Tutorial on Gradient and Q
Plus Open Issues

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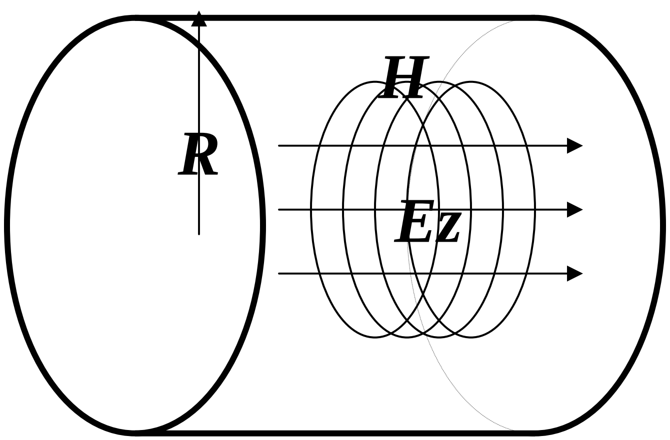
Outline

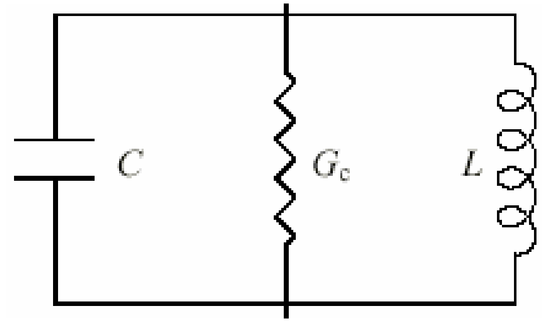
- Theoretical expectations
  - Elementary Cavities, figures of merit
  - Surface Resistance
  - Critical RF Magnetic Field
- Departures from theory
  - Surface Resistance
  - Multipacting
  - Thermal breakdown of SC at imperfections
  - Field emission, cleanliness, processing by voltage breakdown
  - Increasing surface resistance at high fields (Q-slope)
  - Global thermal breakdown (problem only for f > 2 GHz)
- Open Issues for this workshop

Cavities – Figures of Merit

Radiofrequency Cavities
- Single Cells

TM$_{010}$ mode

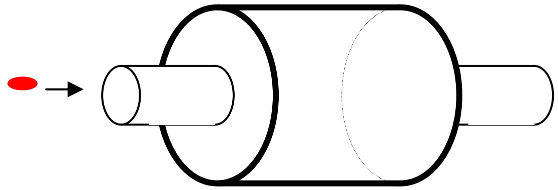




$$E_z = E_0 J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}$$

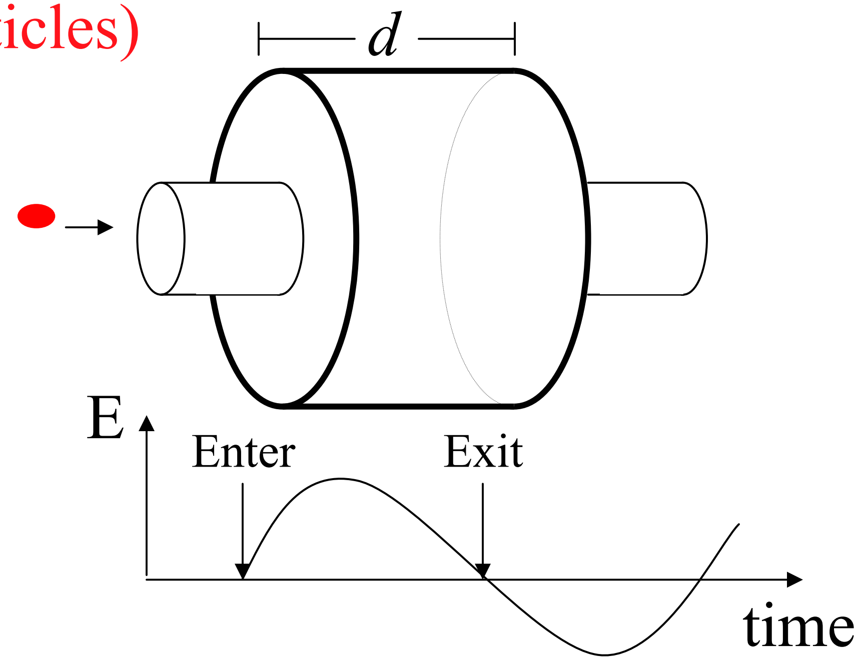
$$H_\phi = -i\frac{E_0}{\eta} J_1\left(\frac{2.405\rho}{R}\right) e^{-i\omega t},$$

•Add beam tube for charge to enter and exit



$$\omega_{010} = \frac{2.405c}{R},$$

Figures of Merit
Accelerating Voltage/Field
($v = c$ Particles)



- For maximum acceleration need

$$T_{\rm cav} = \frac{d}{c} = \frac{T_{\rm rf}}{2}$$

so that the field always points in the same direction as the bunch traverses the cavity

- Accelerating voltage then is:

$$V_c = E_0 \left| \int_0^d e^{i\omega_0 z/c}\, dz \right| = dE_0 \frac{\sin\left(\frac{\omega_0 d}{2c}\right)}{\frac{\omega_0 d}{2c}} = dE_0 T.$$

- Accelerating field is: $E_{\rm acc} = \dfrac{V_c}{d} = 2E_0/\pi.$

Figures of Merit- Peak Fields

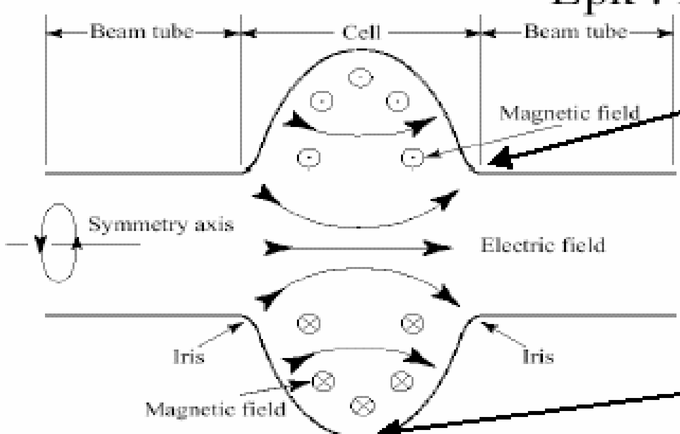
- *For* E_{acc} → important parameter is E_{pk}/E_{acc} Typical 2 - 2.6
- Make as small as possible, to avoid problems with field emission - more later.

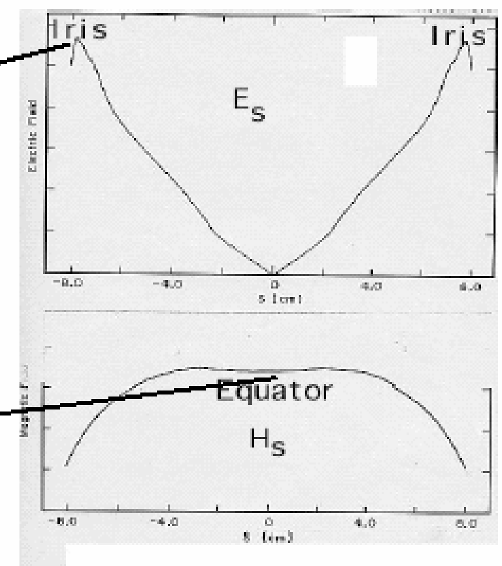
Typical 40 - 50 Oe/MV/m

- Equally important is H_{pk}/E_{acc}, (for superconducting cavities). To maintain SC
- H_{pk}/E_{acc} can also lead to premature quench problems (thermal breakdown).

- Ratios increase when beam tubes are added to the cavity.

Epk : Electric field high at iris





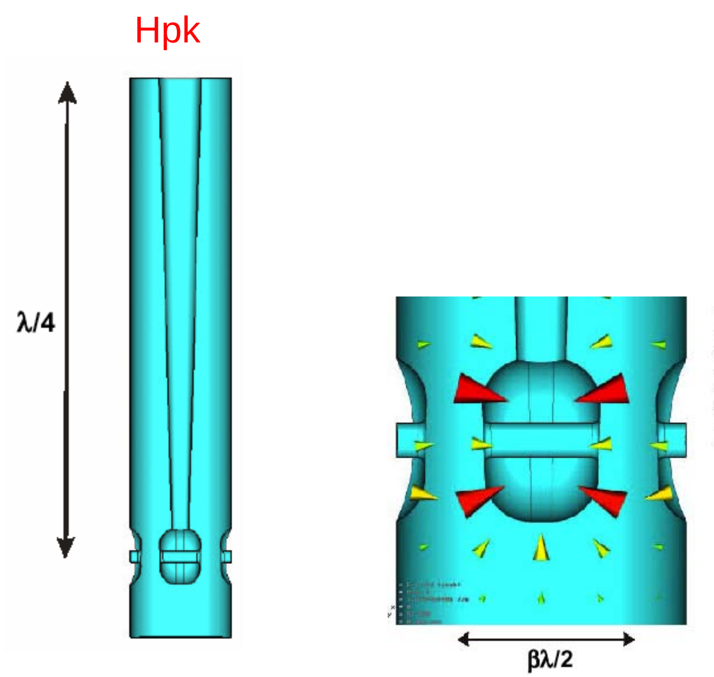
Hpk : Magnetic field high at equator

Peak fields for low beta cavities are higher

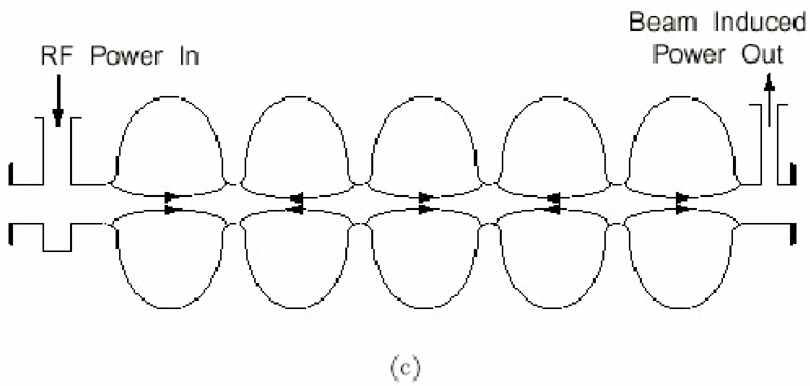
Typical

Epk/Eacc = 4 - 6

Hpk/Eacc = 60 - 200 Oe/MV/m

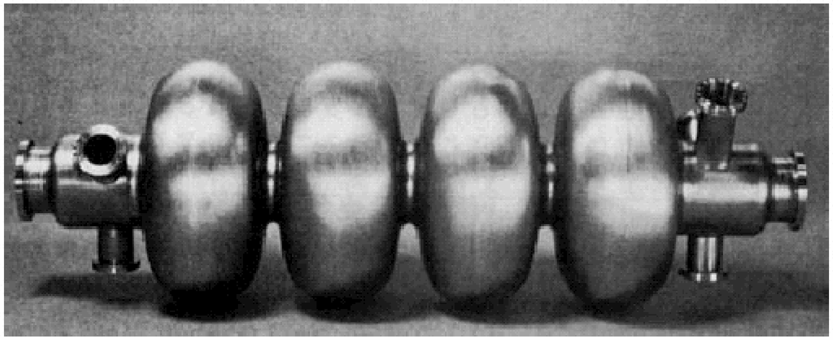


Multi-Cell Structures for v/c ≈ 1



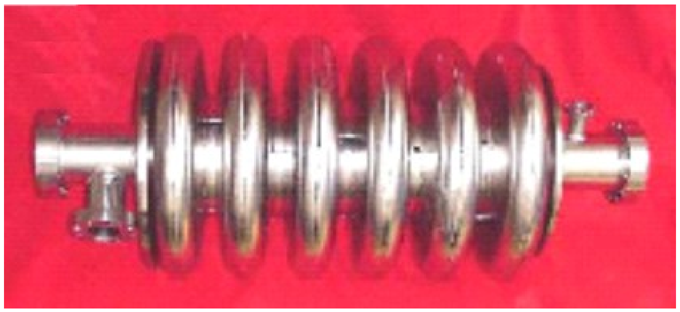
Standing Wave

π phase shift



Beta = 0.5 examples

Spoke Resonator



Figures of Merit

Dissipated Power, Stored Energy, Cavity Quality (Q)

- Surface currents ($\propto H$) result in dissipation proportional to the surface resistance (R_s):

$$\frac{dP_c}{ds} = \frac{1}{2} R_s |\mathbf{H}|^2$$

- Dissipation in the cavity wall given by surface integral:

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, ds$$

- Stored energy is: ⟶

$$U = \frac{1}{2} \mu_0 \int_V |\mathbf{H}|^2 \, dv$$

- Quality (Q)

$$Q_0 = \frac{\omega_0 U}{P_c} = 2\pi \frac{U}{T_{rf} P_c}$$

which is ~ 2 π number of cycles it takes to dissipate the energy stored in the cavity → Easy way to measure Q

- $Qnc \approx 10^4$, $Qsc \approx 10^{10}$

Figures of Merit

Shunt Impedance (R_a)

- Shunt impedance (R_a) determines how much acceleration one gets for a given dissipation (analogous to Ohm's Law)

$$R_{\mathrm{a}} = \frac{V_{\mathrm{c}}^2}{P_{\mathrm{c}}}$$

→ To maximize acceleration, must maximize shunt impedance.

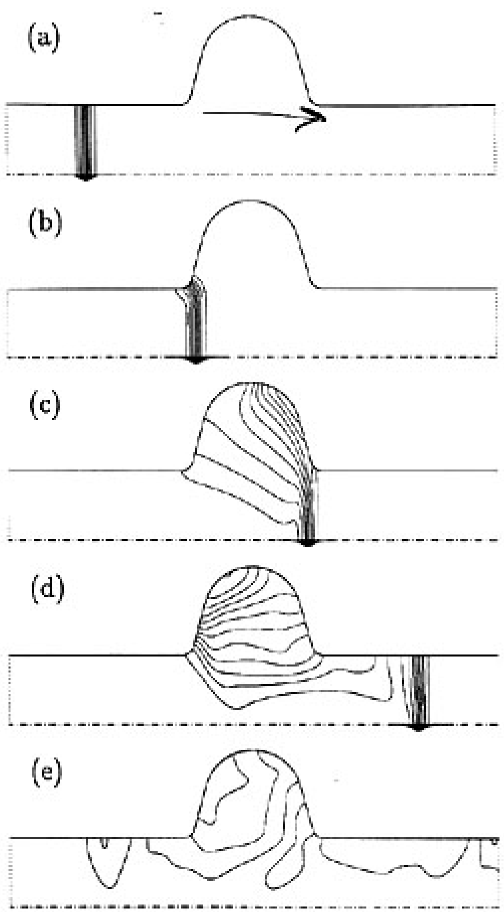
Another important figure of merit is $\frac{R_{\mathrm{a}}}{Q_0} = \frac{V_{\mathrm{c}}^2}{\omega_0 U},$

•Ra/Q only depends on the cavity geometry → Cavity design impacts mode excitation

Excitation of disruptive (higher-order) modes by the beam scales as R_a/Q → in conflict with the above requirement. (Solved by using SRF, high Q)

(Some) Further SC Features

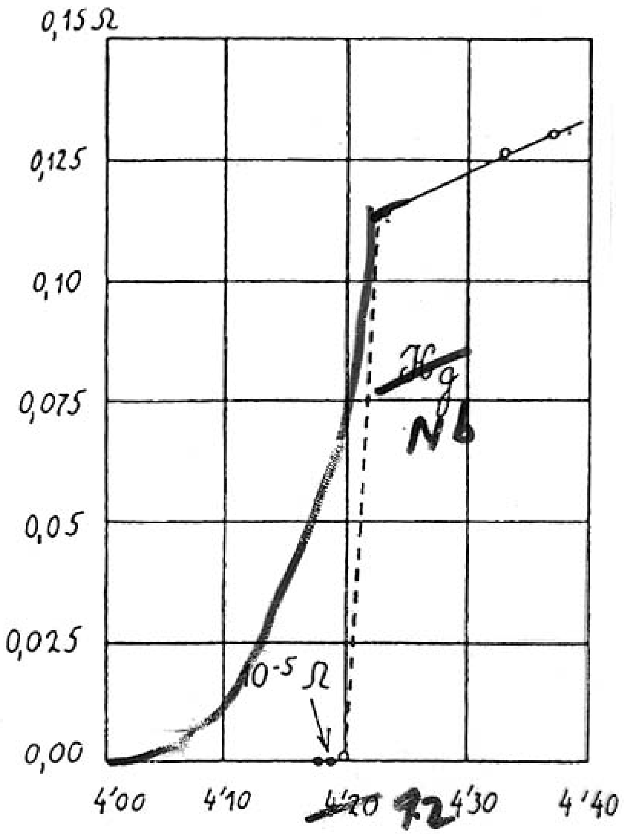
- Large beam tube & Fewer cells
  - Reduces the interaction of the beam with the cavity (scales as size^3) →
  - The beam quality is better preserved (important for, e.g., FELs).
  - HOMs are removed easily → better beam stability → more current accelerated (important for, e.g., B-factories)
  - Reduce the amount of beam scraping → less activation in, e.g., proton machines (important for, e.g., SNS, Neutrino factory)



Surface Resistance - Superconductivity

Superconductivity

Heike Kammerlingh-Onnes, 1911: SC in mercury

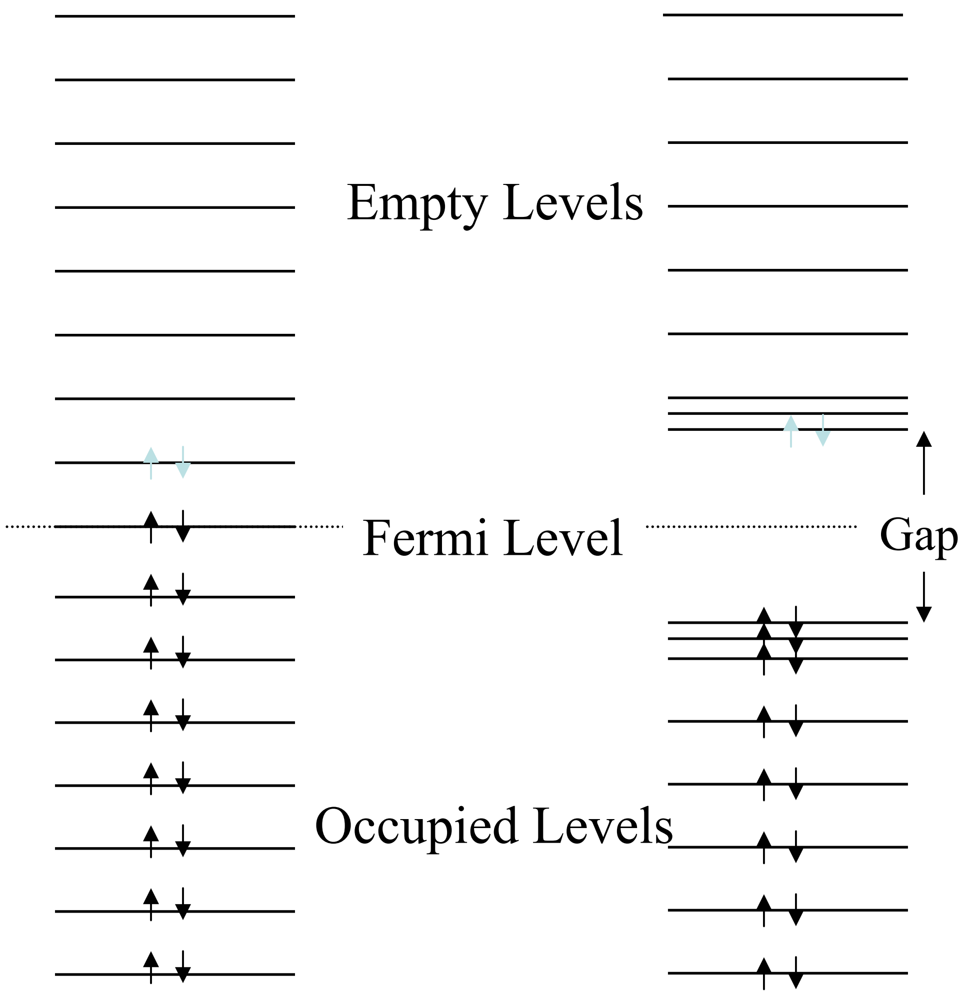


surement of superconductivity by Kamerlingh Onnes

4 The Convergence of Classical Concepts circa 1900

Figure 1-2. Heike Kamerlingh Onnes. Courtesy AIP ... Library and

Energy Gap



Normal conductor

Superconductor
(electrons condense into Cooper pairs)

At $T > 0$K, some "normal" electrons not yet condensed into pairs

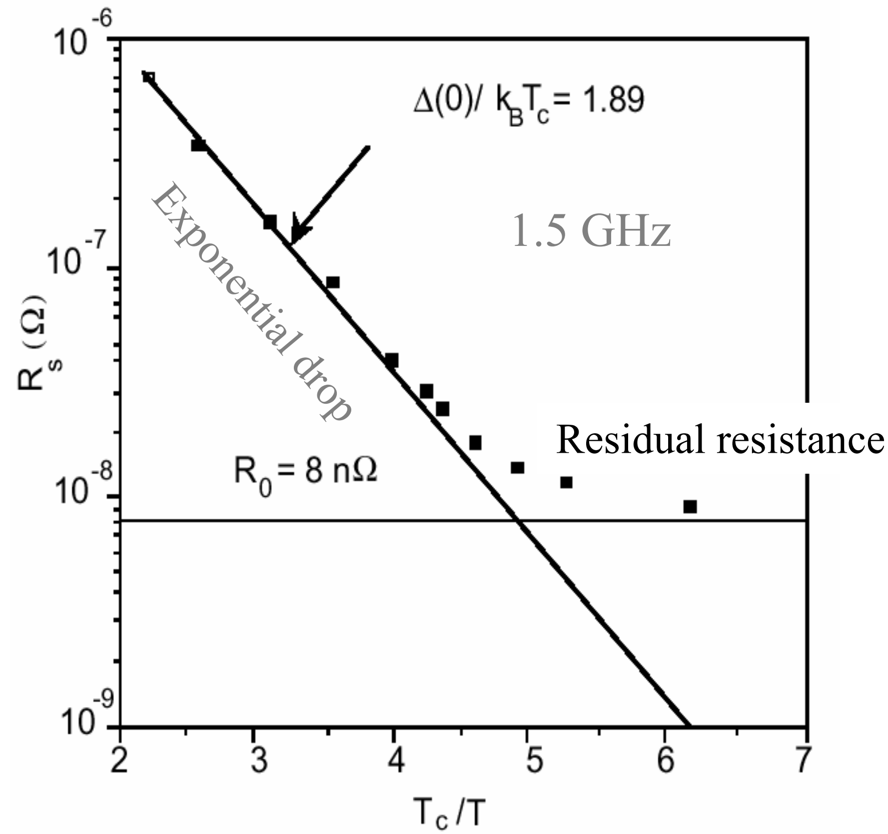
$$n_{\mathrm{normal}} \propto \exp\left(-\frac{\Delta}{k_{\mathrm{B}}T}\right)$$

Superconductors: RF Resistance

- In the simple two fluid model,
- DC resistance is zero because SC fluid shorts out the NC fluid.
- In RF fields, there are finite (but small) RF losses because Cooper pairs don't follow the time-varying field due to their inertia
- → nc electrons "see" some electric field.

$10\ n\Omega \Rightarrow Q = 2.5\ x10^{10}$

Compare with Cu: Rs ~ 10 mΩ



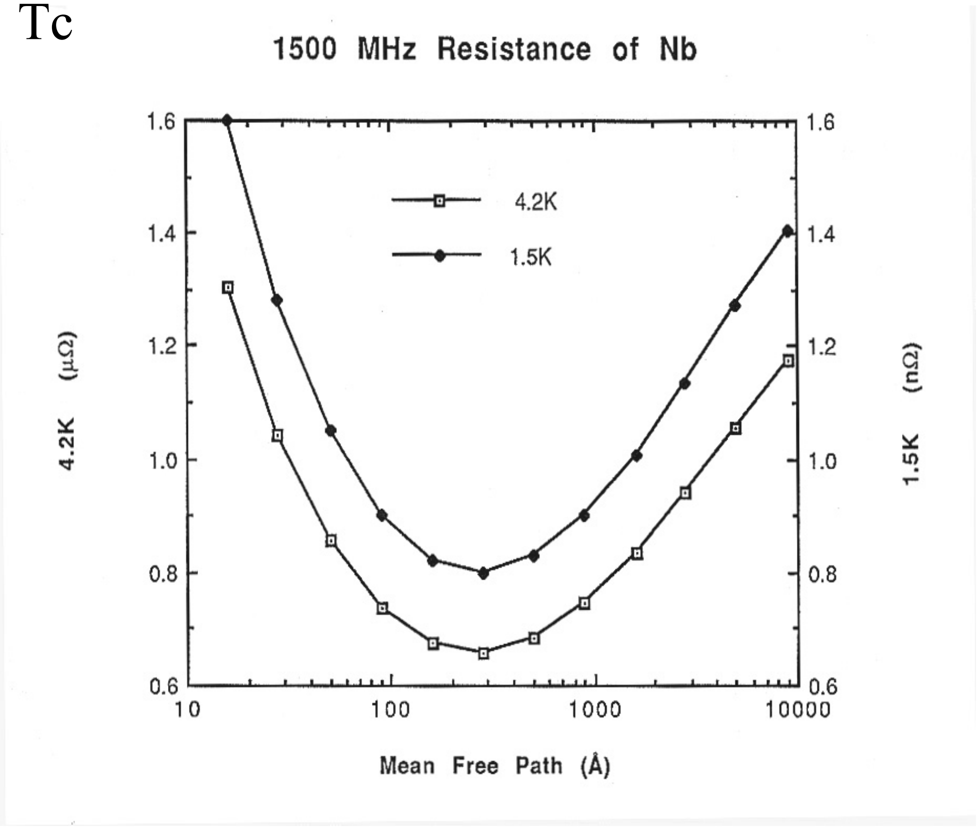
$$R_s = A_s \omega^2 \exp\left(-\frac{\Delta(0)}{k_B T}\right)$$

