Superconducting Radiofrequency Accelerating Structures

Lutz Lilje

DESY -MPY-

TAS2008

Acknowledgement

- Several people were supporting with viewgraphs etc.
  - H. Hayano KEK
  - H. Padamsee Cornell
  - D. Reschke, W. Singer DESY
- This lecture came on rather short notice
  - Might be a bit ‘rough’
  - I would appreciate your comments for improvement!

References (Real Paper…)

- Accelerator Cavities
  - Accelerator Physics Courses
    - Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen, Klaus Wille, Teubner Verlag, Studienbücher, 2. Auflage 1996
    - Proceedings of CERN ACCELERATOR SCHOOL (CAS), Yellow Reports
      - General Accelerator Physics, and topical schools on Vacuum, Superconductivity, Synchrotron Radiation, Cyclotrons, and others… http://schools.web.cern.ch/Schools/CAS/CAS_Proceedings.html
      - E.g. 5th General CERN Accelerator School, CERN 94-01, 26 January 1994, 2 Volumes, edited by S.Turner
  - Accelerator Physics General
    - Handbook of Accelerator Physics and Engineering, A.W.Chao and M.Tigner, World Scientific, 1998
  - Historical and Sociological Aspects
    - A BRIEF HISTORY AND REVIEW OF ACCELERATORS, P.J. Bryant, CERN, Geneva, Switzerland, CERN 94-1
    - Pions to Quarks, edited by L. M. Brown, M. Dresden and L. Hoddeson, (New York: Cambridge Univ. Press, 1989).
    - The Birth of Particle Physics, edited by L. M. Brown and L. Hoddeson (New York: Cambridge University Press, 1983).
    - Galison, Peter u. Bruce Hevley (Hg.): Big science: the growth of large-scale research. Stanford Univ. Pr., 1992
    - Traweek, Sharon: Beamtimes and lifetimes: the world of high energy physicists. Harvard University Press 1988
    - Rhodes, Richard, Die Atombombe
- Superconductor Technology for Accelerators
  - Superconducting Accelerator Magnets, K.H.Mess, P.Schmüser, S.Wolff, WorldScientific 1996
  - Superconducting RF
    - RF Superconductivity for Accelerators, H. Padamsee, J. Knobloch, and T. Hays, John Wiley & Sons, 1998.
    - The Superconducting TESLA Cavities, B. Aune et al., PRST-AB, 3, September 2000, 092001.

References (Virtual)

- Wikipedia
  - http://en.wikipedia.org/wiki/Particle_accelerator
- SRF Workshop Tutorials
  - http://www.lns.cornell.edu/public/SRF2005/program.html
  - http://www.pku.edu.cn/academic/srf2007/program.html#tutorial
- Accelerators
  - Lecture by Rüdiger Schmidt (german)
    - http://rudi.home.cern.ch/rudi/lectures%20darmstadt/overview.htm
  - LHC: http://lhc.web.cern.ch/lhc/
  - XFEL: http://xfel.desy.de/tdr/tdr/index_eng.html
  - ILC: http://www.linearcollider.org/cms/

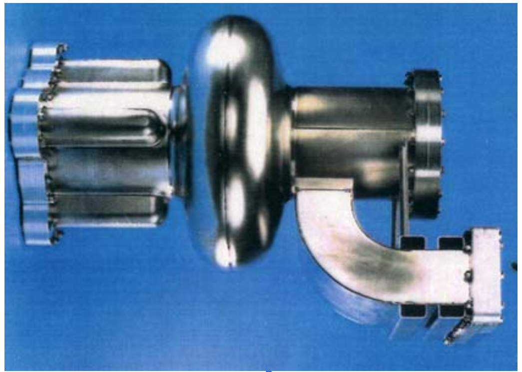
Outline of the lectures

- Lecture 1
  - Radiofrequency (RF) cavities
    - A variety of superconducting RF (SRF) cavities in pictures
    - Cavity Parameters: The Pillbox cavity
    - Acceleration of a bunched beam
  - Superconductivity basics
  - RF superconductivity
  - Limitations of superconducting RF cavities
    - Diagnostic tools
    - Surface and material science
    - Defects
      - Thermal conductivity
    - Field emission
    - Multipacting
    - Increased surface resistance at high field
- Lecture 2
  - Cavity Design
  - (Cryomodule Design)

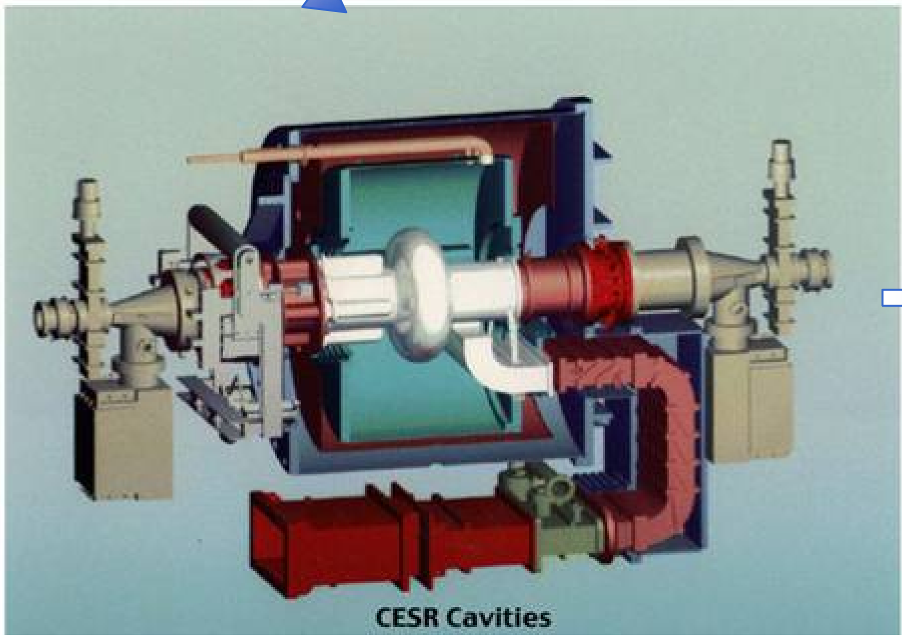
SRF cavities

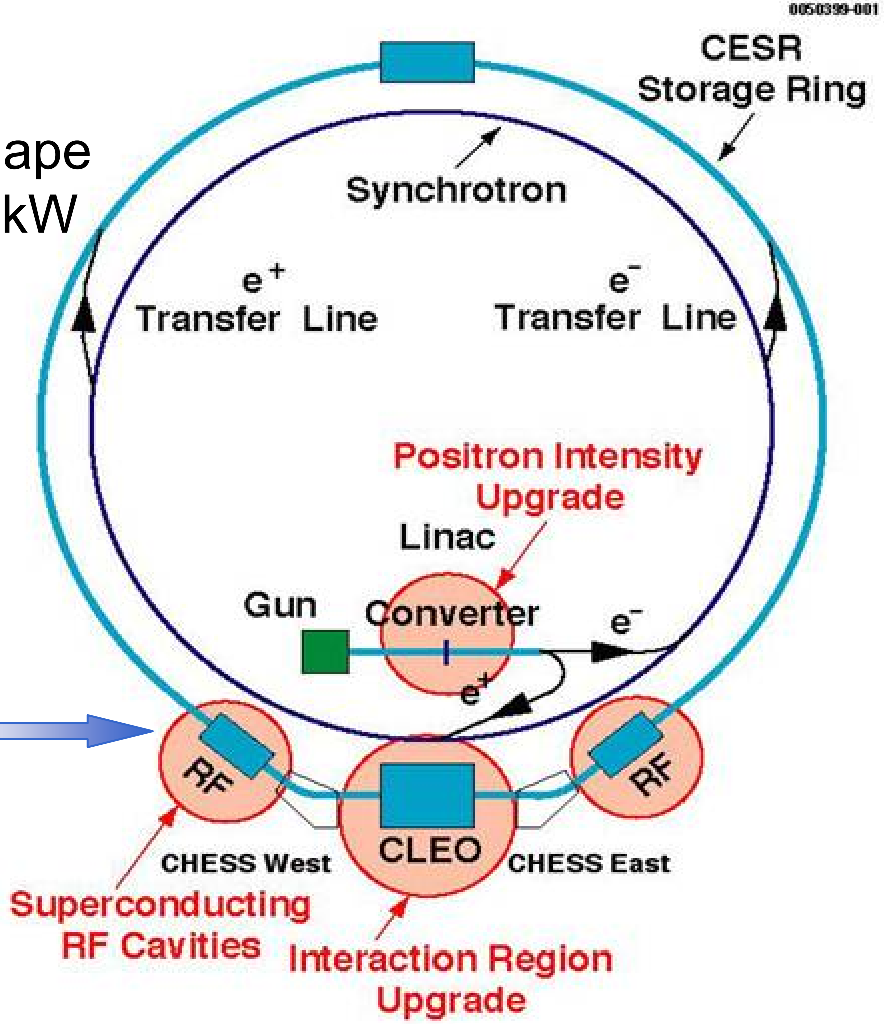
- What do they actually look like?
  - Protons
  - Ions
  - Electrons

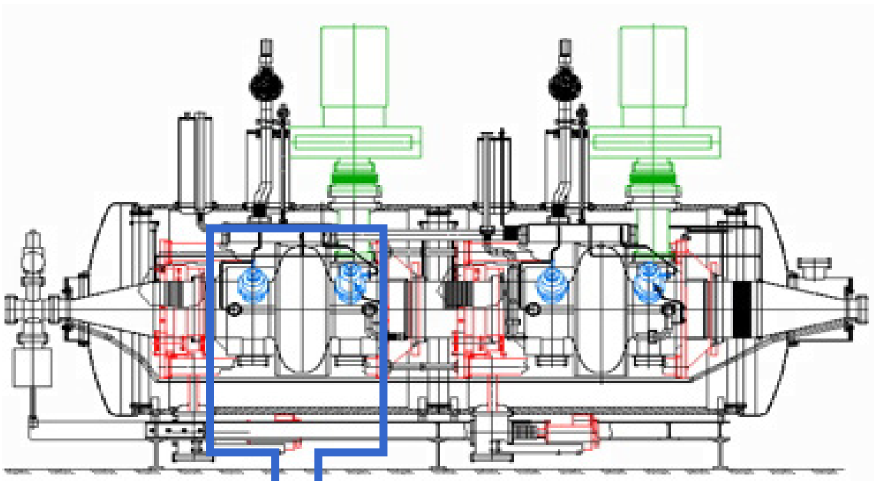
High luminosity rings (CESR)

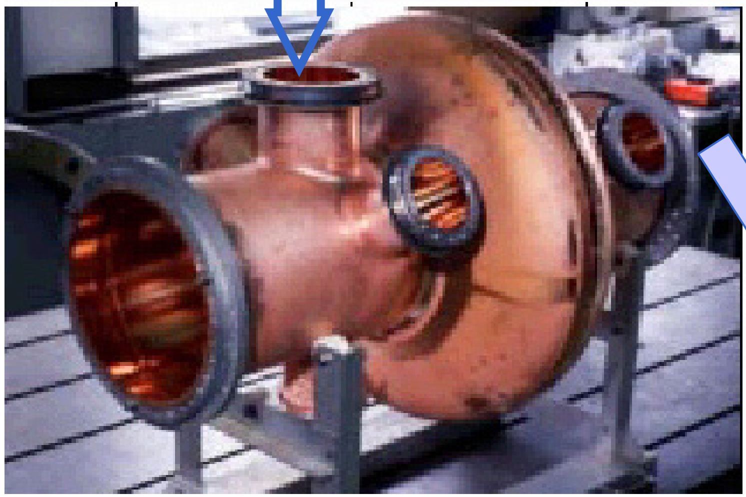


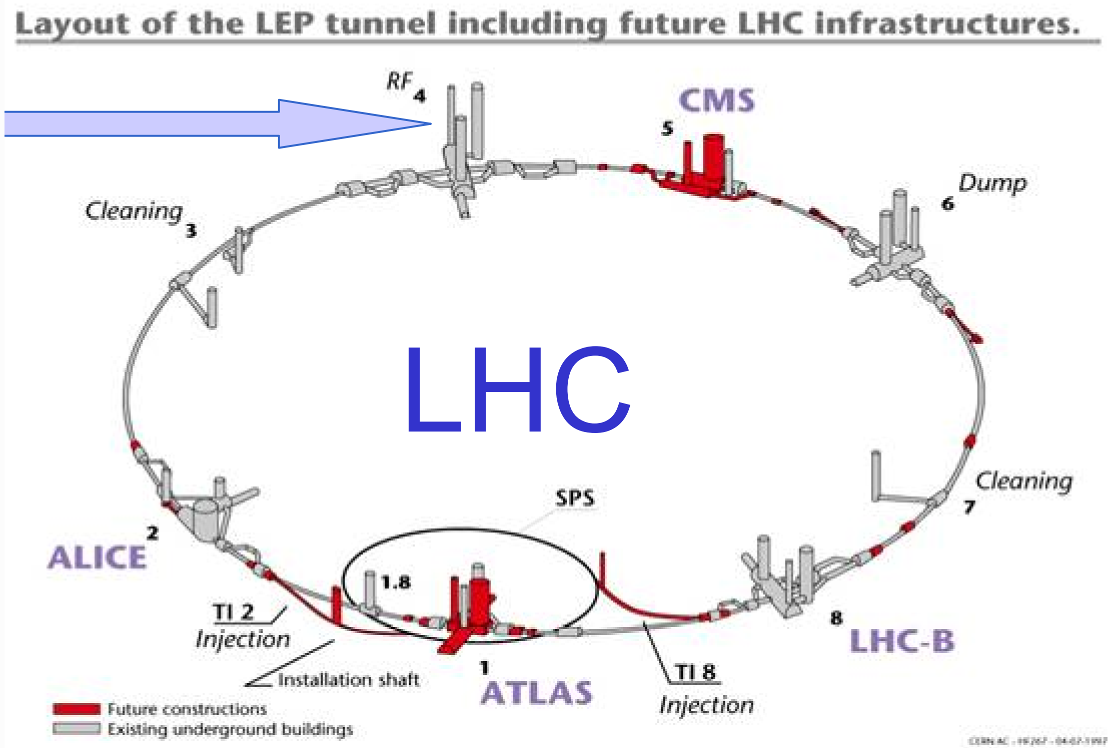
- Low Impedance Shape
- Beam Power > 270kW

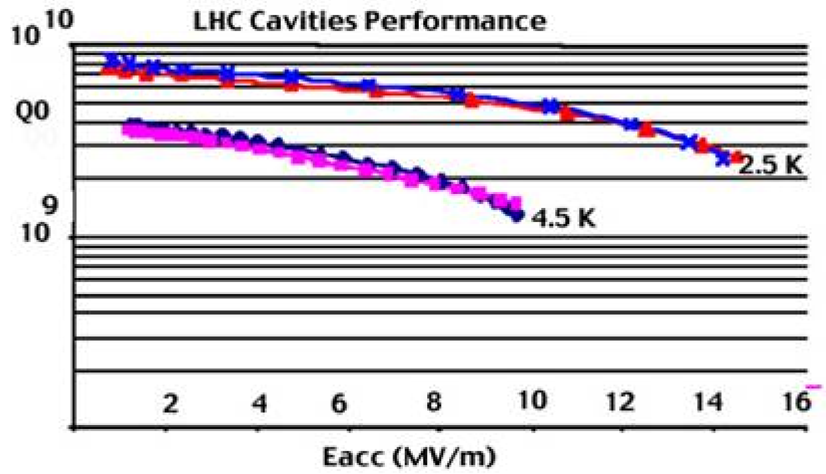










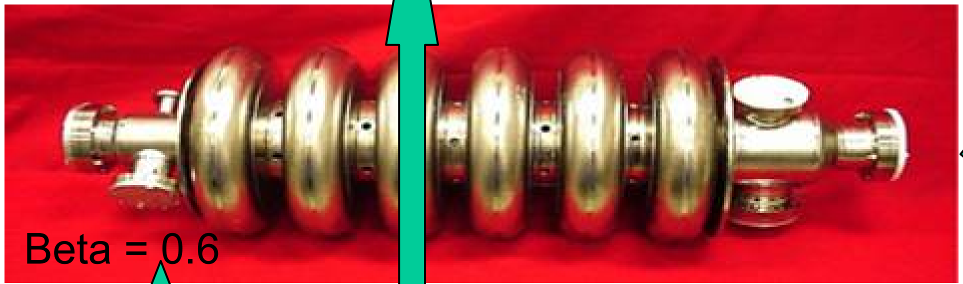


400 MHz

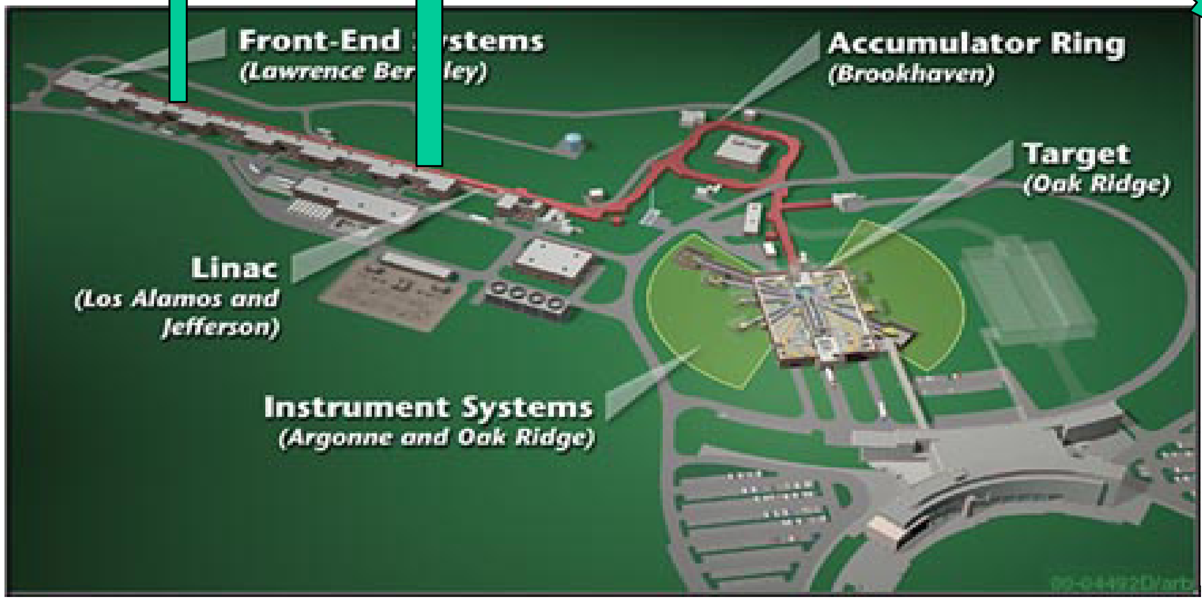
16 Nb/Cu Cavities

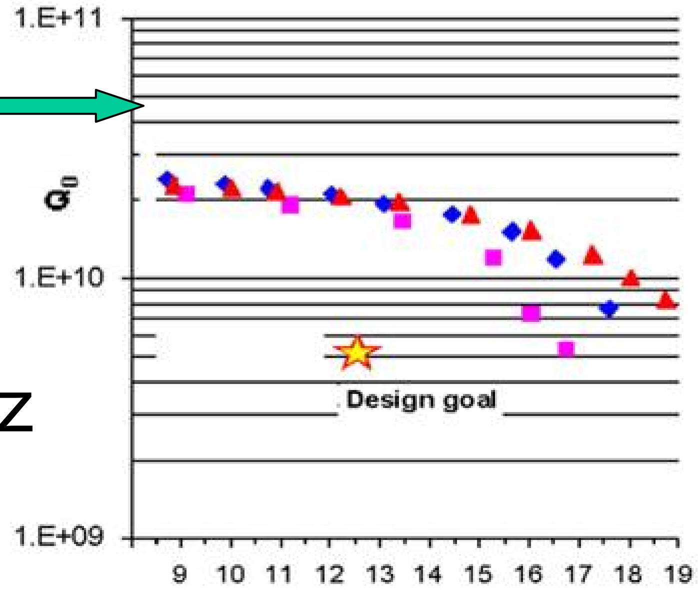
CORNELL UNIVERSITY -

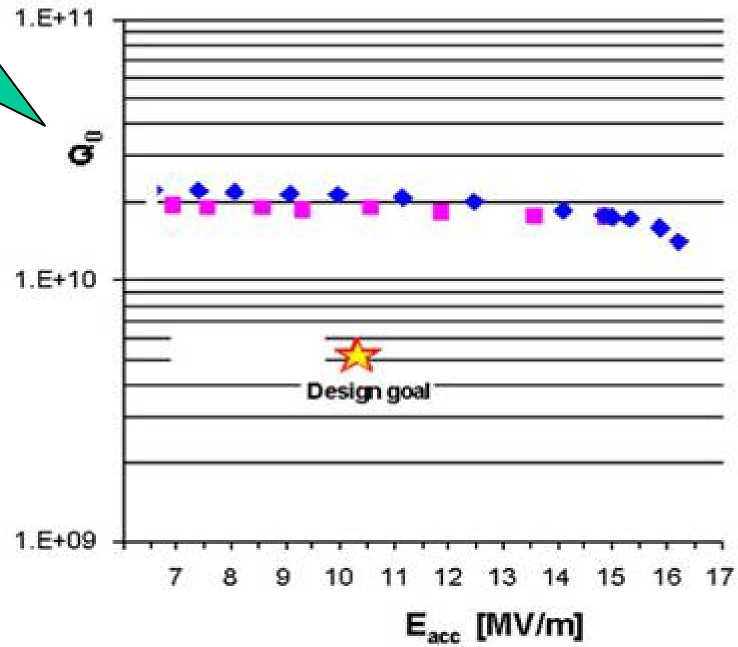
SNS (Spallation Neutron Source)

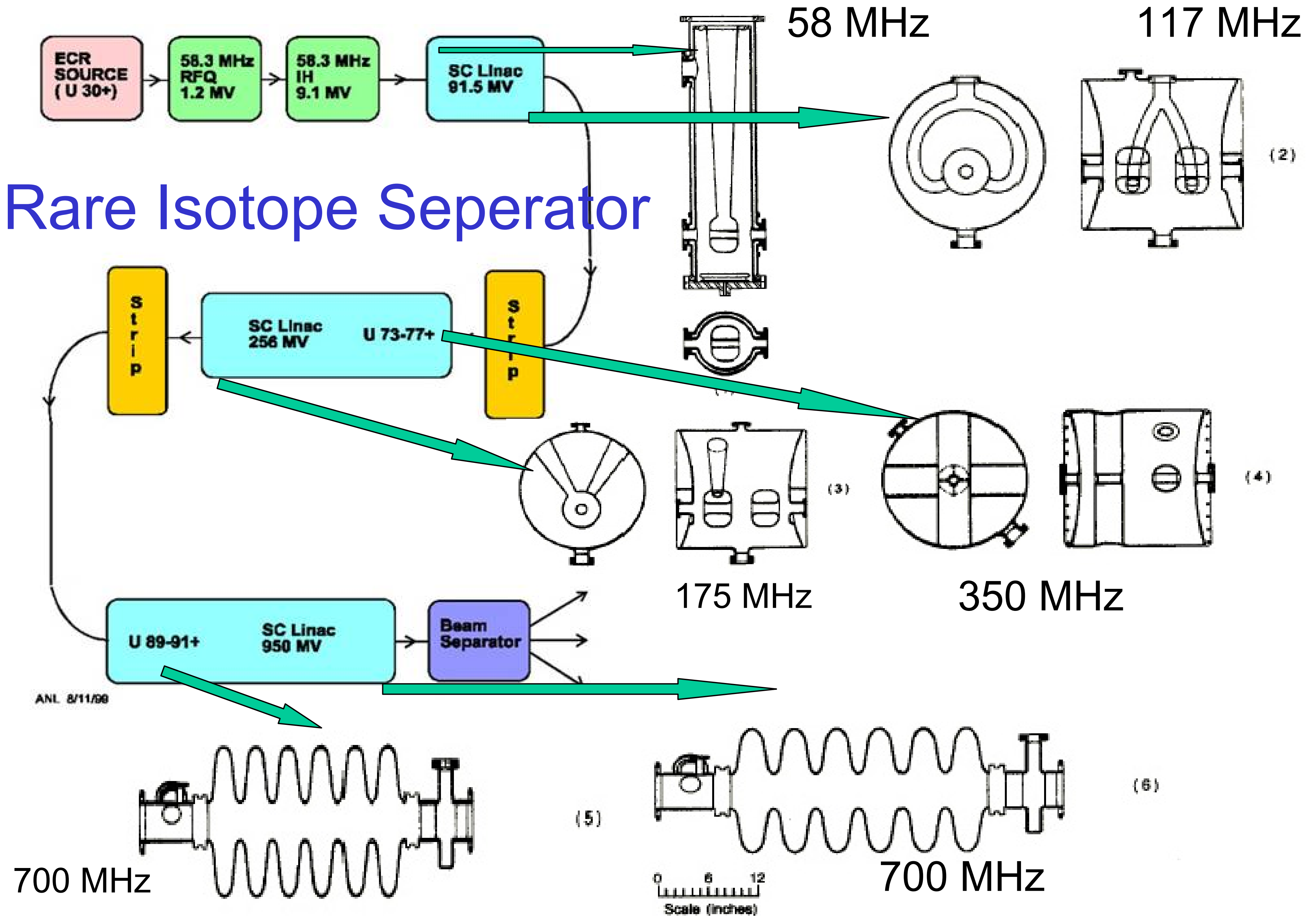


800 MHz





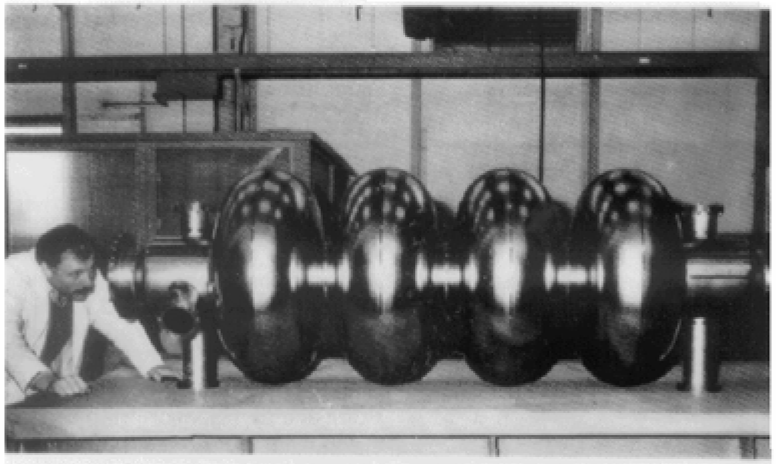


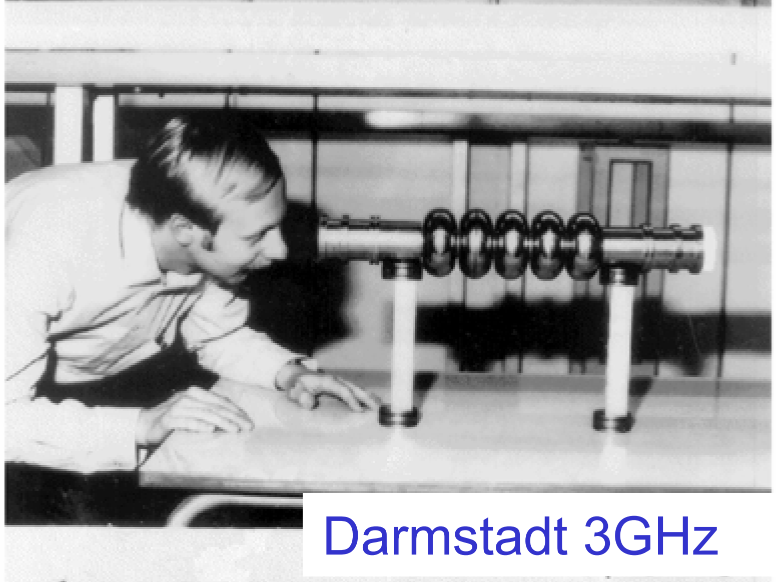


ECR SOURCE (U 30+)
58.3 MHz RFQ 1.2 MV
58.3 MHz IH 9.1 MV
SC Linac 91.5 MV
58 MHz
117 MHz
(2)
Rare Isotope Seperator
Strip
SC Linac 256 MV
U 73-77+
Strip
(3)
(4)
175 MHz
350 MHz
U 89-91+
SC Linac 950 MV
Beam Separator
ANL 8/11/98
(5)
(6)
700 MHz
0 6 12
Scale (inches)
700 MHz

