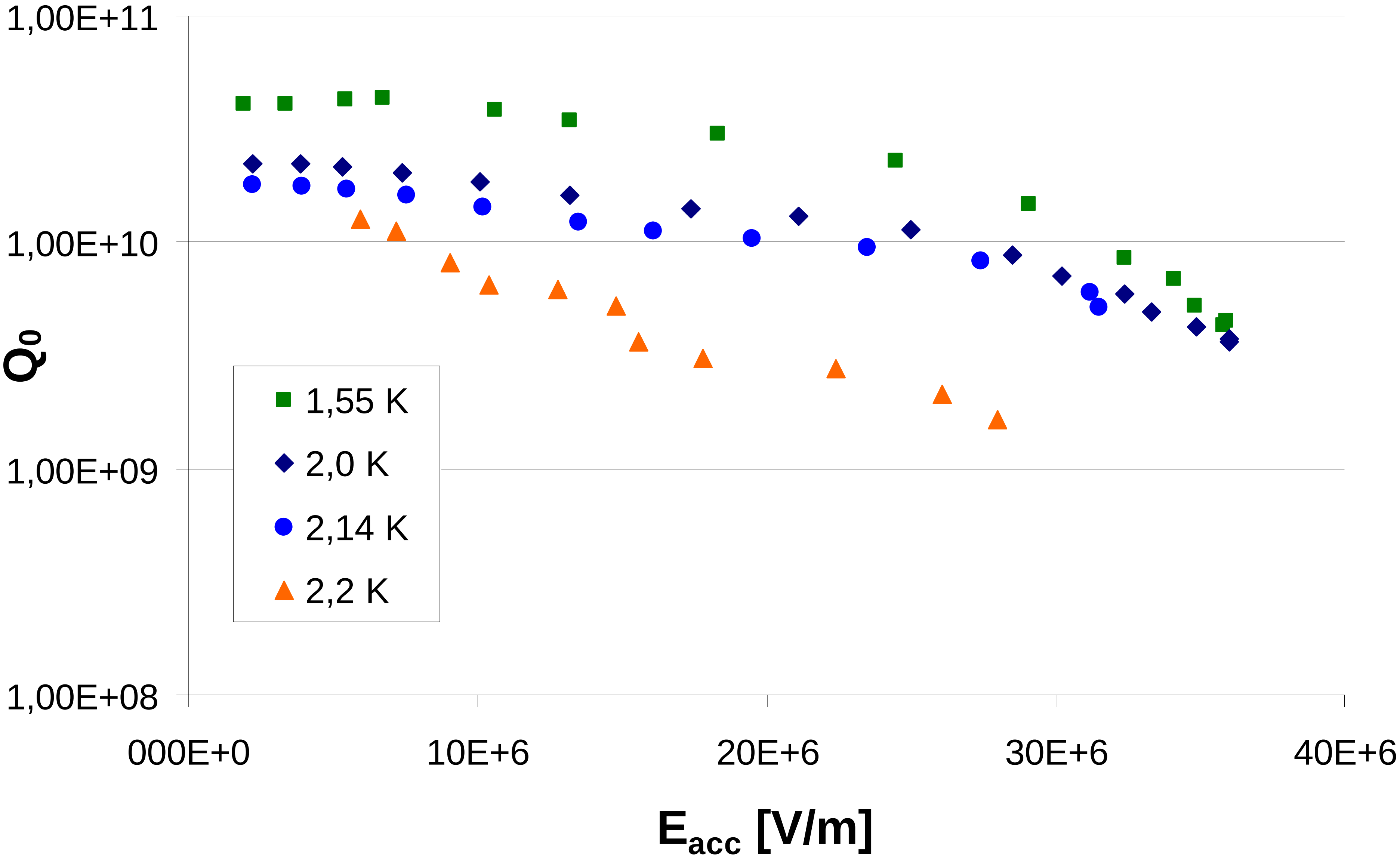
$R_{BCS}(T)$

R_{RES}

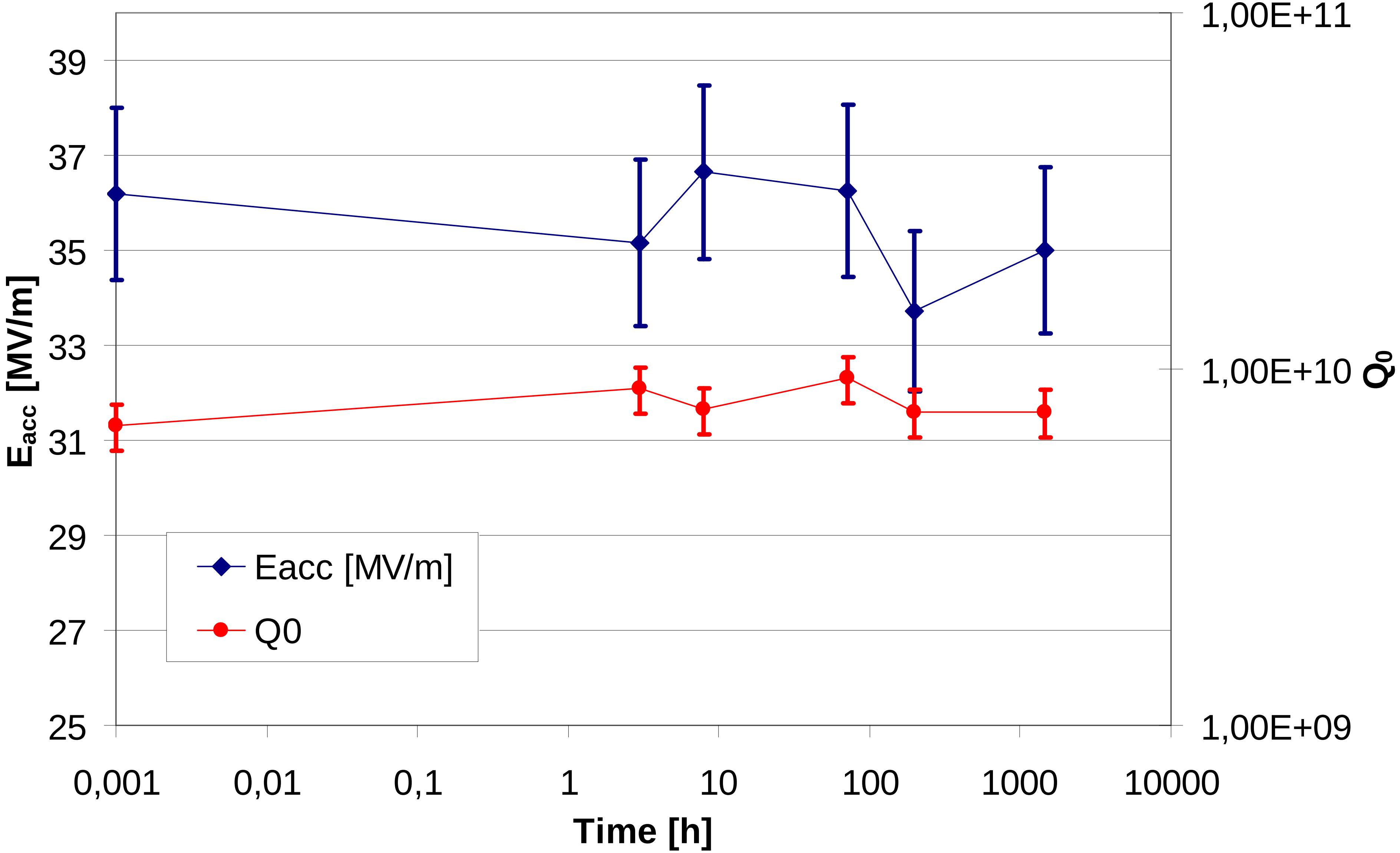
Q(E_{acc}) before bake



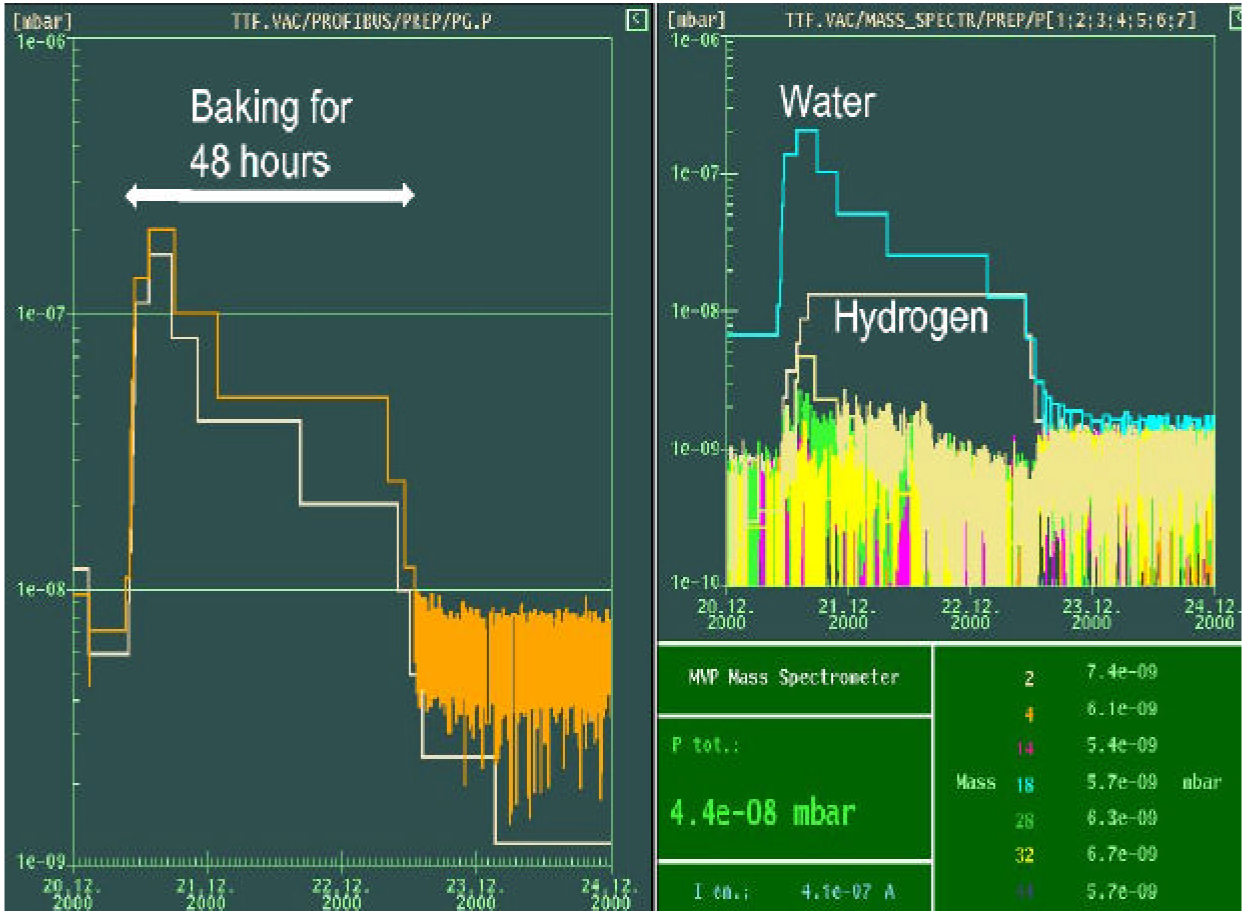
Q(E_{acc}) after bake



Air exposure of a baked niobium surface



Residual gas analysis during bakeout



MVP Mass Spectrometer

P tot.:

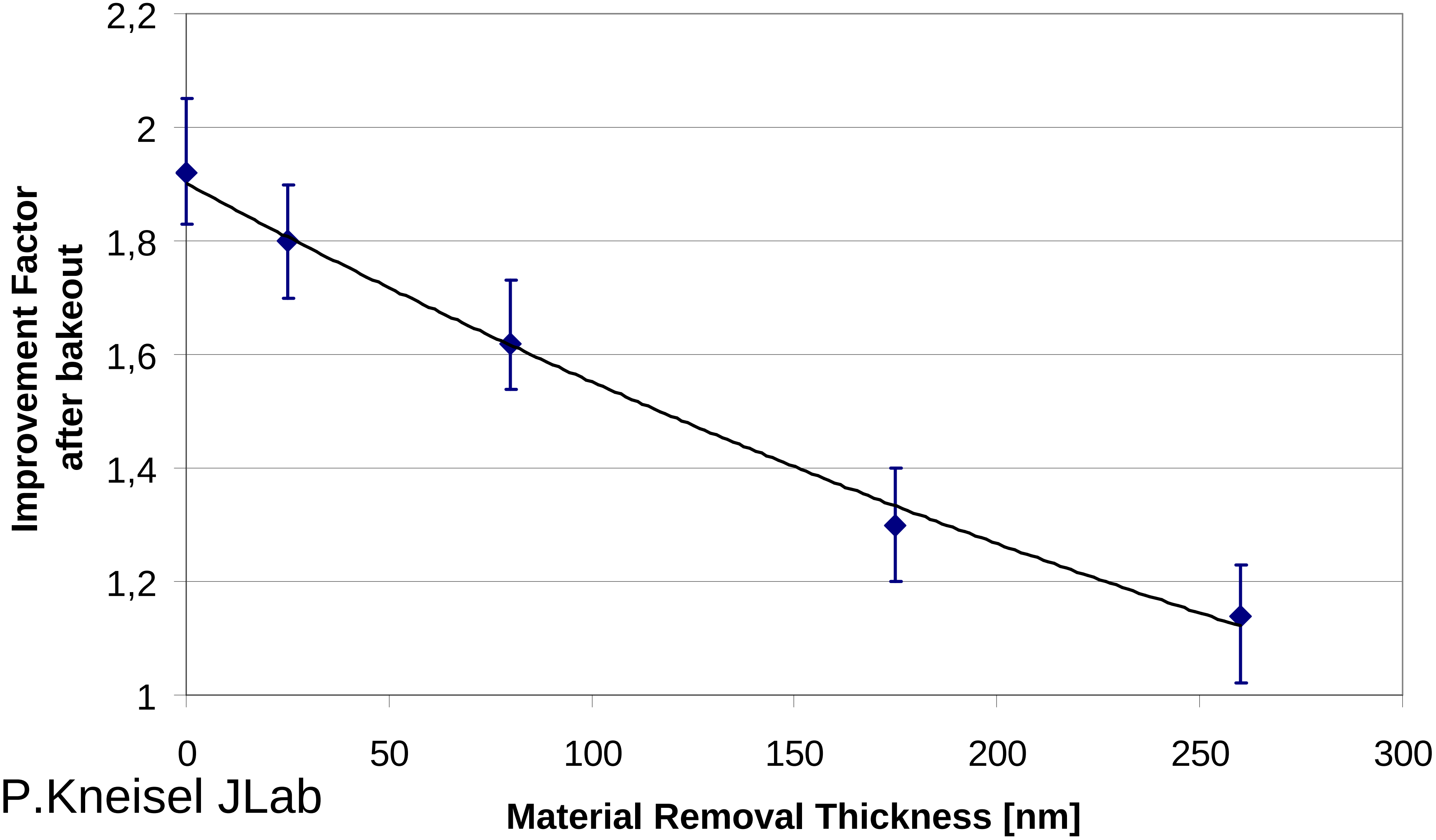
4.4e-08 mbar

I em.: 4.1e-07 A

Mass	2	7.4e-09	mbar
	4	6.1e-09	
	14	5.4e-09	
	18	5.7e-09	
	28	6.3e-09	
	32	6.7e-09	
	[illegible]	5.7e-09	

- It is mostly water and hydrogenf
- Bake-out effect stays even after a new exposure to air and high pressure water rinsing, therefore it is unlikely that adsorbed gasses play a role.

