SRF LIMITATIONS

Jean Delayen

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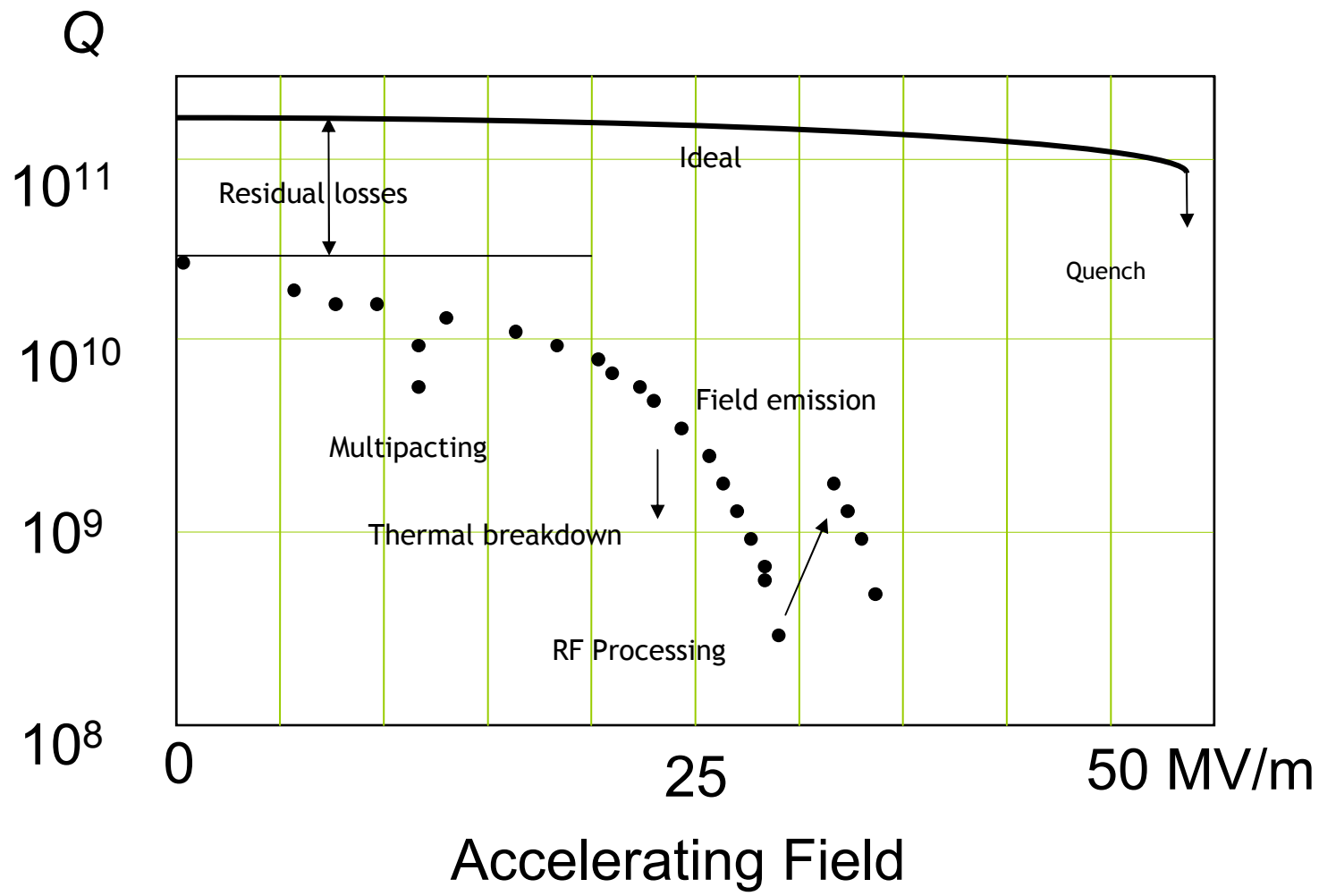
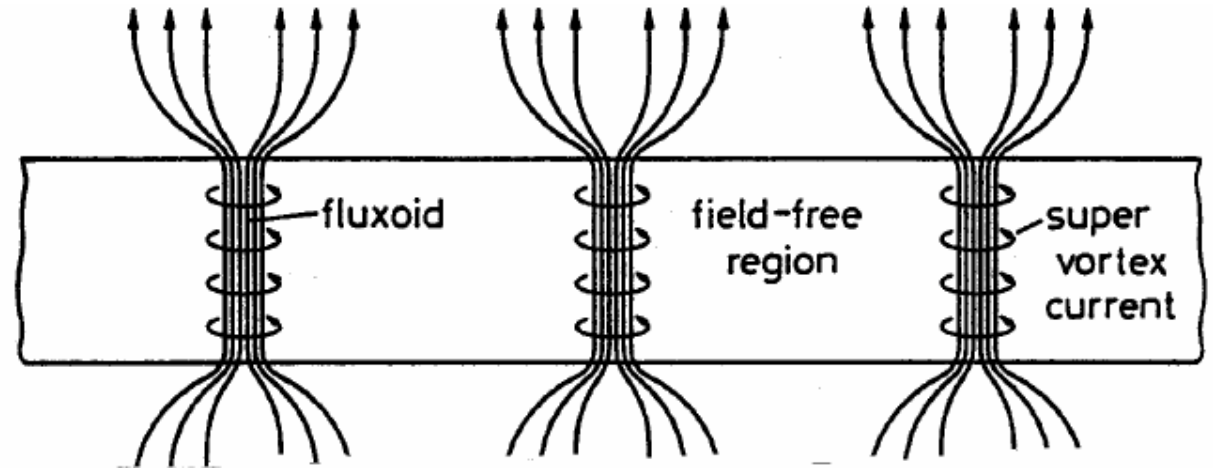
The Real World



Trapped Magnetic Field

A parallel magnetic filed is expelled from a superconductor.

What about a perpendicular magnetic field?



The magnetic field will be concentrated in normal cores where it is equal to the critical field.

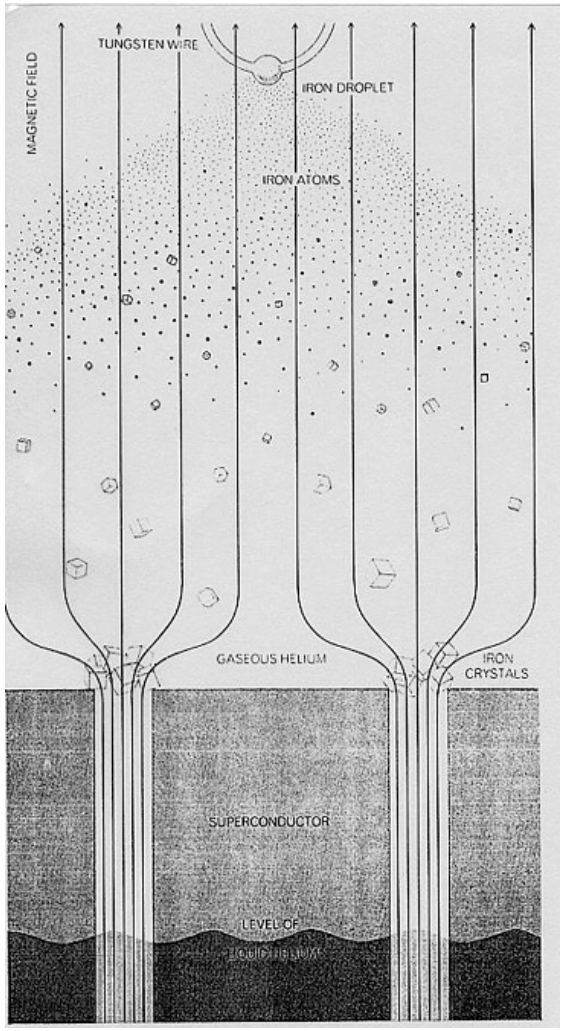
Residual Surface Resistance

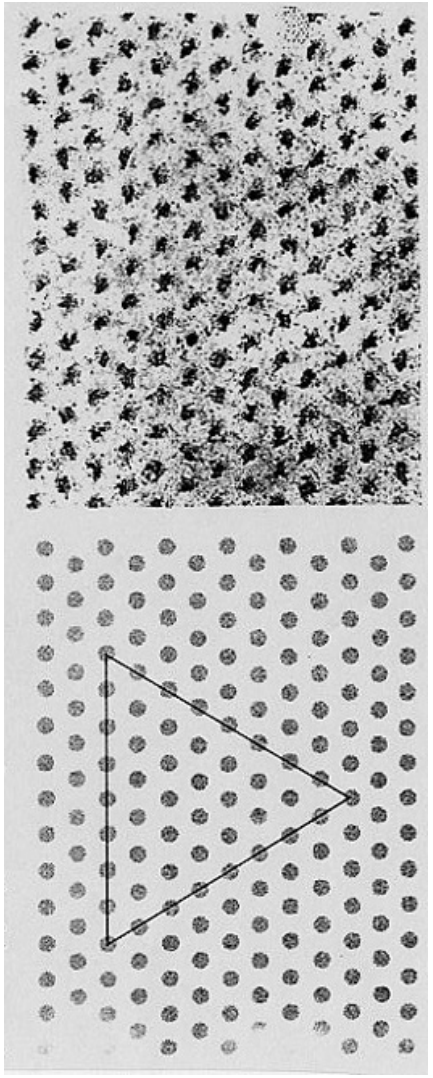
- No strong temperature dependence
- No clear frequency dependence
- Not uniformly distributed (can be localized)
- Not reproducible
- Can be as low as 1 nΩ
- Usually between 5 and 30 nΩ
- Often reduced by UHV heat treatment above 800C

Origin of Residual Surface Resistance

- Dielectric surface contaminants (gases, chemical residues, dust, adsorbates)
- Normal conducting defects, inclusions
- Surface imperfections (cracks, scratches, delaminations)
- Trapped magnetic flux
- Hydride precipitation
- Localized electron states (photon absoption)

Trapped Magnetic Field





Trapped Magnetic Field

A fraction H / H_c of the material will be in the normal state.

This will lead to an effective surface resistance $\rho_n \left(H / H_c \right)$

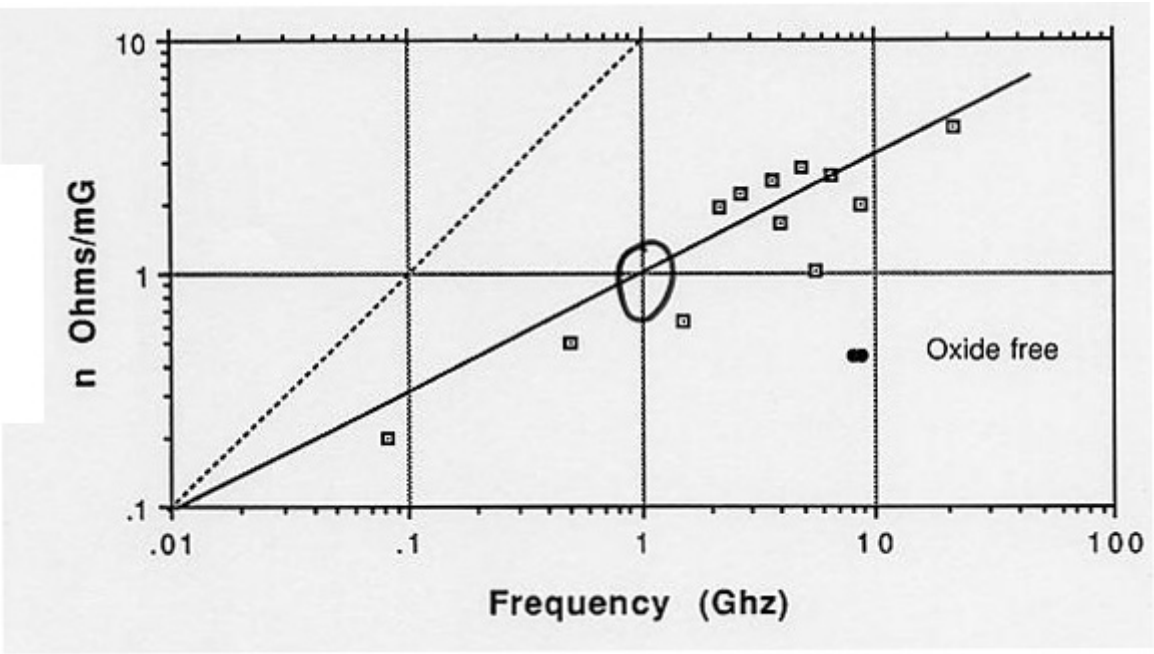
For Nb: $\rho_{eff} \approx 0.5 \text{ to } 1 \text{ n}\Omega/\text{mG} \text{ around } 1 \text{ GHz}$

While a cavity goes through the superconducting transition, the ambient magnetic filed cannot be more than a few mG.

The earth's magnetic shield must be effectively shielded.

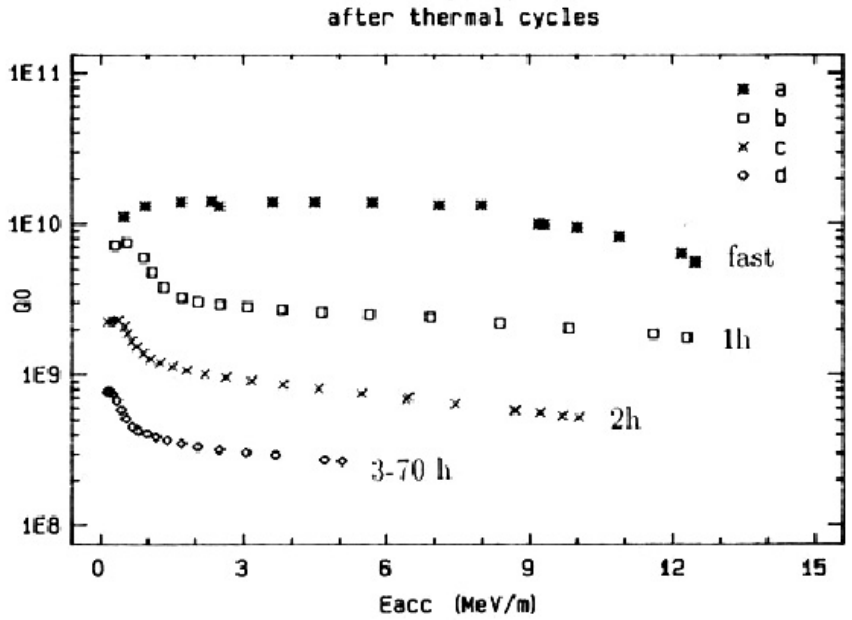
In cavities made of composite materials, thermoelectric currents can cause trapped magnetic field.

Trapped Magnetic Field



Q Disease

Cavities that remain at ~100K for an extended period of time experience a sharp increase of surface resistance



Q Disease

At room temperature, the hydrogen moves freely through niobium

At lower temperature, H precipitates to form a hydride with poor superconducting properties: Tc=2.8 K, Hc=60 G

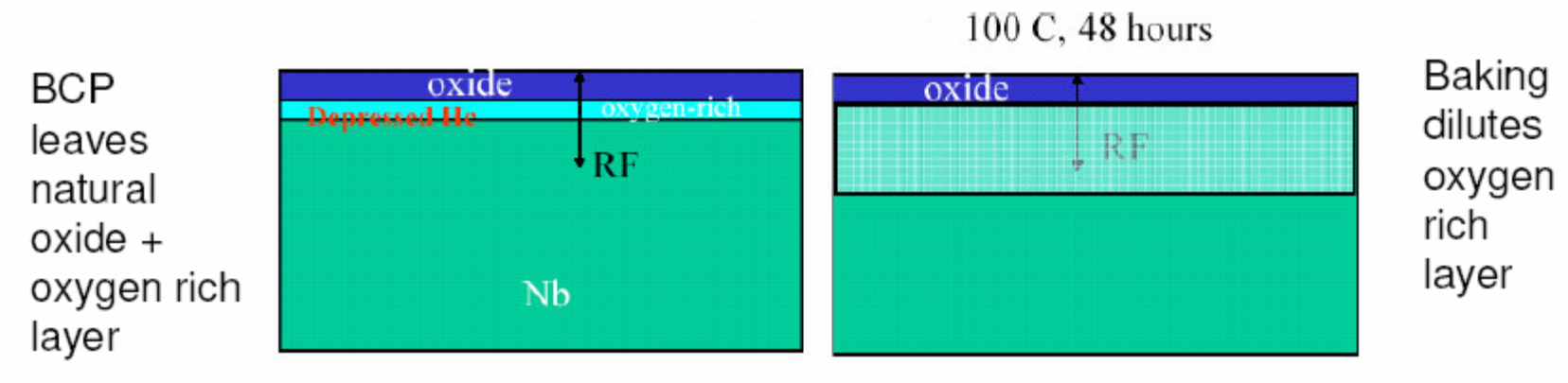
At room temperature the required concentration to form a hydride is 10^3-10^4 ppm

At 150K it is <10ppm

Can be eliminated by baking cavity at 600-800C

High Field Q-Drop

- Decrease of Q at high field not associated with x-rays
- Still an area of investigation
- Many models
  - Magnetic field related
  - Electric field related
- Strong indication that it is related to the concentration of oxygen at the surface
- Reduced or eliminated by mild baking around 120C



High Field Q-Drop

Pollution Model

- Important impurities in Nb are O, N, C, H
- A "pollution layer" (1- 10 nm) of high O concentration resides below the oxide (some spotty evidence for this from surface analysis)
- This layer weakens the superconducting properties of the thin layer, e.g., by lowering Hc1 and Hsh
  - Magnetic flux begins to penetrate at lower field, and cause RF losses.
- At 100 C, 48 hours, O diffuses (typically 100 nm)
  - N and C are unlikely to be responsible because these diffuse much more slowly compared to Nb (<< 1 nm)
- Baking dilutes the pollution layer, raising Hc1 and Hsh.