Niobium bulk cavities

CERN 350 MHz





Darmstadt 3GHz

TESLA
1,3 GHz

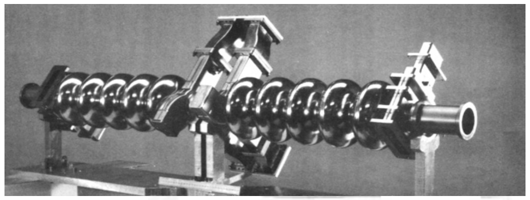
Livingston plot for SRF cavities

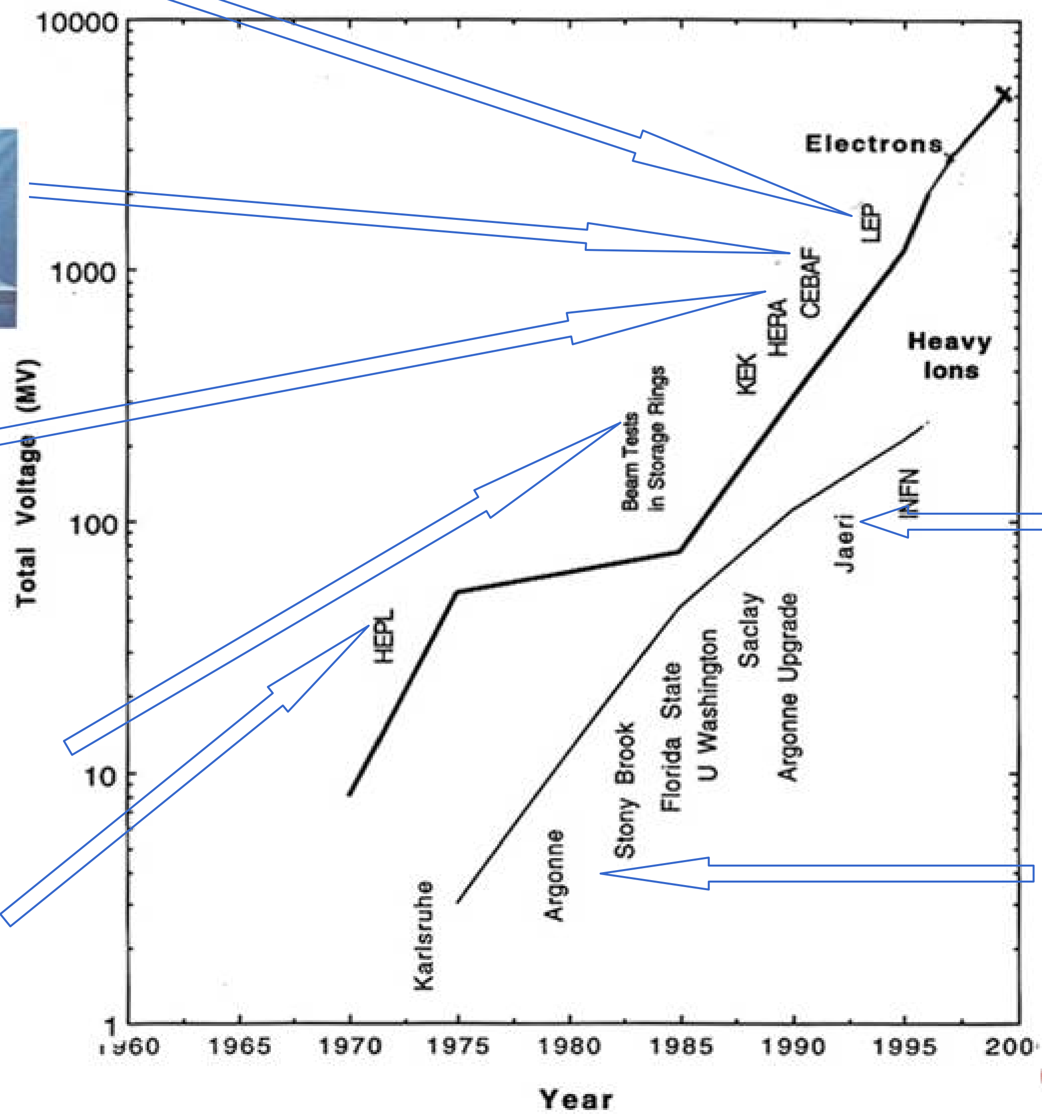
Courtesy H. Padamsee

Total >1000 meters

> 5 GV

Nb/Cu Technology



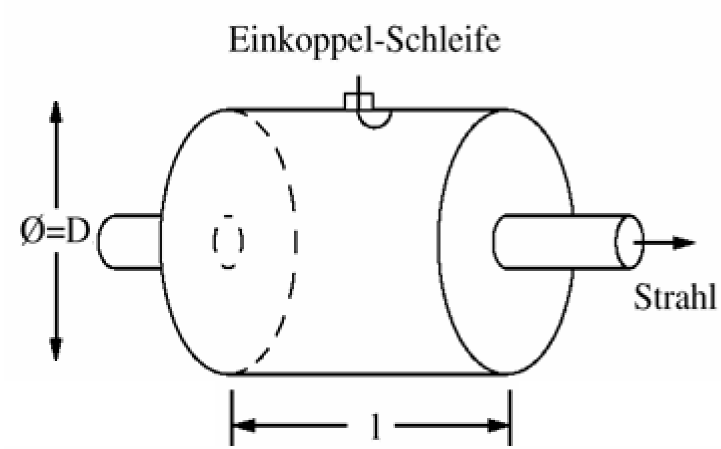


CORNELL UNIVERSITY

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

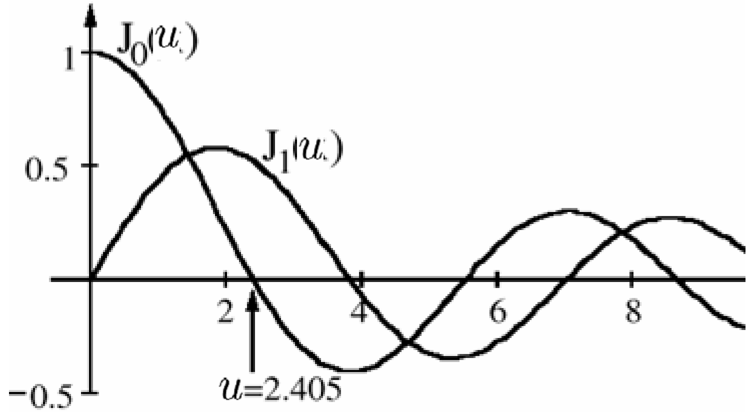


Example: cylindrically symetric cavity - Pillbox

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

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

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



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

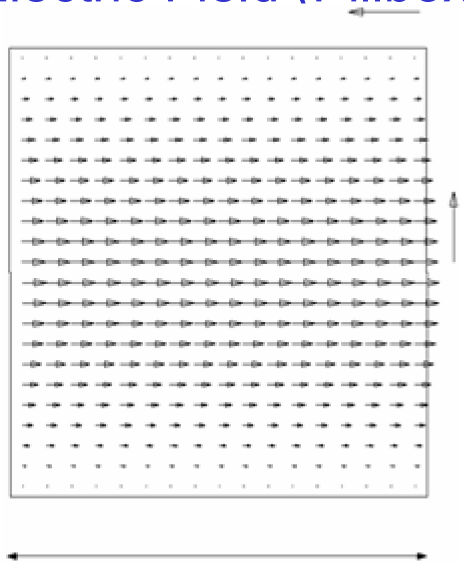
Stored Energy: $U = \frac{1}{2}\varepsilon_0 E_0^2\, J_1^2(2.405)\, l\, \pi \left(\frac{D}{2}\right)^2$

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

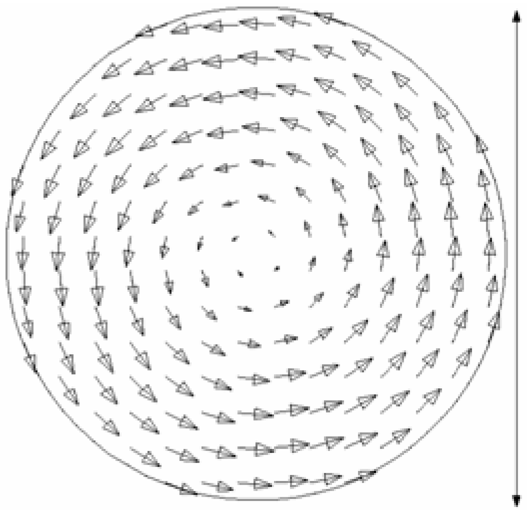
Field Distributions in Cavities

Electric Field (Pillbox):



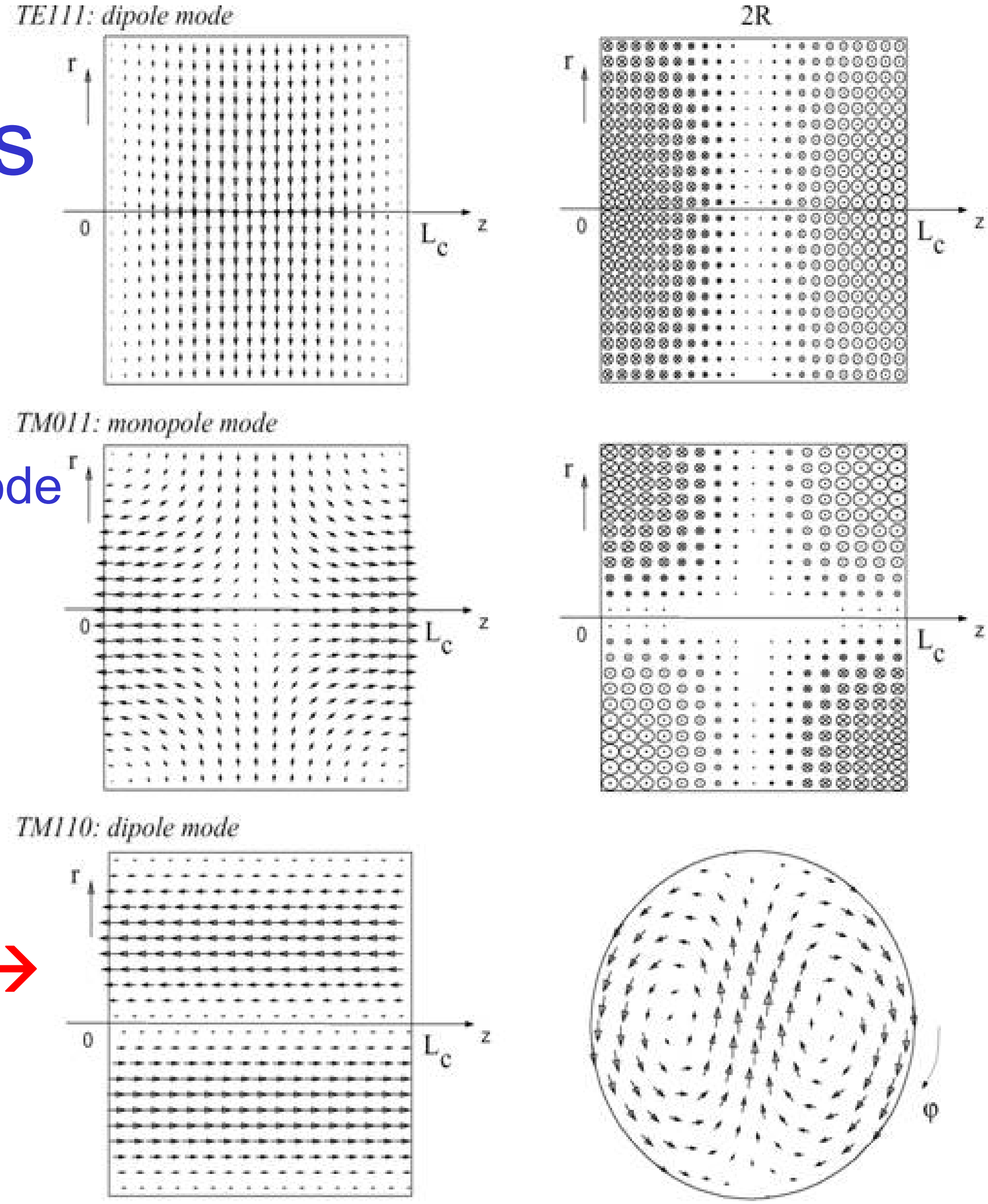
← TM010 : accelerating mode

Magnetic Field :



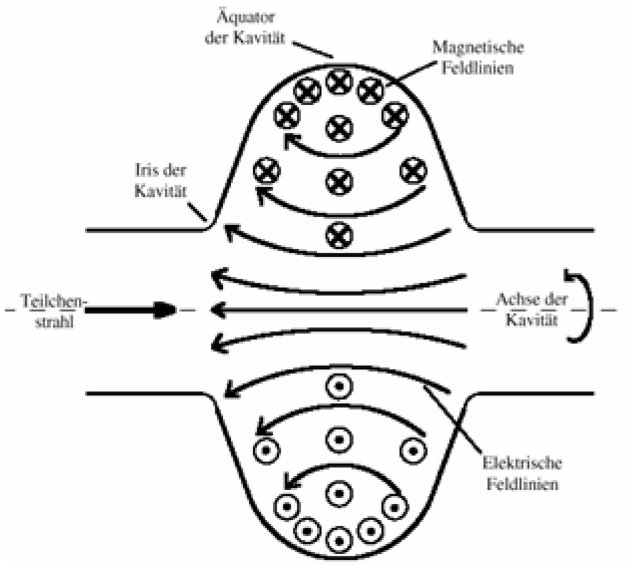
D (front view)

Other modes : e.g. deflecting modes →



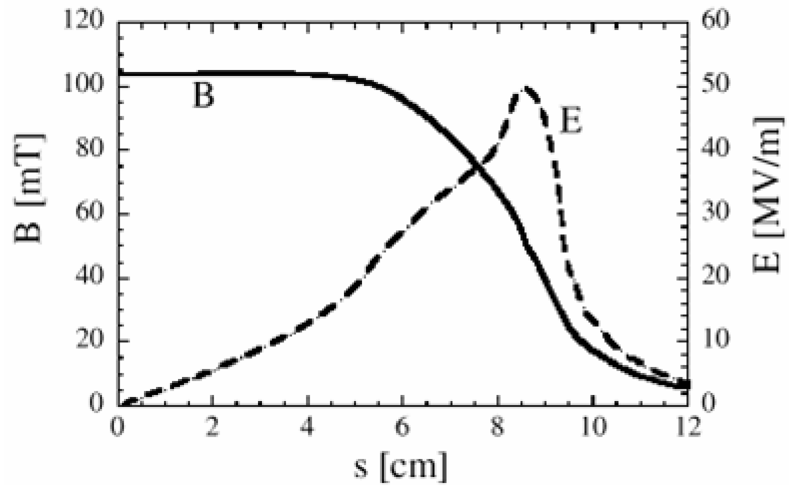
Field Distributions in Cavities

Elliptical cavity:



Numerical solution for surface fields:

⇒

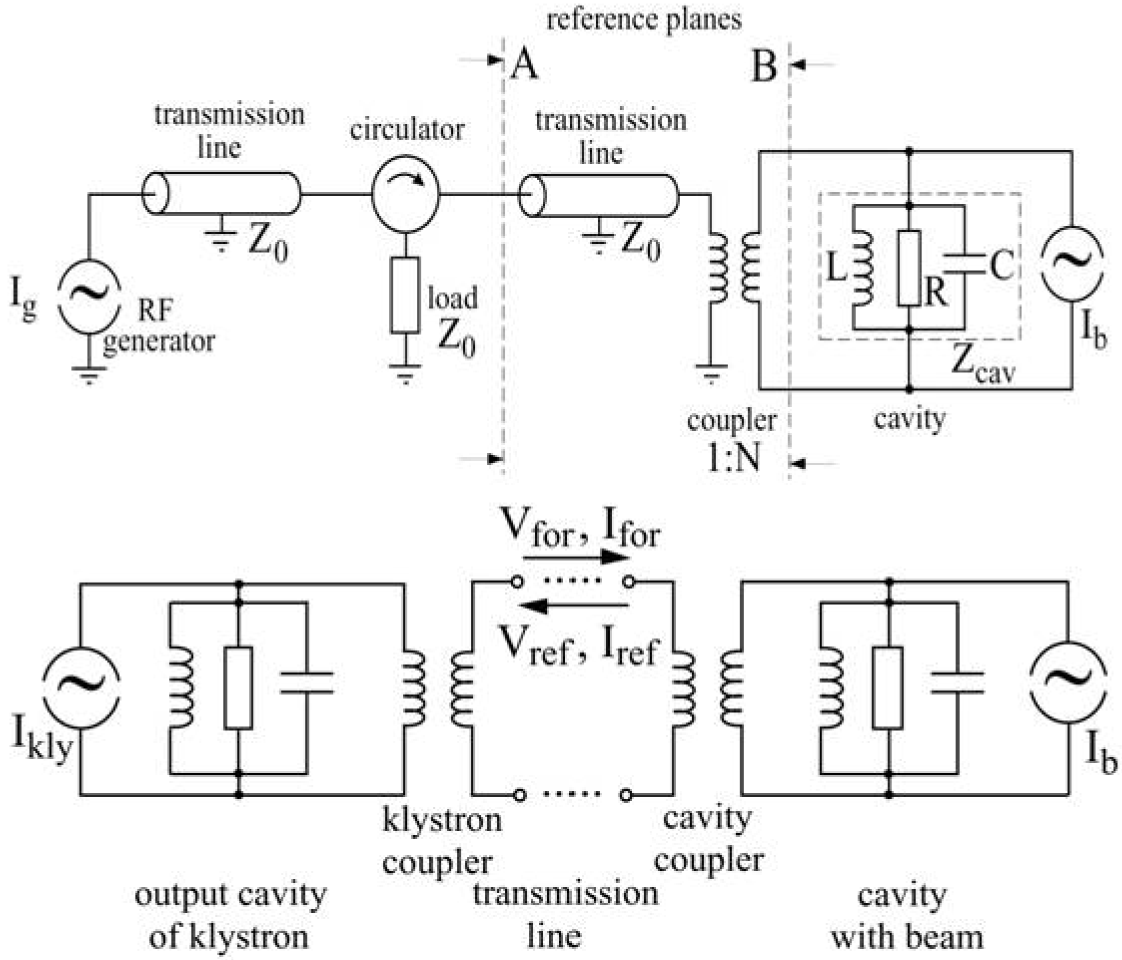


Relations for the surface fields to acclerating gradient:

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

⇒ **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 :

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

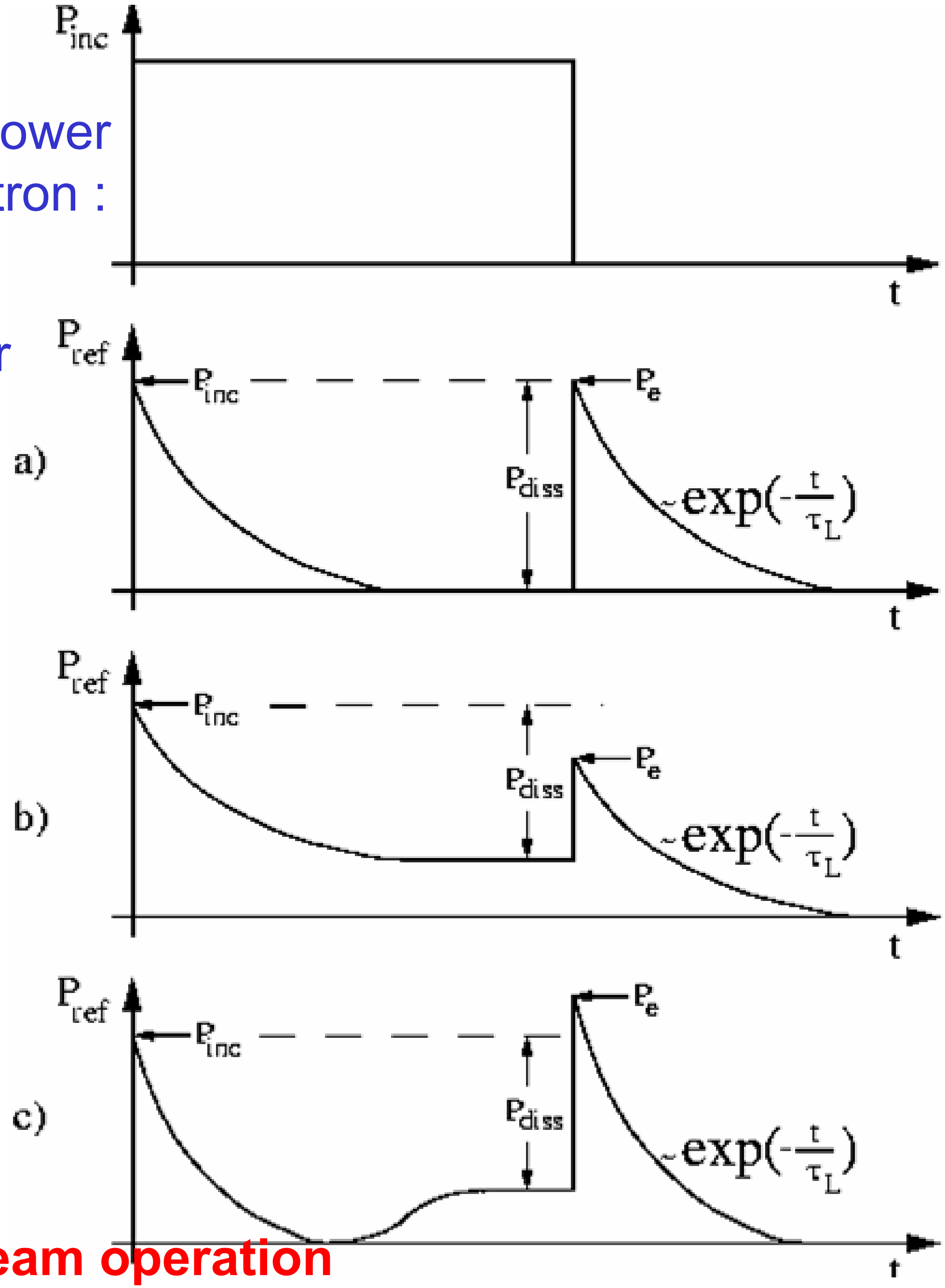
Coupling factor :

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

Acceleration of a bunched beam

Incident power from Klystron :

Reflected power to Klystron :

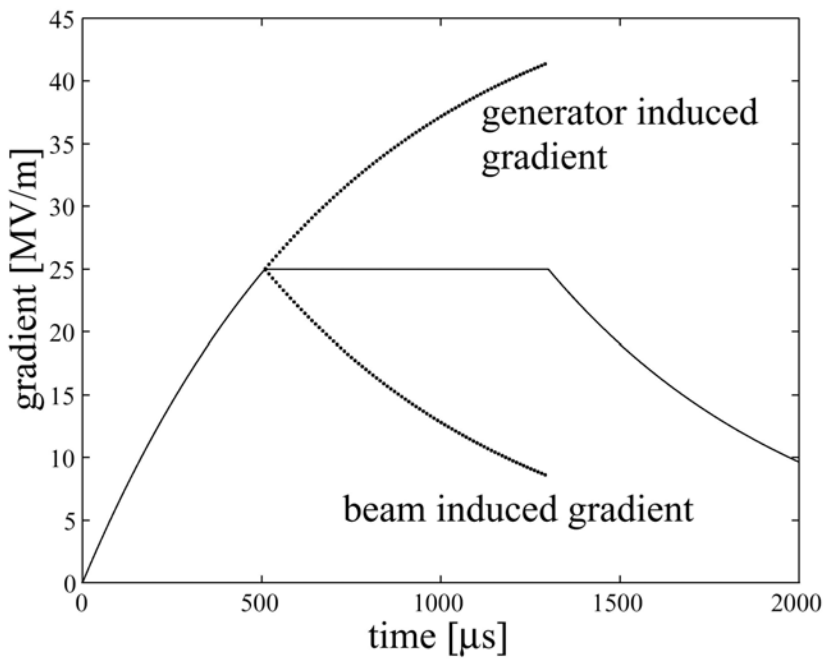


$\beta = 1$

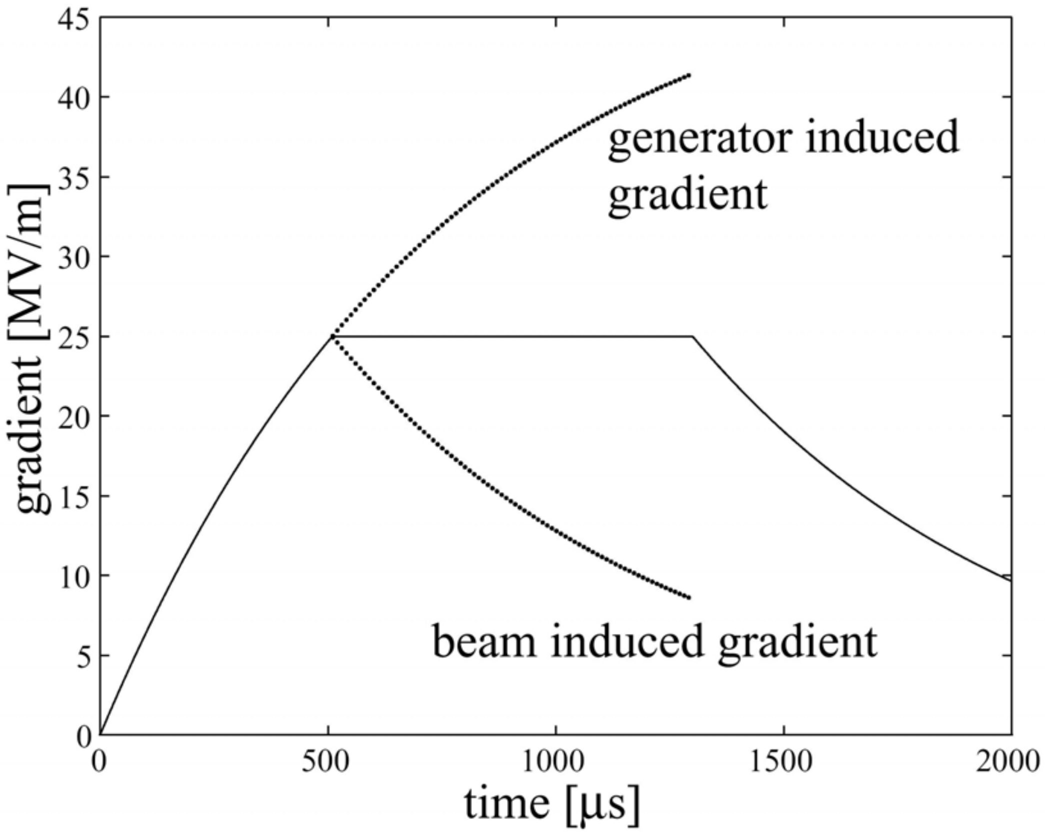
$\beta < 1$

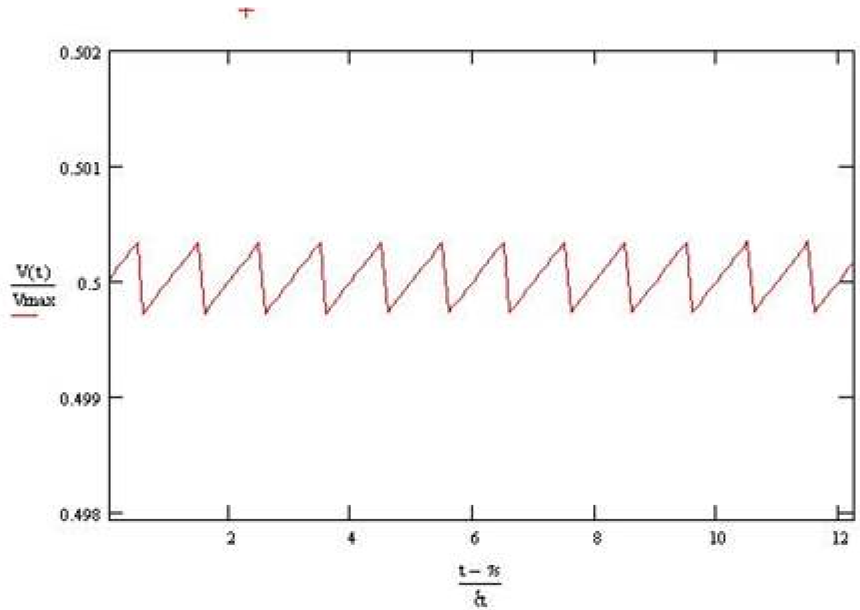
$\beta > 1$

For beam operation



Acceleration of a bunched beam



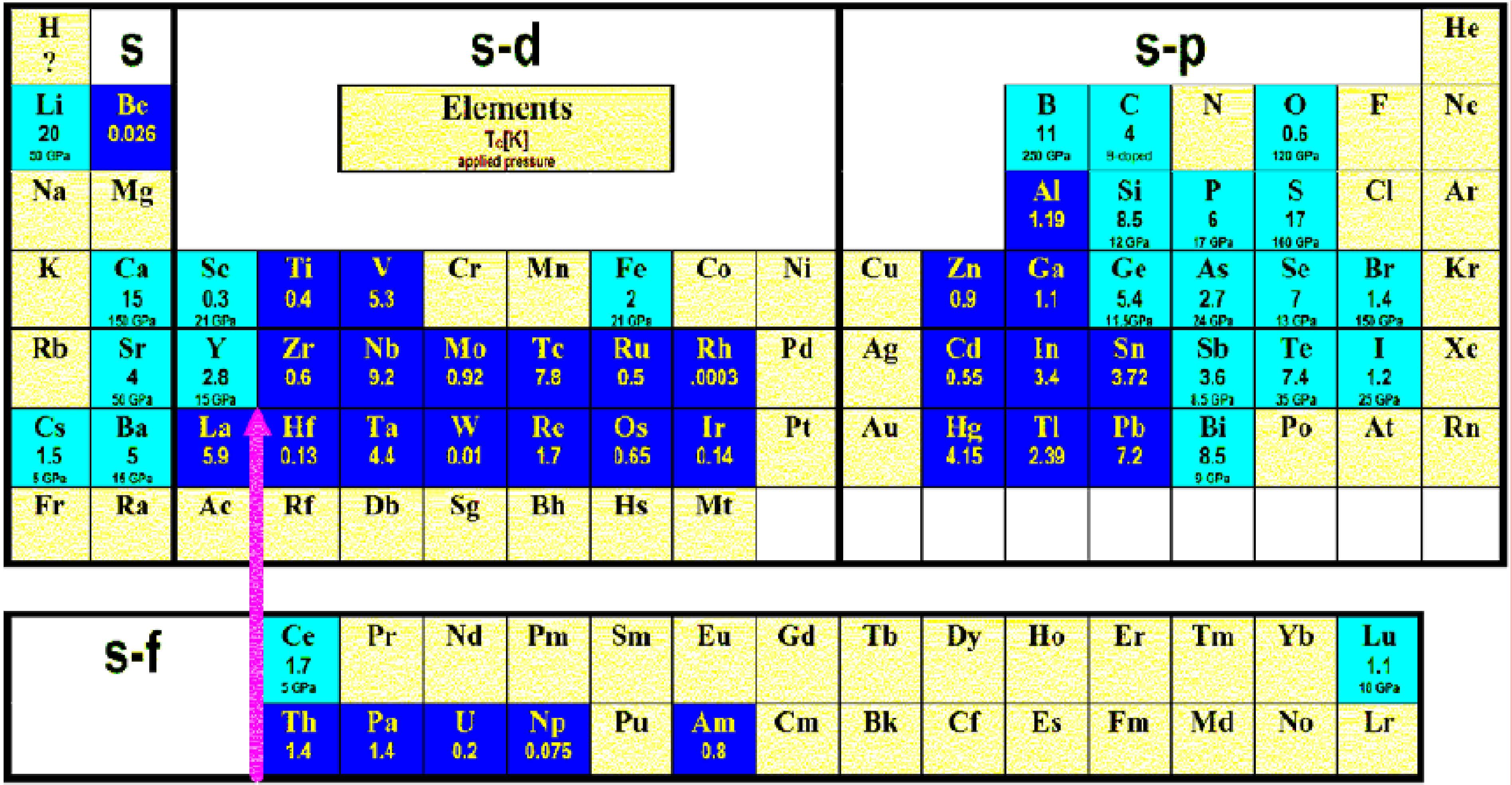


- Let's see what happens, when the Q_{ext} is wrong…

Outline of the lecture

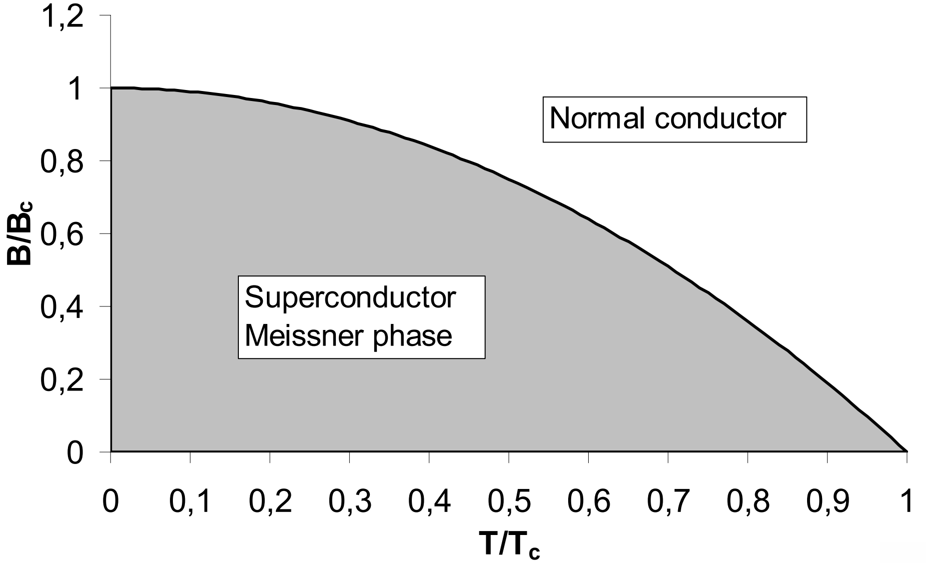
- RF cavities
- Superconductivity basics
- RF superconductivity
- Limitations of superconducting RF (SRF) cavities