Thickness of the surface layer affected by the bake effect



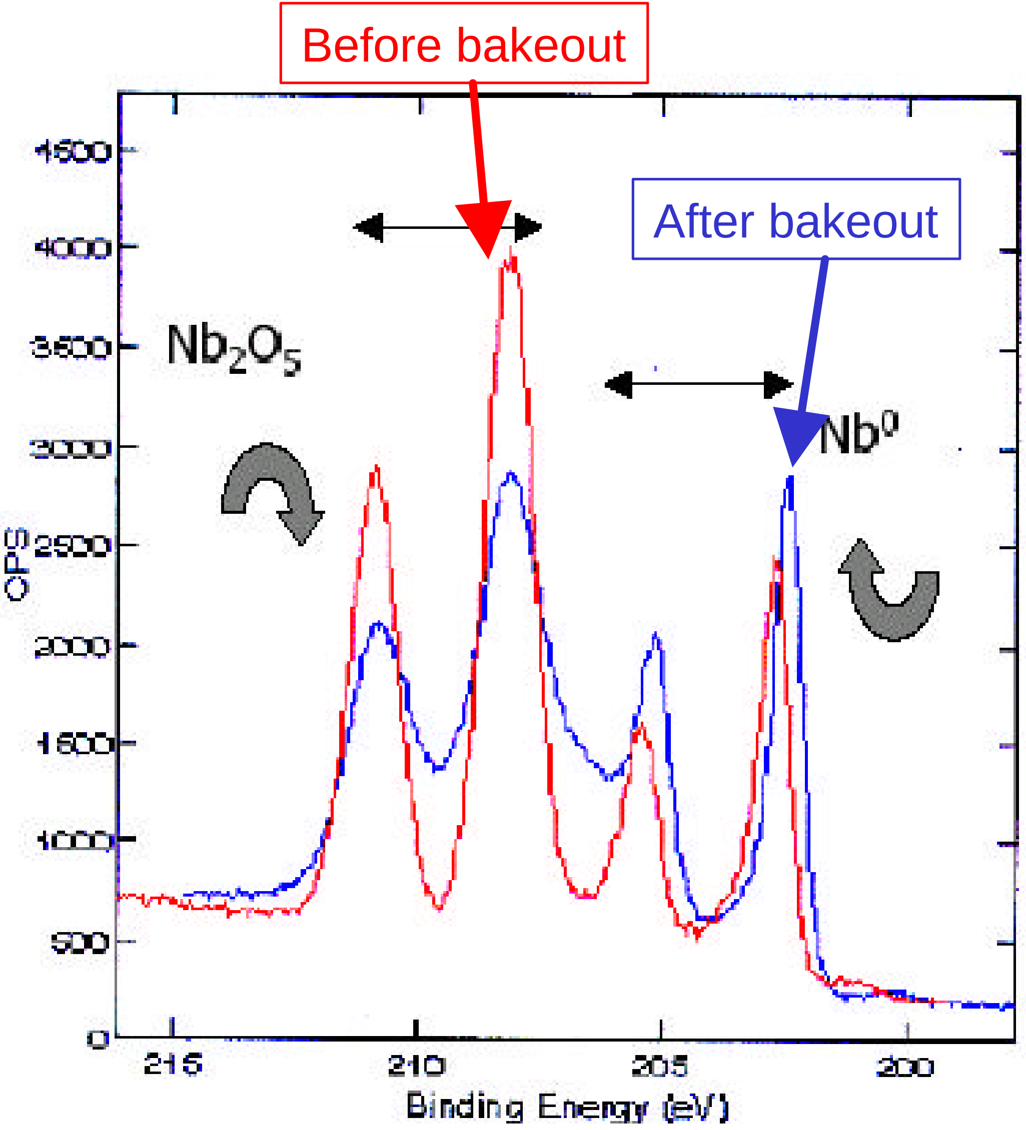
P.Kneisel JLab

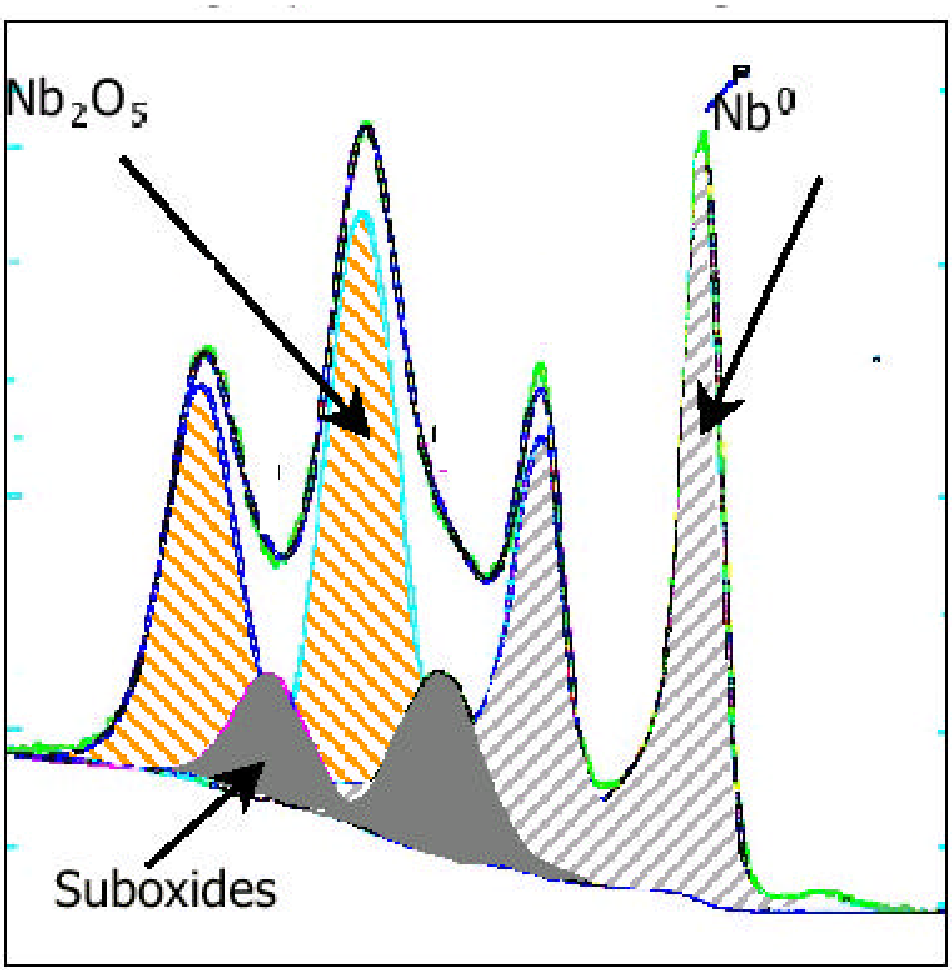
What is the reason for the baking effect?

- Evaporation of chemical residues from the surface ?
- Impurity diffusion in the surface layer ?
  - Hydrogen
  - Oxygen
- A closer look on the surface properties of niobium is necessary:
  - Do surface barriers play a role?
  - Are the pinning properties changed by the bakeout?

Changes in surface oxides ?

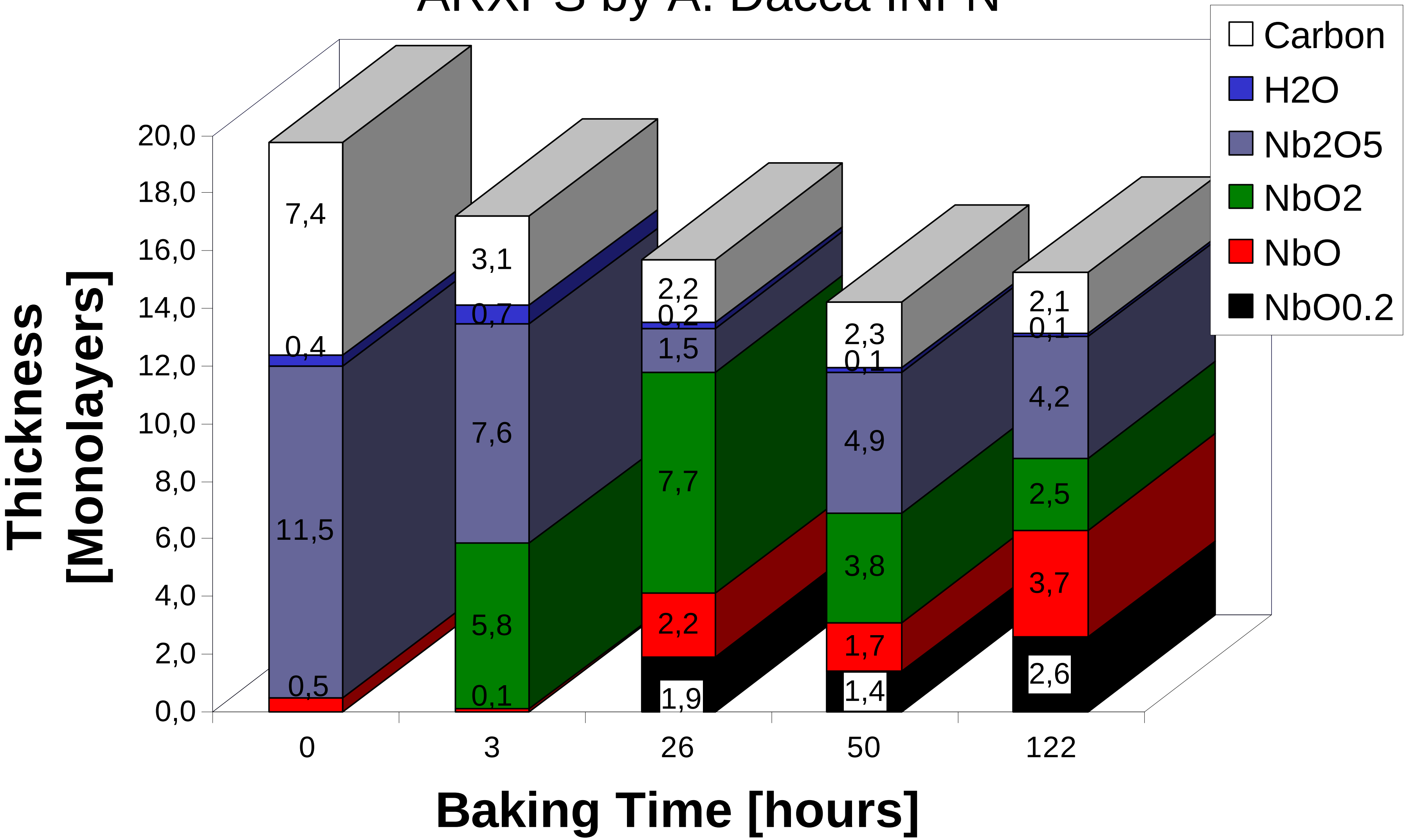
C. Antoine CEA





Change of the oxide structure ?

ARXPS by A. Dacca INFN

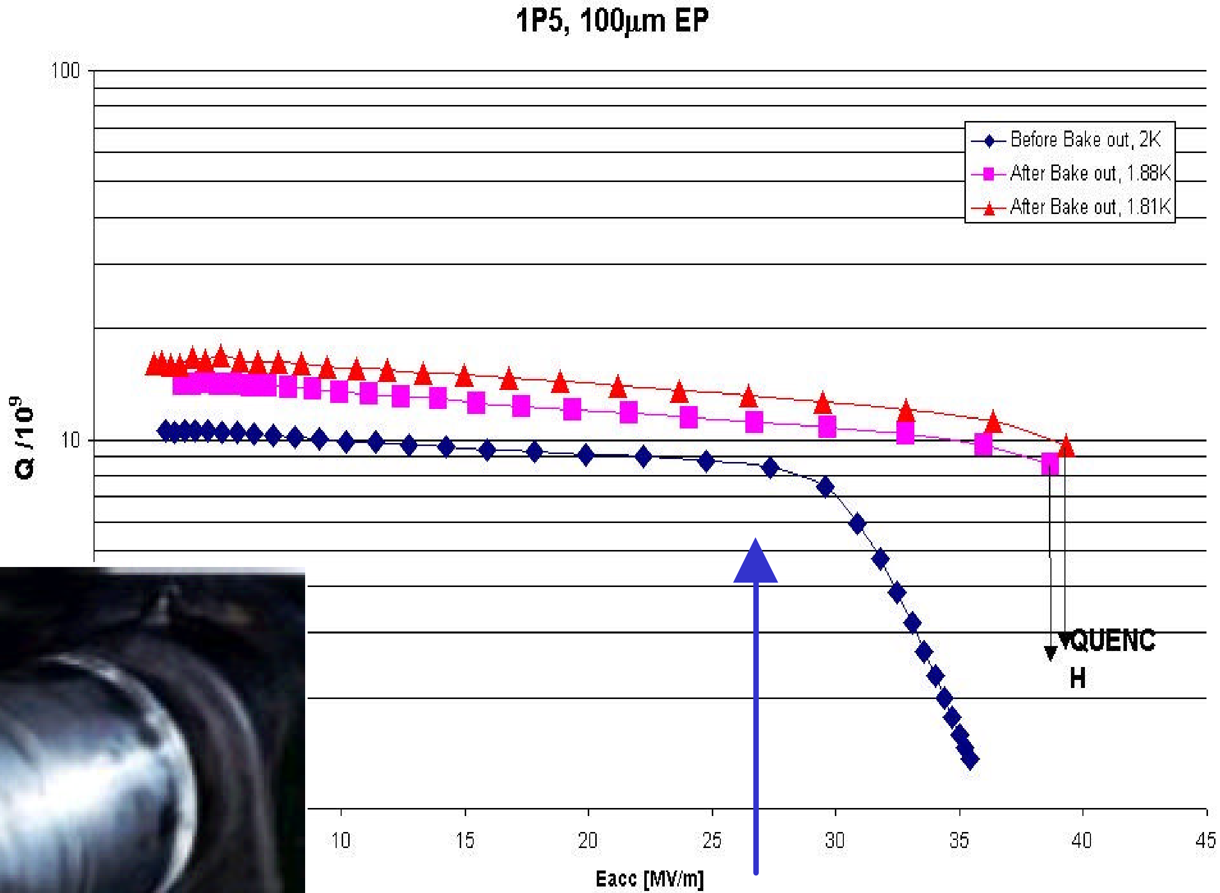


Outline

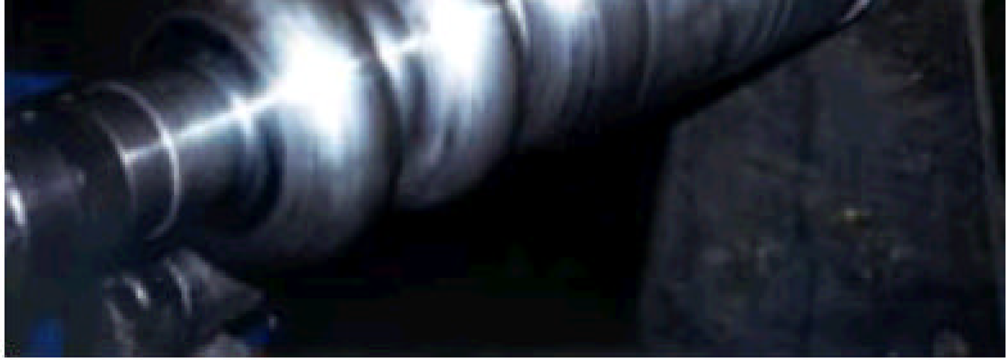
- Example: TESLA cavities
  - What is TESLA?
  - Choice of superconductor
  - Design of SRF cavities
  - Manufacturing issues
  - Surface preparation
  - Current state-of-the-art cavity performance
  - Higher gradients for TESLA-800
    - Electropolishing
    - Alternative manufacturing techniques
    - ‘Superstructure’
  - Operating SRF cavities