High Field Q-Drop

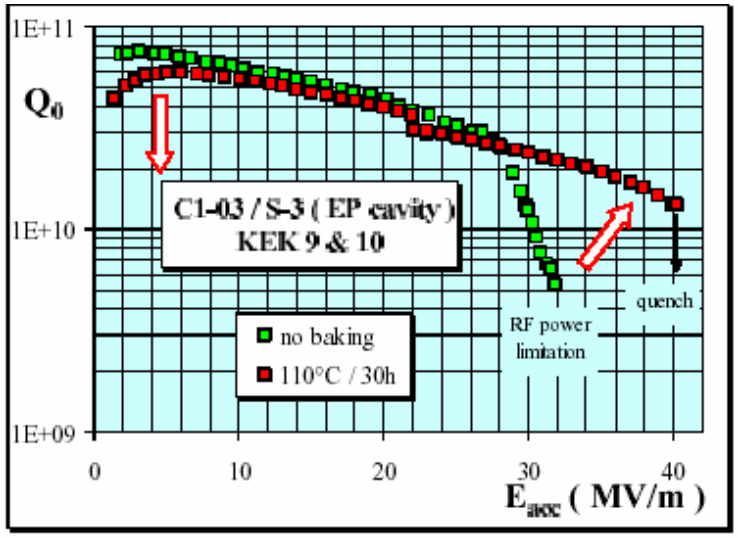
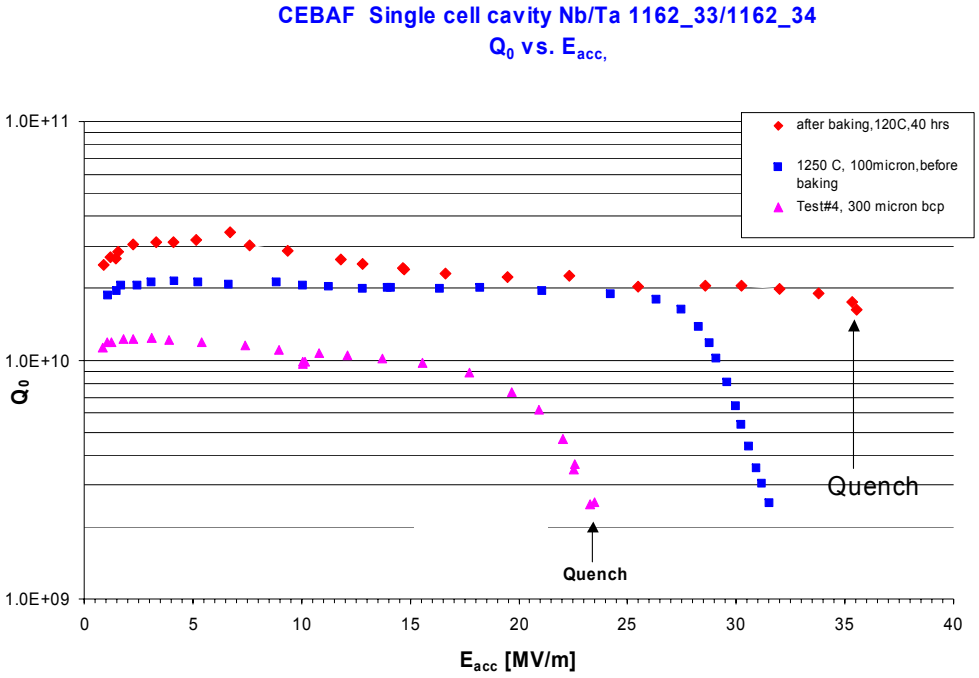
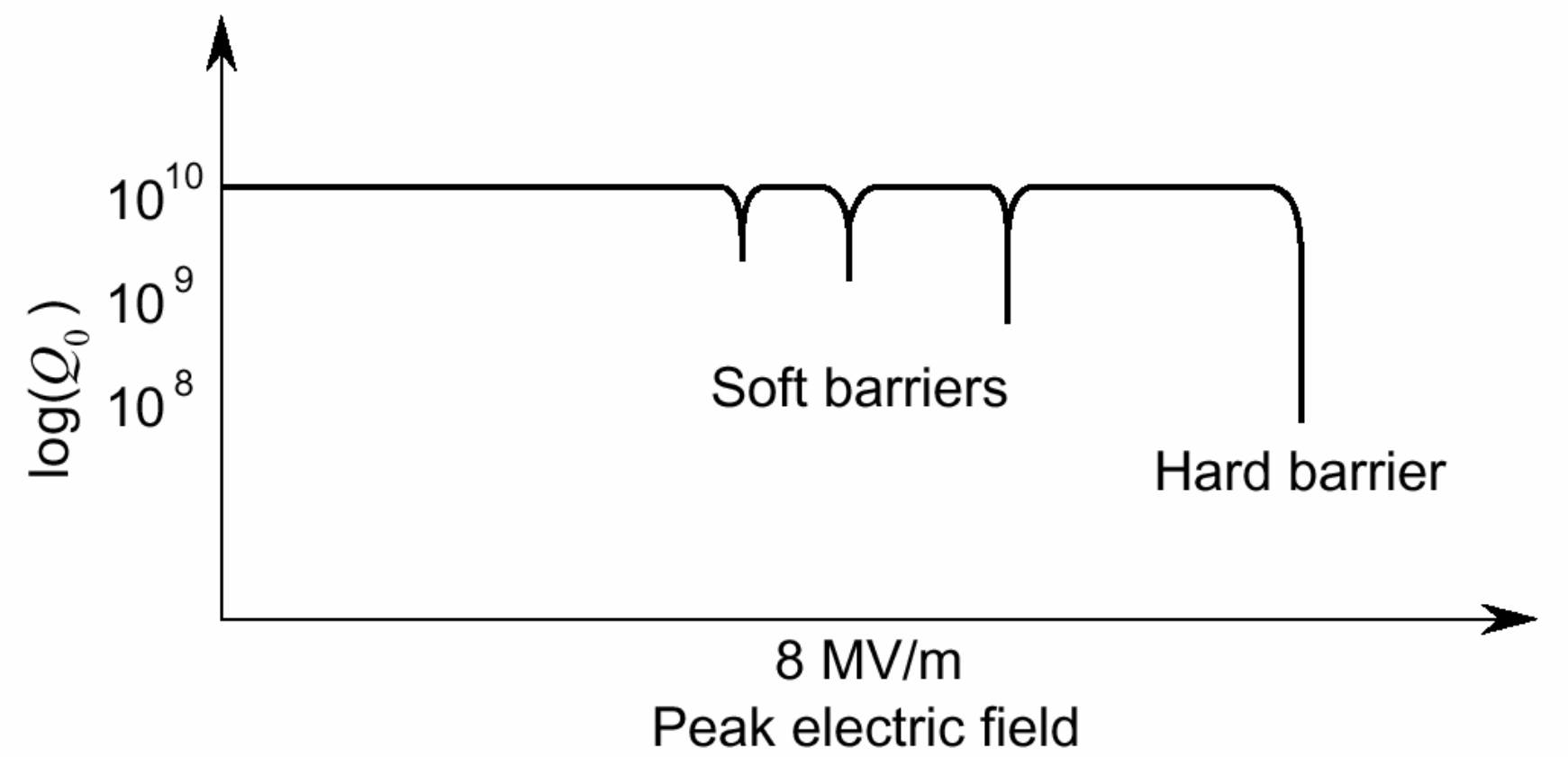


Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].



Multipacting



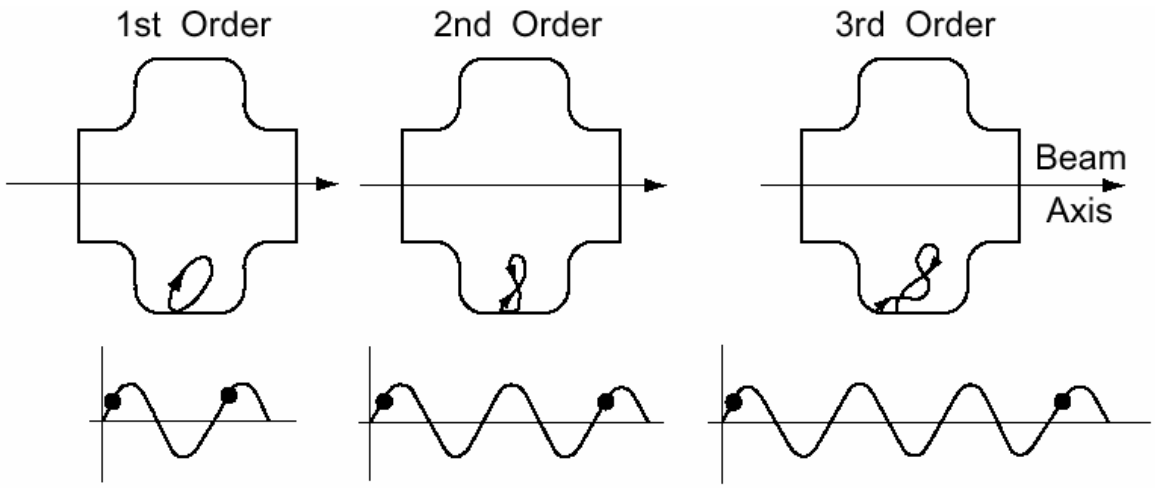
Multipacting

Multipacting is characterized by an exponential growth in the number of electrons in a cavity

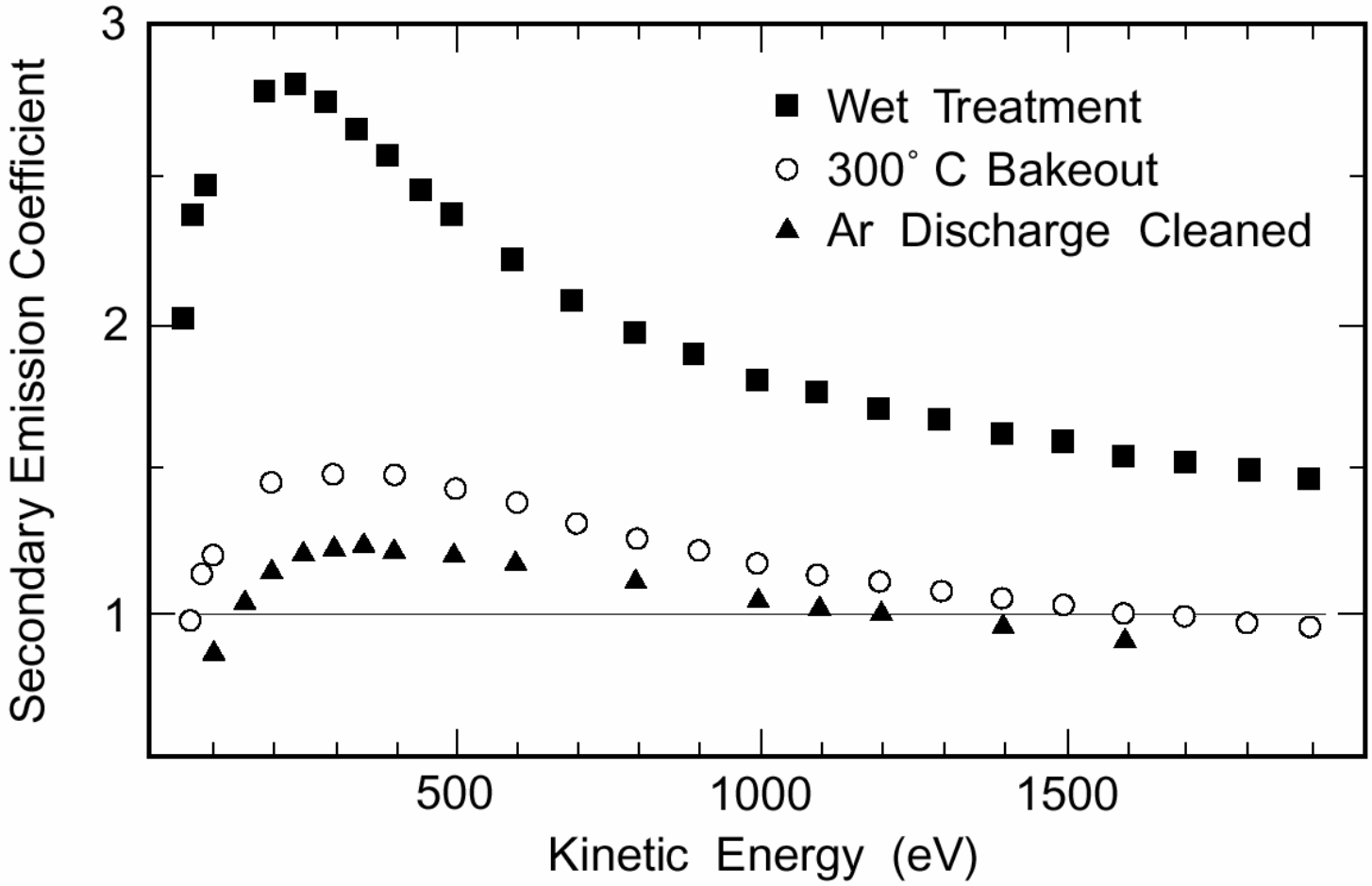
Multipacting requires 2 conditions:

Electron motion is periodic (resonance condition)

Impact energy is such that secondary emission coefficient is >1



Multipacting



Secondary Emission in Niobium

STUDIES OF MULTIPACTING IN AXISYMMETRIC CAVITIES FOR MEDIUM-VELOCITY BEAMS*

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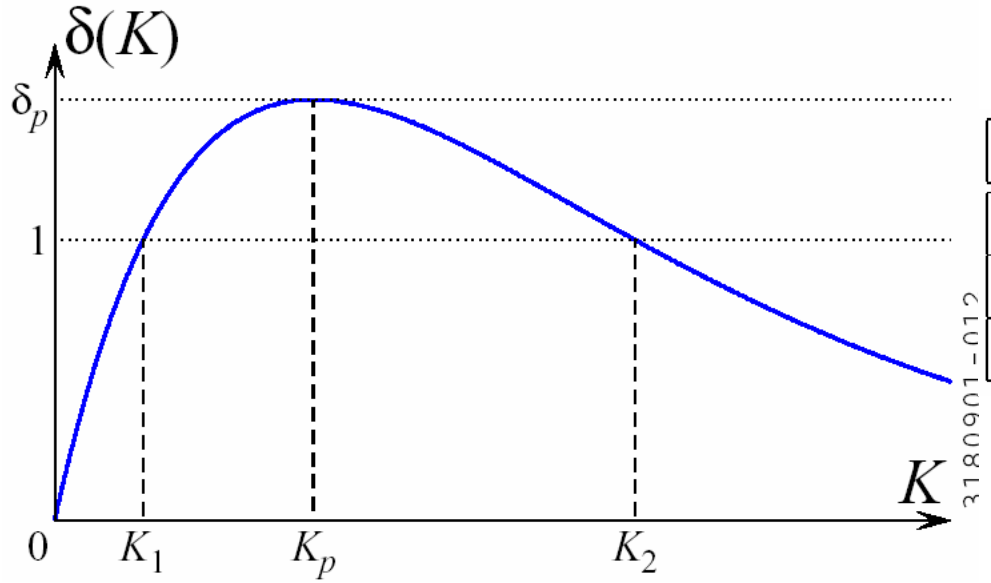
National Superconducting Cyclotron Lab, Michigan State University, East Lansing, Michigan
F. Krawczyk
Los Alamos National Laboratory, Los Alamos, New Mexico
H. Padamsee
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York