Examples of Superconductors: Pure Elements



- Superconductor **(Blue)** / Superconductor under pressure **(Light Blue)**
- From: SUPERCONDUCTING MATERIALS – A TOPICAL OVERVIEW, R. Hott et al. FZK

Superconductors in magnetic fields (Type I)



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

Temperature dependence:

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

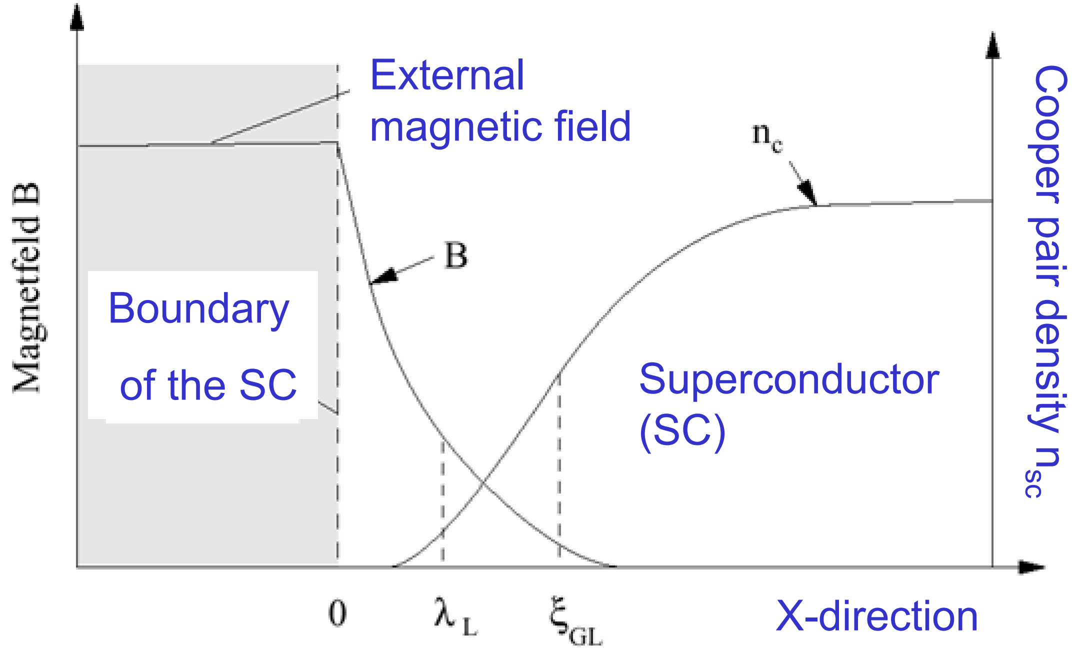
Penetration depth:

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

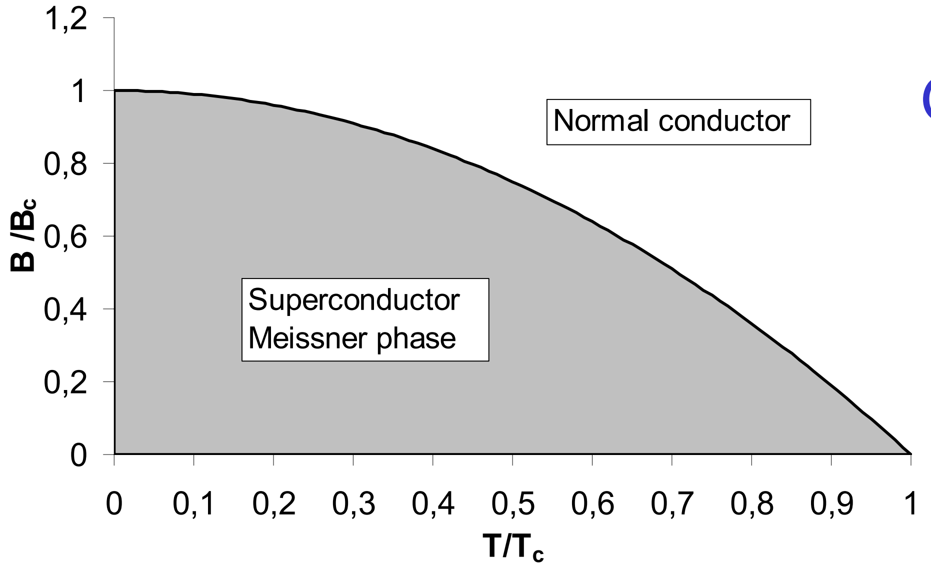
$$\lambda_L(T) = \lambda(0)\left(1 - \left(\frac{T}{T_c}\right)^4\right)^{-\frac{1}{2}}$$

Coherence length:

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



Superconductors in magnetic fields (Typ II)

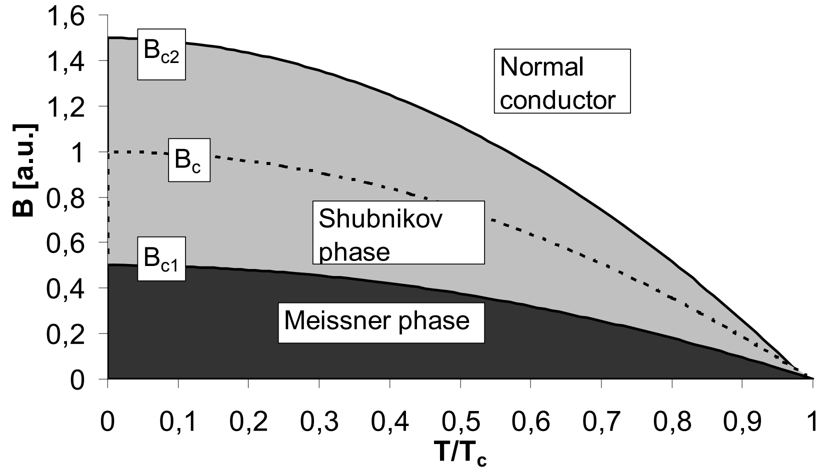


Ginzburg-Landau-Parameter:

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

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.)

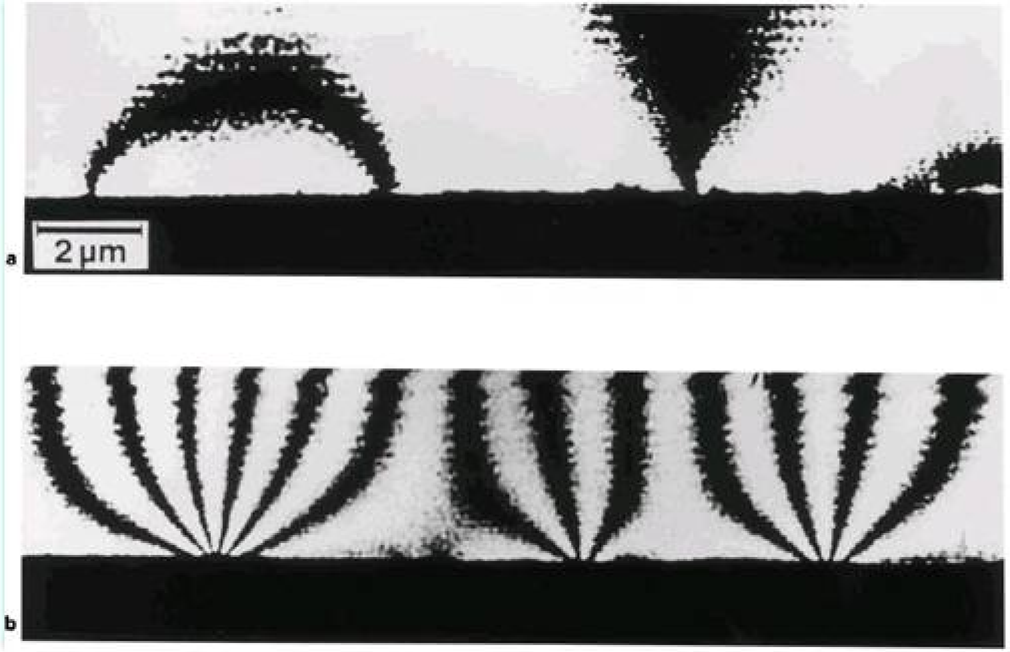


Fig. 6. Interference micrographs of magnetic lines of force penetrating superconducting Pb films: (a) film thickness 0·2 µm; (b) film thickness 1·0 µm.

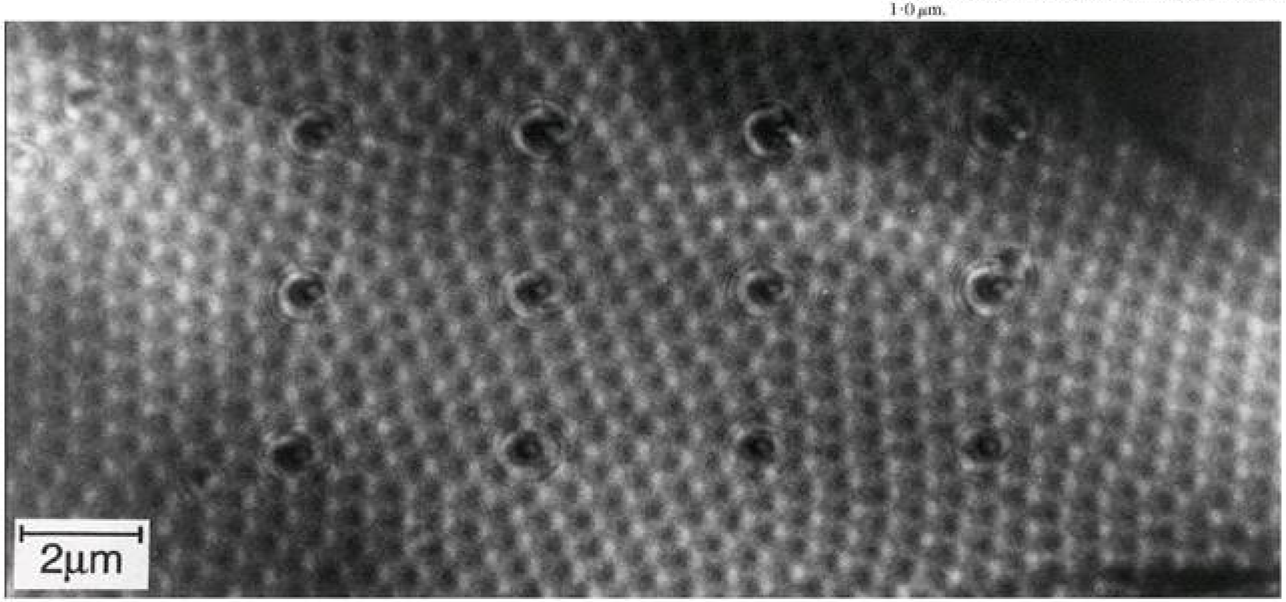


Fig. 16. Vortex configuration near black defects ($T = 7{\cdot}5$ K, $H = 75$ gauss).

Fluxons stick to defects !

This is good for magnets, but bad for cavities.

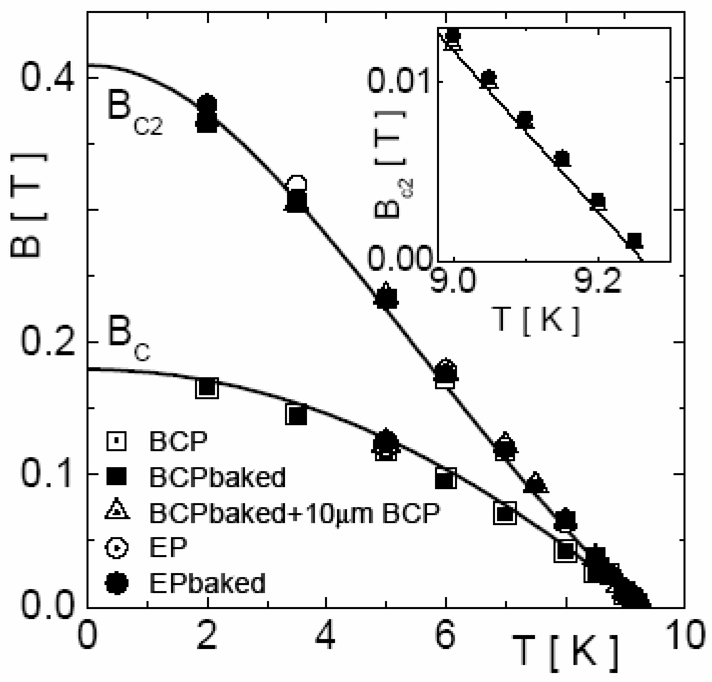
$$R_{fl} = \eta \frac{B_{ext}}{B_{c2}} R_{surf,nc}$$

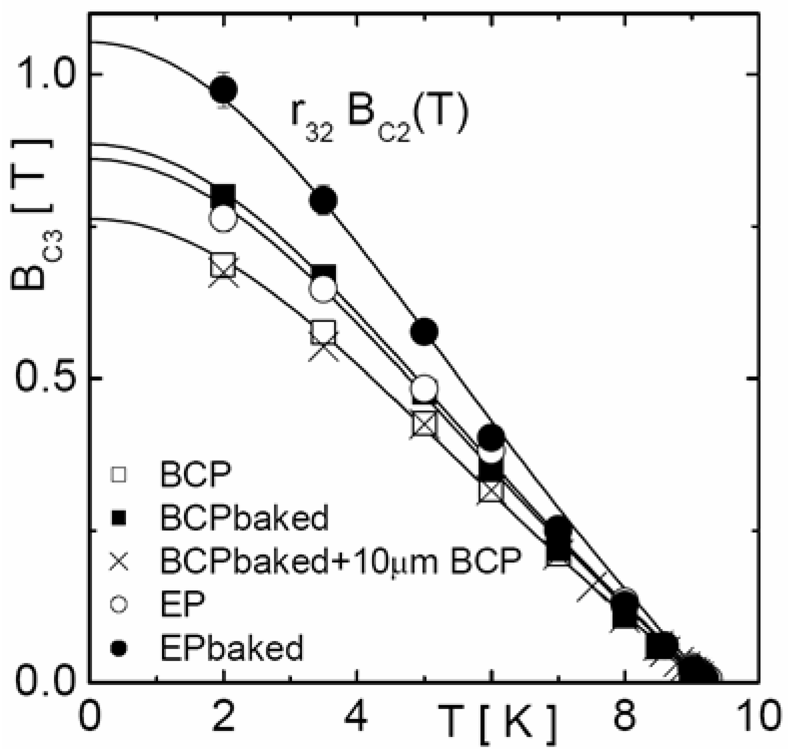
S. Casalbuoni,
L. von Sawilski,
P. Schmüser,
B. Steffen et al.

Susceptibility Measurements: Niobium Properties

- Surface treatment does not change the bulk properties e.g. B_c and B_{c2}
- Surface critical field B_{c3} depends on surface preparation
  - EP vs. BCP
  - Baking
- Open question: What is the relation to the RF critical field?

	BCP	EP
T_c [K]	9.263 ± 0.003	
RRR	≈ 300	
surf. roughness on grain [nm]	≈ 1	
steps at grain bound.	1-5 μm	$\lesssim 0.1\mu$m
$B_c(0)$ [mT]	180 ± 5	
$B_{c2}(0)$ [mT]	410 ± 5	
$J_c(0,0)$ [A/mm^2]	240 ± 10	180 ± 10





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:

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

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

⇒ 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.

$\Rightarrow$ 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:

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

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

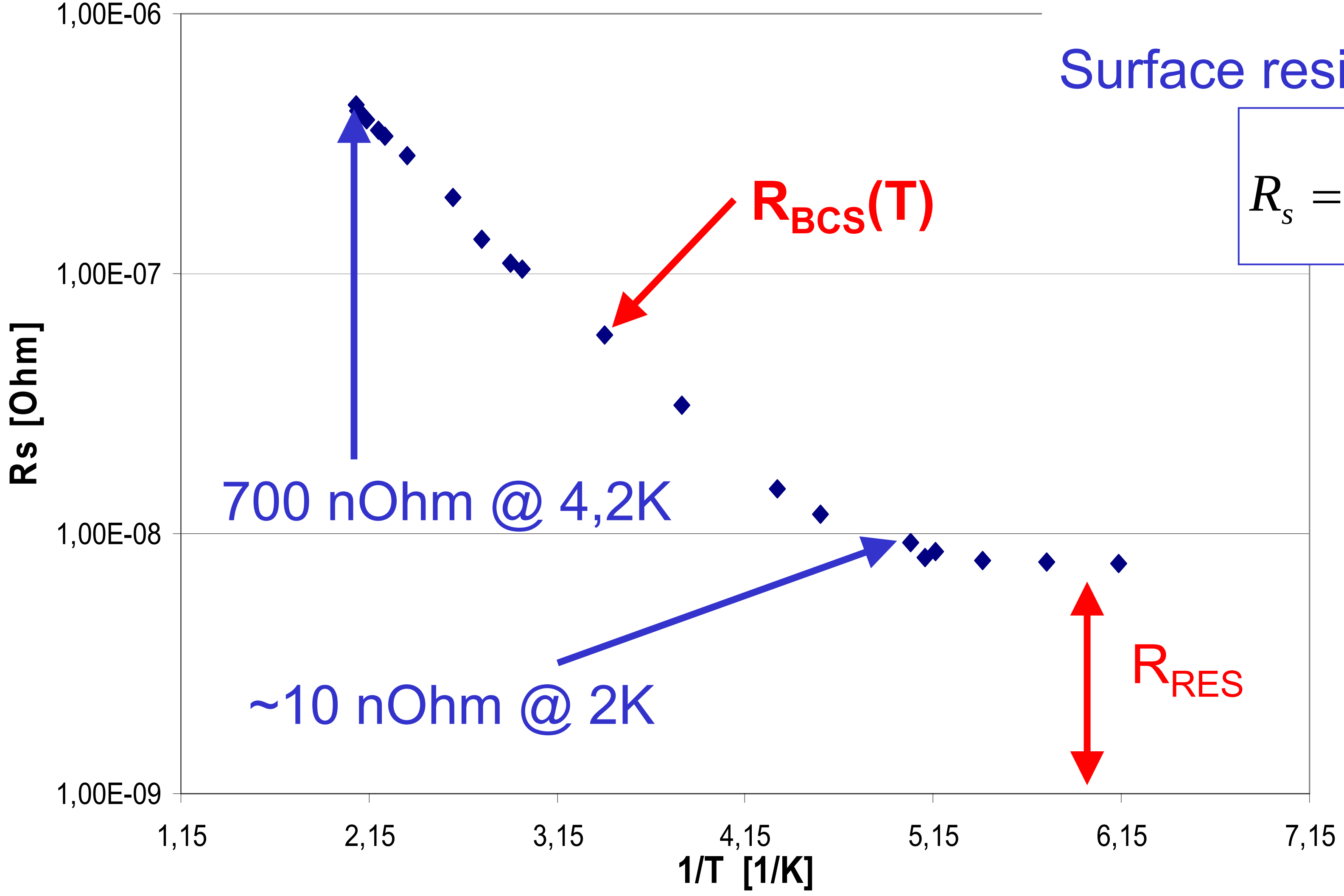
Geometry factor:

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

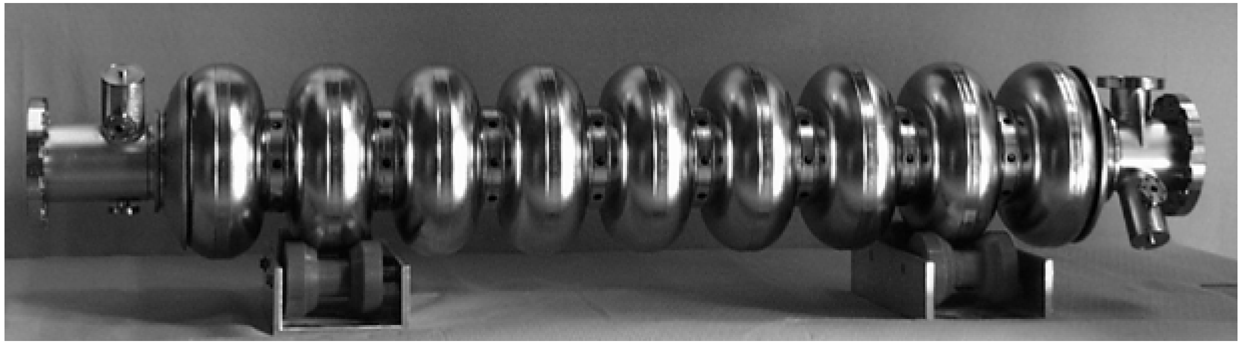
G = 270 Ohm

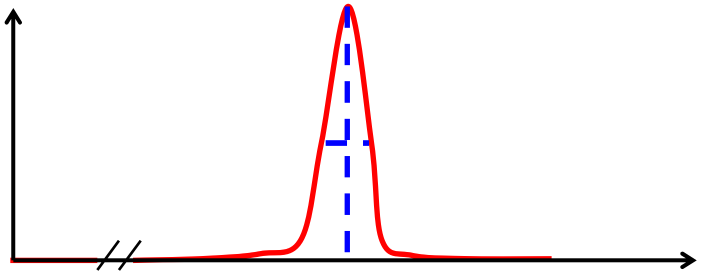
Surface resistance:

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



Cavities for ILC -RF surface resistance





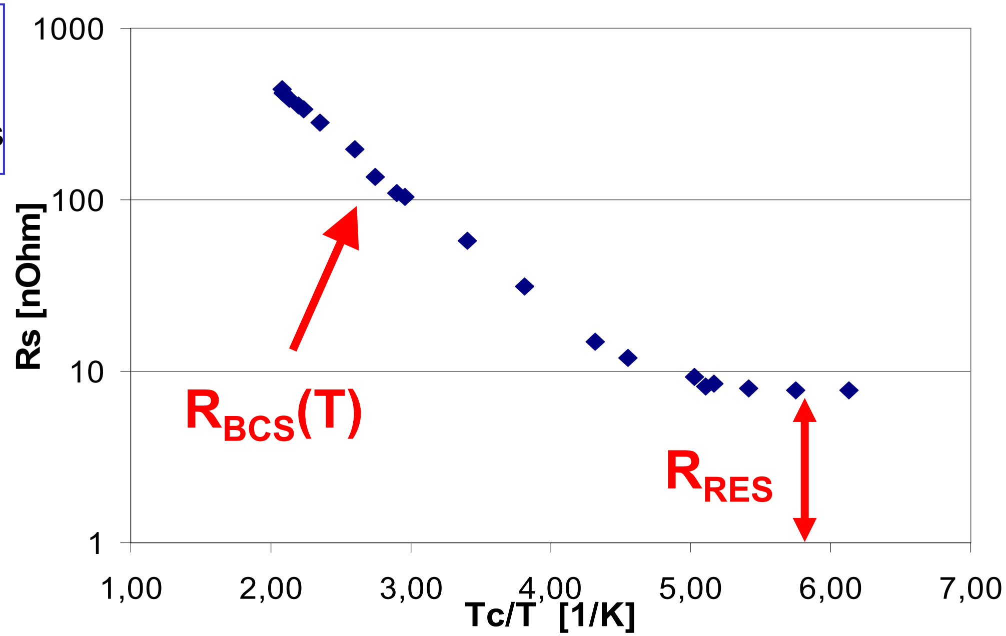
$f_o = 1.300.000.000\,\text{Hz}$

Quality factor:

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

RF surface resistance:

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



'Natural' Bandwidth:

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

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

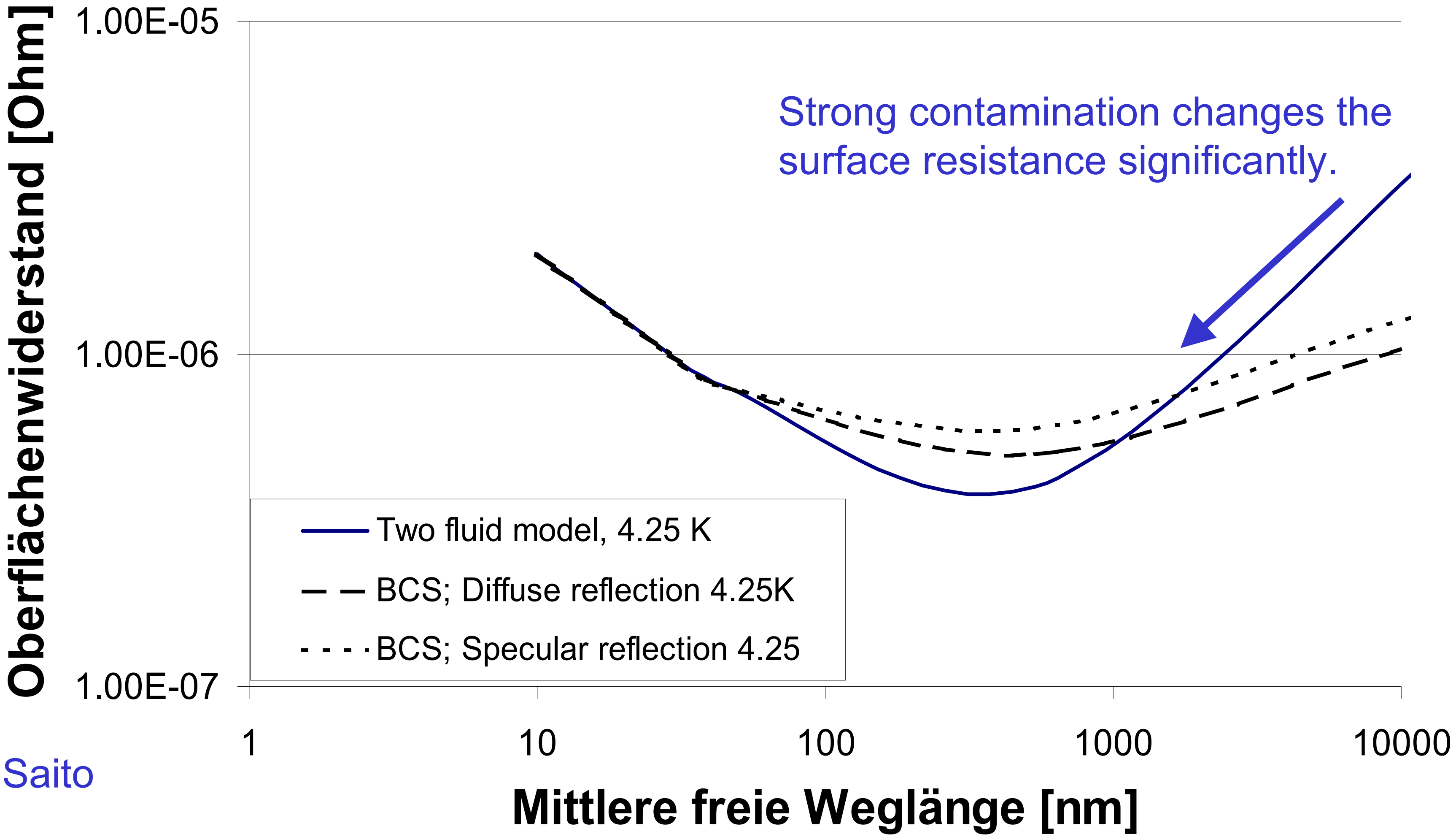
Line width with main coupler

$\Delta f \approx 300$ Hz

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

Surface resistance and mean free path

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



Kneisel, Saito

Surface resistance and electric conductivity

Normalconductor (Copper): $R_s = \frac{1}{\sigma\delta}$ At 1 GHz: $\sigma = 1\ \mu m$

$R_s = 4\ m\Omega$

Superconductor (Niob):

$$j = j_n + j_s = (\sigma_n - i\sigma_s)E$$

$$Z_s = R_s + iX_s$$

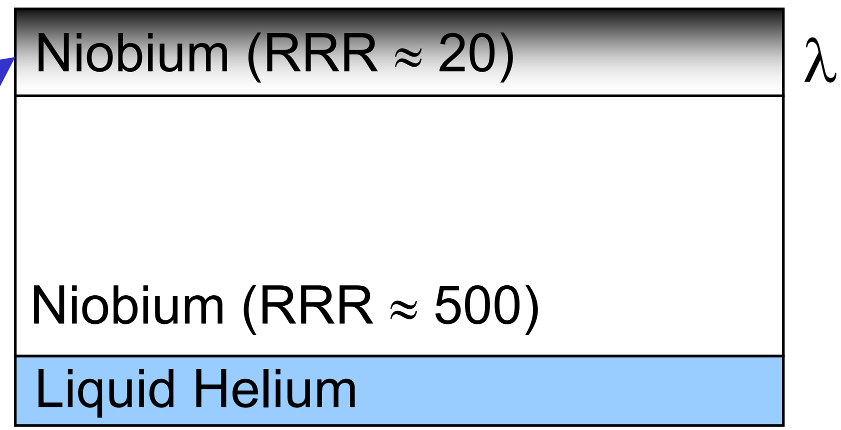
σ_n Conductivity of normal electrons,
σ_s Cooperpairs

$$\sigma_s >> \sigma_n$$

$$R_s = \mathrm{Re}(Z_s) \propto \sigma_1$$
$$\propto l$$

Mean free path

⇒ 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:
    - We have to shield sc cavities from magnetic fields to have a low surface resistance!