More resistance the more NC electrons are excited

More resistance the more the sc pairs are jiggled around

Frequency, Temperature and electron mfp Dependence of Rs

$R_s = A(\lambda_L, \xi_0, l)\; f^2\; e^{(-\Delta_0/kT)}$ for T < 0.5 Tc



λ_L London penetration depth

ξ_0 Coherence length of Cooper pairs

v_F Fermi velocity

Δ_0 Energy gap

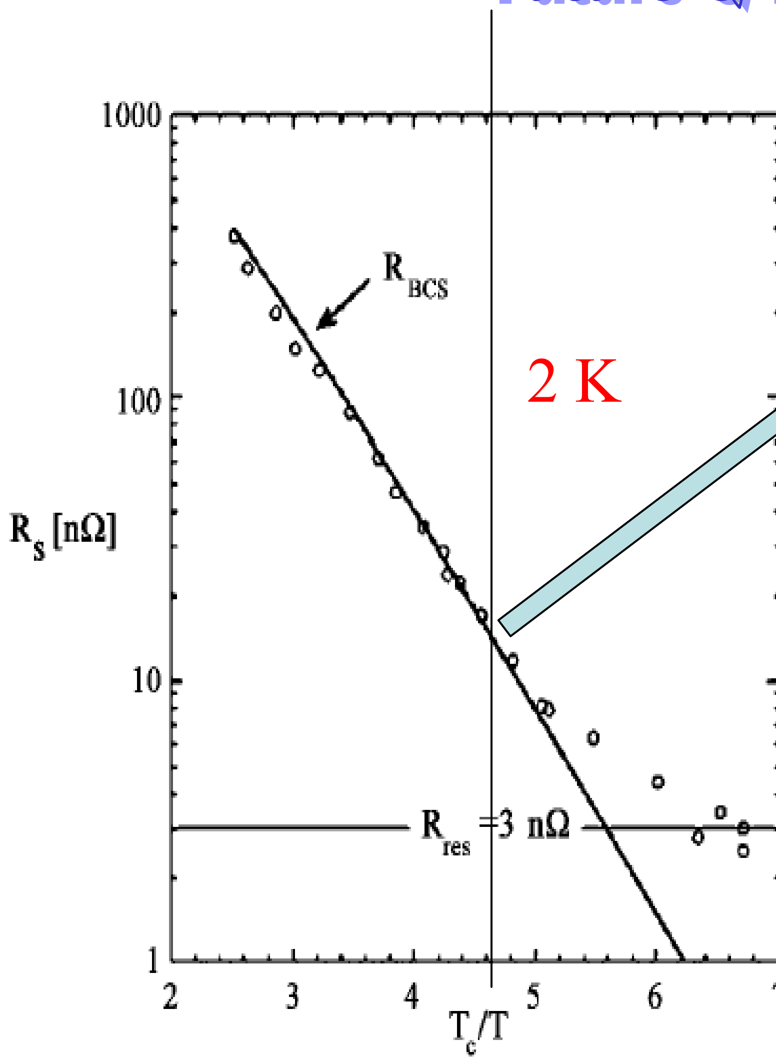
l electron mean free path

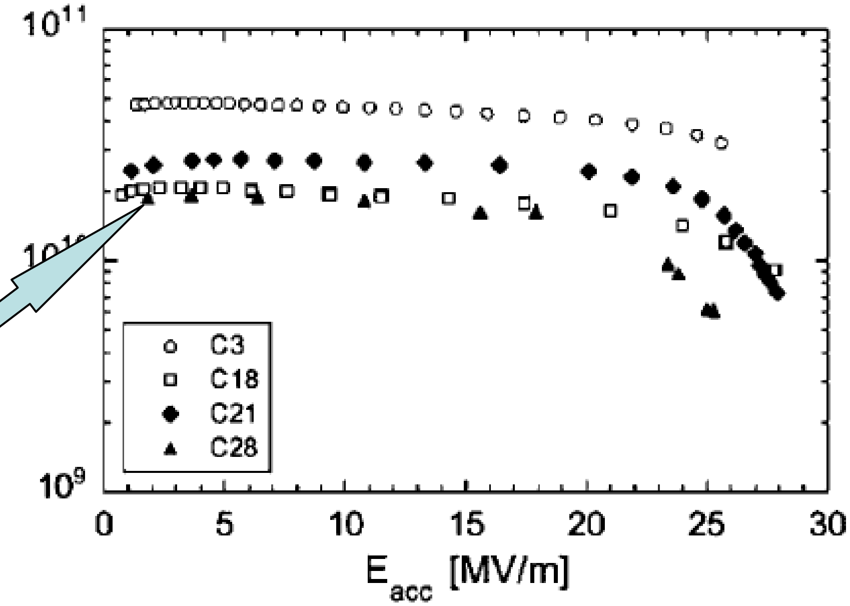
Tc = SC transition temperature

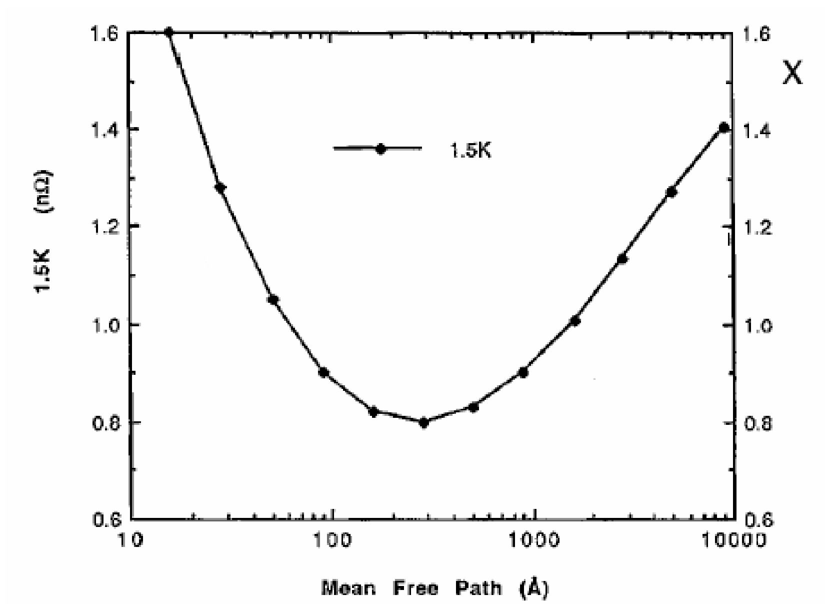
$$R_{bcs} = 3x\; 10^{-4} \left[\frac{f\,(GHz)}{1.5}\right]^2 \left(\frac{1}{T}\right) e^{-(17.67/T)}$$

Above 2 GHz, the f^2 x exponential temperature dependence causes global thermal instability to keep Eacc < 30 MV/m

Future Q Improvements ?







BCS Contribution still important
At 1300 MHz and 2 K

T = 2 K, Rs = 14 nΩ, Q = 2.6 $x10^{10}$

TESLA Q = 10^{10}

Lower mean free path, Q = 3 - 4 $x10^{10}$

Or Lower Temperature

T = 1.8 K, Q = 6.3 $x10^{10}$

T = 1.7 K, Q = 1.1 $x10^{11}$

T= 1.6 K , Q = 1.9 $x10^{11}$

Shield Earth's magnetic field to $<$ 1 mOersted

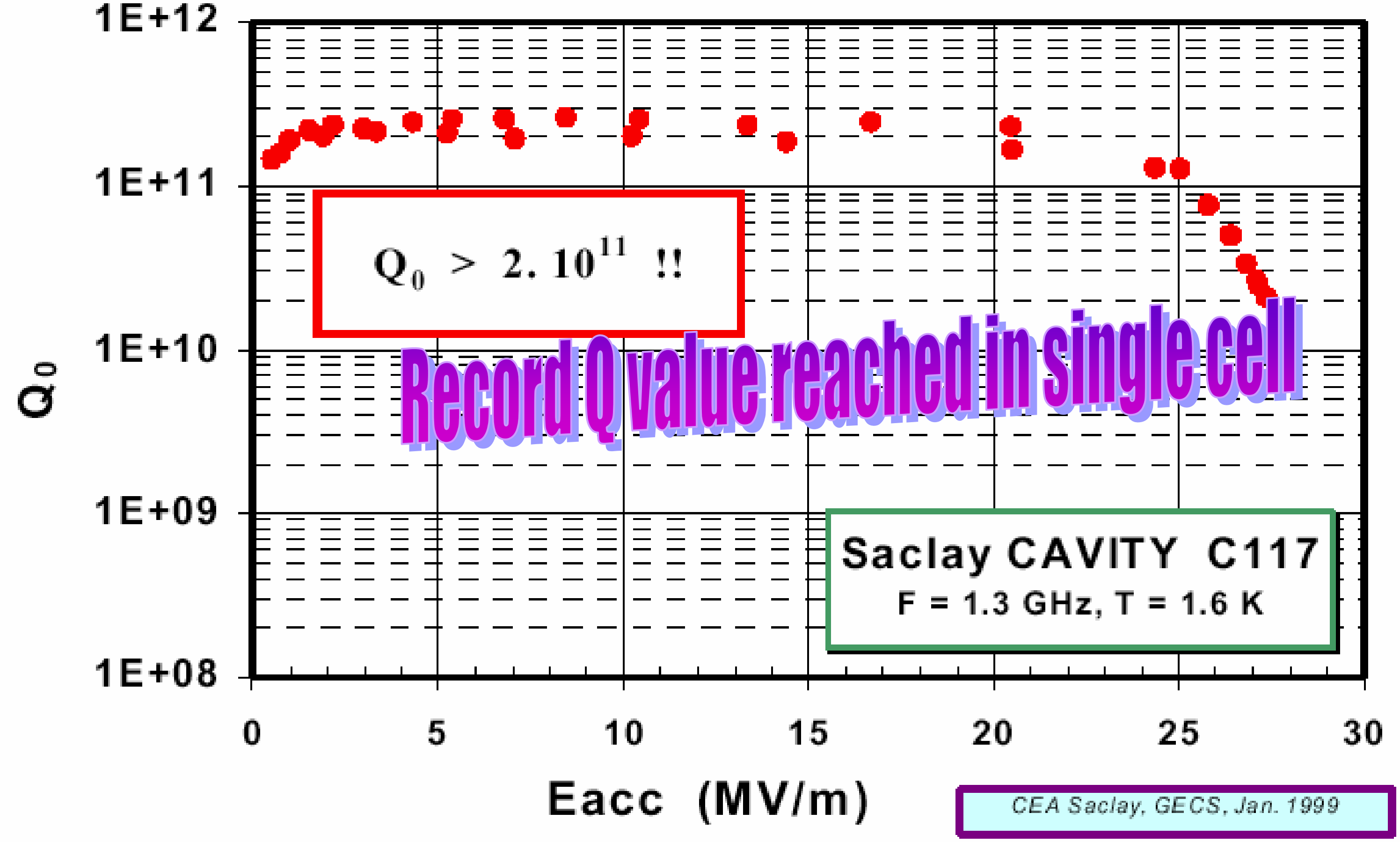
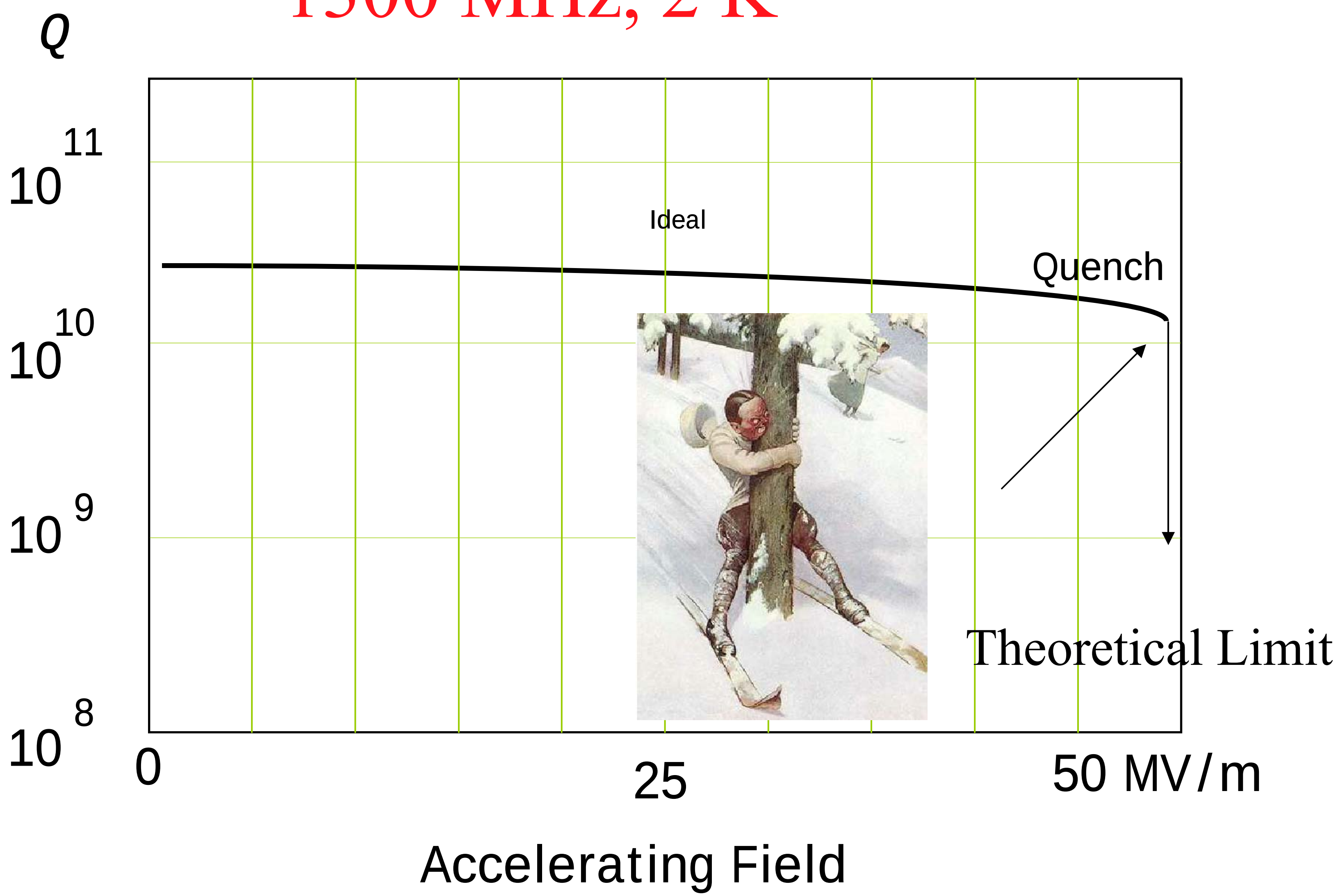
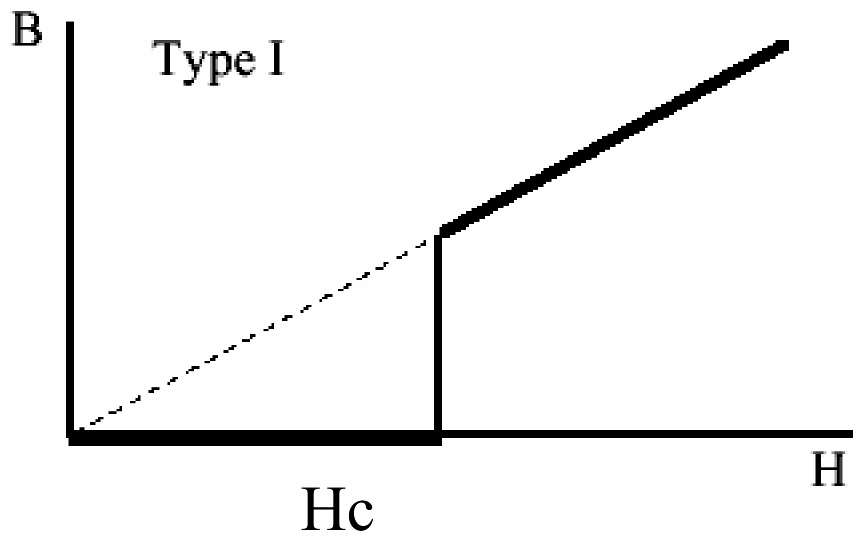


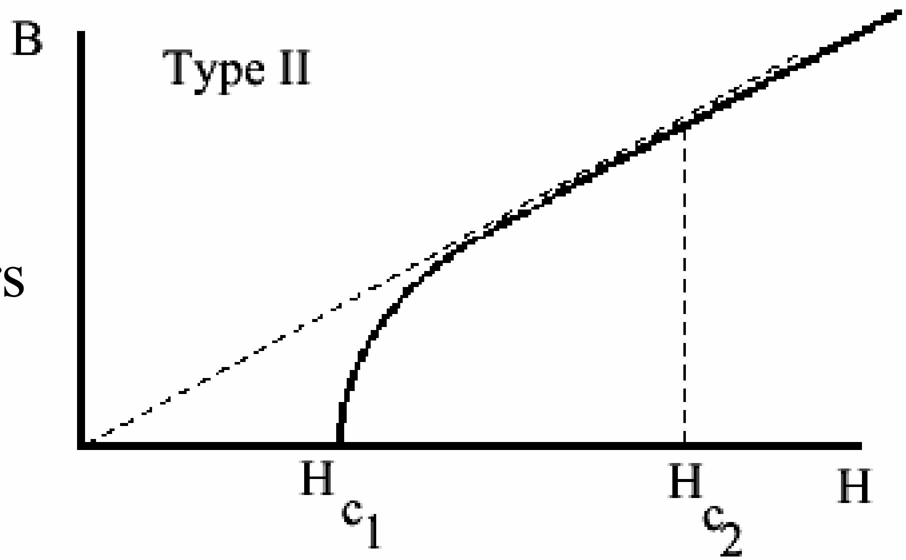
Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q_0 exceeding 2.10^{11}.

Ideal SC Cavity Behavior
1300 MHz, 2 K



DC
Critical
Magnetic
fields





Dirty Superconductors

The larger Hc2/Hc1
More type II

RF Critical Magnetic Field

- Phase transition, flux nucleation requires some time
  - (1 μs?)
- → So $H_{rf} > H_{c1}$
- even $H_{rf} > H_c$ up to the superheating field.

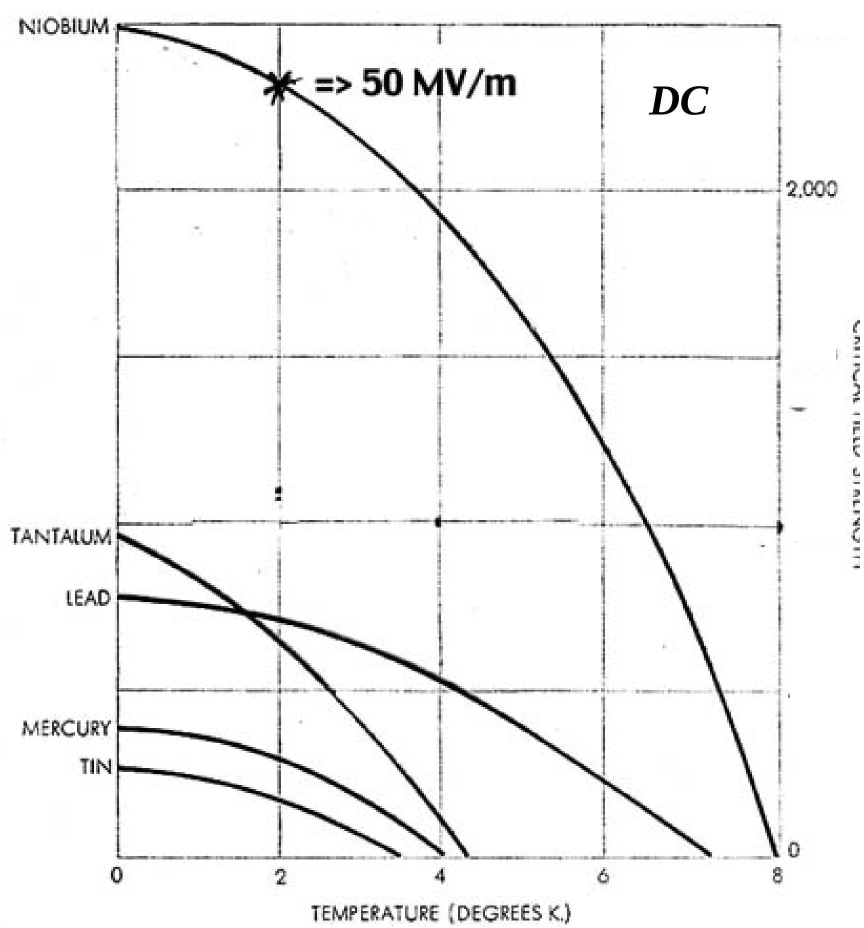
- At T= 0 K
  - Critical RF field, Hsh, for Nb is about 2400 Oe (240 mT).

- For typical $v = c$ cavities this is achieved at an accelerating field of $E_{acc} \approx 50$ MV/m.

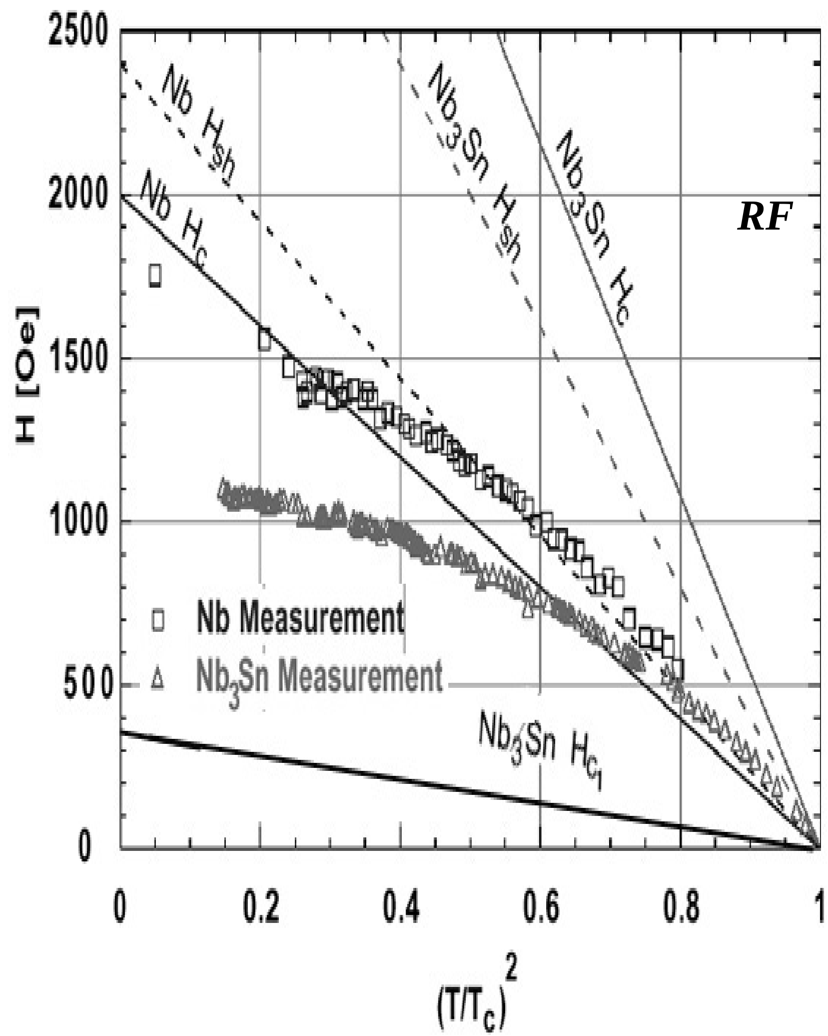
New considerations suggest H_{sh} is about 1800 Oe (Saito's talk)

DC/RF Critical Field for Superconductors

Superconductors only remain in the superconducting state if the applied field is less than the critical magnetic field H_c (2000 Oe for Nb)



→ For RF can exceed H_c up to the superheating field.



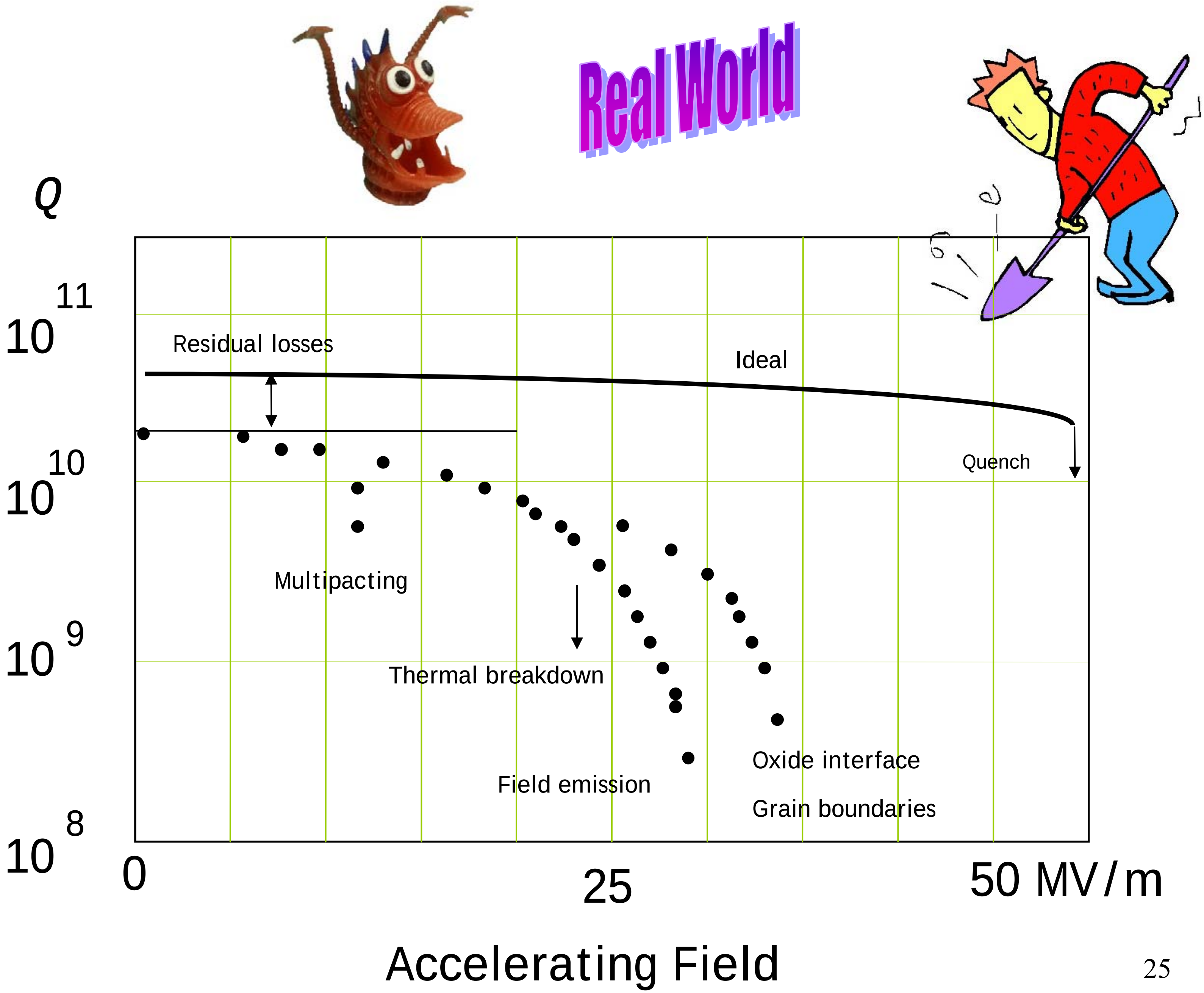
Theoretical RF Electric Field

- No known theoretical limit
- In SC test cavities, SC survives up to
  - Epk = Pulsed 220 MV/m
  - 145 MV/m CW over cm^2 area
- Single cell 1300 MHz accelerator cavity to Epk = 95 MV/m, CW (Rongli's Talk)

The Real World

–

Departure from Theory

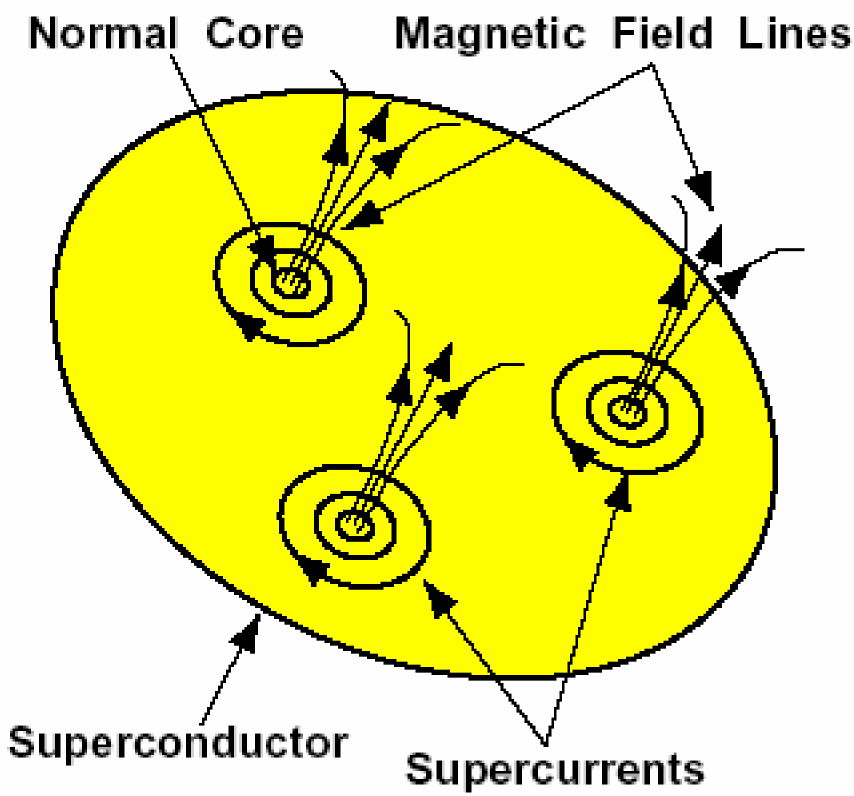

Real World
Q
10^{11}
10^{10}
10^{9}
10^{8}
Residual losses
Ideal
Quench
Multipacting
Thermal breakdown
Field emission
Oxide interface
Grain boundaries
0
25
50 MV/m
Accelerating Field

