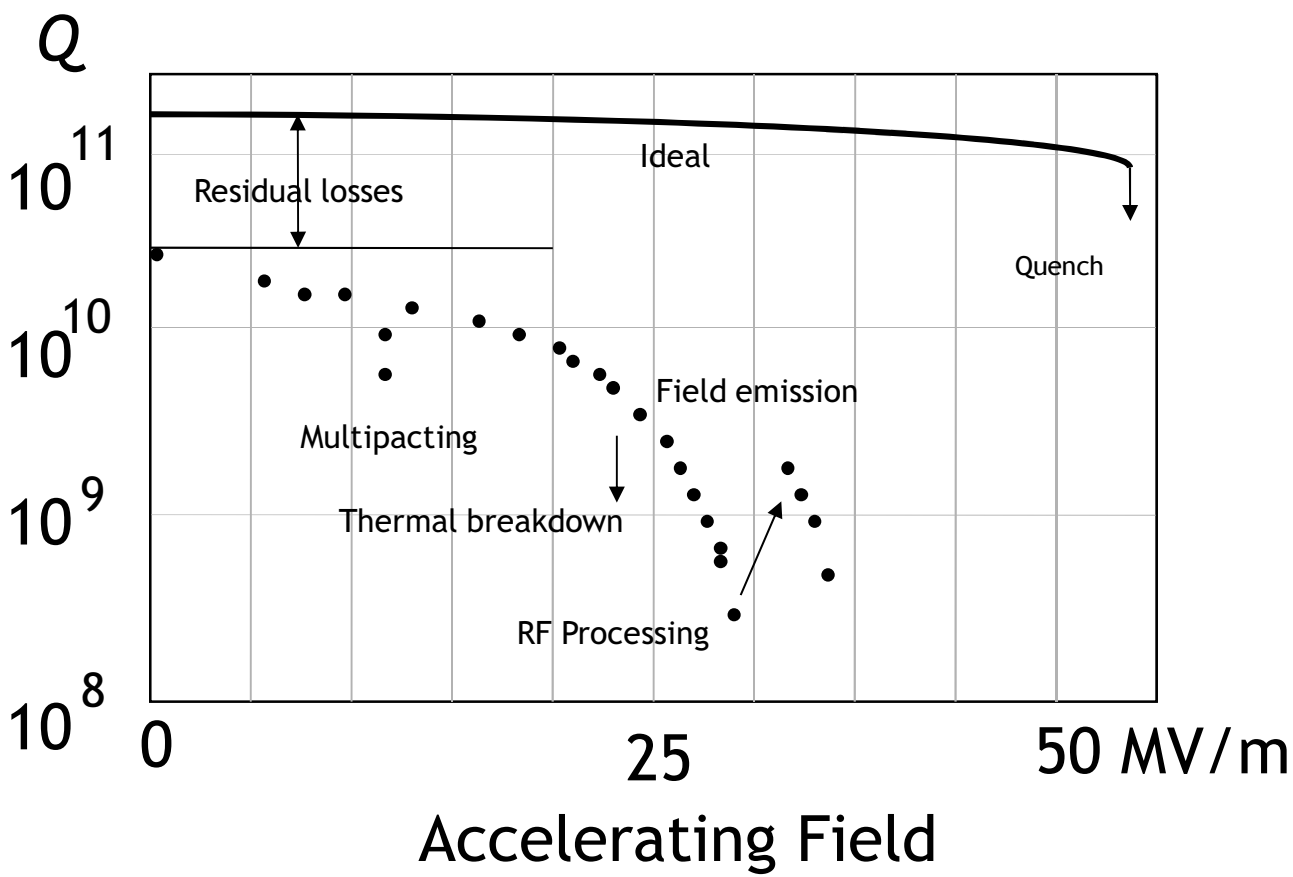
The real world …

What limits real cavities?



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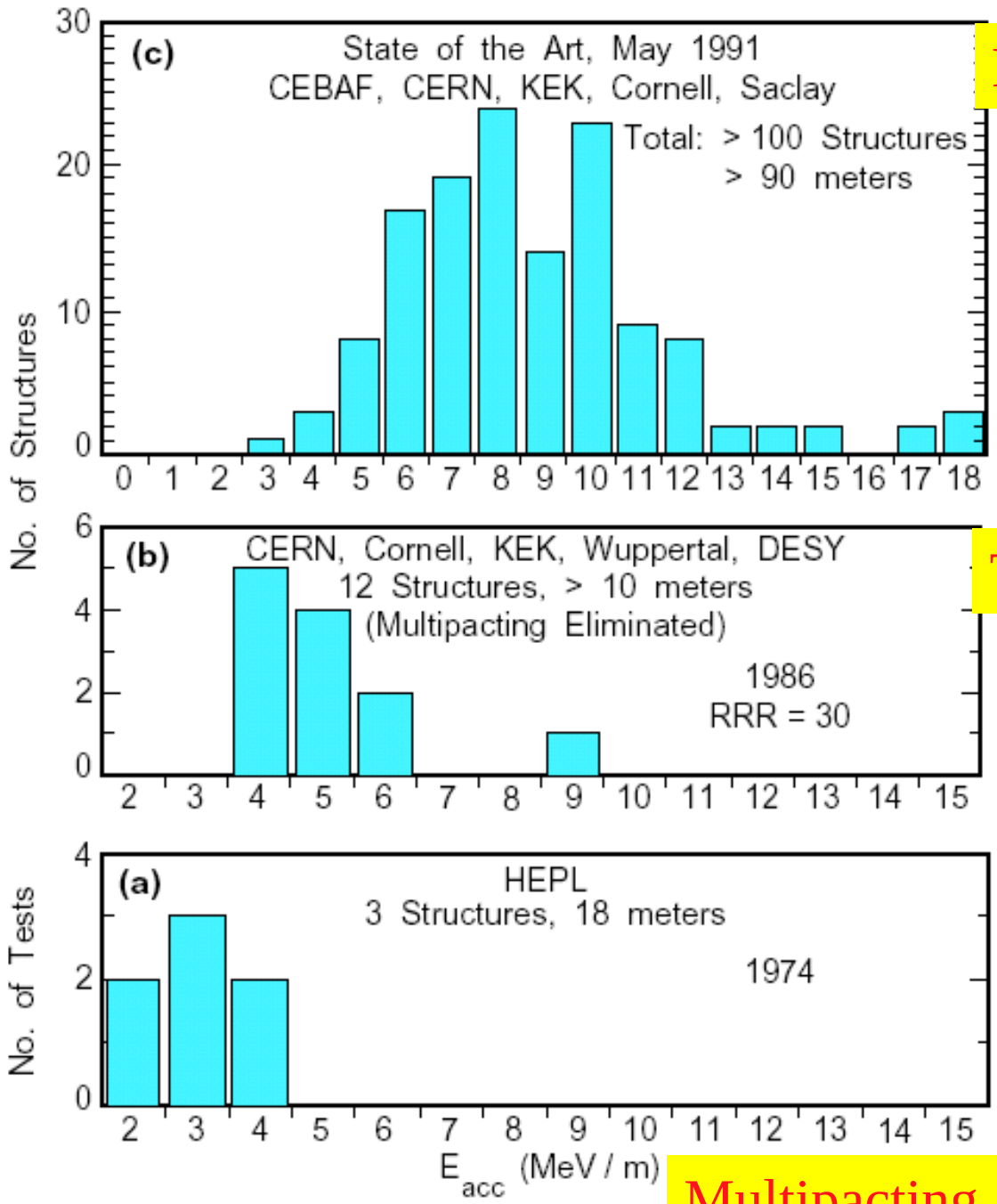


Field Emission

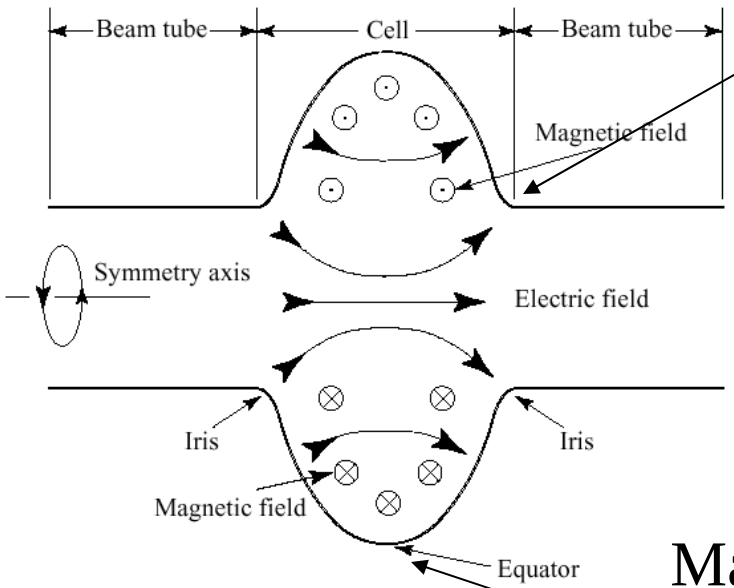
Thermal breakdown

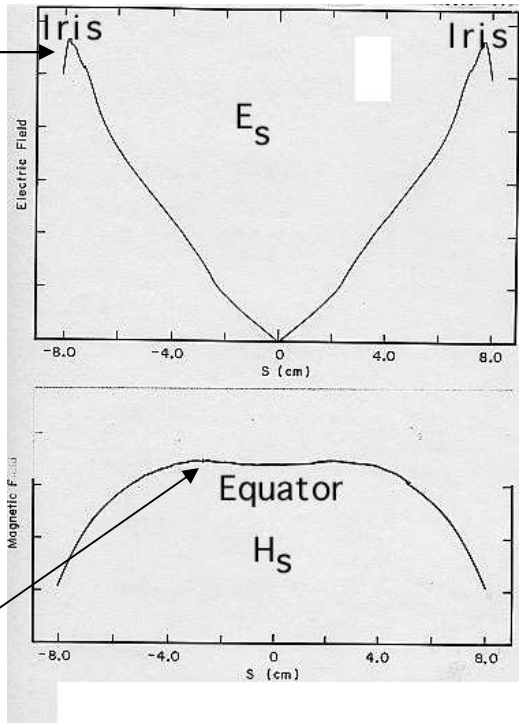
Multipacting

Success Story

Gradients have been improving steadily due to understanding of limiting phenomena and invention of effective cures

Electric field high at iris

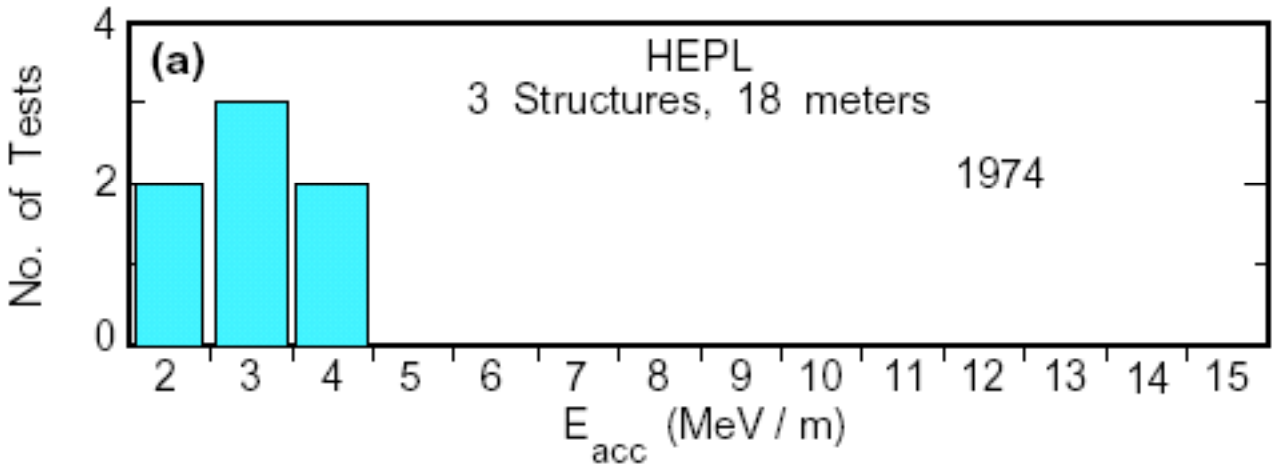




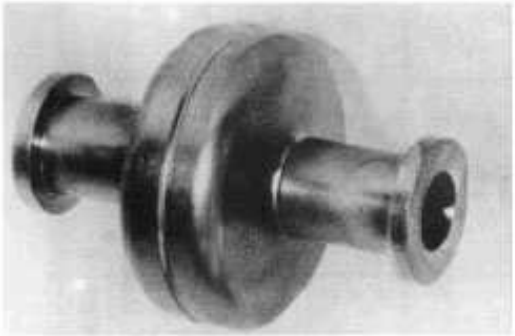
Magnetic field high at equator

Multipacting

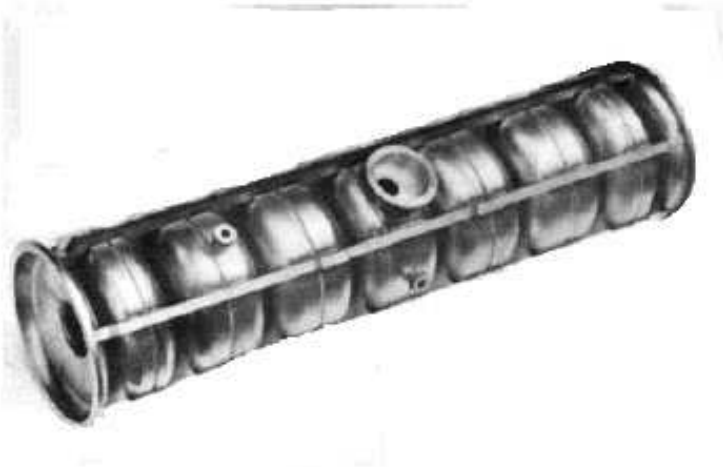
- MP is due to an exponential increase of electrons under certain resonance conditions



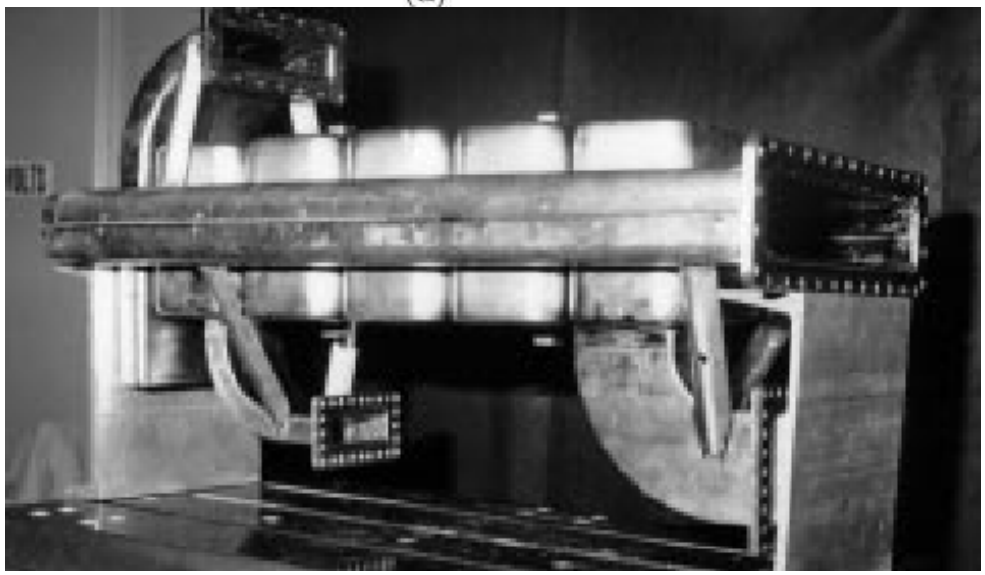
Multipacting in Nearly Pill-Box Shaped Cavities



(a)