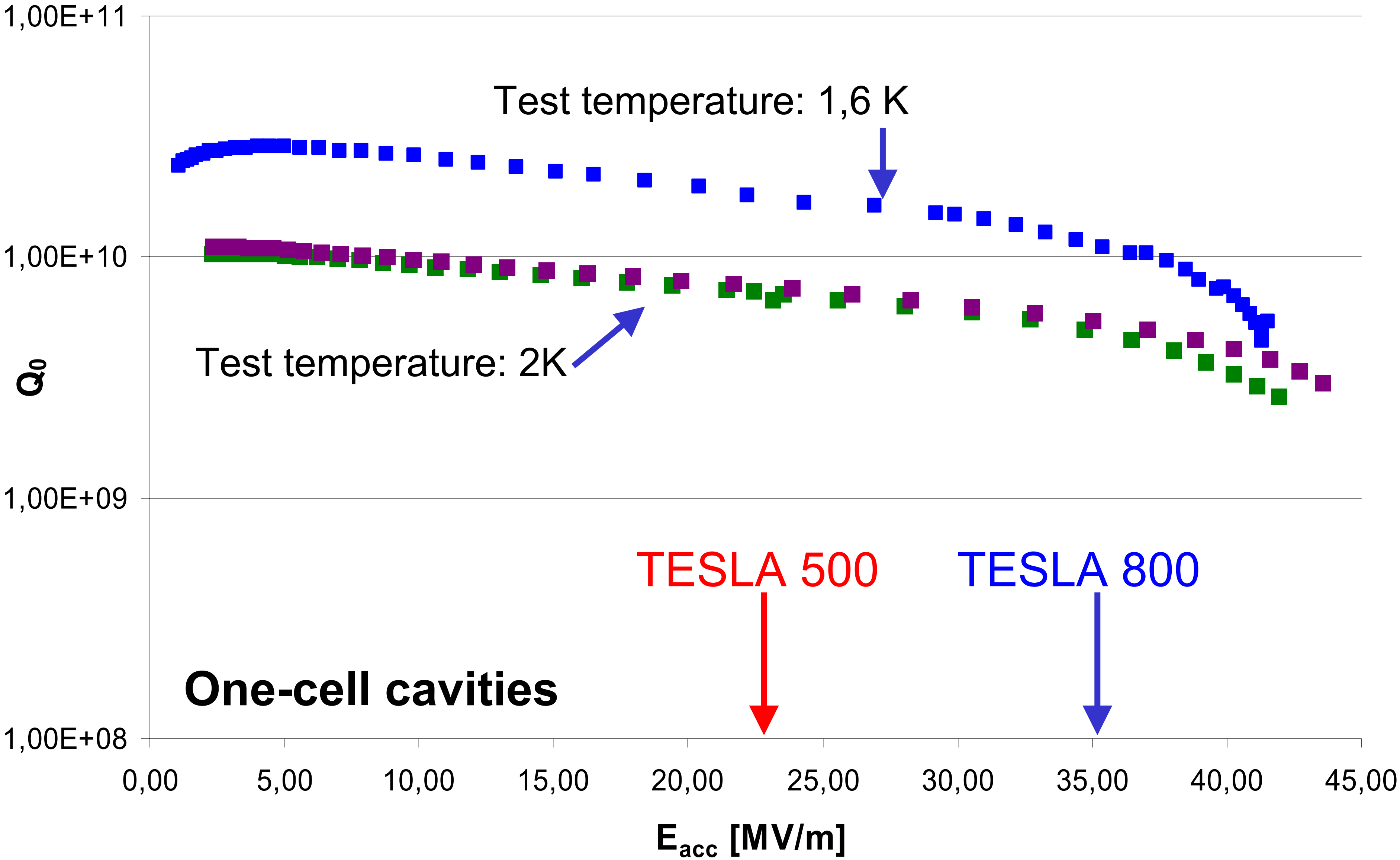
$$R_{fl} = \eta \frac{B_{ext}}{B_{c2}} R_{surf,nc}$$

- Measured values
  - Typically: R_{res} = 5-10 nOhm
  - Lowest: R_{res} = 1-2 nOhm

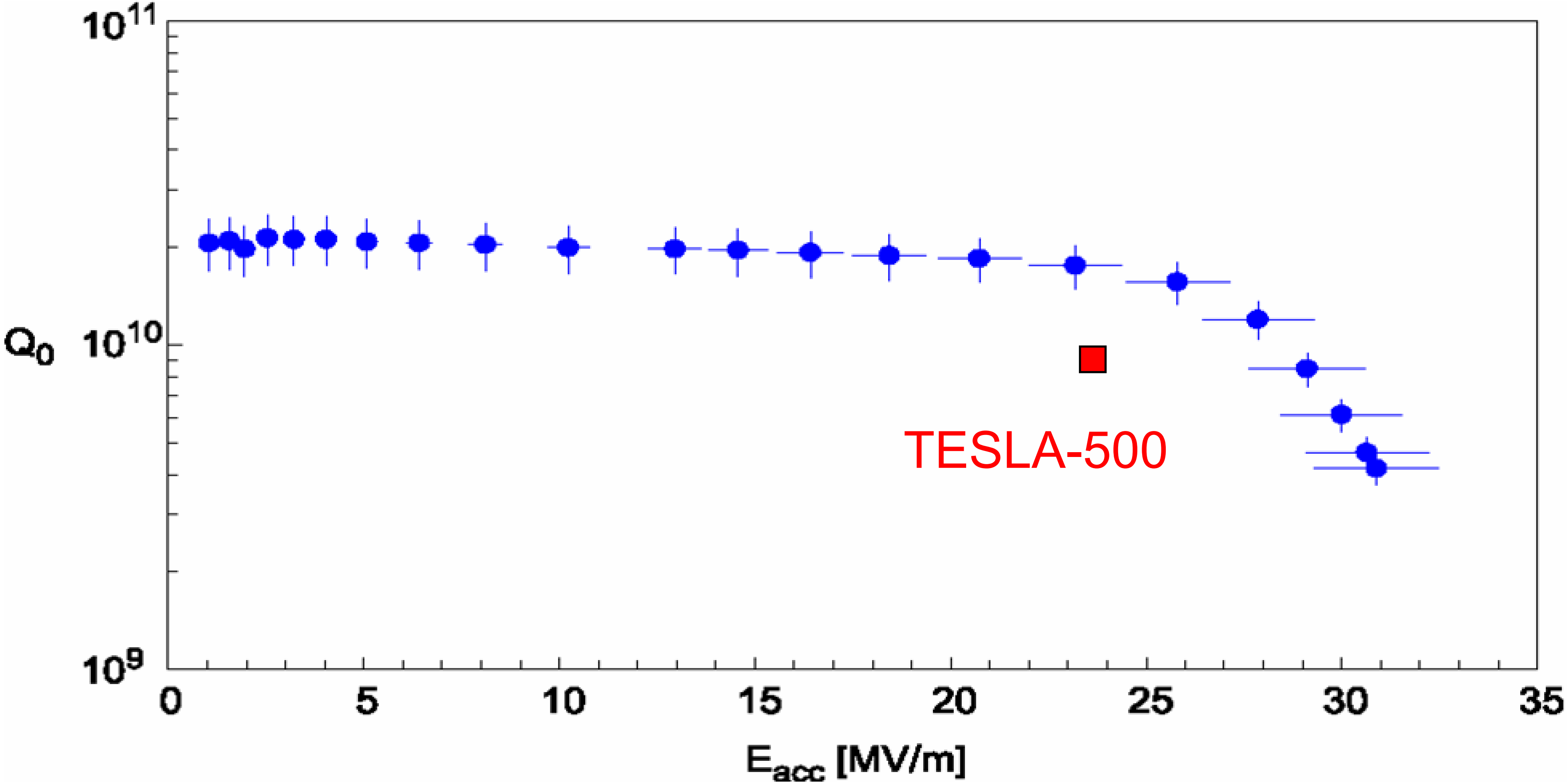
Surface resistance and accelerating gradient

- 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 @ $Q_0 = 1 \bullet 10^{10}$ for TESLA-500

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

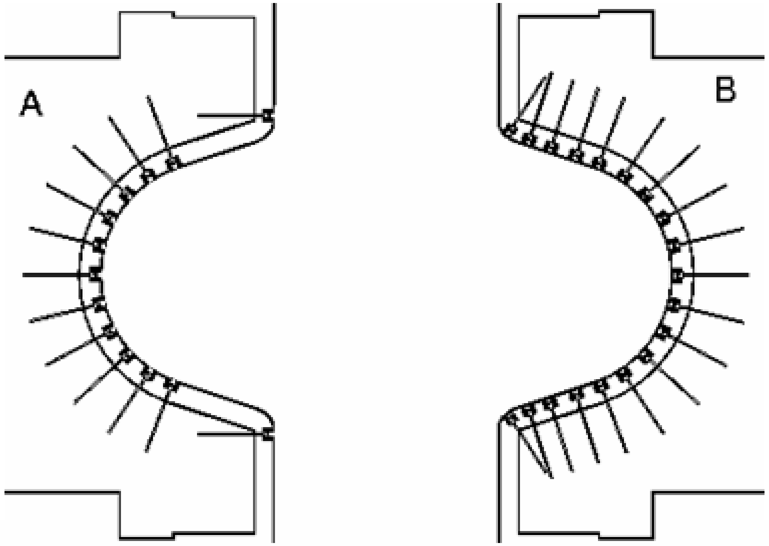
Temperature mapping system

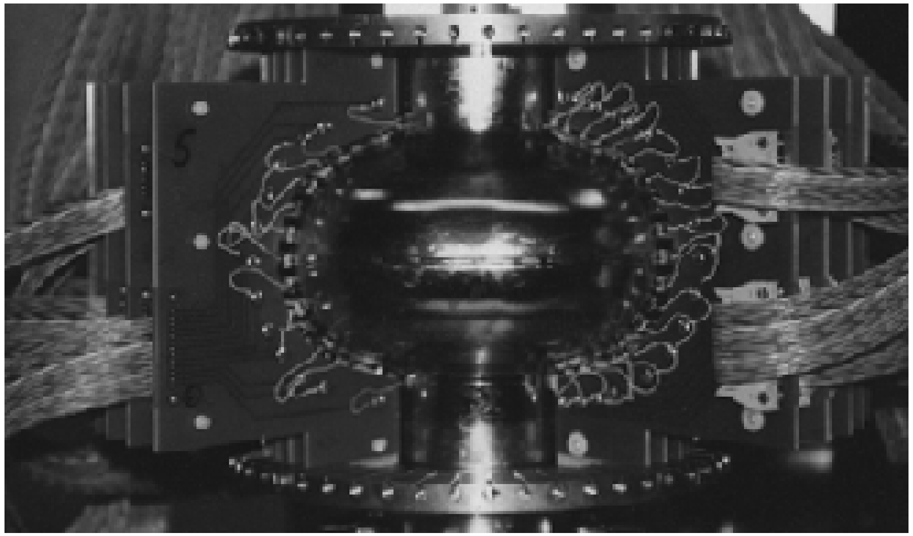
Temperature mapping is a very important tool to understand the loss mechanisms in superconducting cavities.

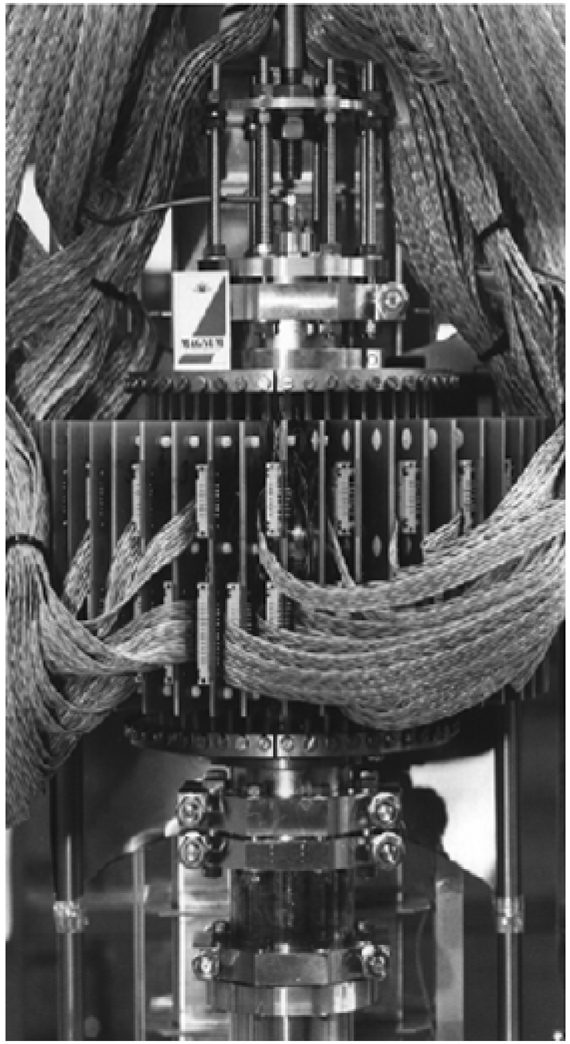
All loss mechanisms have typical signatures:

-local heating for local defects, multipacting and field emission

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







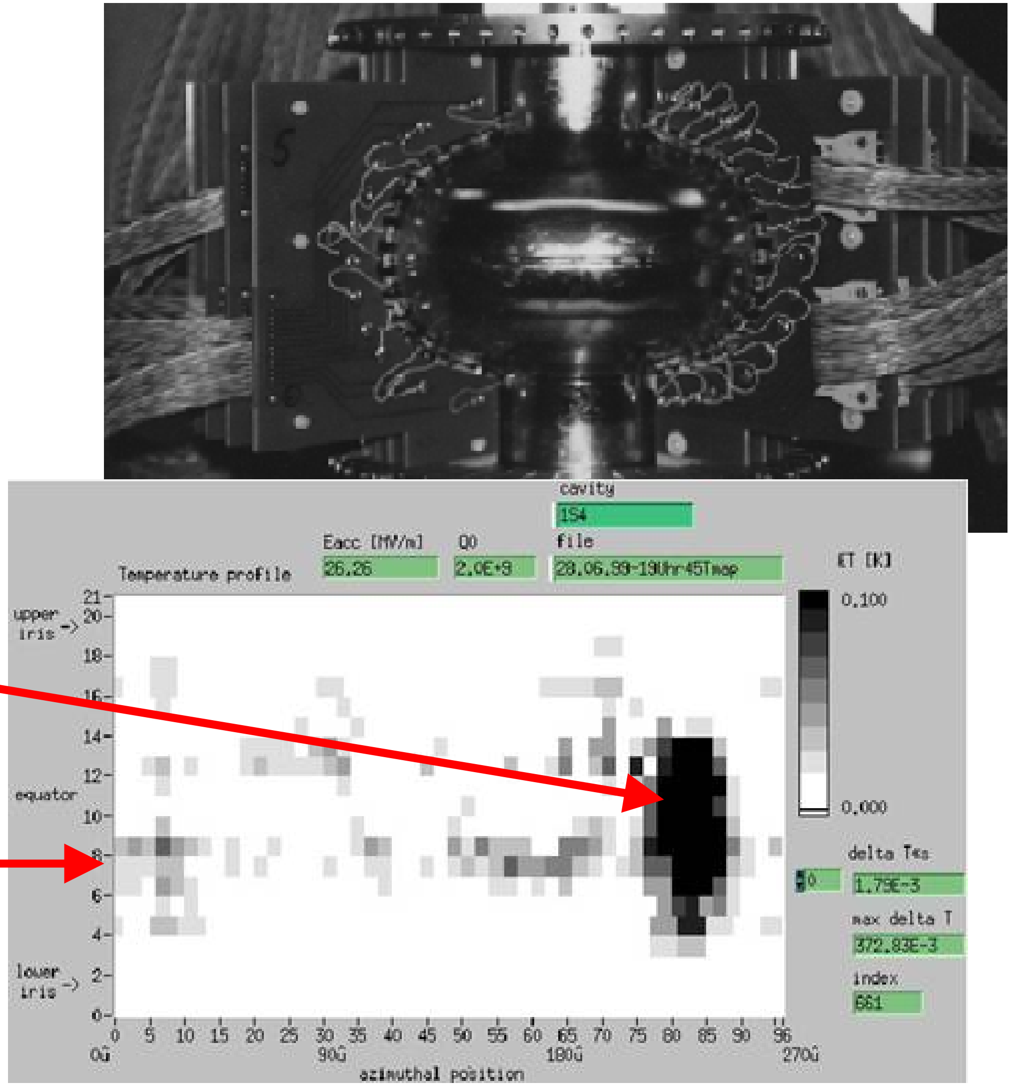
Temperature mapping system

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



Outline of the lecture

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

Break

Outline of the lecture

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

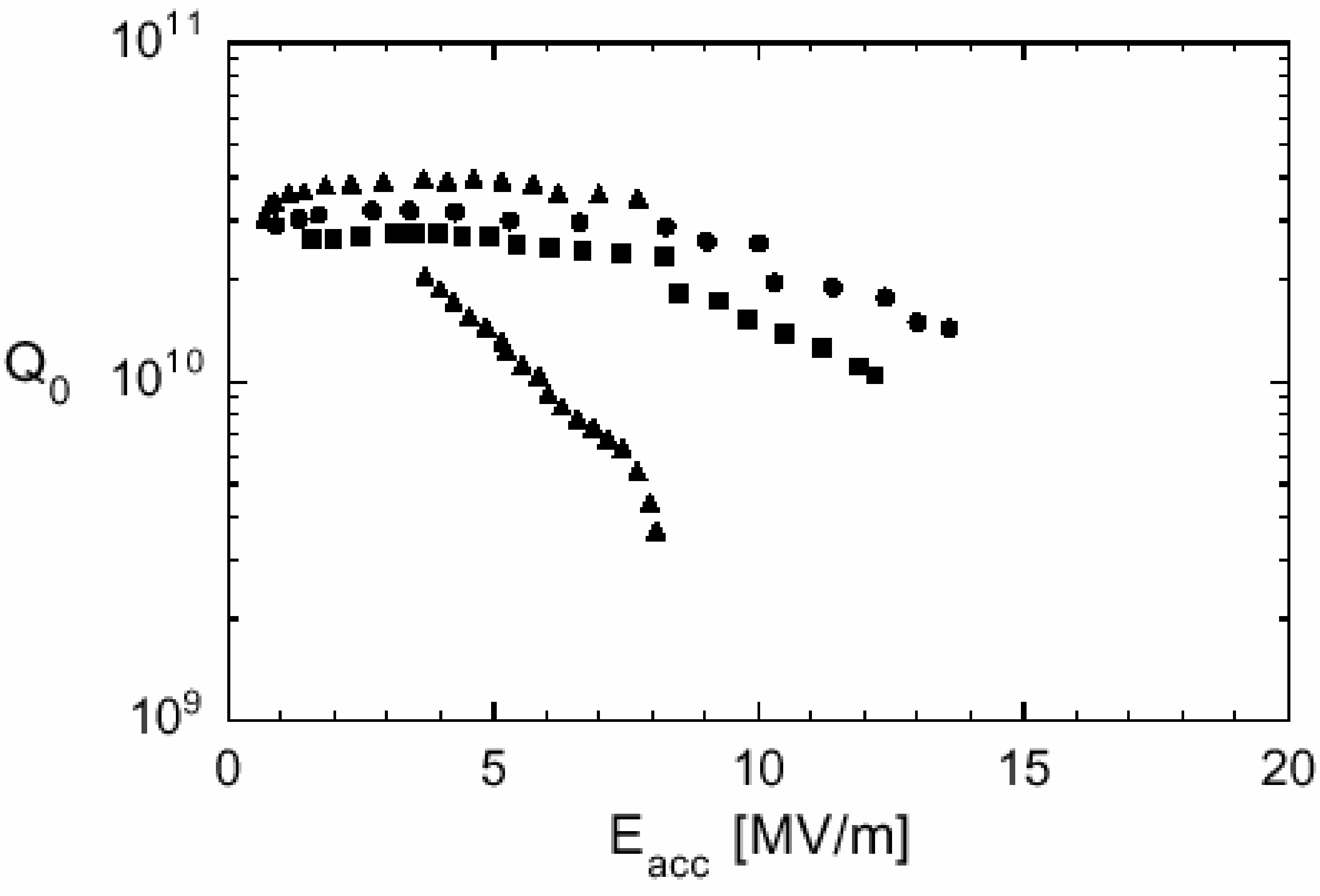
Limitations of SRF Cavities

- Thermal effects
  - Defects
    - Foreign material inclusions, holes etc.
  - Weld defects
- Increased surface resistance
  - Due to material dissolved in the niobium
    - Hydrogen
    - Oxygen in the surface region (?)
- Electron effects
  - Field emission
  - Multipacting

Thermal Breakdown (Quench)

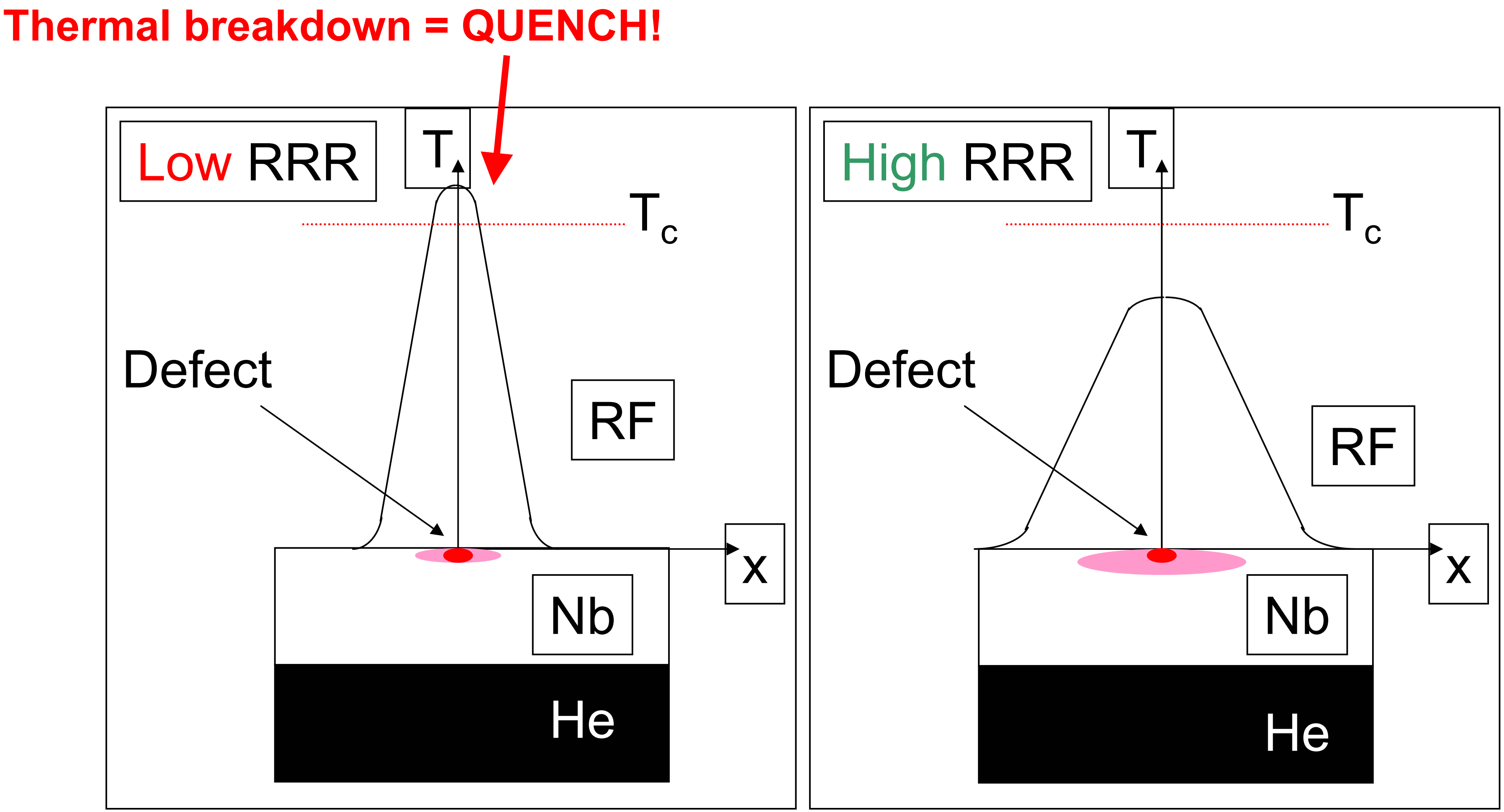
- Temperature of part (or all) of surface exceeds T_c, dissipating all stored energy.
- Localised effect $\Rightarrow$ surface defect has higher R_s.
- Quench (thermal breakdown) occurs when surrounding material cannot transport the increased thermal load to the helium.
- Possible solution:
  – High RRR $\Rightarrow$ better thermal conductivity
  – But: Nb Material becomes very soft!

Examples Of Cavities With Material Defects

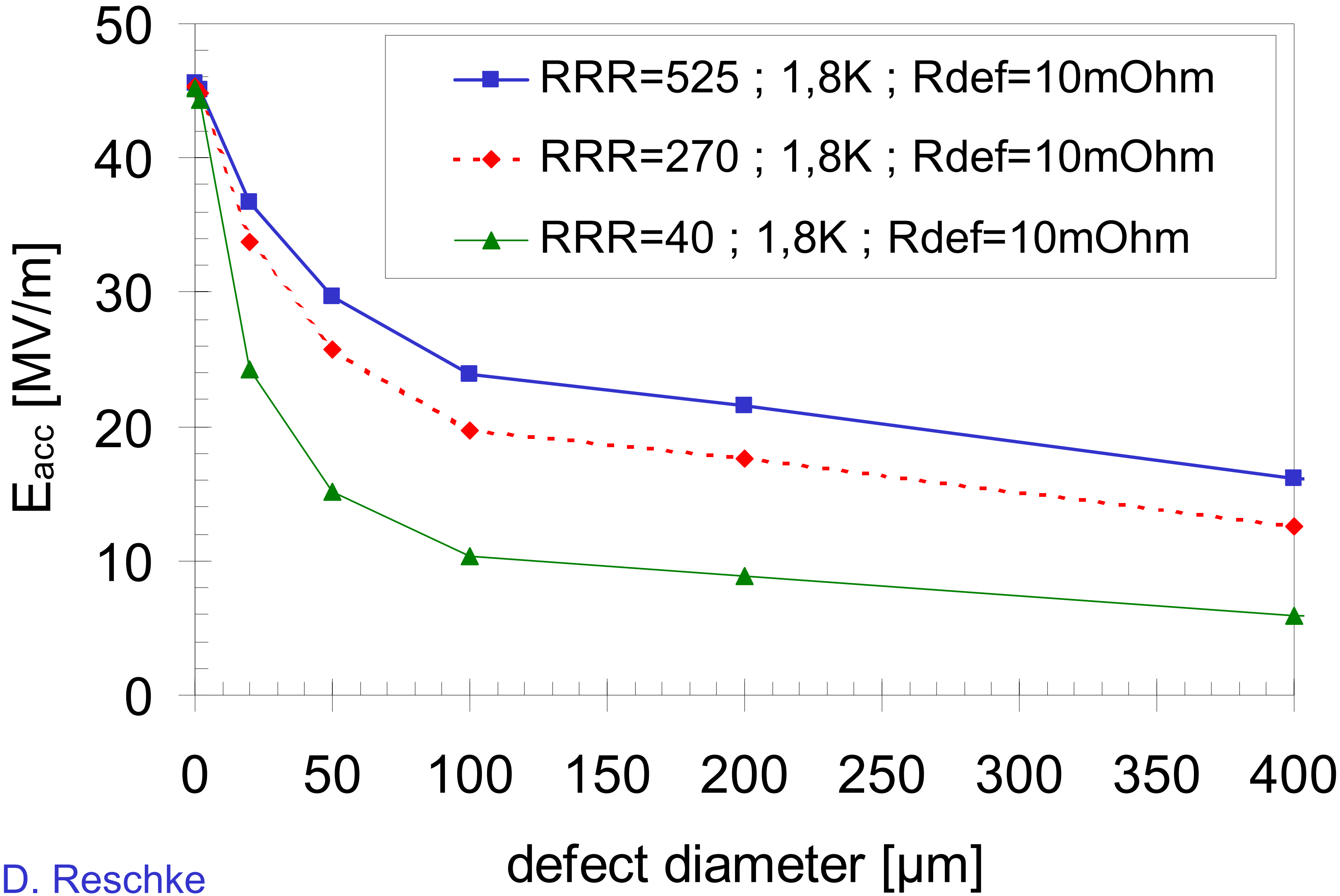


No eddy-current scanning was applied on the niobium sheets used in these cavities from the first production series.