Spun and EP cavities

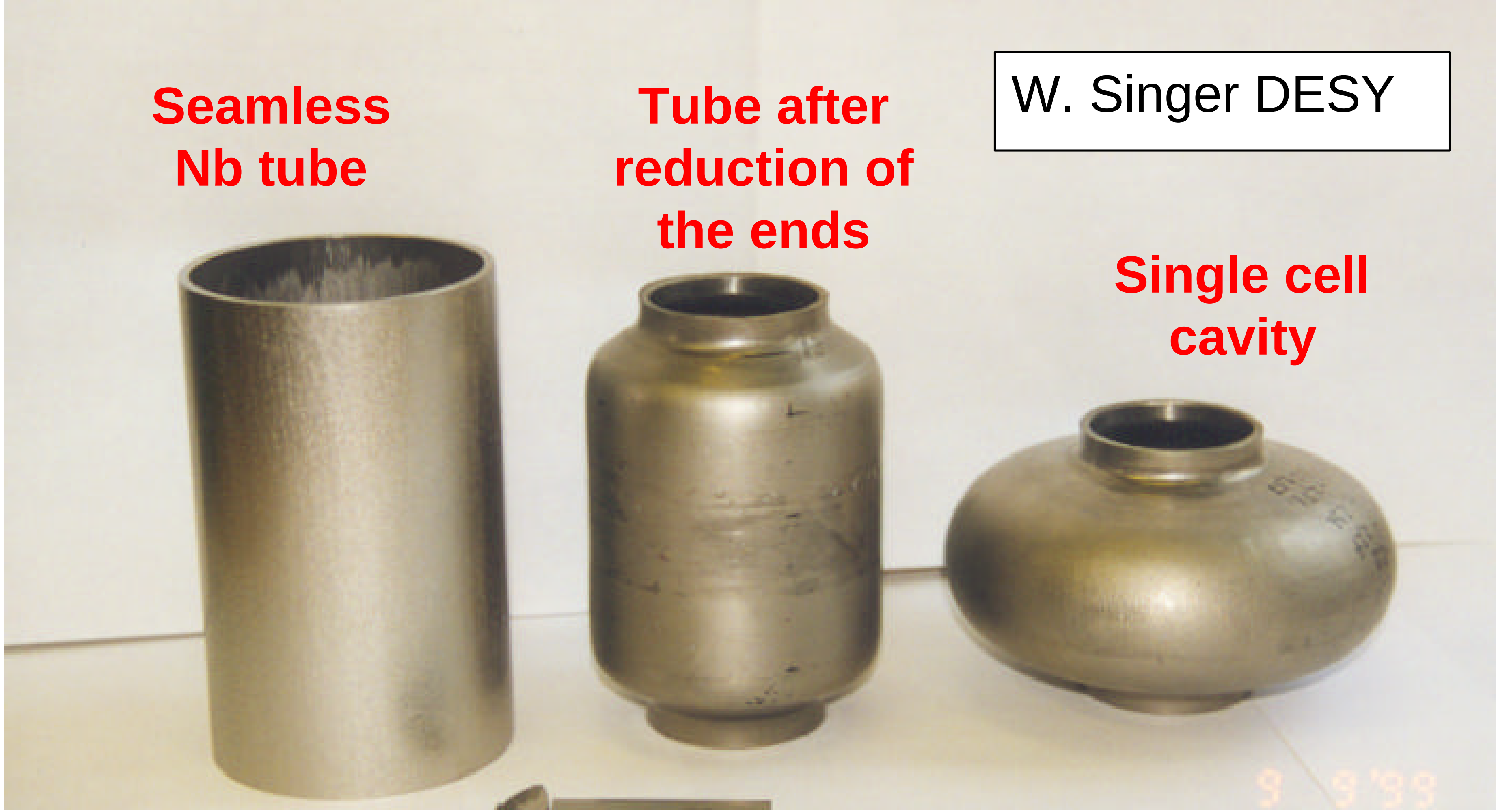
Palmieri (INFN-LNL), CERN-CEA-DESY Collaboration



One-cell cavity



Hydroforming

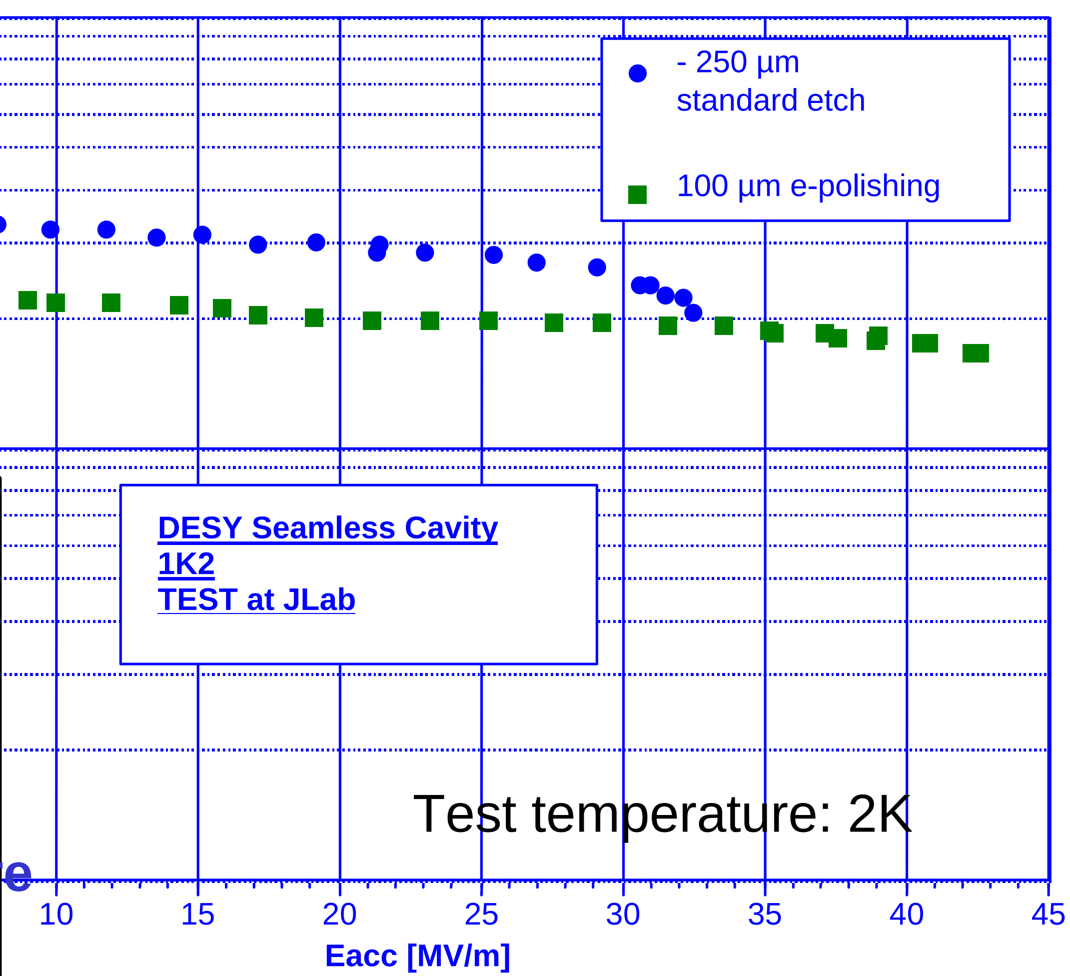


Two stages of cavity forming

Hydroforming and EP

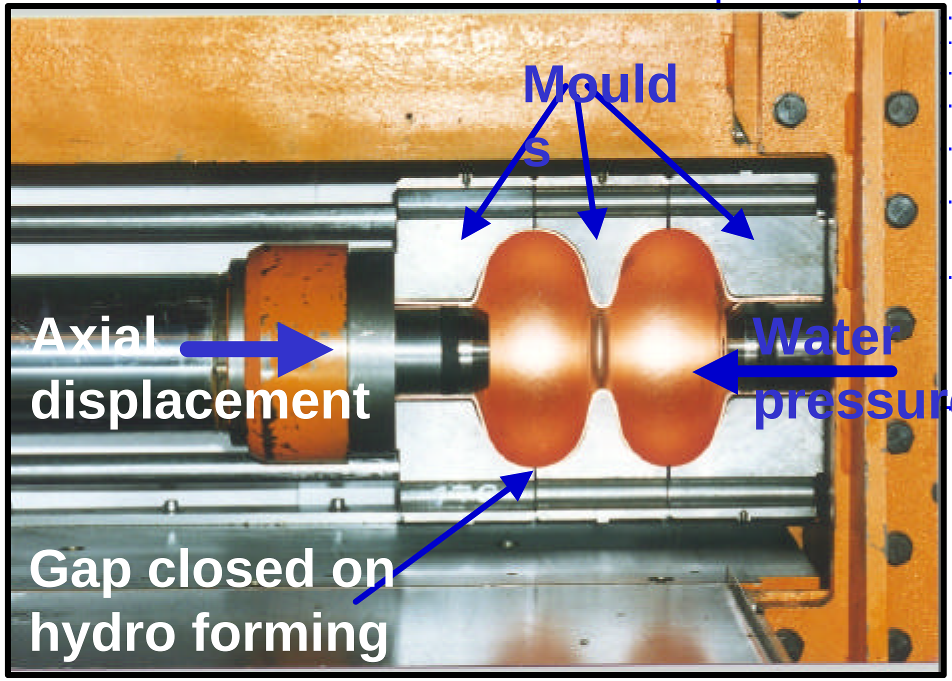
Kneisel TJANF
Kaiser, Singer DESY
Saito KEK