Residual Resistance

Known Causes of Residual Resistance

- Insufficient cleaning: chemical residue
- Joint losses at flanges, if attenuation insufficient
- Trapped DC magnetic flux due to insufficient shielding of earth's field
- Nb-Hydride island formation if bulk H content is too high (> 2 wt ppm)

Residual Resistance Due to DC Flux Trapping

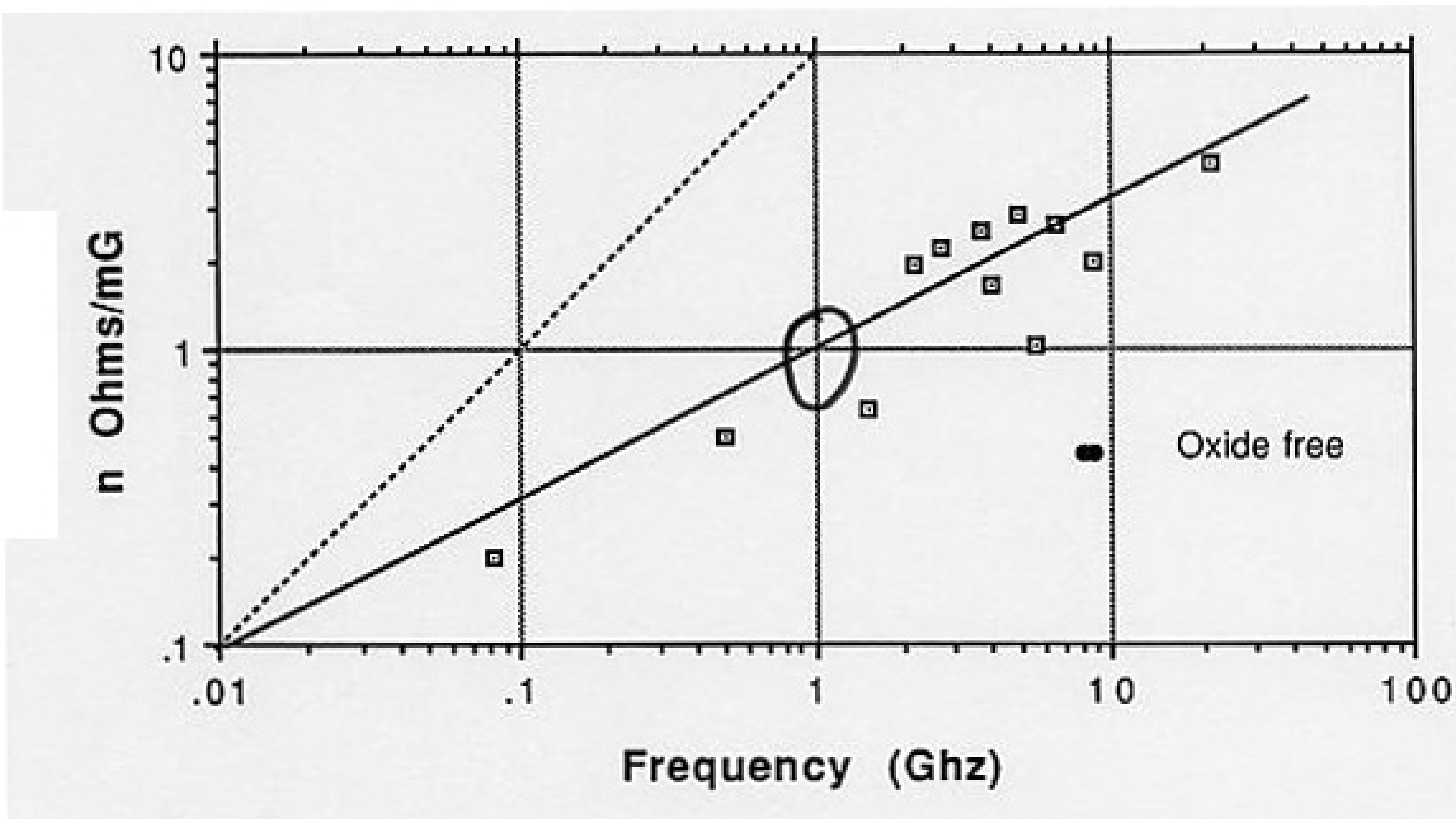


$$R_{\mathrm{mag}} = N\frac{\pi\xi_0{}^2}{A}R_{\mathrm{n}}$$

$$AH_{\mathrm{ext}} = N\Phi_0,$$

$$R_{\mathrm{mag}} = \frac{H_{\mathrm{ext}}}{2H_{\mathrm{c2}}}R_{\mathrm{n}}.$$

RF Residual Resistance Due to Trapped Flux



Thermocurrents Cause Trapped Flux

102 *May 23, 1997 – 12:51*

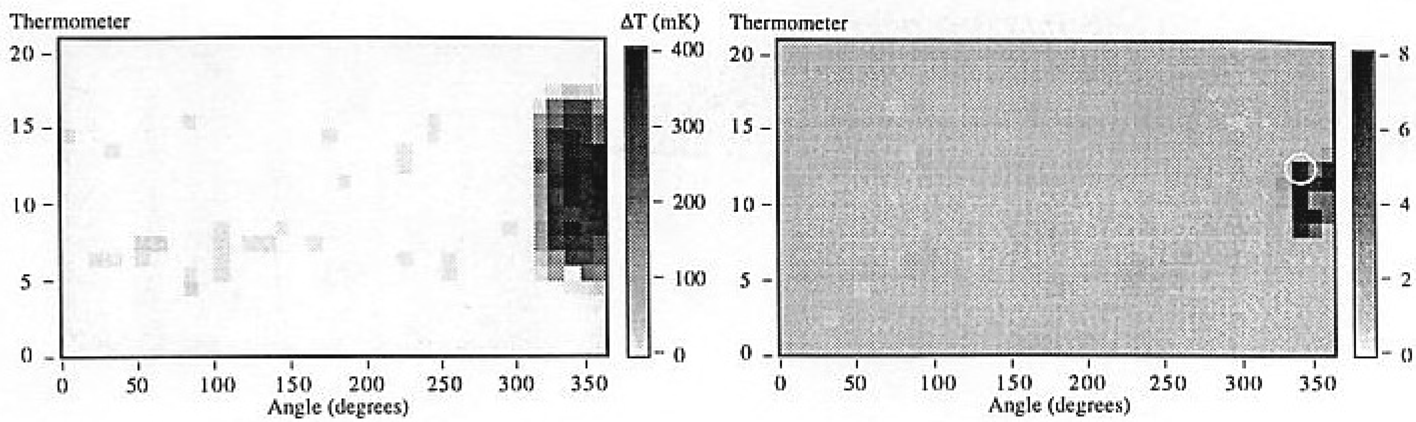
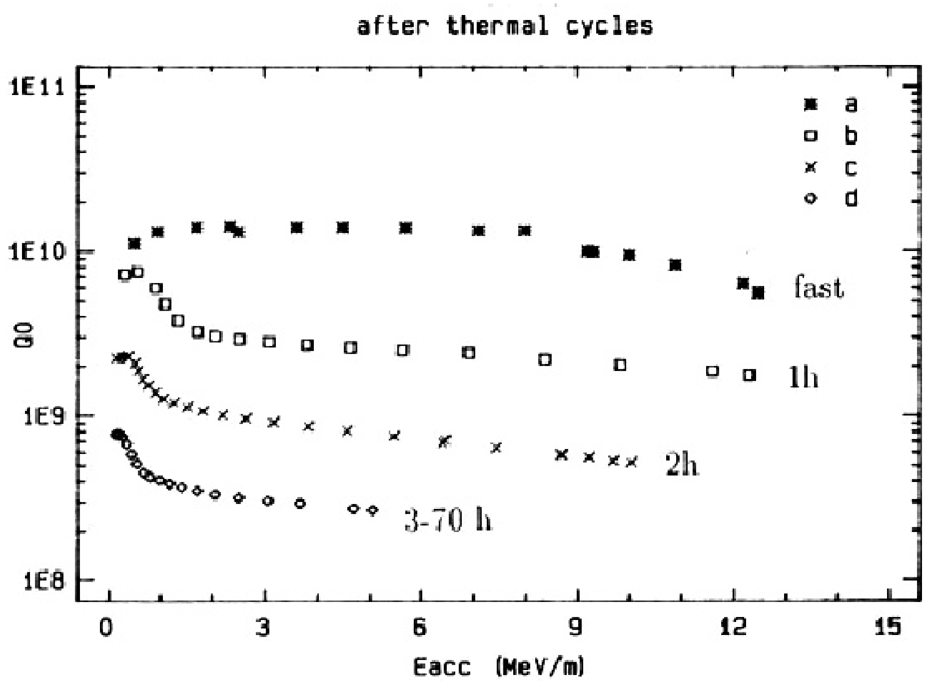
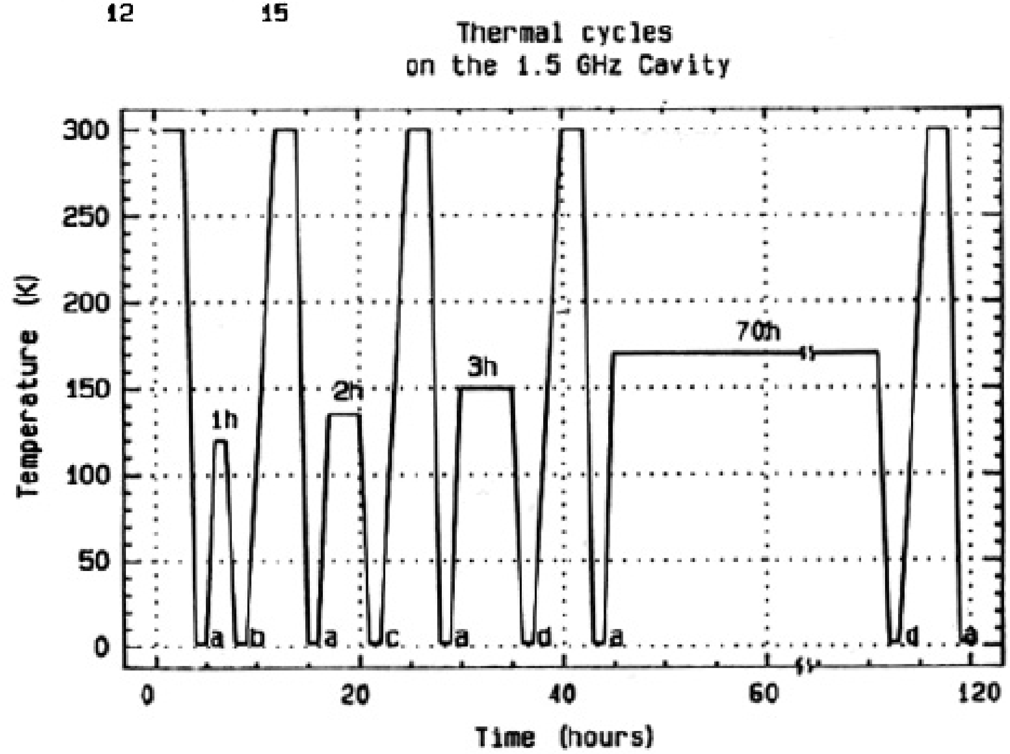


Figure 5.30: (a) Defect initiated thermal breakdown in progress in LE1-32. Even a 20 μm etch was unable to remove the defect. (b) Ratio of the surface resistance in LE1-32 after several breakdown events to that before breakdown. Dark regions indicate that the surface resistance increased.



Residual Resistance due to excess H in the bulk

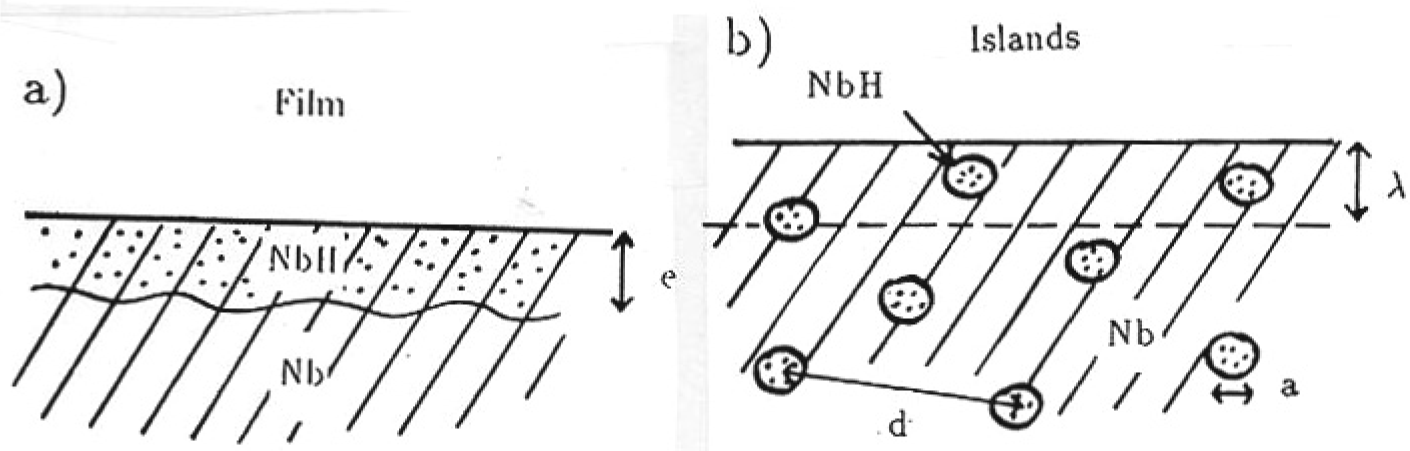


Mechanism and Explanation of Symptons

At room temperature H moves freely,
there is some evidence of surface enrichment

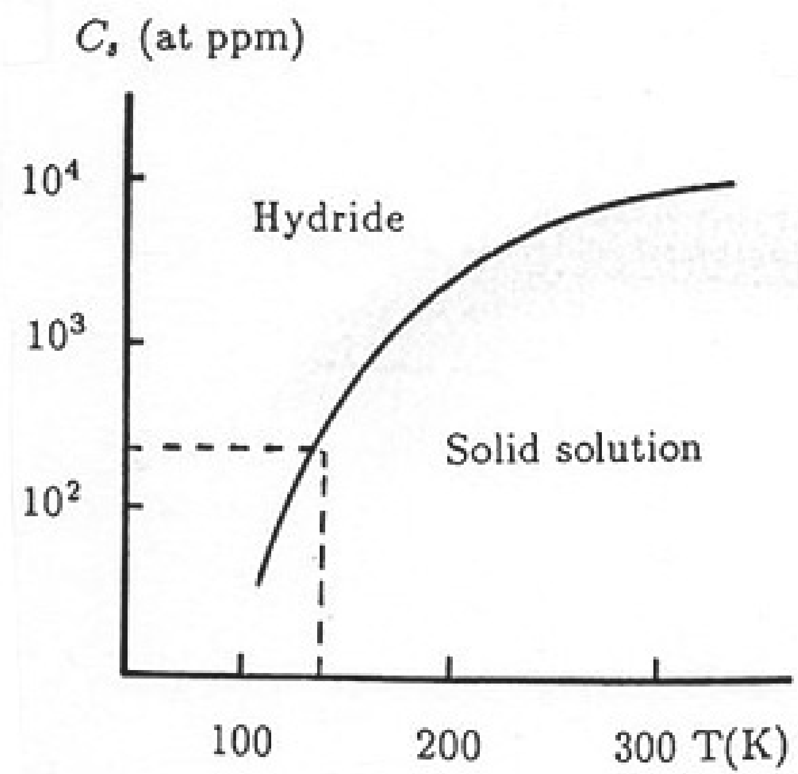
When a cavity is cooled the dissolved hydrogen precipitates as a hydride phase that has high rf loss
Tc of hydride = 2.8 K, Hc = 60 Oersted

This explains shape of Q vs E curves of Q-disease cavities



At room temperature the required conc. to form hydride phases is very high, e.g 4600, 7400 wt ppm

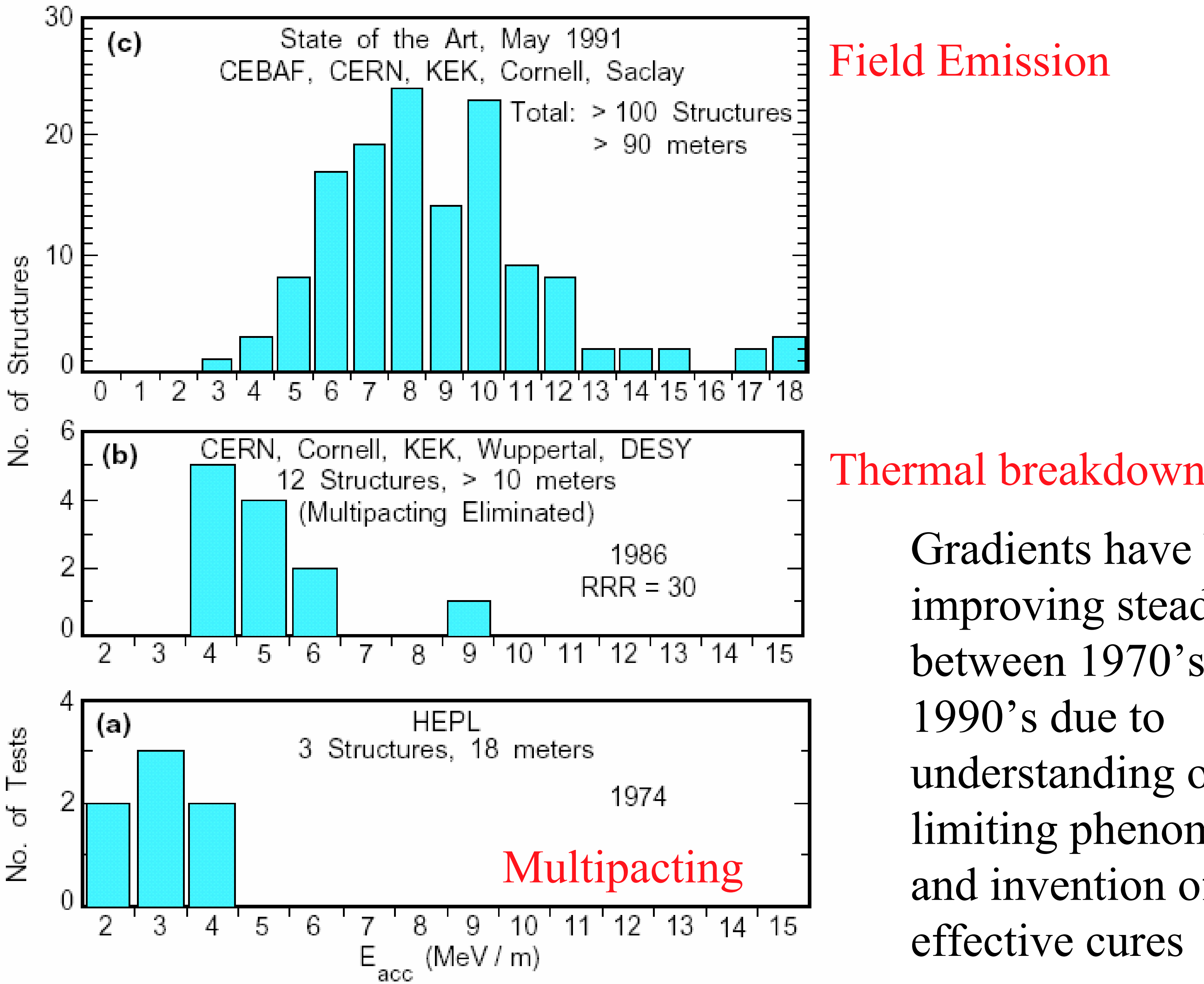
Below 150 K
the required concentration drops to < 10 wt ppm.



Gradient Limiting Mechanisms

Gradient Limiting Mechanisms

- Multipacting
- Thermal Breakdown
- Field Emission
- Medium and High Field Q-slopes
- Global Thermal Instablility (high frequency)

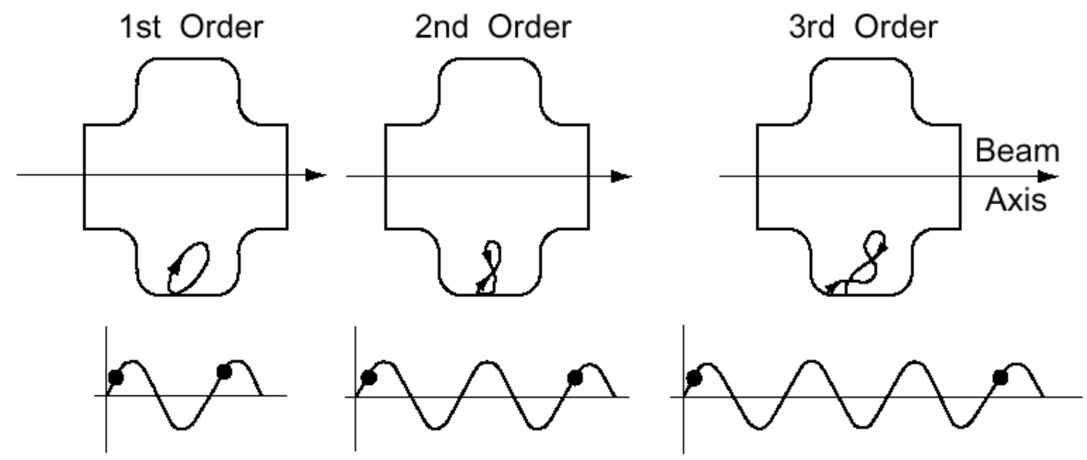


Gradients have been improving steadily between 1970’s to 1990’s due to understanding of limiting phenomena and invention of effective cures

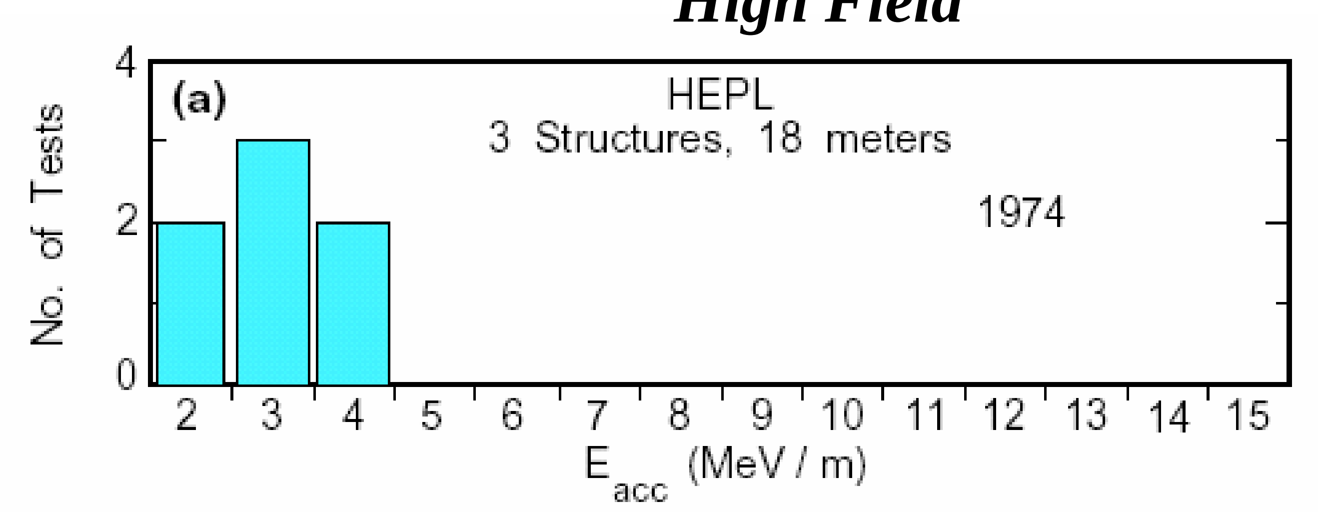
Multipacting

Multipacting

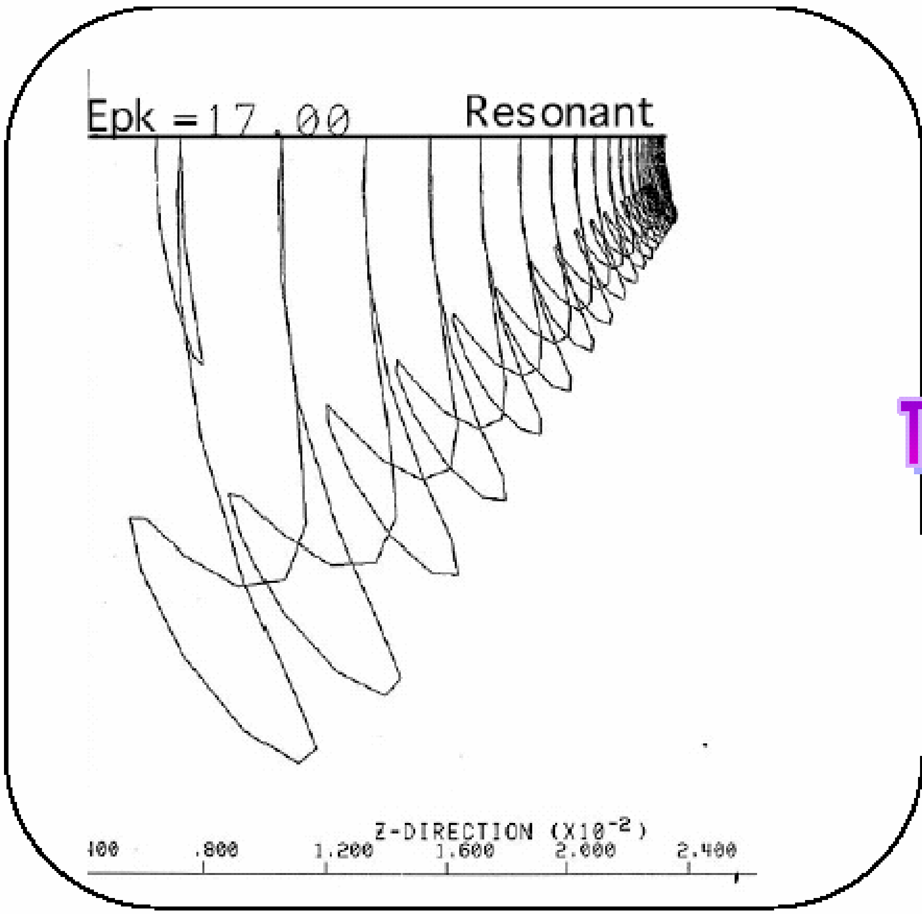
- MP is due to an exponential increase of electrons under certain resonance conditions