Stabilising Normalconducting Defects

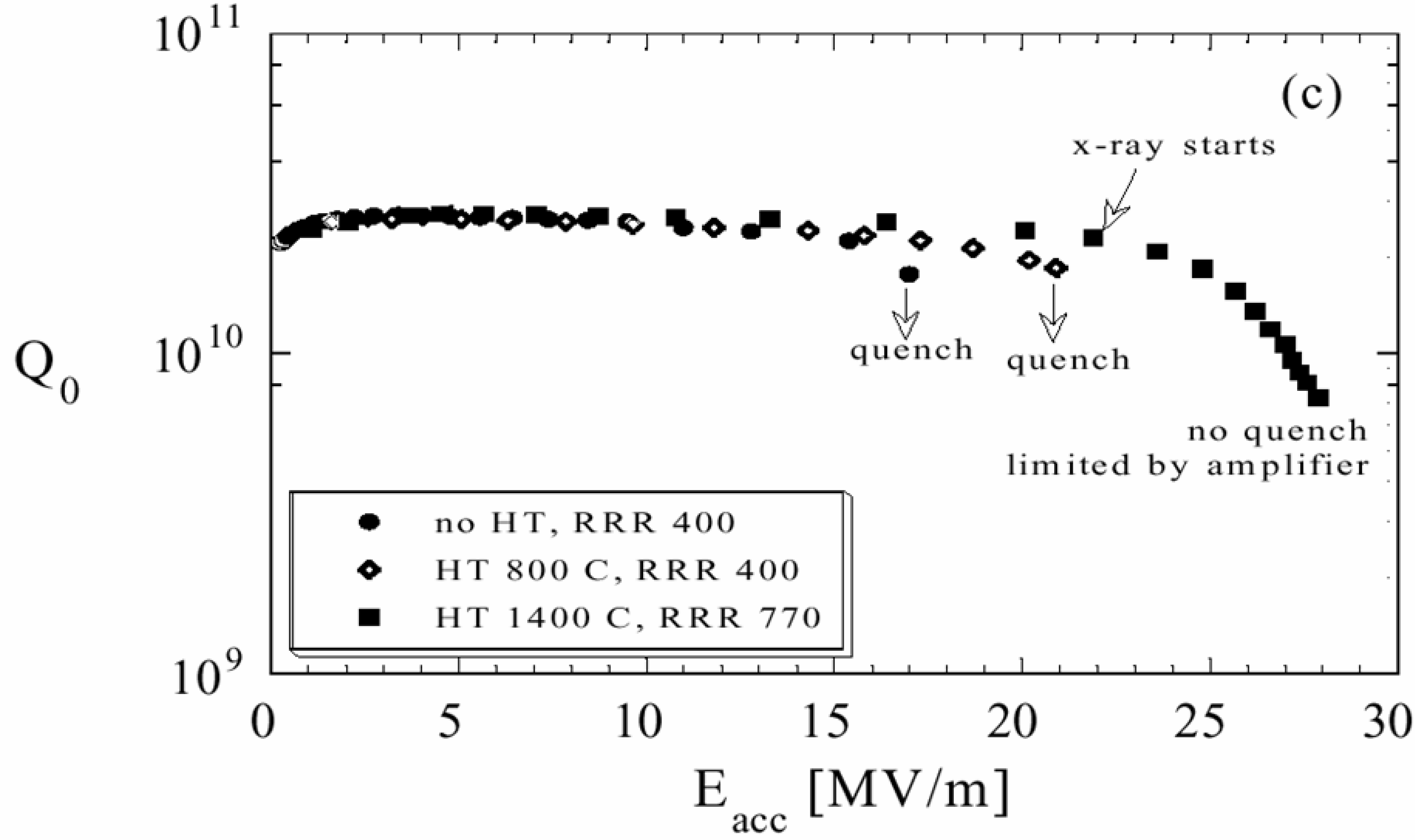


Thermal Models: Numerical Calculations



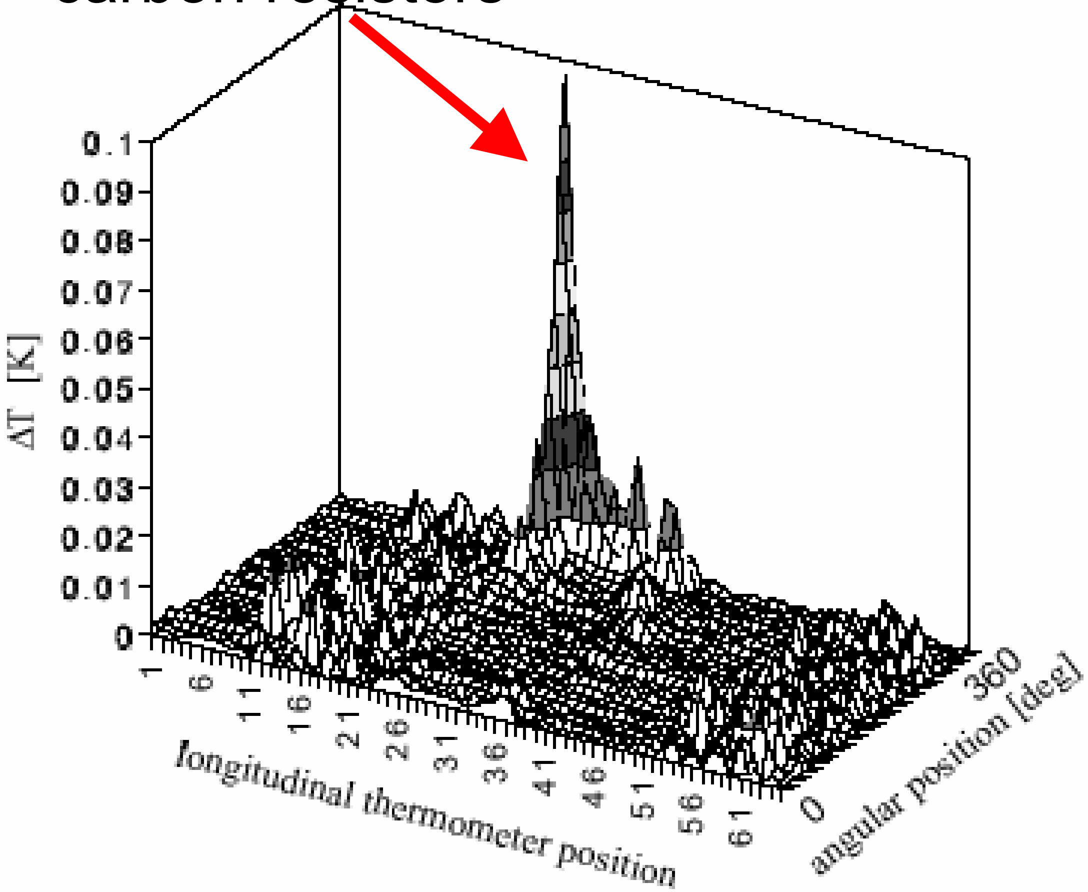
D. Reschke

Benefit Of The High Temperature Heat Treatments

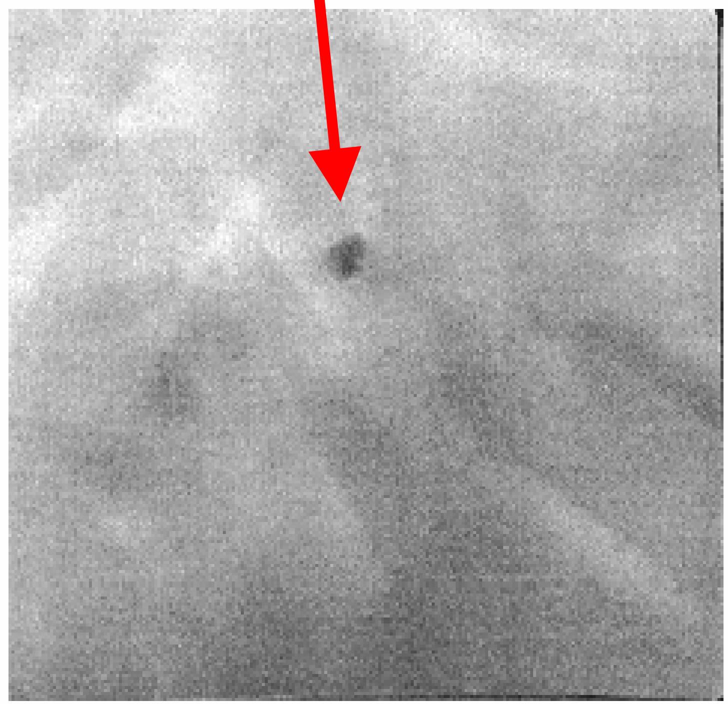


Example Of A Material Defect

Heating on the outside surface measured with carbon resistors



Defect found with X-ray technique: Tantalum

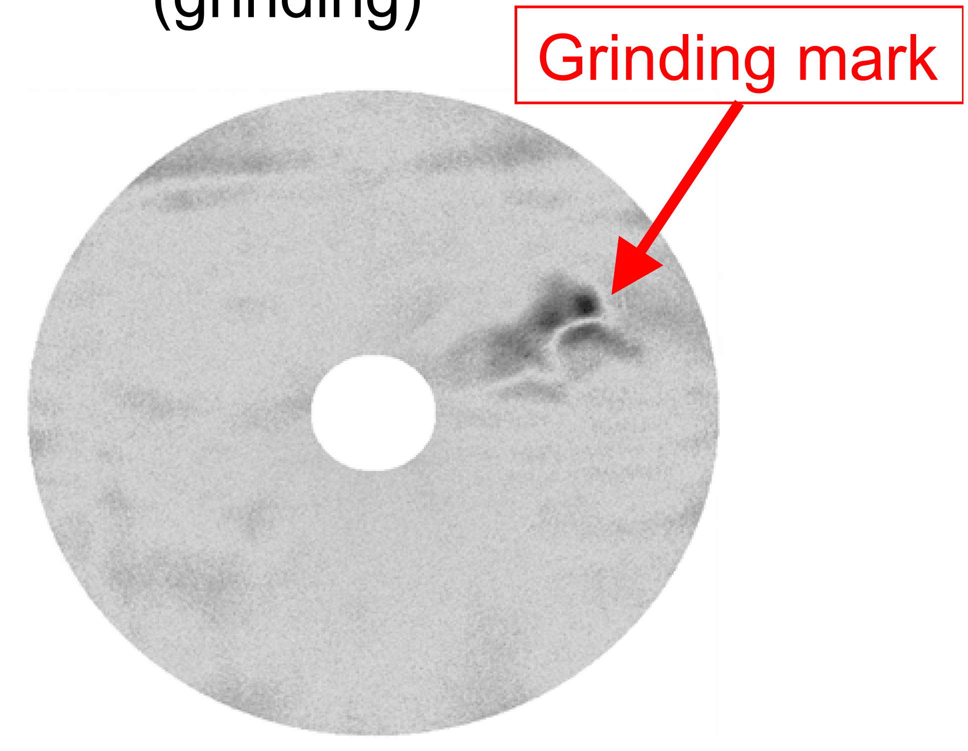


Quality Control Of Nb For Cavities

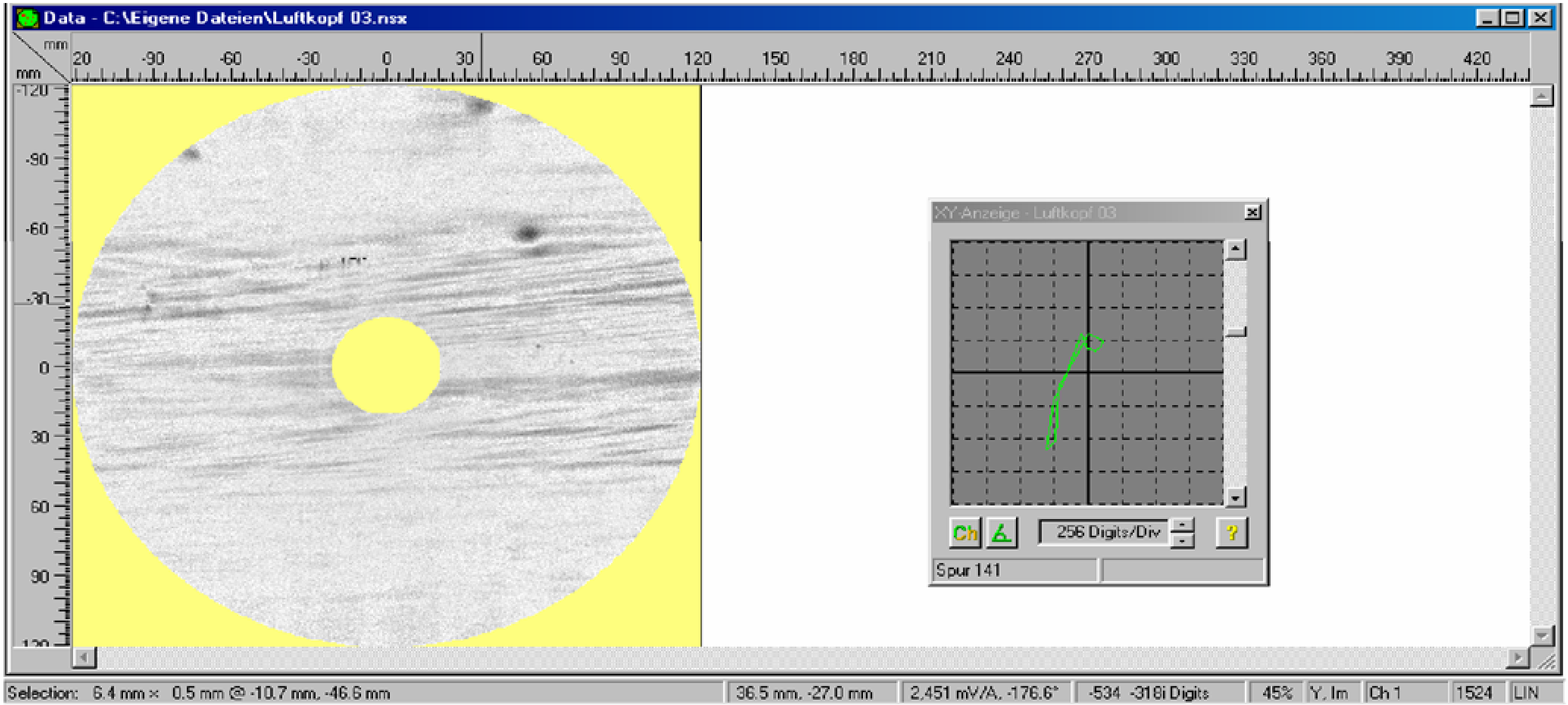
- **Eddy current** scanning of all sheets
  - measures change of electric resistance
  - 0.5mm depth, 40 µm defect dia. sensitivity
  - rejection rate of sheets about 5 %
- **SQUID scanning** under development
- Some **special investigations** are possible on demand
  - x-ray radiography (defect visualization)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

Eddy Current Scanning

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

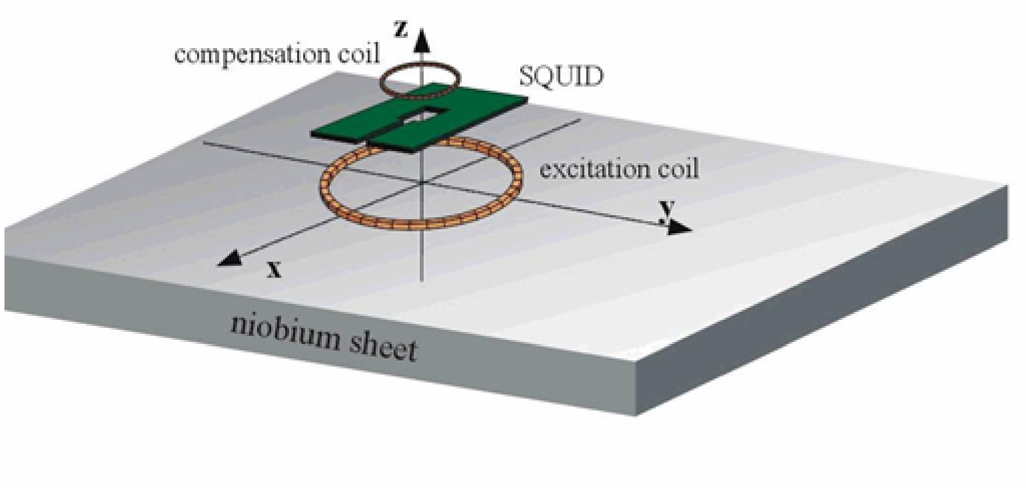


Result of eddy current scanning a Nb disc, dia. 265 mm



Global view, rolling marks and defect areas can be seen

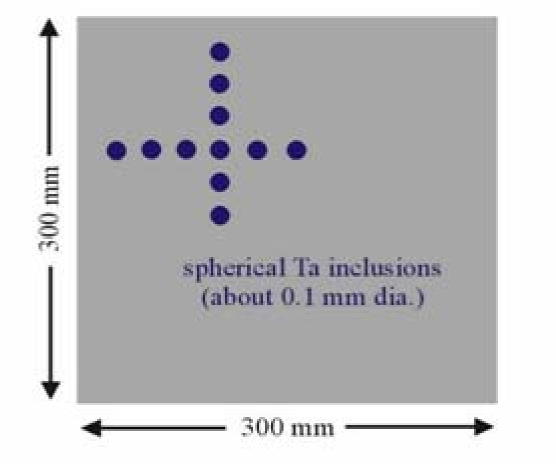
Real and imaginary part of conductivity at defect, typical Fe signal

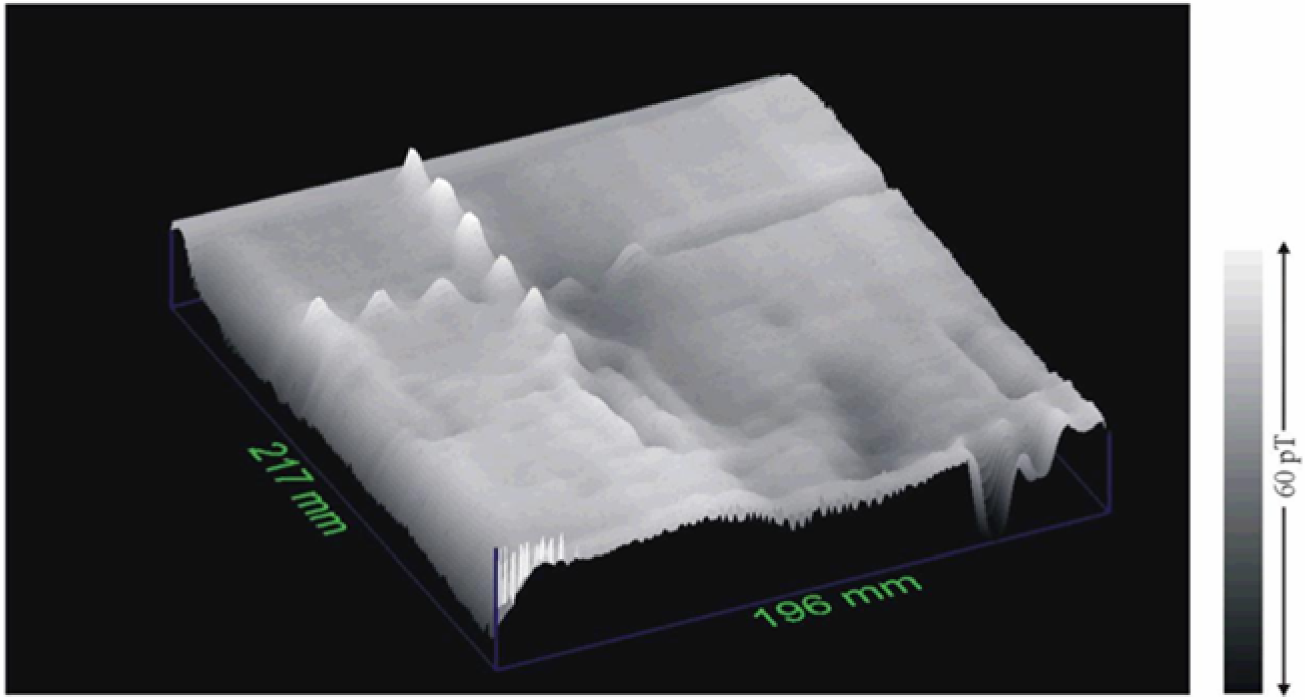


Principal arrangement of SQUID scanning

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.

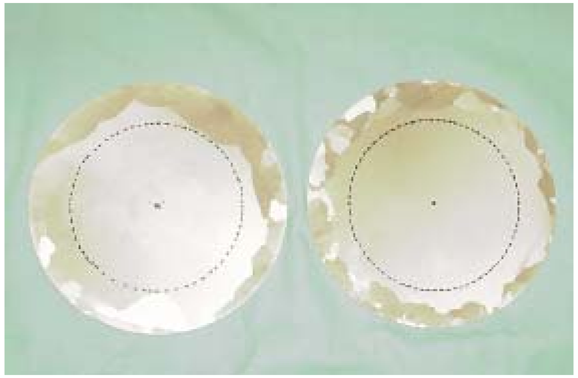
Lutz Lilje DESY -MPY-

Potential Alternatives to Fine-Grain Material

- Recent development at JLab (P. Kneisel, G. R. Myneni et al.)
  - Try to cut sheets directly from ingots
    - Potential reduction of cost: no rolling etc.
    - Potentially less inclusions from sheet fabrication
  - Smoother surface already from etching
    - No electropolishing necessary?
    - (Or: Is surface roughness the final clue to cavity performance)

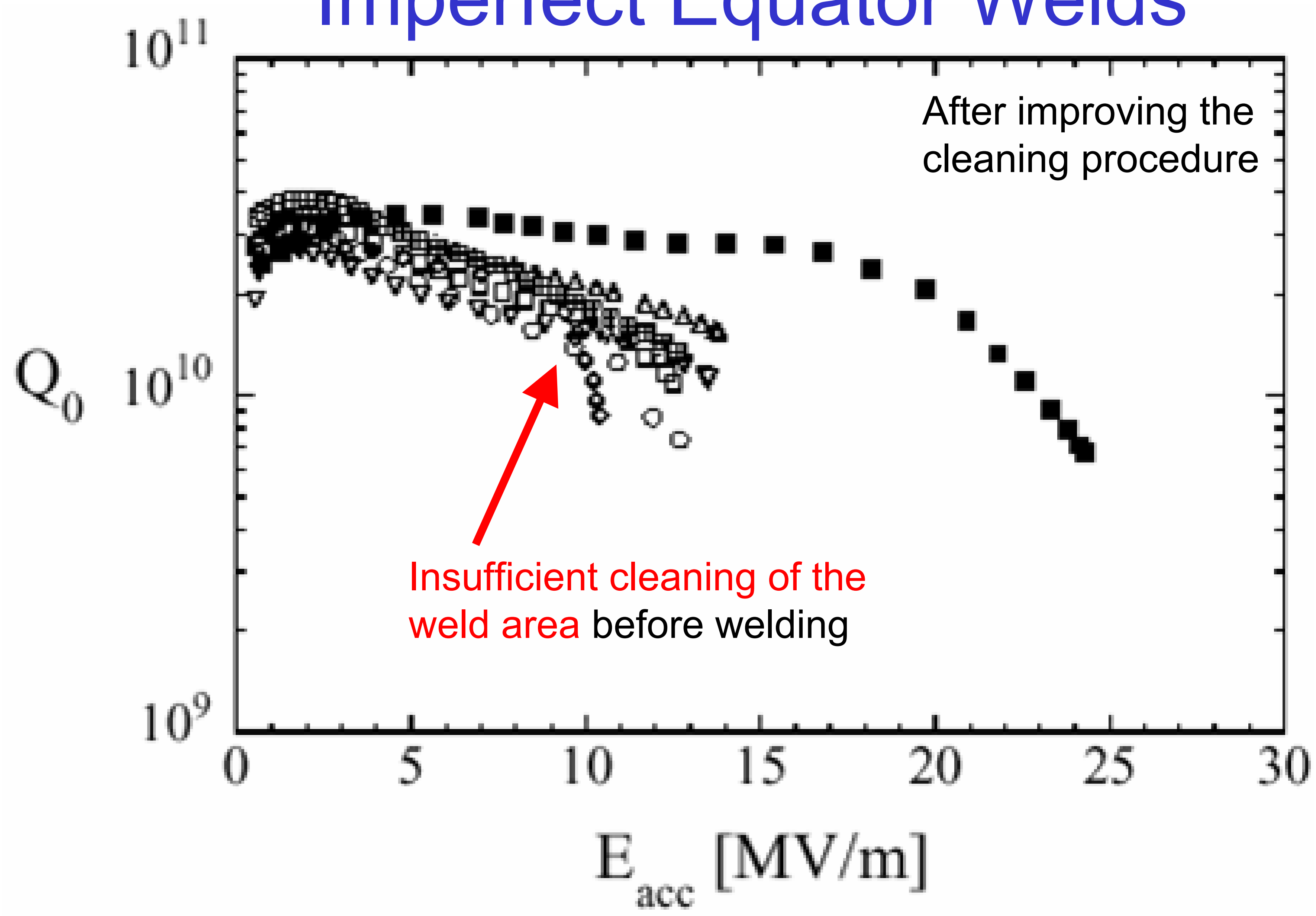
– Large-grain material

– Single-grain material



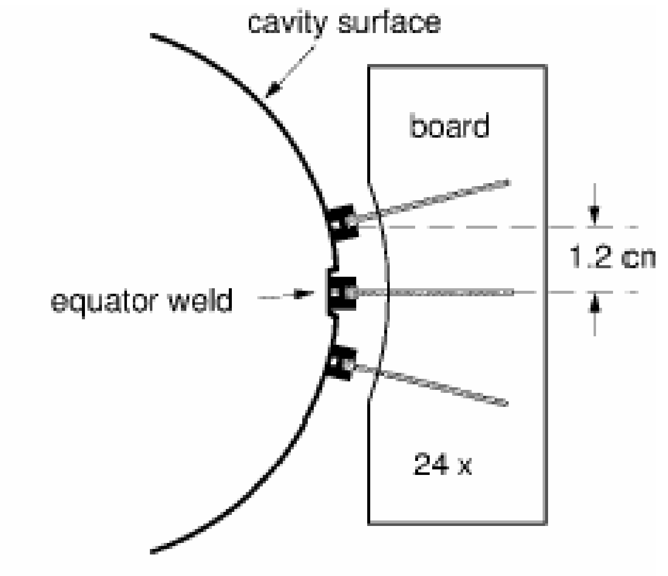
Standard Cavity Production (EB welding)

Imperfect Equator Welds



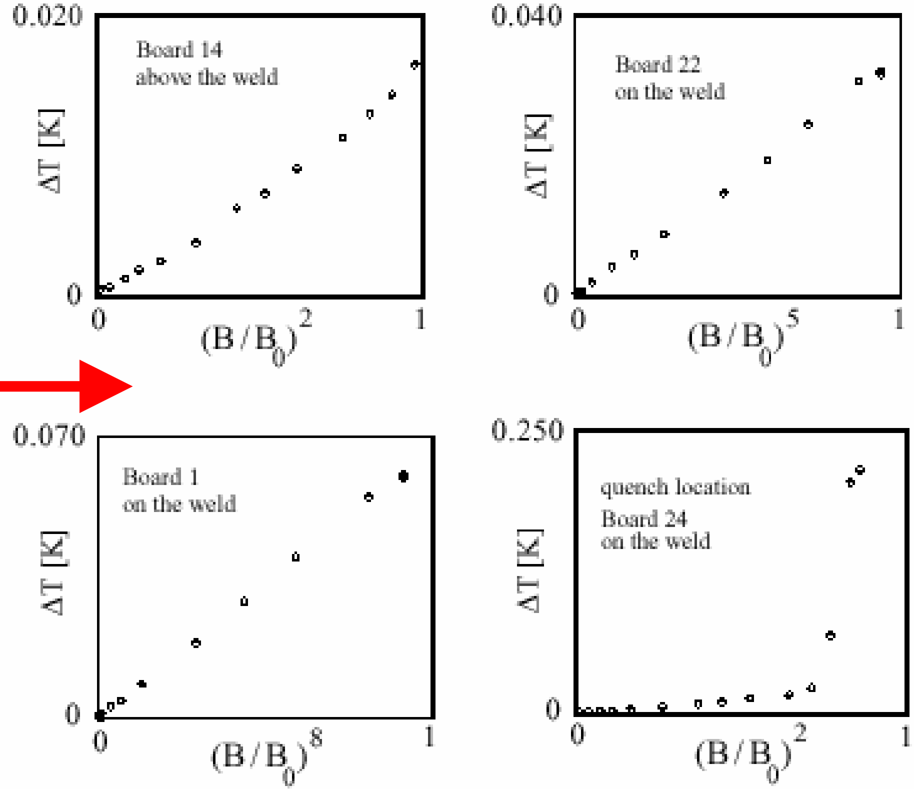
Imperfect Equator Welds

Temperature mapping of the equator region

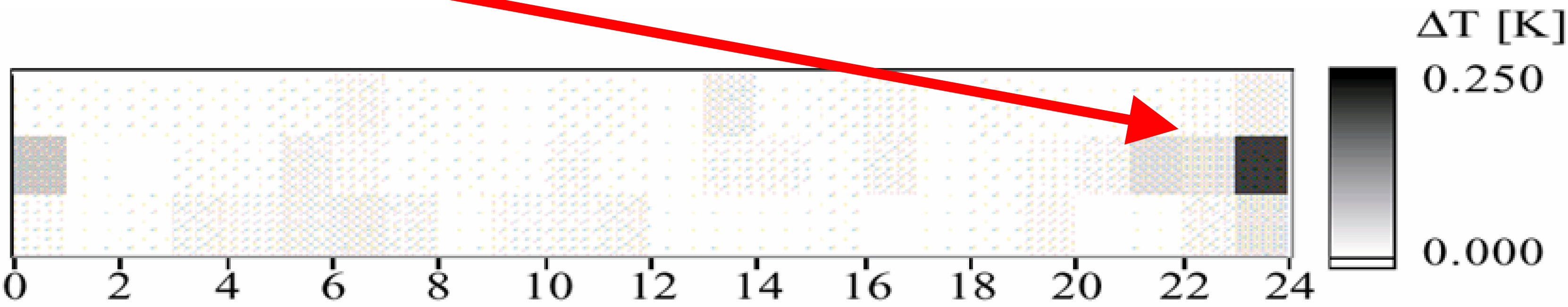


Thermometer response:

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



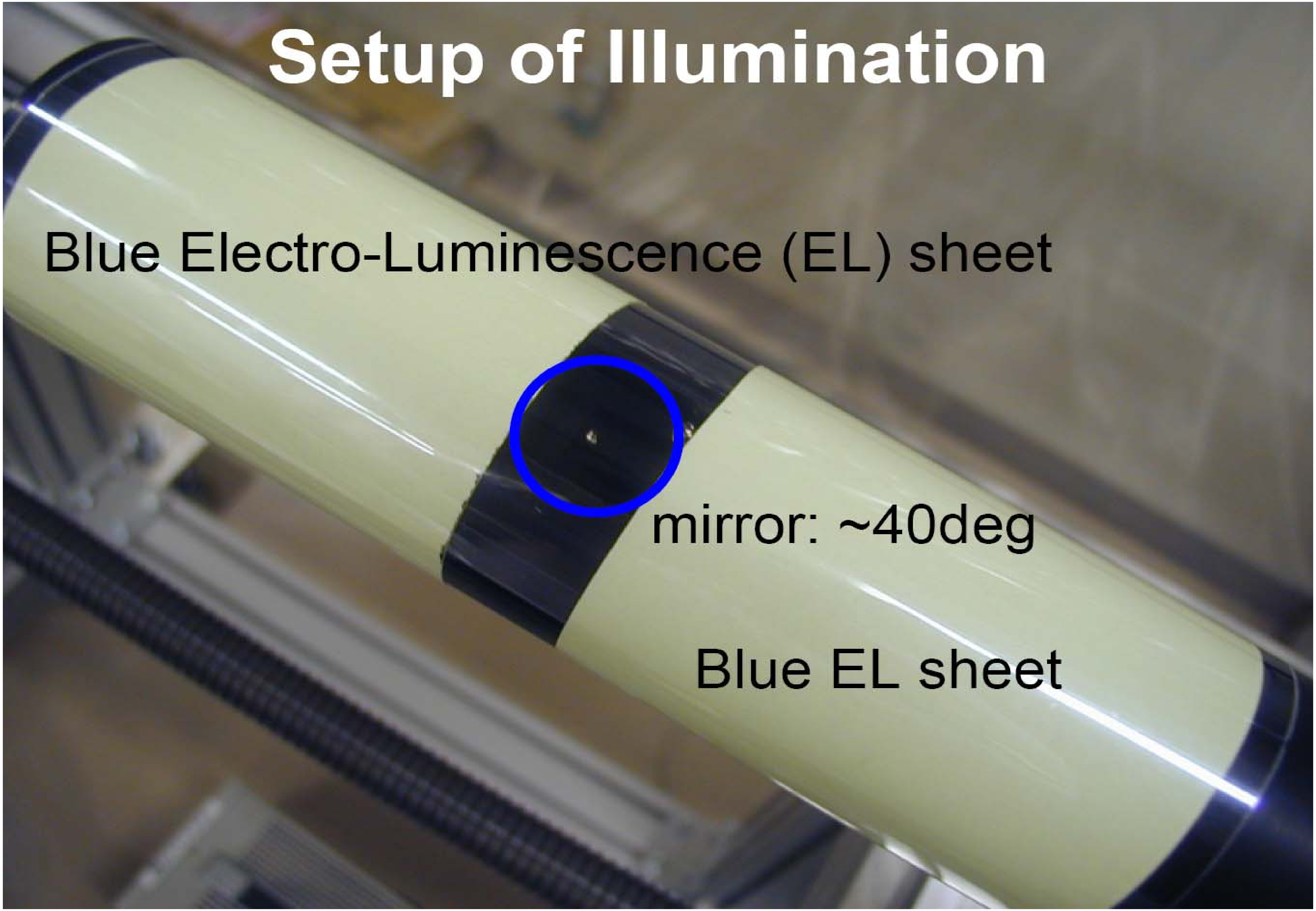
Heating on the equator

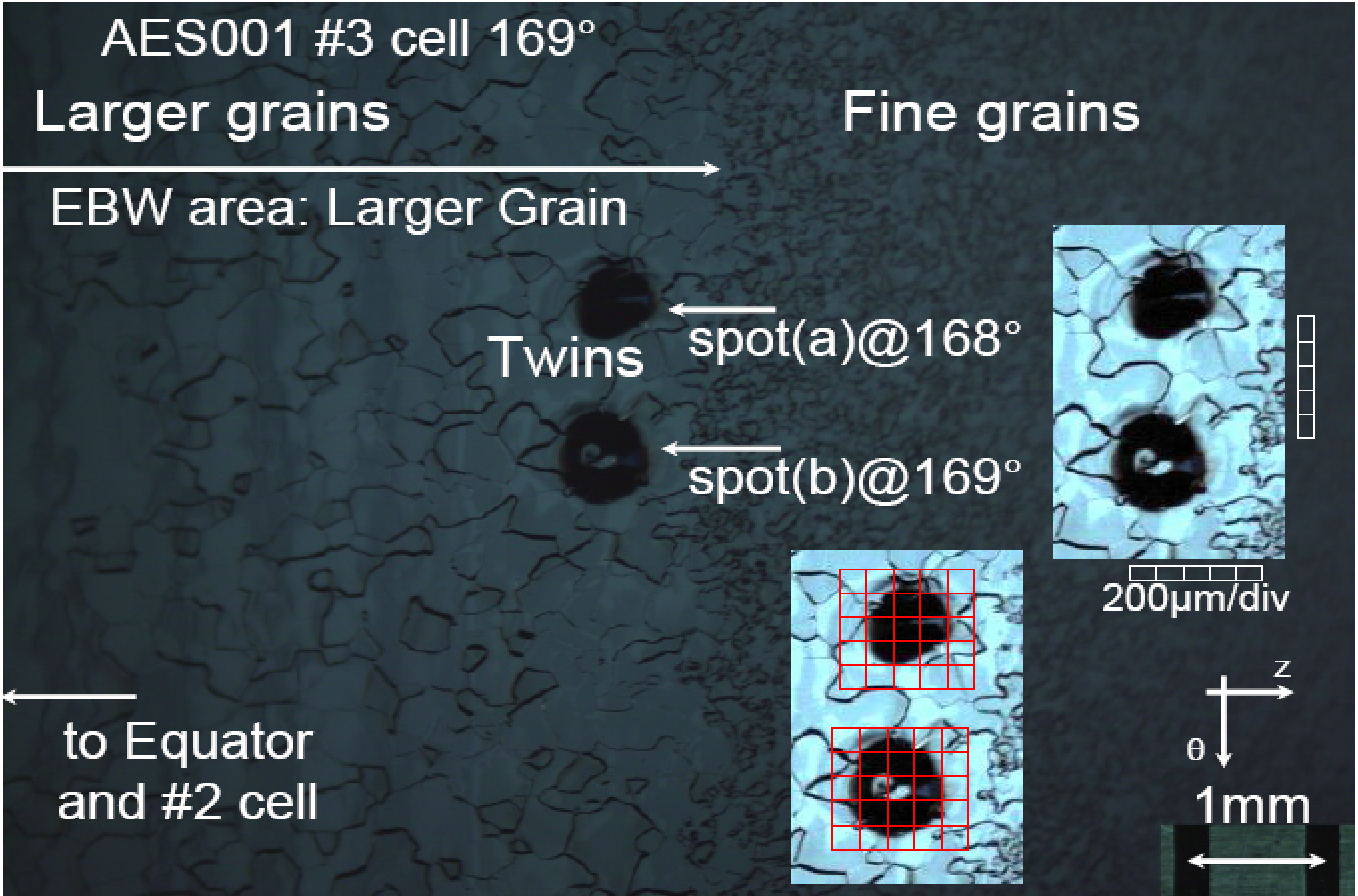


High-Resolution Optical Inspection

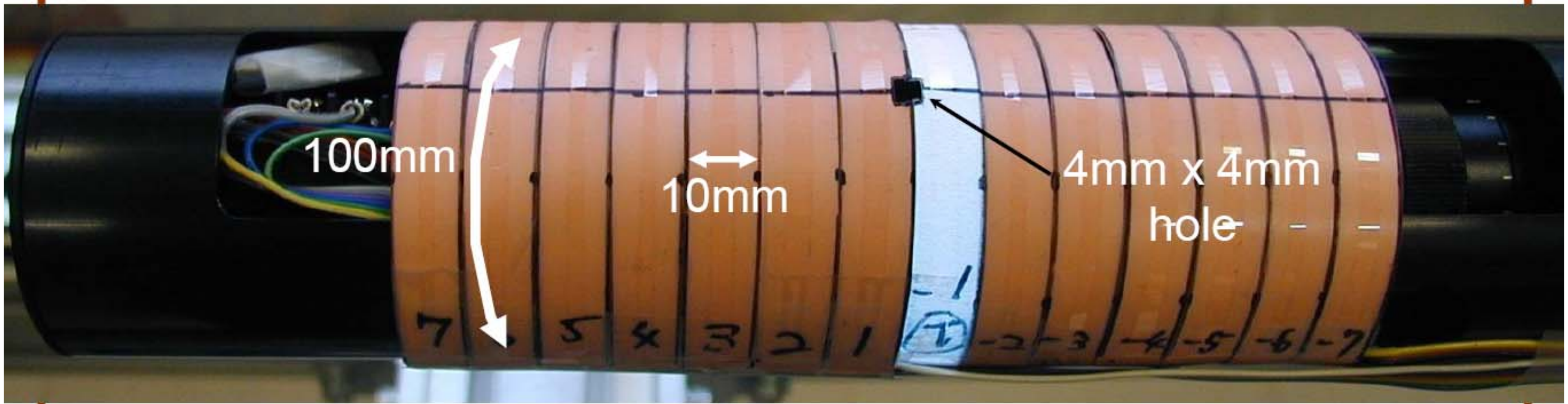
- Very new development by japanese colleagues to reduce reflections
  - Improved lighting technique using flat electro-luminescense strips
  - Damping of vibrations
- Resolution down to a few micrometer!

Setup of Illumination



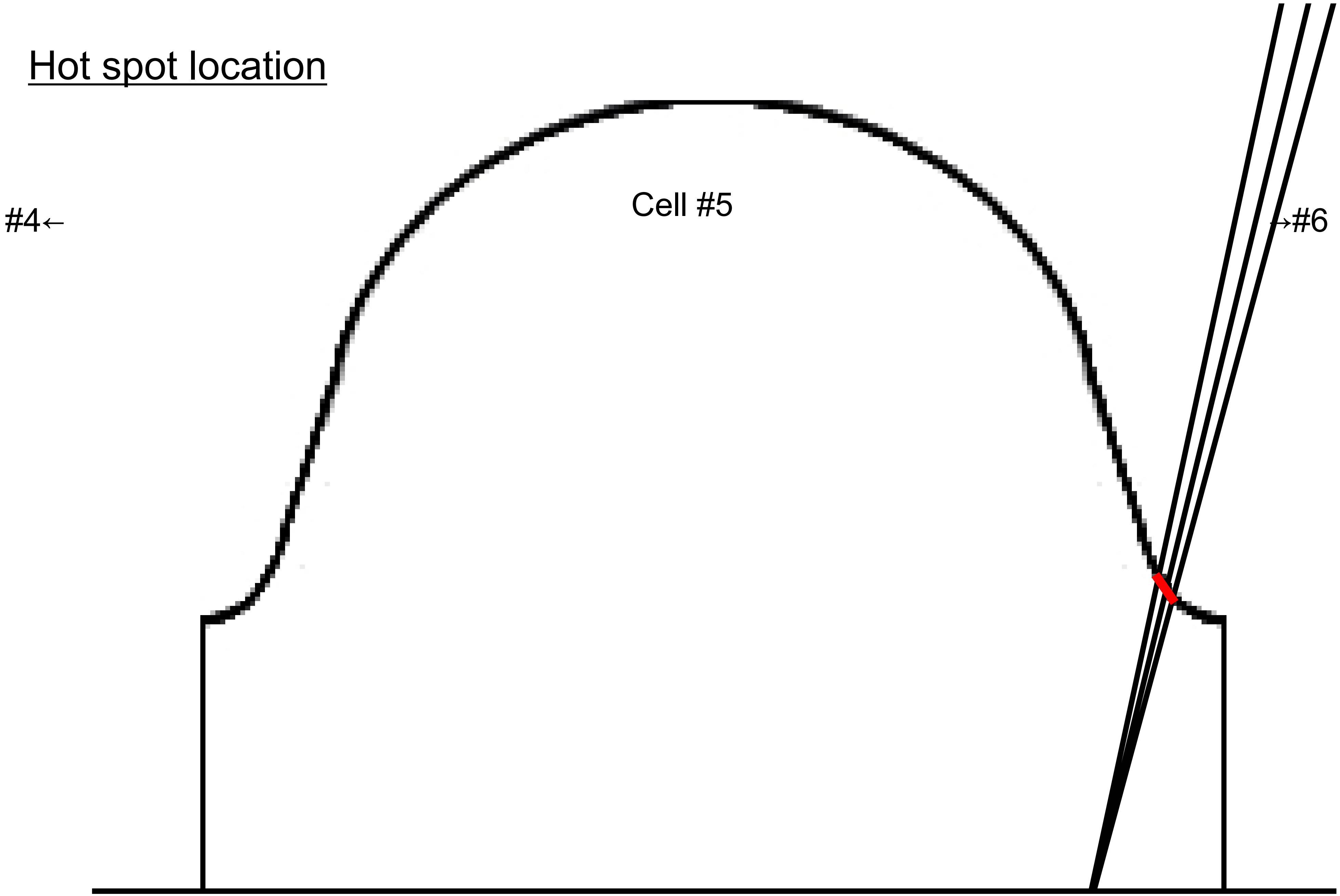

AES001 #3 cell 169°
Larger grains
Fine grains
EBW area: Larger Grain
Twins
spot(a)@168°
spot(b)@169°
200μm/div
to Equator
and #2 cell
z
θ
1mm

Stripe Illumination(SI)



- Fourteen Electro-Luminescence(EL) strip sheets are 10mm in axial direction and cover 100mm in azimuthal direction.
- These fourteen strips can be turned ON/OFF one by one.
- Assuming that cavity's interior surface is a complete mirror, we can measure wall gradients of the cavity's interior surface with these ELs.

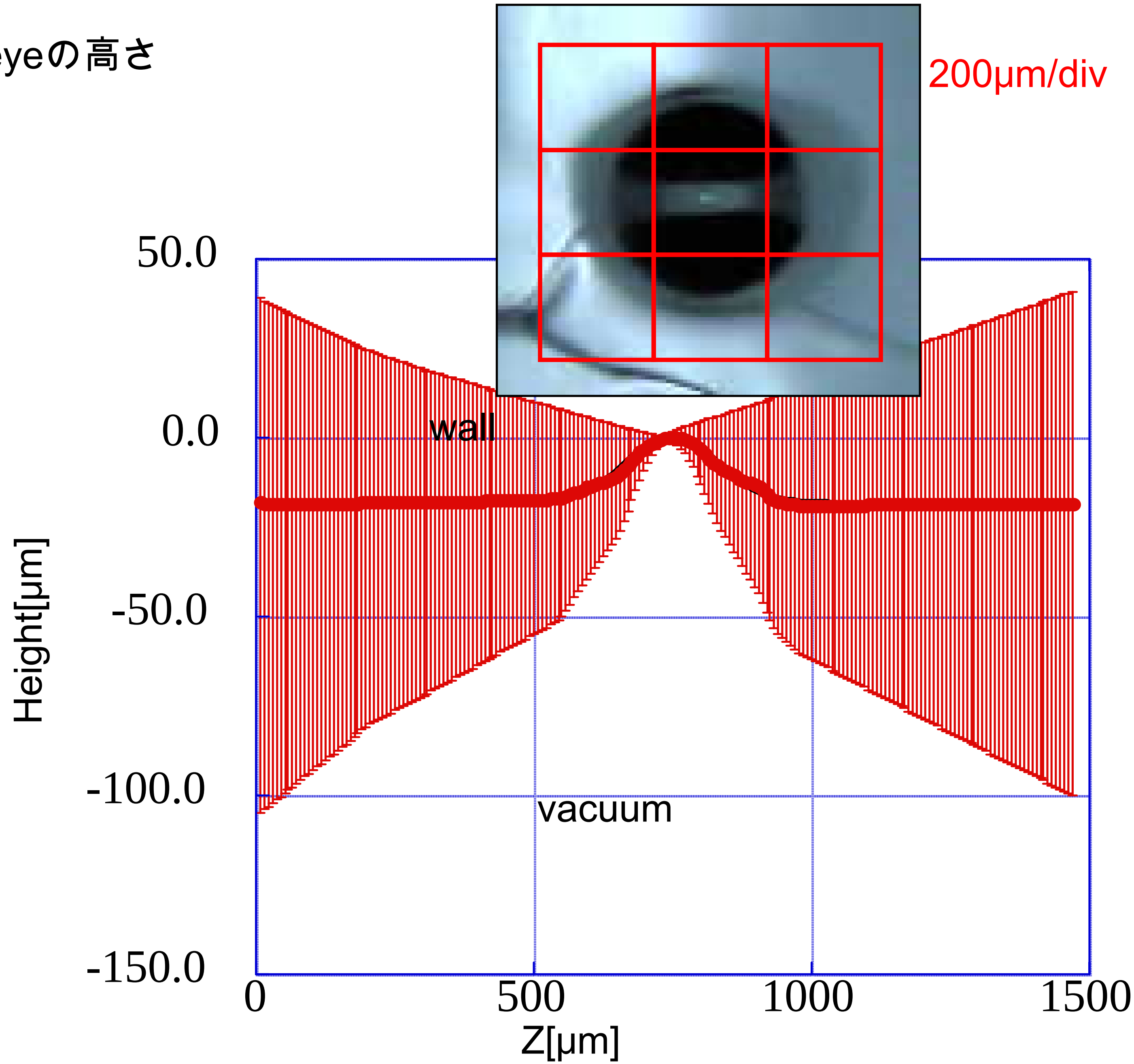
Hot spot location



Lutz Lilje DESY -MPY- 13.03.2008


AC80: cat's eye
@cell#5_equator
100μm
This does not match to T-map hot spot.
Need to check again.
1mm

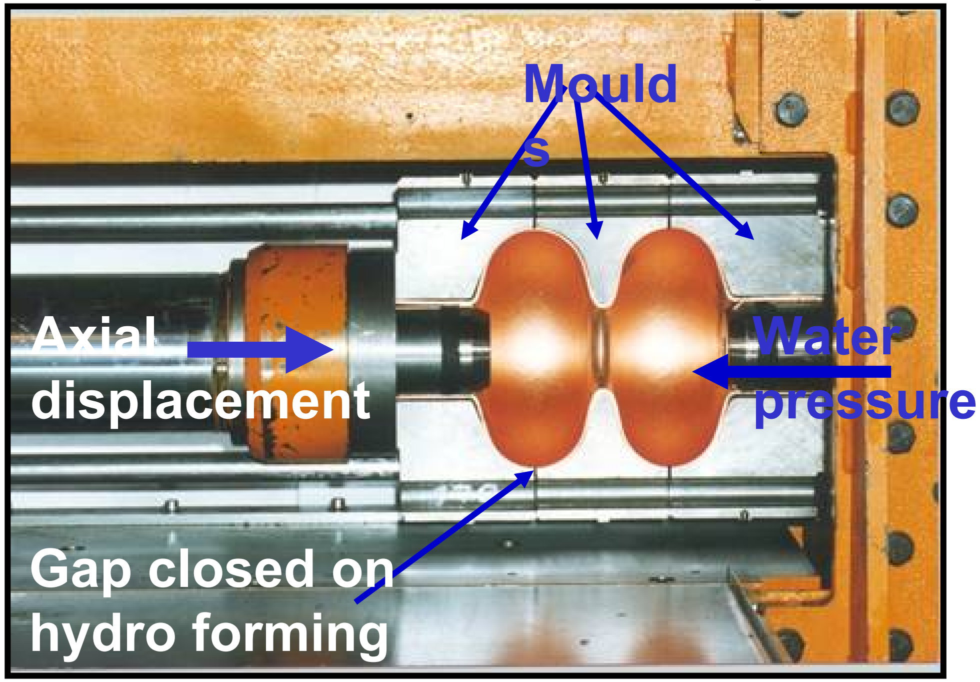
AC80: cat's eyeの高さ



Hydroforming and Spinning

W. Singer (DESY) et al. and E. Palmieri et al.

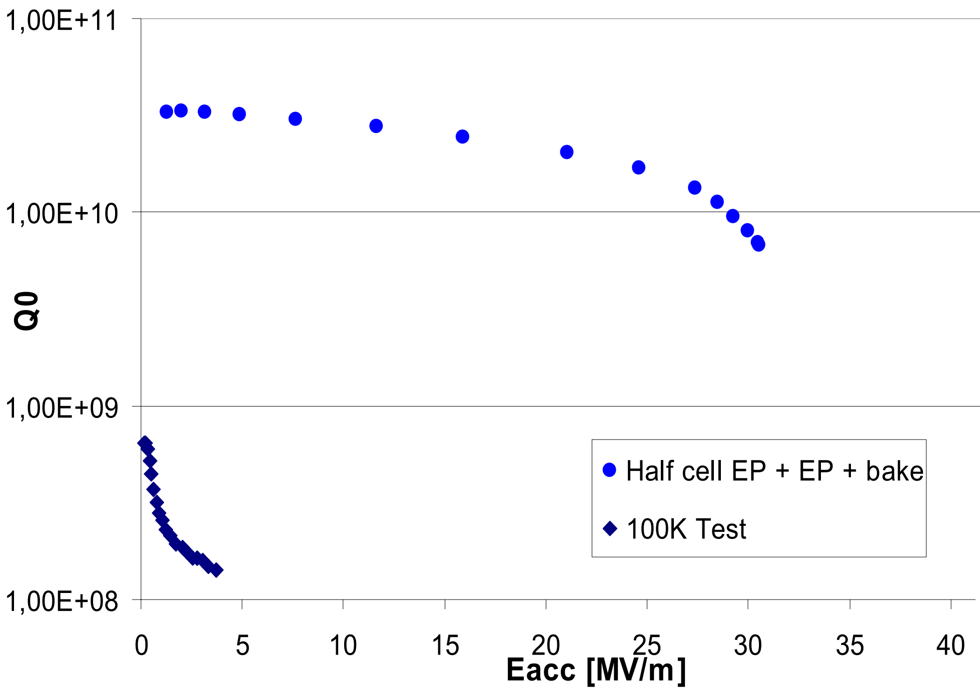
- No equator welds
  - End groups of the cavities still need welds
- Very good performance on single-cells has been demonstrated
- First Multi-cells have been built but performance needs improvements
- Industrialisation of the process is not far advanced



Degradation of the Surface Resistance

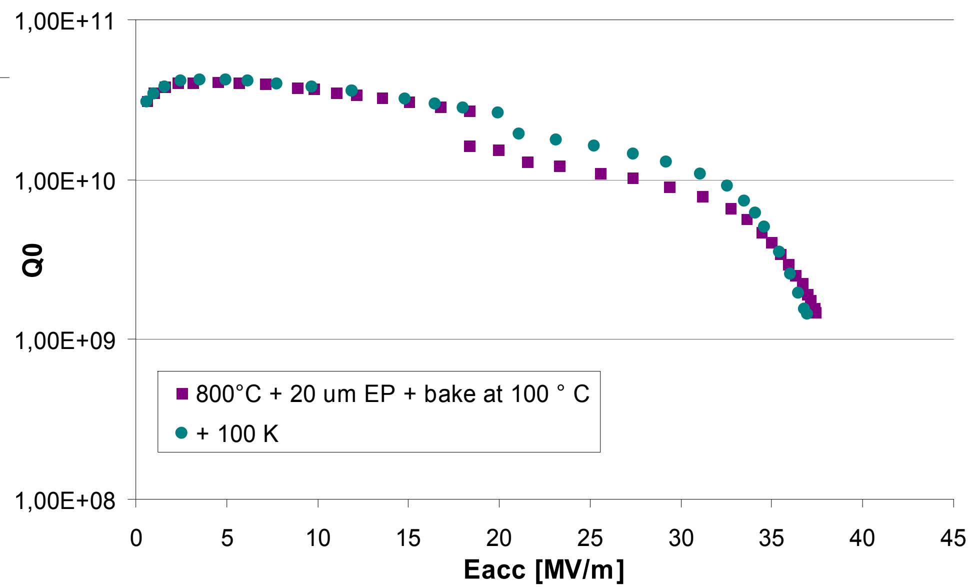
- There are two effects which are related to the composition of the niobium material
  - ‘Q-disease‘
    - Pure niobium can be loaded interstitially with hydrogen from material cutting. tumbling, etching or electropolishing
    - During cooldown an lossy Nb-H phase is built at the surface
    - Very low Q already at small gradients
  - ‘Q-drop‘
    - Not fully understood yet
    - Likely due to a contamination of the surface layer with oxygen

Hydrogen Contamination Of High Purity Niobium: Q-disease



Interstitially dissolved hydrogen (from the chemical treatments) in niobium can degrade the cavity performance substantially.

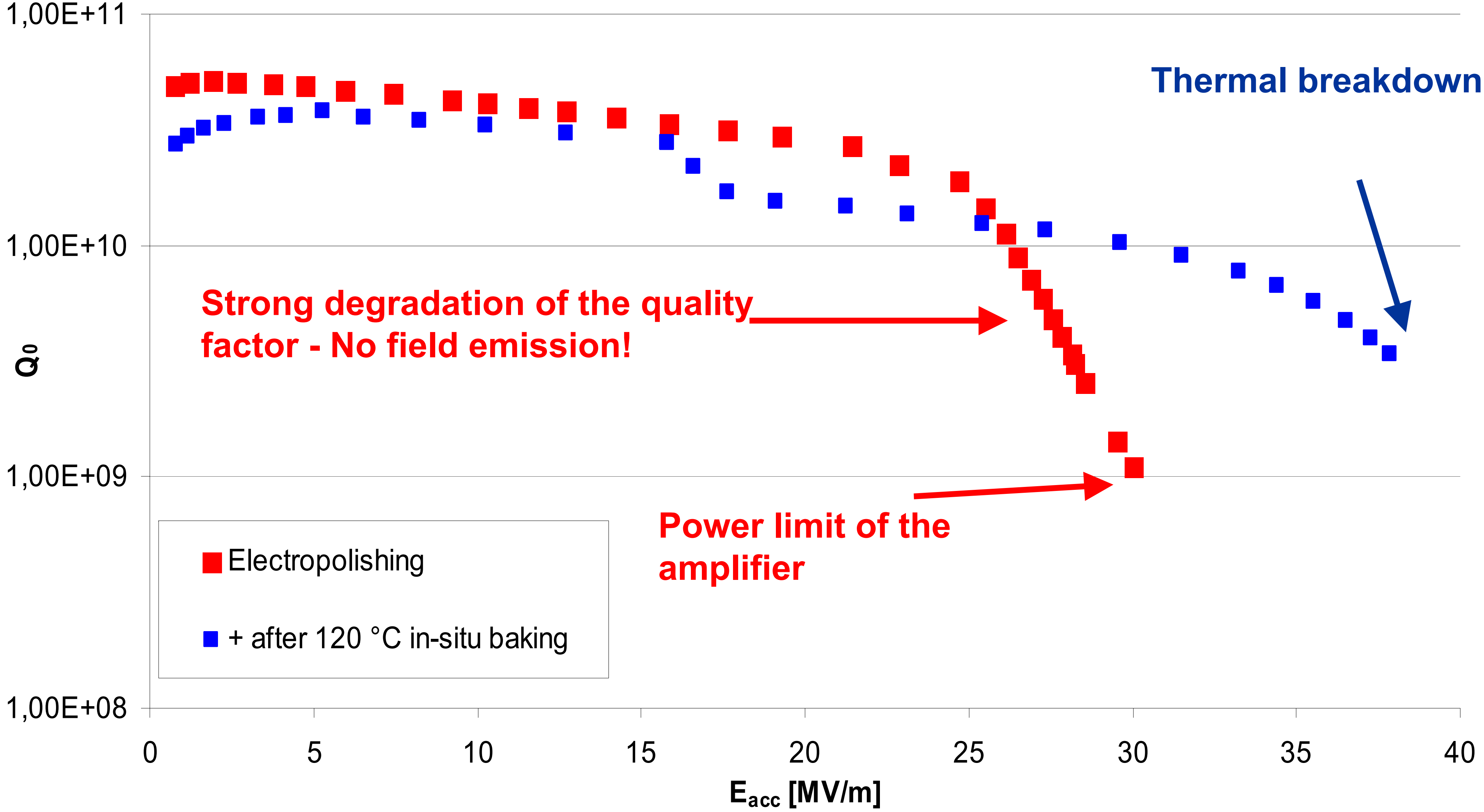
High temperature treatment at 800°C reduces the amount of hydrogen and avoids 'Q-disease'

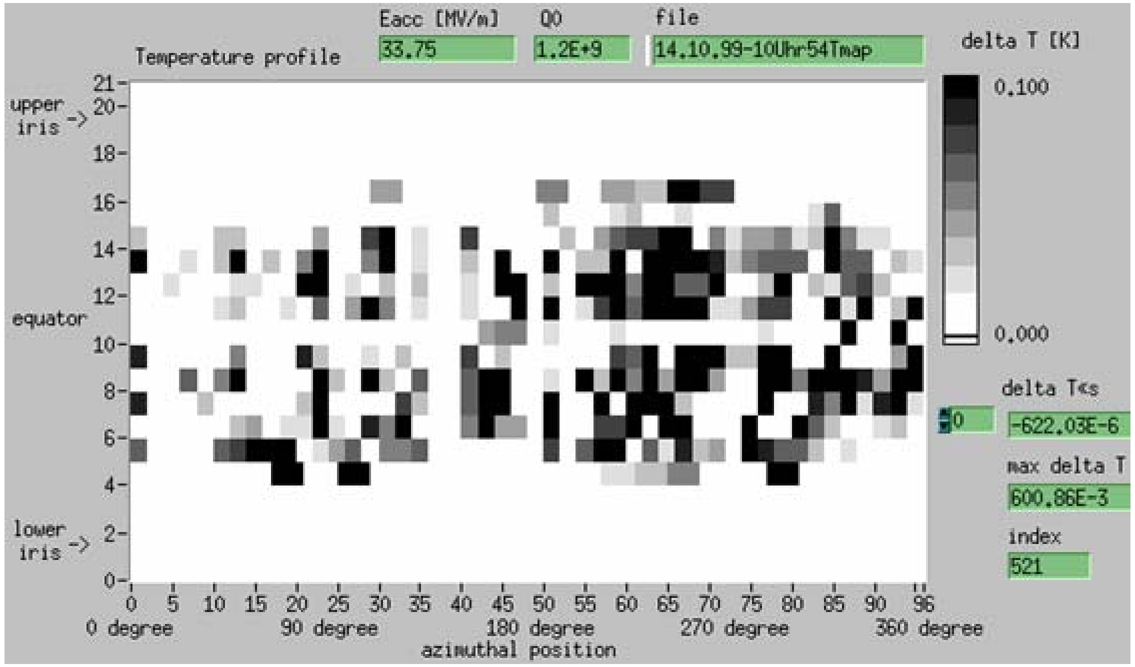


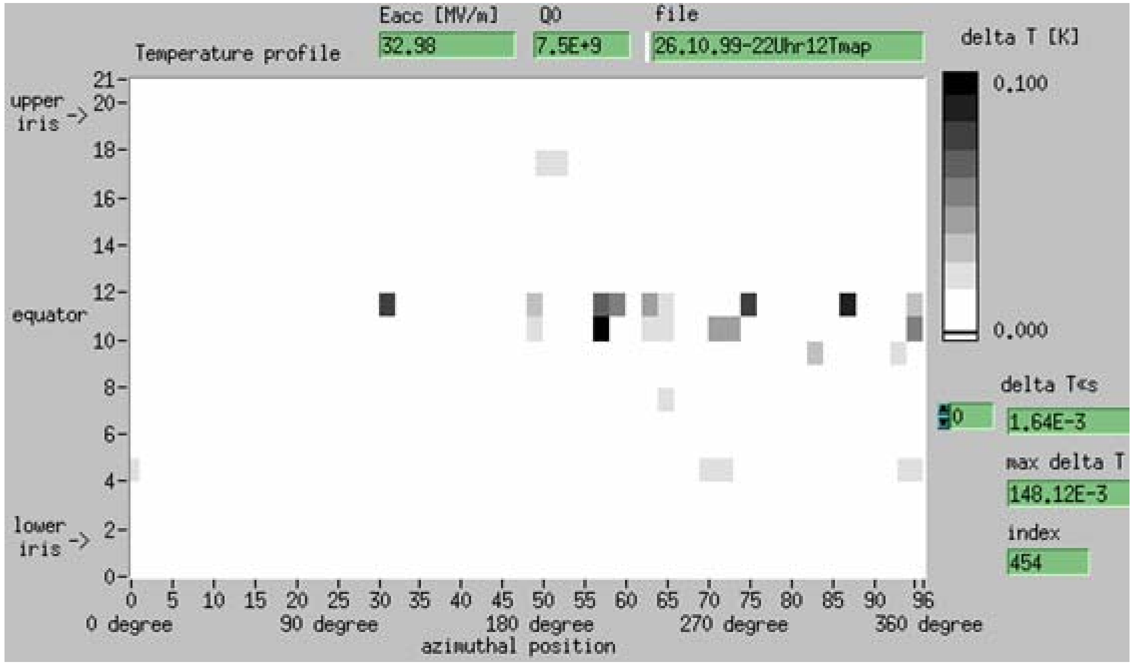
‘Q-drop‘ and In-situ Baking

- Heating of the cavity
  - 100 - 120 °C
  - Duration: ca. 40 hours
  - Pressure below 10^{-6} mbar
  - Inert gas atmosphere on the outside
- This changes the RF properties of the superconductor
  - And this is not fully understood!