One-cell cavity

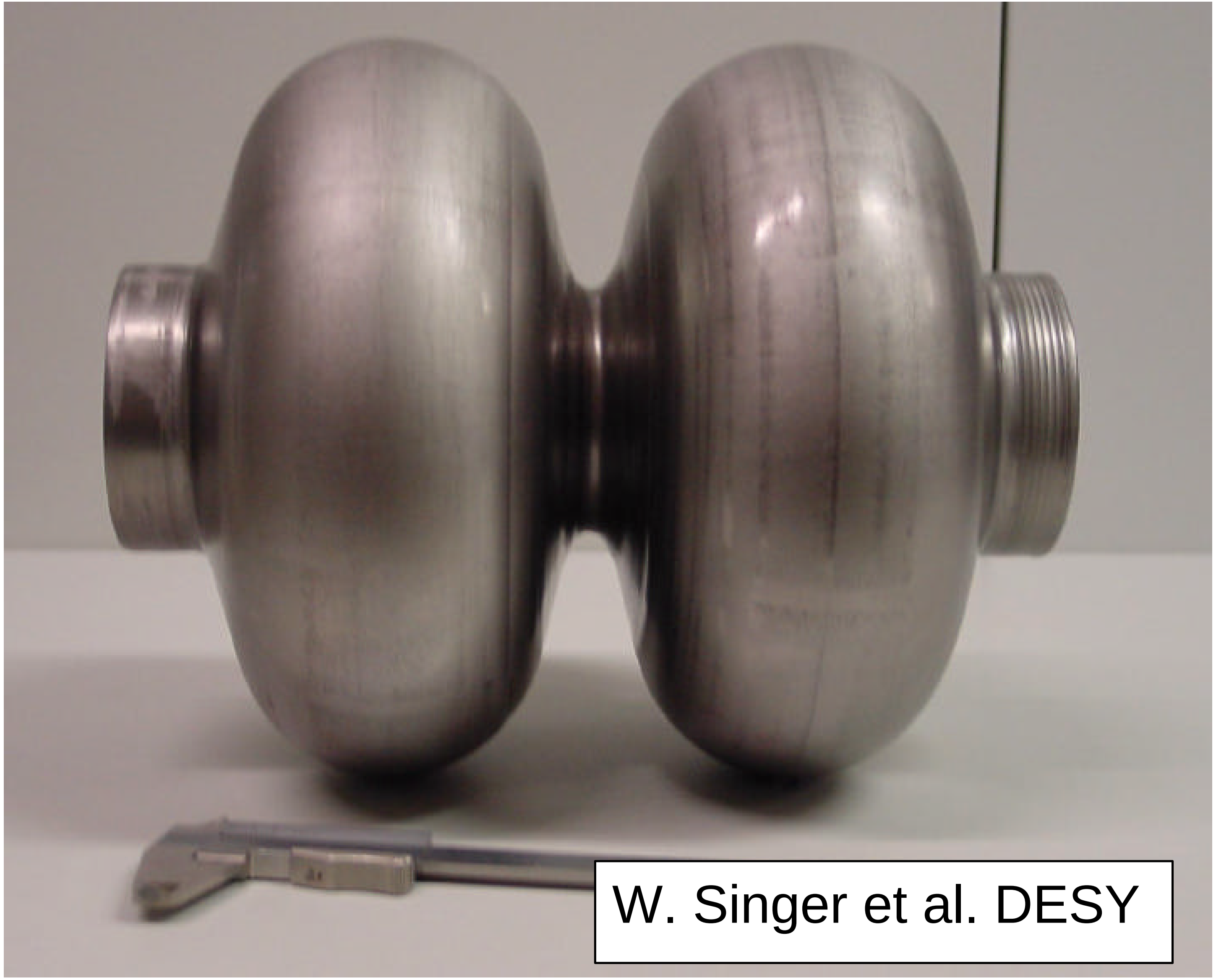


DESY Seamless Cavity
1K2
TEST at JLab

Test temperature: 2K



Hydroformed niobium 2-cell cavity



W. Singer et al. DESY

Hydroforming of Nb-Cu cells

W. Singer et al. DESY

Hydroformed Nb-Cu one-cell cavities

W. Singer et al. DESY

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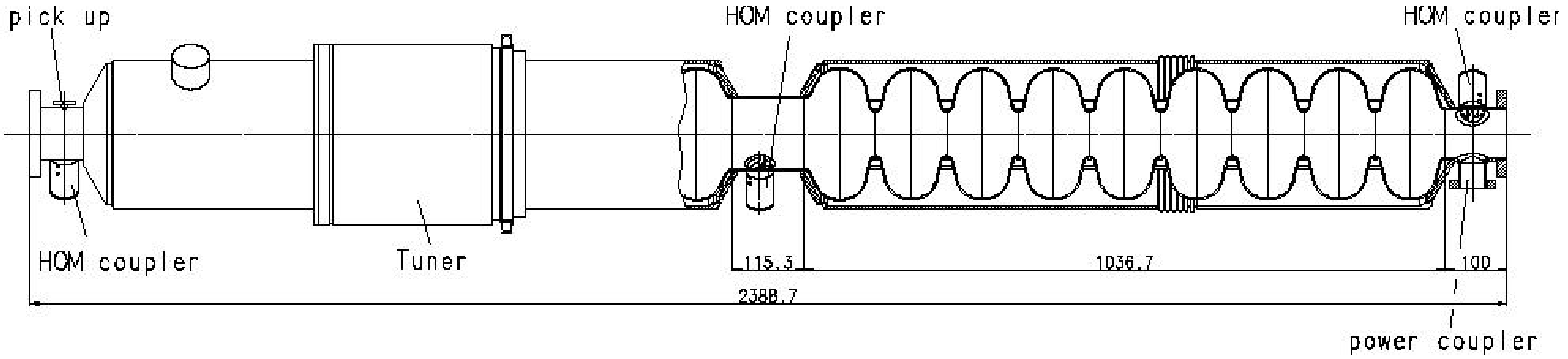
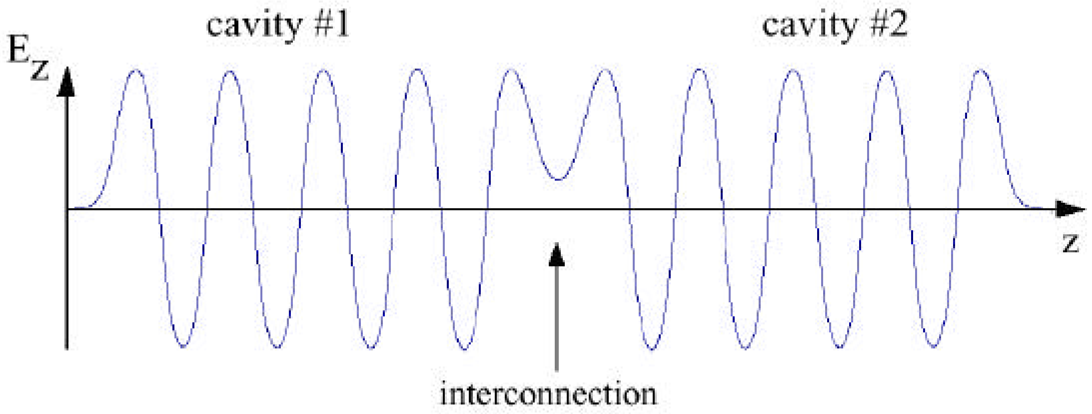
TESLA 2 x 9 Superstructure

J. Sekutowicz, M. Liepe et al.



Field profile:



Benefits:

- 6% larger active accelerating length as compared to normal nine-cell design

- less main and HOM couplers

Comparison of two accelerating schemes for TESLA-500 (nine-cell vs. superstructure)

Layout	L_{active} [m]	E_{acc} [MV/m]	No. of power coupler	No. of HOM coupler	No. of freq. tuners	Filling factor L_{active}/L_{total}	P_{trans} [kW]
9-cell	1.04	23.4	20592	41184	20592	78.6	232
2x9-cell	2.08	22	10926	32778	21852	84.8	437

Superstructure

J. Sekutowicz, M. Liepe et al.

- higher fill factor L_{acc} / L_{total}
- less RF couplers

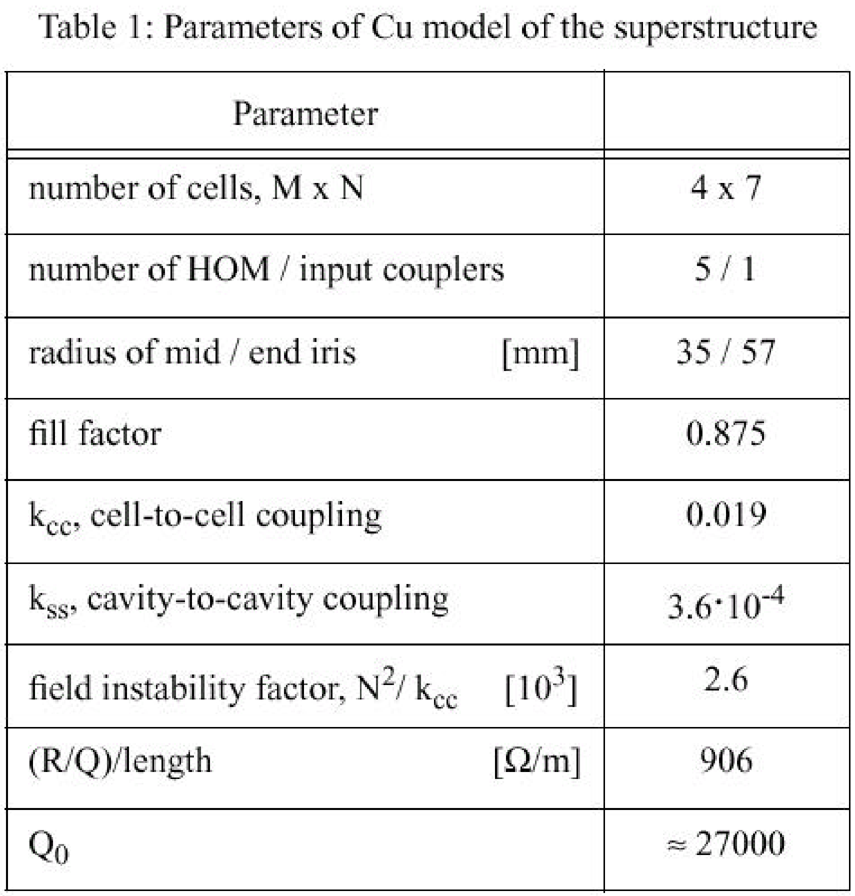
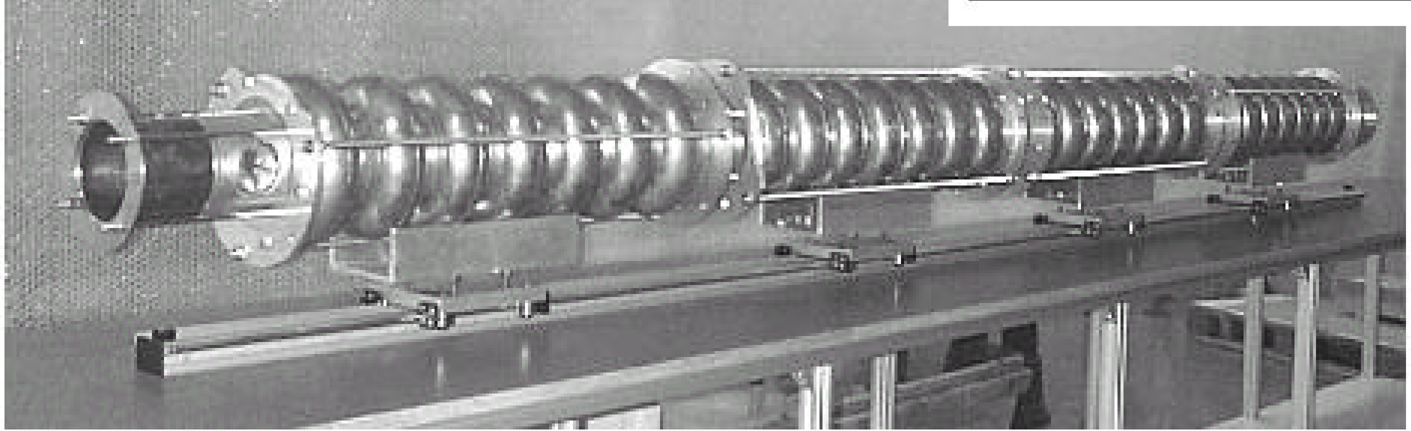


Table 1: Parameters of Cu model of the superstructure

Parameter	
number of cells, M x N	4 x 7
number of HOM / input couplers	5 / 1
radius of mid / end iris [mm]	35 / 57
fill factor	0.875
k_{cc}, cell-to-cell coupling	0.019
k_{ss}, cavity-to-cavity coupling	$3.6 \cdot 10^{-4}$
field instability factor, N^2 / k_{cc} $[10^3]$	2.6
(R/Q)/length [Ω/m]	906
Q_0	≈ 27000



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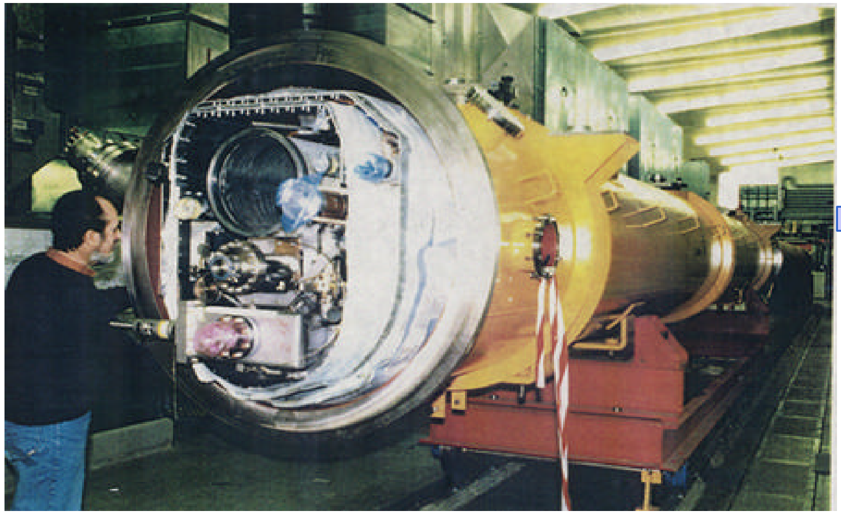
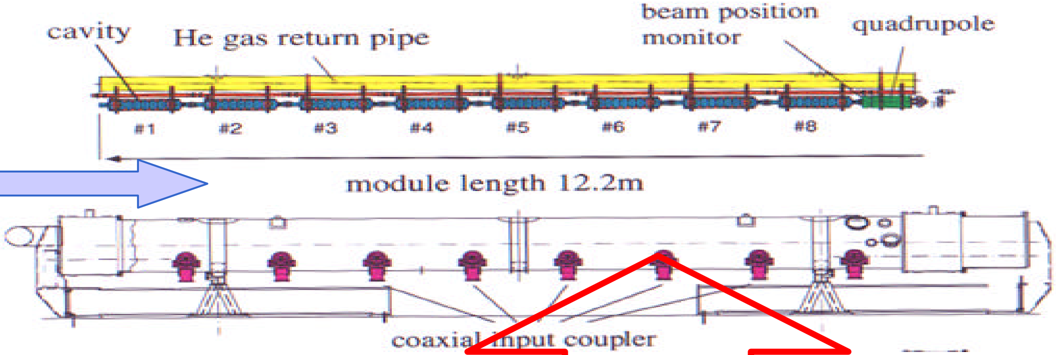
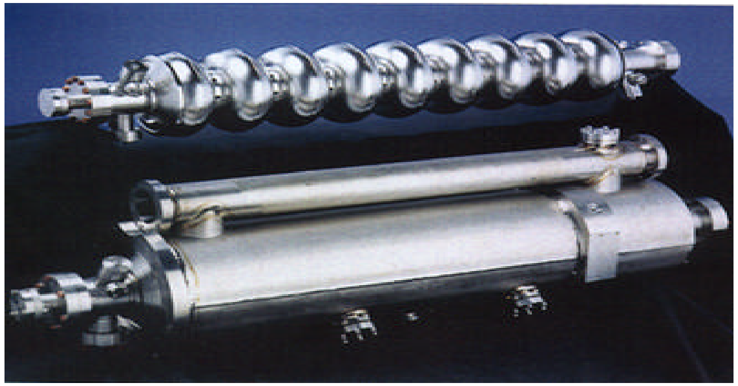
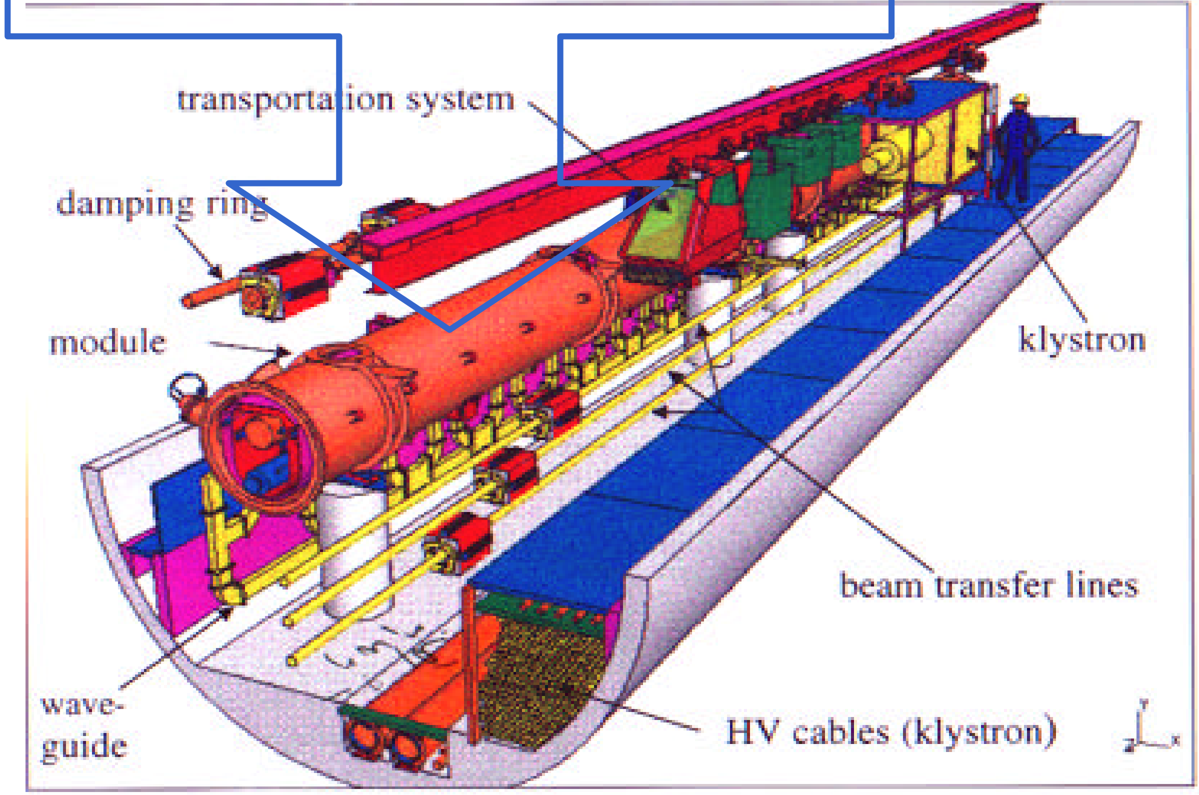
Operating SRF cavities

- Cryostats
- RF Couplers
- Piezoelectric tuner
- Low-level RF control
- Real world example (if the internet does work…)