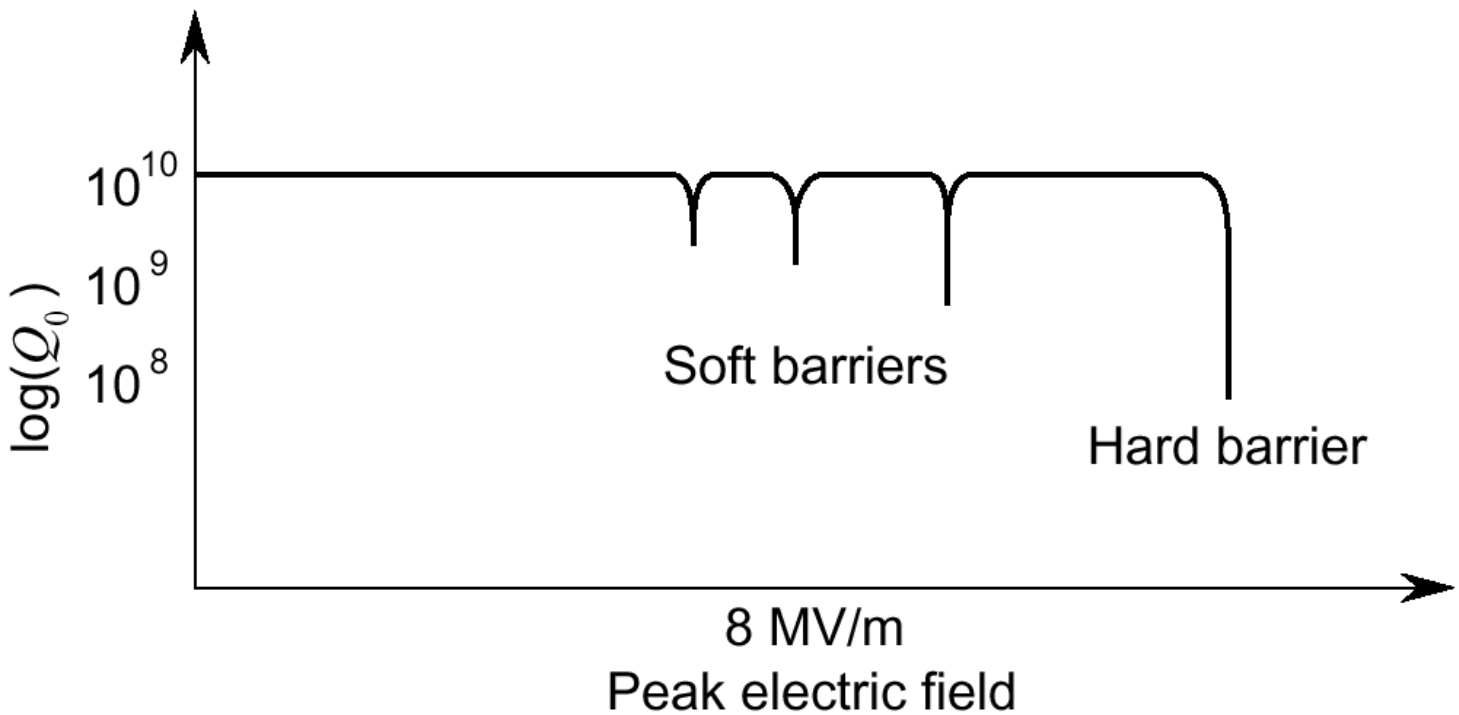


(b)



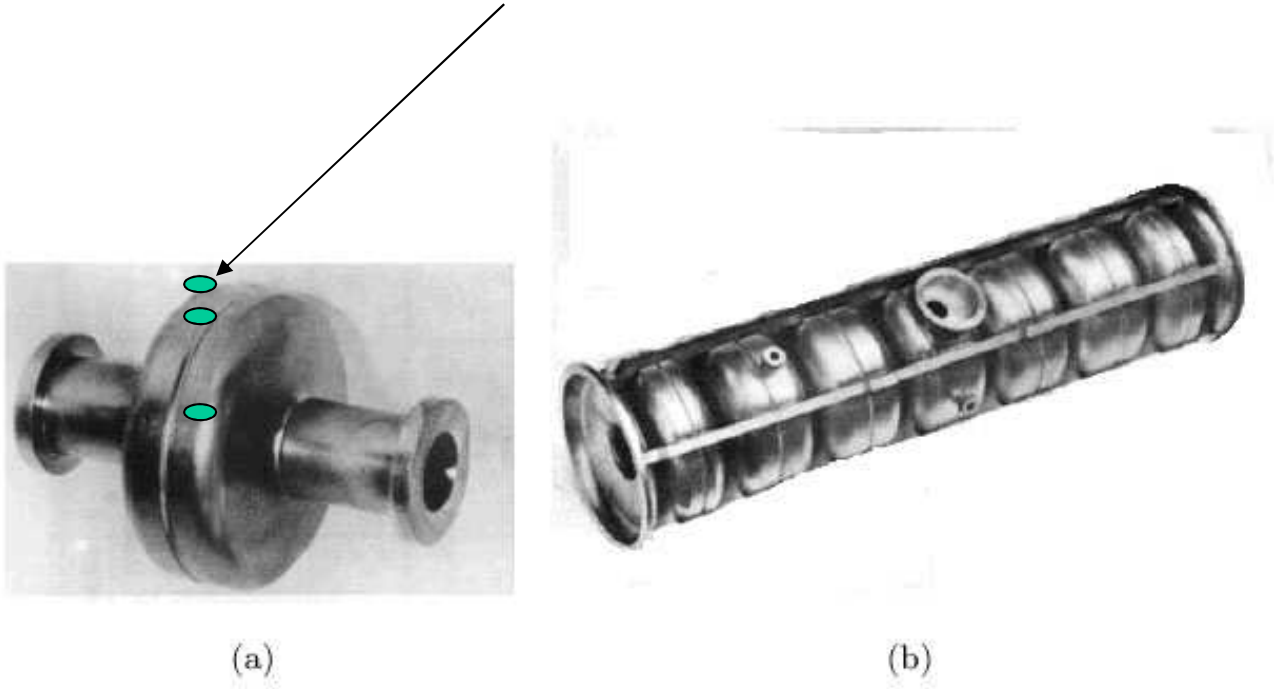
Early SRF cavity geometries frequently limited by multipacting, usually
at < 10 MV/m

Multipacting as Seen in Q vs E curve



Multipacting in Nearly Pill-Box Shaped Cavities

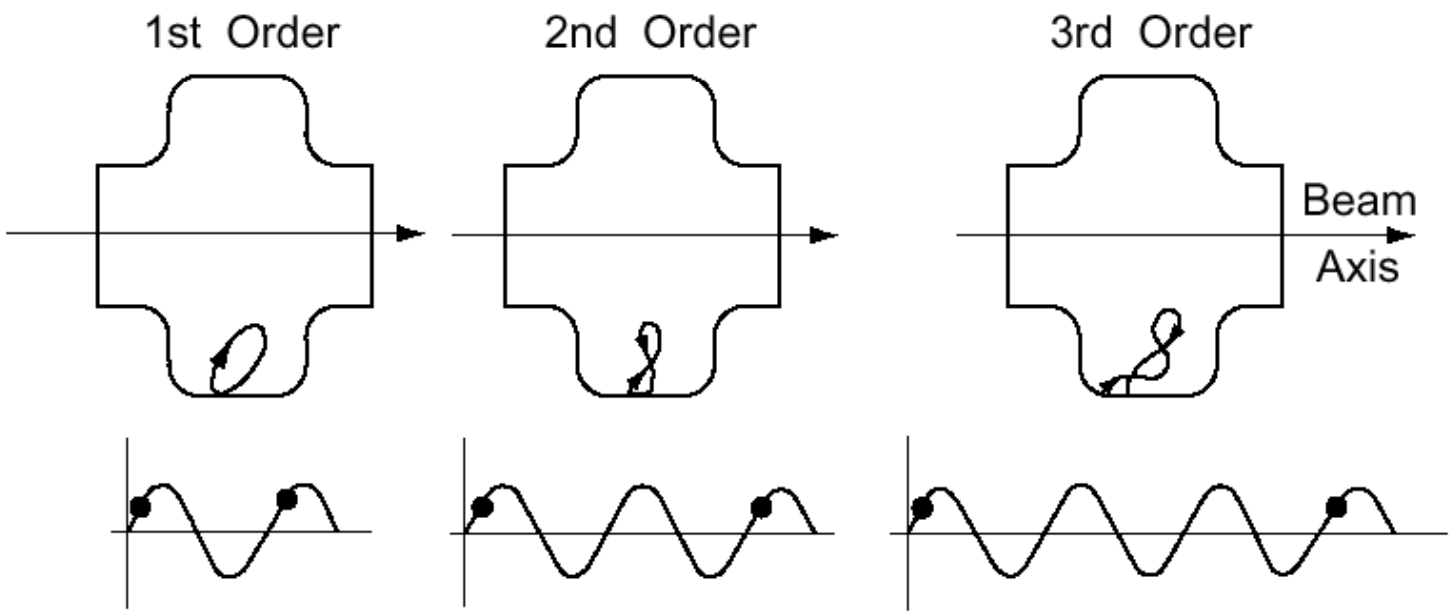
Thermometers show heating in barriers



(a) (b)

Multipacting

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



High Field ***Low Field***

Multipacting

Cyclotron frequency $$\omega_c \propto \frac{\mu_0 H e}{m}$$

Resonance condition:

Cavity frequency (ω_g) = n x cyclotron frequency $$\omega_g = n\omega_c$$

→ Possible MP barriers given by $$H_n \propto \frac{m\omega_g}{n\mu_0 e}$$

electrons are accelerated by the electric
field while the magnetic field turns them around, the impact energy scales as

$$K \propto \frac{e^2 E_\perp^2}{m\omega_g^2},$$

where $E_\perp$ is magnitude of the component of $\mathbf{E}$ perpendicular to the surface

Field Levels for Barriers

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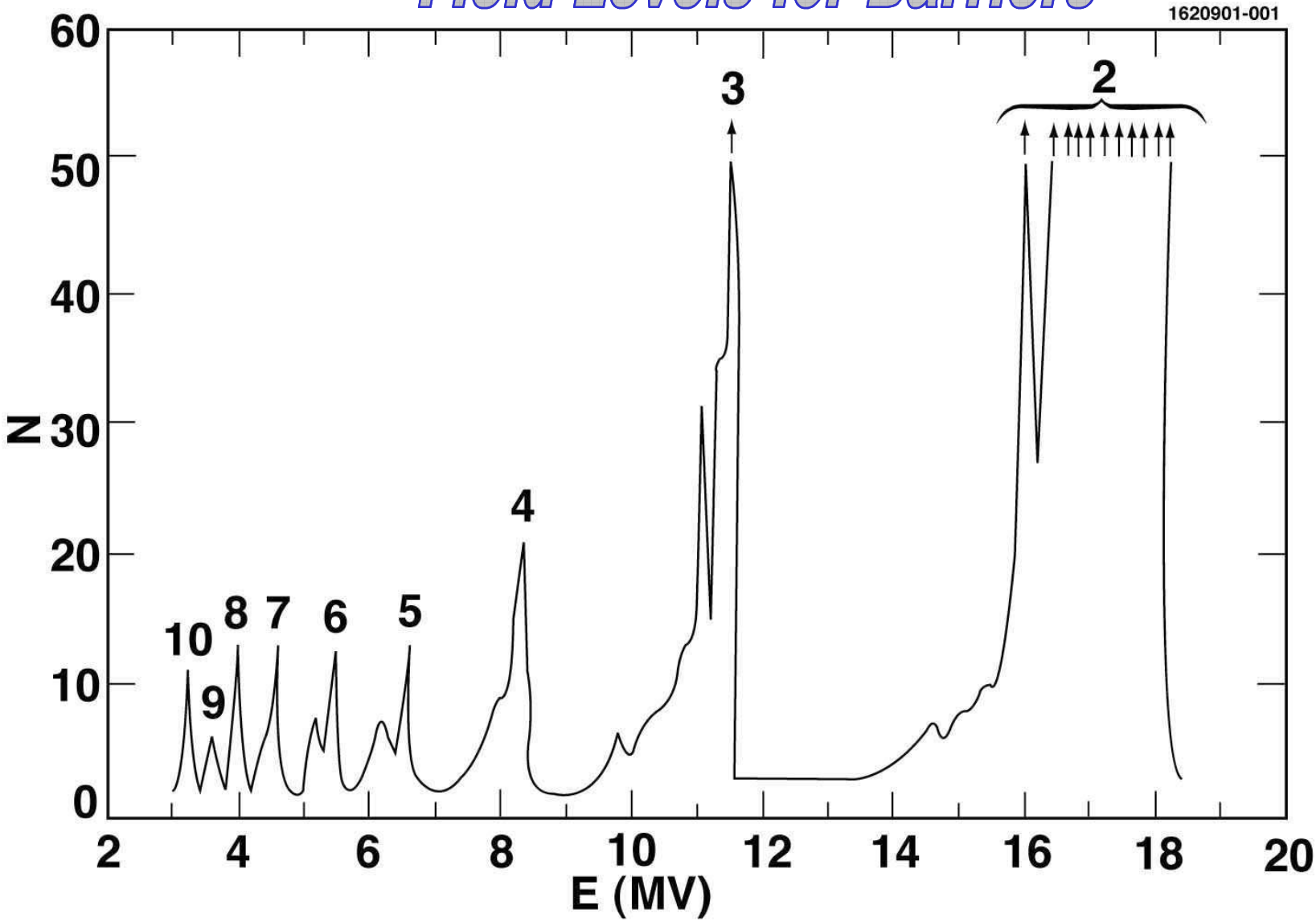

Simulated Trajectories

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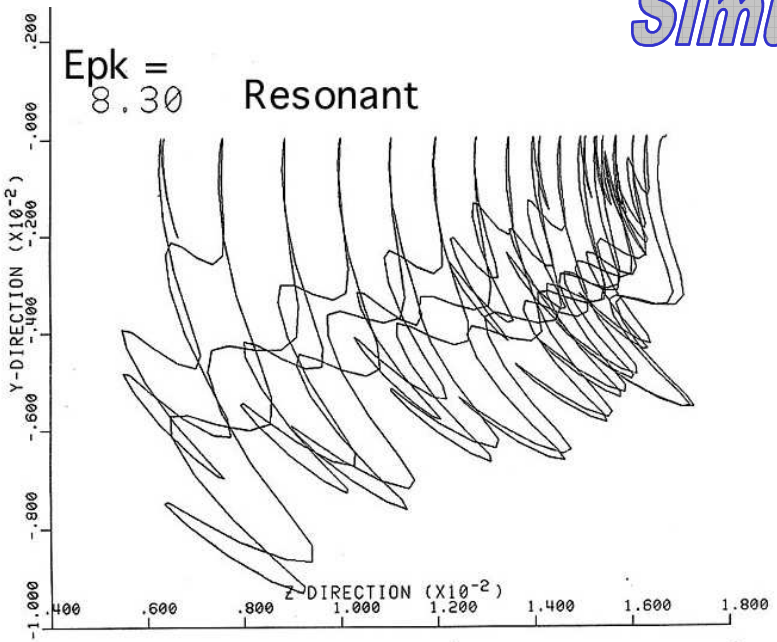
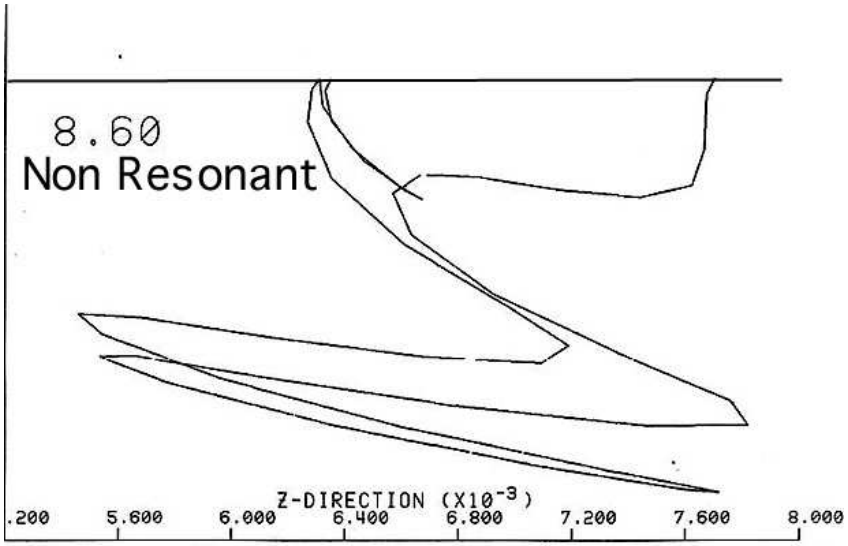
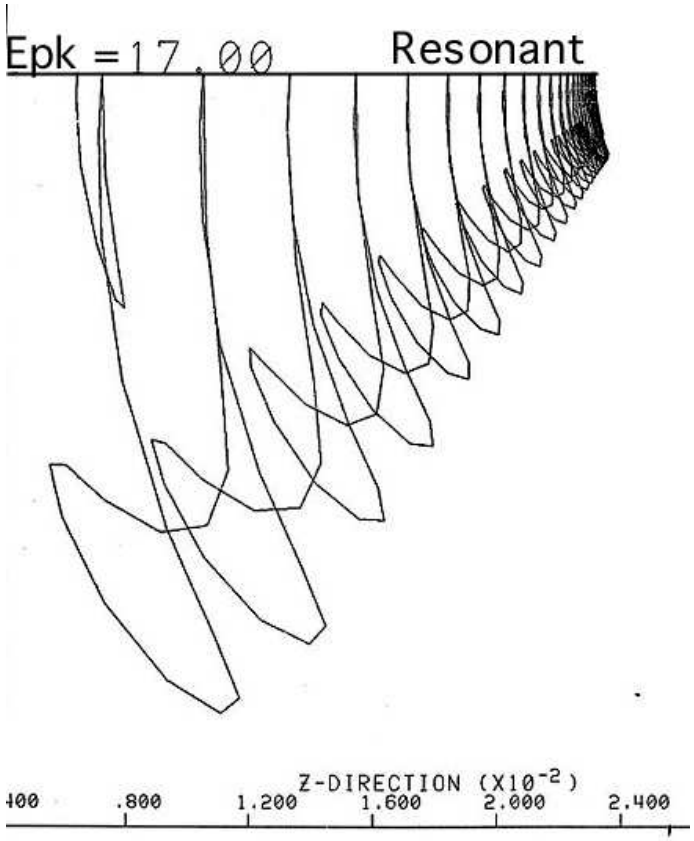
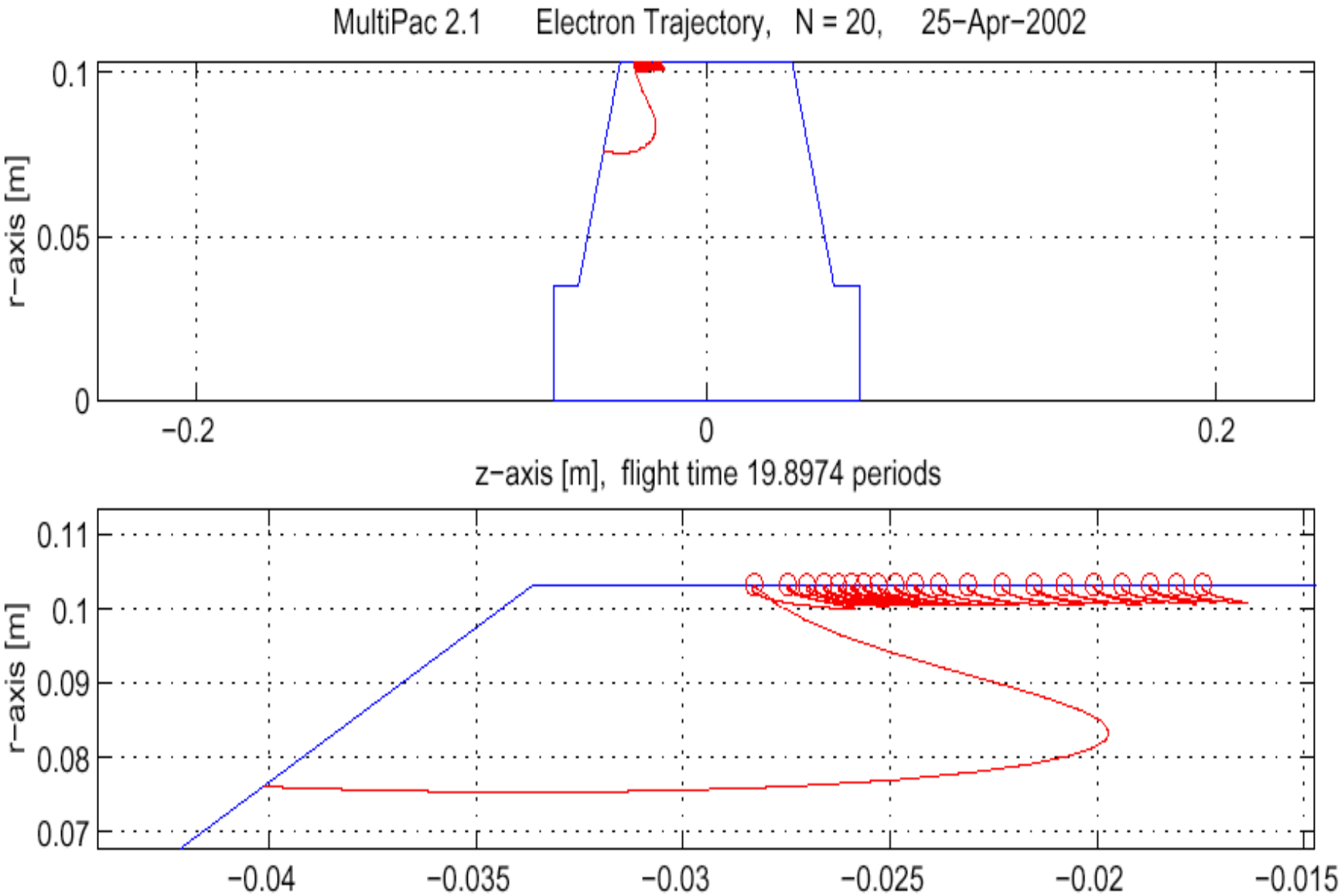