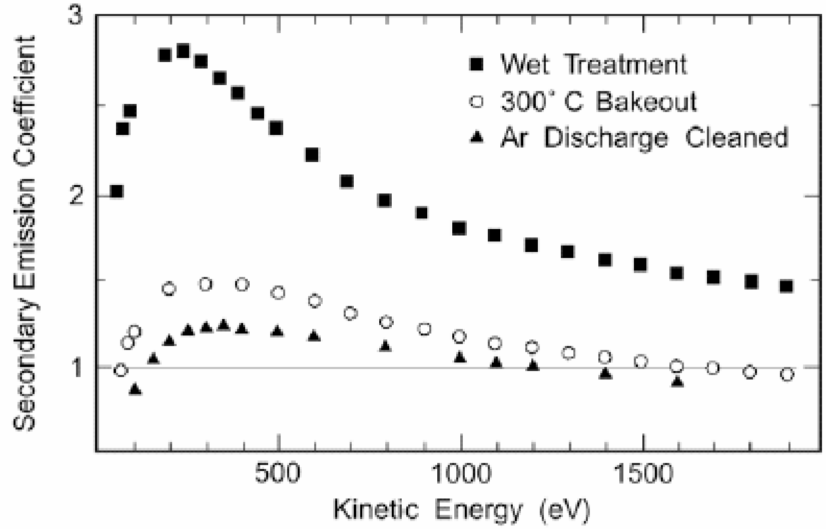


High Field ***Low Field***

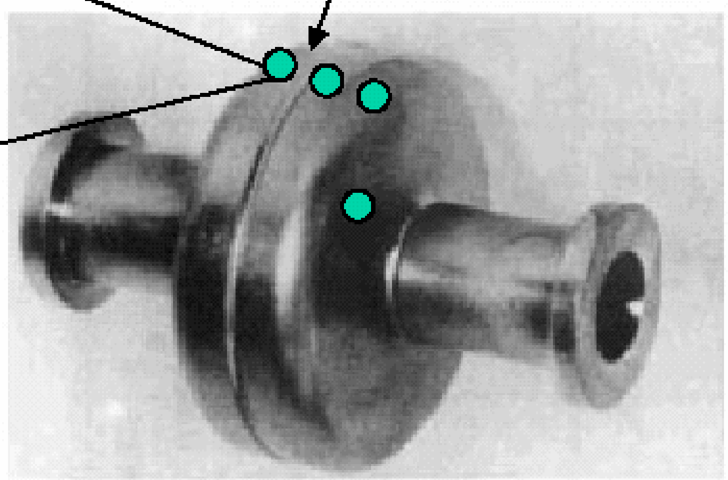


Simulated Electron Trajectories

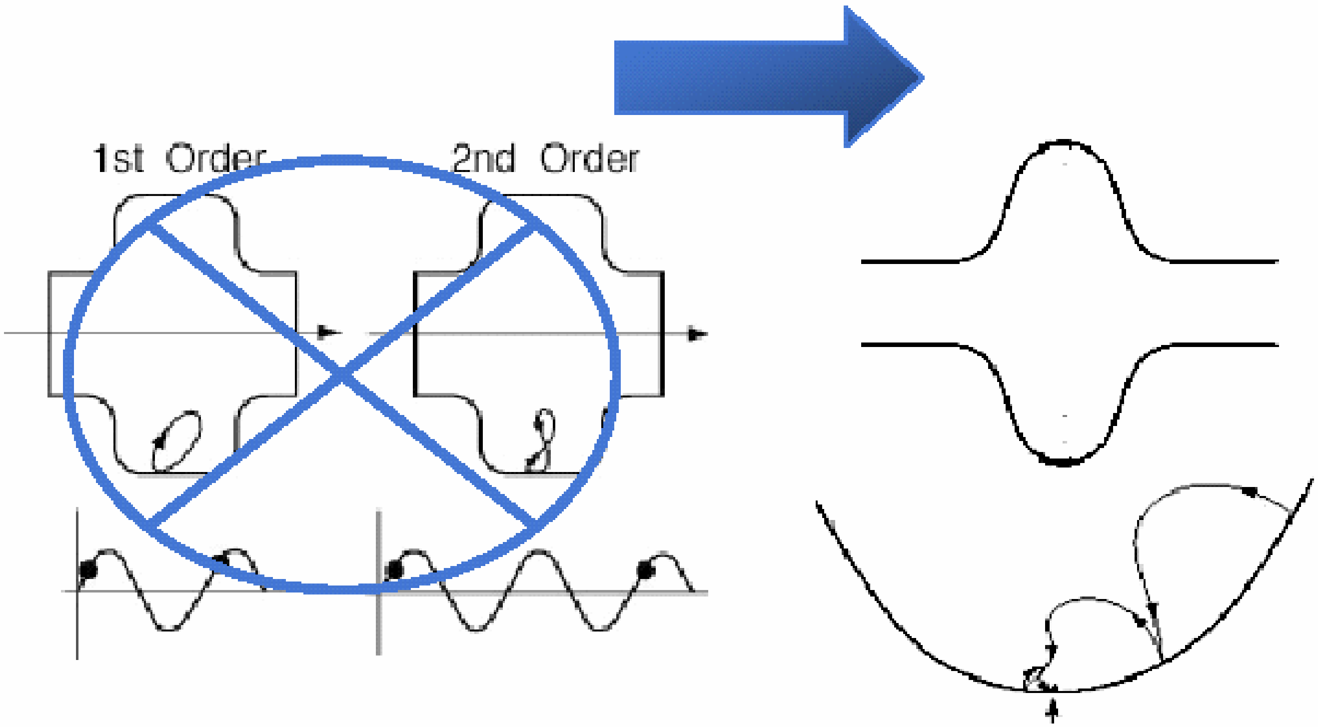




These thermometers show heating



Solution to Multipacting



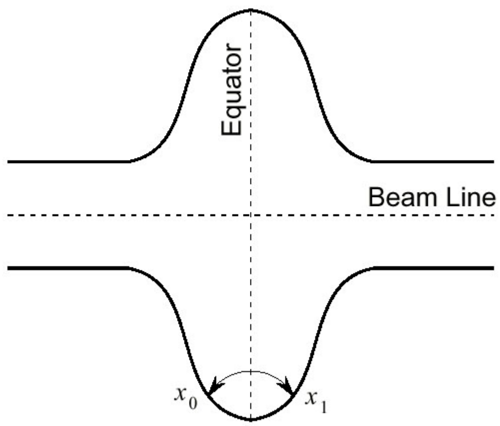
Electrons drift to equator

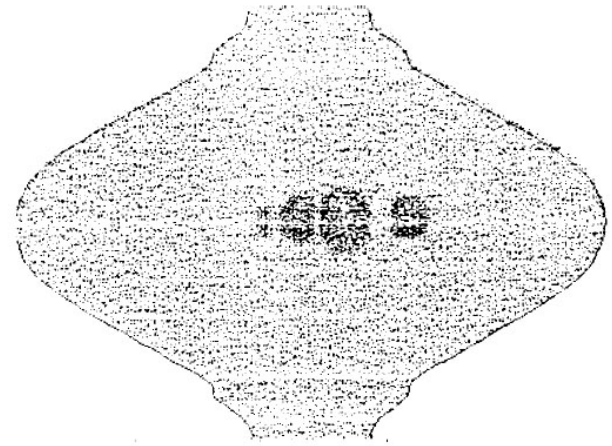
Electric field at equator is ≈ 0

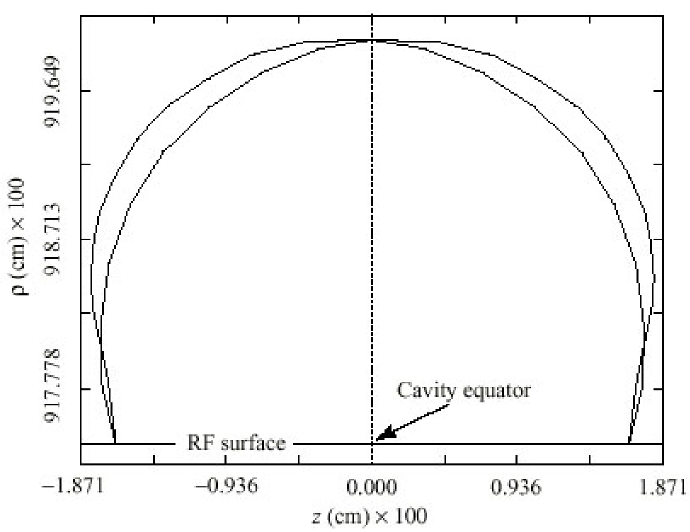
→MP electrons don't gain energy

→MP stops

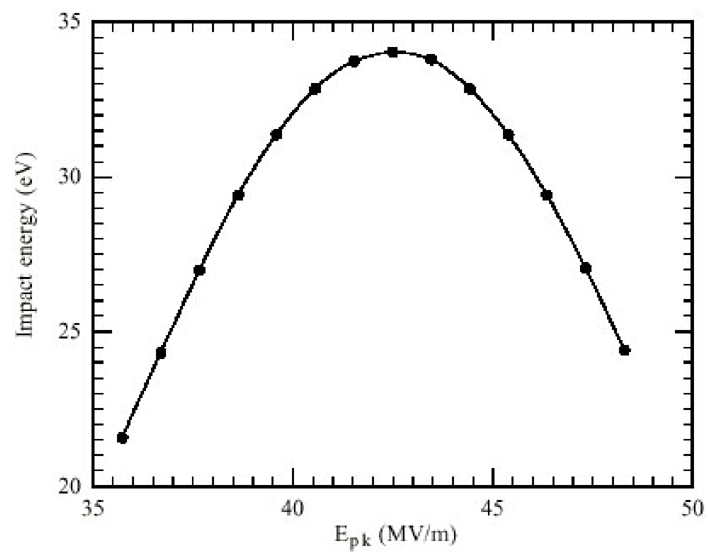
Two Point Multipacting Remains







(a)



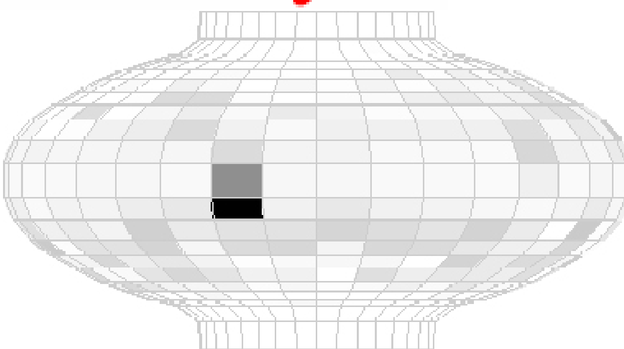
(b)

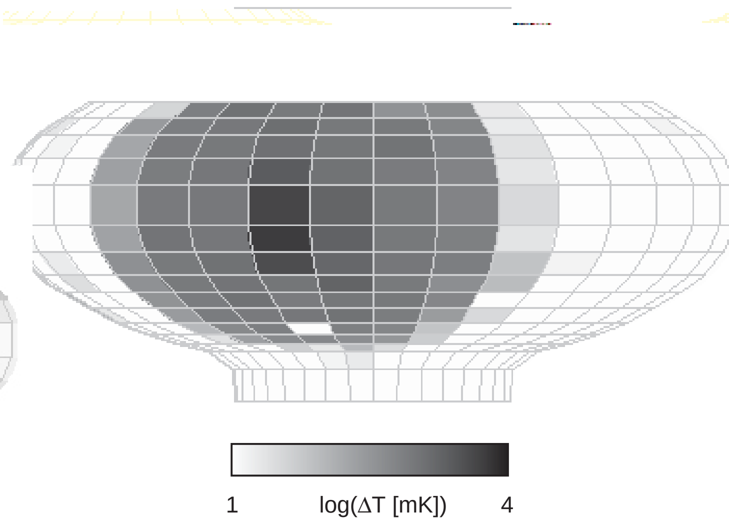
Low impact energy -> easily processed

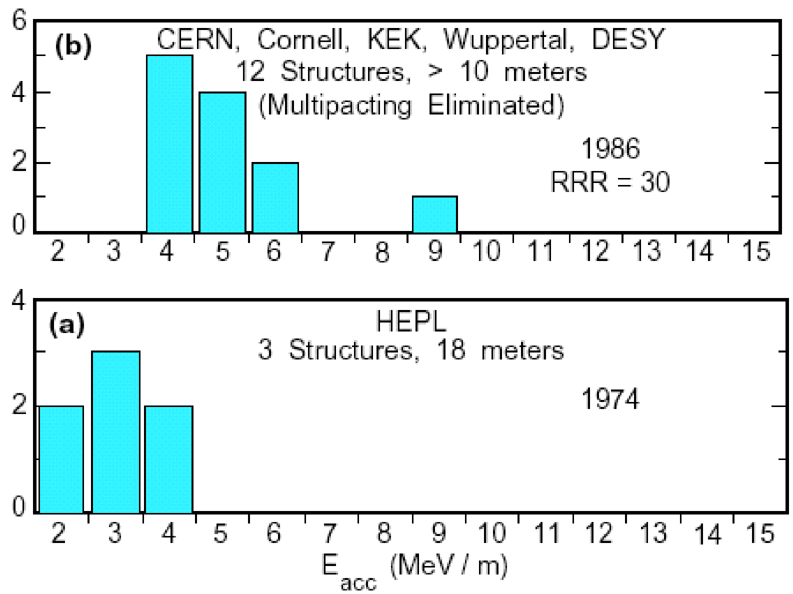
Thermal Breakdown

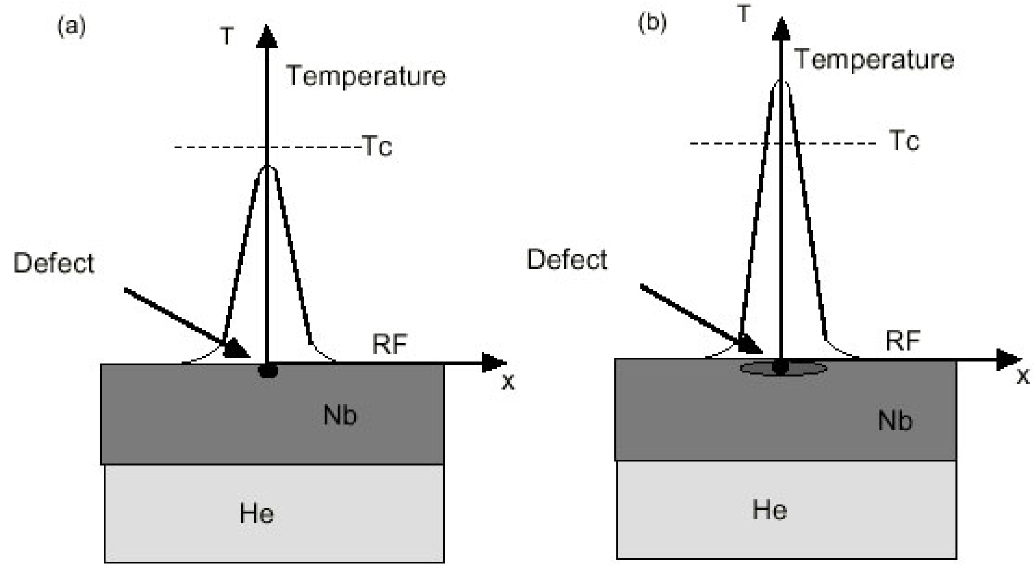
Sub-mm Size Defects Lead to Quench of Superconductivity

Thermal Breakdown

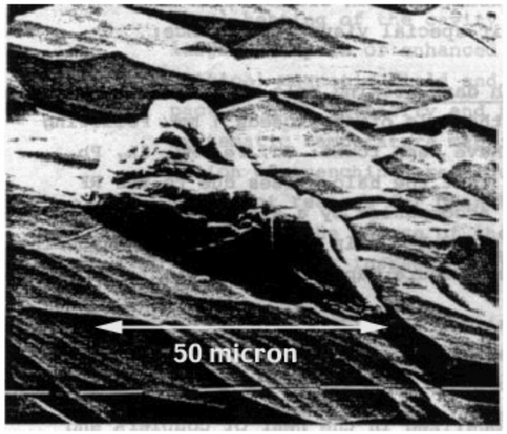


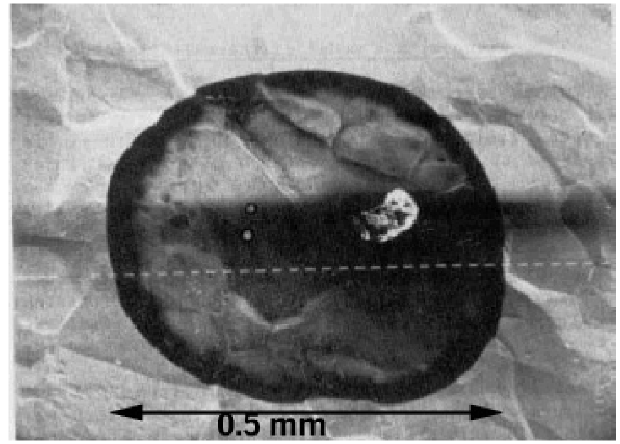


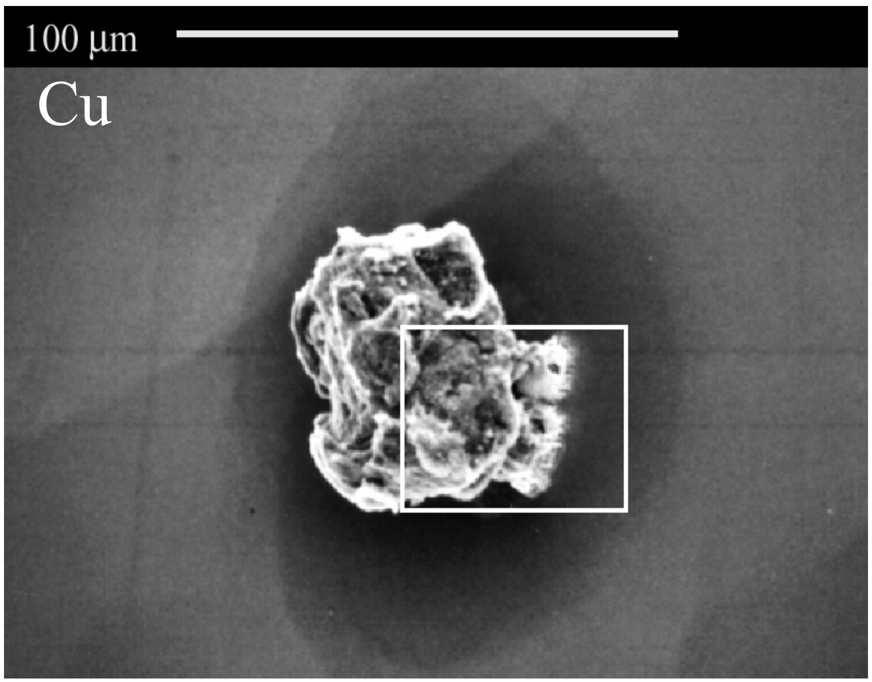


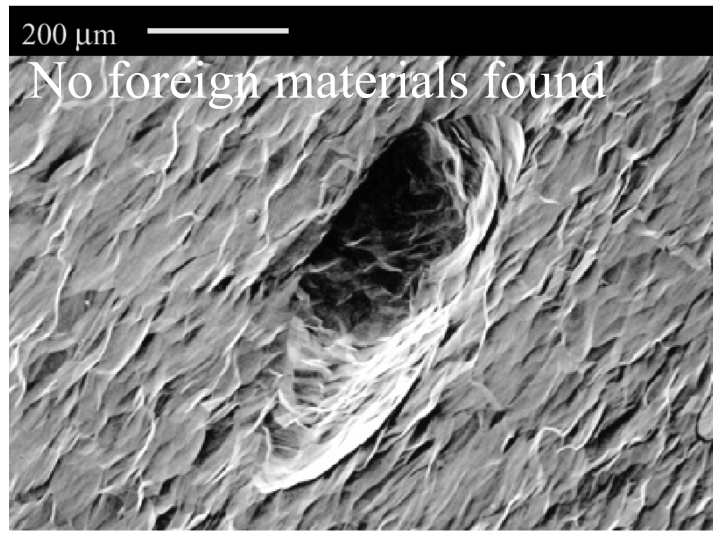


Typical Defects





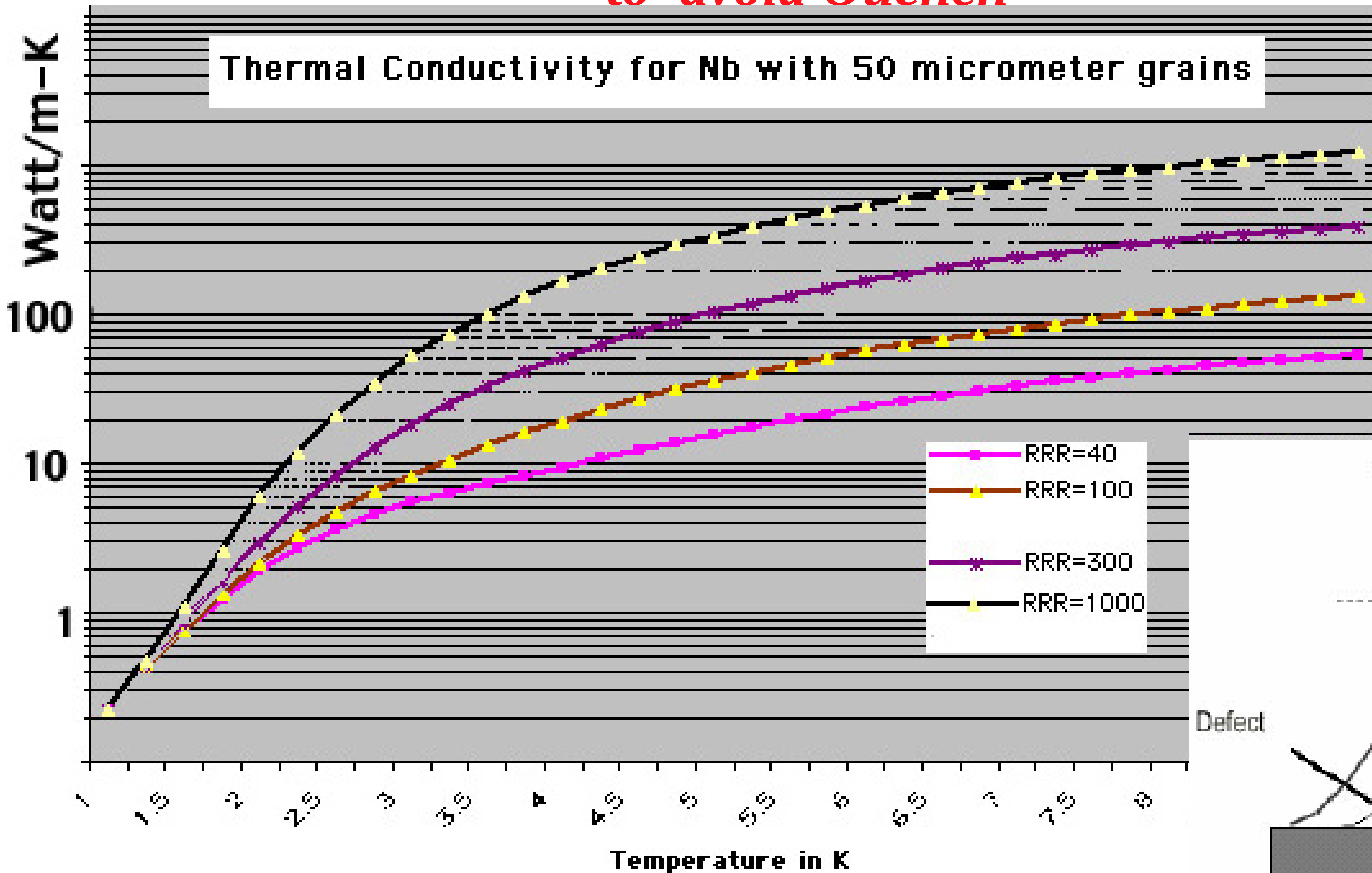


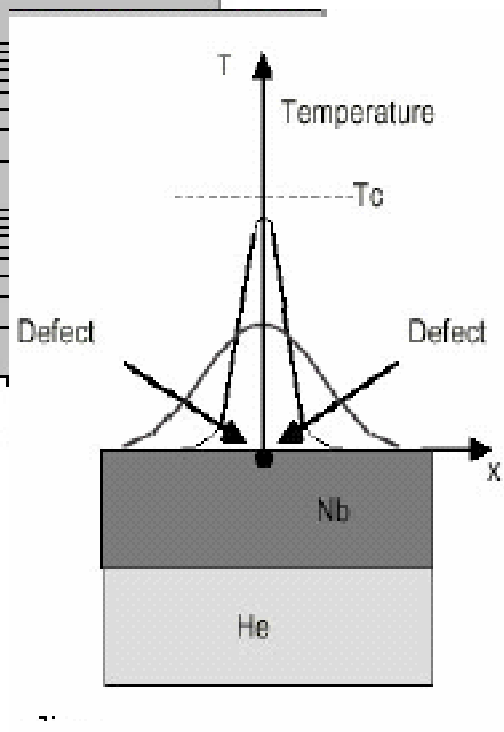


Surface defects, holes can also cause TB

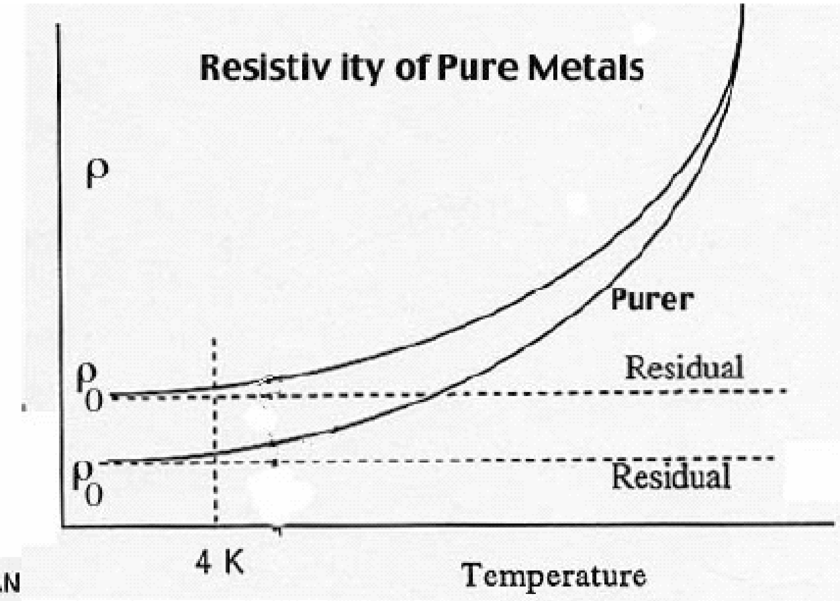
0.1 – 1 mm size defects cause TB

Improve Bulk Thermal Conductivity (and RRR) by raising purity to avoid Quench

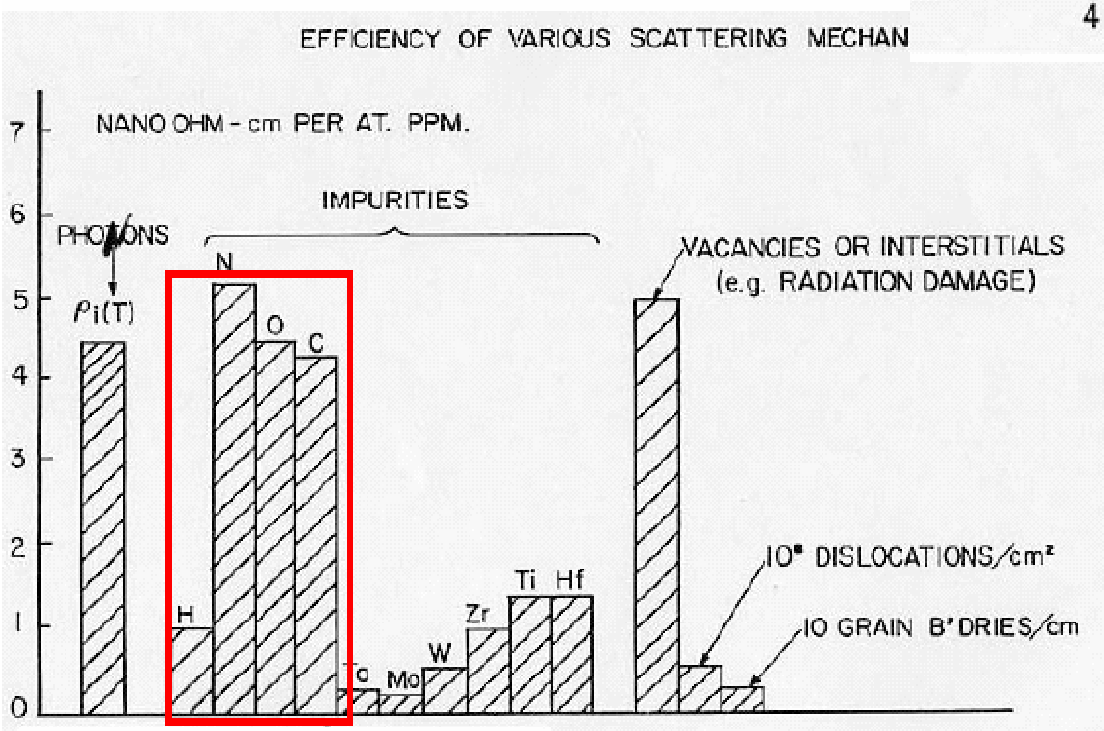




Meaning of RRR



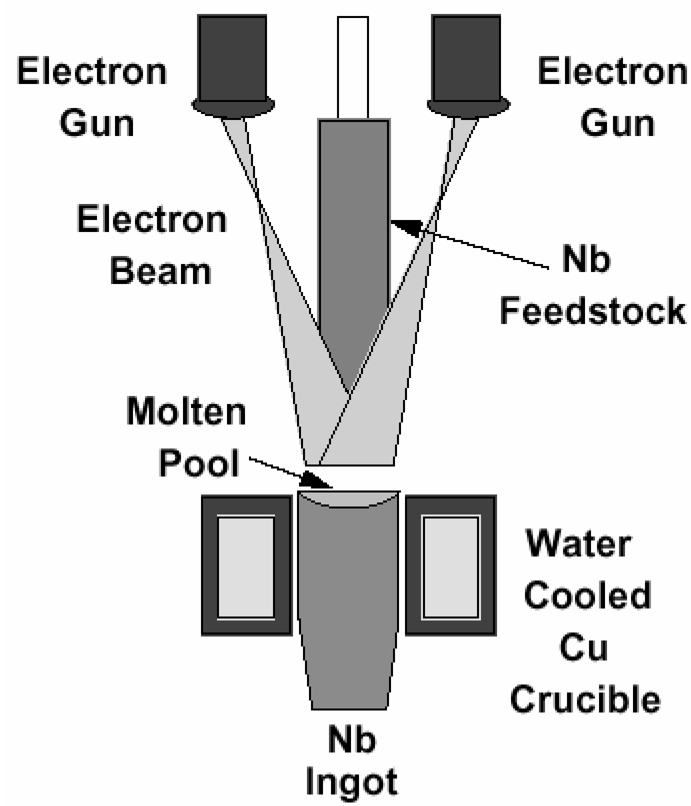
Impurities scatter electrons



Niobium Purification

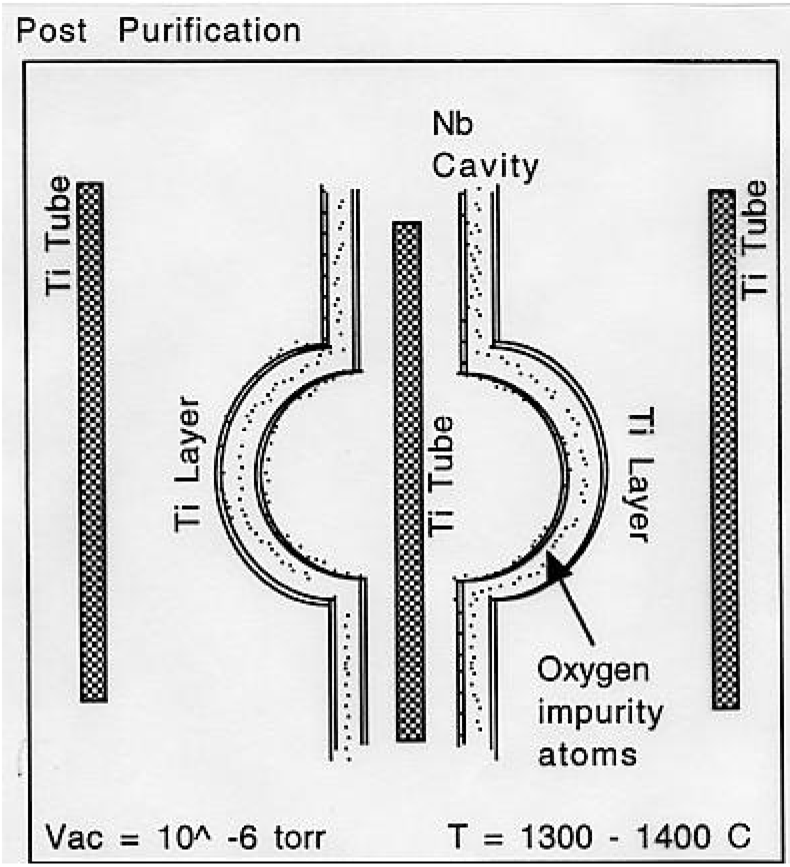
- Can produce high Nb purity by e-beam melting in a vacuum furnace

- Currently industry produces RRR 300-400 Nb.
- Reactor grade Nb is RRR = 40
- Theoretical limit is RRR = 32,000.