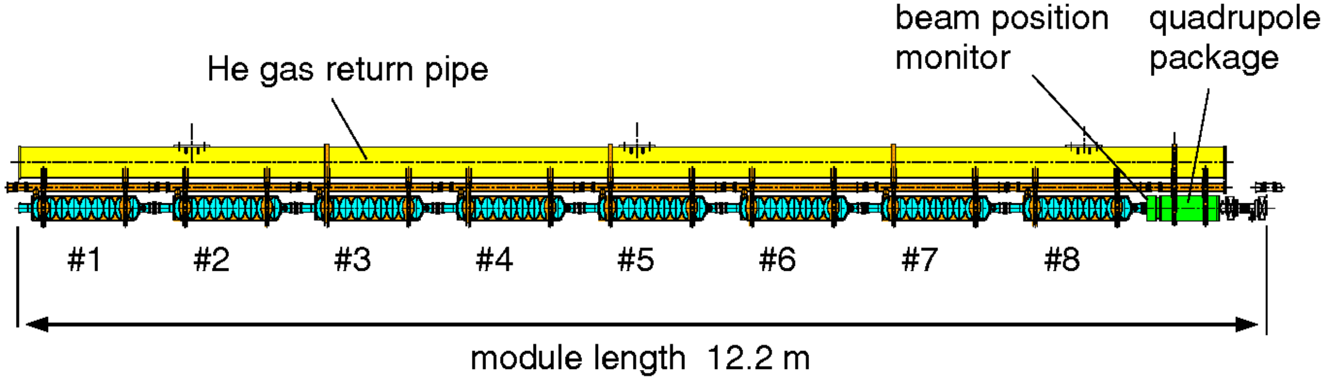


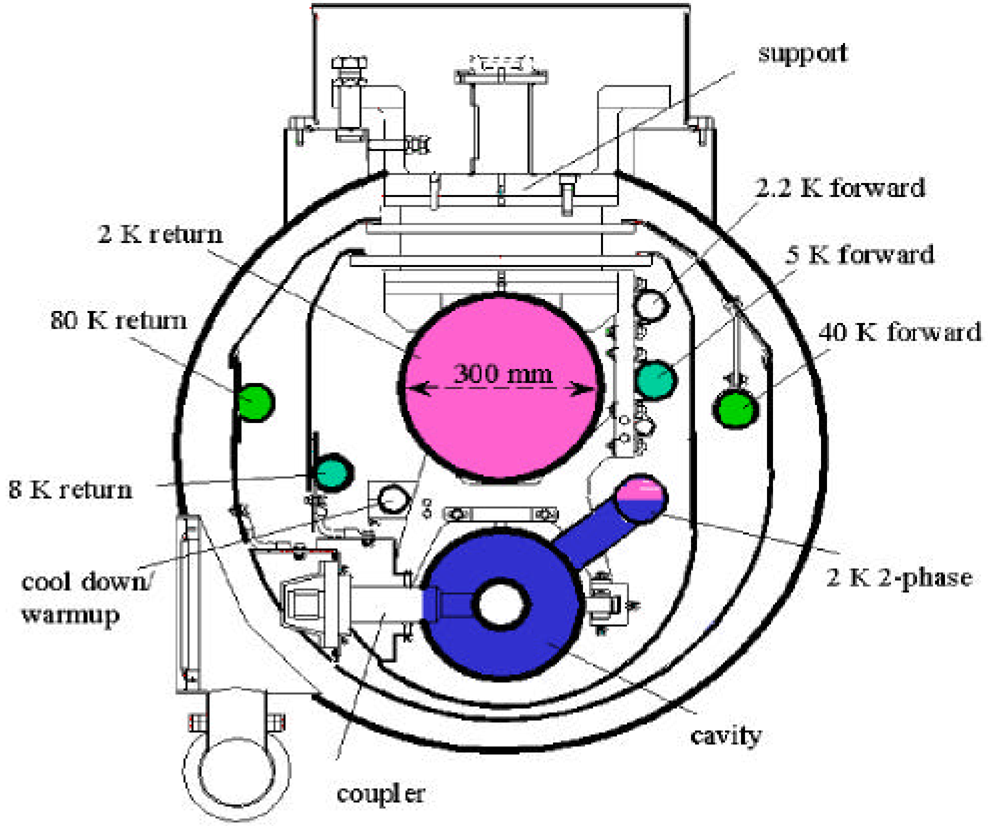
Cryogenic system

- 2 K operation
- Liquid superfluid Helium

Accelerator Module for TESLA

Length increases to ~17 m





Operating SRF cavities

- Cryostats
- RF Couplers
- Piezoelectric tuner
- Low-level RF control
- Real world example (if the internet does work…)

Specification of the TESLA High Power Coupler

	TTF	**TESLA 9-cell / upgrade**	**TESLA superstructure / upgrade**
beam power + control margin (27%)	250 kW	250 kW / 500 kW	555 kW / 1110 kW
repetition rate	10 Hz	5 Hz	5 Hz
coupling	adjustable (10^6 - 10^7)	fix ($3*10^6$)	fix ($2.5*10^6$)
cavity position during cool down	flexible (15 mm longitudinal)	fix point (1.5 mm longitudinal)	fix point (1.5 mm longitudinal)

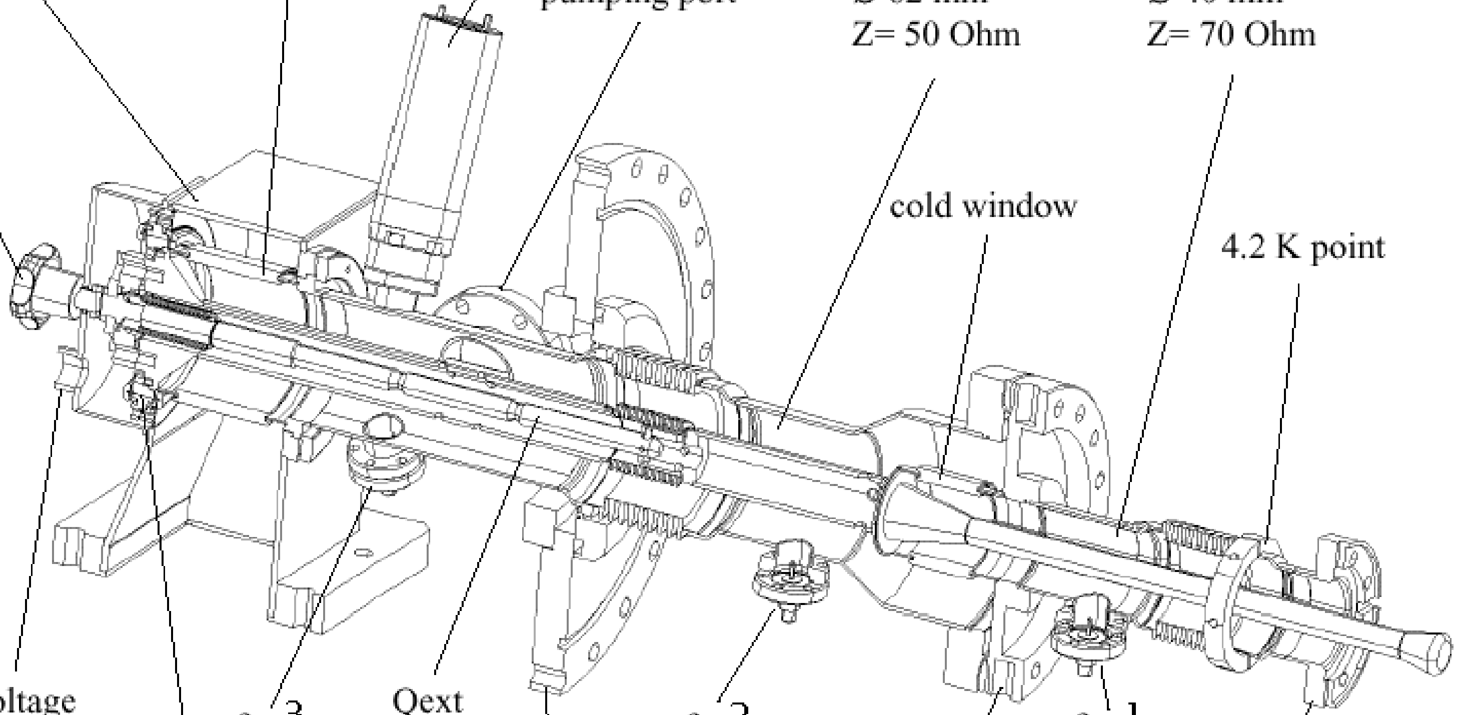
General Parameters

frequency	1.3 GHz
operation	pulsed: 500 µsec risetime, 800 µsec flat top with beam
power for High Power Processing in situ	1 MW at reduced pulse length (500 µsec and repetition rate 1 Hz)
2 K heat load	0.06 W
4 K heat load	0.5 W
70 K heat load	6 W
diagnostic	sufficient for safe operation and monitoring

Requirements of Couplers for SC Cavities

- strong mismatch in absence of beam between cavity and generator
  -> full reflection
- cold warm transition, low heat loads
- it has to be cleaned to the standard of the sc cavity surfaces (usually by dustfree water)
- clean assembly of coupler to the cavity in the class 10 clean room
- protection of the clean cavity surface during assembly to the cryostat
- safety against window failures during operation
- diagnostic

TESLA Coupler TTF 3



waveguide to
coax
transition

room
temperature
window

light detector (PM)