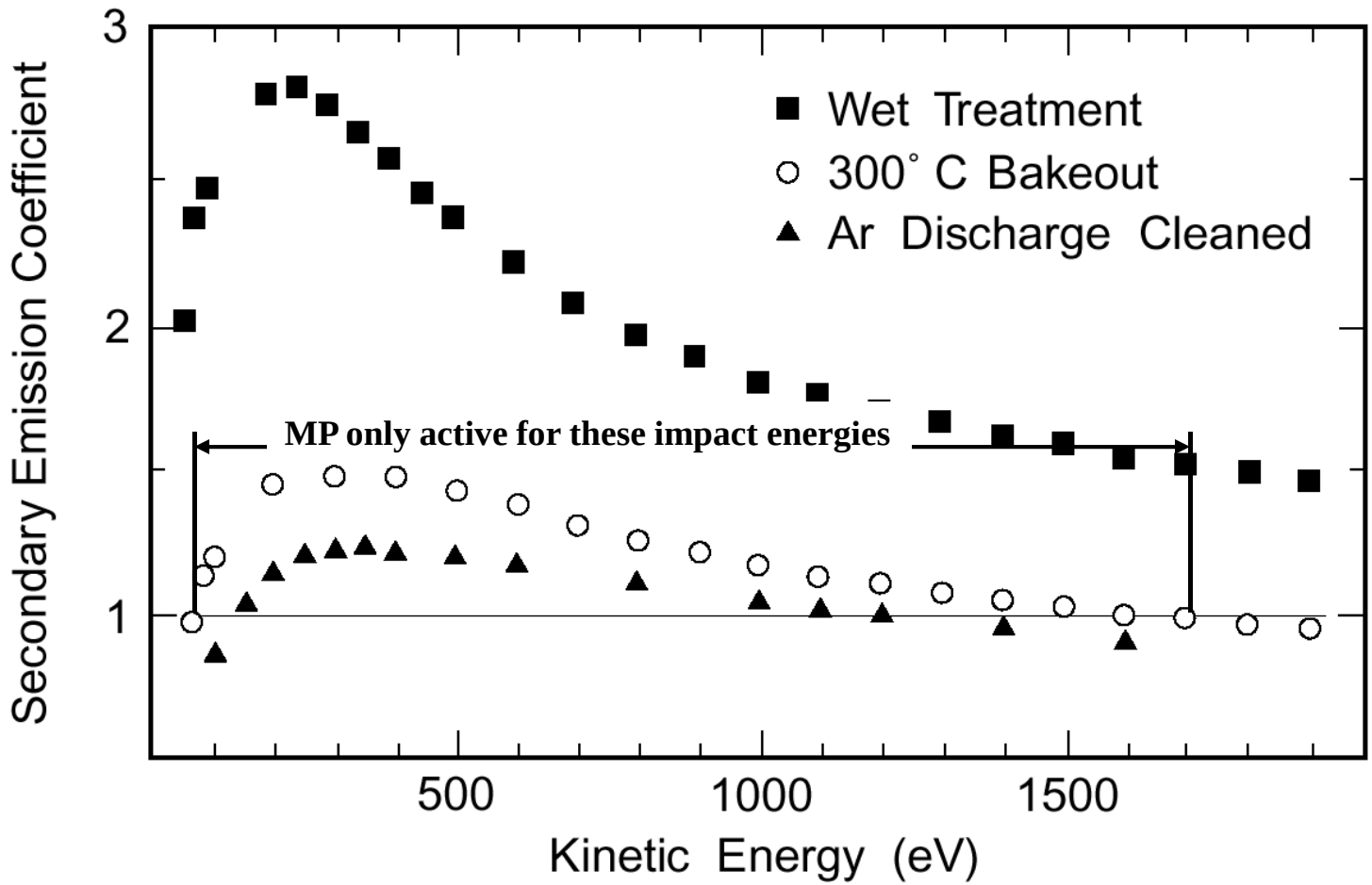


Many MP Simulation Codes Exist



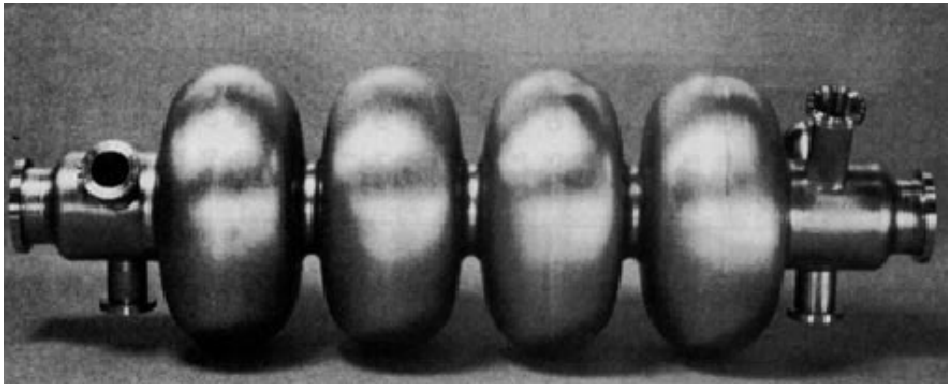
Multipacting, Secondary Emission Coefficient

- Not all potential barriers are active because electron multiplication has to exceed unity.

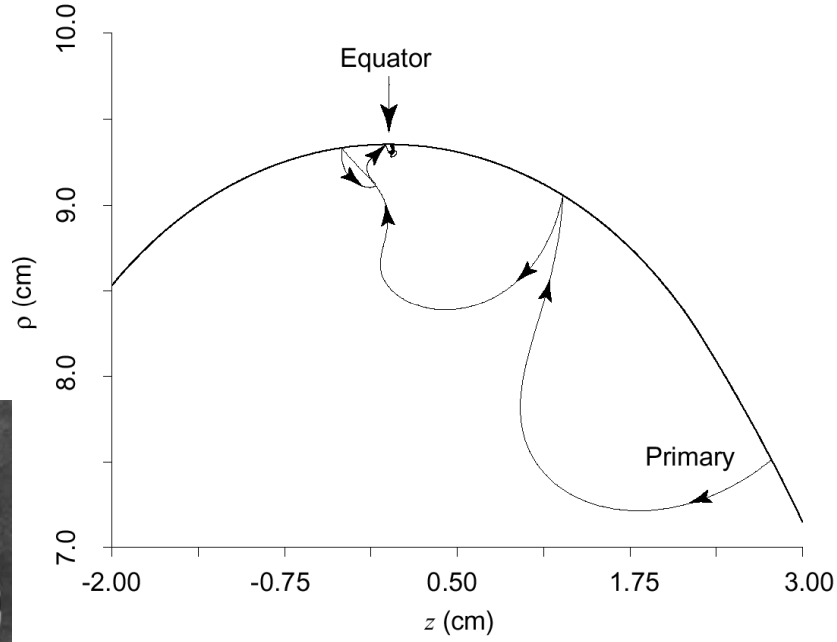


Multipacting Solution

- In cavities, solved multipacting by adopting a spherical, (elliptical) shape.

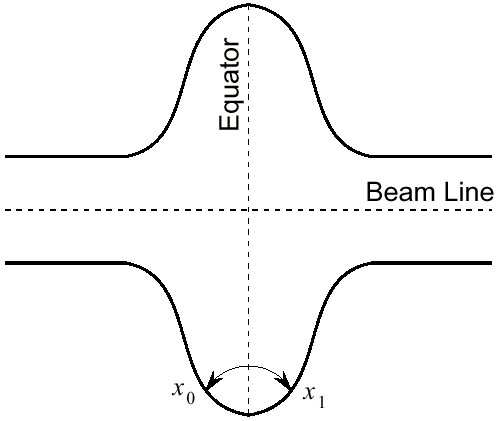


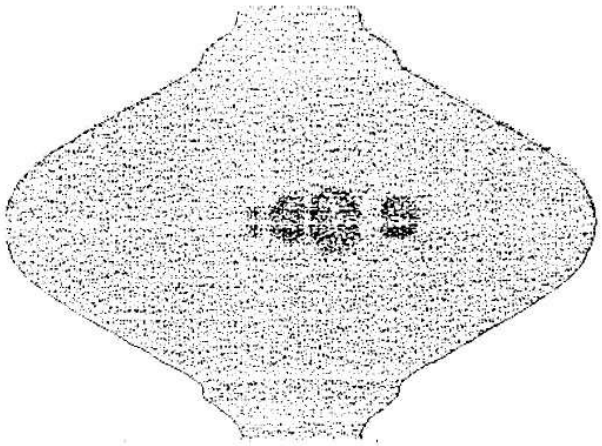
350-MHz LEP-II cavity (CERN)

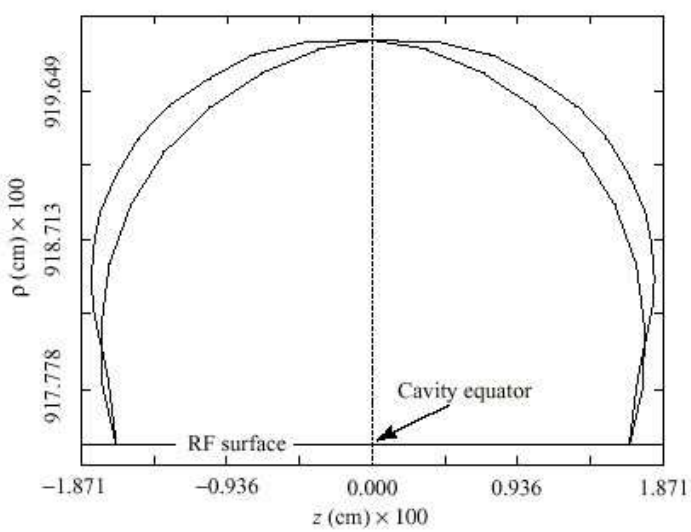


Electrons drift to equator
Electric field at equator is ≈ 0
→MP electrons don't gain energy
→MP stops

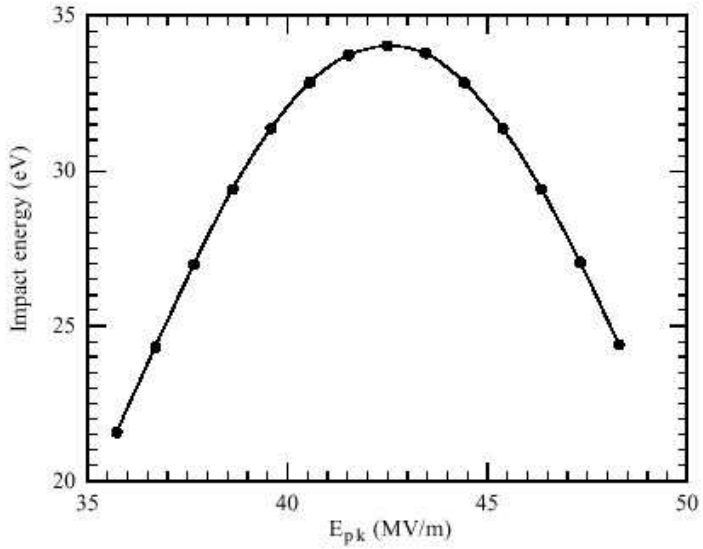
Two Point Multipacting







(a)



(b)

Two Side Multipacting Simulation

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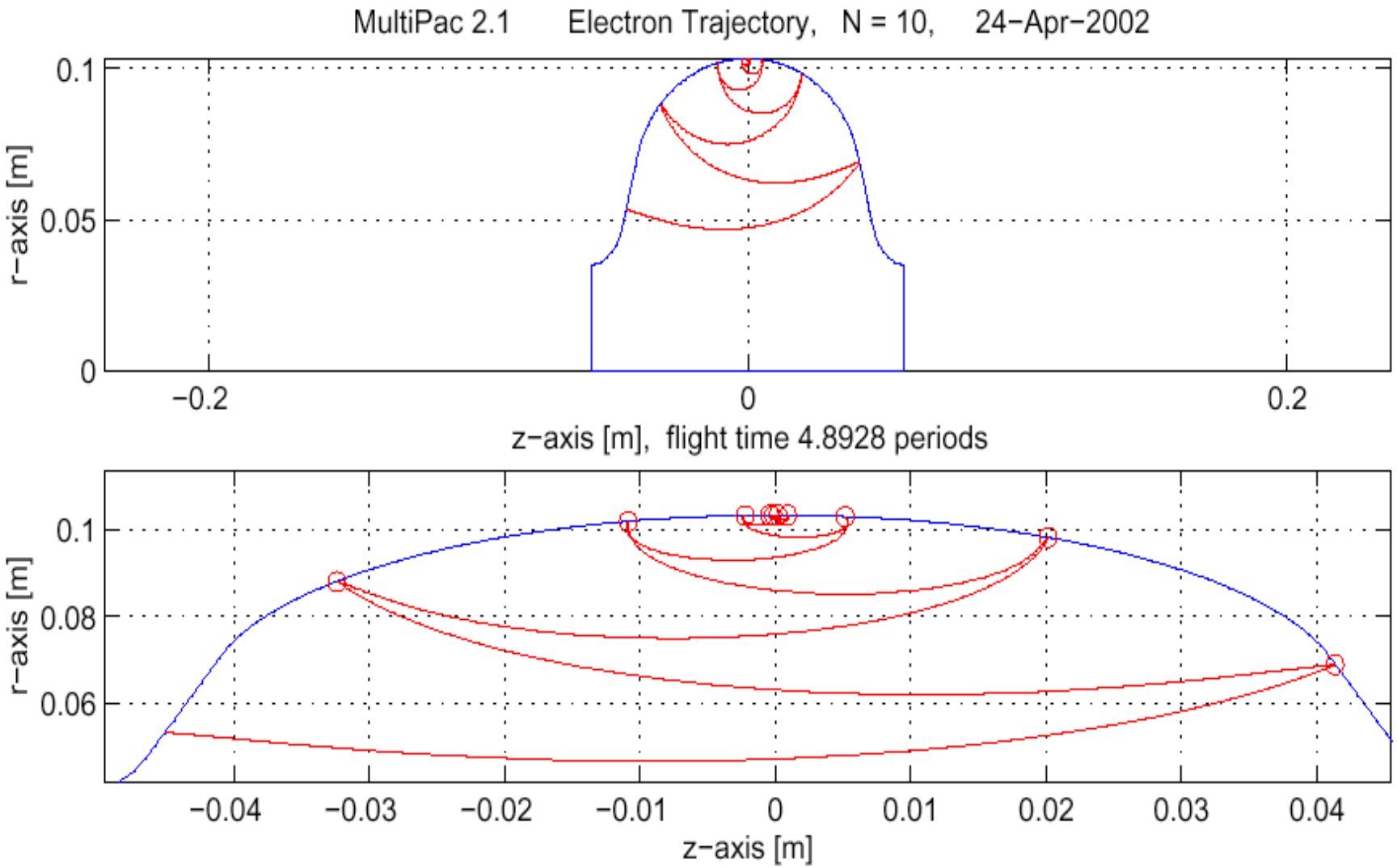