Condition	K_1	K_2
high SEY	~ 27 eV	$\gtrsim$ 2000 eV
typical SEY	~ 40 eV	~ 1000 eV
low SEY	~ 150 eV	~ 750 eV

Secondary Emission in Niobium

INFLUENCE OF VARIOUS VACUUM SURFACE TREATMENTS ON THE SECONDARY ELECTRON YIELD OF NIOBIUM

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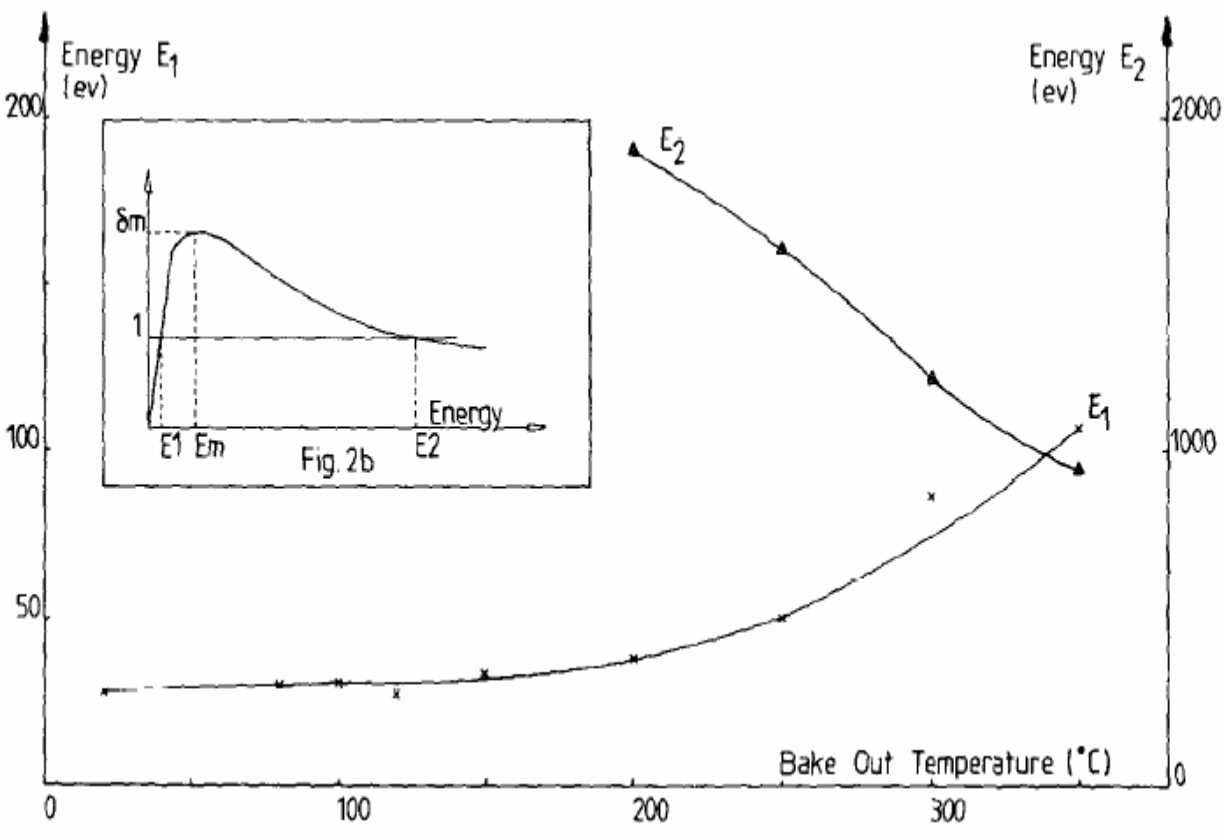
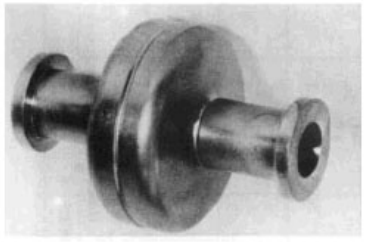
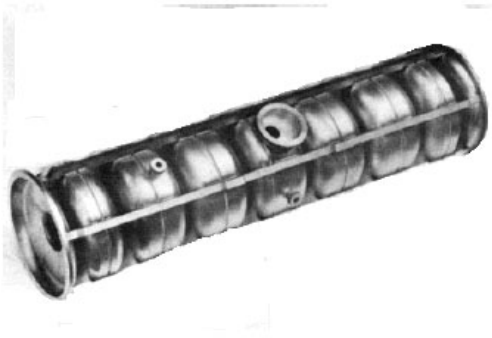


Multipacting

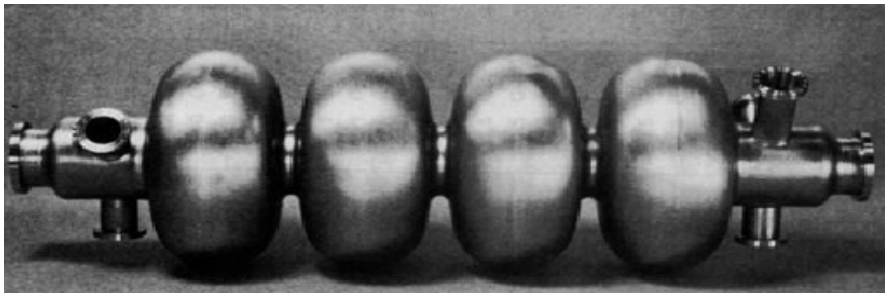
Multipacting was “eliminated” by rounding the shape of the pill-box cavity



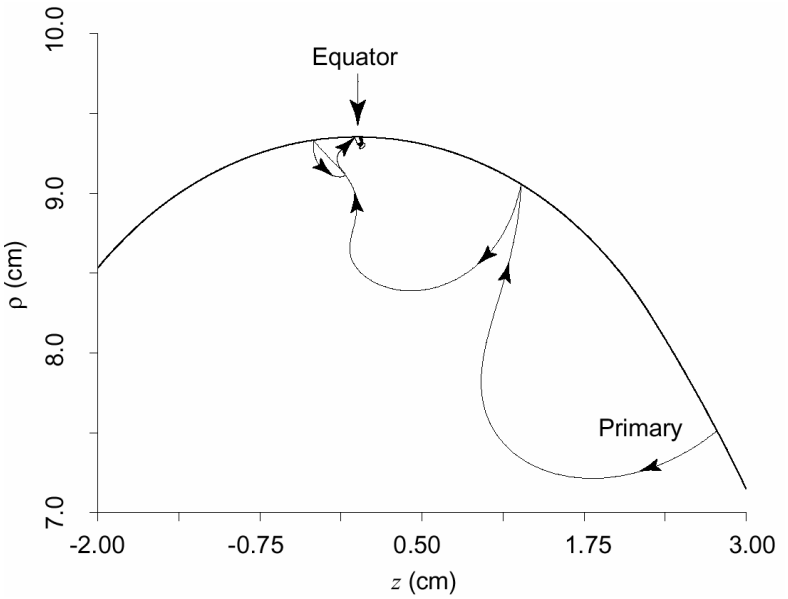
(a)



(b)

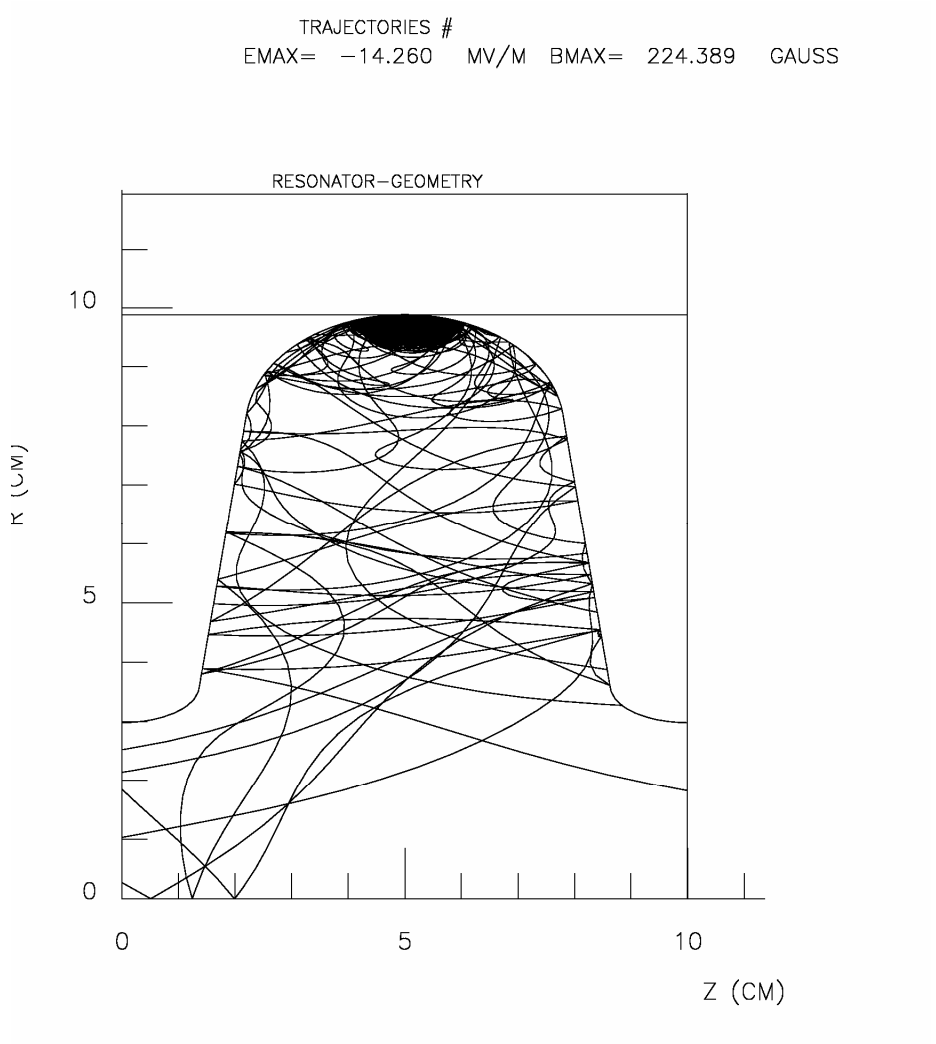


350-MHz LEP-II cavity (CERN)

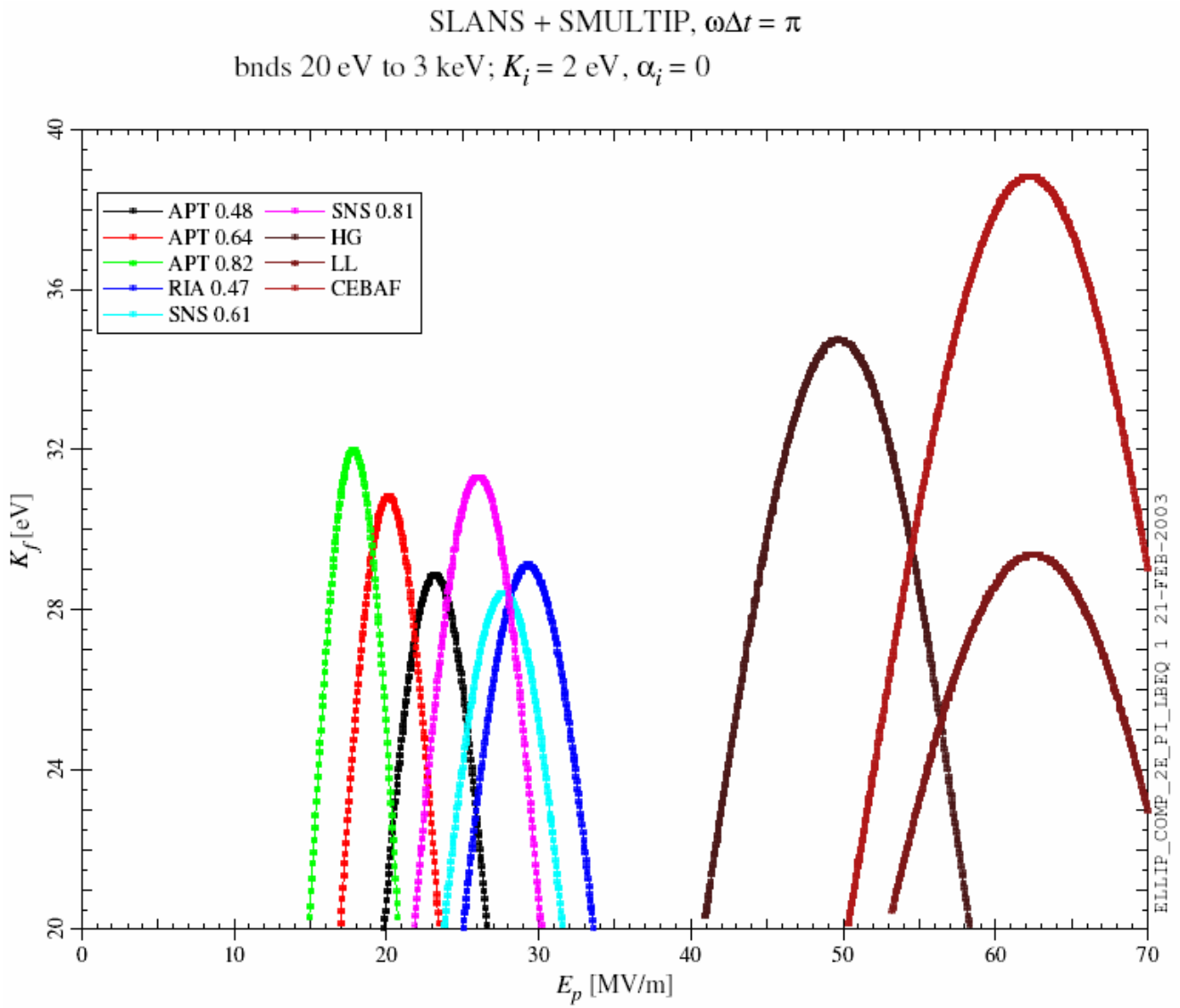


Electrons drift to equator
Electric field at equator is ≈ 0
→MP electrons don’t gain energy
→MP stops