Improvement by ‘In-situ’ baking







Temperature mapping at 33MV/m

... before in-situ bakeout at 120°C

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

⇒ Global effect

... after in-situ bakeout at 120°C

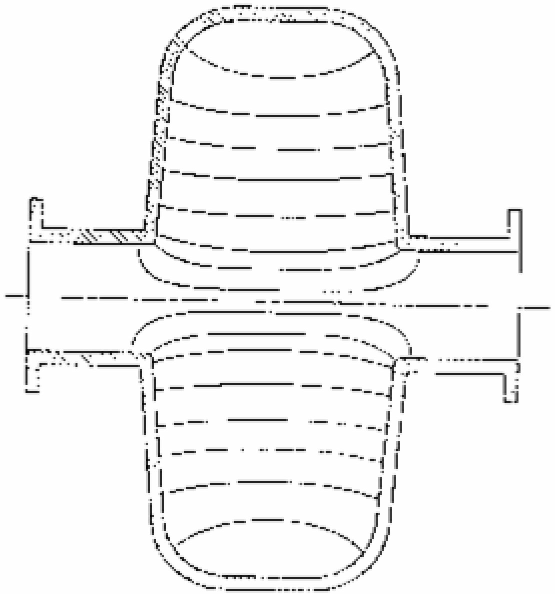
⇒ Heating of the equator welding

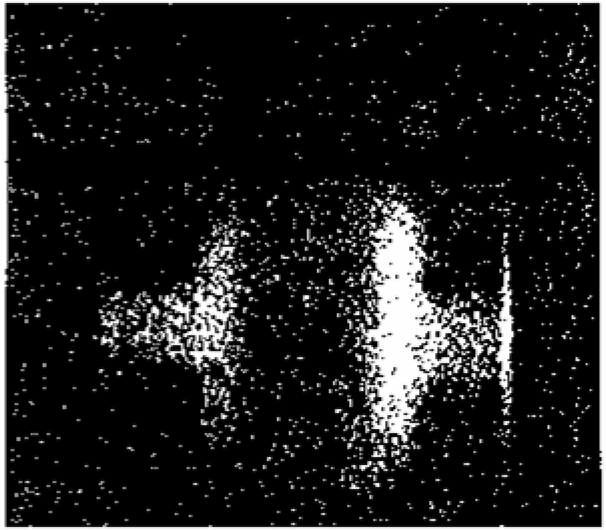
⇒ Change of the surface properties of the niobium

Electron Effects: 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.

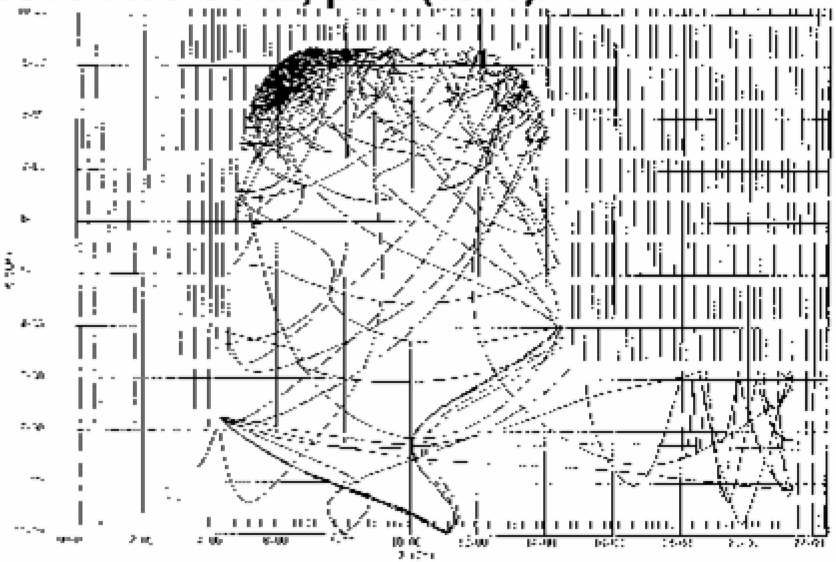
S-Band TM010 Resonator
Stanford, late 1960-ies





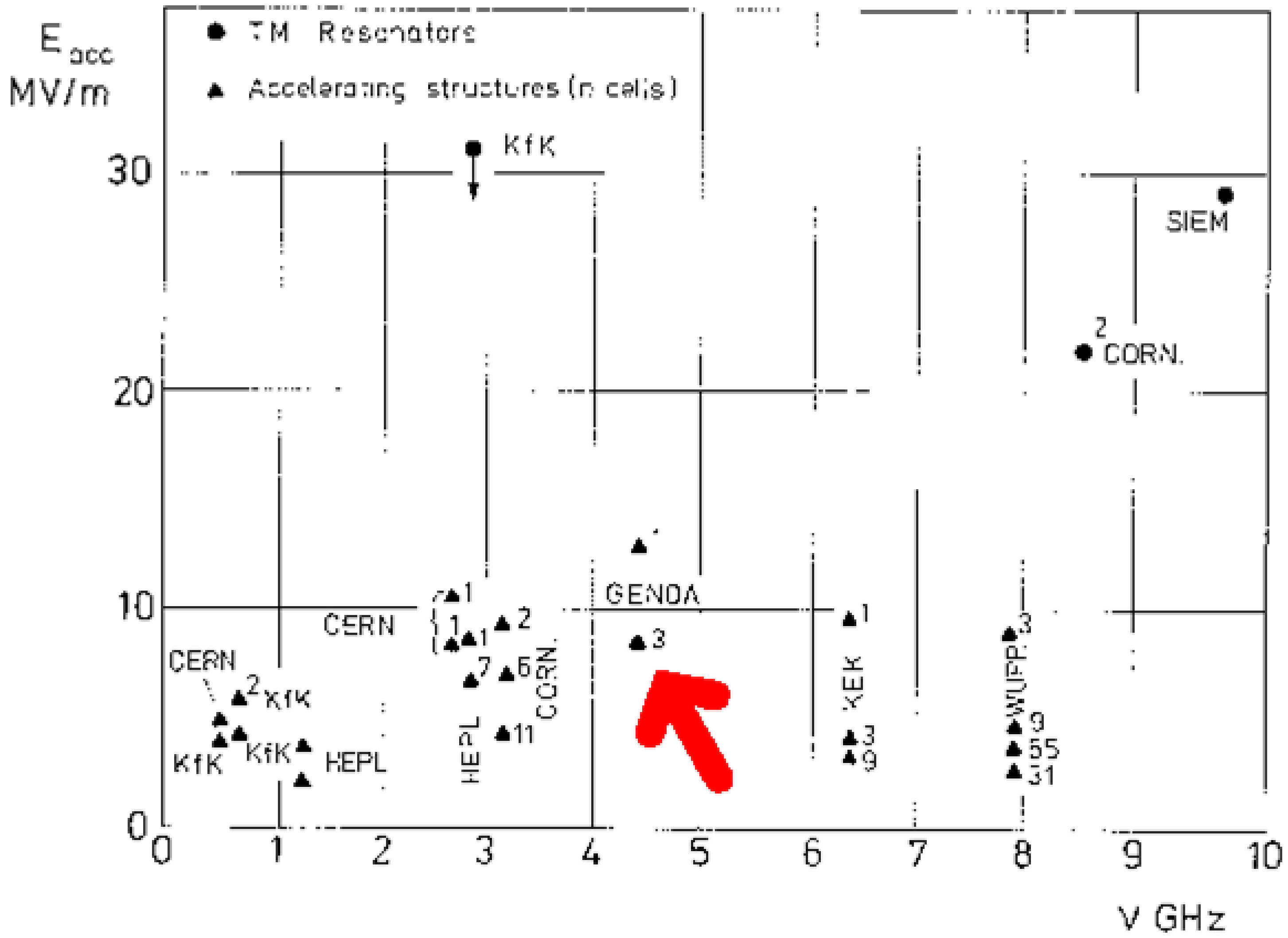
X-ray mapping

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



Simulated electron trajectories

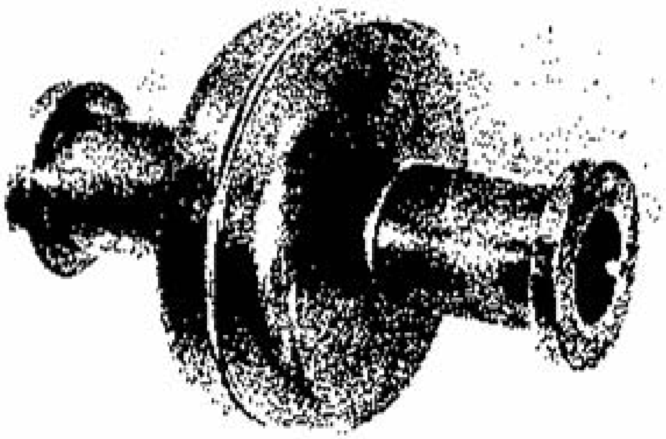
this is the standard geometry for about 15 years;
unfortunately the cylindrical geometry is favourable for electron multipacting



Accelerating gradient vs. frequency

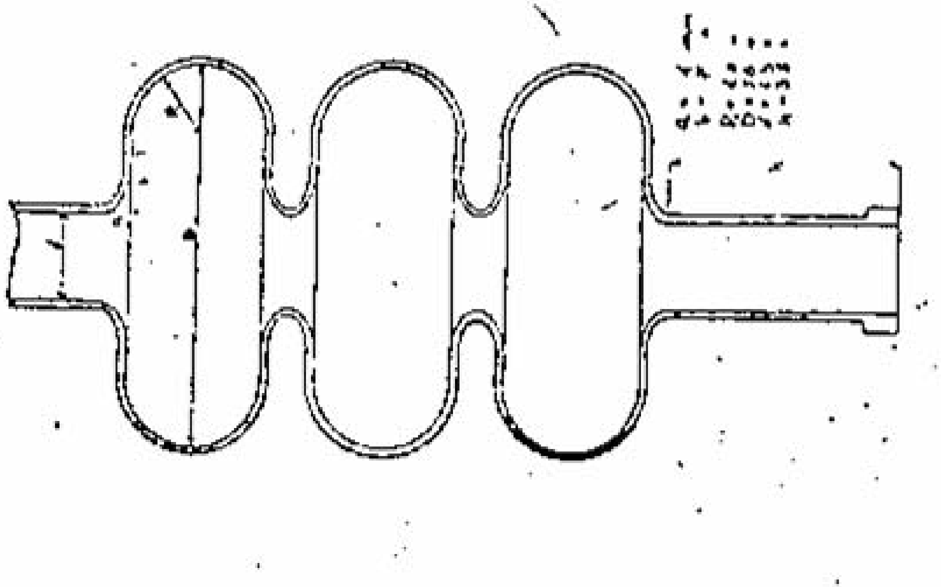
from A. Citron, Compilation of experimental results and operational experience First Workshop on RF Superconductivity, Karlsruhe, Germany, 1980

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



about 3 MV/m

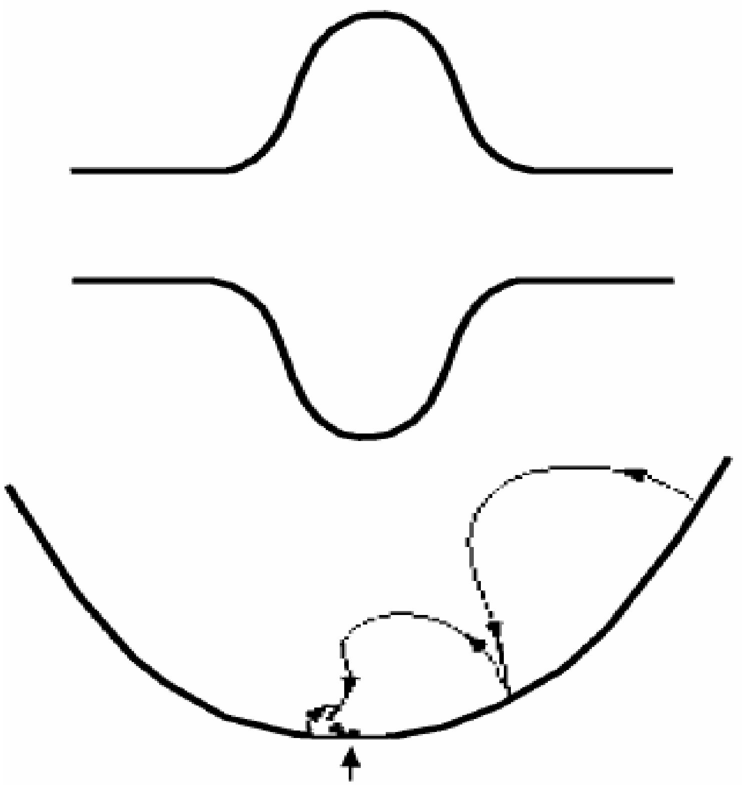
C-band Structure
Genoa, about 1980
the first spherical geometry
realized because of easier manufacturing

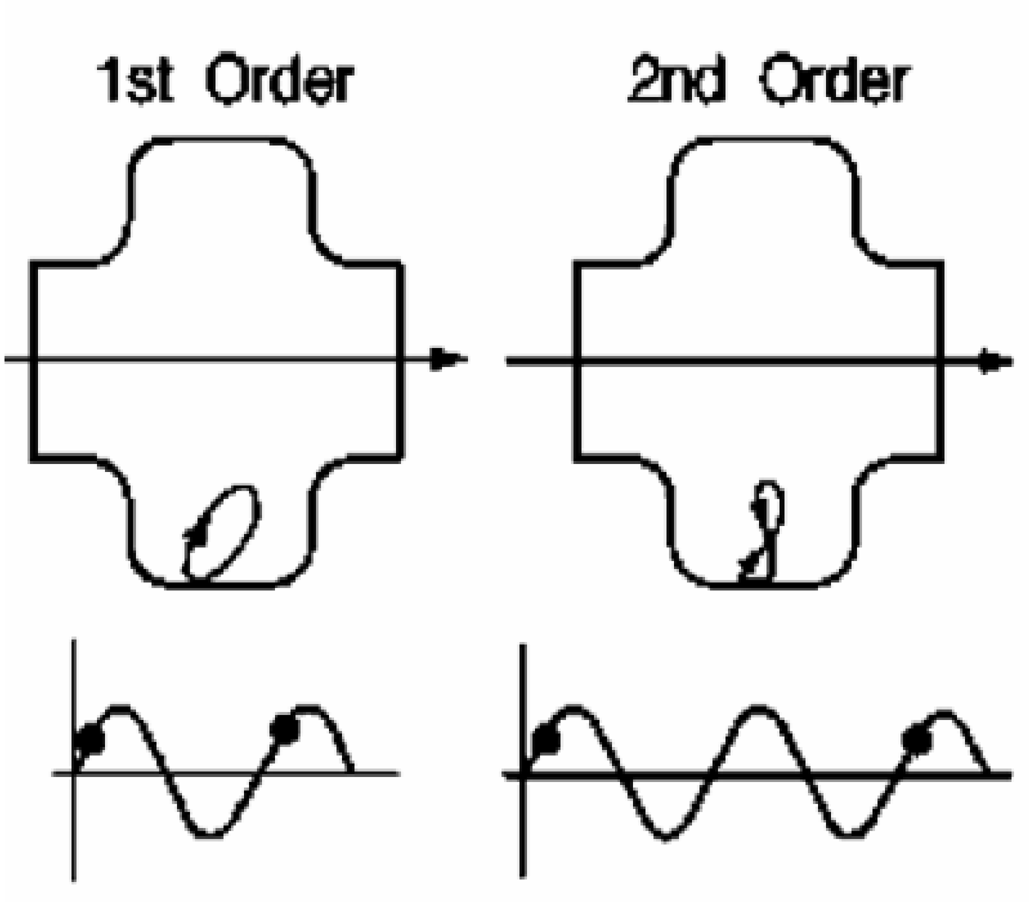


8 MV/m !!!

Multipacting in superconducting cavities

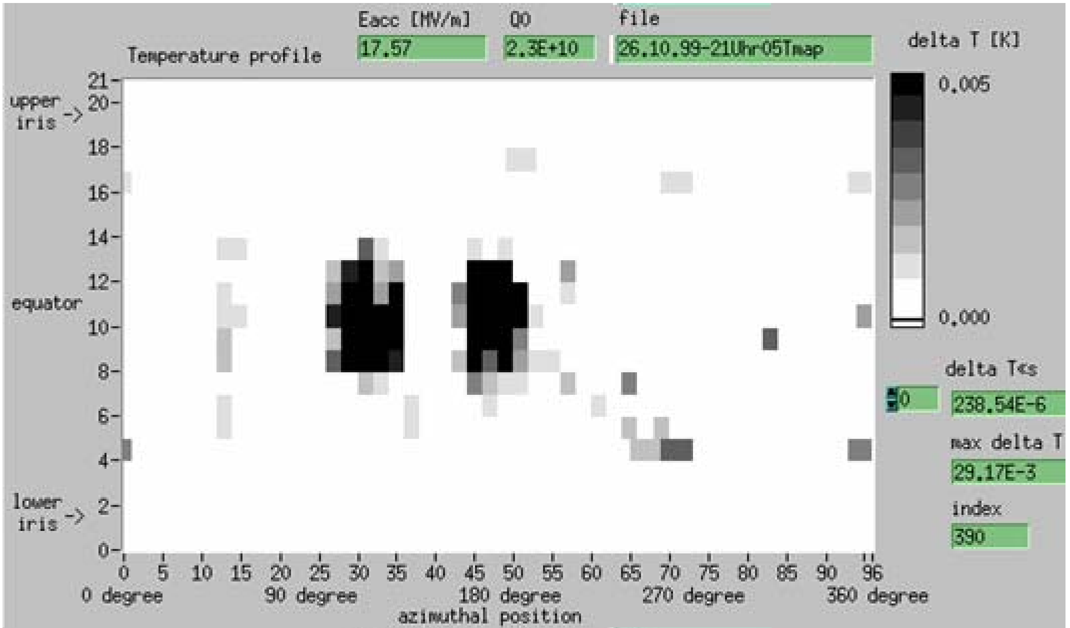
In a cavity with a nearly pill-box-like shape, electrons can multiply in the region shown.

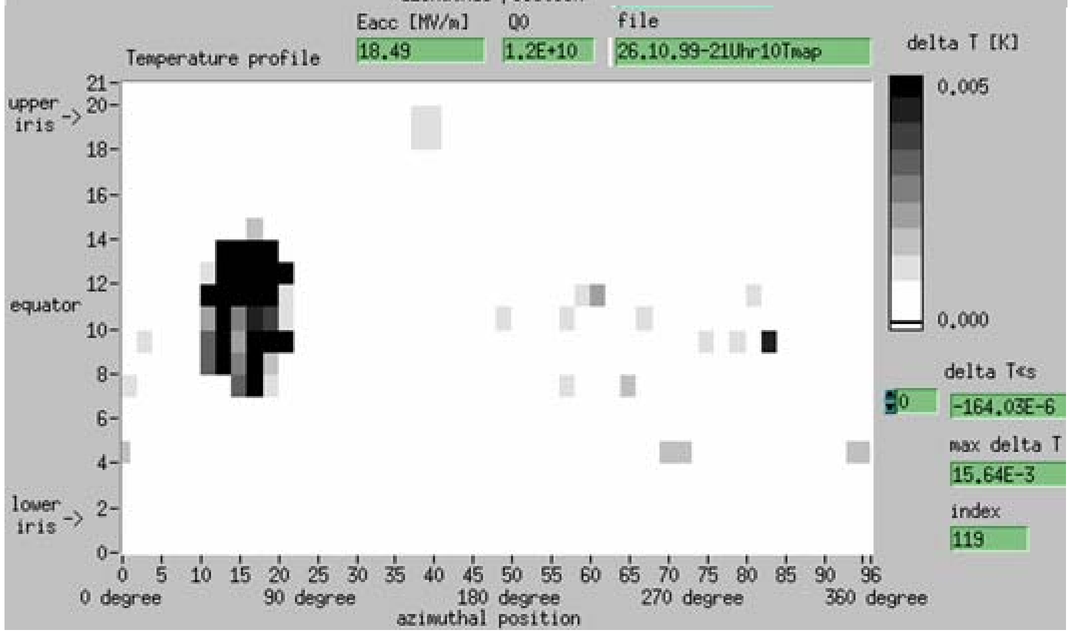


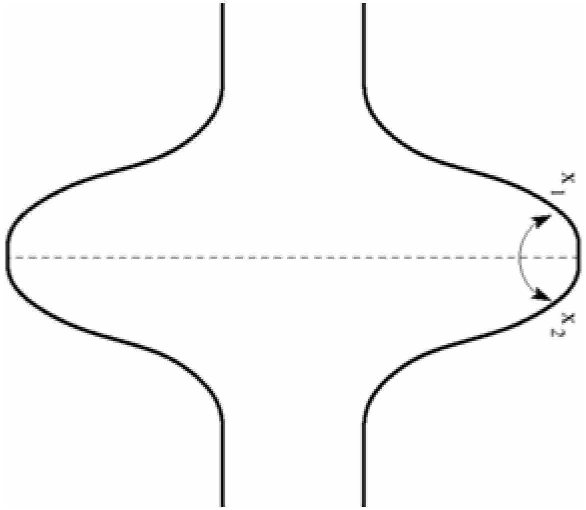


When the cavity shape is rounded, the electrons drift to the zero-field region at the equator. Here the electric field is so low that the secondary cannot gain enough energy to regenerate.

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







Multipacting: Temperature mapping

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

Electron Effects:Field Emission

- 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
- Primary limitation over past 5-10 years
  - Strongly related to the cavity handling
  - Very clean surface preparation and handling are needed
    - This is by no means trivial!
      - Especially for multi-cell cavities
    - On-going effort needed in quality control
  - Short introduction into cavity preparation
    - For more details please check out the reference material

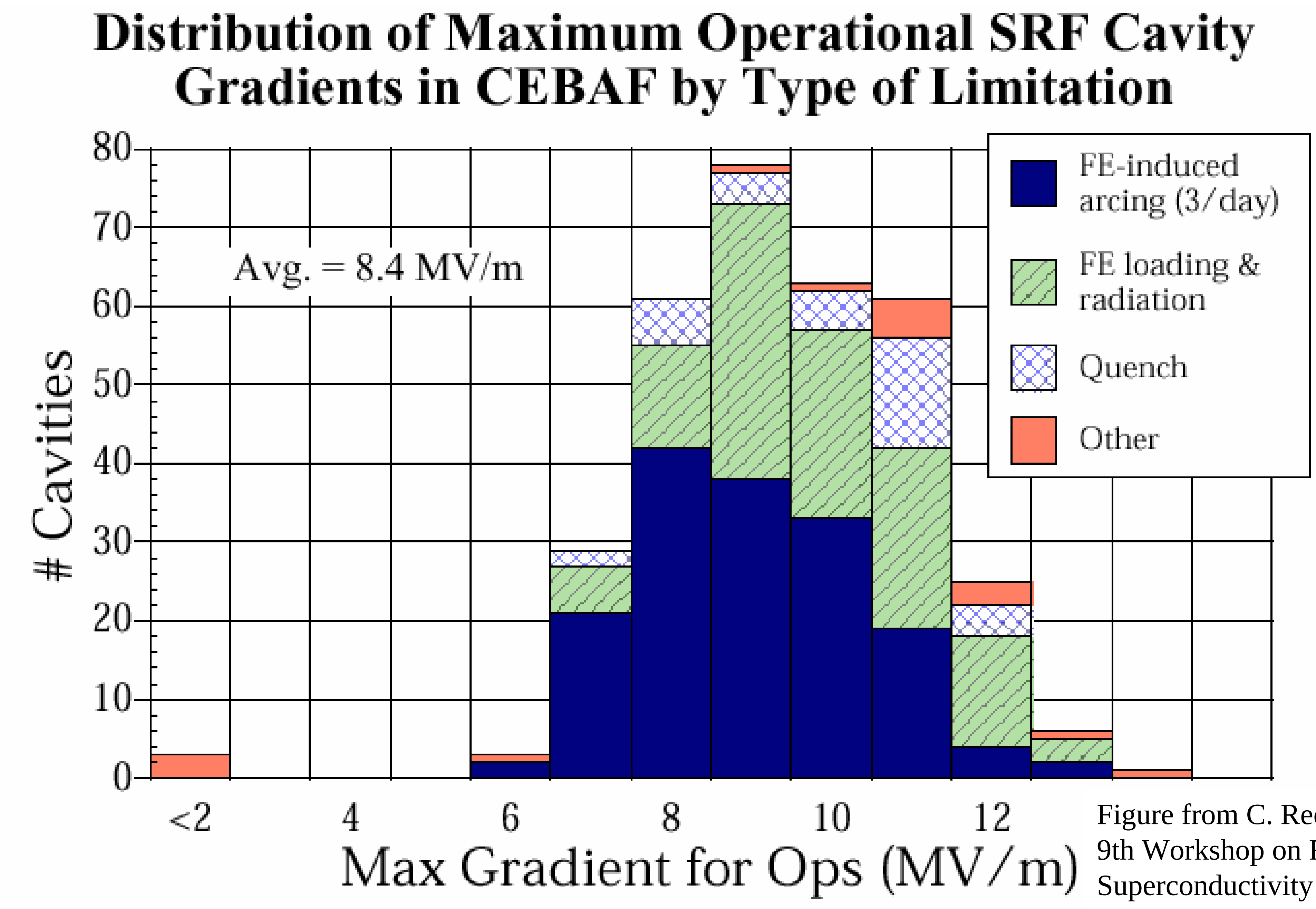
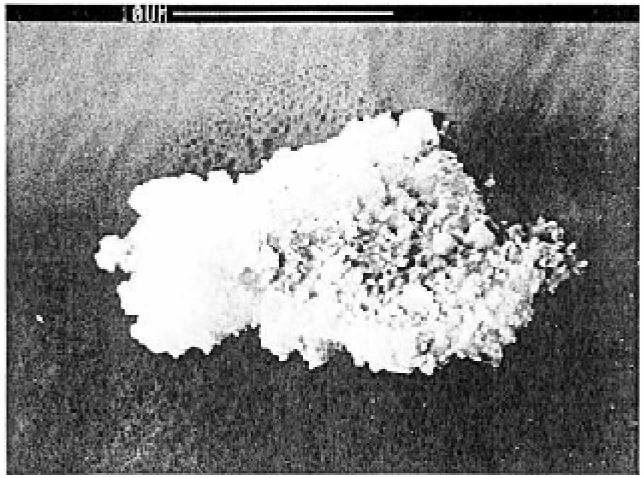
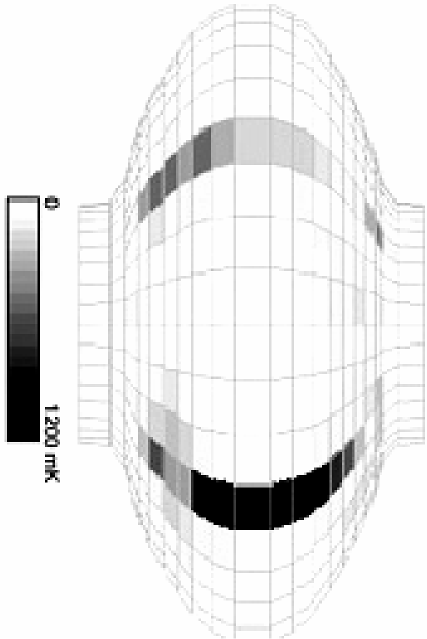


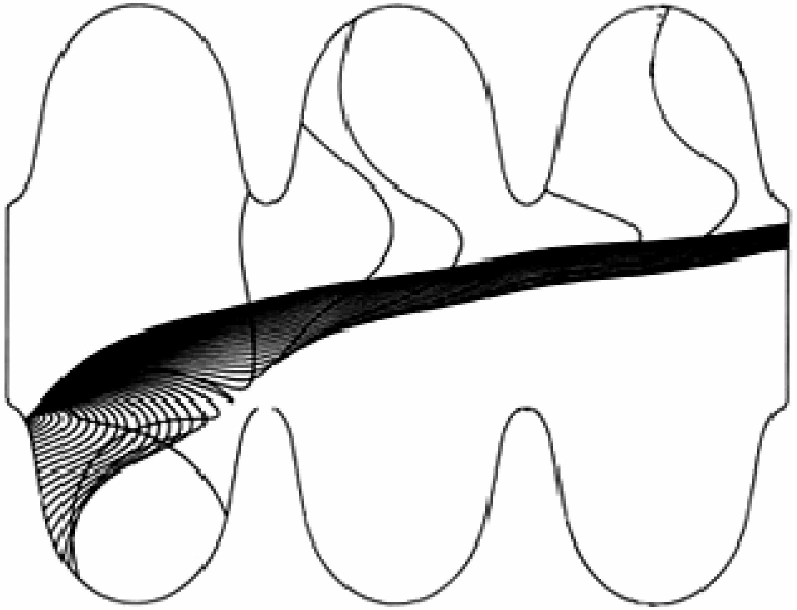
Figure from C. Reece, 9th Workshop on RF Superconductivity