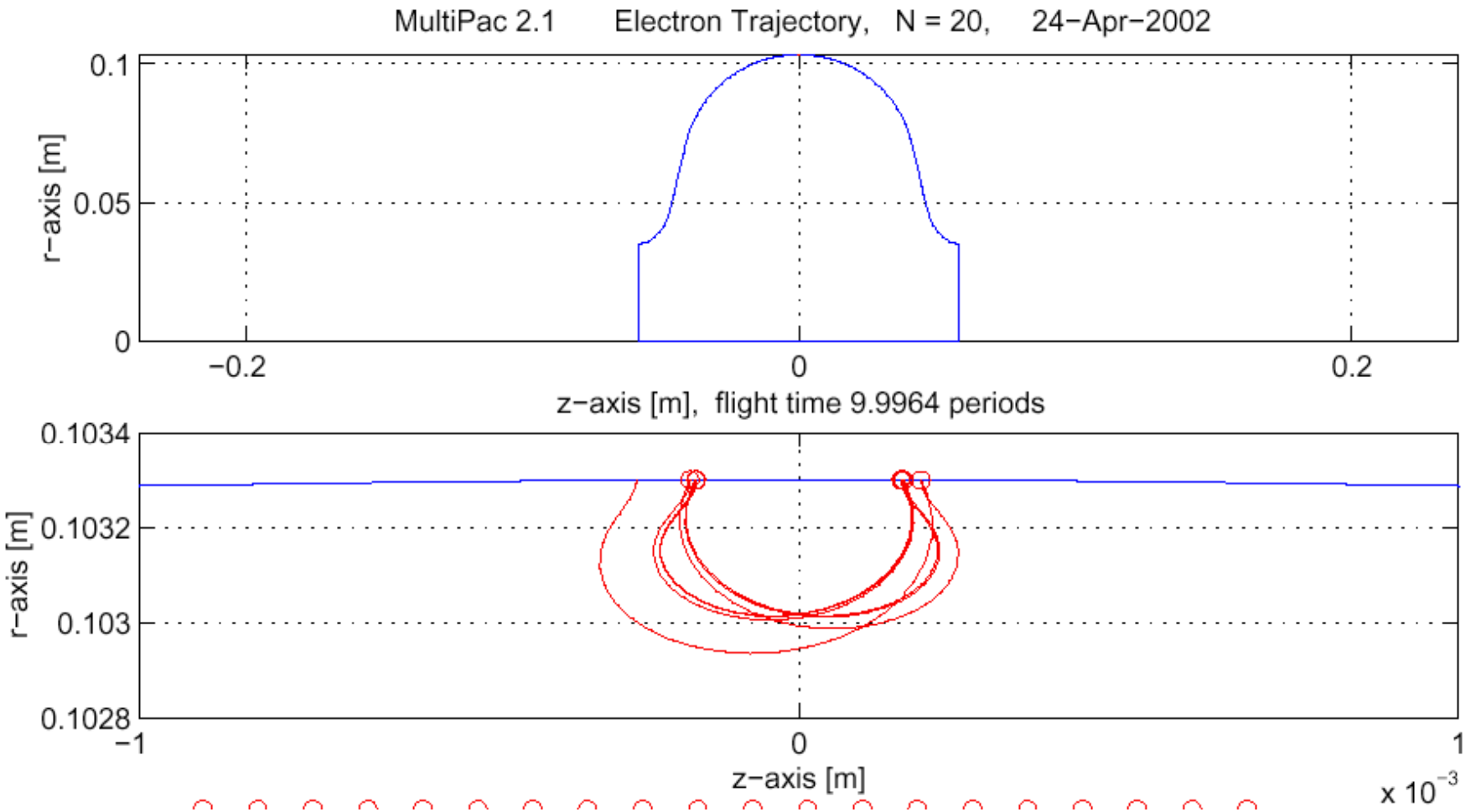
MultiPac 2.1 Electron Trajectory, N = 20, 24−Apr−2002
0.1
0.05
0
r−axis [m]
−0.2
0
0.2
z−axis [m], flight time 9.9964 periods
0.1034
0.1032
0.103
0.1028
r−axis [m]
−1
0
1
z−axis [m]
x 10^−3

Study Field Limitations Using Thermometry

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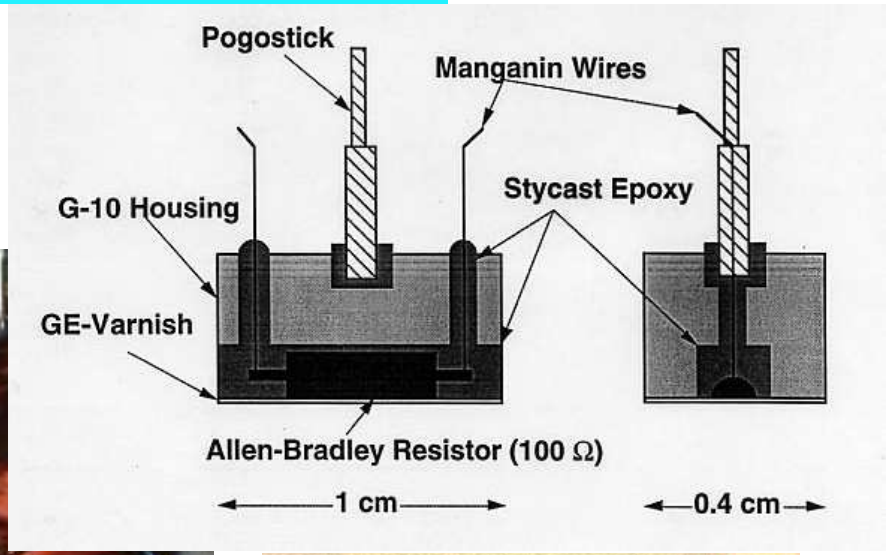

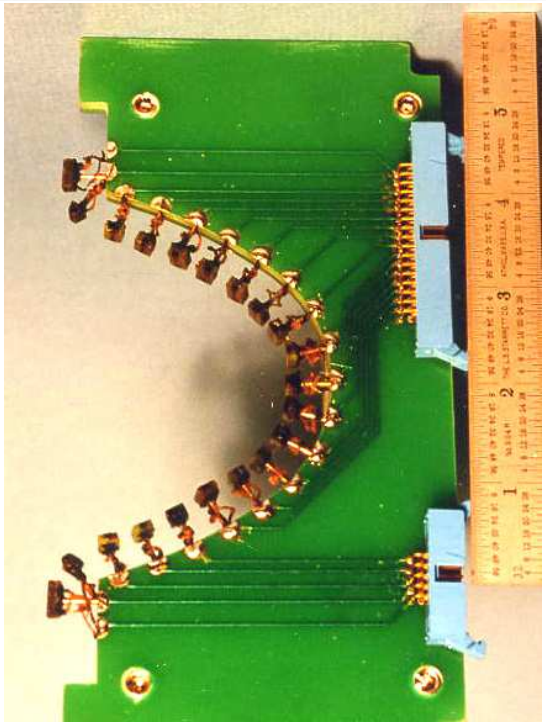

Temperature Map Movie for Two Point Multipacting Resulting in Thermal Breakdown

Thermal Breakdown From Defects

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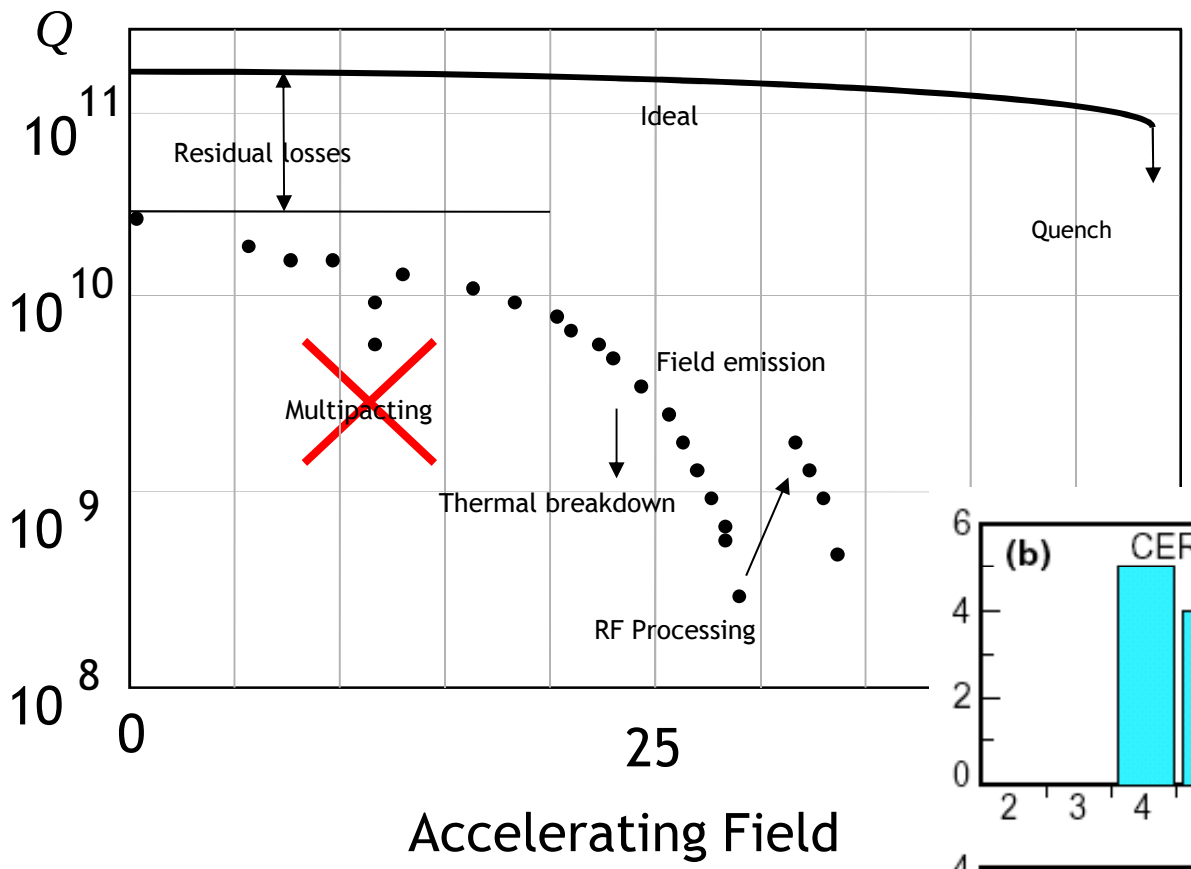
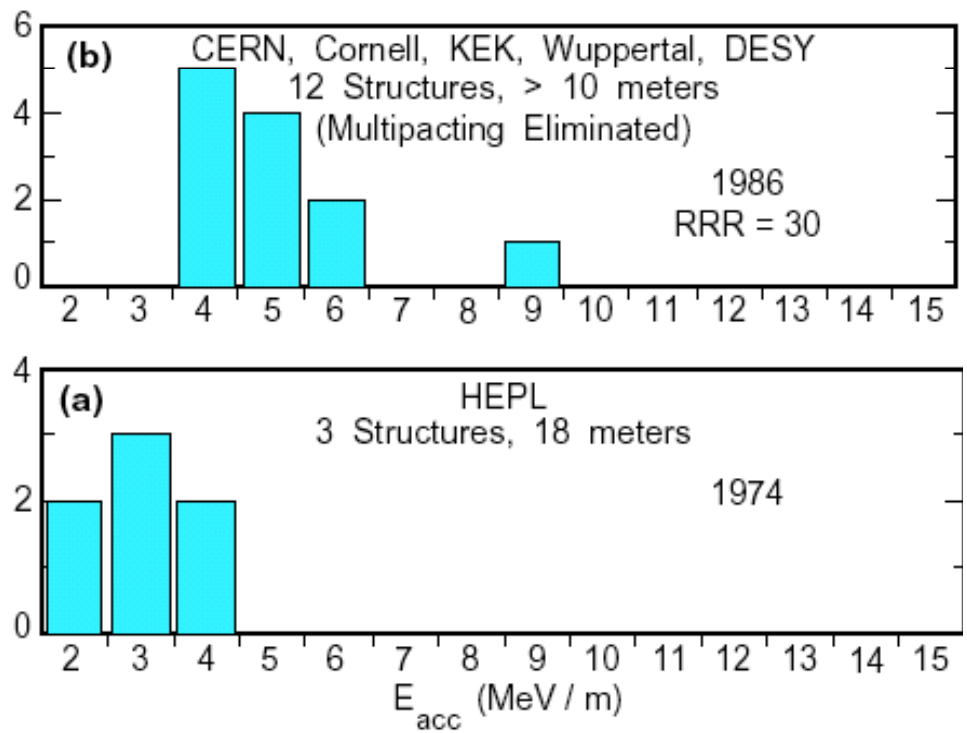
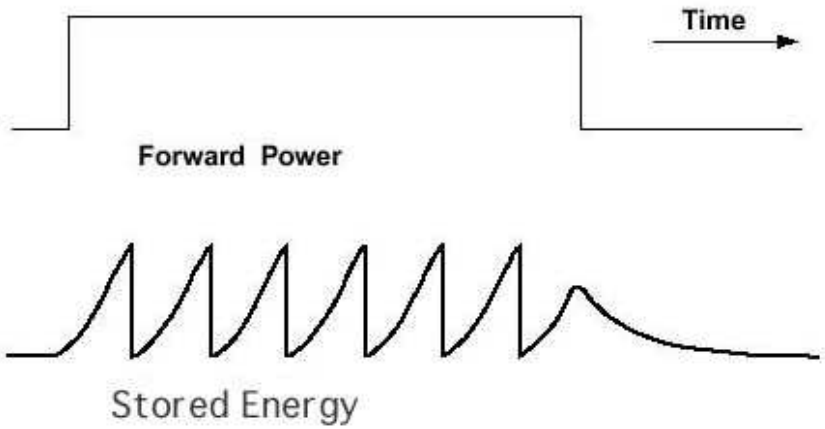


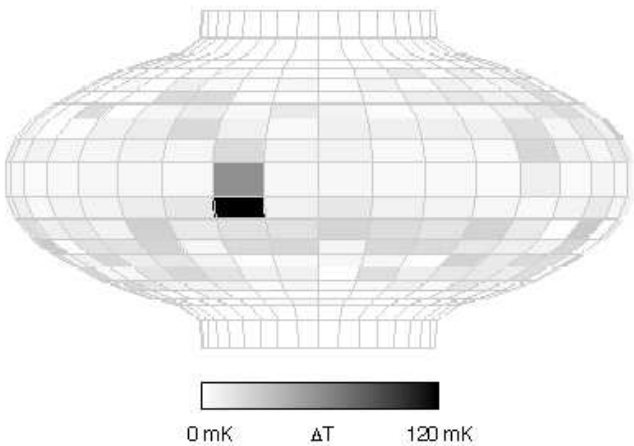


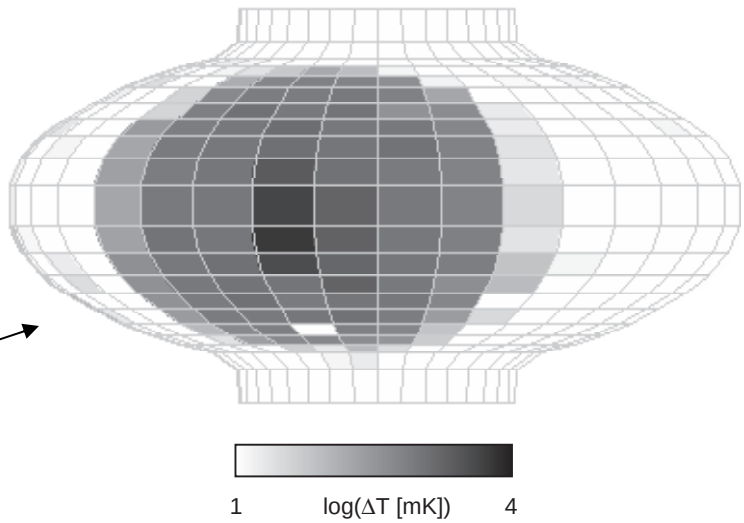
Thermal Breakdown

- Very strong heating observed over extended areas.
- Often centered on a hotspot.