Multipacting Simulation



Multipacting



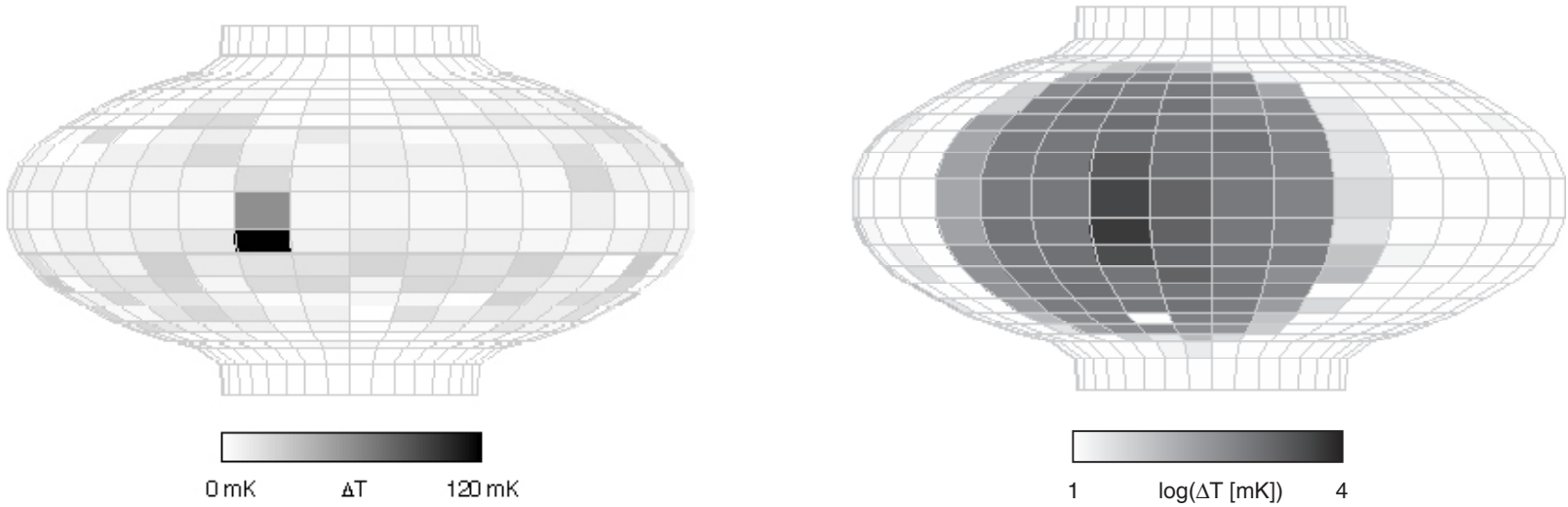
Thermal Breakdown

Localized heating

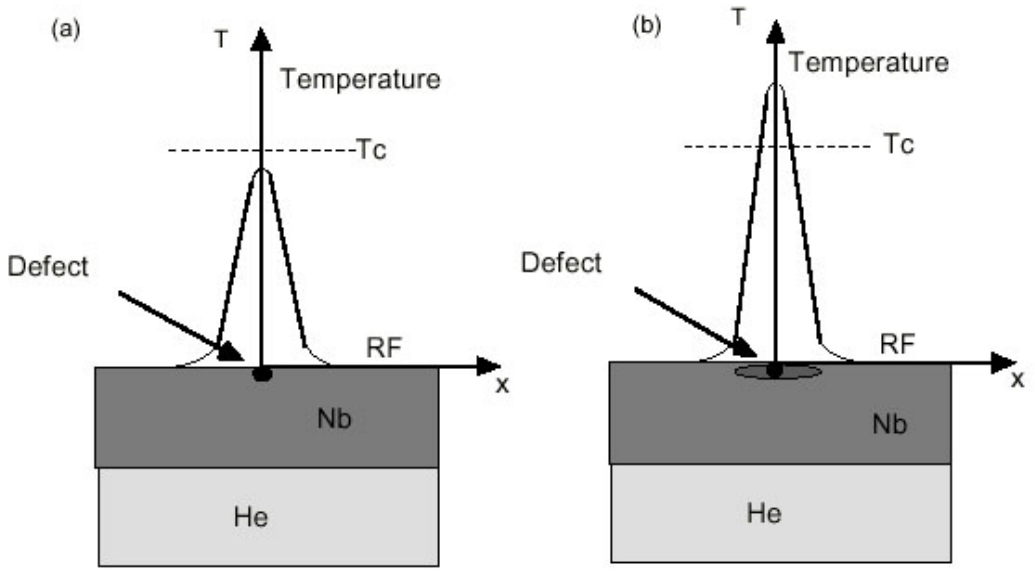
Hot area increases with field

At a certain field there is a thermal runaway, the field collapses

- sometimes displays a oscillator behavior
- sometimes settles at a lower value
- sometimes displays a hysteretic behavior



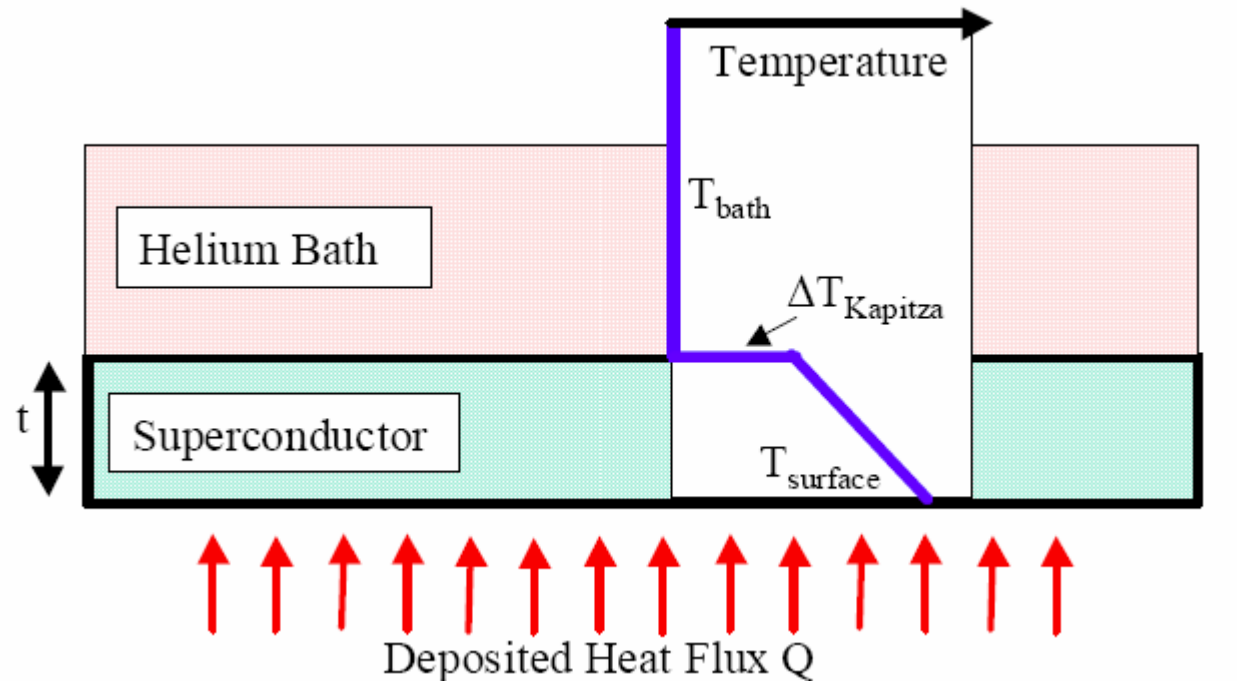
Thermal Breakdown



Thermal breakdown occurs when the heat generated at the hot spot is larger than that can be evacuated to the helium bath

Both the thermal conductivity and the surface resistance of Nb are highly temperature dependent between 2 and 9K

Thermal Breakdown



Residual Resistance Ratio

RRR is the ratio of the resistivity at 300K and 4.2K

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

RRR is related to the mean free path.

For Nb: $l(T = 4.2K) \approx 27\ RRR\ (\text{Å})$

RRR is related to the thermal conductivity

For Nb: $\lambda(T = 4.2K) \approx RRR/4\ (\text{W. m}^{-1}\text{. K}^{-1})$

Residual Resistance Ratio

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.

Thermal Conductivity of Nb

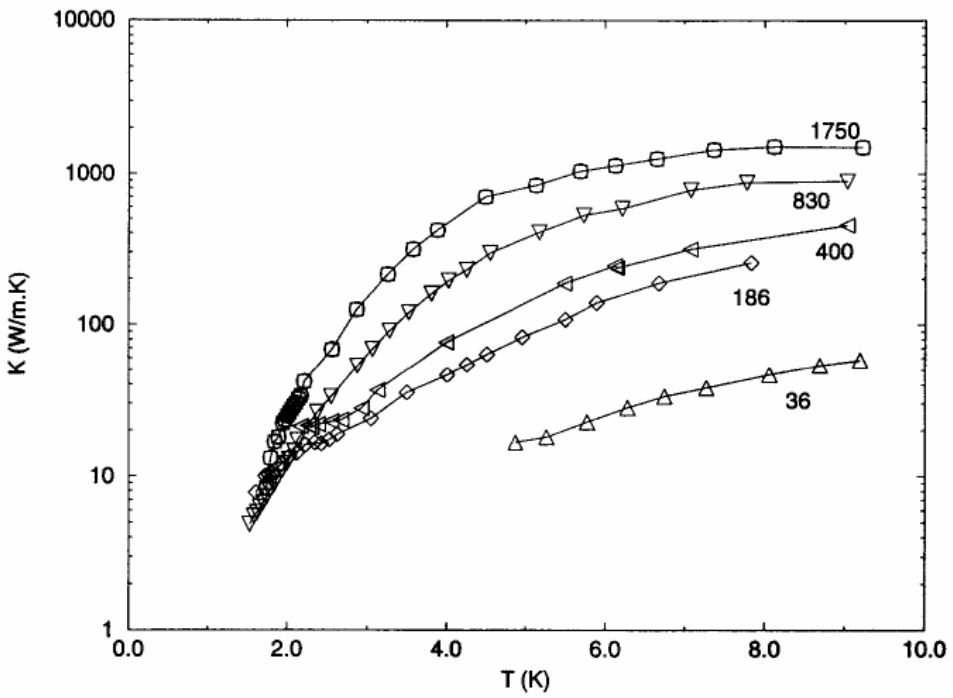
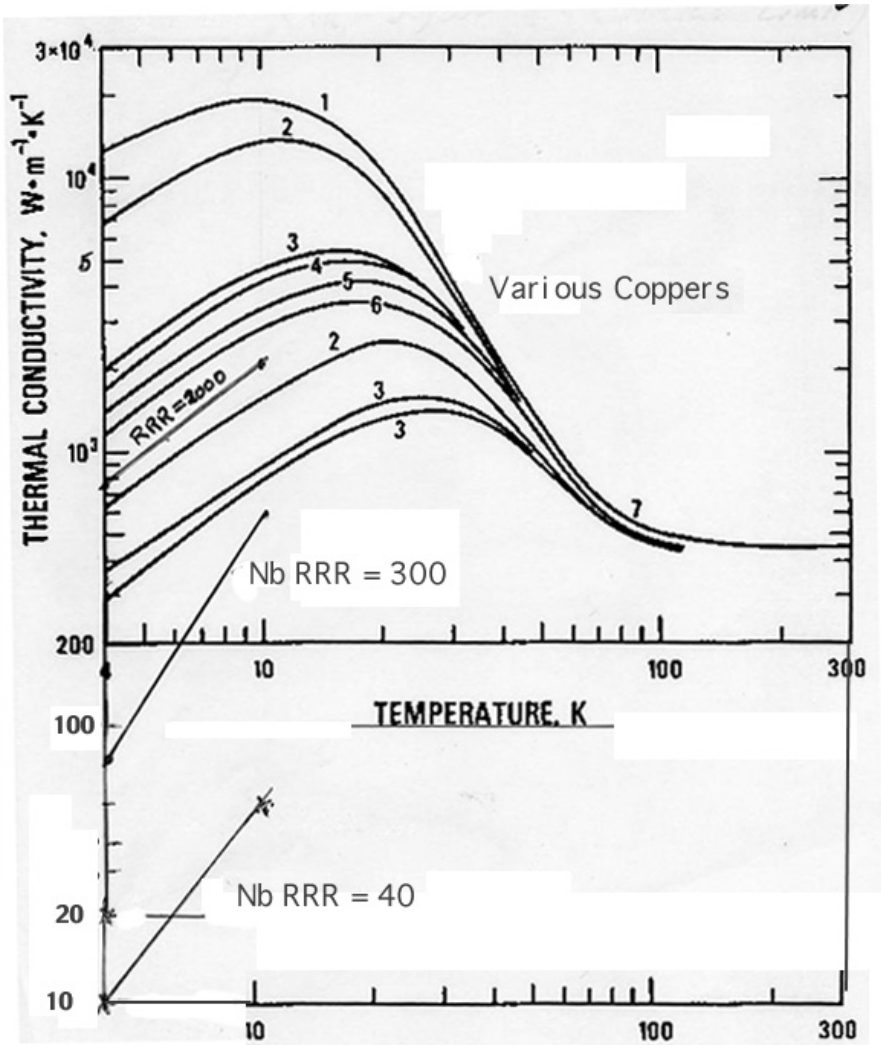
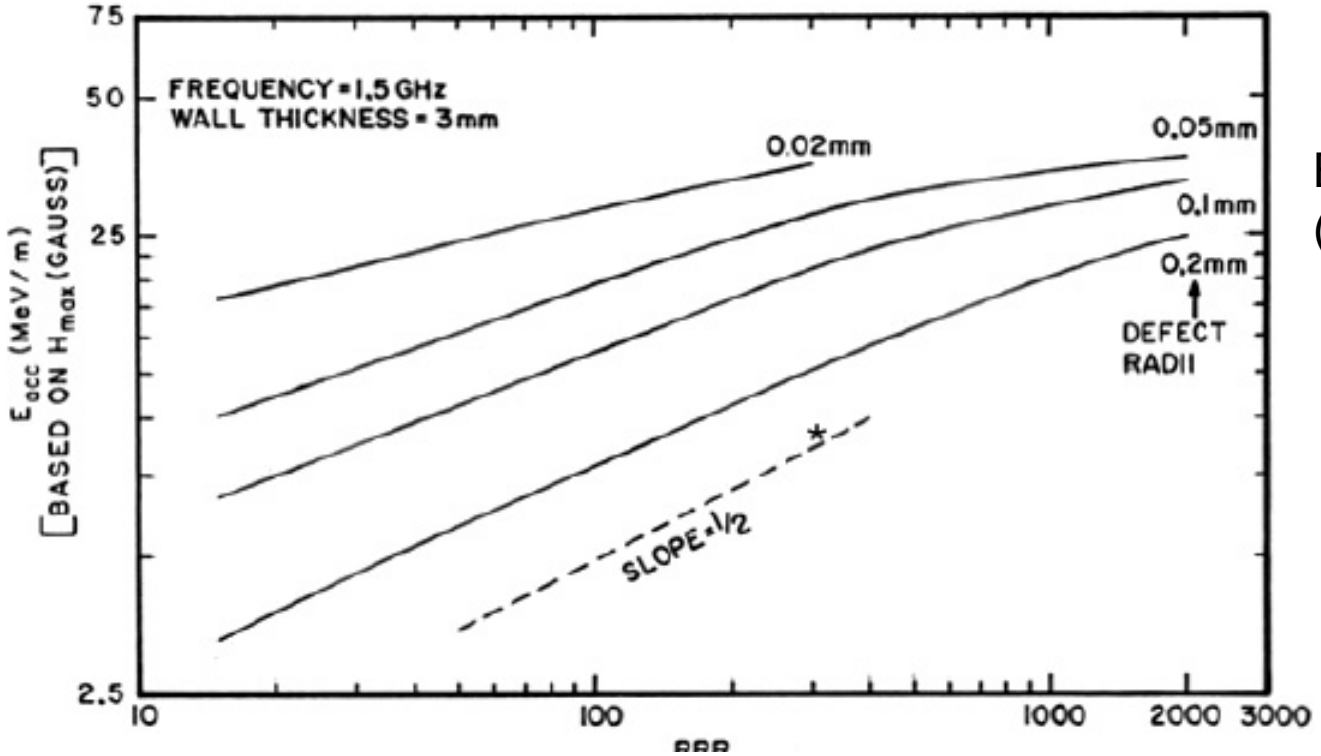


Fig. 3 The thermal conductivity of niobium as a function of temperature, for various RRR values.