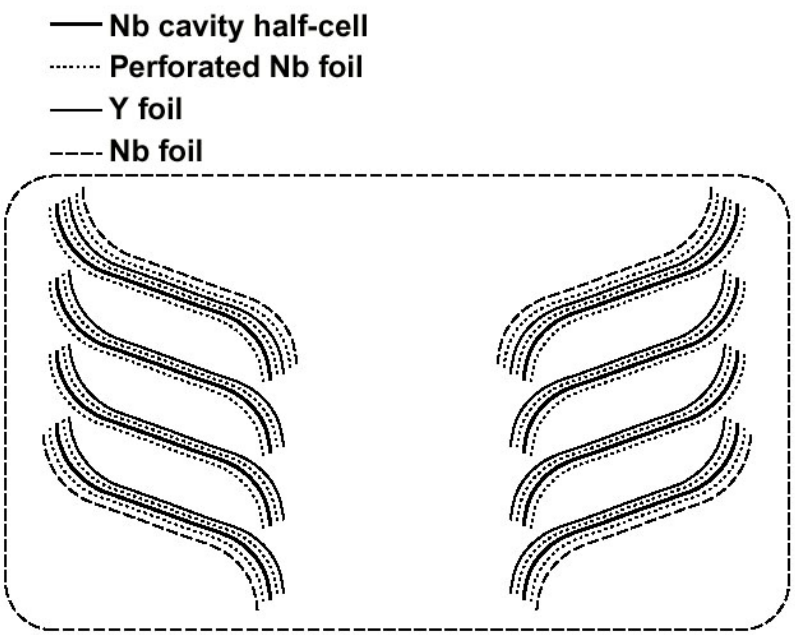
RRR: Residual resistance ratio = resistivity at room temperature divided by the resistivity at 4.2 K (in the normal conducting state!). κ_T scales ≈ linearly with RRR.

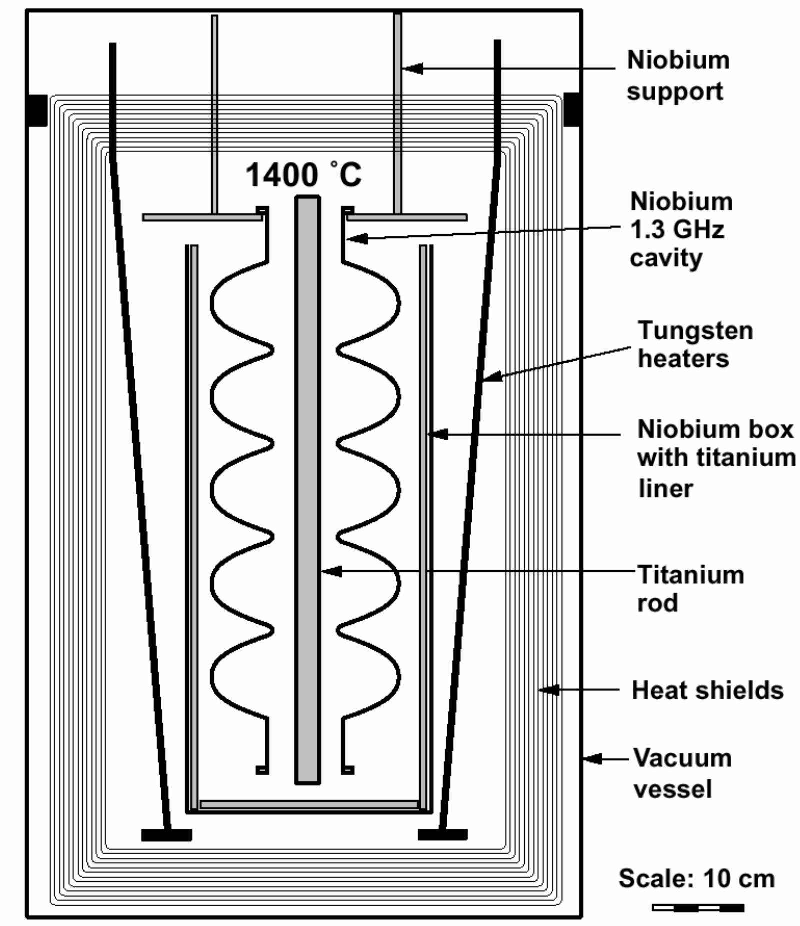
Post Purifying Niobium



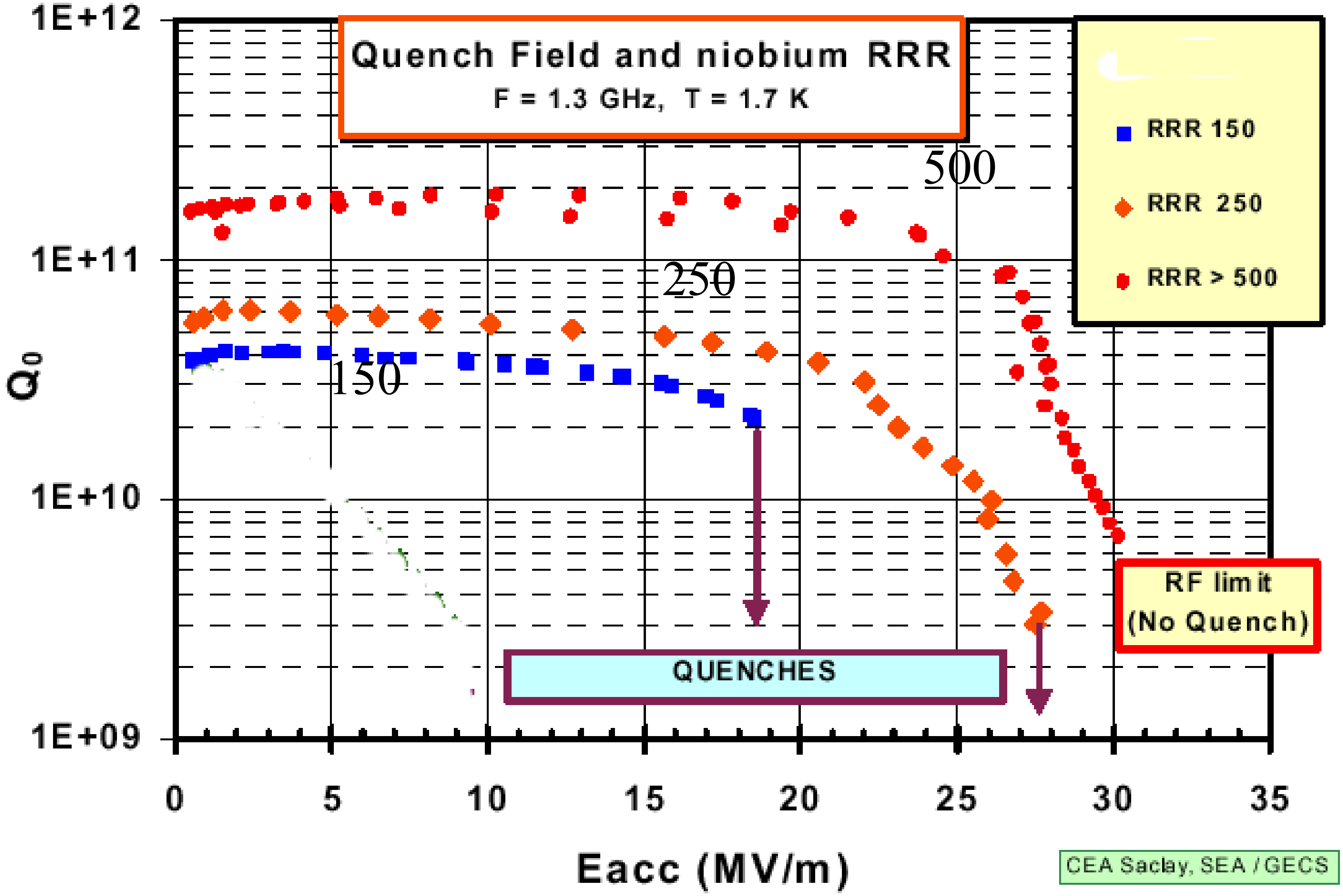
- After cavity or half-cell is produced
  - Heat in vacuum furnace to ~ 1400 C
  - Evaporate Ti on cavity surface
  - Use titanium as getter to capture impurities
  - Later etch away the titanium
  - Doubles the purity (RRR ~ 600 if originally RRR = 300)

Post Purifying Niobium Half Cells and Complete Cavity Successful



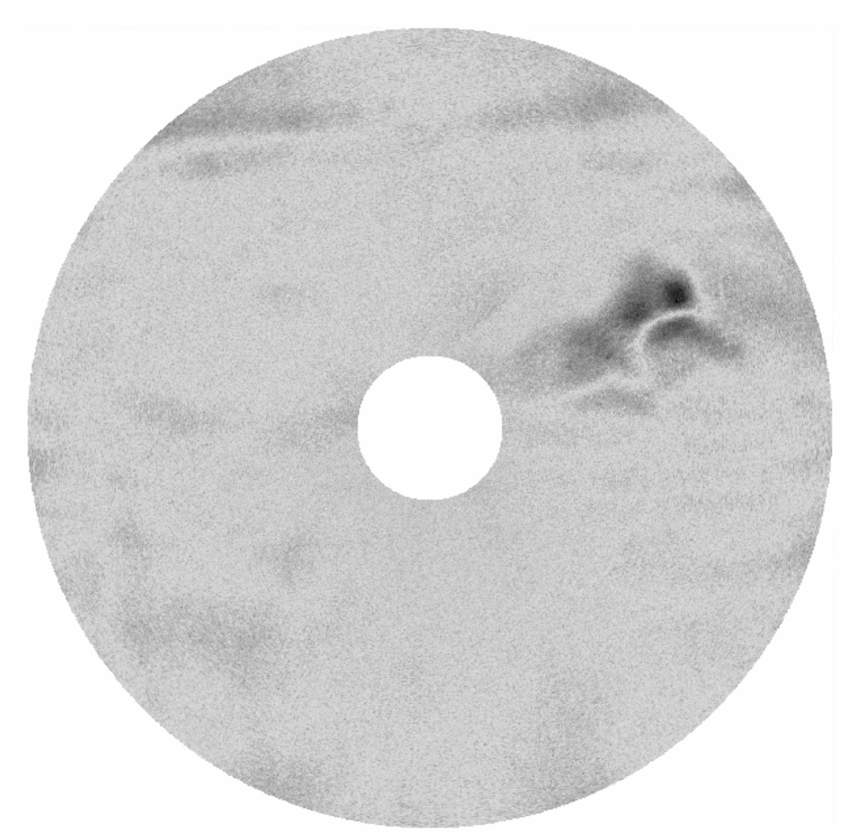


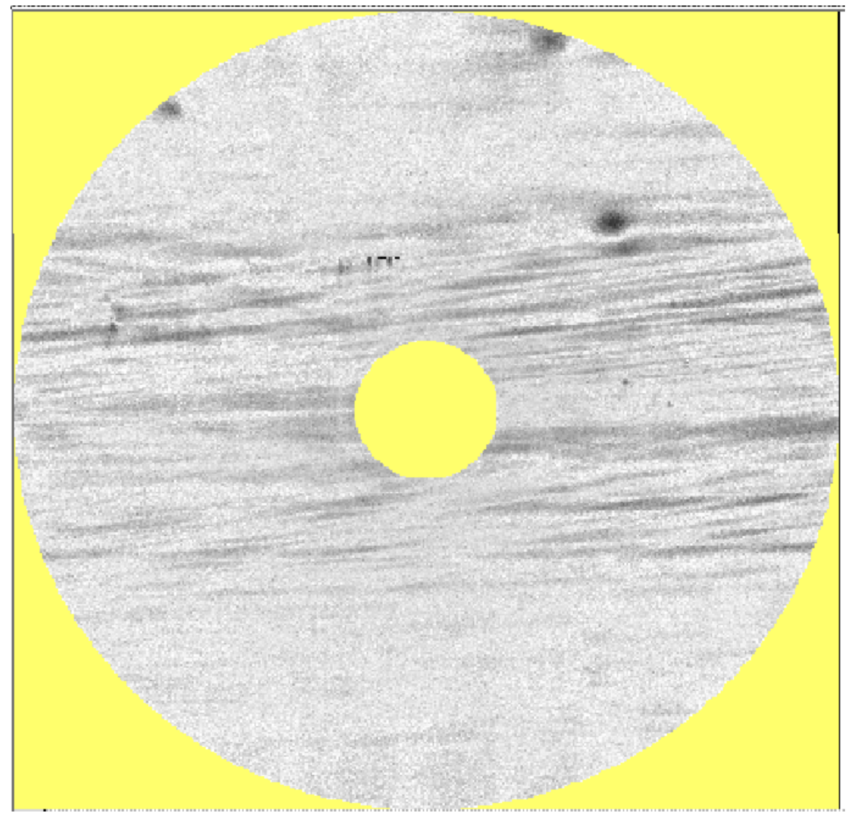
Same Single Cell Cavity, Repeated Post Purification



Avoid Defects in Starting Sheet Material
Eddy Currents to Check the Niobium

Large inclusions as well as bad spots on the niobium surface can be found, also non harmful signatures such as rolling lines.

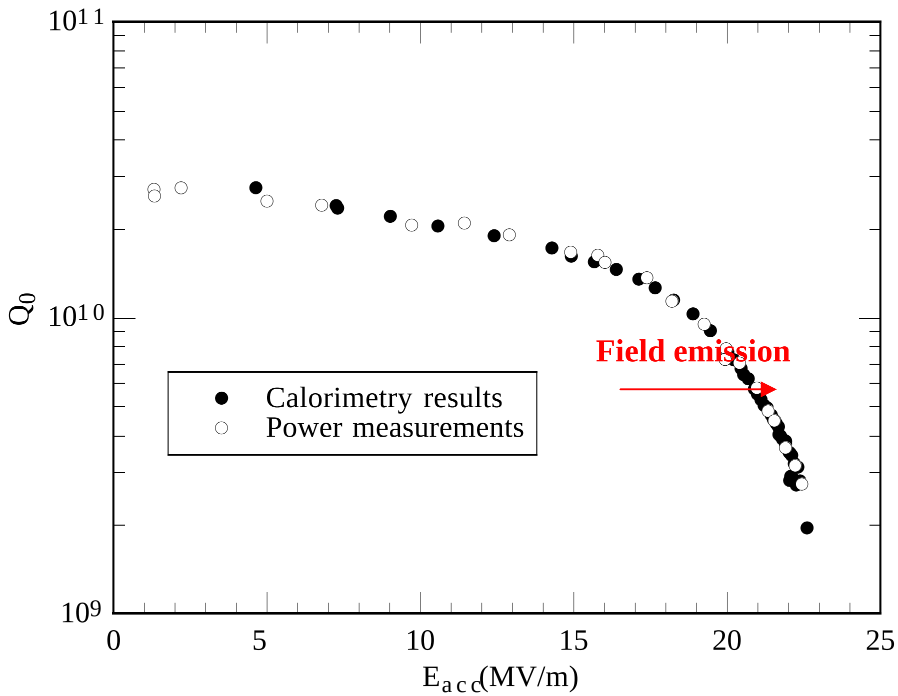


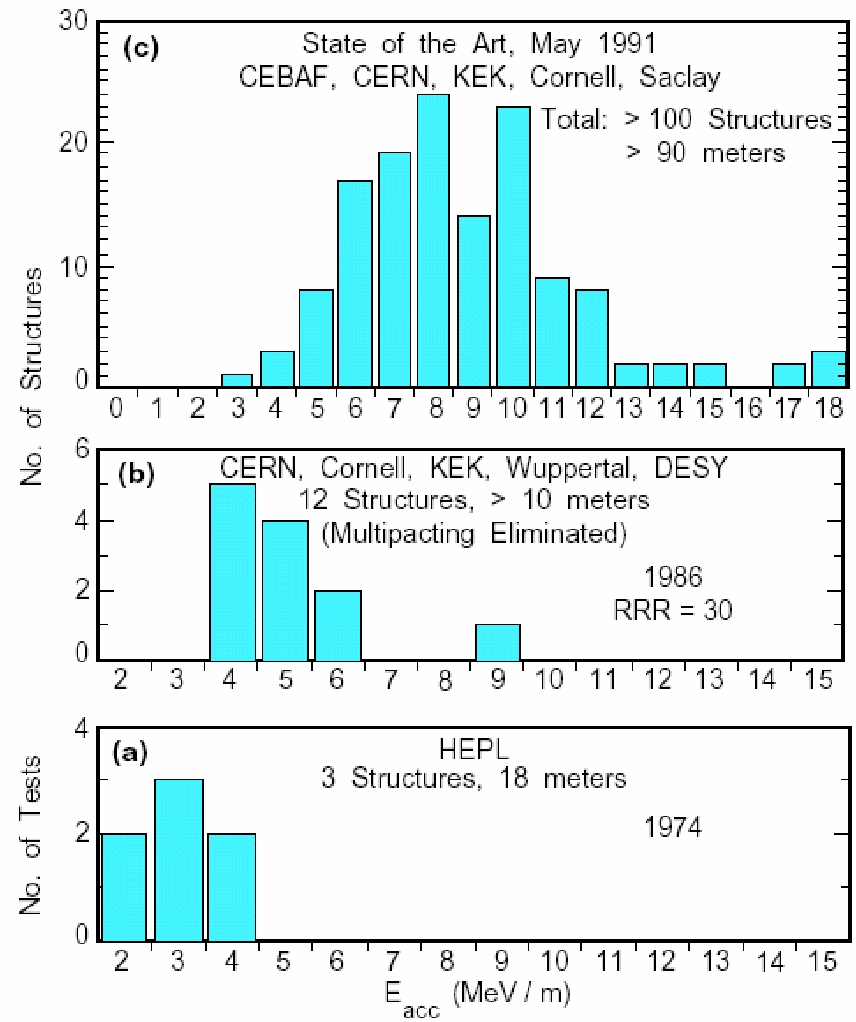


Electron Field Emission

Electron field emission (1990's)

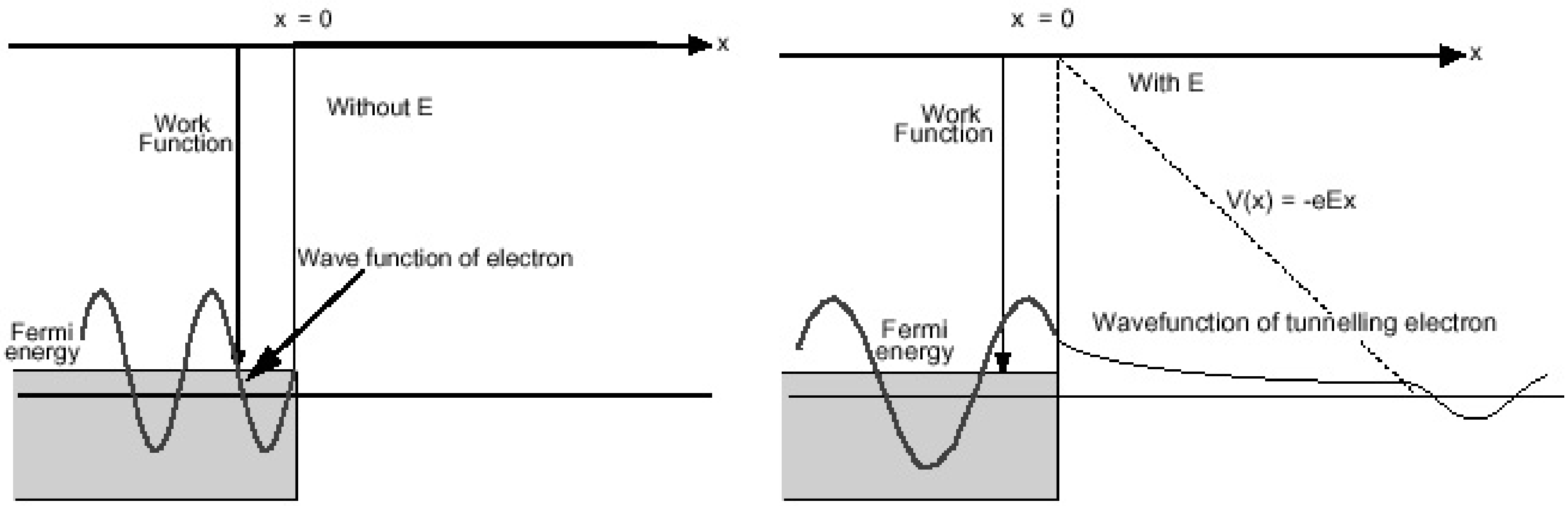
- Responsible for an exponential drop of the cavity quality (Q) at high field.





- X rays detected
- Current detected
- *X rays and current may strike peripheral devices!*

Field Emission Theory



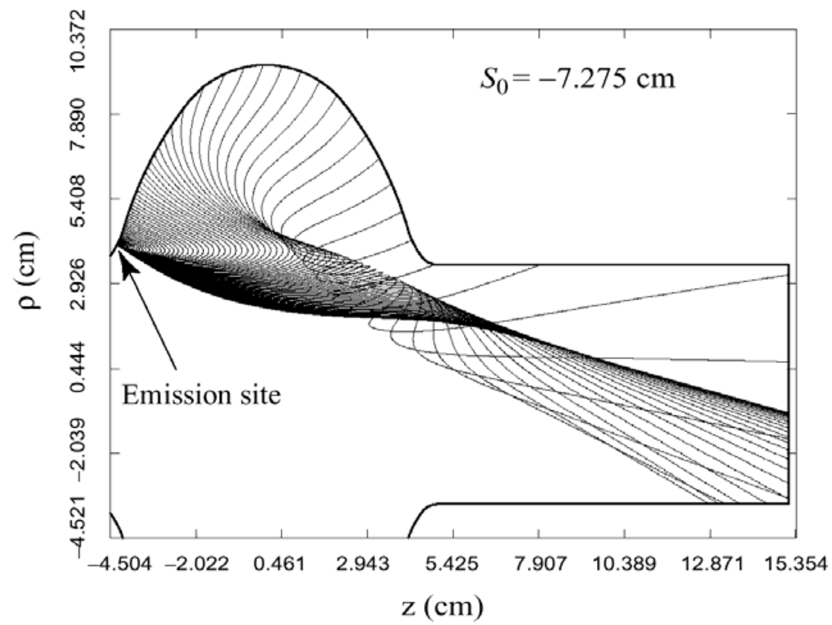
- QM tunneling theory predicts exponential *Fowler–Nordheim* emission current density.

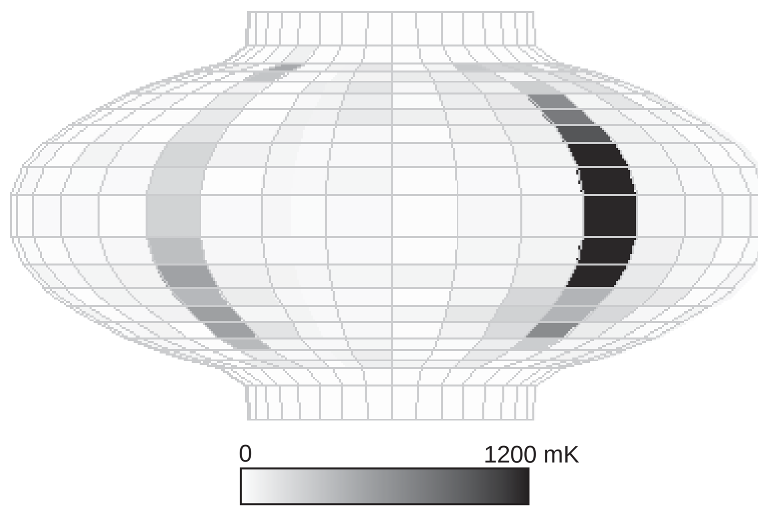
$$j_{FN} = C_1 E^2 \exp\left(-\frac{C_2}{E}\right)$$

Field Emission

- Acceleration of electrons drains cavity energy
- Impacting electrons produce line heating detected by thermometry.

Impact also produces bremsstrahlung x rays.