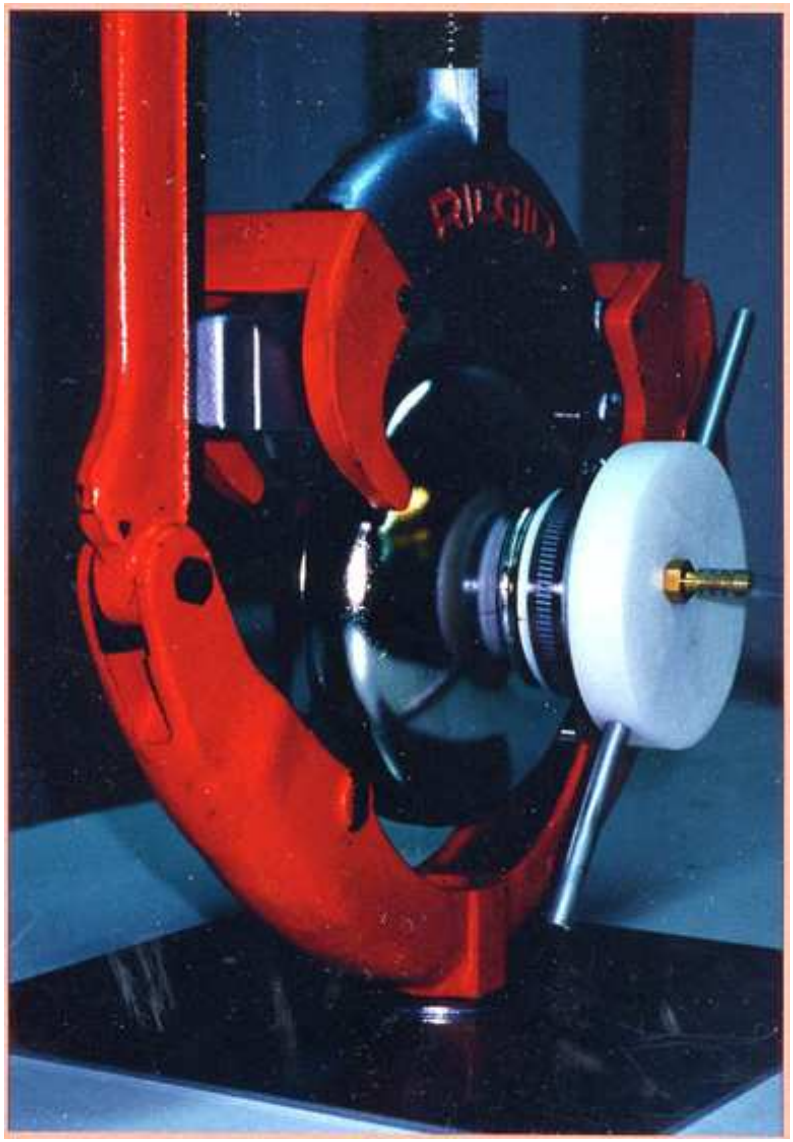


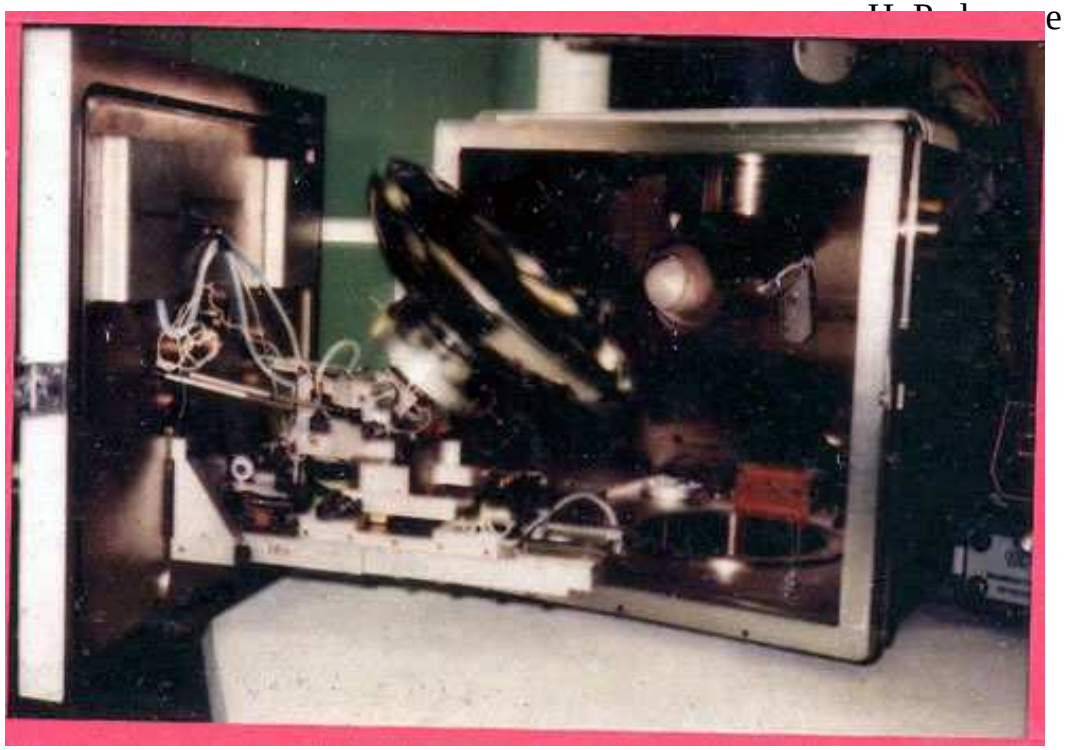
Field cannot be increased!

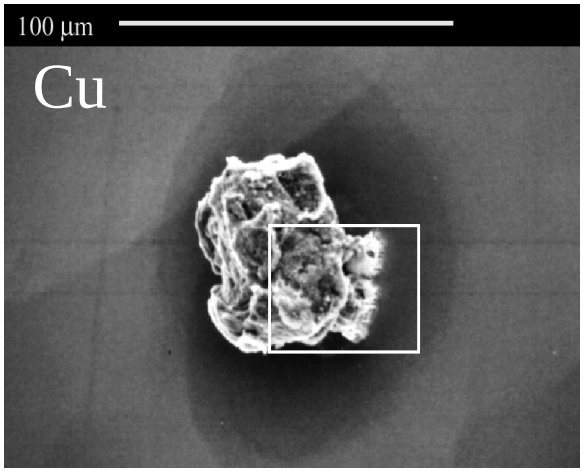




Temperature Map Movie of Defect Induced Quench







Dissection

Theory of thermal breakdown

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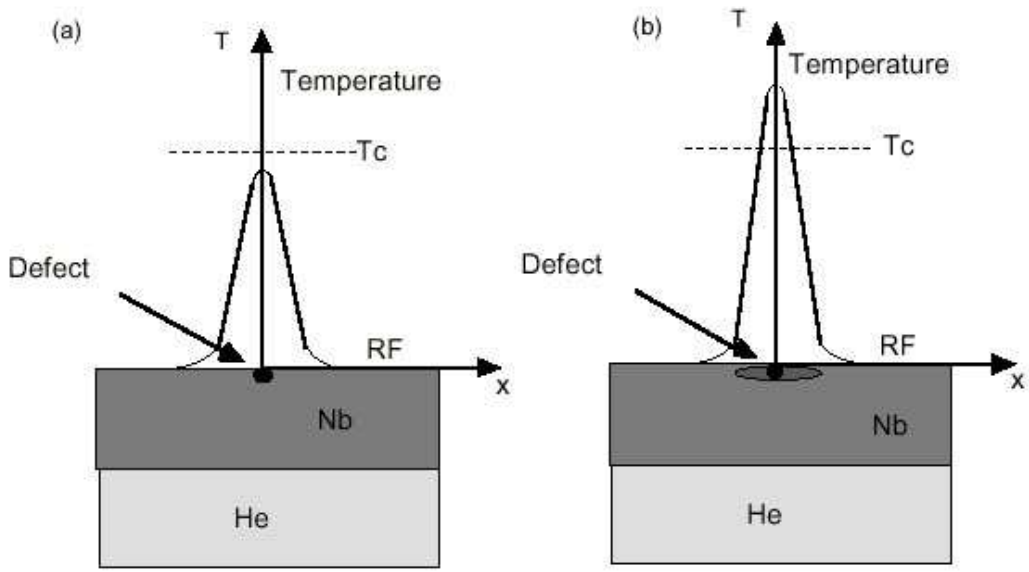


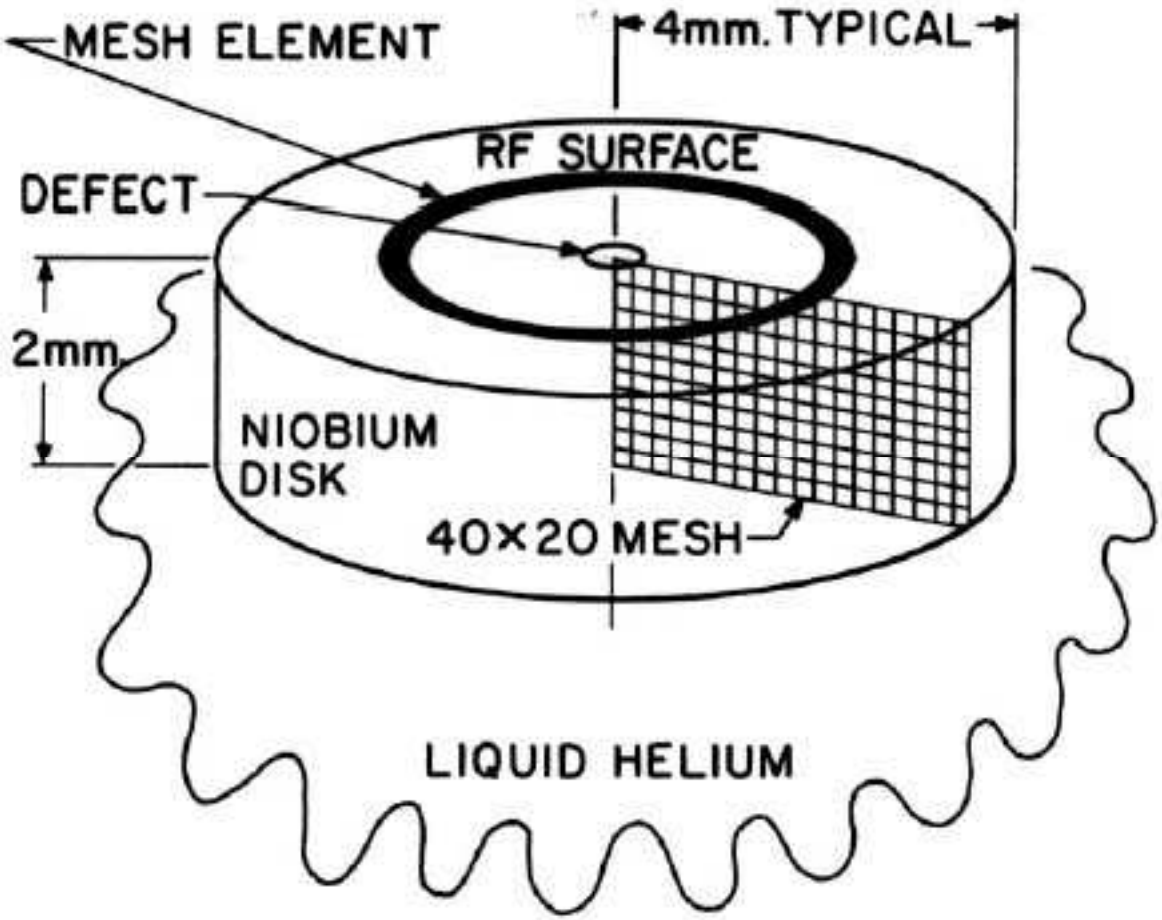
- TB is a premature *quench* of the superconducting state.
- A normal conducting spot triggers quench when it heats the Nb above T_c.

Breakdown field given by
(very approximately):

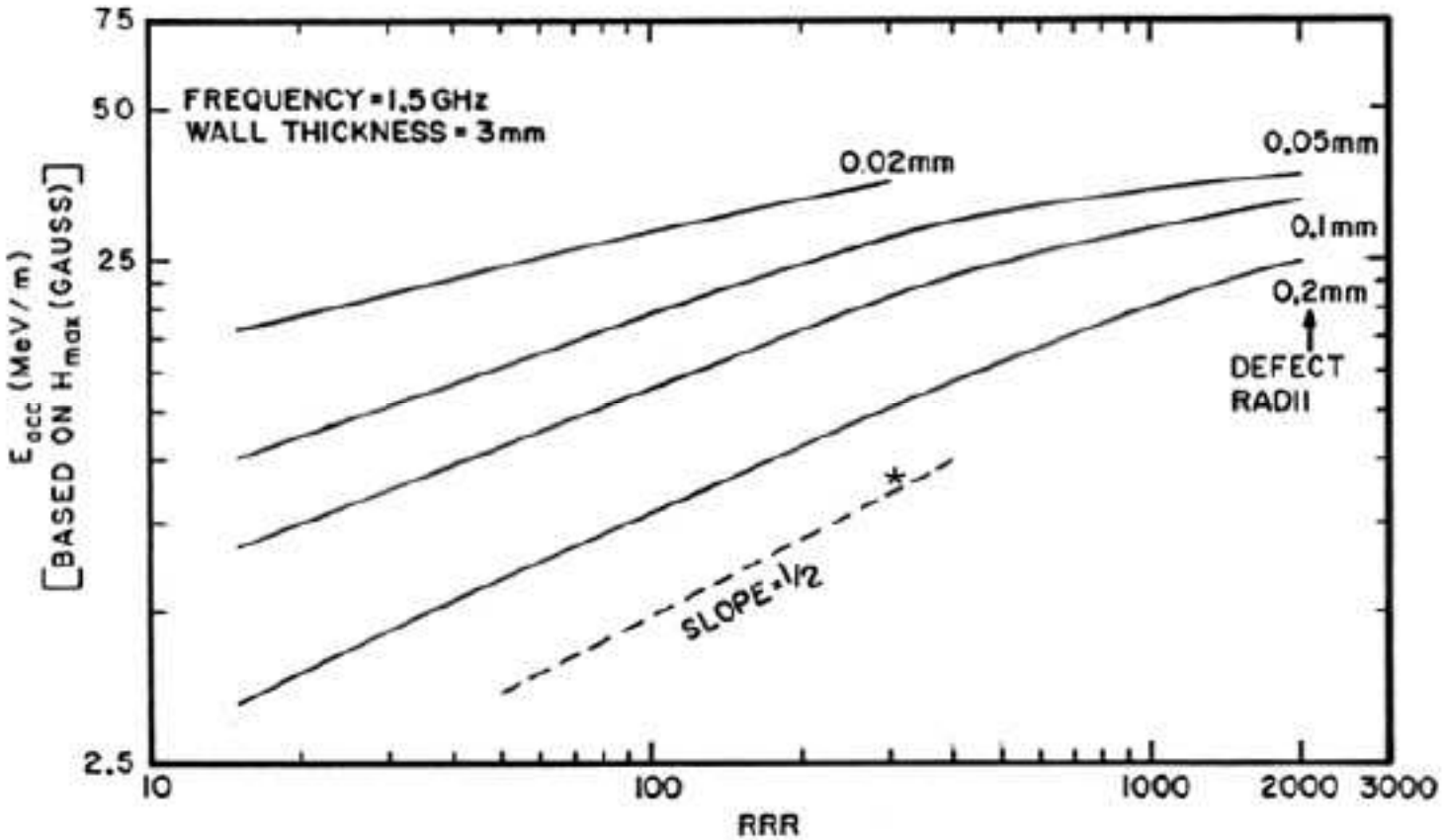
$$H_{tb} = \sqrt{\frac{4\kappa_T (T_c - T_b)}{r_d R_d}}$$

κ_T: Thermal conductivity of Nb
R_d: Defect surface resistance
T_c: Critical temperature of Nb
T_b: Bath temperature