Thermal Breakdown

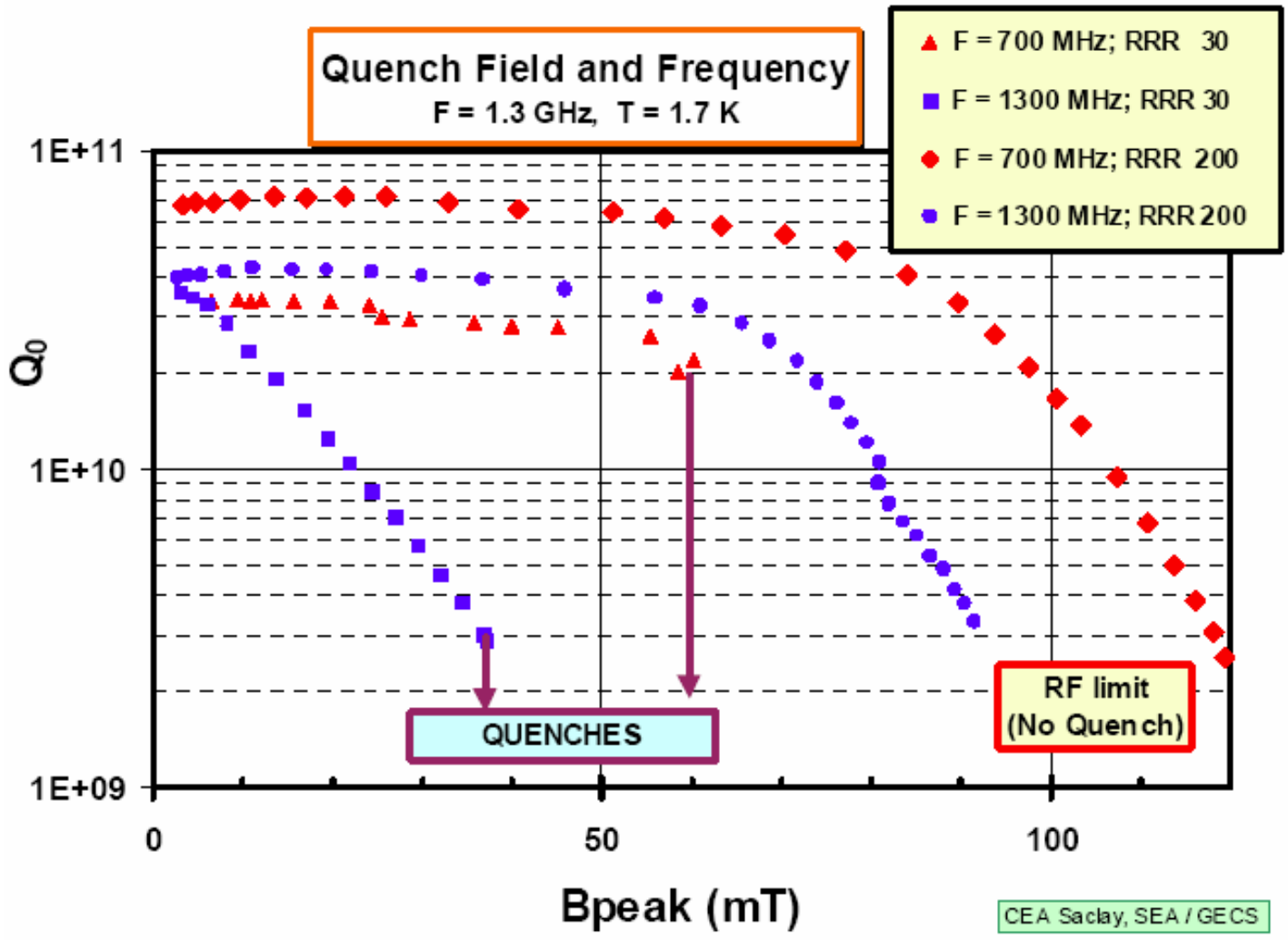


Breakdown field given by (very approximately):

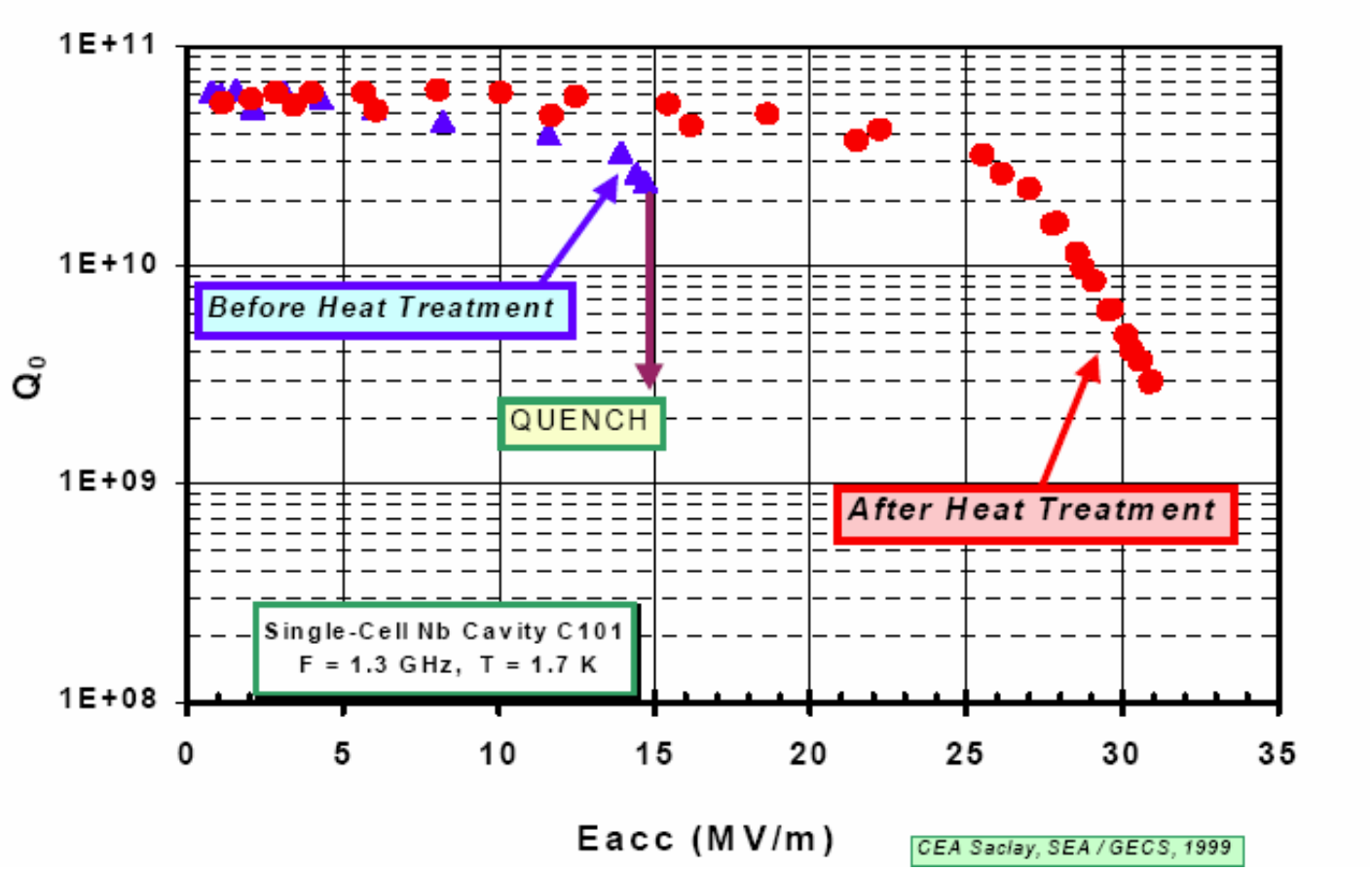
$$H_{tb} = \sqrt{\frac{4\kappa_T (T_c - T_b)}{r_d R_d}}$$

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

Thermal Breakdown

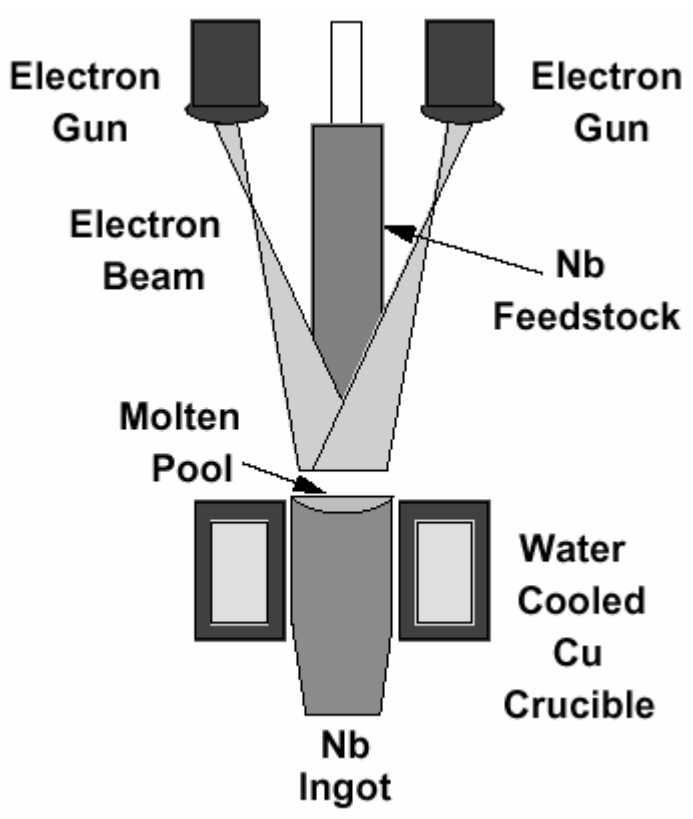


Thermal Breakdown



Niobium Purification

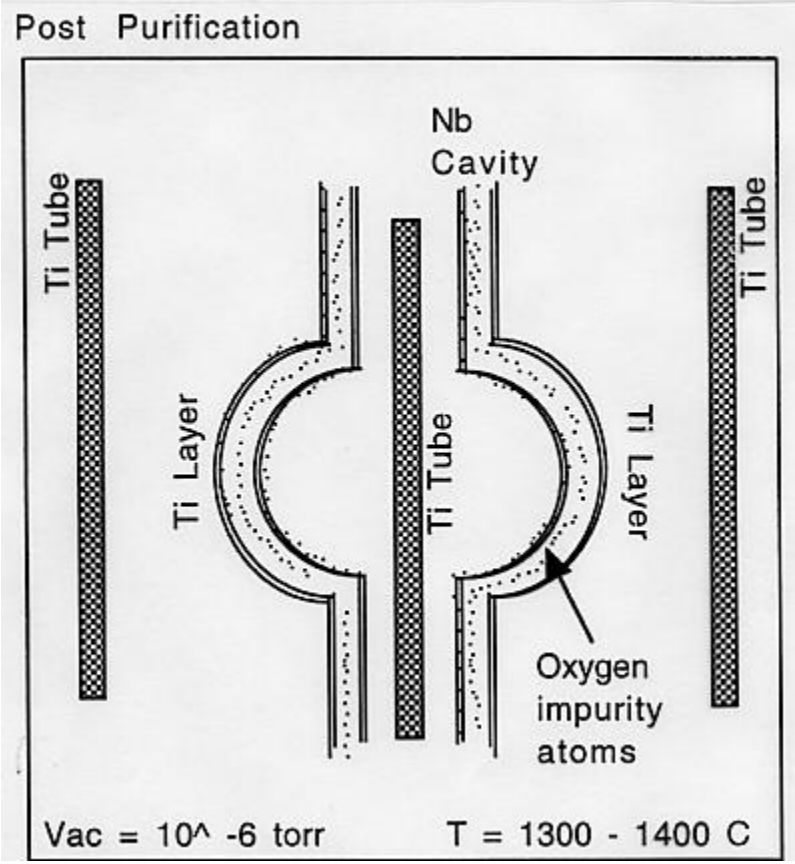
- Can produce high Nb purity by e-beam melting in a vacuum furnace



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

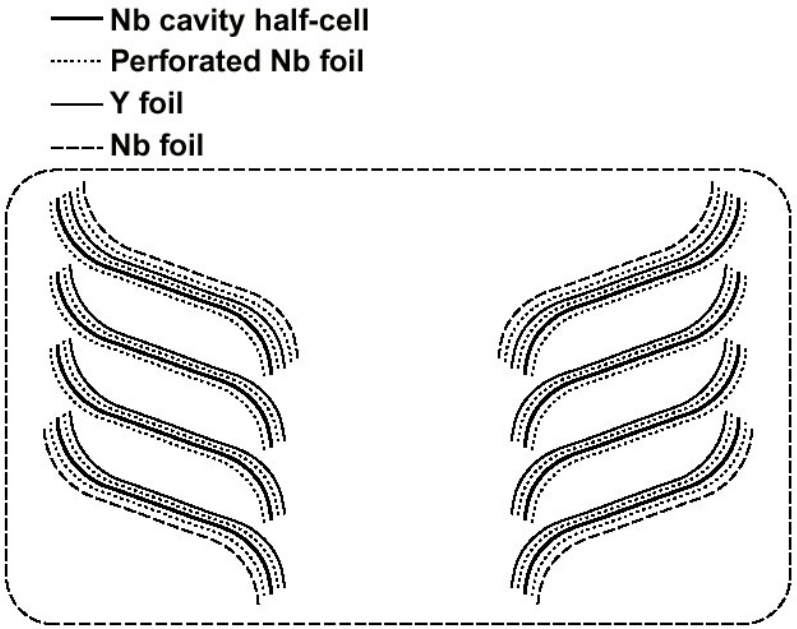
RRR: Residual resistance ratio = resistivity at room temperature divided by the resistivity at 4.2 K (in the normal conducting state). κ_{th} scales ≈ linearly with RRR