warm vacuum
pumping port

warm coax
Ø 62 mm
Z= 50 Ohm

cold coax
Ø 40 mm
Z= 70 Ohm

Qext
tuning
knob

cold window

4.2 K point

bias voltage
feedthrough

e− 3
pickup

Qext
tuning
rod

e− 2
pickup

e− 1
pickup

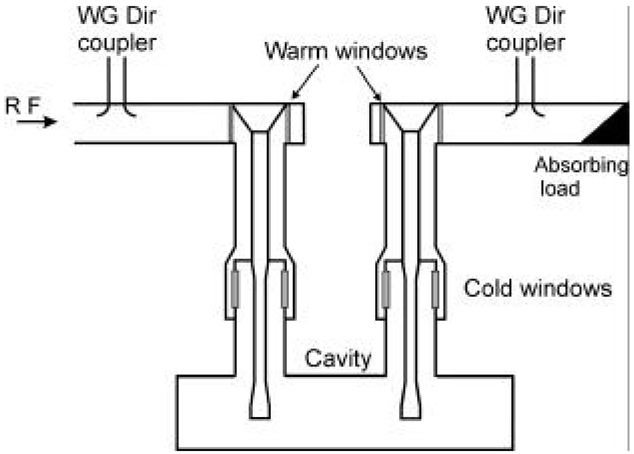
isolating
Kapton foil

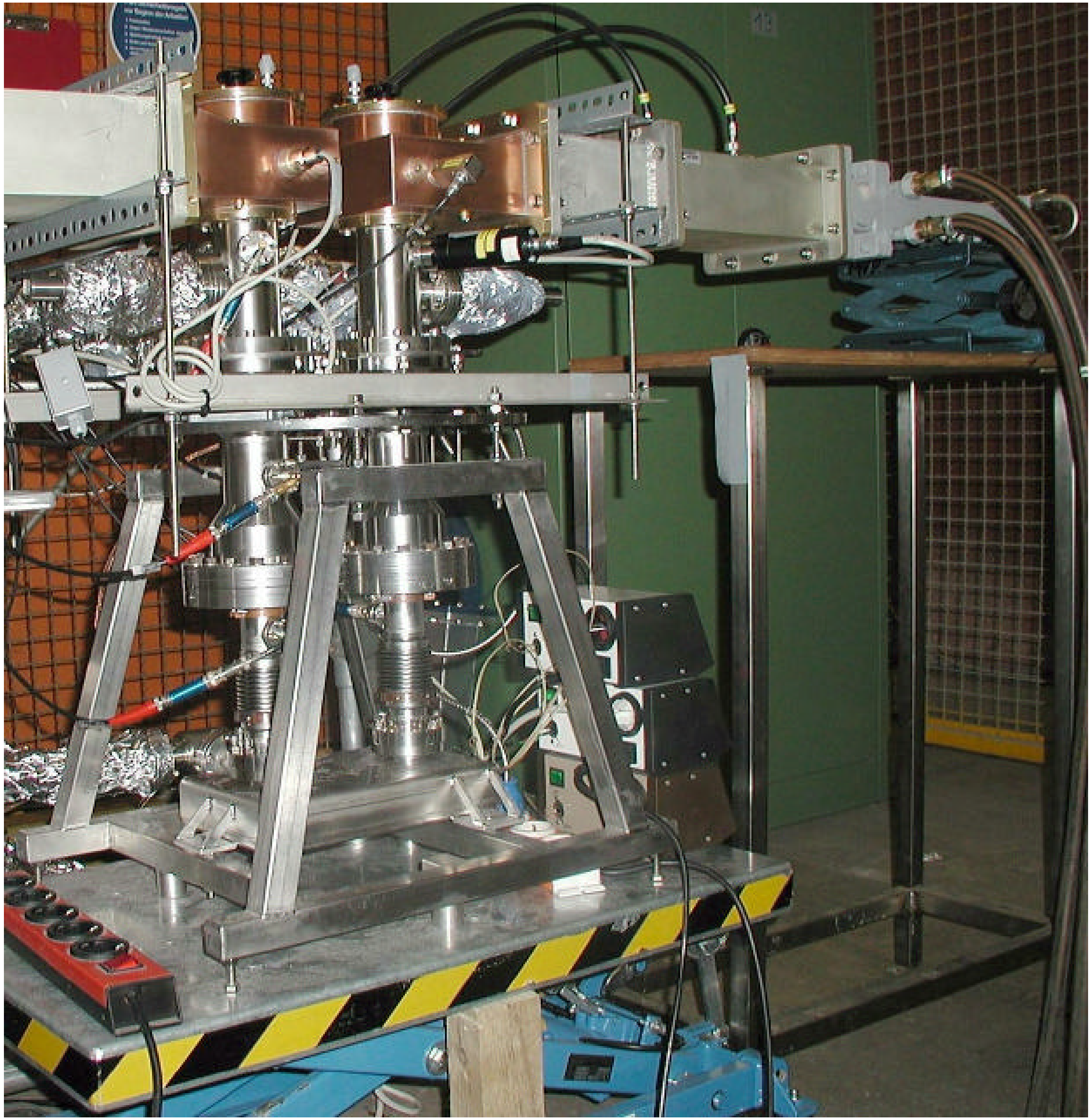
roomtemperature
isolation vacuum
flange

70 K point

1.8 K
flange to
cavity

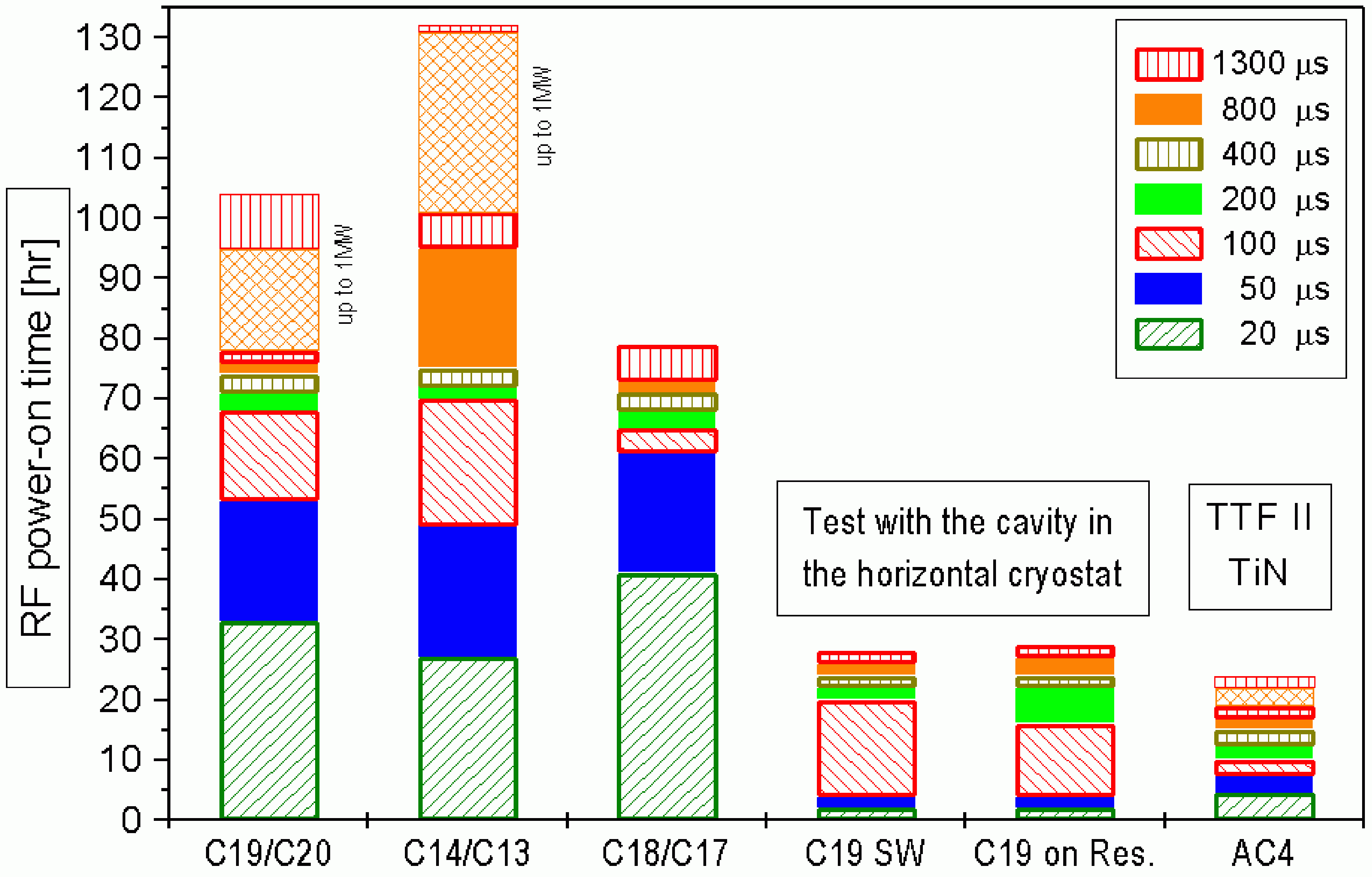
Teststand



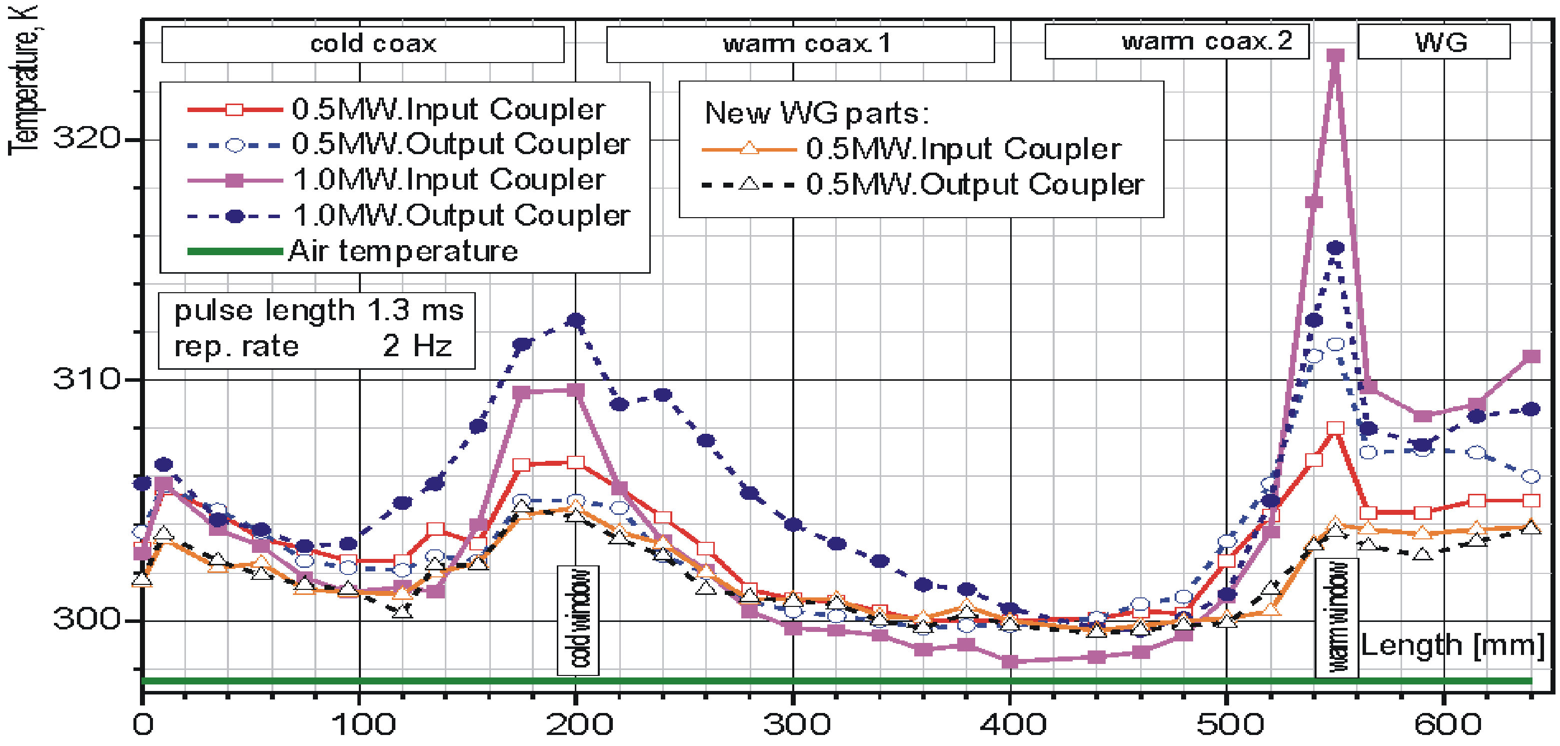


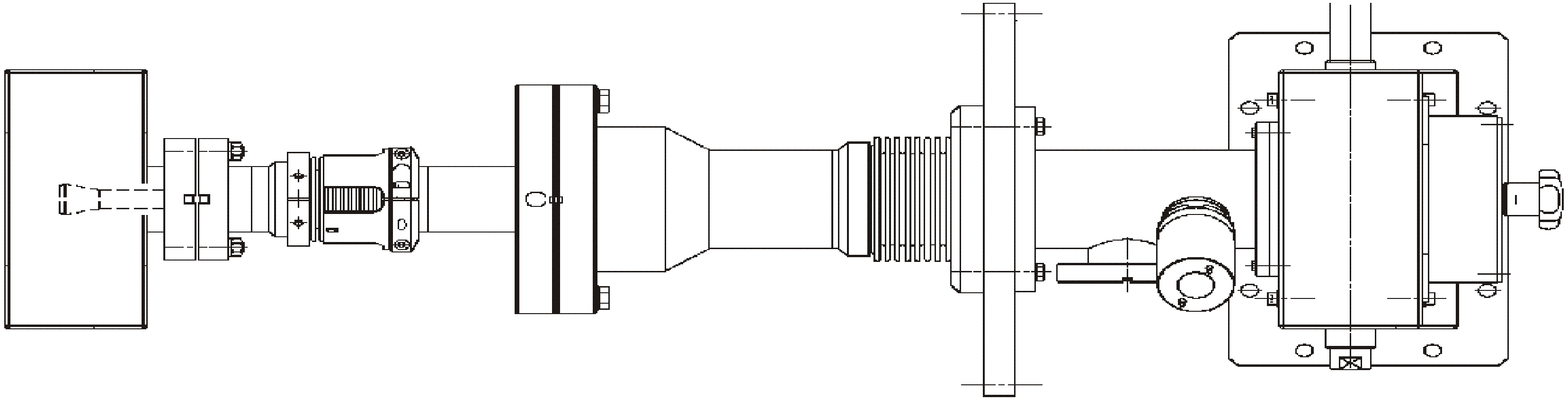
- traveling wave
- room temperature

Duration of Processing



Temperature Profile at Room Temp.





Coupler Operation in the TTF Linac

- we have produced 60 couplers of different designs for TTF

- all are tested

- 24 couplers are operated in the TTF-FEL up to now for more than 10000 h

- most of the time at about 100 kW (in favor of SASE experiments)

- up to 400 kW during processing of couplers and cavities

- going to higher power levels above 180 kW without additional conditioning high e$^-$ signals were seen at the end of the pulse

- by changing the pulse shape on the end the activity could be suppressed

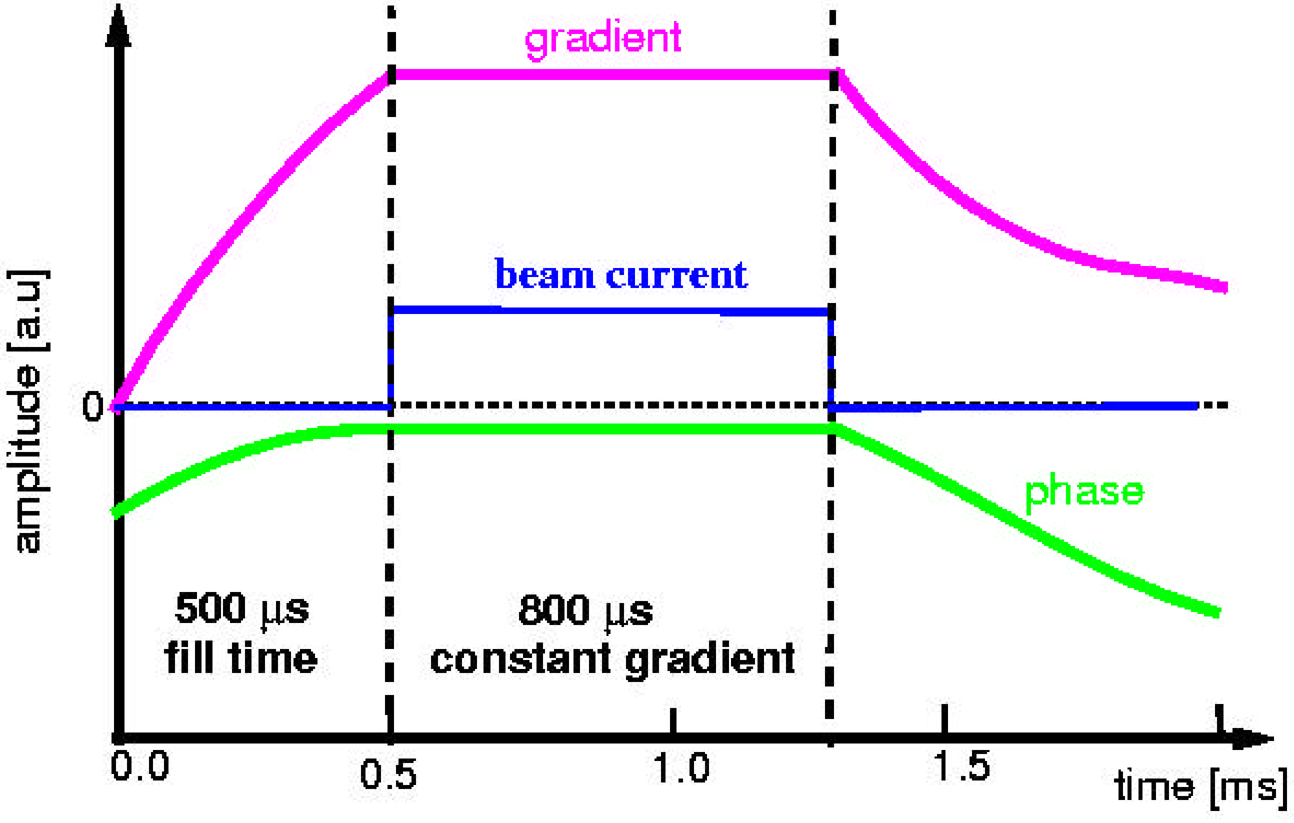
Operating SRF cavities

- Cryostats
- RF Couplers
- Pulsed operation
  - Low-level RF control
  - Piezoelectric tuner
- Real world example (if the internet does work…)