Simulation


MESH ELEMENT
4mm. TYPICAL
RF SURFACE
DEFECT
2mm
NIOBIUM DISK
40×20 MESH
LIQUID HELIUM

Simulations for Thermal Breakdown



Typical Defects

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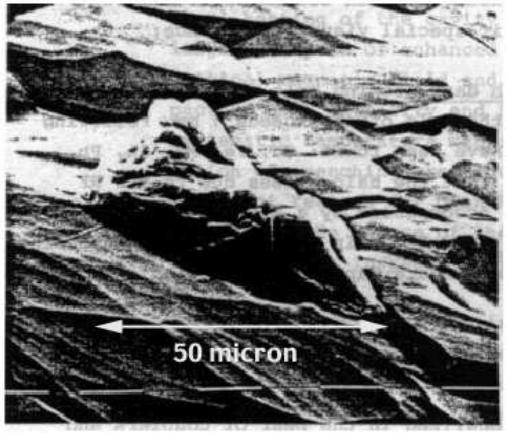
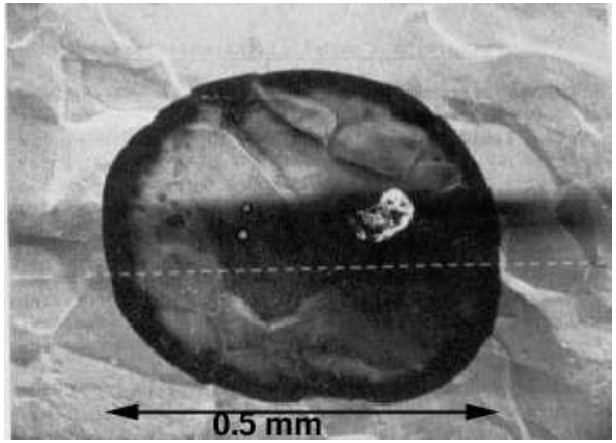
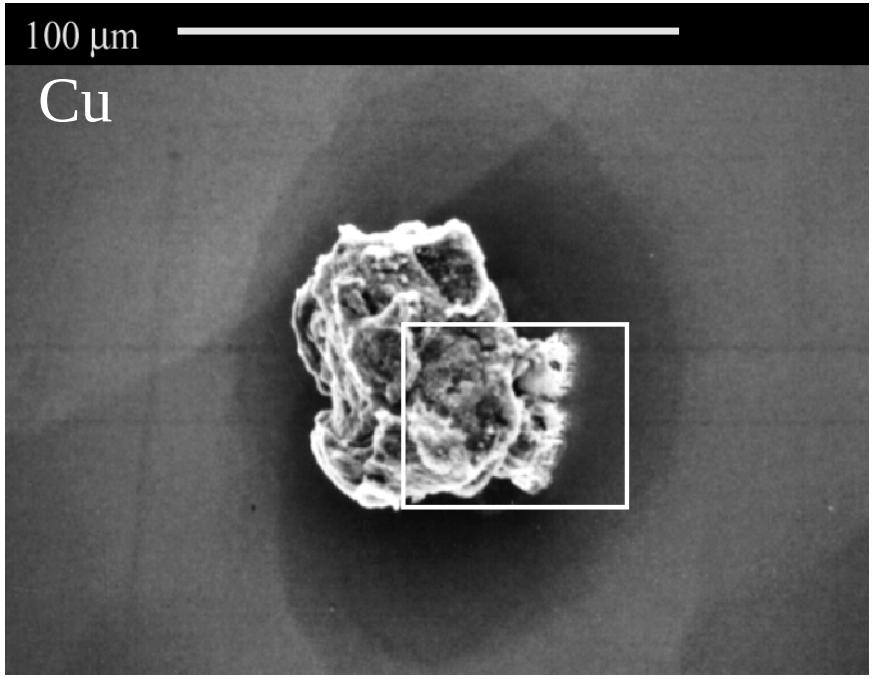
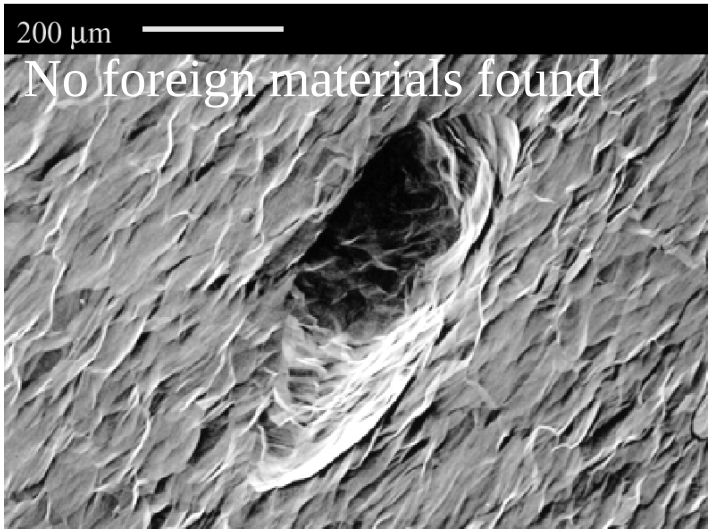








Surface defects, holes can also cause TB

0.1 – 1 mm size defects cause TB

Avoiding Thermal Breakdown

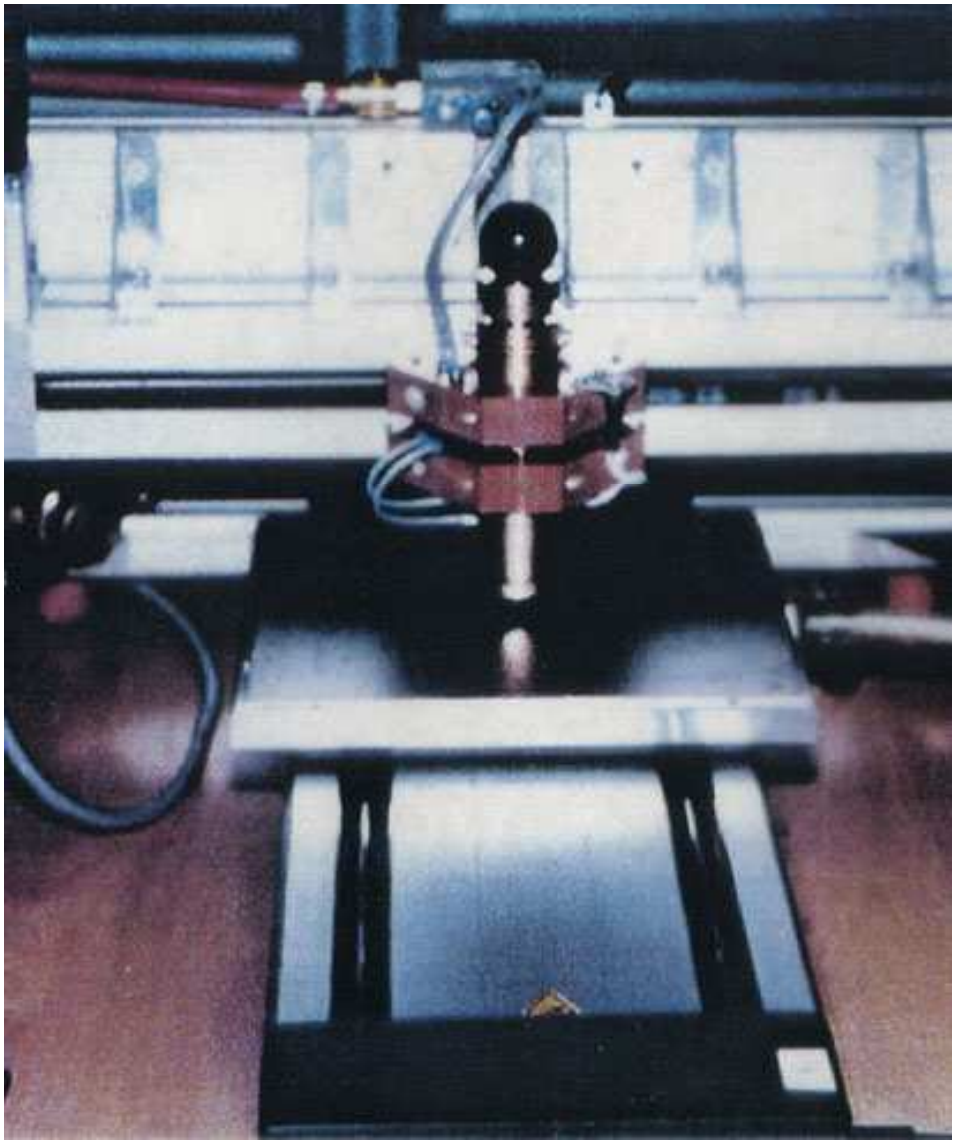
A. Avoid the defects (easier said than done!)

- High quality Nb (e.g., rollers during production run must be very clean to avoid embedding inclusions)
- Good cavity production techniques (deep drawing, spinning, welding …)
- Clean assembly of all cavity vacuum equipment

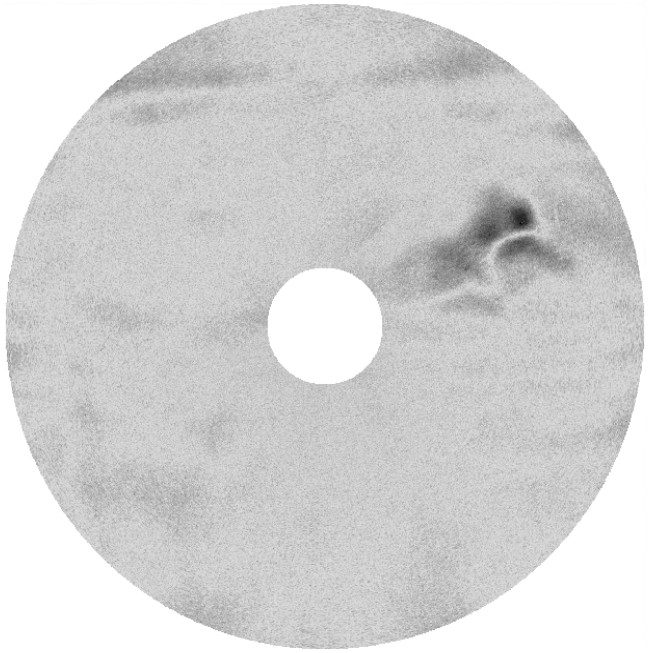
B. Tolerate unavoidable defects but "neutralize" them by thermally stabilizing them → improve the thermal conductivity of Nb.

$$H_{tb} = \sqrt{\frac{4\kappa_T (T_c - T_b)}{r_d R_d}} \quad H_{\mathrm{tb}}\uparrow \text{ if } \kappa_T \uparrow$$

Avoiding Defects



Eddy Current
Scanning Device



Eddy Currents to Check the Niobium

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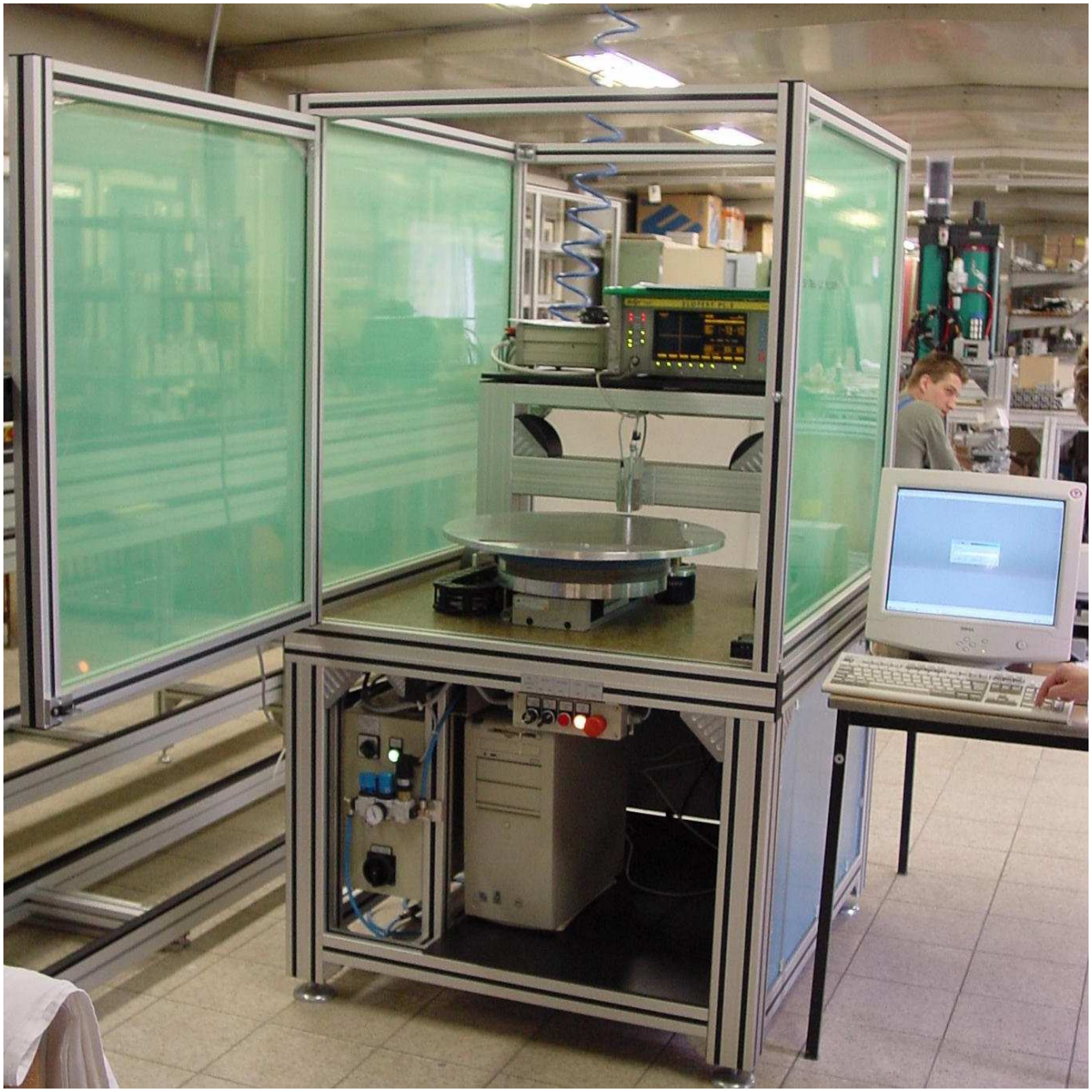
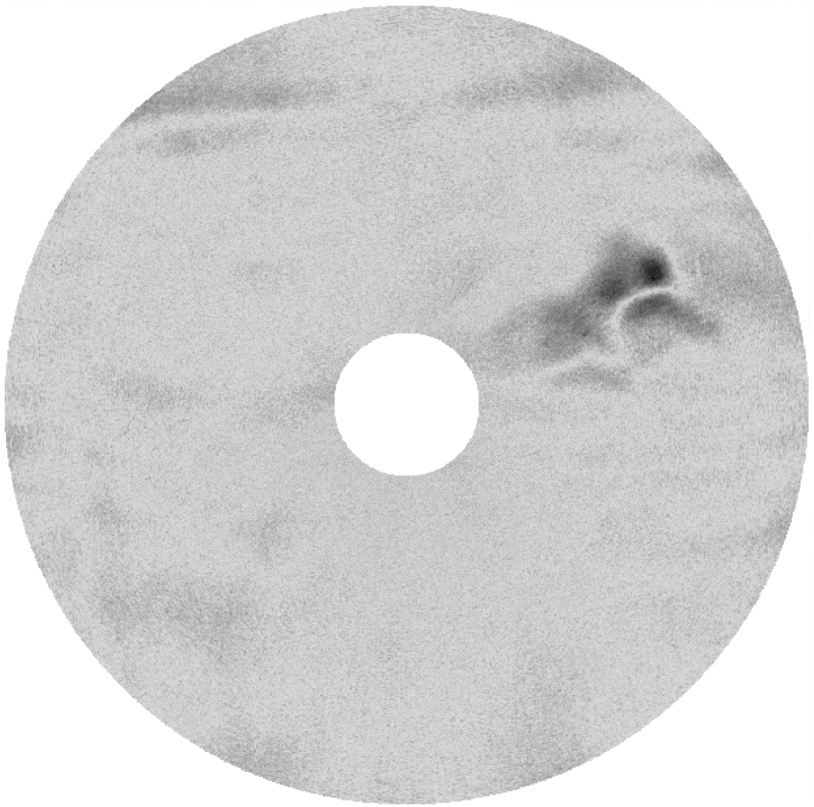
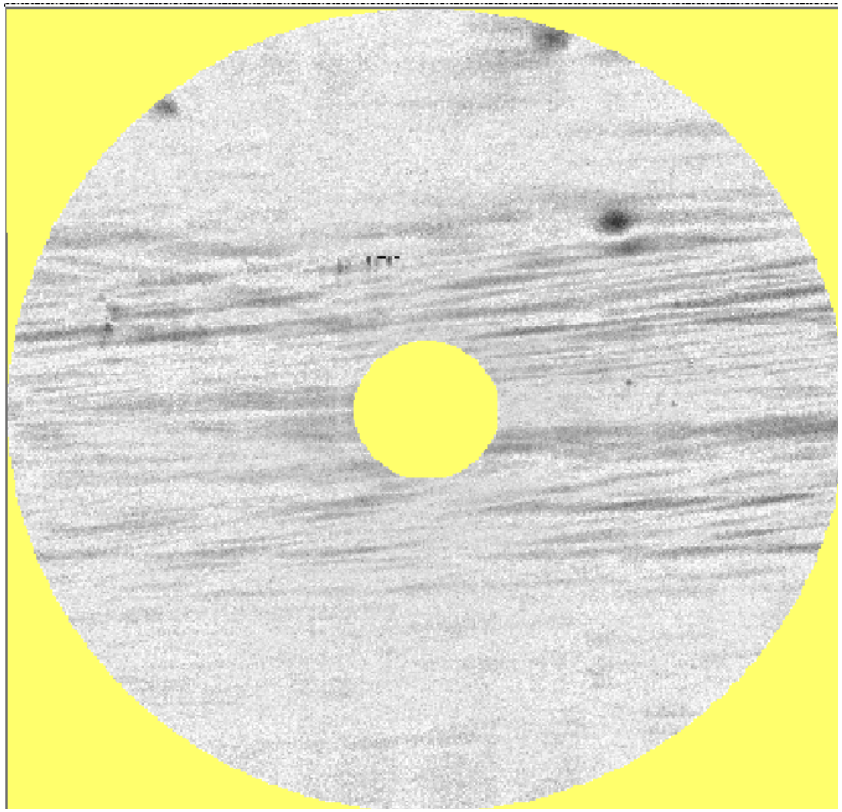
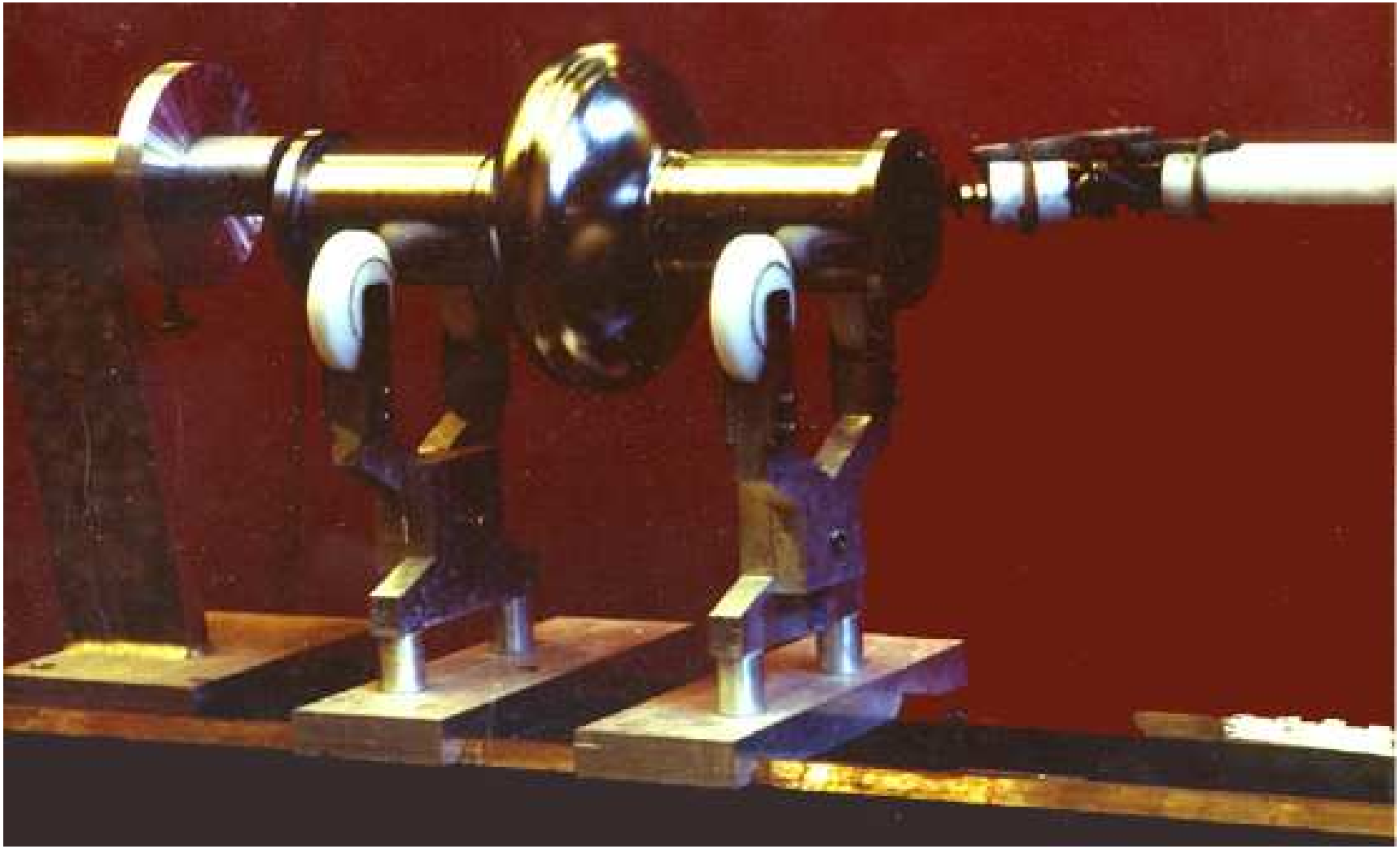