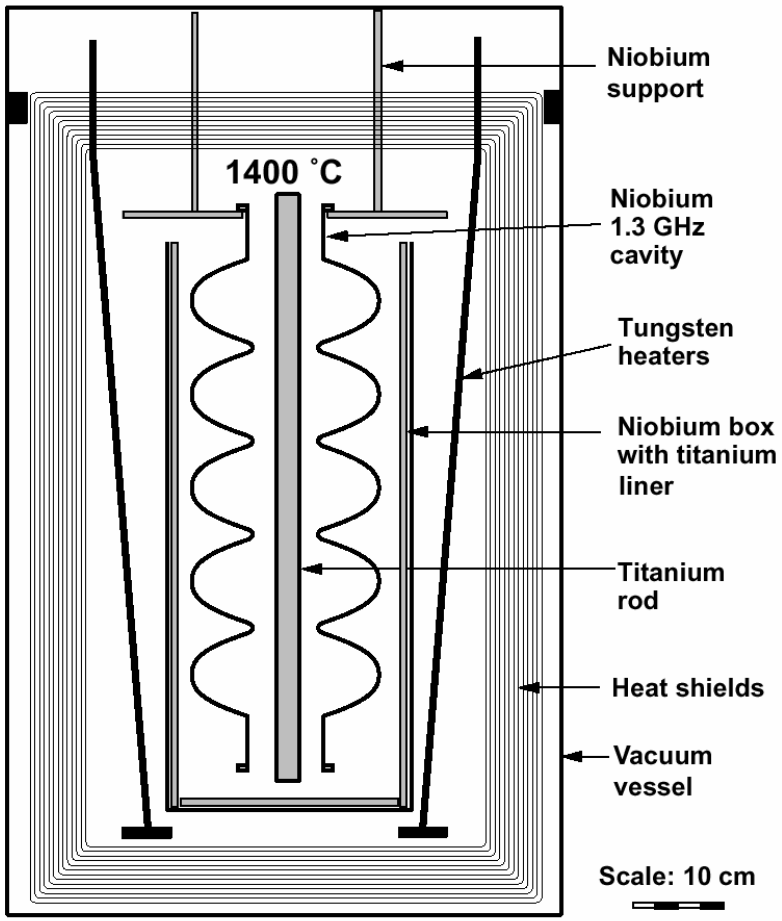
Niobium Purification



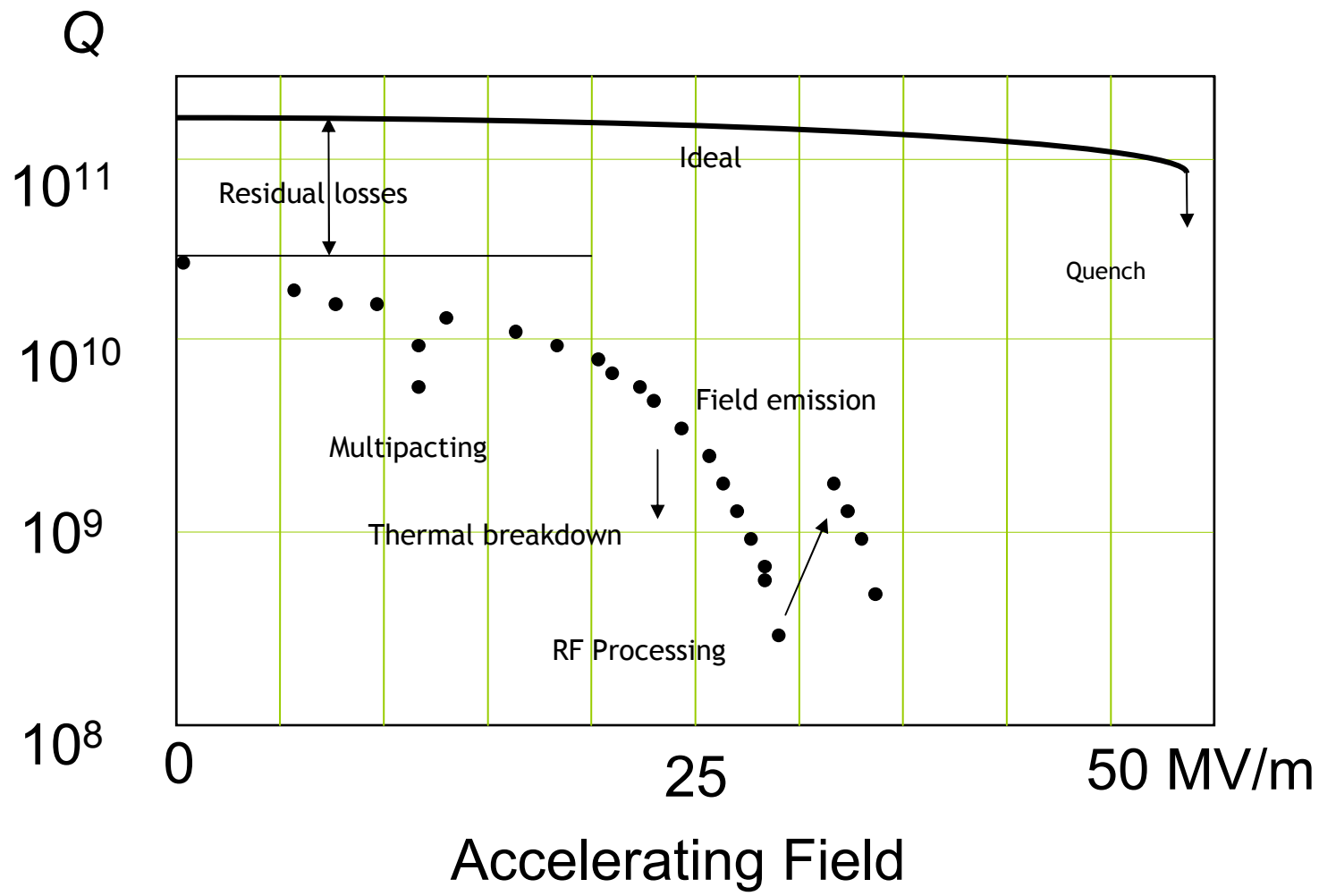
- After cavity or half-cell is produced
  - Heat in vacuum furnace to ~ 1400 C
  - Evaporate Ti on cavity surface
  - Use titanium as getter to capture impurities
  - Later etch away the titanium
  - Doubles the purity (RRR ~ 600 if originally RRR = 300)

Post Purifying Niobium





The Real World

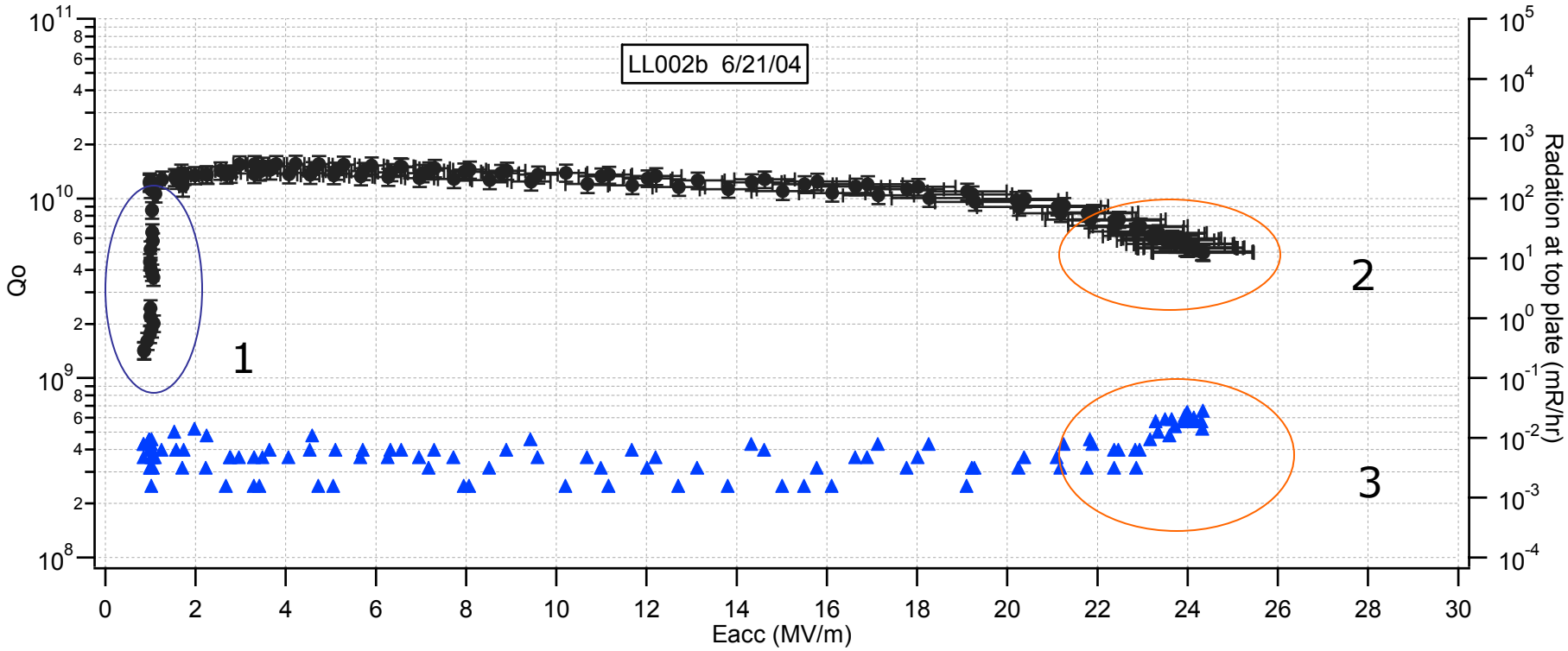


Field Emission

Characterized by an exponential drop of the Q

Associated with production of x-rays and emission of dark current

Vertical Test Performance - Radiation



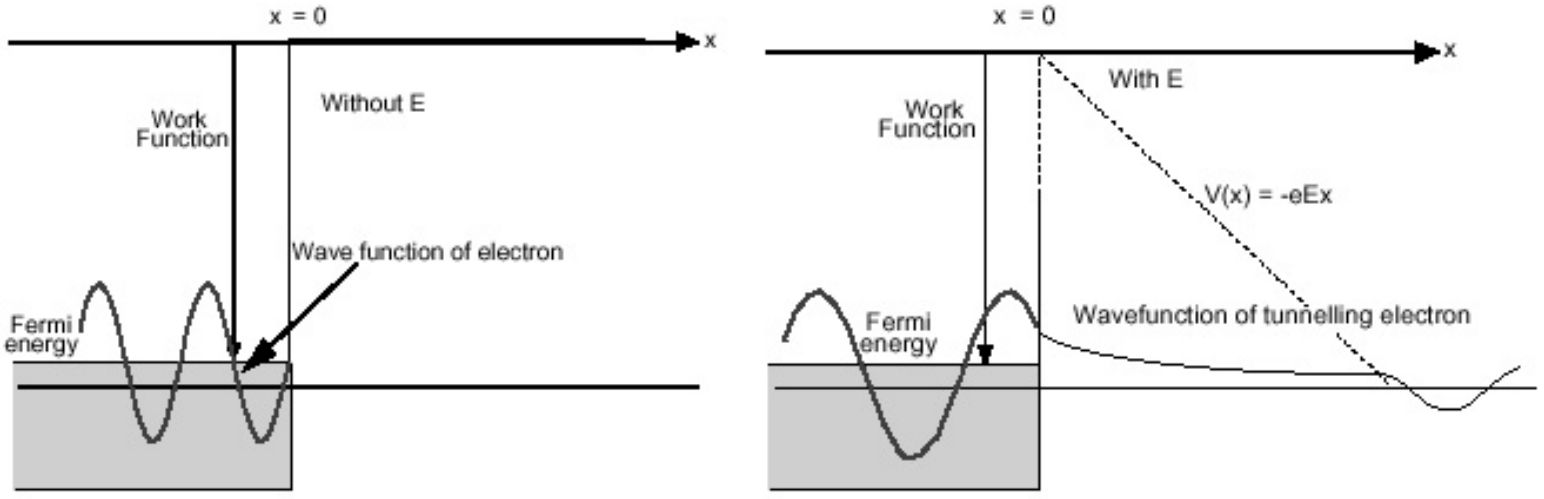
1 – Q_0 as a function of bath temperature 4.2K- 2K

2- Additional source of heating lowers Qo

3- X-rays present outside cryogenic dewar is typical of field emission

DC Field Emission from Ideal Surface

Fowler-Nordheim model



$$J = \frac{1.54\times10^{-6}\,E^2}{\Phi}\exp\left(-\frac{6.83\times10^{9}\,\Phi^{3/2}}{E}\right)$$

J : Current density (A/m^2)

E : Electric field (MV/m)

Φ : Work function (eV)

Field Emission in rf Cavities

$$J = k\frac{1.54\times10^{-6}(\beta E)^{5/2}}{\Phi}\exp\left(-\frac{6.83\times10^{9}\,\Phi^{3/2}}{\beta E}\right)$$

β: Enhancement factor (10s to 100s)

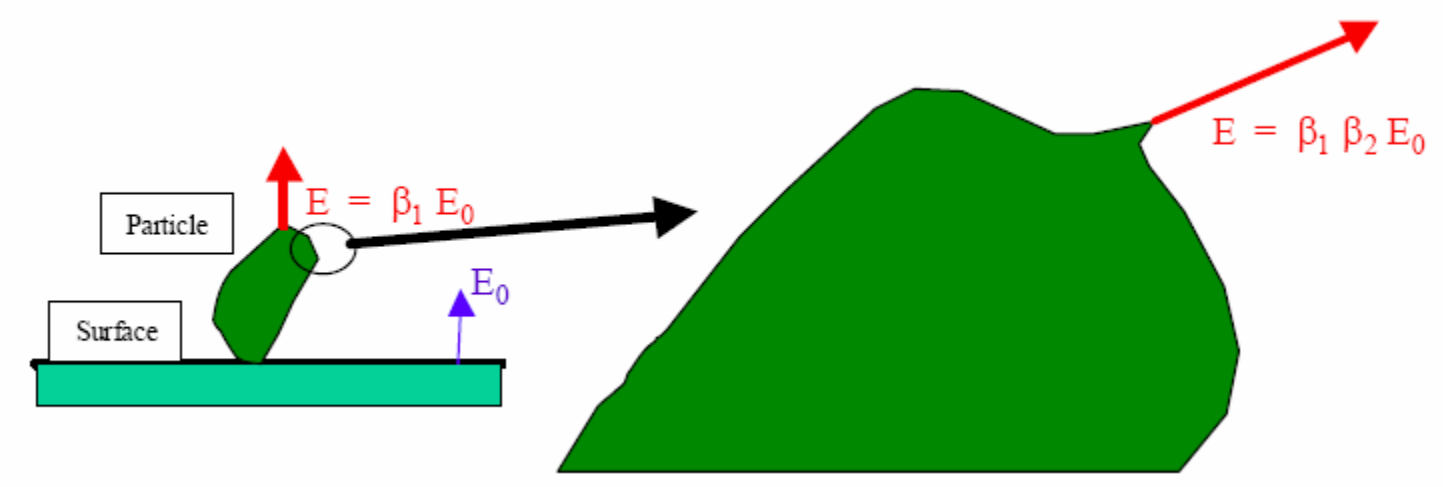
k: Effective emitting surface ($\sim 10^{-9\rightarrow-13}$)

Geometrical Origin of Field Enhancement

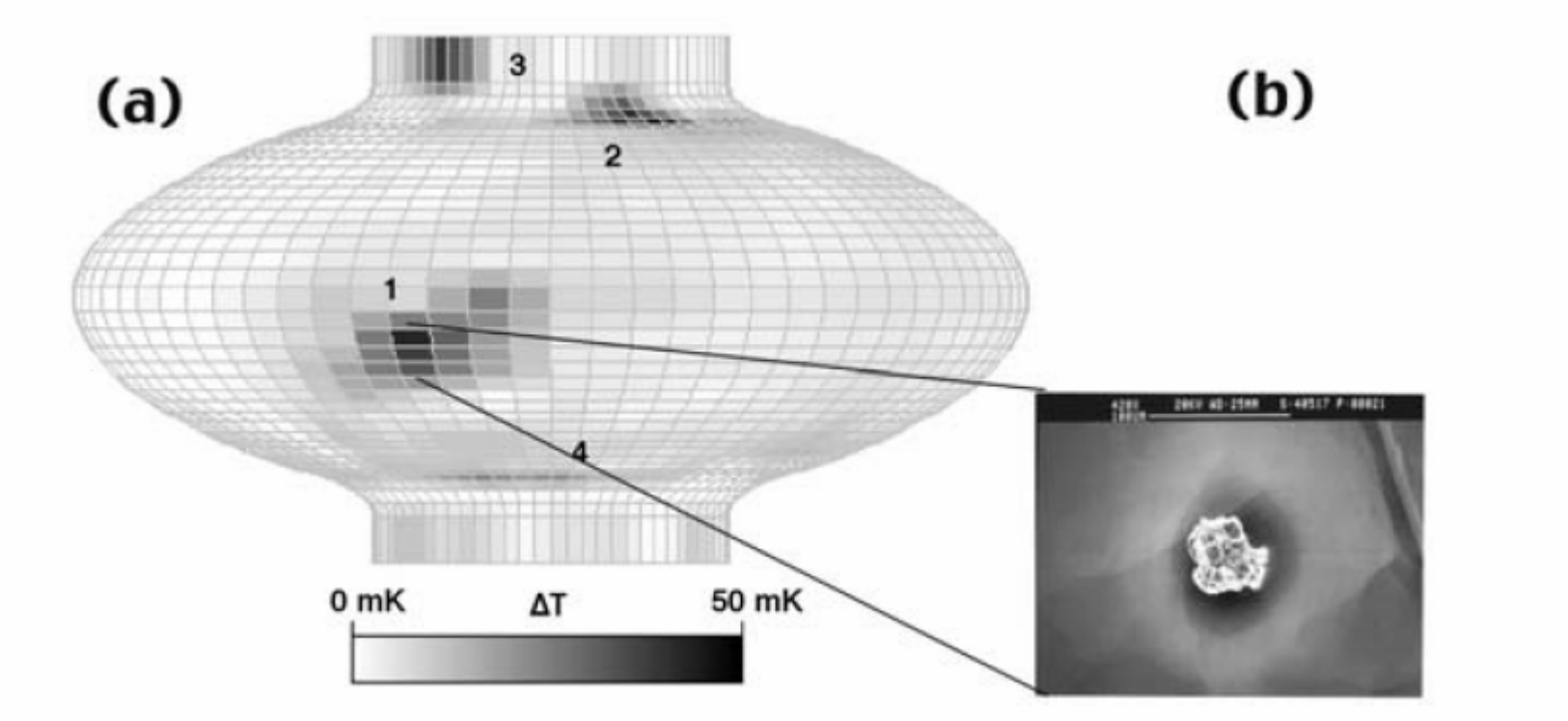
Smooth particles show little field emission

Simple protrusions are not sufficient to explain the measured enhancement factors

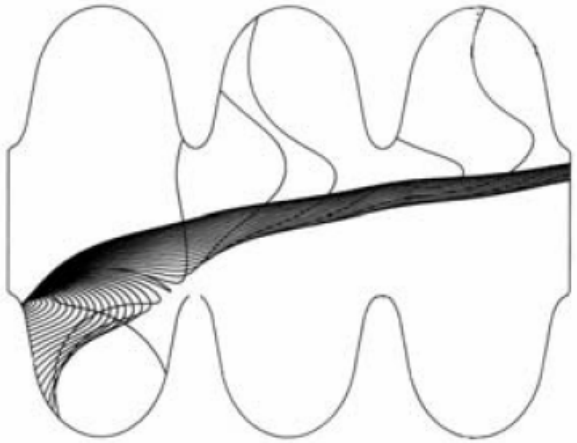
Possible explanation: tip on tip (compounded enhancement)