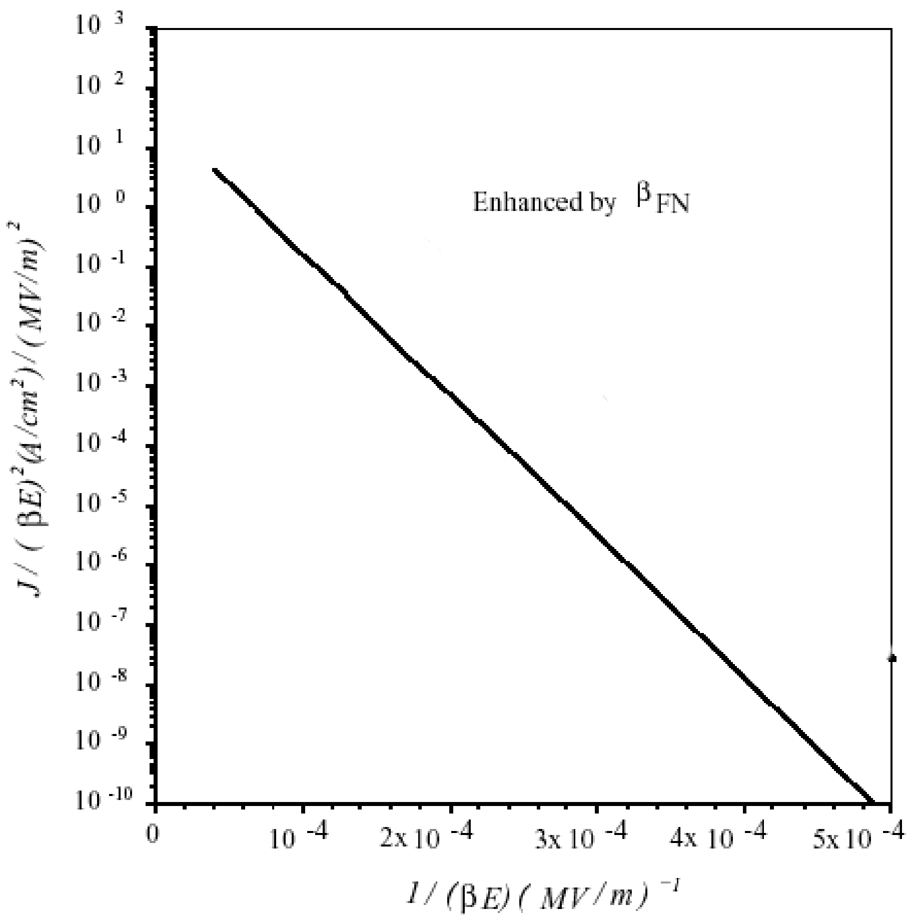


Problem With Theory

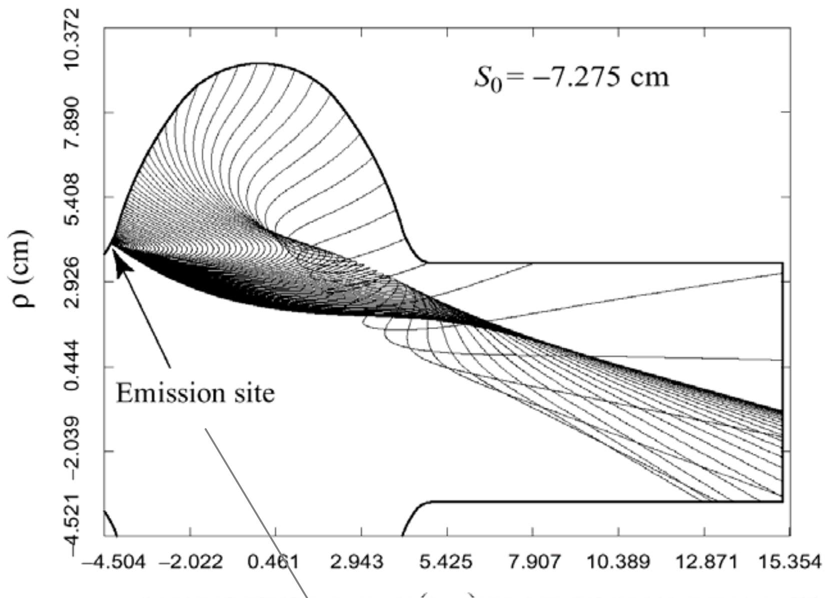
- FE in cavities occurs at fields that are up to 1000 times lower than predicted → need β_{FN}.

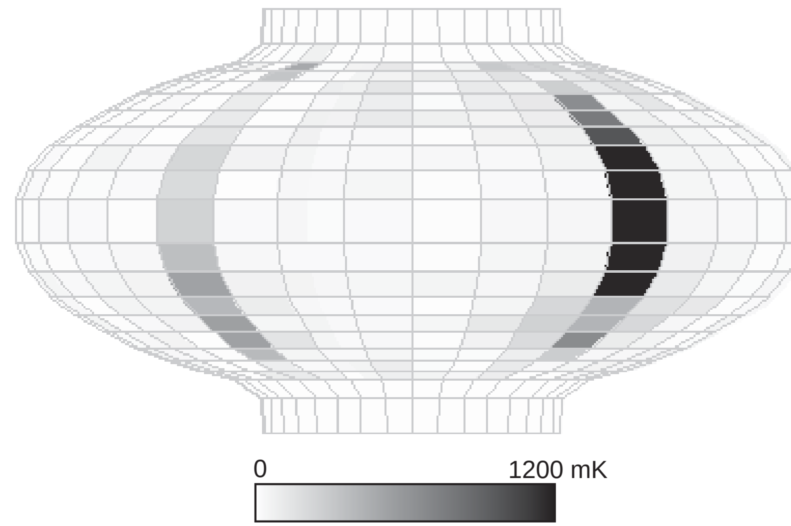
$$j_{FN} = C_1(\beta_{FN}E)^2 \exp\left(-\frac{C_2}{\beta_{FN}E}\right)$$

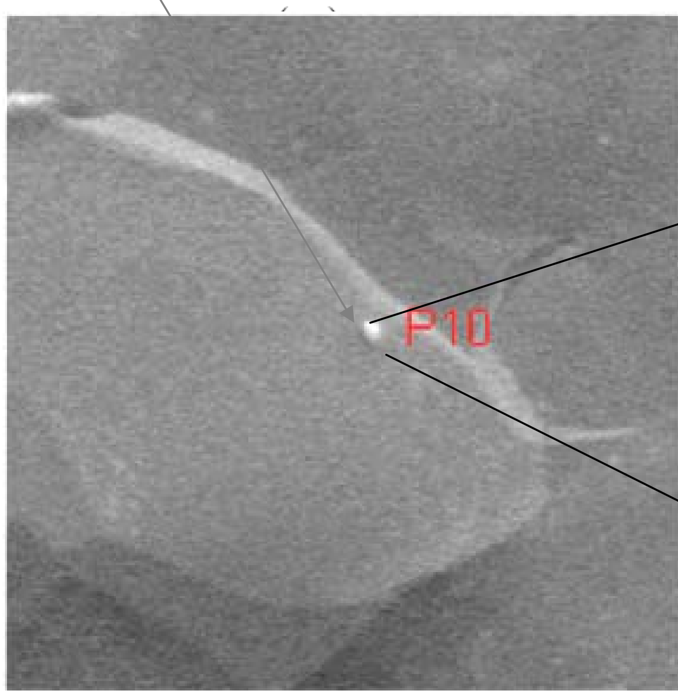
- $50 < \beta_{FN} < 1000$

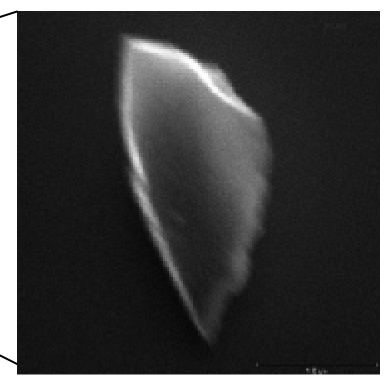


Electron field emission





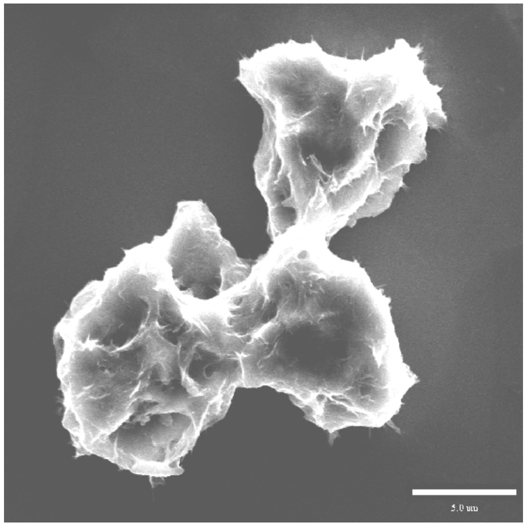


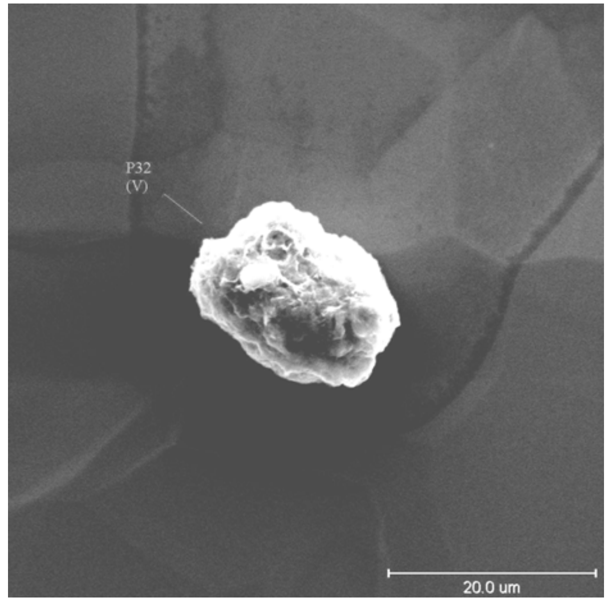


1 - 2 μm, C

Strong Emitters and Weak Emitters

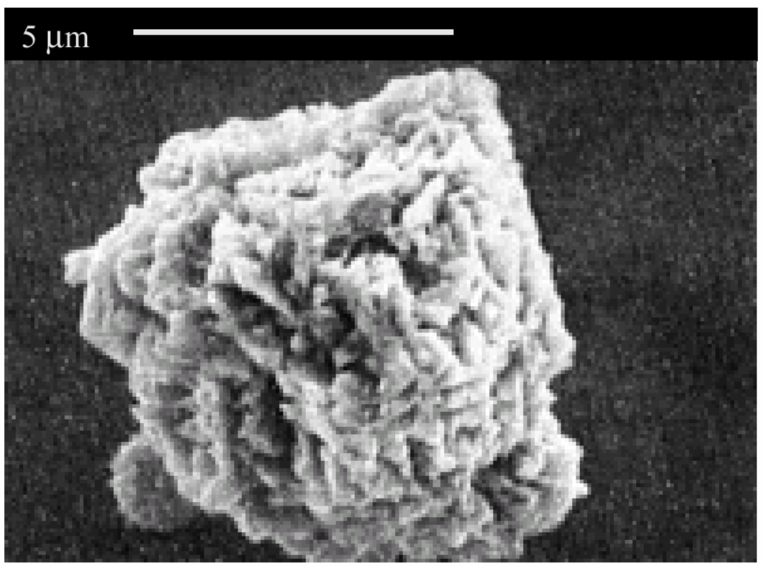
V



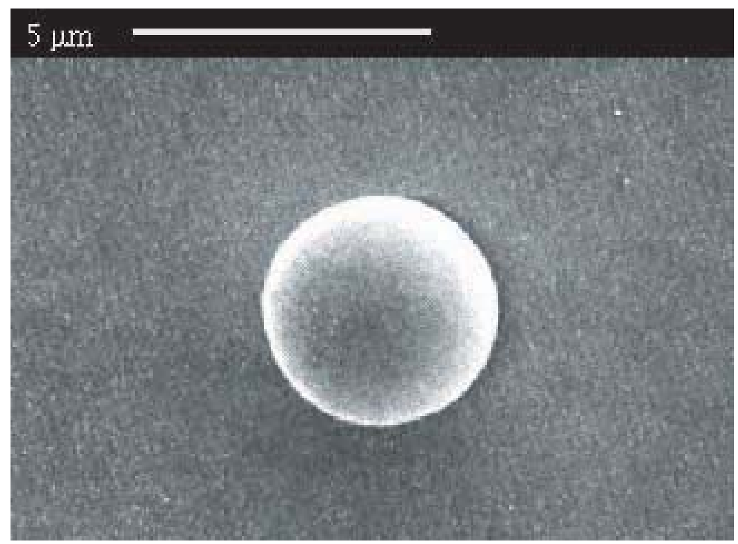


- *Tip-on-tip* model explains why only 10% of particles are emitters for Epk < 200 MV/m.

Ni

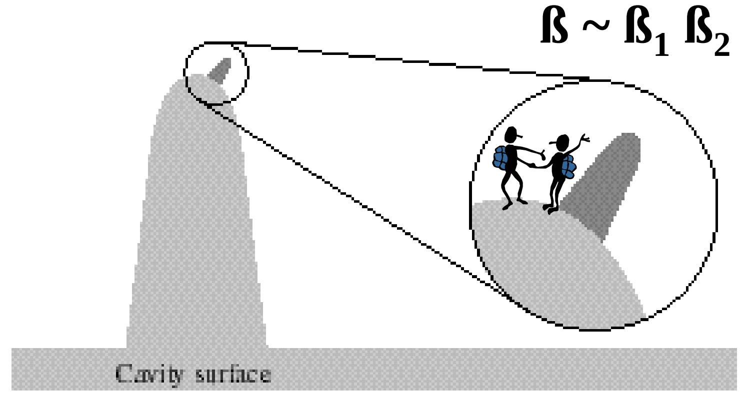


- Smooth nickel particles emit less or emit at higher fields.

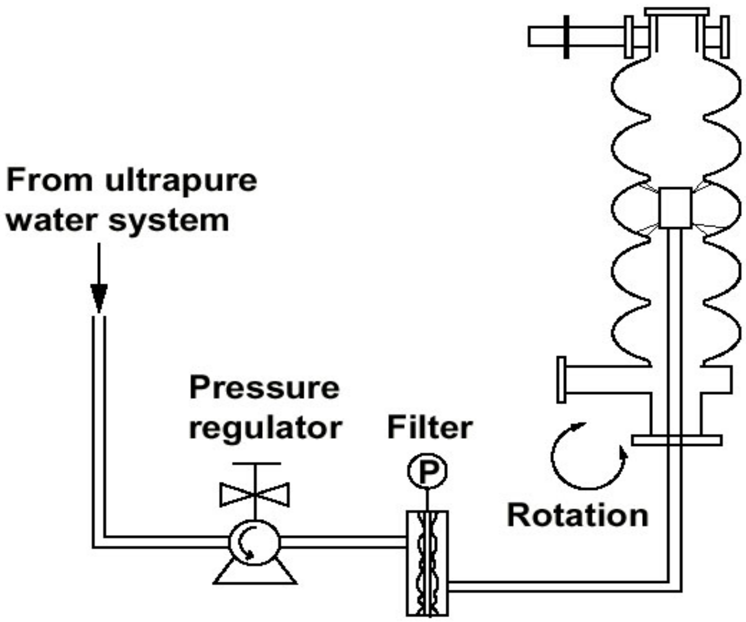


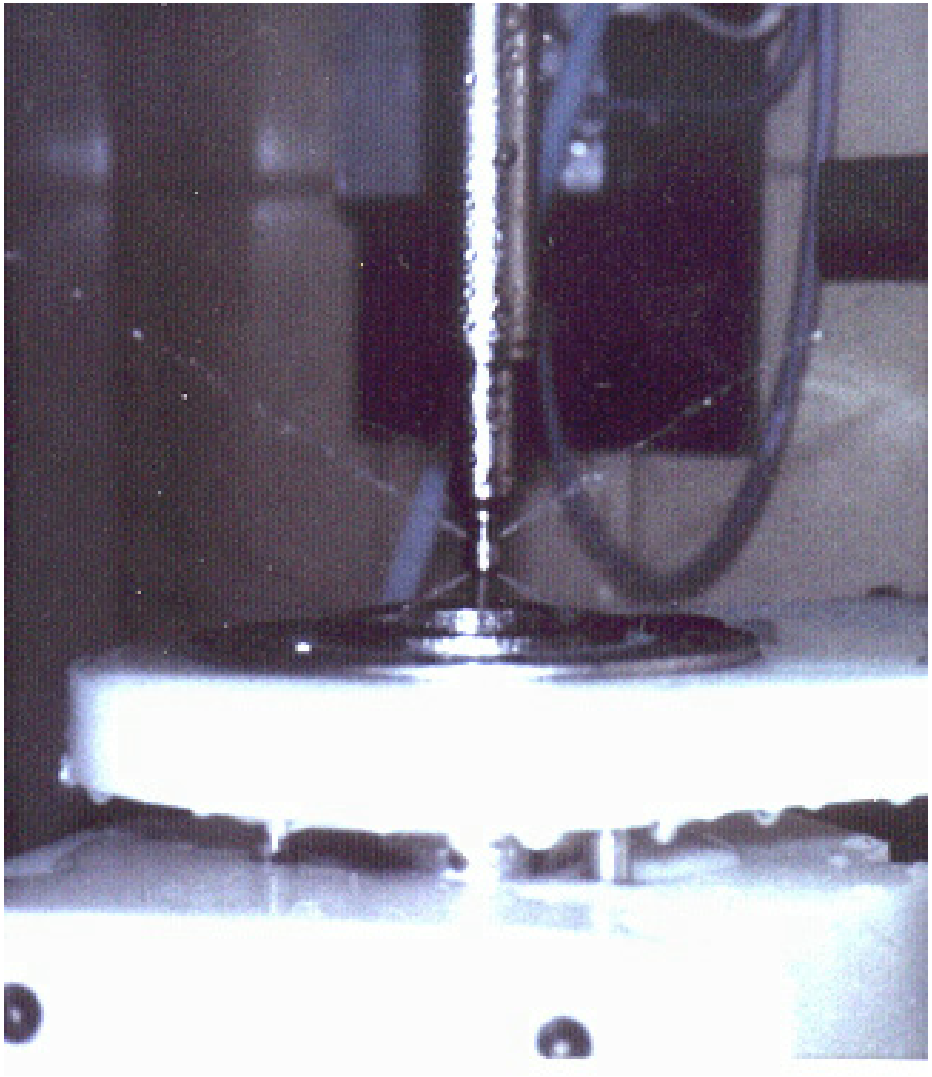
Field emission

- Smooth particles don't emit.
- *Tip-on-tip* model may explain some emission.



High Pressure Water Rinsing Eliminates Field Emitters



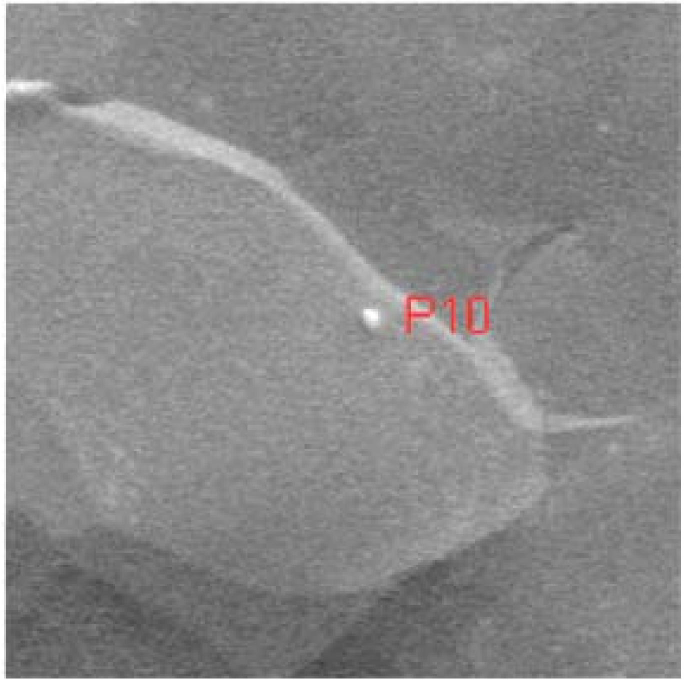


100 atm jet water rinsing

Possible New Method?
What is Snow Cleaning? (Reschke)

Assembly in Class 100 Clean Room

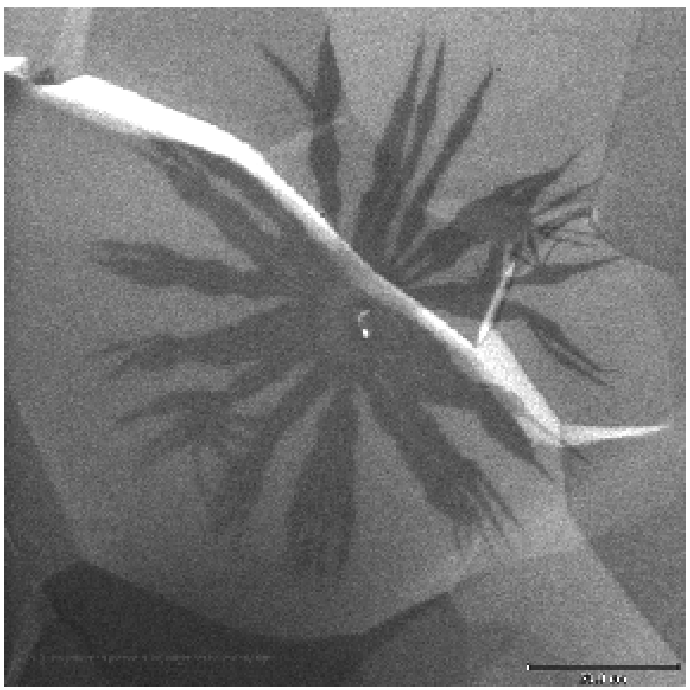
< 100 particles/cu.ft   > 1 µm

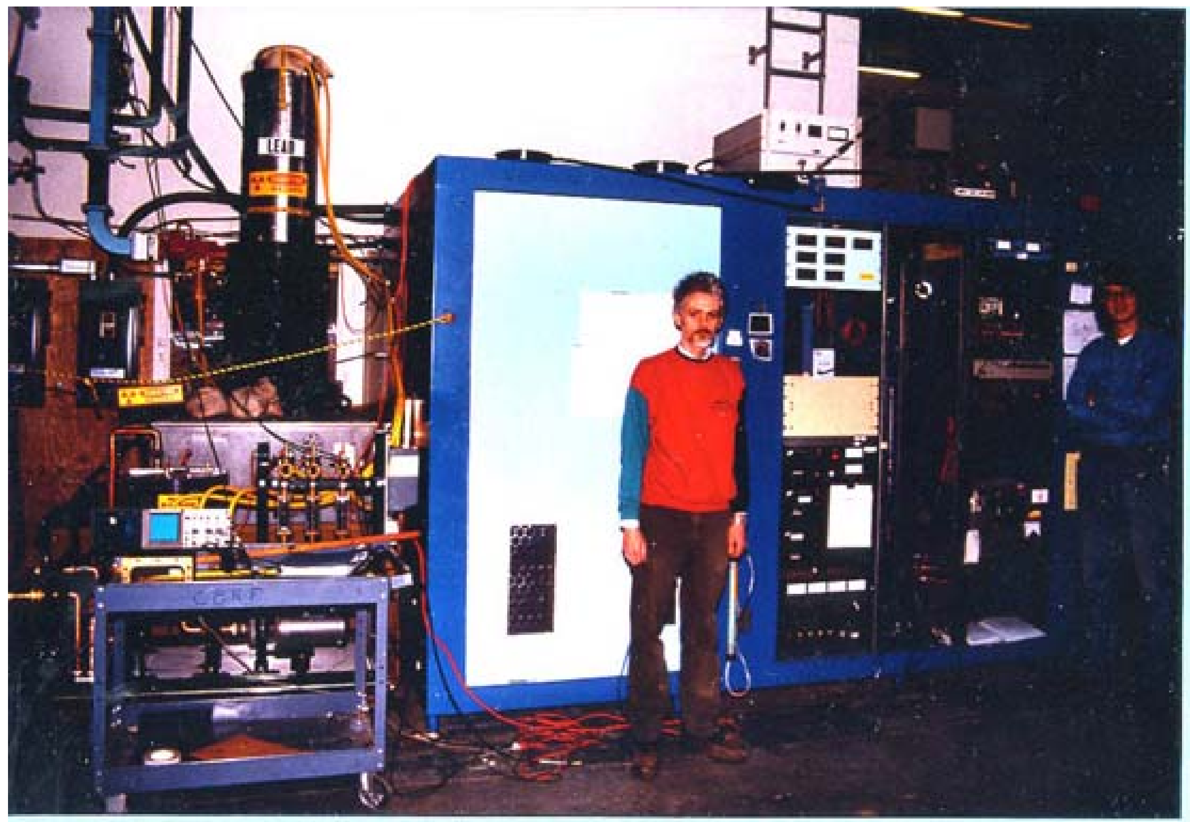


High Power RF Processing

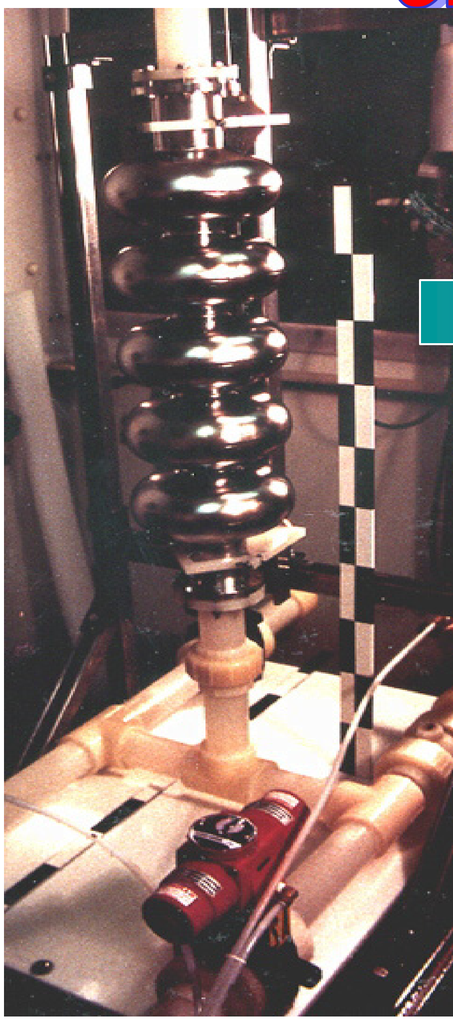
Burn off Remaining Electron Emitters
With High Power RF by Sparking