Large inclusions as well as bad spots on the niobium surface can be found, also non harmful signatures such as rolling lines.





Repair Defect By Grinding



Thermal Conductivity and RRR

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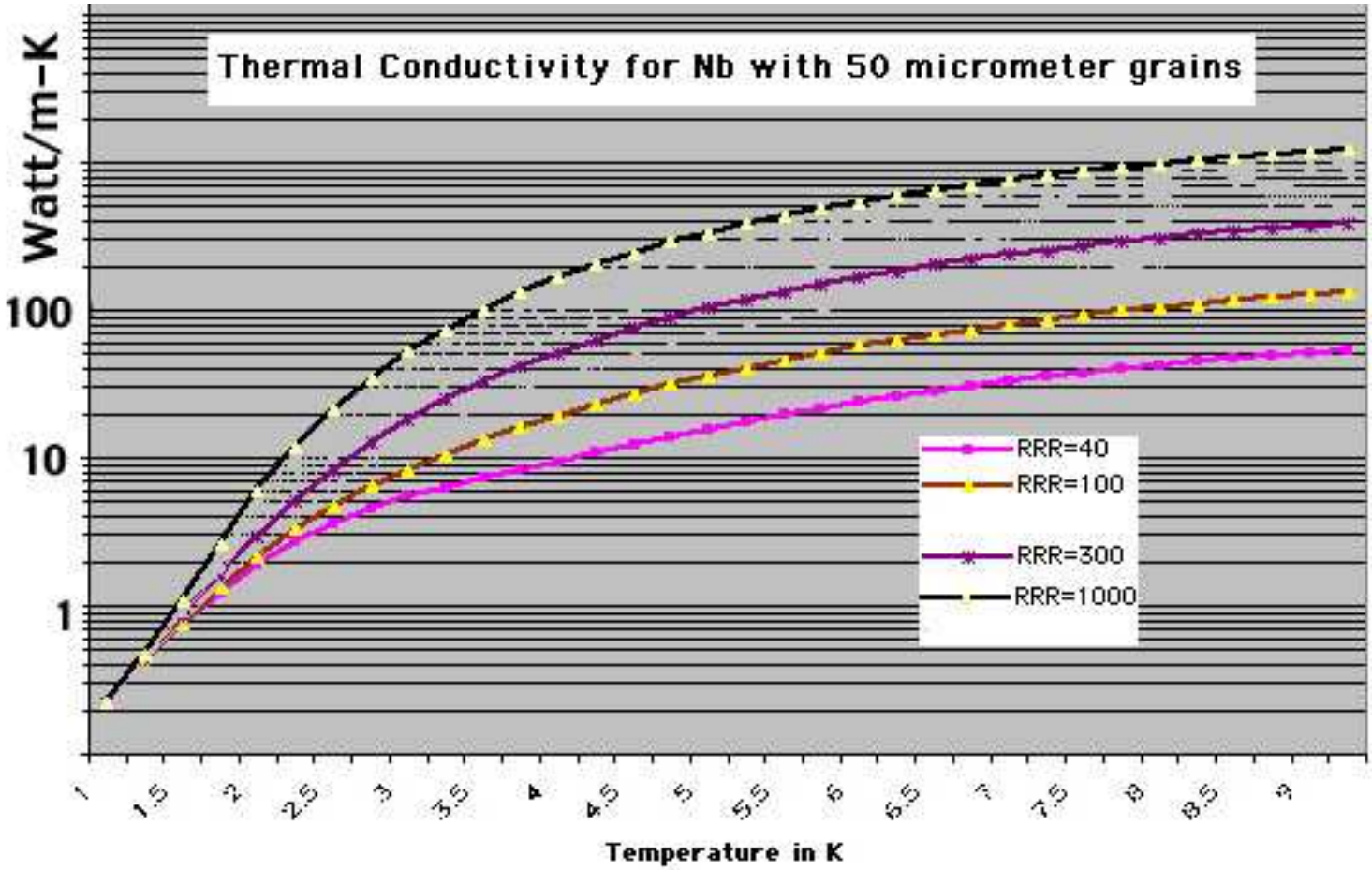
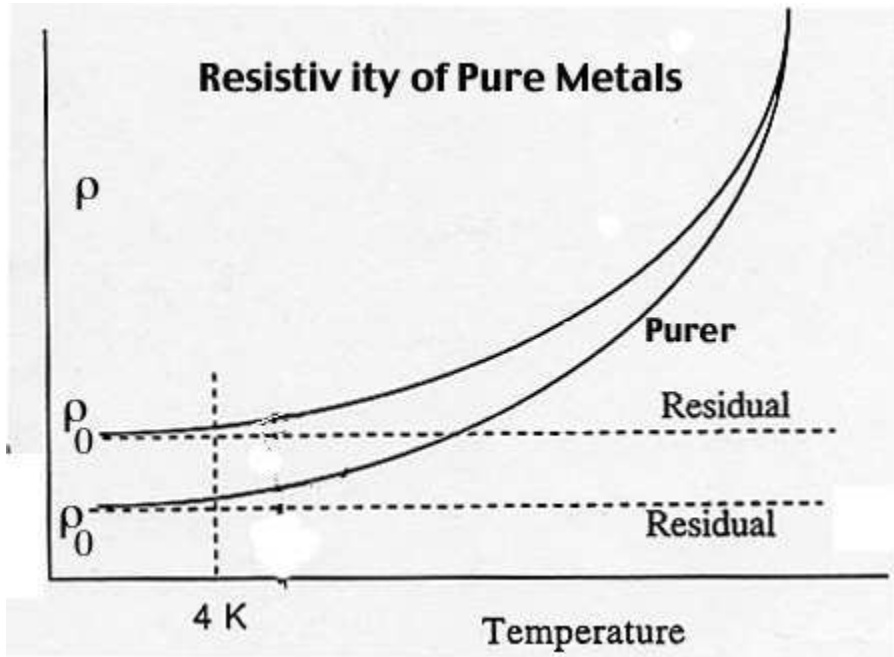




$$\mathrm{RRR} = \frac{\text{resistivity 300 K}}{\text{residual resistivity at low temperature (normal state)}}.$$

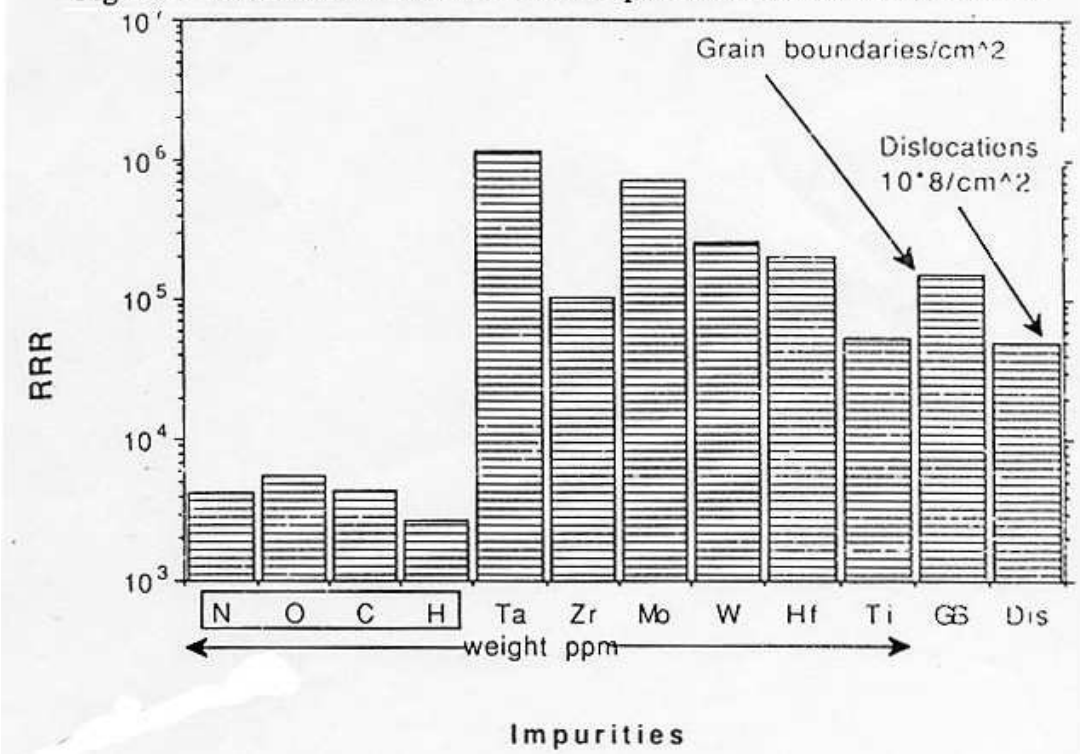
How Impurities Influence RRR

Table 6.1: Expected residual resistivity ratio contribution for niobium for 1 ppm wt of impurities[a]

Element	RRR	Element	RRR
H	2640	Zr	102 000–239 000
N	4230	Hf	200 000
C	4380	W	262 000–721 000
O	5580	Mo	717 000
Ti	53 700	Ta	1 140 000

[a]The ideal RRR due to phonon scattering is 35 000. To obtain the RRR one must add the resistance contributions for each impurity element in parallel to the resistance contribution from phonons.

Figure 9: The effect on RRR of various impurities and mechanical defects.