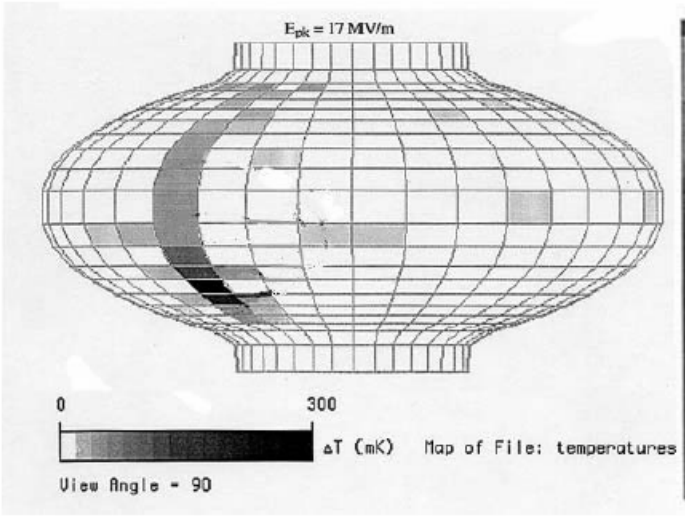


Localized Defects



Field Emission

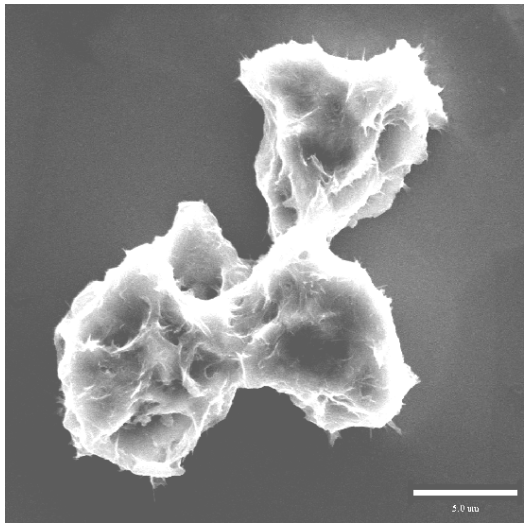


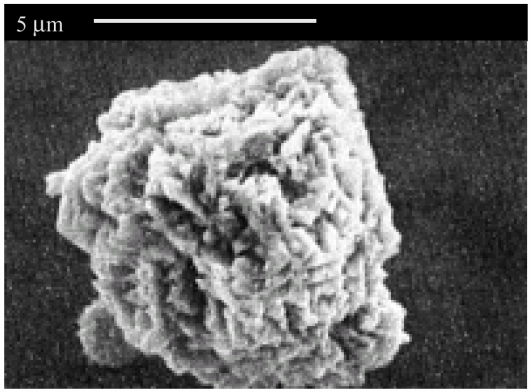


Example of Field Emittors

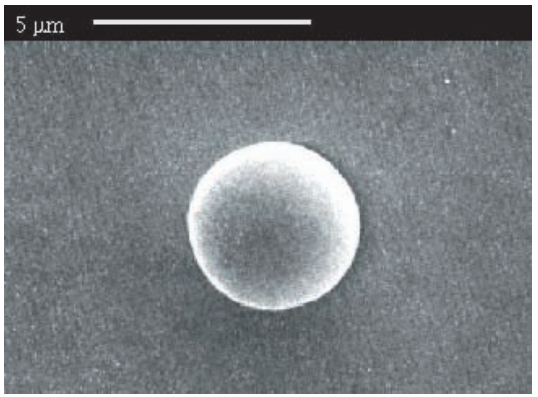
Fig. 11 Example of a scratch and a particle on a niobium surface.

V





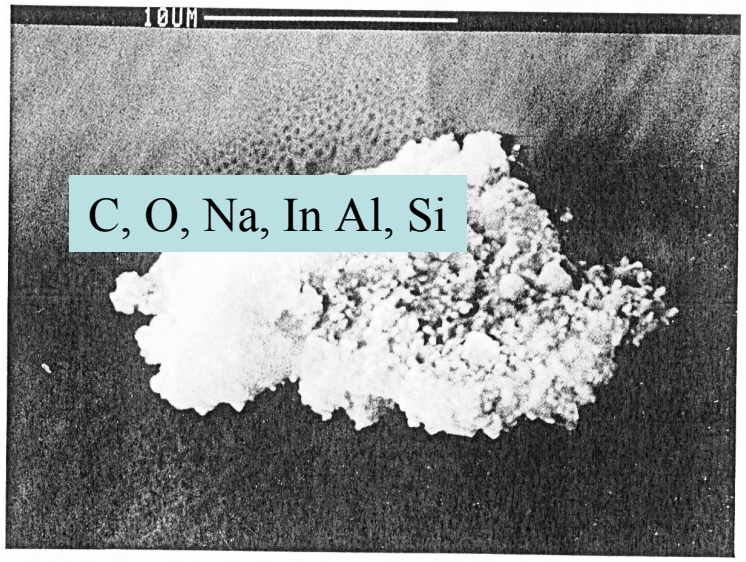
Ni

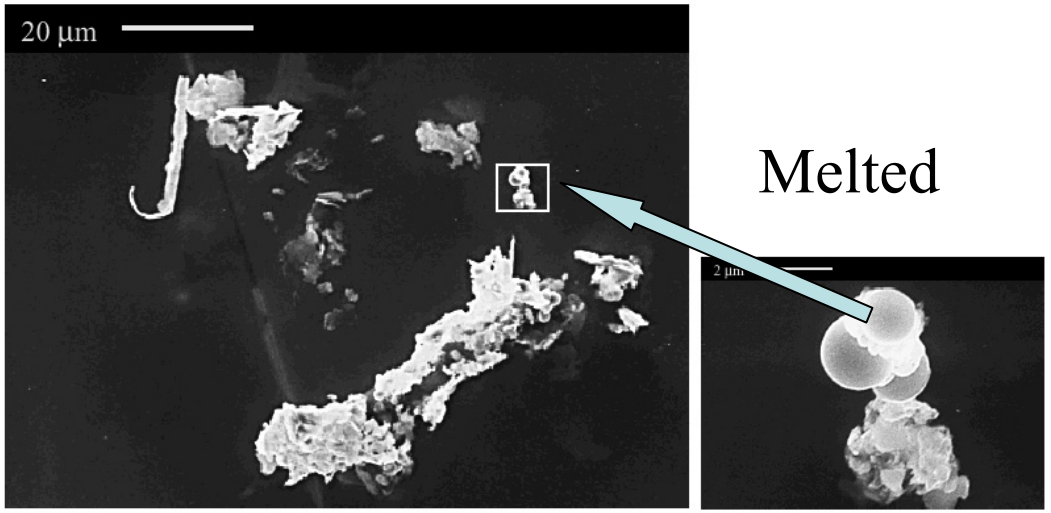


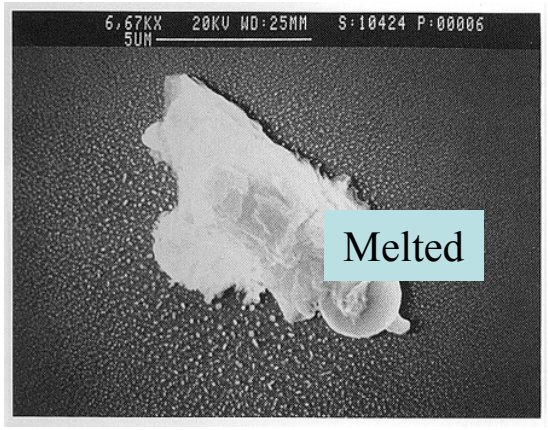
Ni

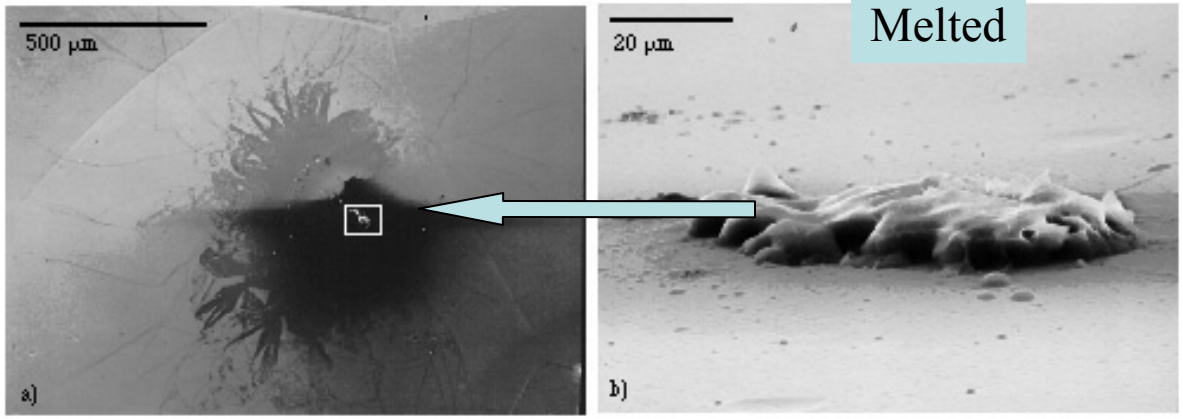
Example of Field Emittors

Stainless steel



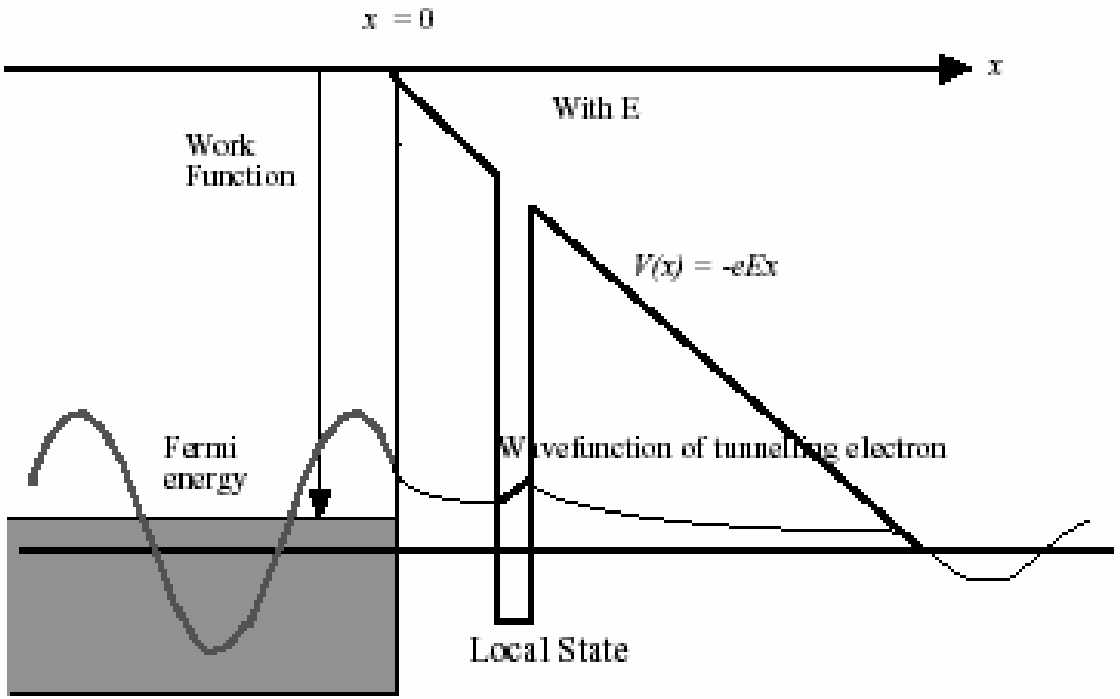






Enhancement by Absorbates

Adsorbed atoms on the surface can enhance the tunneling of electrons from the metal and increase field emission



Field Emission

Surface electric field is not a fundamental limitation

- Surface fields above 100 MV/m over many cm^2 have been maintained cw in superconducting cavities (>200 MV/m for ms)

However field emission is still the main limitation

The main cause of field emission is particulate contamination

Contamination Prevention

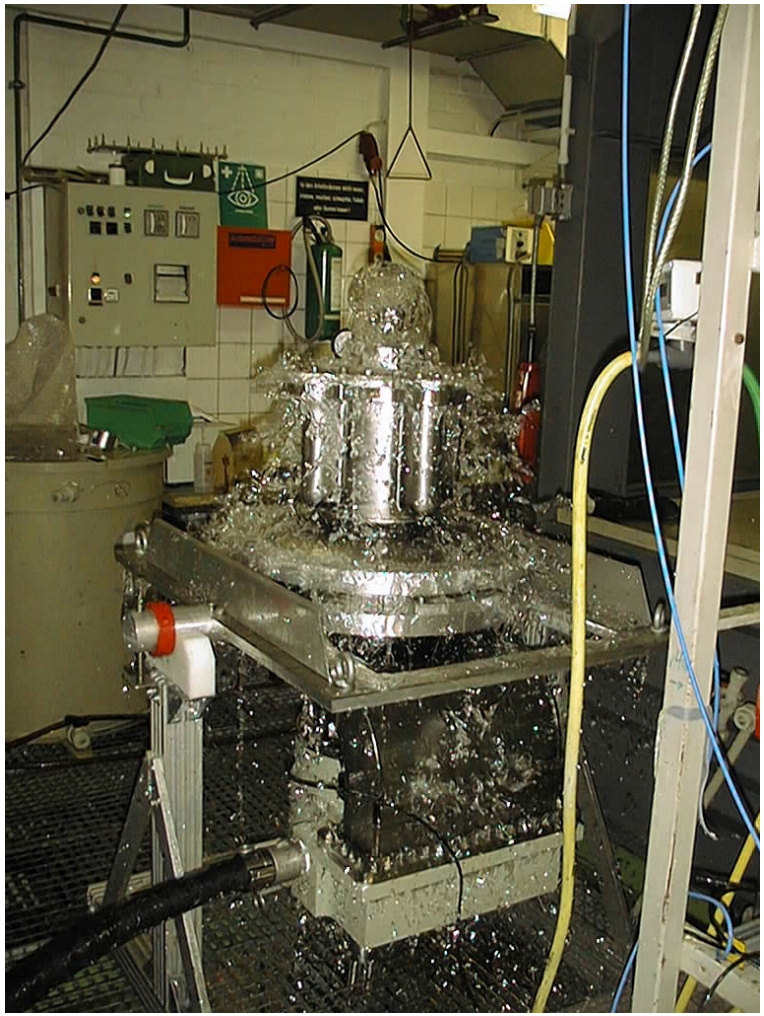
- **Sources of contamination**
  - Processing Chemicals (filtered!)
  - High Purity Water (>18 MWcm, <0.02 mm filter)
  - Clean Room environment (entrance, class 10)
  - Particulates on equipment,tooling,hardware,clothing, gloves..