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

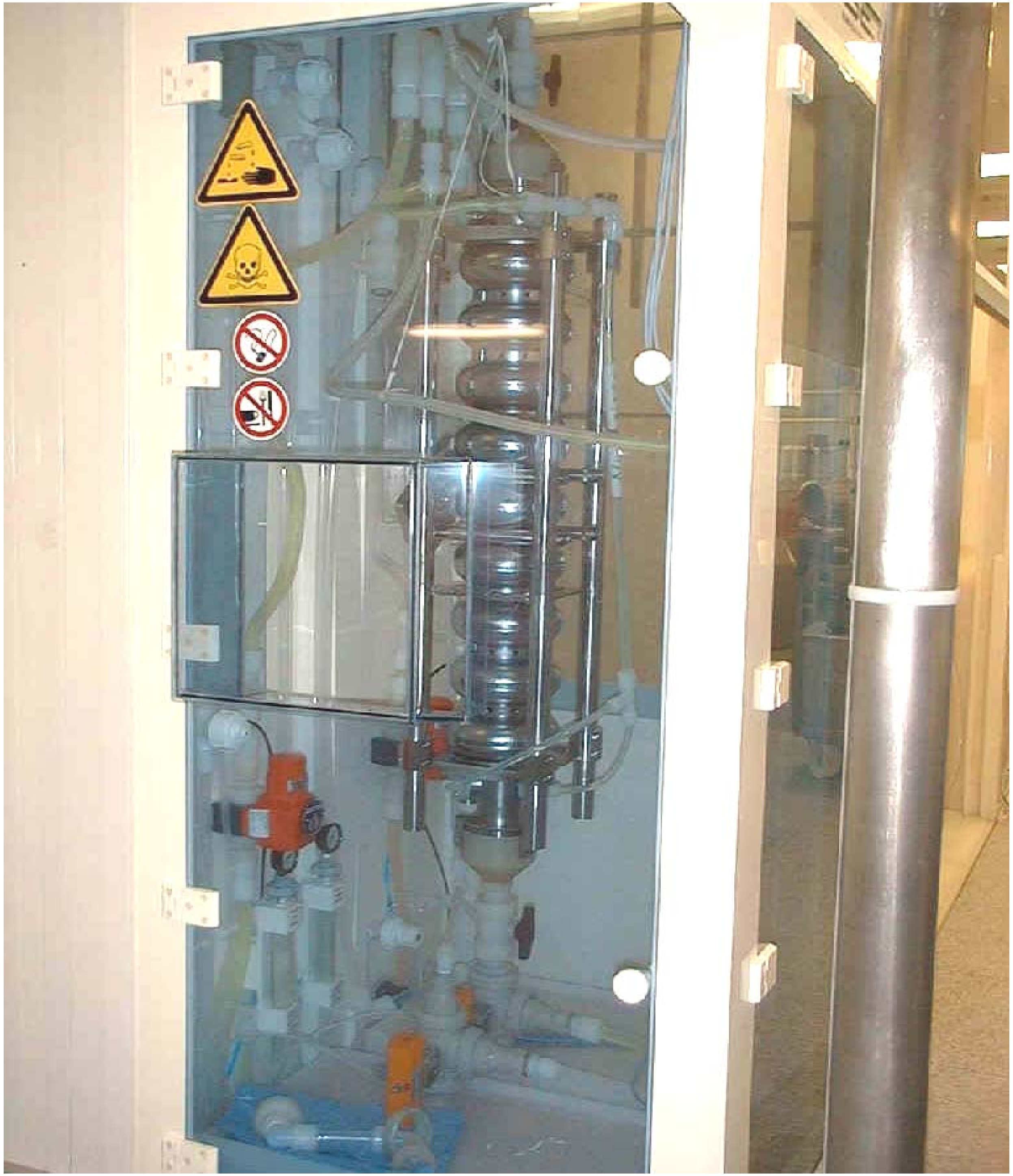
Mini-Excursion: Cavity surface preparation

- Clean room technology is essential
  - Ultra-sound cleaning
  - Ultra-pure water rinse
  - Ionized nitrogen blowing
  - …
- Removal of damage layer after forming
  - Etching or Electropolishing
- Final surface preparation
  - Electropolishing
  - High-pressure ultra-pure water rinse
  - ‘In-situ‘ bake-out

Cleanroom Technology for SC Cavities

- the small surface resistance of the superconducting necessitates avoidance of NC contaminations larger than a few mm
    - detailed material specification and quality control need to be done
    - tight specification for fabrication e.g. welds have to be implemented
    - clean room technology is a must (e.g. QC with particle counts, monitoring of water quality, documentation of processes)

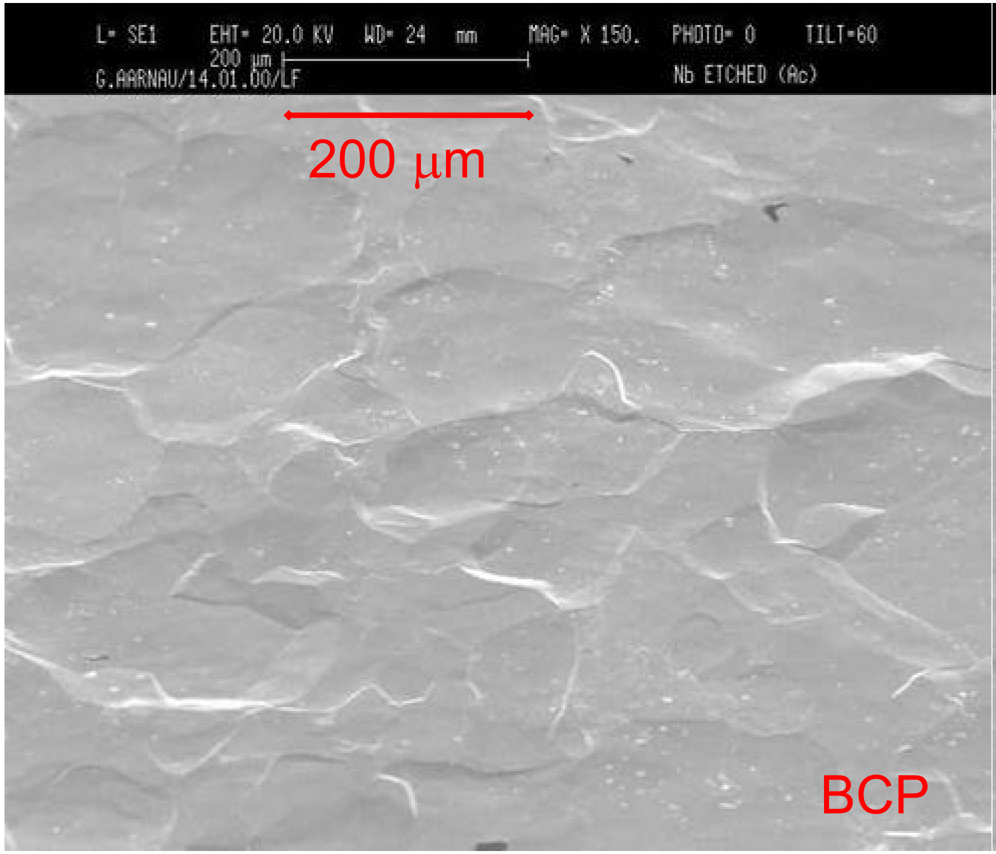
The inter-cavity connection is done in class 10 cleanrooms

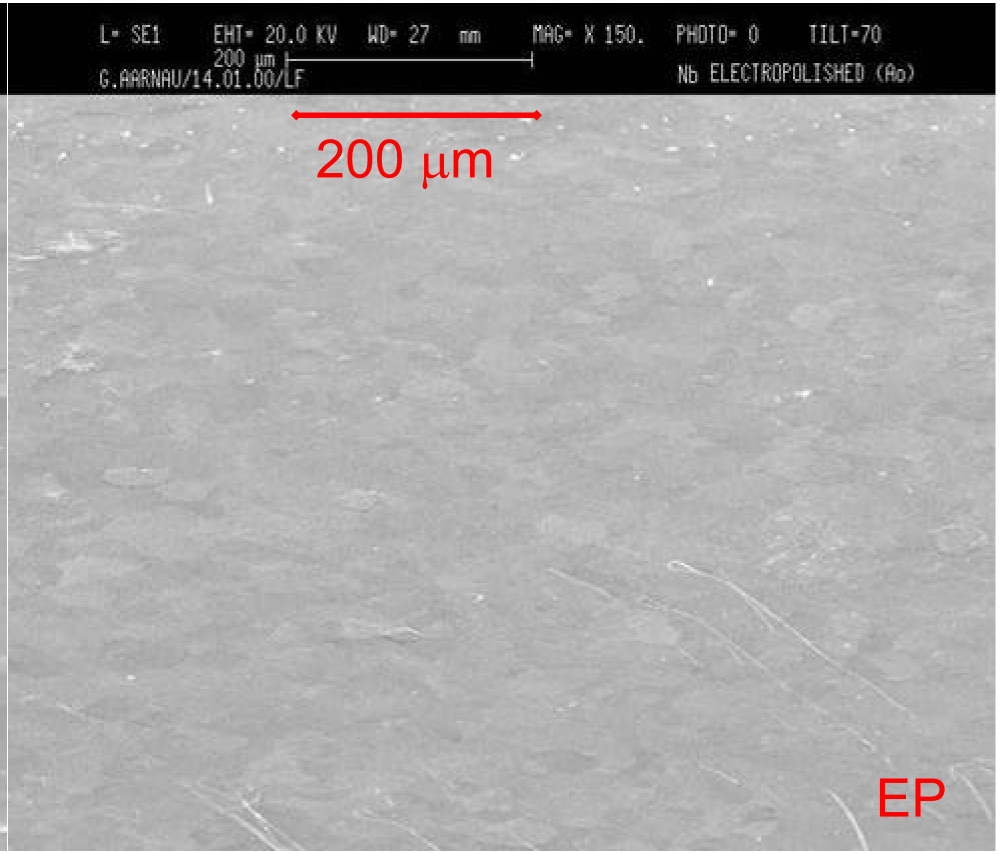


Surface preparation

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

Niobium surface pictures



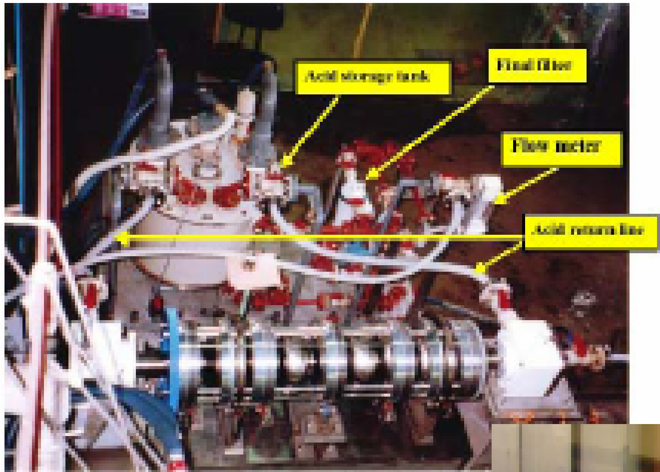


- Etching - “Buffered chemical polish“
- Electropolishing

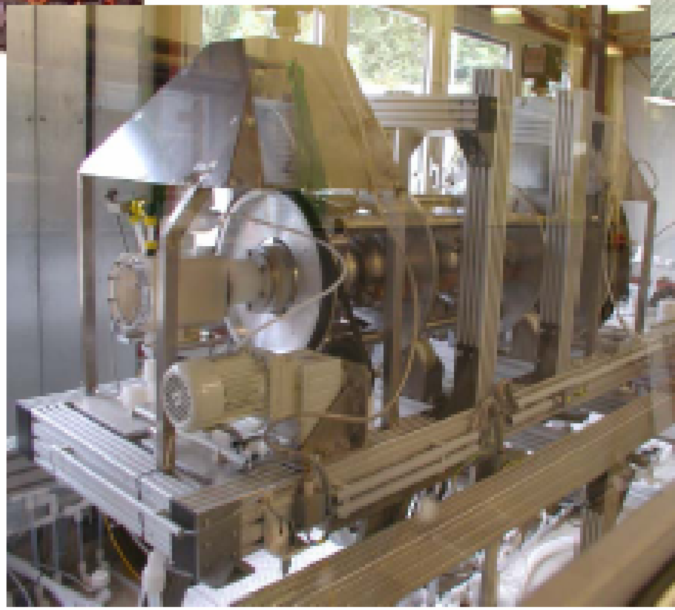
EP- Systems

Compilation by P. Kneisel

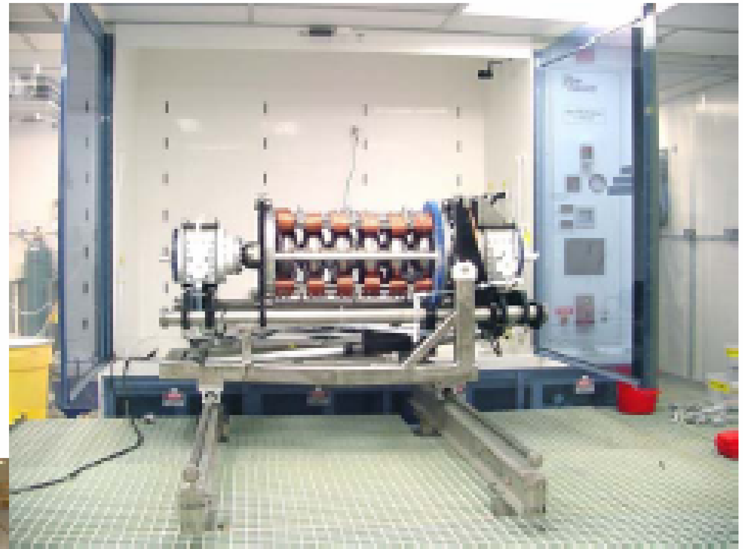
KEK/Nomura Plating



DESY

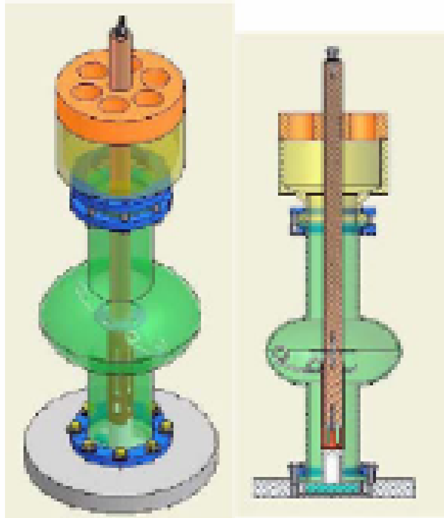


JLab



INFN

Cornell



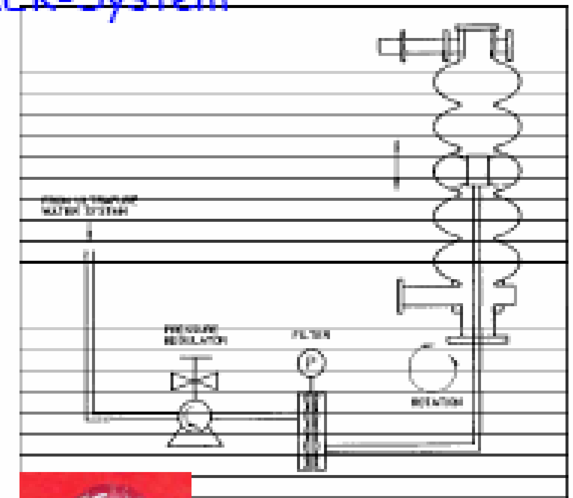
High Pressure Rinse Systems

Compilation by P. Kneisel

DESY-System

Jlab HPR Cabinet

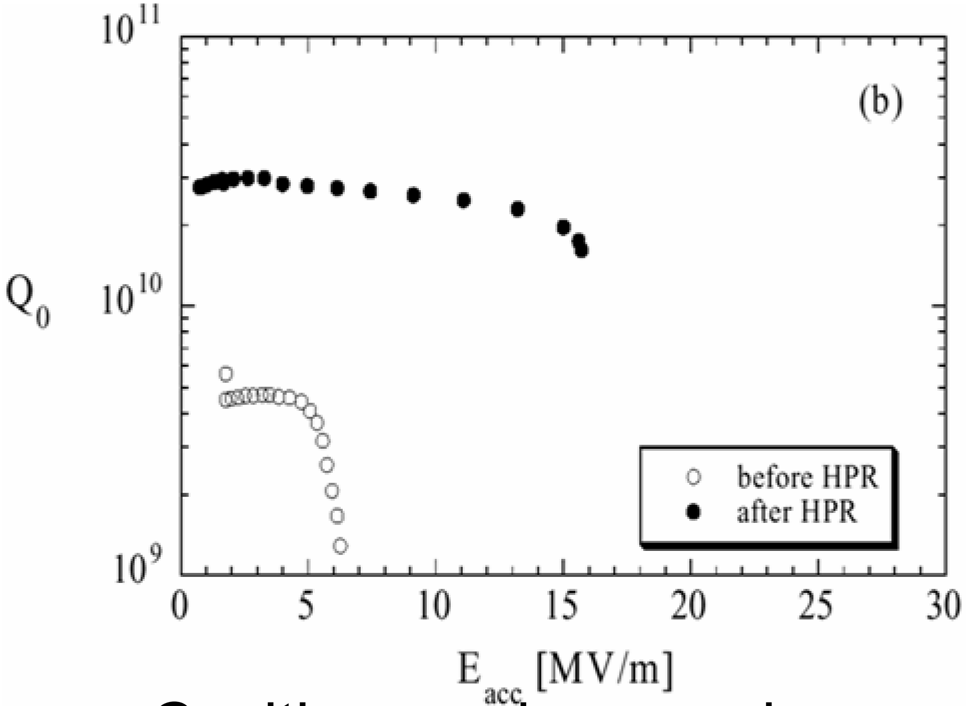
KEK-System



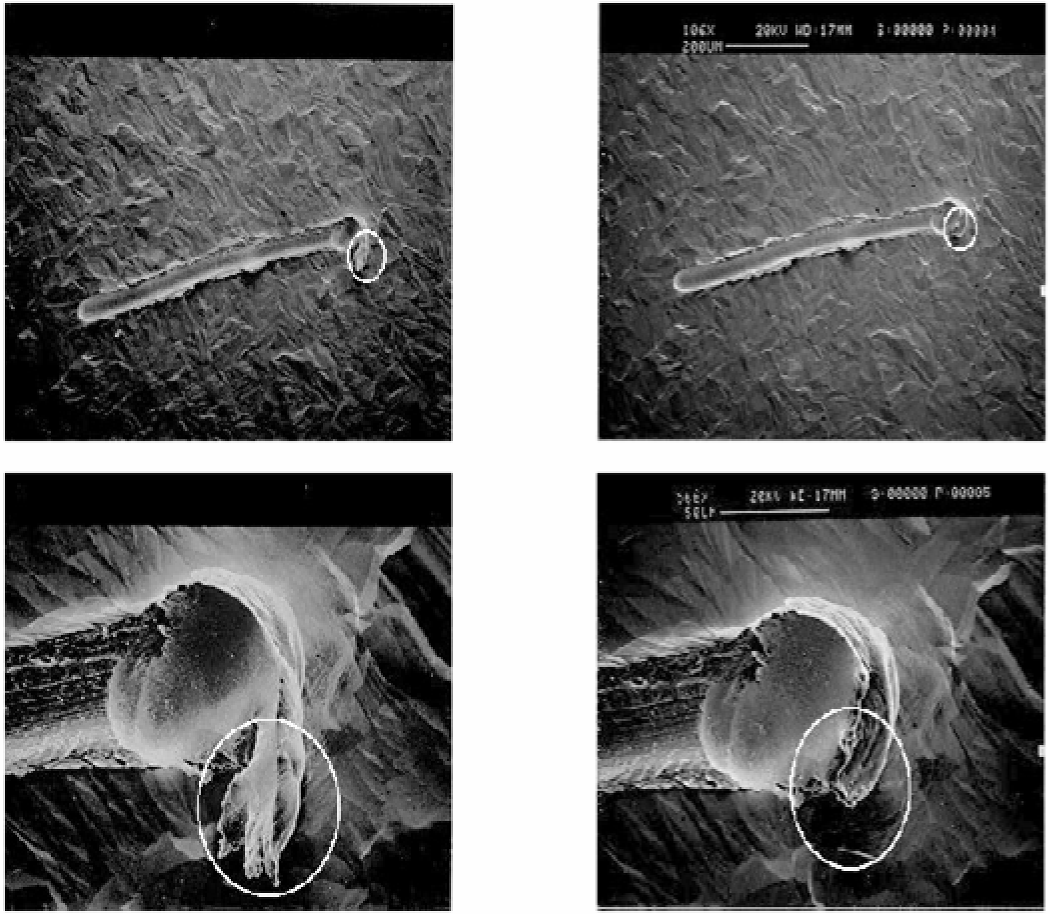
End of Mini-Excursion

- … and back to field emission as a limiting mechanism.

High Pressure Water Rinsing



- Cavities can improve by new rinses
- Particle removal
- Samples show modification of surfaces due to the water jet forces

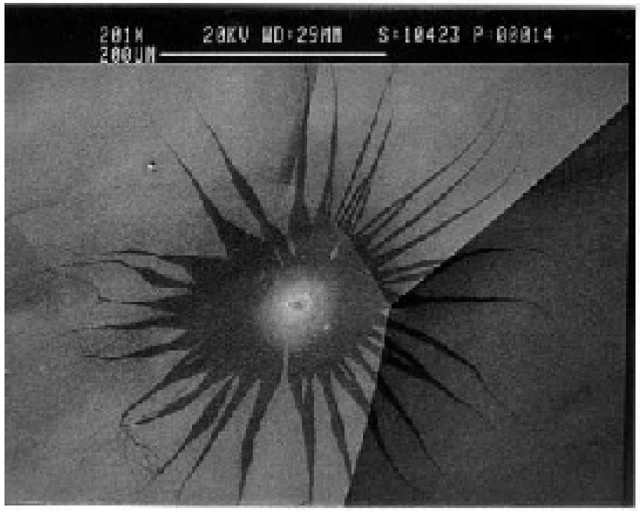


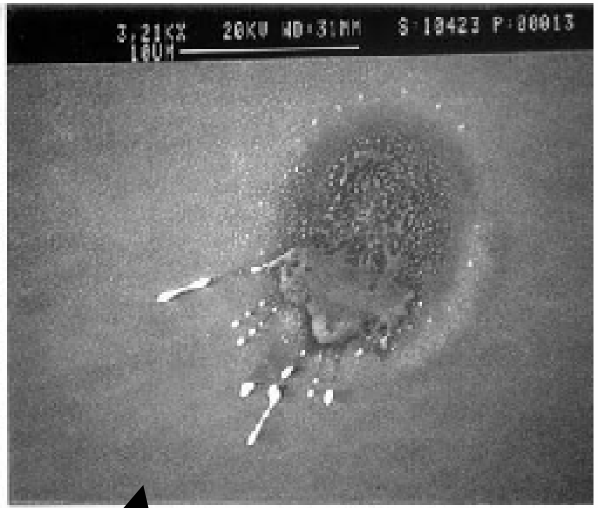
Before HPWR

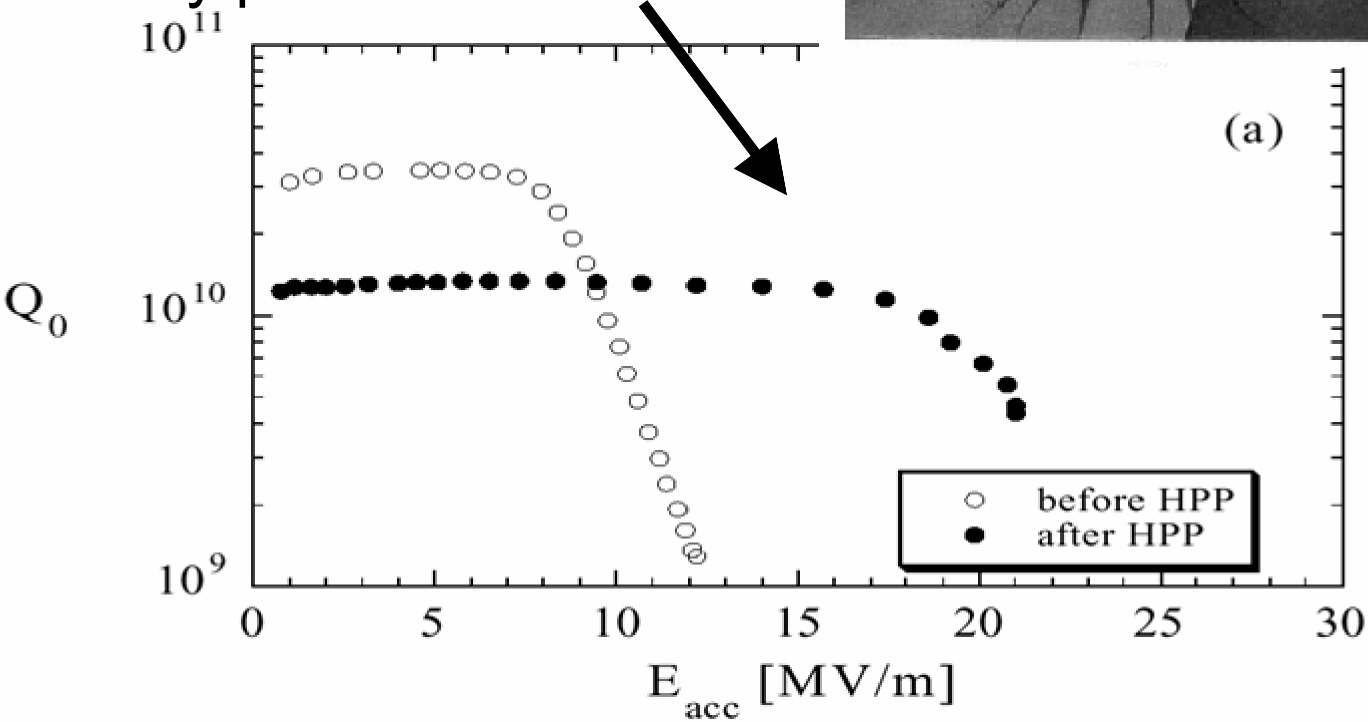
After HPWR

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



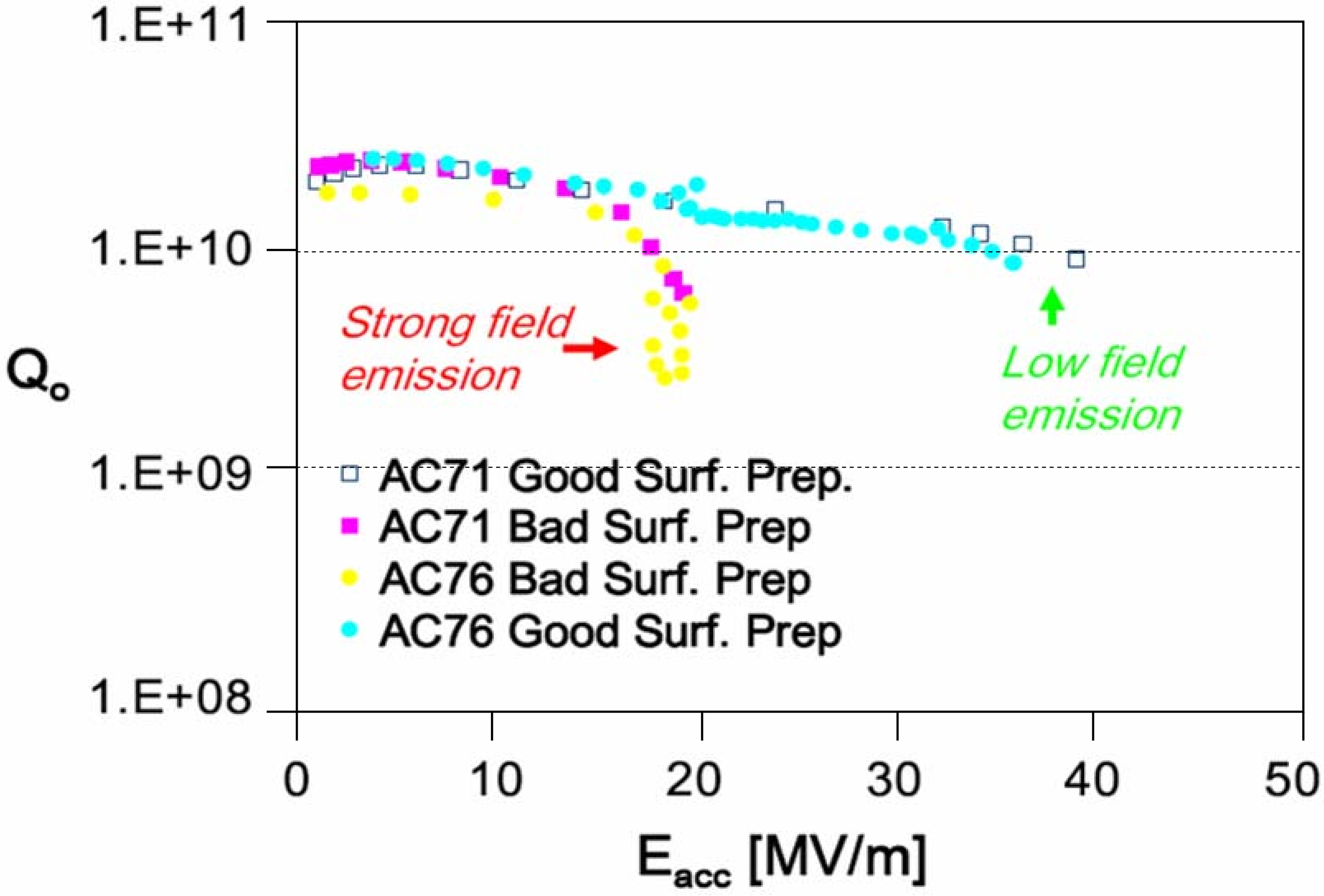




SEM pictures of molten particle after application of high RF power

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

Problems with Reproducibility: Quality Control Needs Improvements



Summary lecture 1

- SRF cavities properties
  - Have very low R_{surf}, very high Q_0
  - Lower RF peak power outweighs required cooling power
  - Can achieve gradients around 40 MV/m in niobium (has been demonstrated in single cells)
- SRF technology
  - Material science is important
    - High purity niobium
    - Cleanroom environment
  - Several fields of science and engineering are involved in the work on SRF cavities

Backup