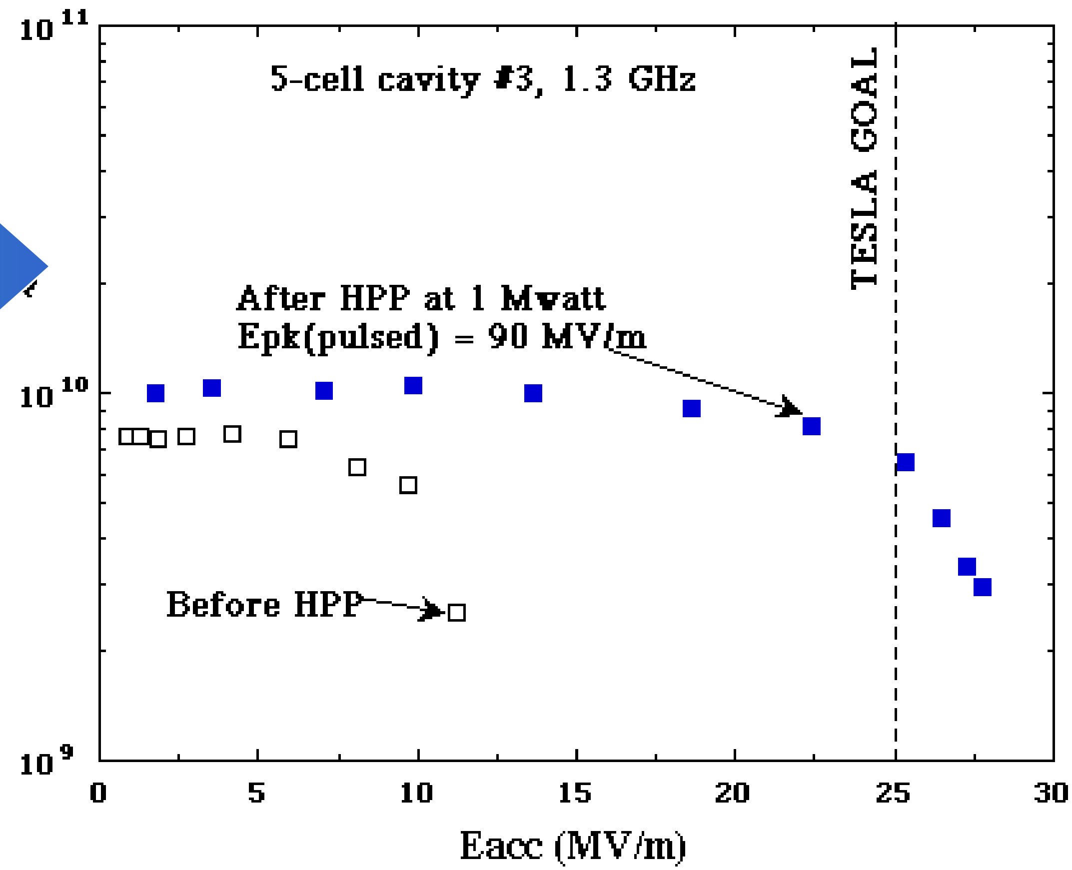
1 MW, 200 μsec pulses

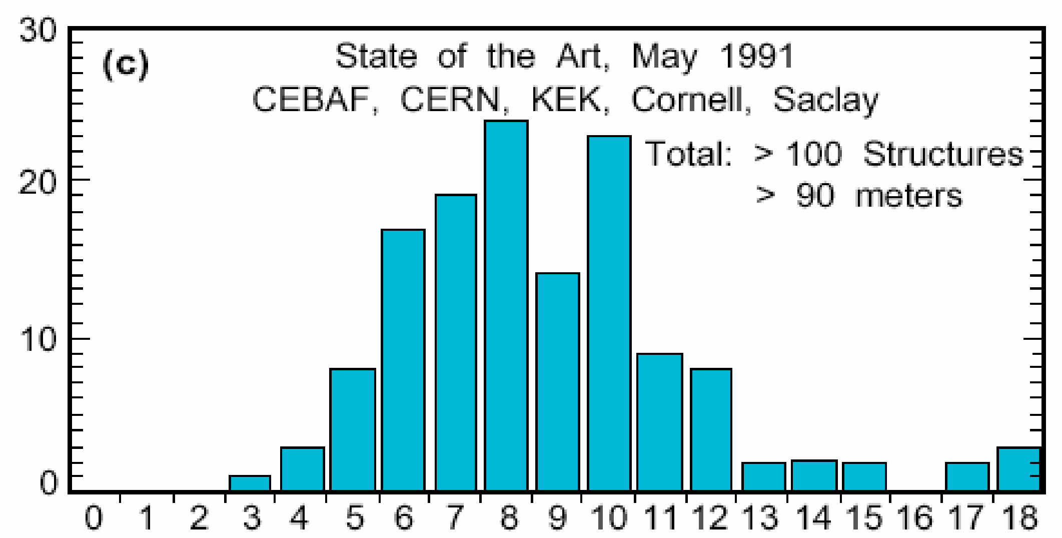




Push for High Gradients :
in several 5-cell 1300 MHz
Gradients > 25 MV/m







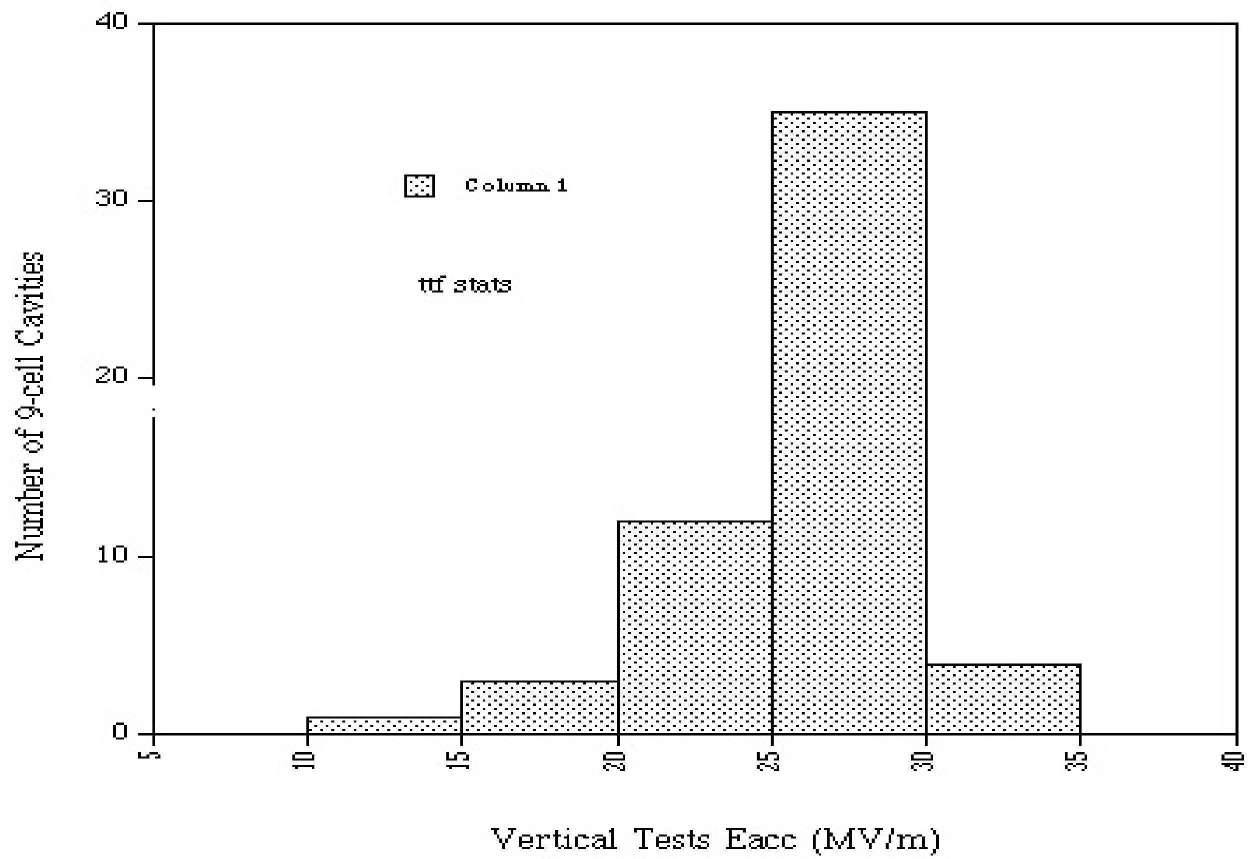
1991 ≈ 10 MV/m

2000 -

25 MV/m

9-cell Cavities

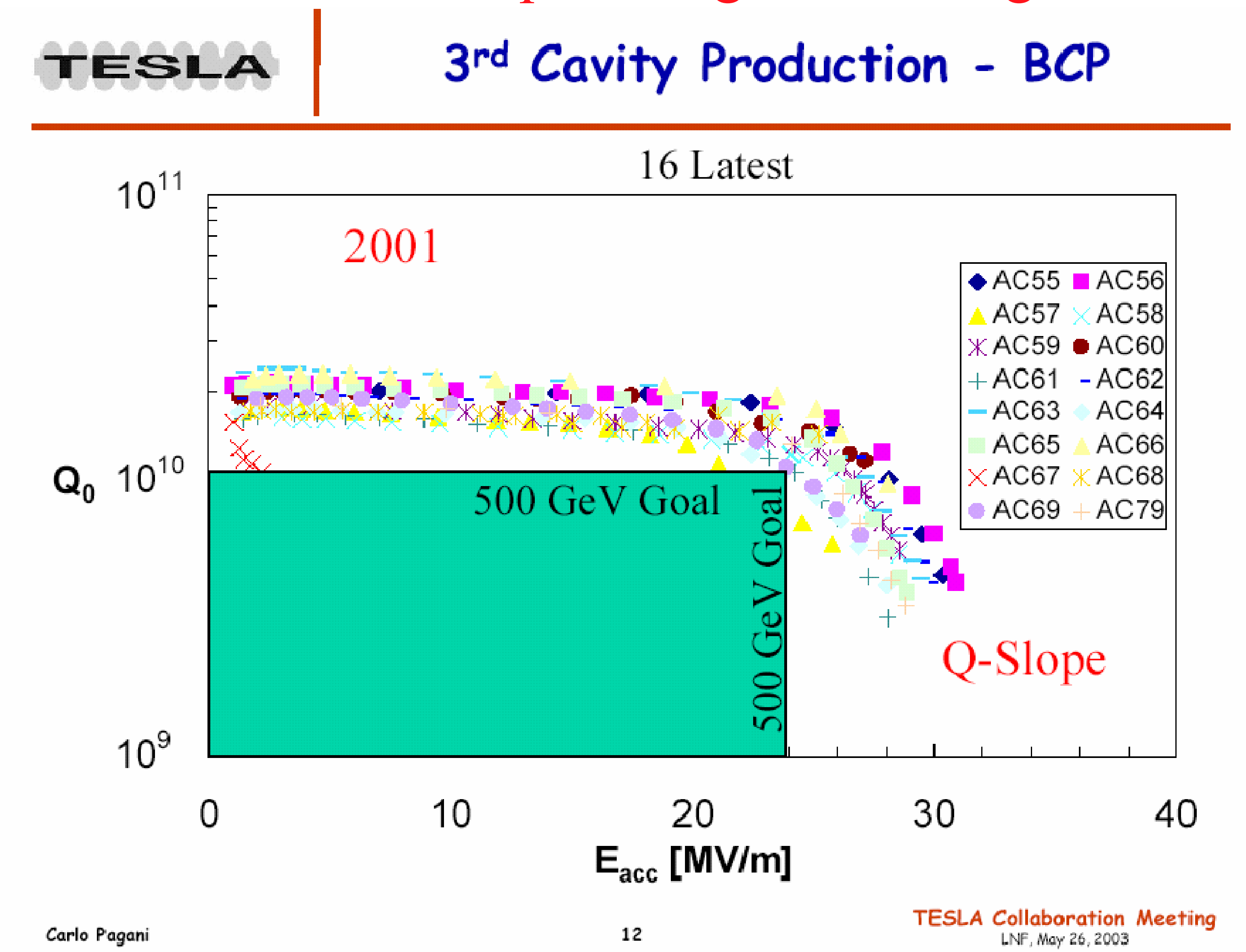
DESY

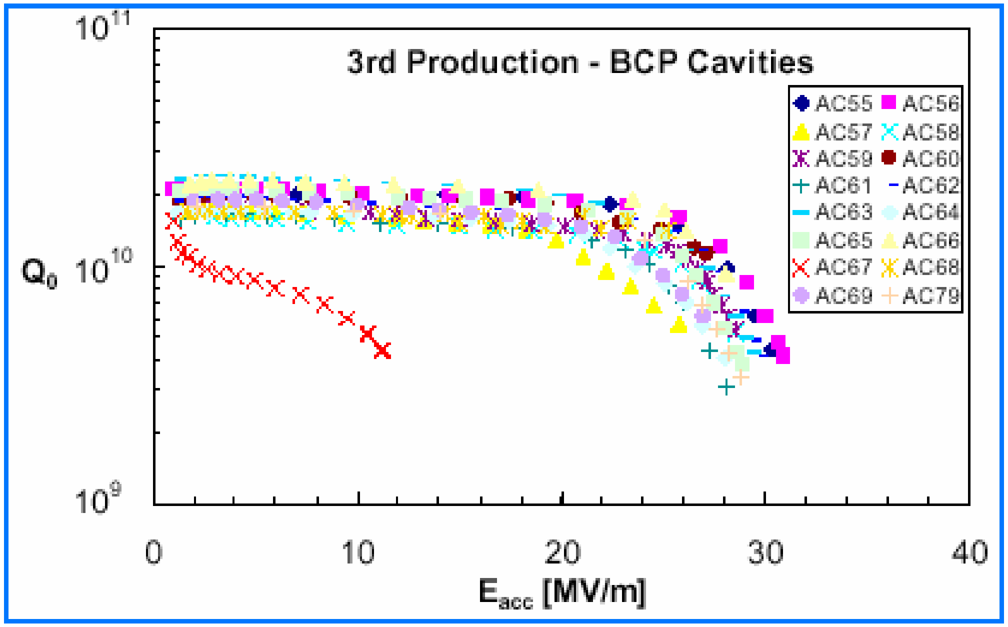


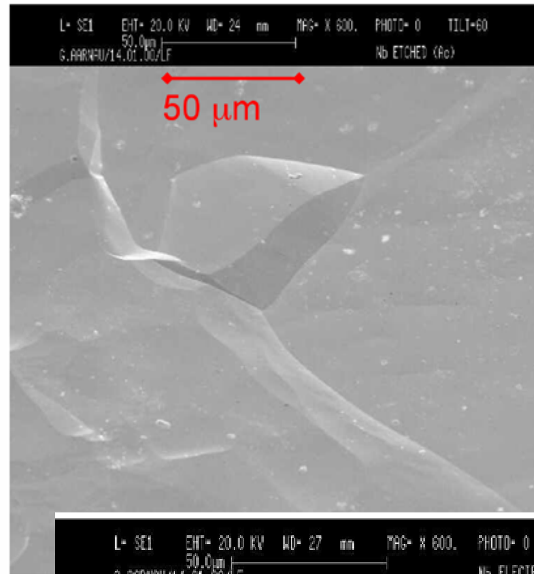
High Field Q-Drop

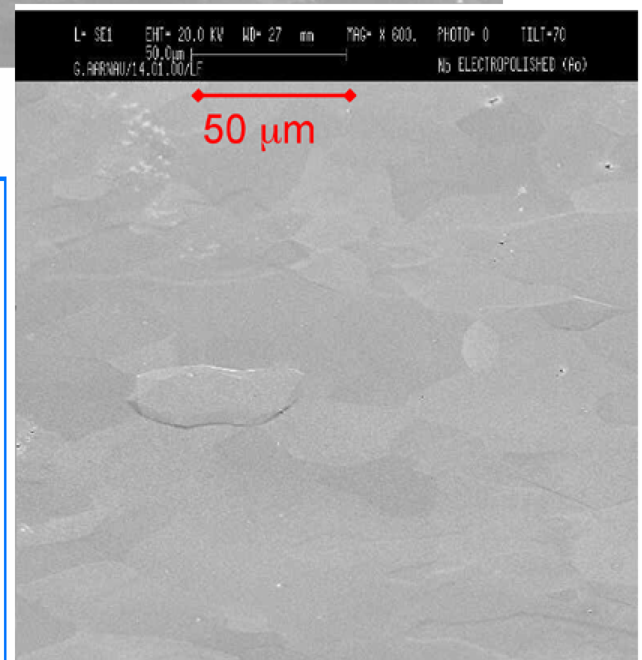
High Field Q-Slope- Cause Not Yet Fully Understood

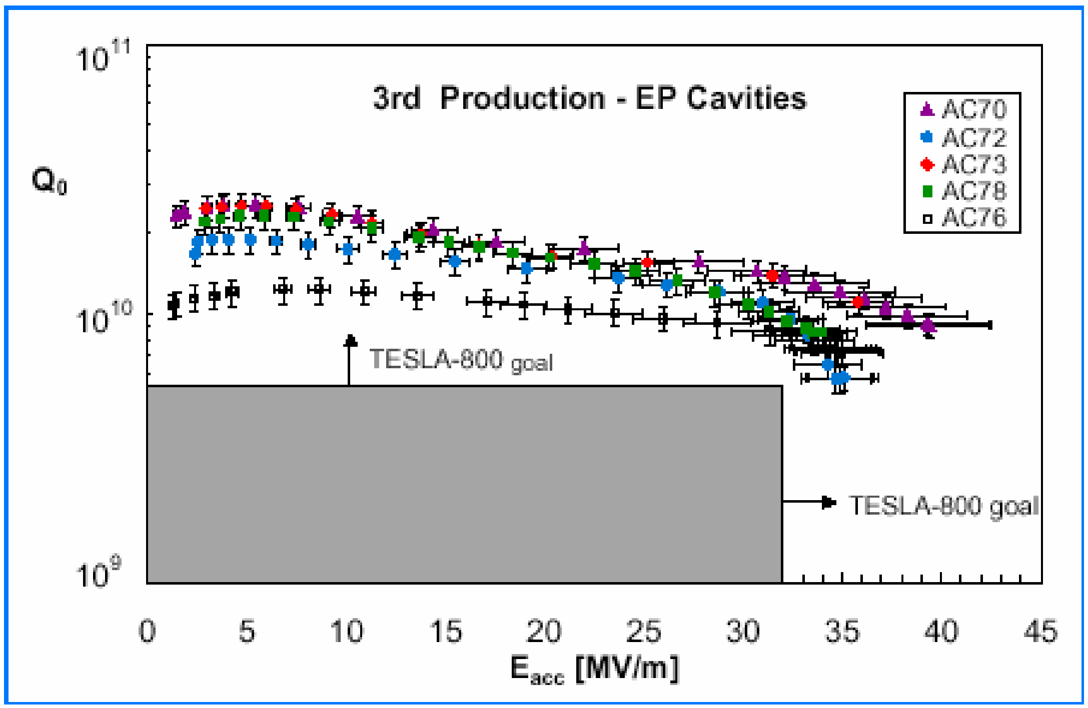
Cures: Electropolishing and Baking 100 C









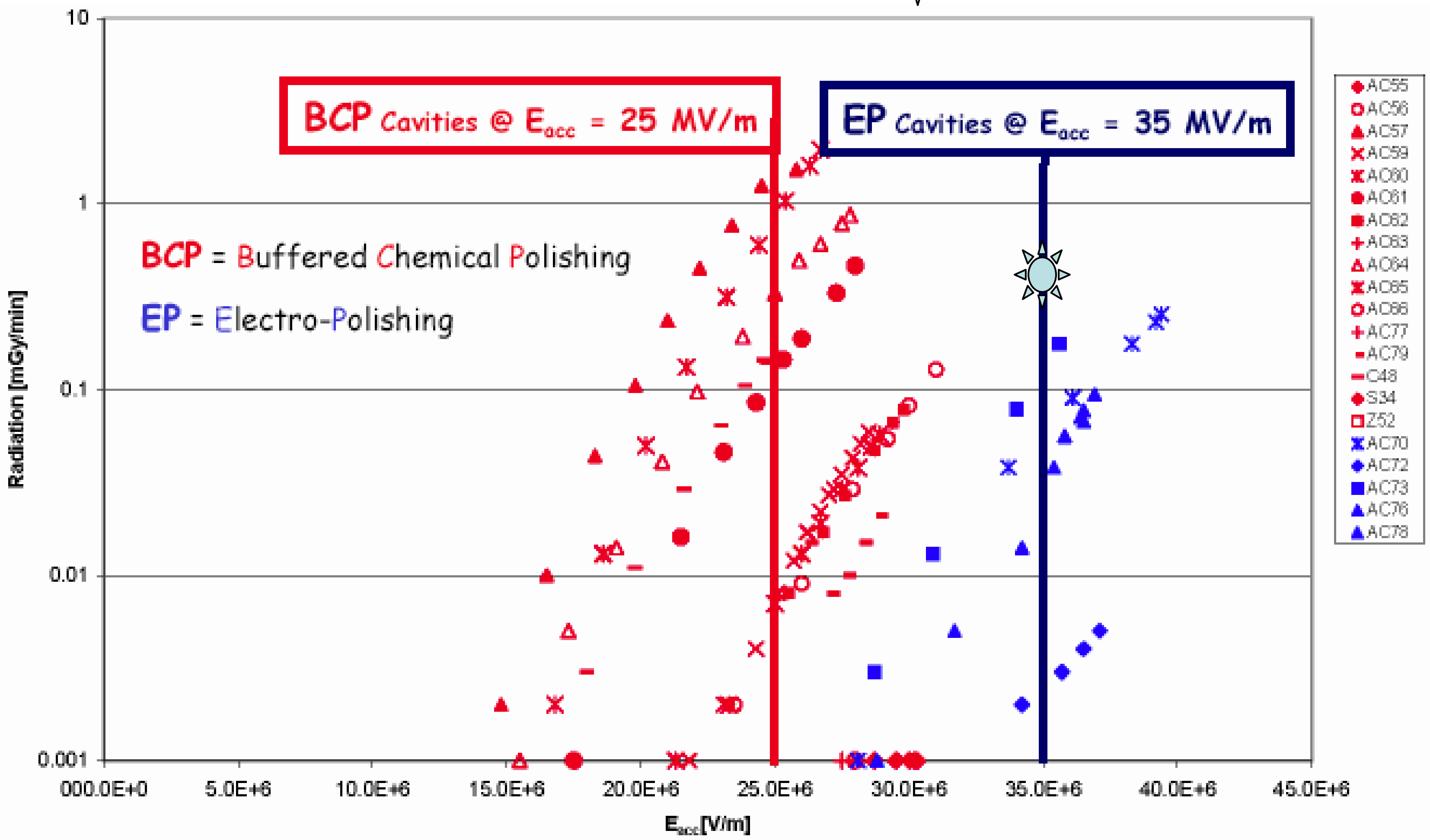


EP and Baking 5 cavities tested

Eacc = 35 - 40 MV/m

All 5 Electropolished Cavities at 35 MV/m show less radiation than BCP cavities at 25 MV/m..cleaner achieved

50 nA @ 35 MV/m per cavity acceptable ≈ 250 mW per cavity at 35 MV/m, estimated corresponding radiation dose