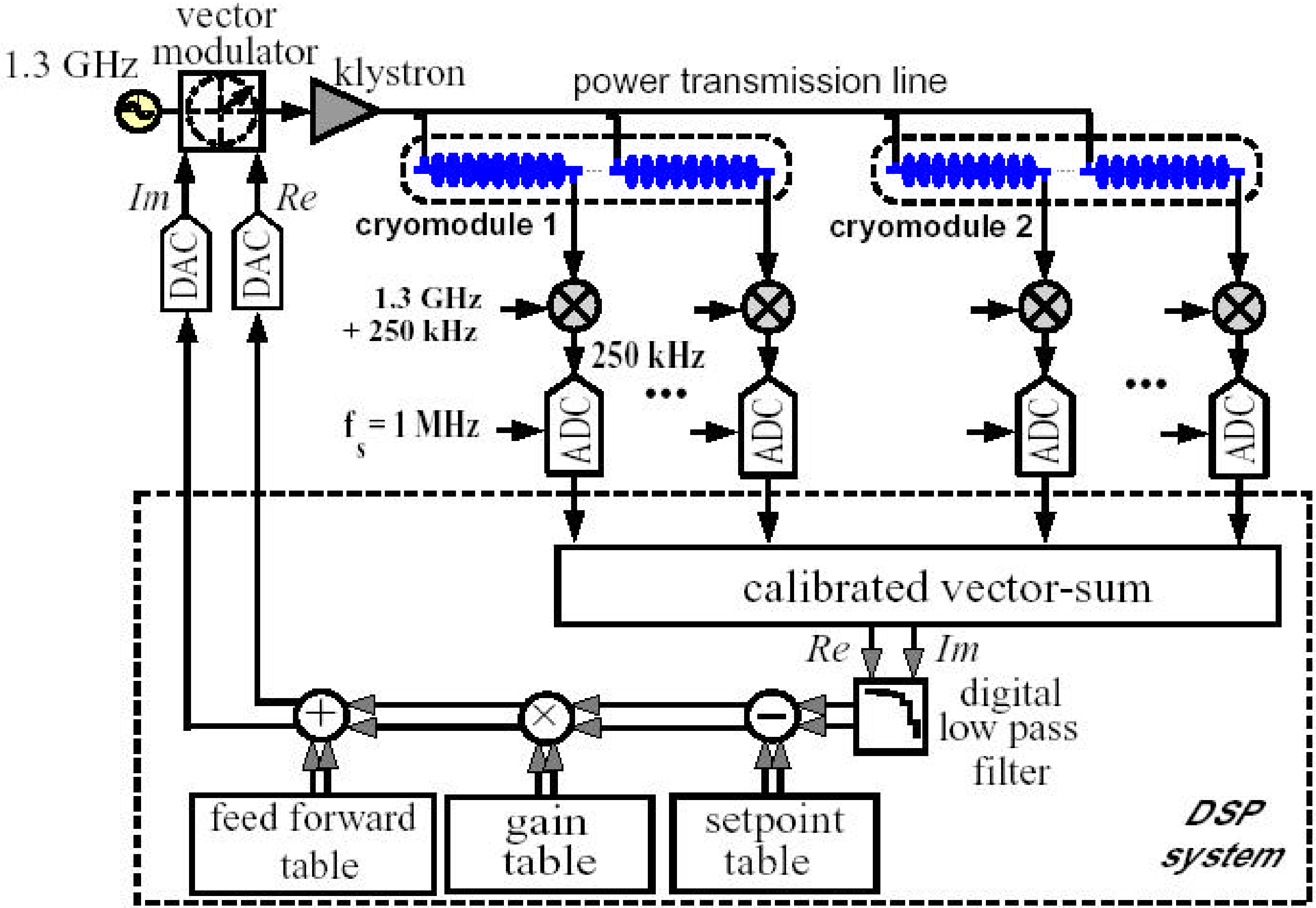
Pulsed acceleration at TESLA

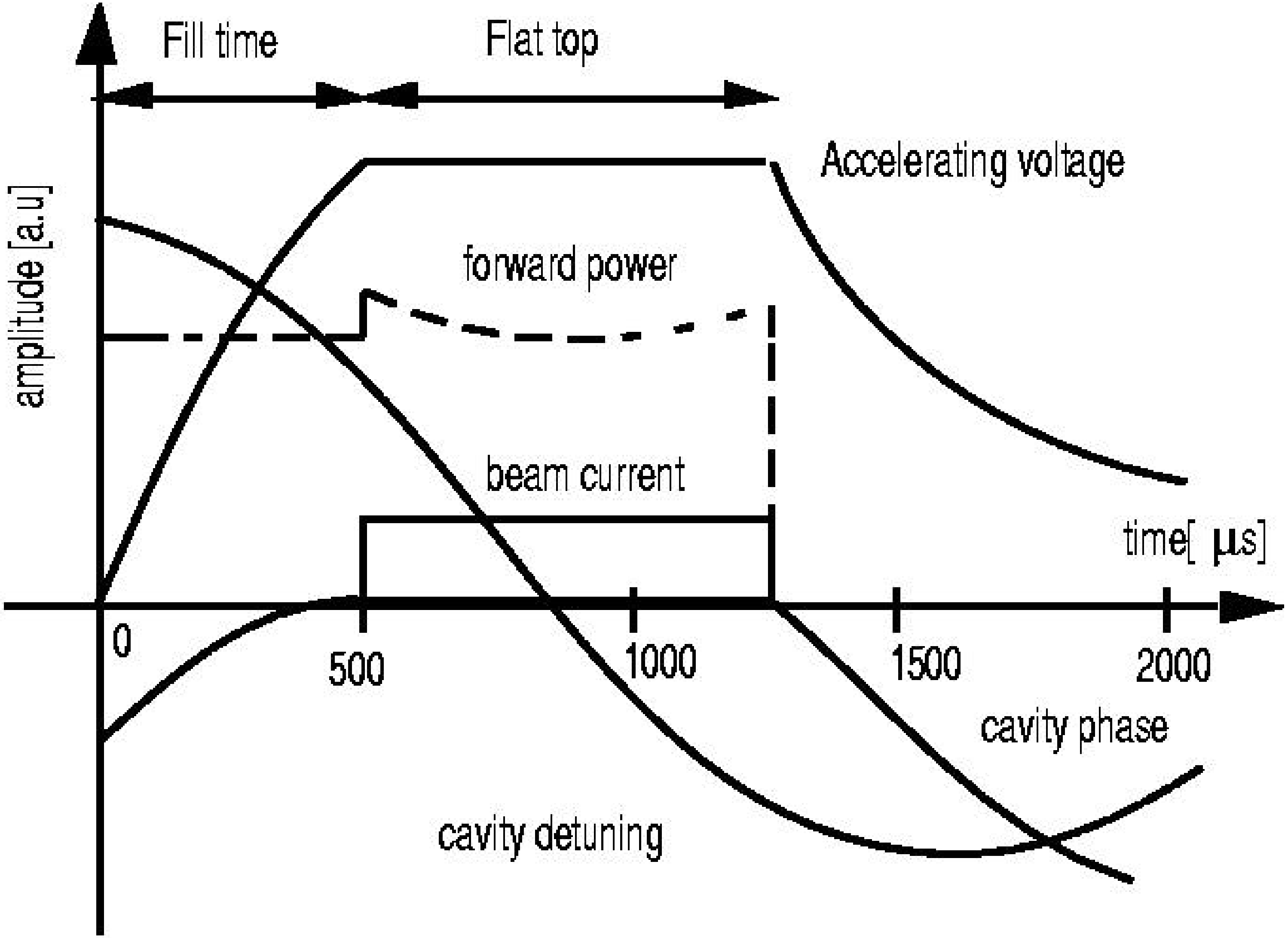
Superconducting cavities at high gradients ⇒ **Pulsed operation to reduce average cryogenic losses**

Pulsed operation: 500 µs fill time + 800 µs constant gradient
10 Hz repetition rate

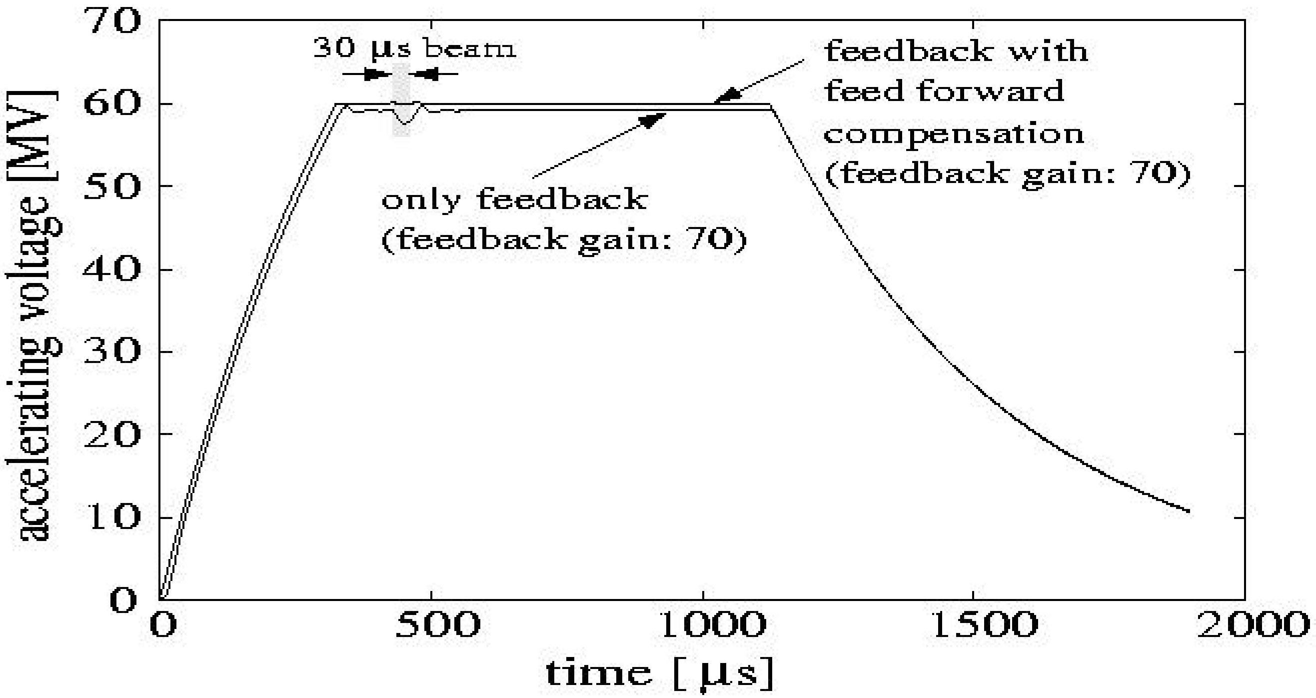


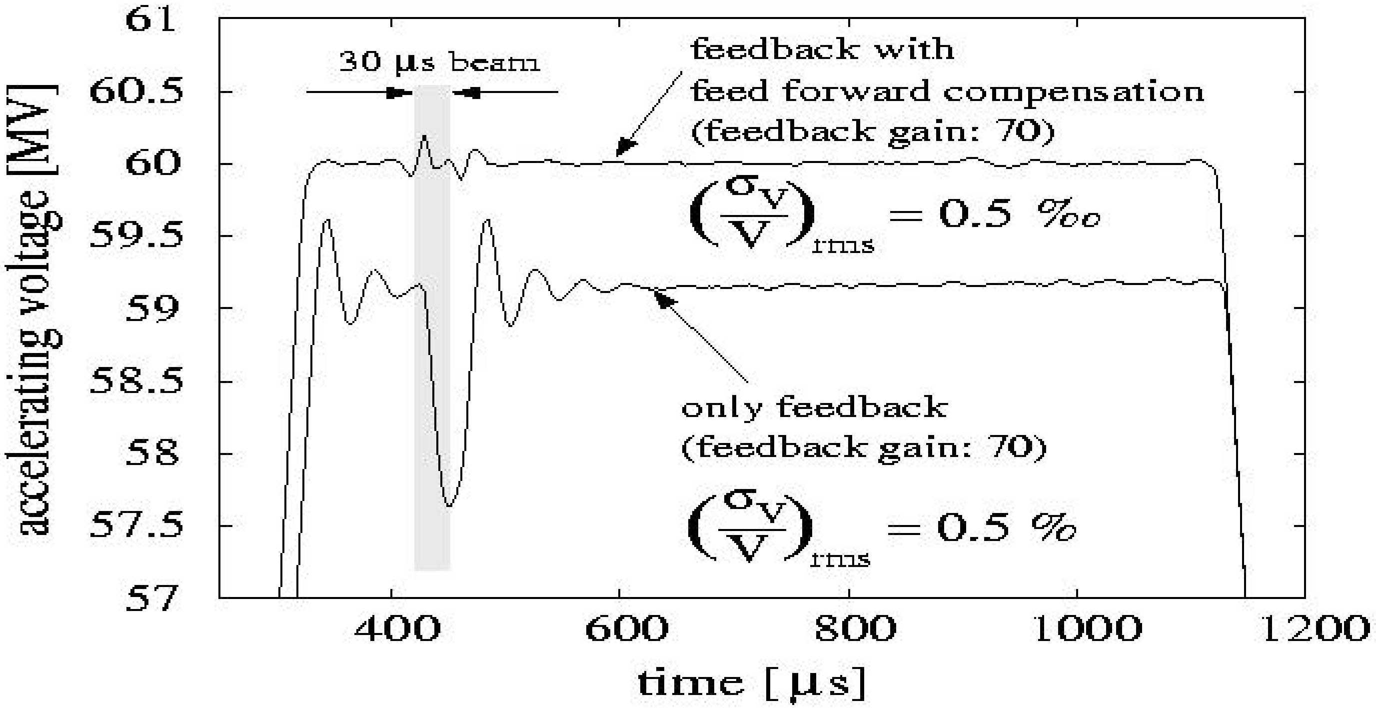
RF control system



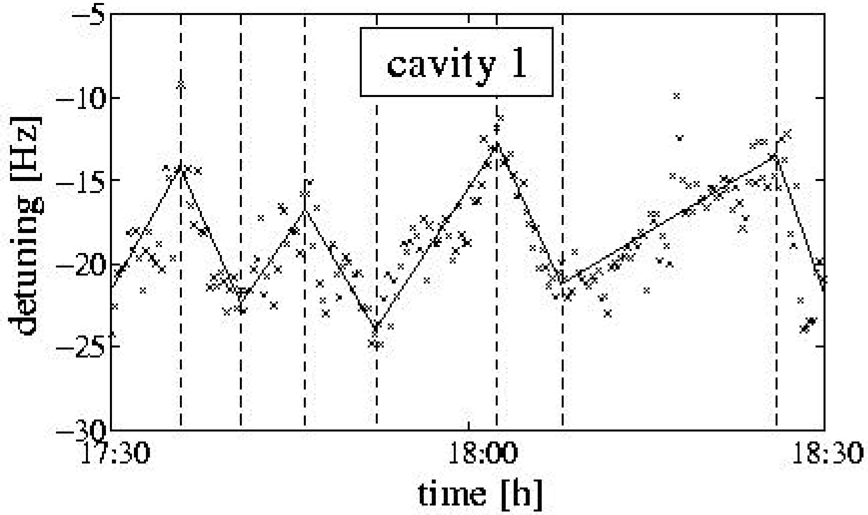

Fill time
Flat top
Accelerating voltage
forward power
beam current
amplitude [a.u]
time[µs]
0
500
1000
1500
2000
cavity phase
cavity detuning

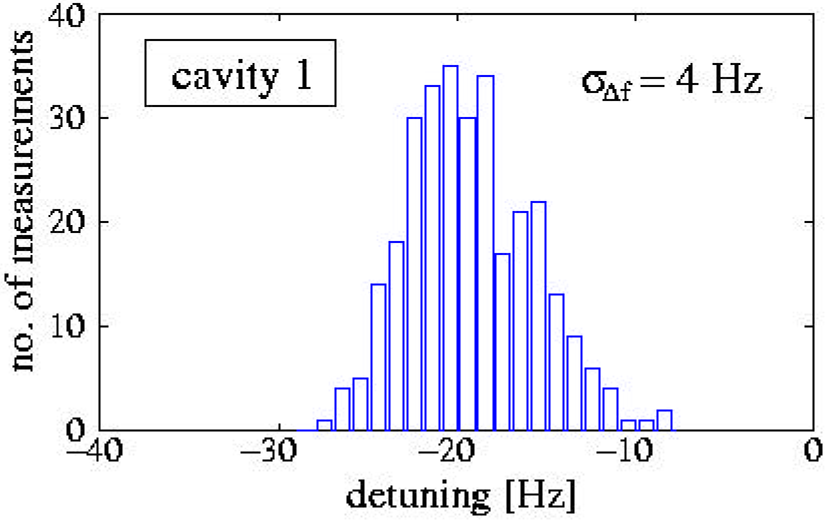
Beam induced transients – Low level RF control