Compare Nb and Cu Thermal Conductivity

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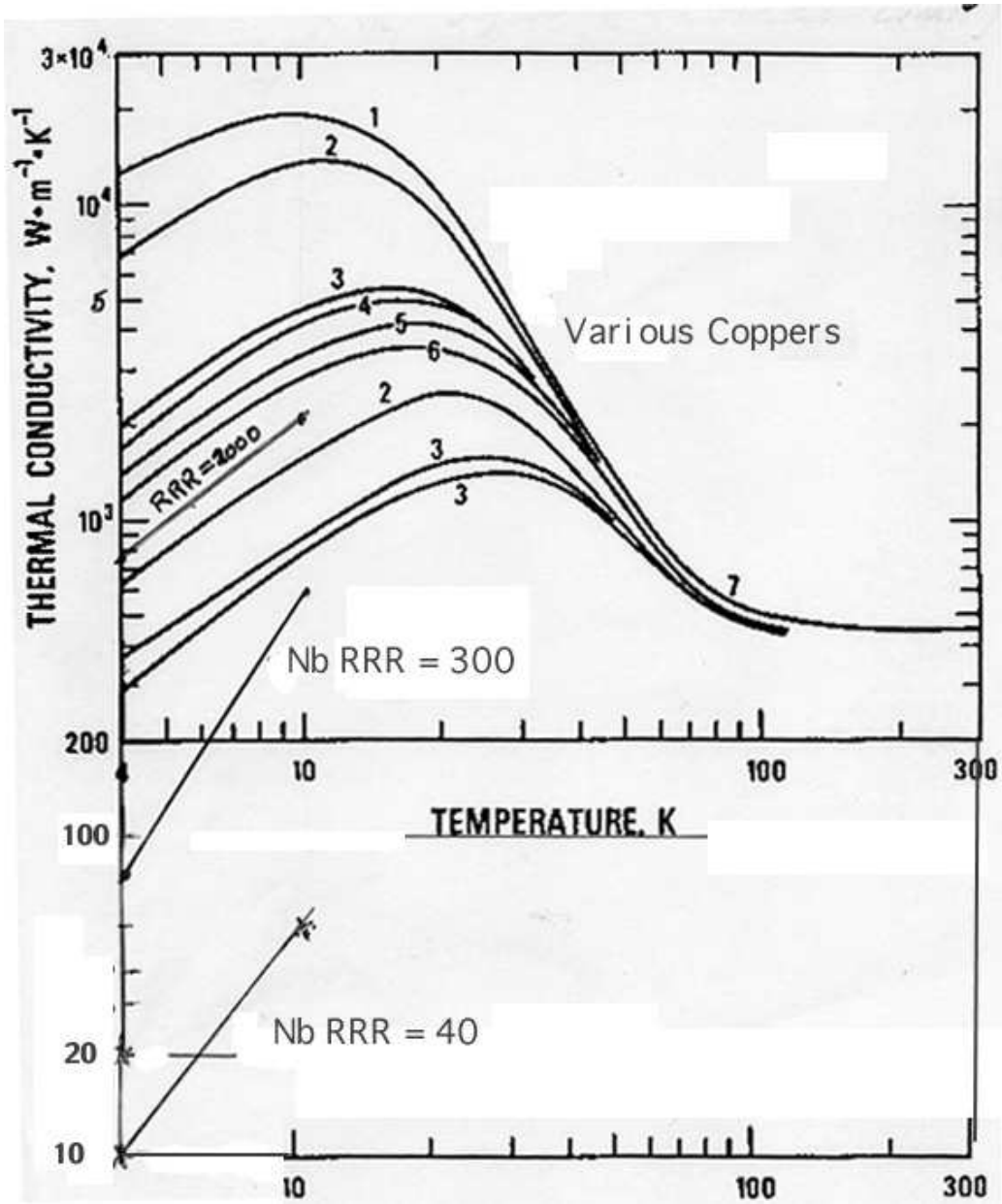
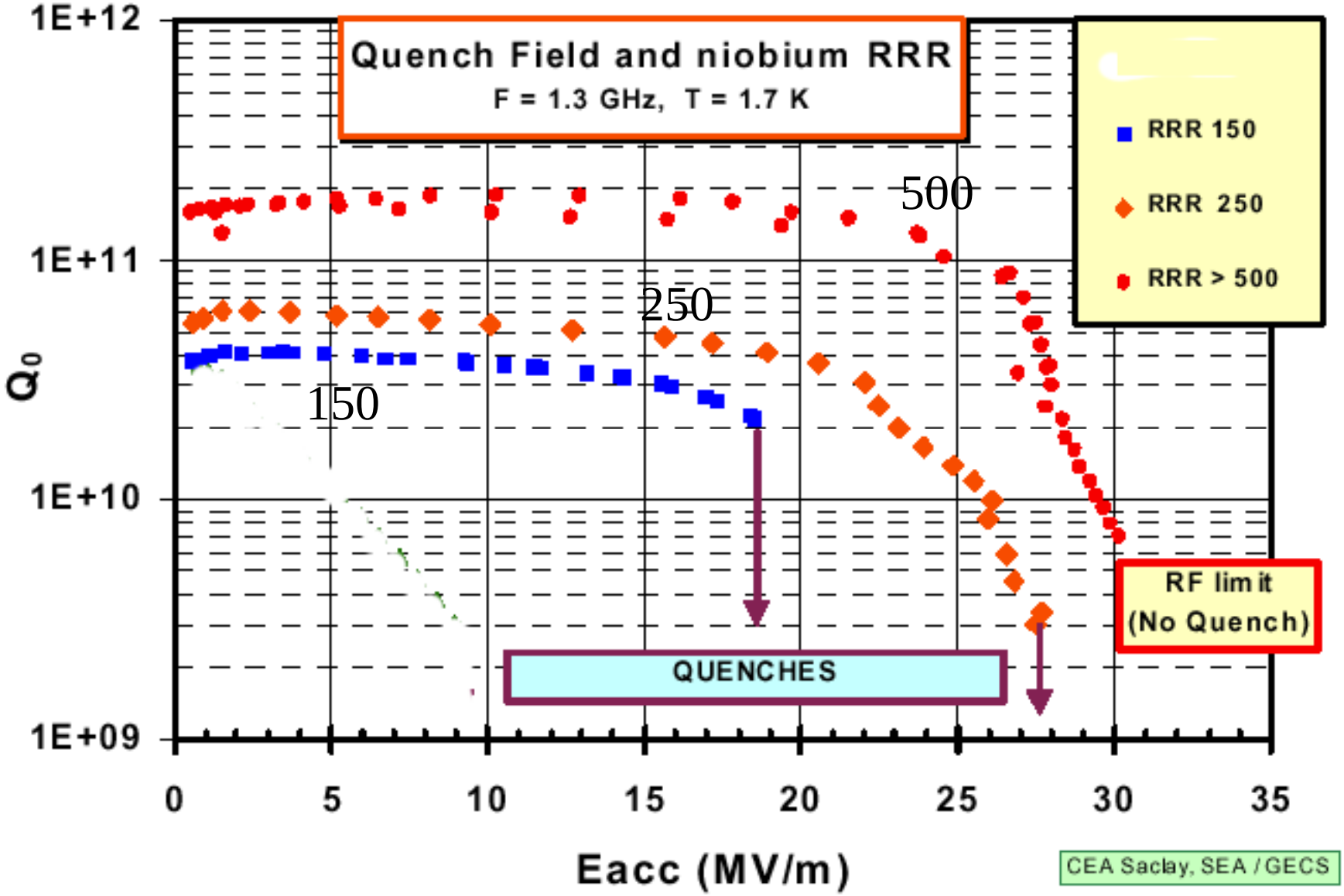
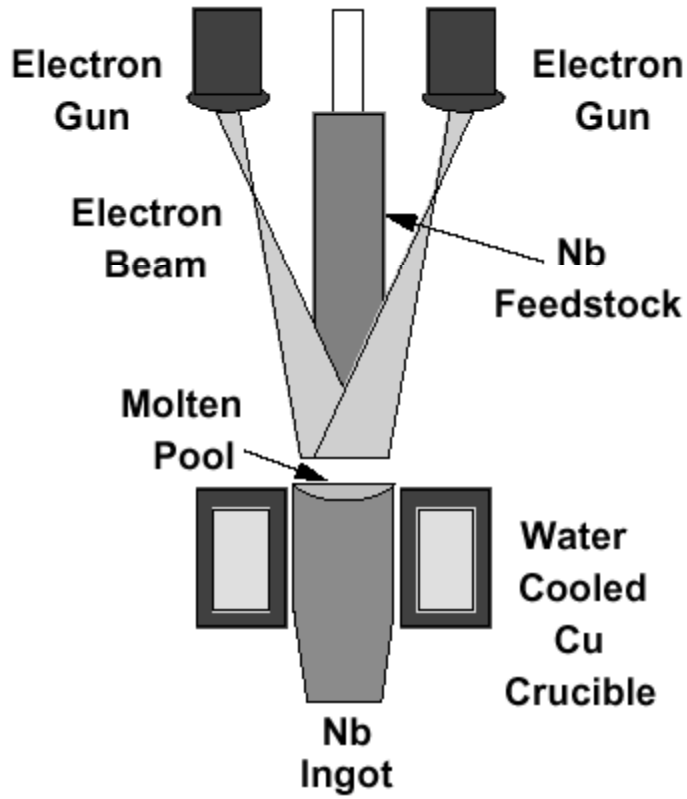



Quench Field and niobium RRR
F = 1.3 GHz, T = 1.7 K
RRR 150
RRR 250
RRR > 500
500
250
150
QUENCHES
RF limit
(No Quench)
1E+12
1E+11
1E+10
1E+09
Q0
0
5
10
15
20
25
30
35
Eacc (MV/m)
CEA Saclay, SEA / GECS

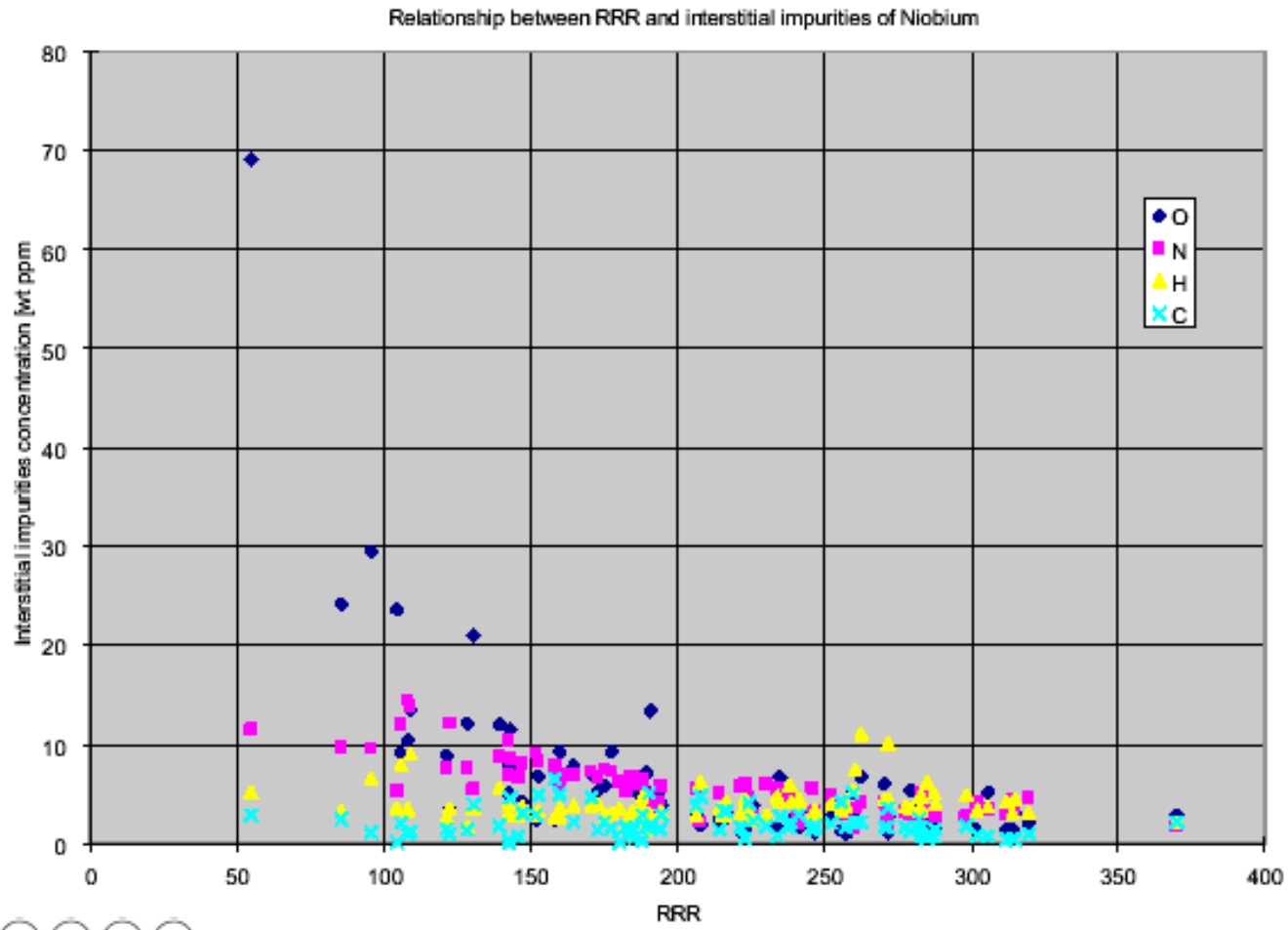
Niobium Purification

- 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.

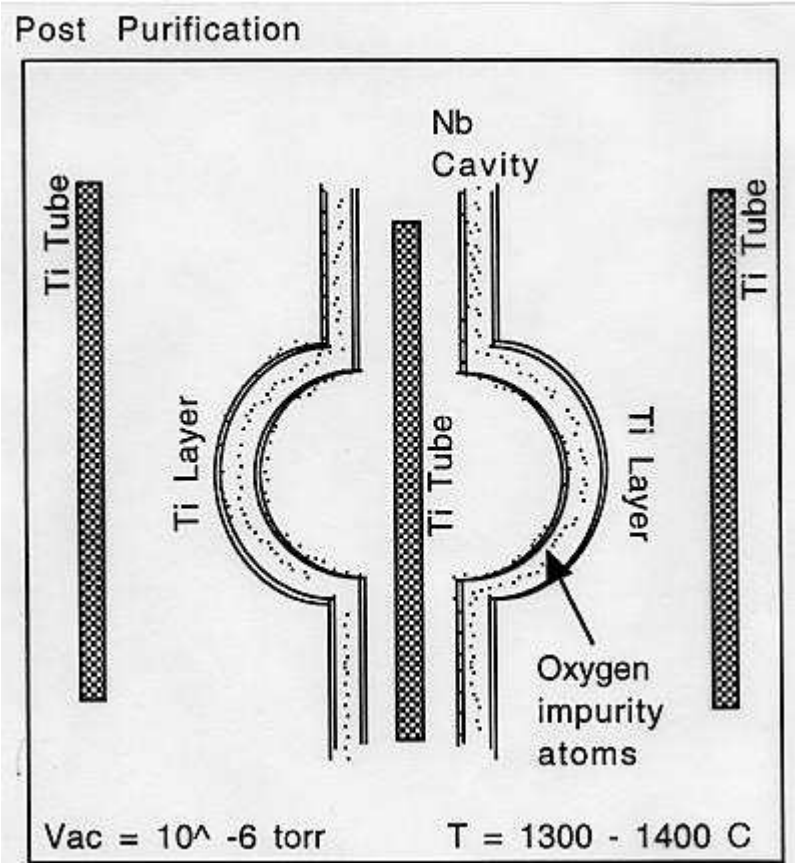


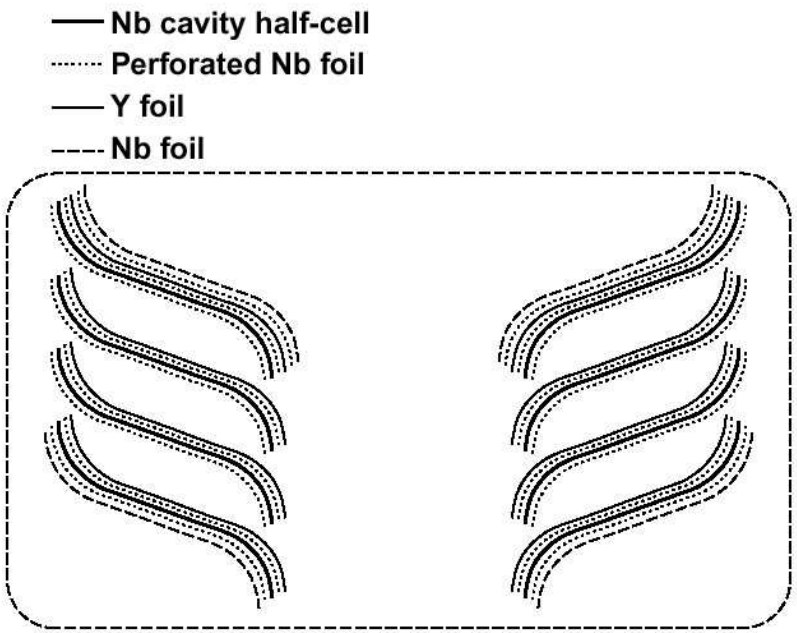
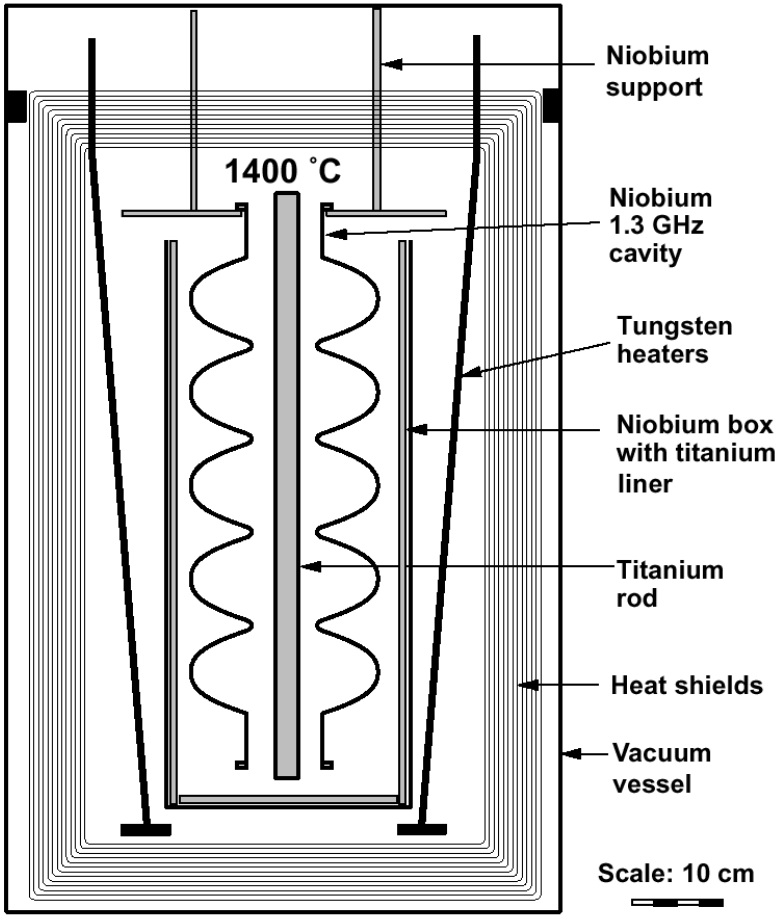
RRR: Residual resistance ratio = resistivity at room temperature divided by the resistivity at 4.2 K (in the normal conducting state!). κ_T scales ≈ linearly with RRR.

Interstitials vs 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