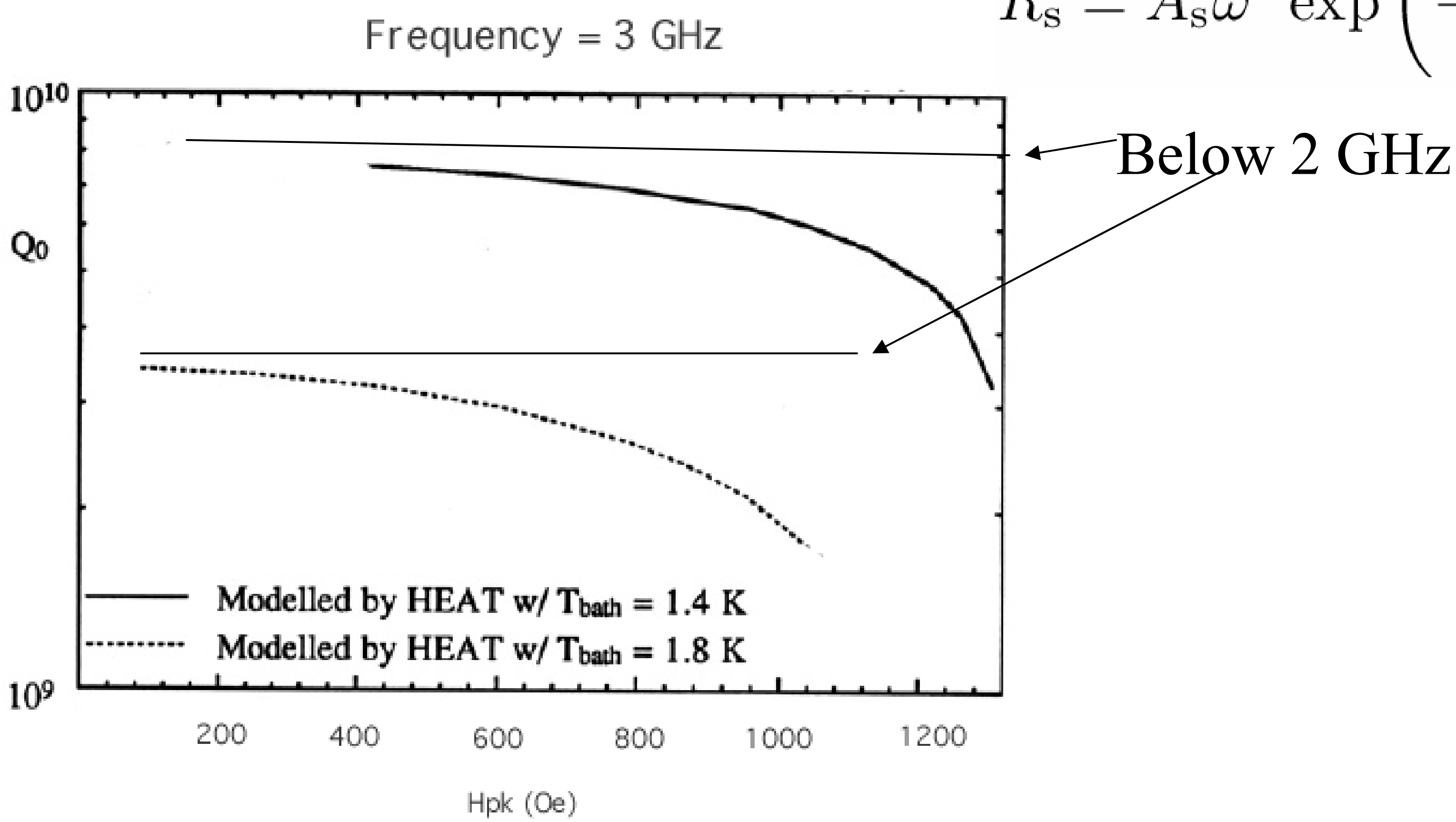


Global Thermal Instability

Global Thermal Instability Due to BCS Surface Resistance

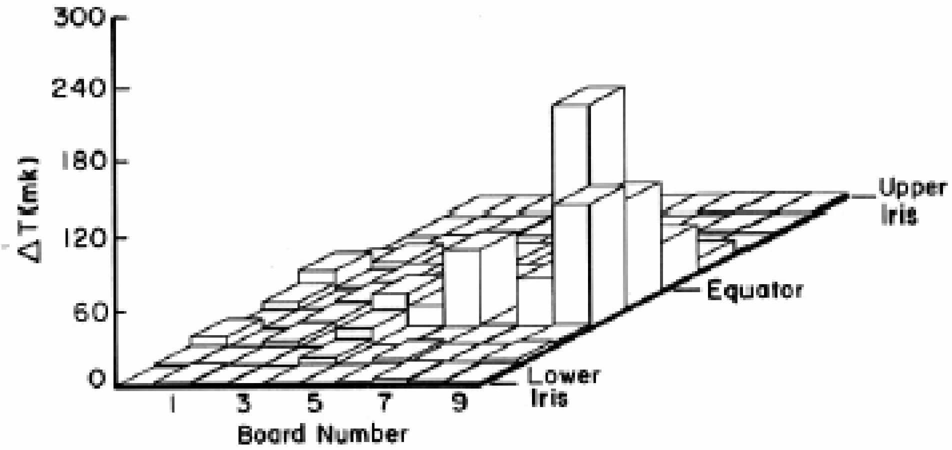
Important only for f > 2 GHz

$$R_s = A_s \omega^2 \exp\left(-\frac{\Delta(0)}{k_B T}\right)$$

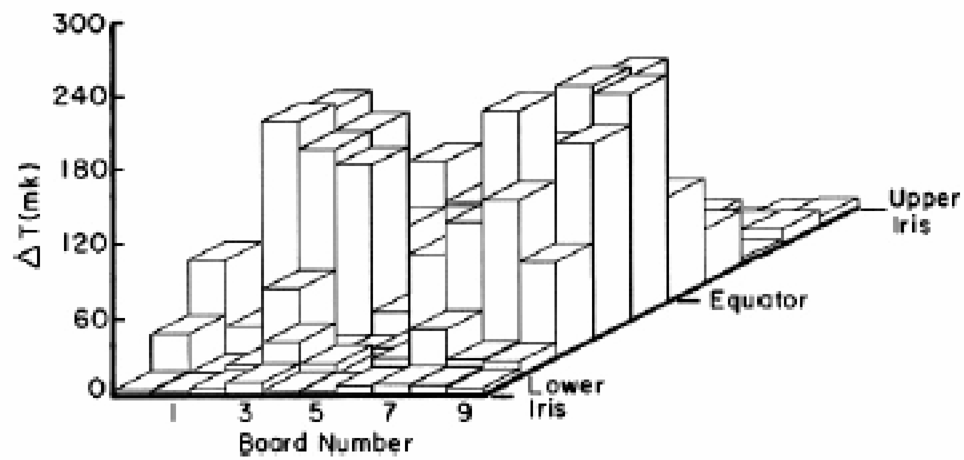


Simulation

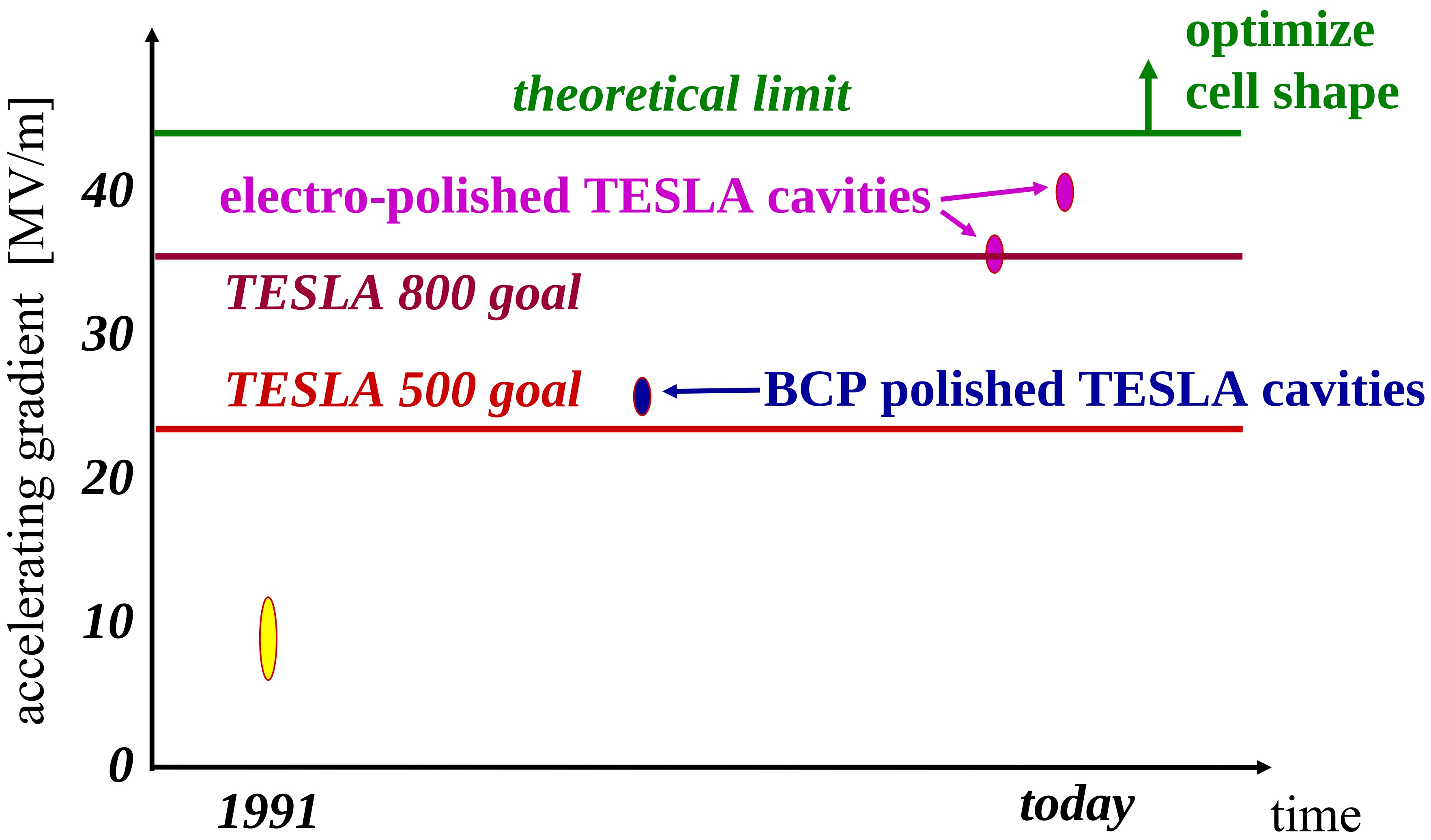
Defect Induced Breakdown



Global Thermal Instability

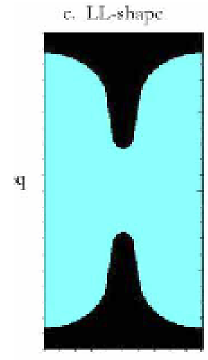


Beyond 40 MV/m

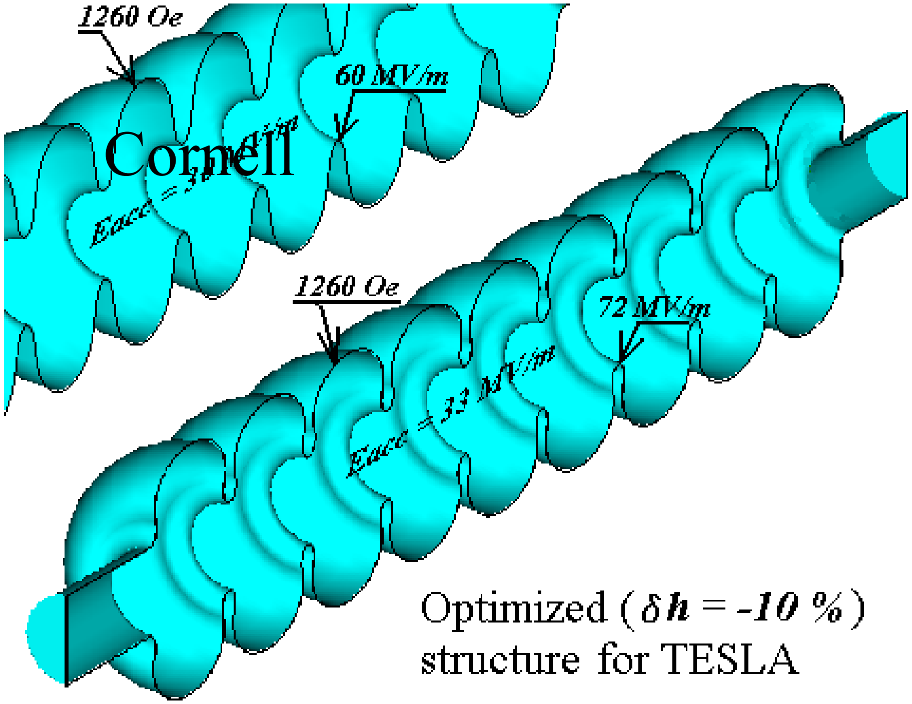

optimize
cell shape
theoretical limit
electro-polished TESLA cavities
TESLA 800 goal
TESLA 500 goal
BCP polished TESLA cavities
accelerating gradient [MV/m]
40
30
20
10
0
1991
today
time

Can We Improve the TESLA Geometry? Sekutowic Review

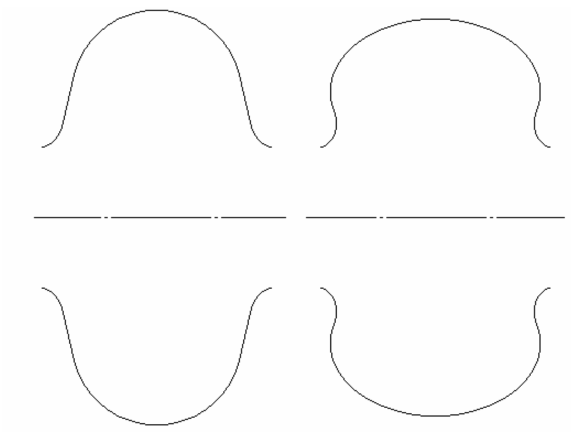
Jlab



Low-Loss

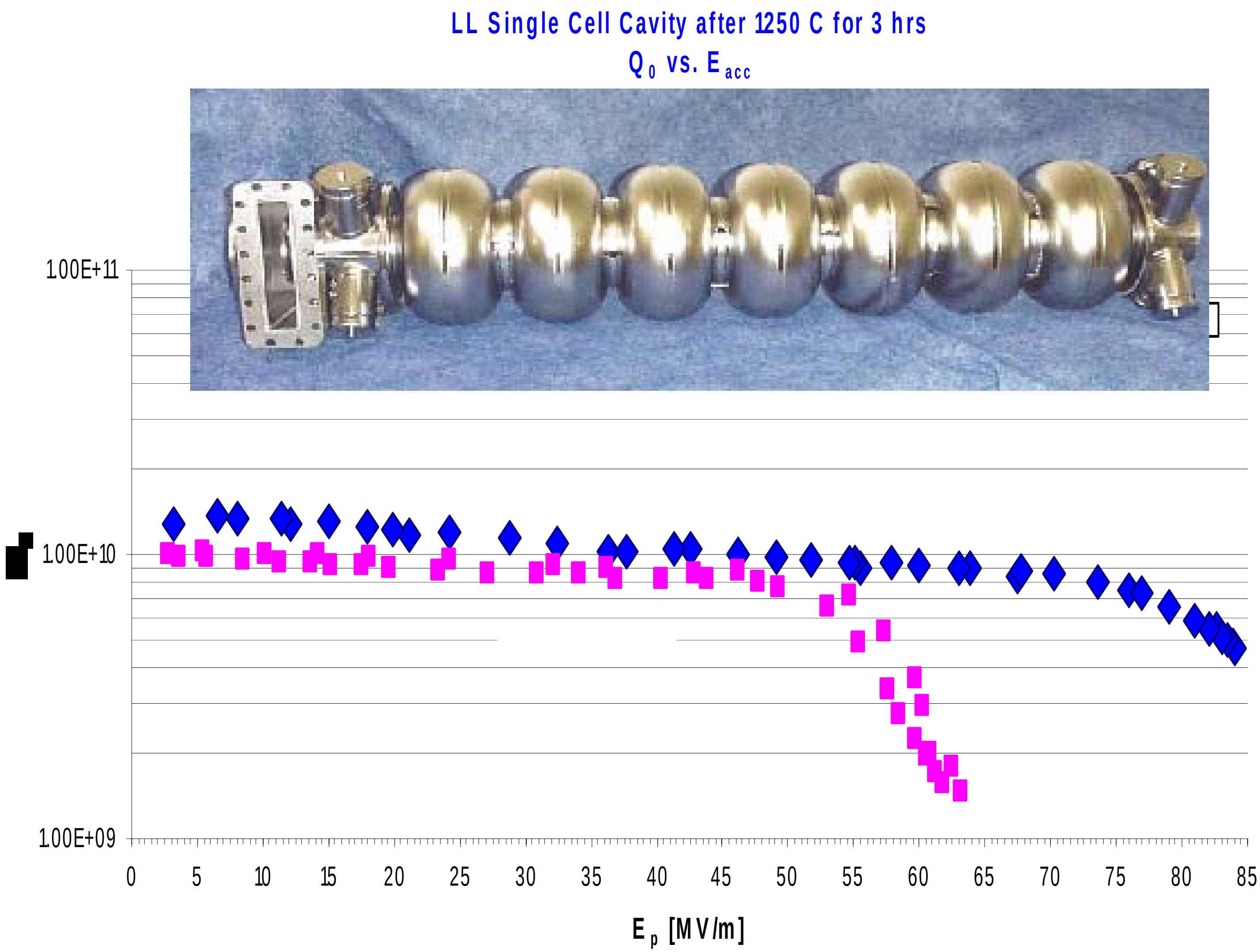


Cornell

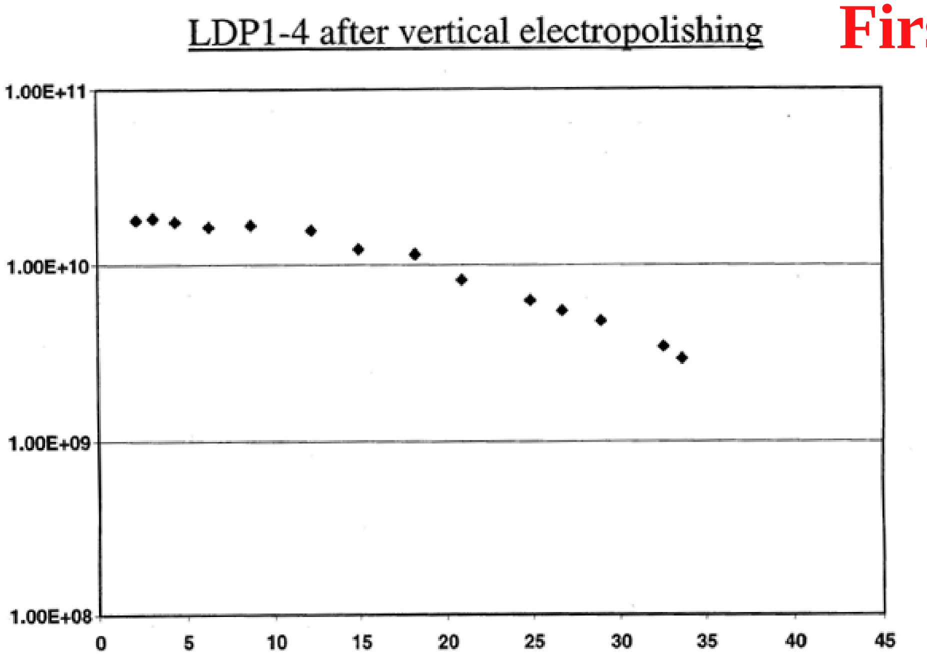


Re-entrant

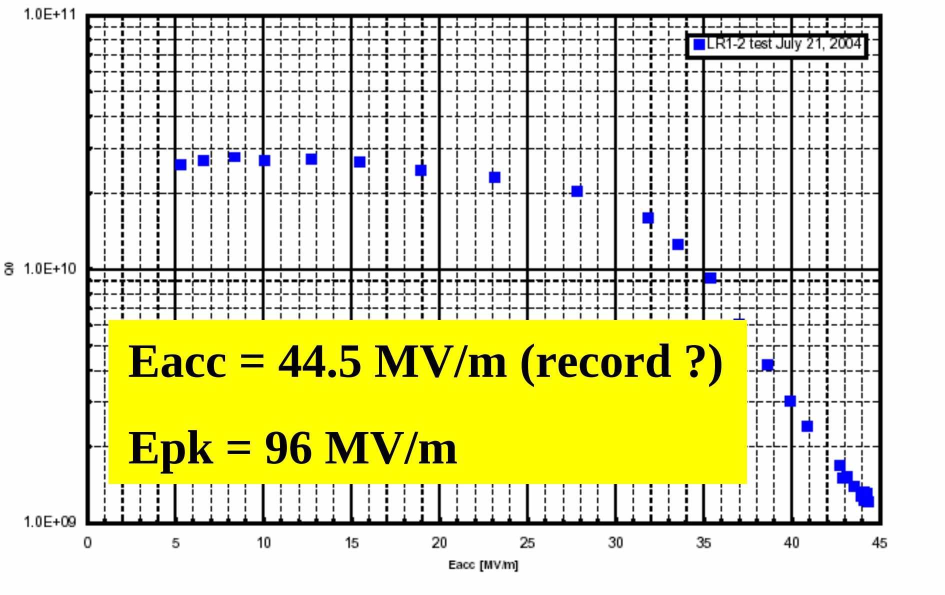
Jlab, Low Loss Shape (Kneisel)



First Results



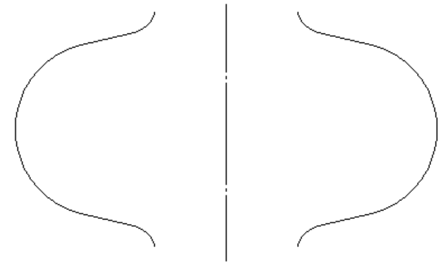
10 20 30 40 MV/m



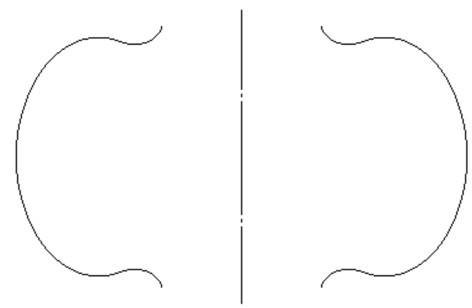
Eacc = 44.5 MV/m (record ?)

Epk = 96 MV/m

TESLA shape



New shape



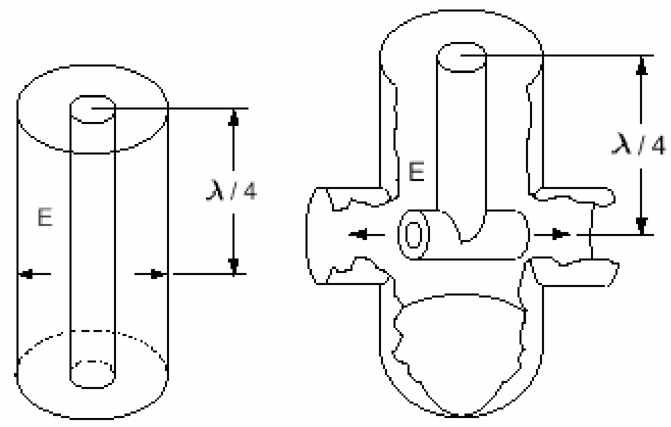
This Workshop

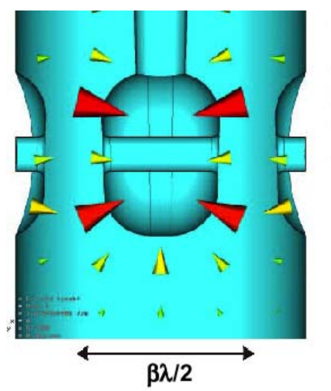
(Some) Open Issues for This Workshop (Gaps in our Knowledge)

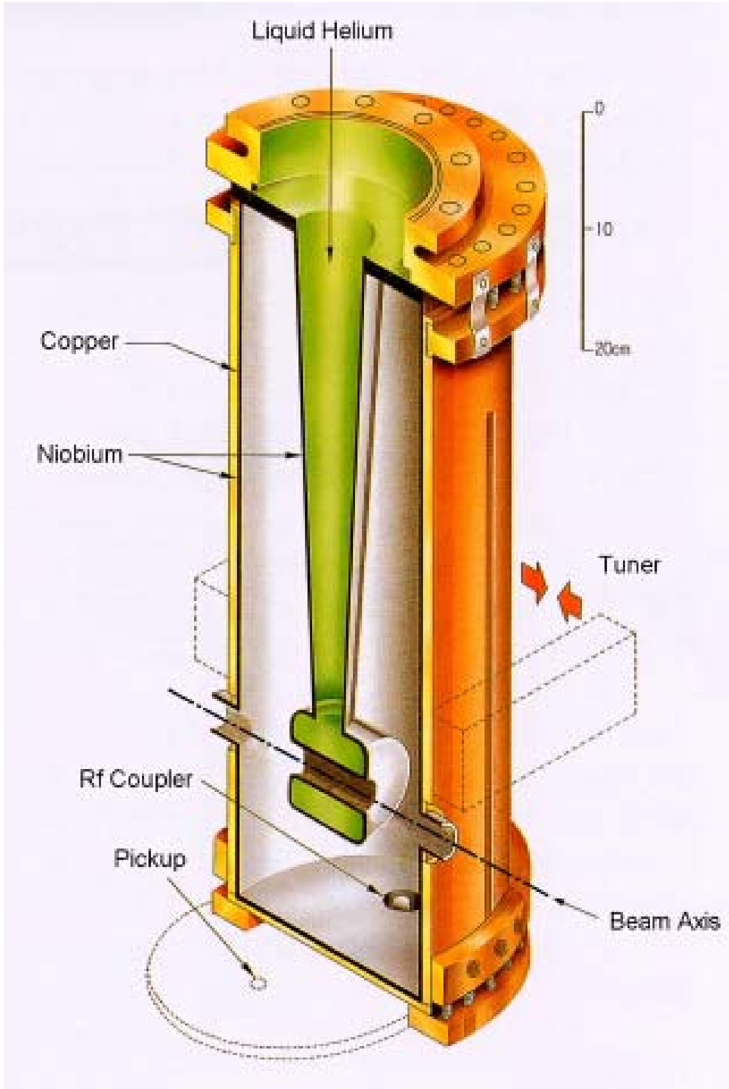
- What is the limiting field for Nb? 50 MV/m, 40 MV/m?
- Will new materials help us get beyond the limiting magnetic field for Nb?
- Are there better cavity geometries for high gradients?
- What is the penalty for operating below 2 K for higher Q?
- Why does the high field Q-slope decrease with baking (100 C)?
- Does EP (without bake) change the high field Q-slope?
- Can field emission be controlled even better?
- Do we need RRR > 300 (post purification) for highest gradients?
- What is the cause of the general Q-slope in Nb-Cu?
- Are there important R&D topics being ignored?

Low beta Cavities Examples

Quarter Wave Resonator







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

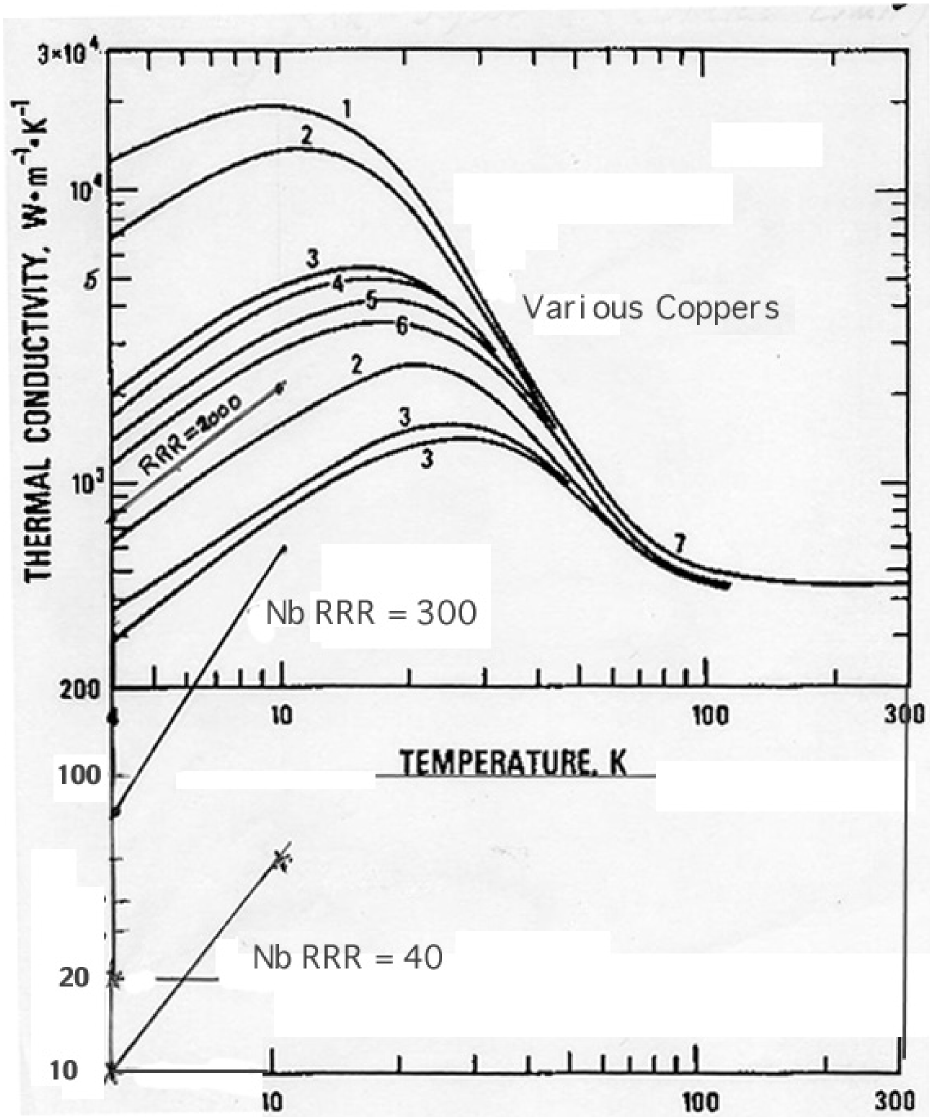
⇒ Theoretical accelerating field limits

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

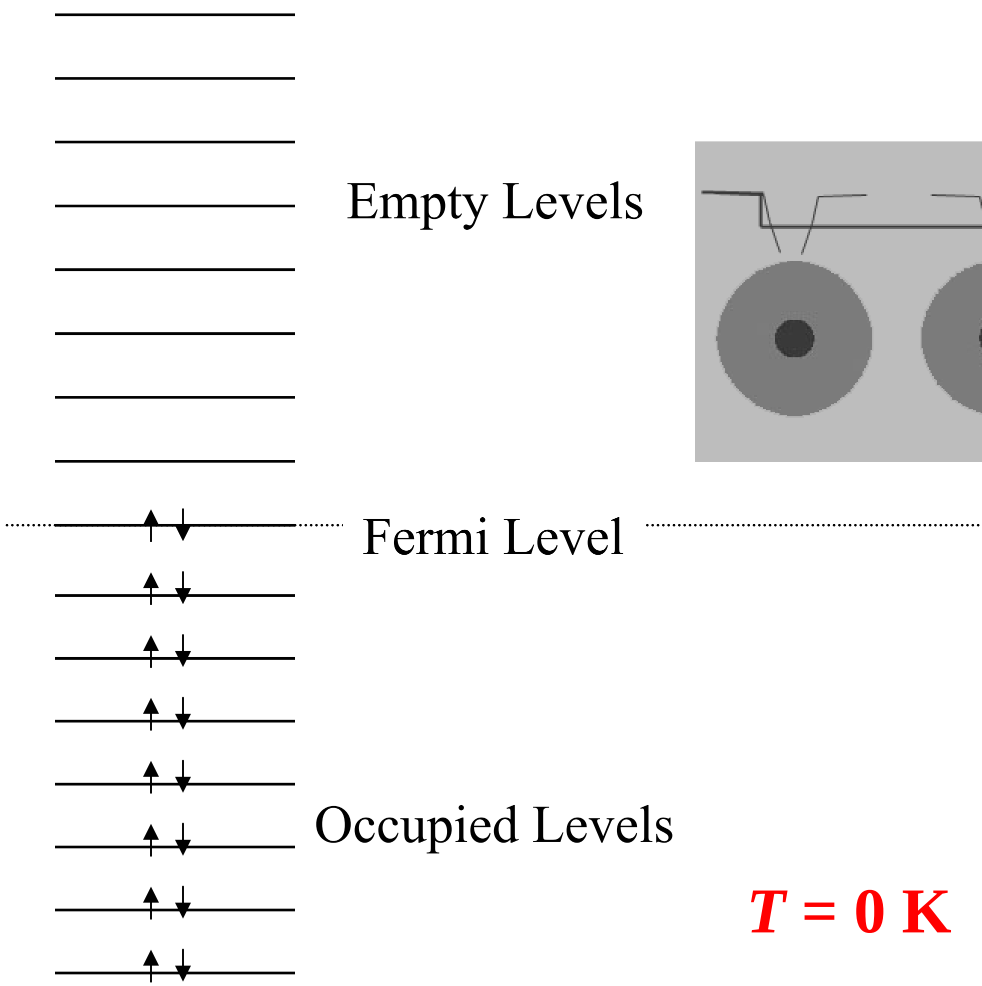
} What is really the fundamental limit for RF cavities?

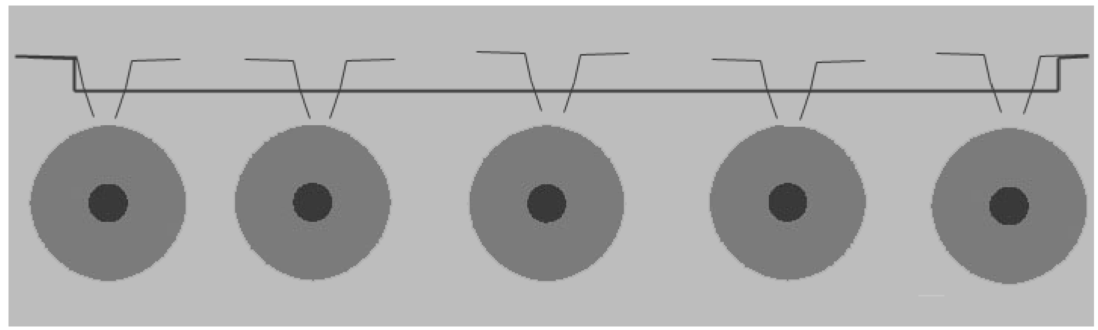
from L. Lilje

Compare Nb and Cu Thermal Conductivity



Field Emission Theory





T = 0 K

Normal conductor