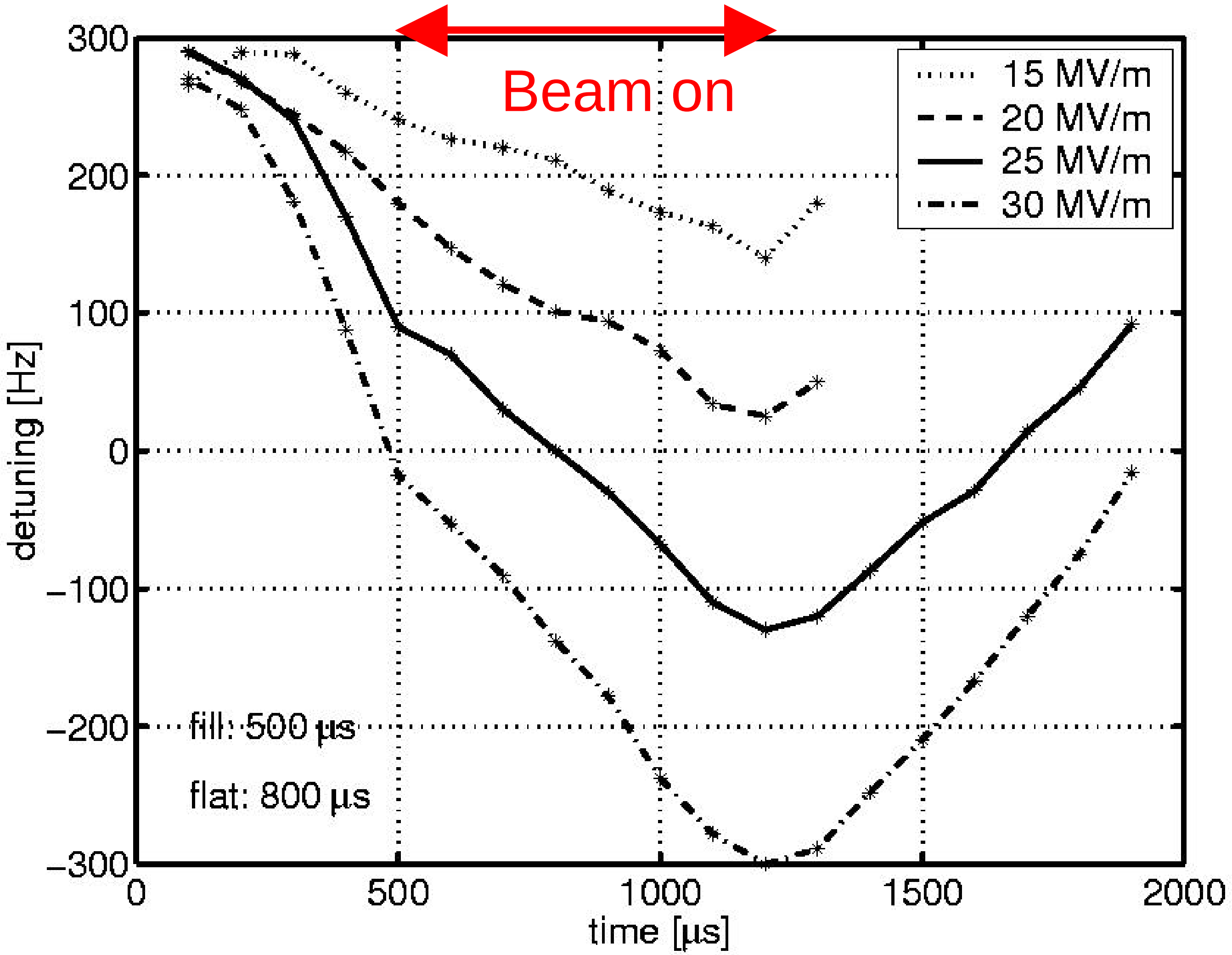


Microphonics





Frequency detuning during RF pulse



Frequency detuning due Lorentz forces of the electromagnetic field in the cavites:

$?f = K \bullet E_{acc}^2$

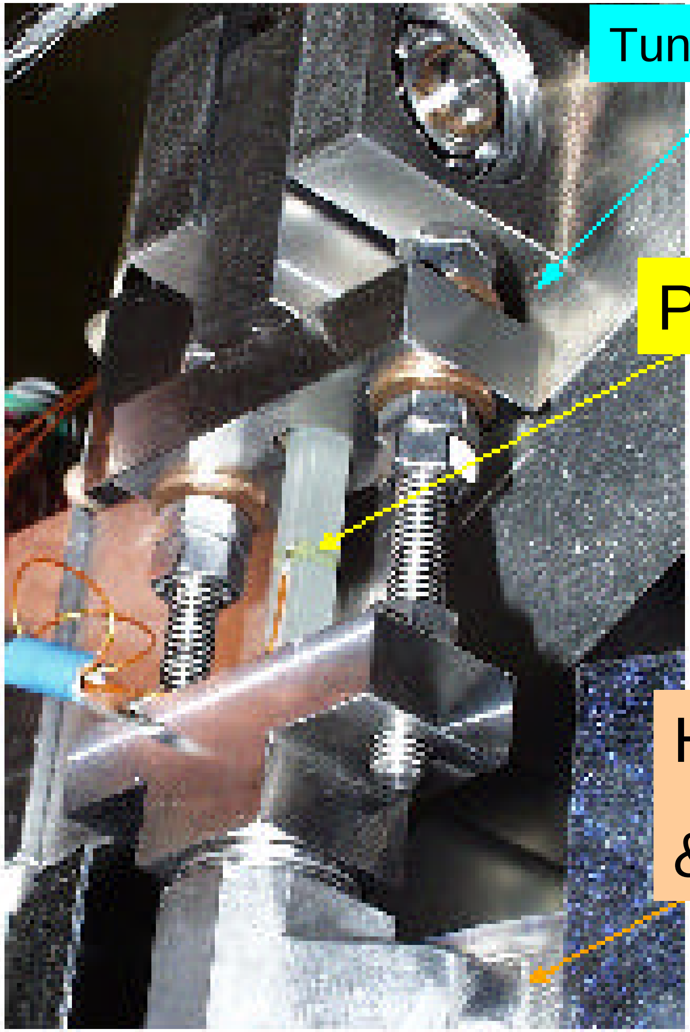
K ˜ 1 Hz / (MV/m)^2

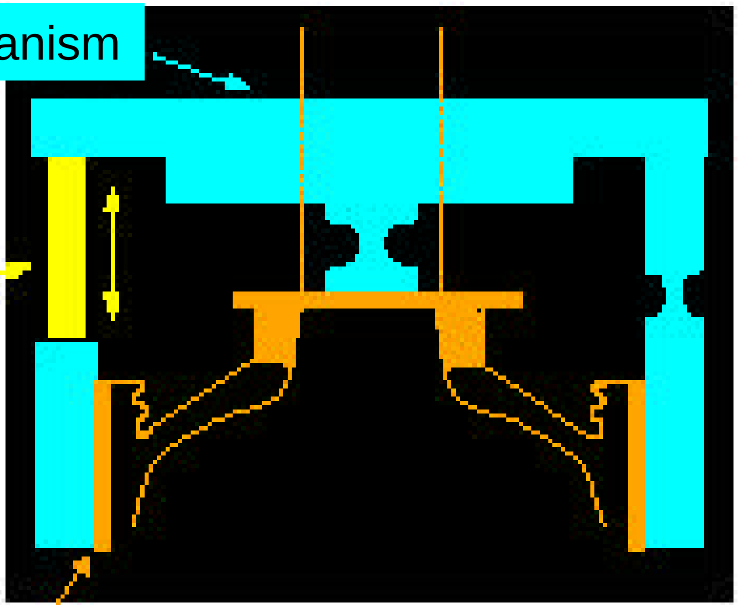
Remember:

Cavity bandwidth with main coupler is ˜ 300 Hz

Piezoelectric tuner

M. Liepe, S. Simrock, W.D.-Moeller





Tuning mechanism

Piezo

He-Tank

& Cavity

Piezo-Actuator:

l=39mm

U_{max}=150V

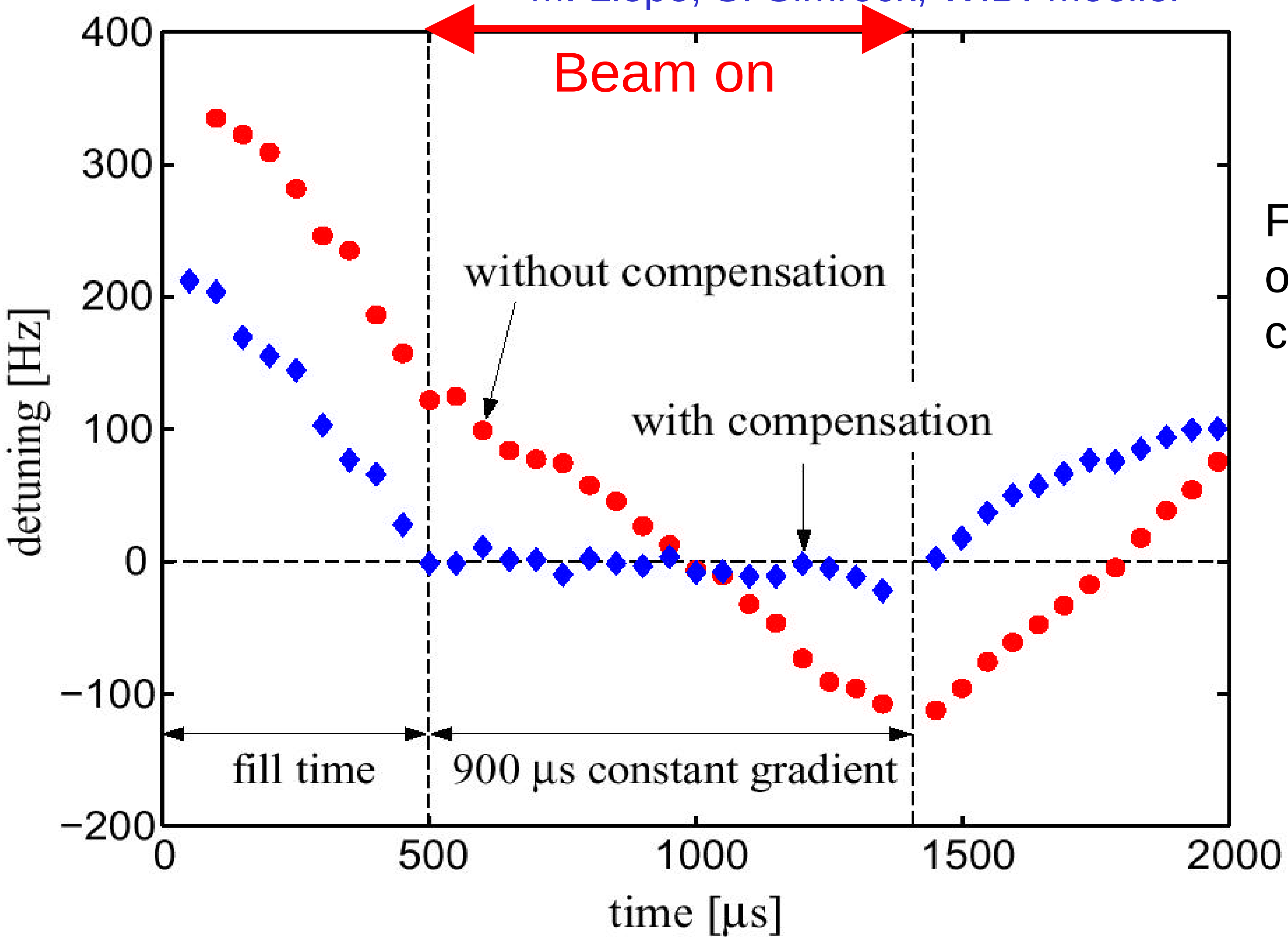
Δ l=3µm at 2K

$\Delta f_{max, static}$= 500Hz

$\Delta f_{max,static}$=500Hz

Frequency stabilisation during RF pulse using a piezoelectric tuner

M. Liepe, S. Simrock, W.D.-Moeller

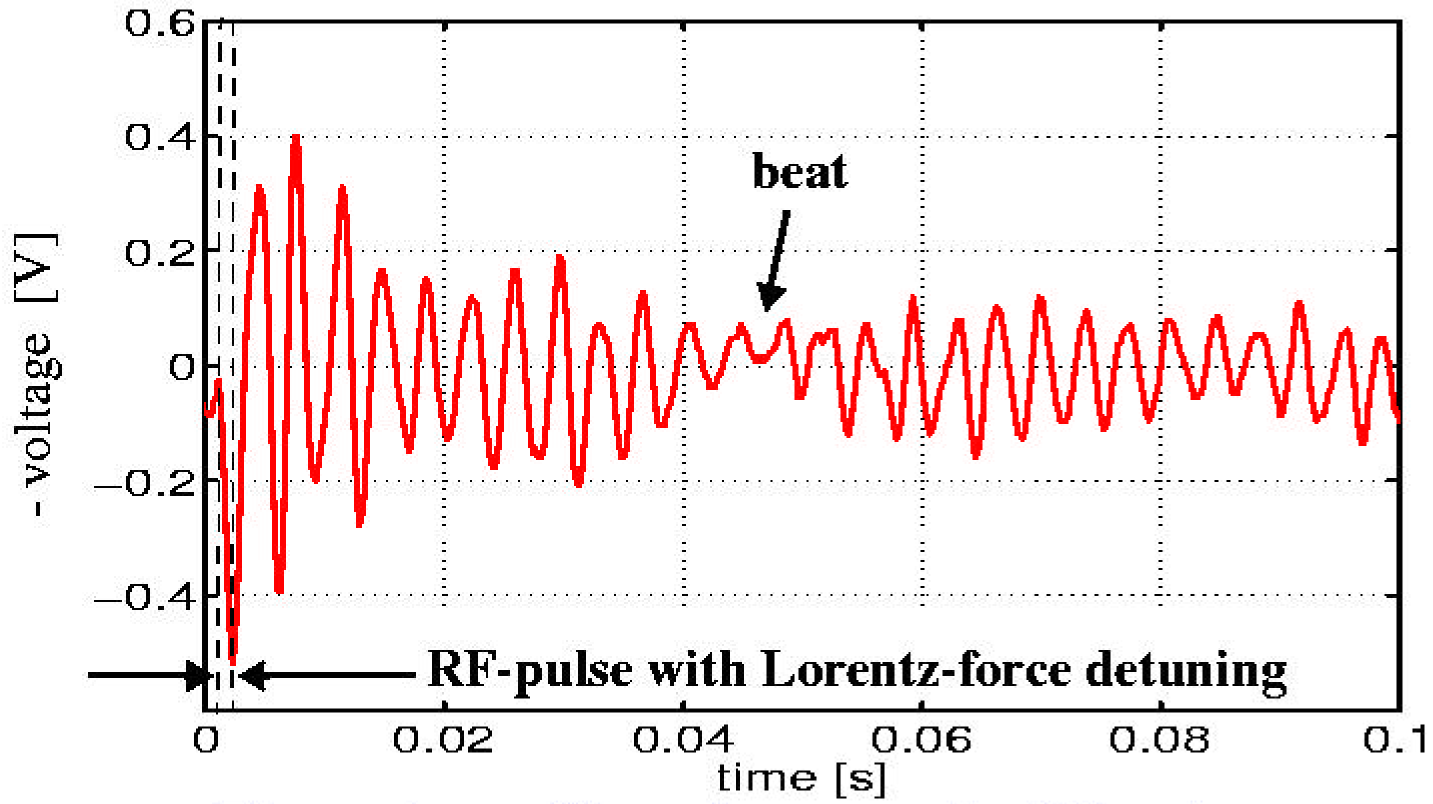


Frequency detuning of 200 - 250 Hz compensated!

The piezo as sensor

mechanical oscillations ⇒ ***measure piezo-voltage***

- TESLA 9-cell Cavity at 30 MV/m with 10 Hz repetition rate



The cavity oscillates between the RF-pulses.

Thanks for your attention!