- **Contamination control**
  - Stringent control of processes and procedures
  - In-line monitoring of particulate levels in air and liquids
  - Scheduled maintenance
  - "Blow-off" with filtered N_2 , monitored by particle counter
  - Use of appropriate hardware (e.g. bolts..)
  - Clever designs (e.g.gaskets, clamp rings, fixtures…)
  - Consistent use of "best practices" through whole assembly process

Contamination Prevention

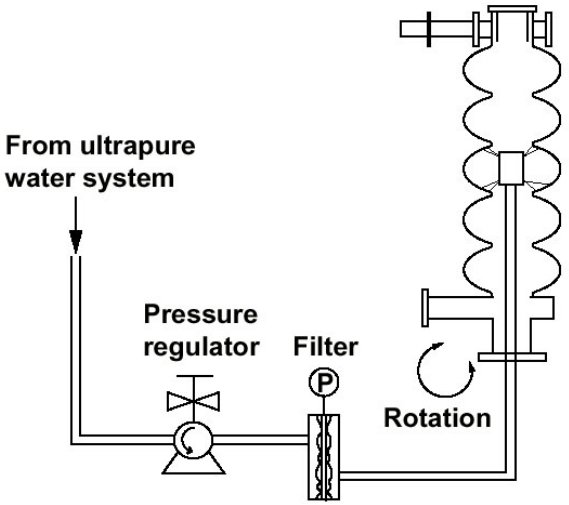
Continuous-flow rinse

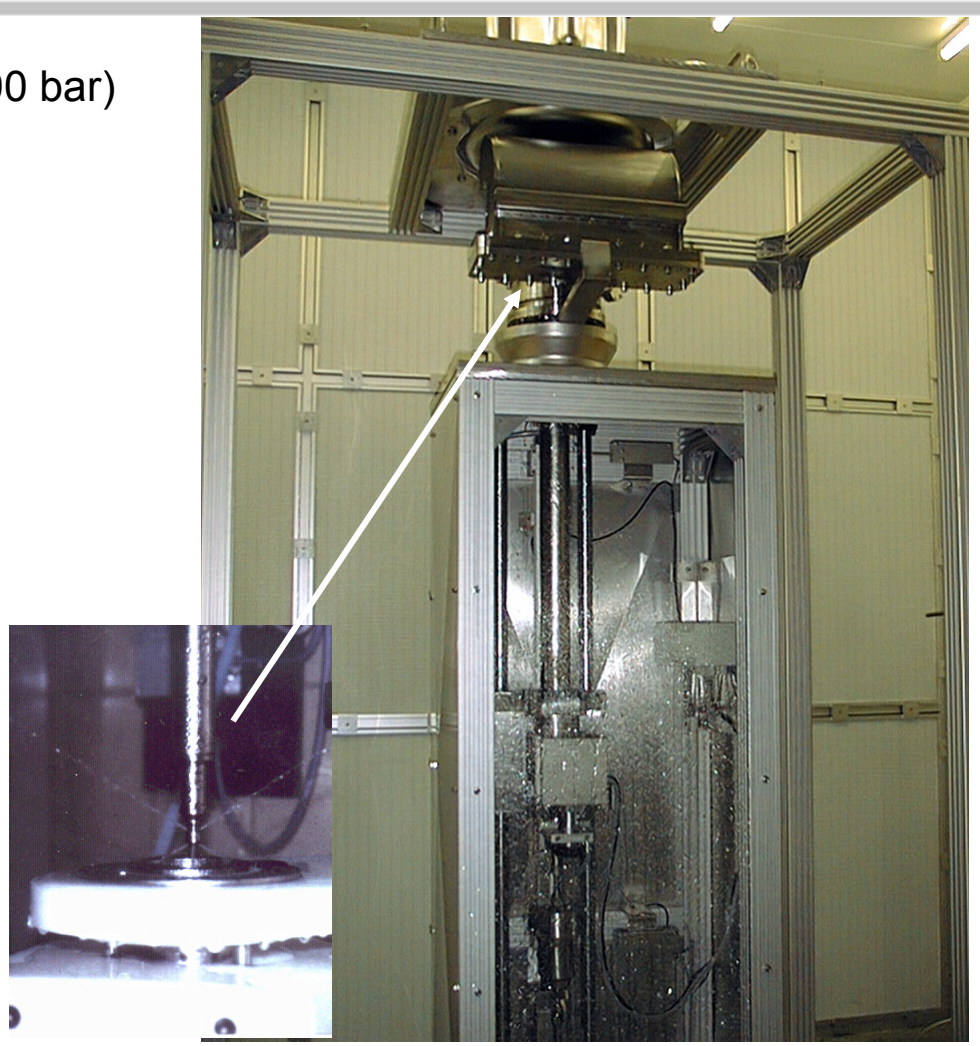
Ultrapure water (18 MΩ-cm) must be used for all treatments



High pressure rinsing (HPR)

- Rinsing of cavities with up to 1000 psi (100 bar) water jets removes many particles.





High Pressure Rinse Systems

DESY-System

Jlab HPR Cabinet

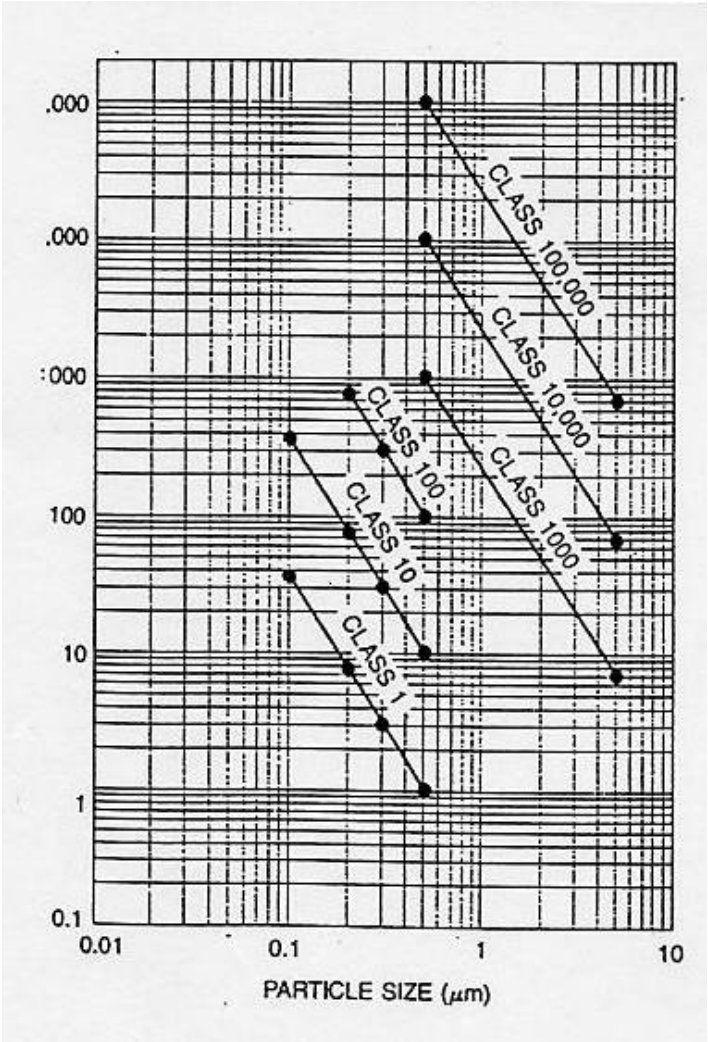
KEK-System

Clean Rooms

All cavities and vacuum components are assembled in a clean rooms (class 100 or better, <100 particle per ft^3 >0.5μm)

Components and tooling must be designed to be clean room compatible

TESLA cavity



Clean Rooms

Post Processing Contamination

Contamination can occur during string and cryomodule assembly

Accelerator beam lines are not clean

Particulate can migrate from beam line to cavities

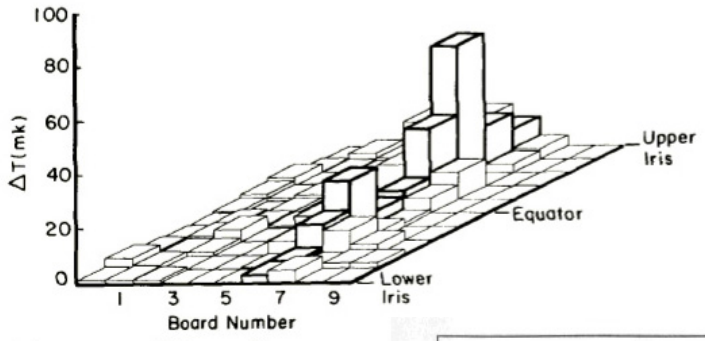
Vacuum accidents happen

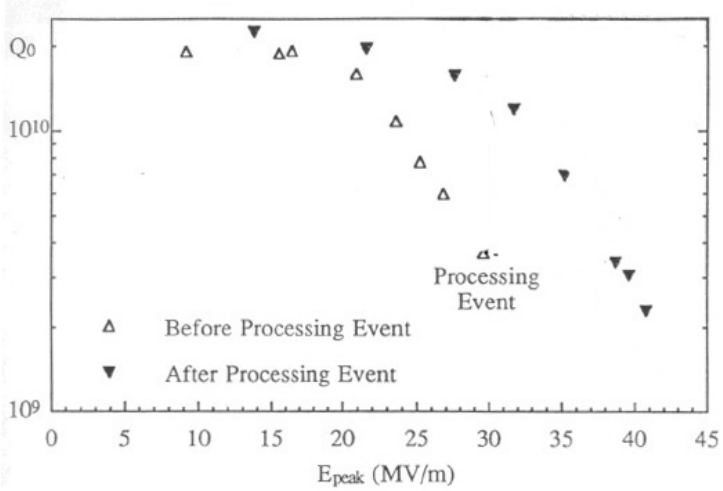
Field emission can occur or increase during operation

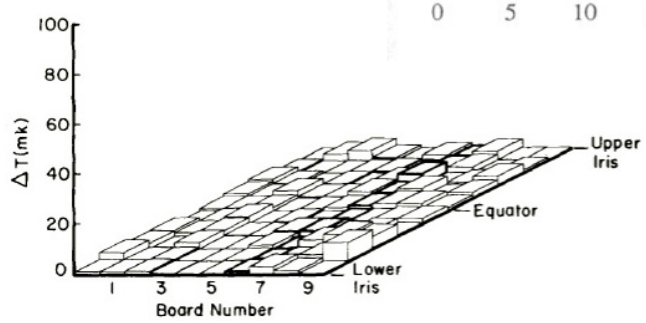
High power processing

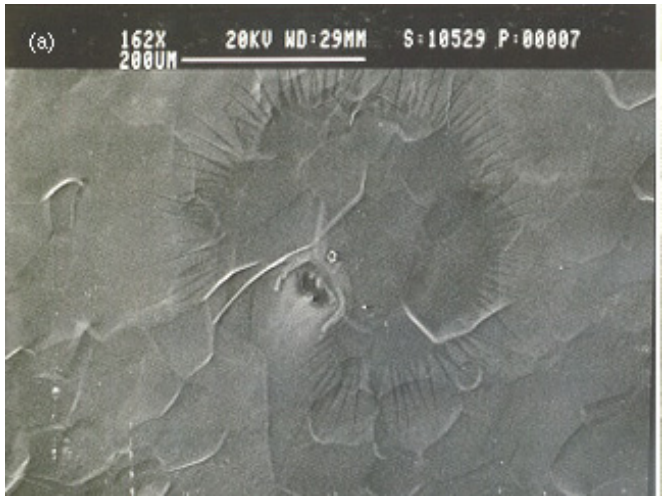
Helium Processing

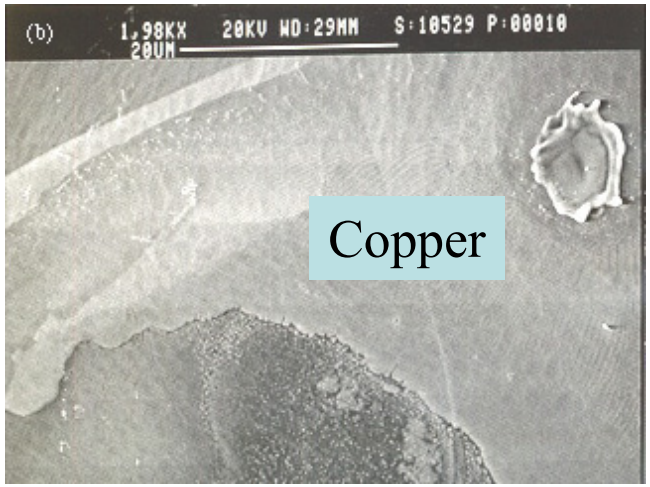
High Power Processing



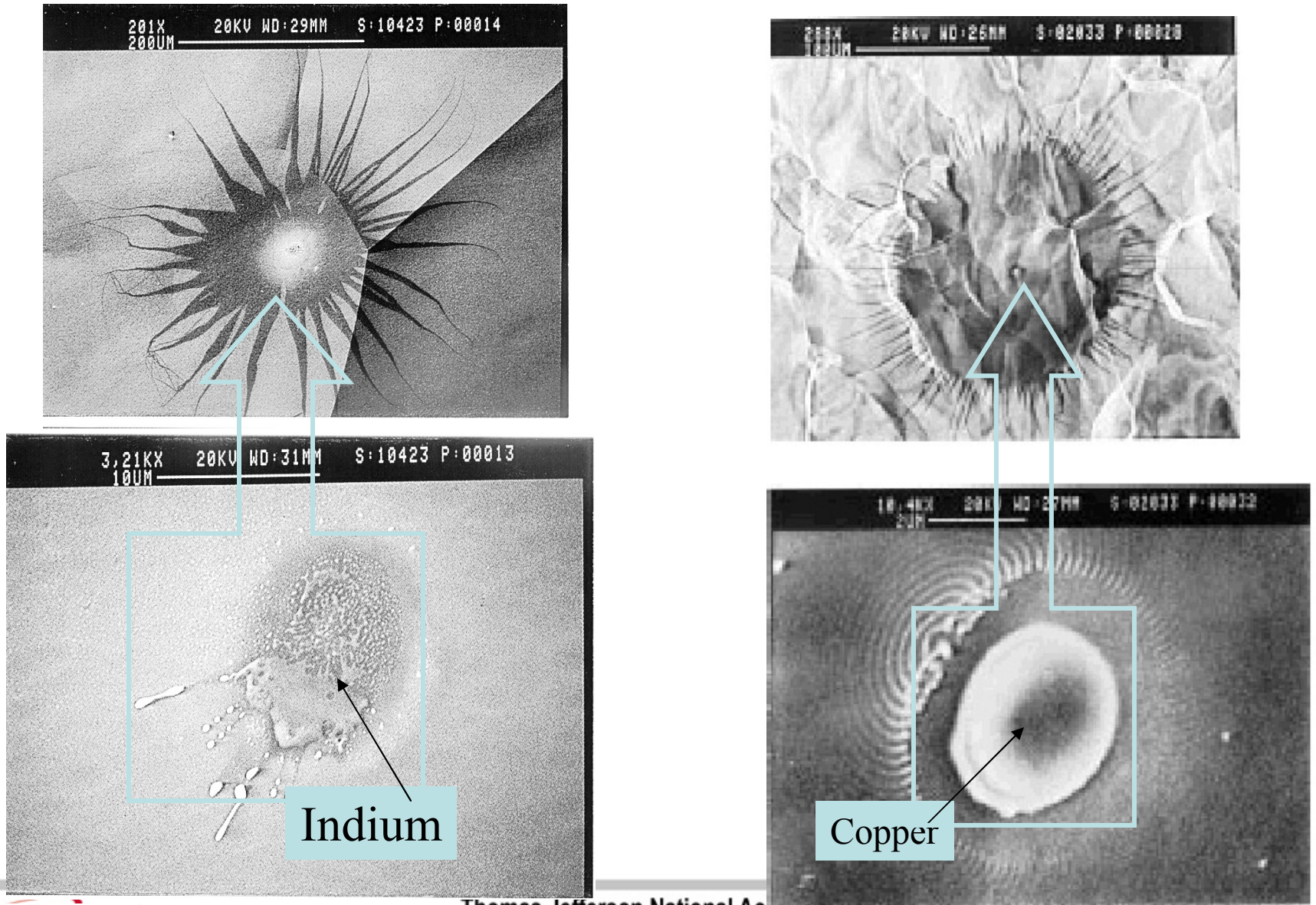








High Power Processing



Helium Processing

Helium gas is introduced in the cavity at a pressure just below breakdown (~10^{-5} torr)

Cavity is operating at the highest field possible (in heavy field emission regime)

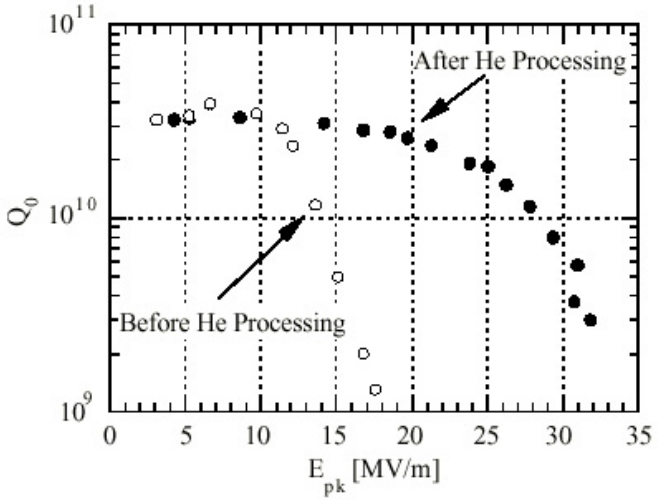
Duty cycle is adjusted to remain thermally stable

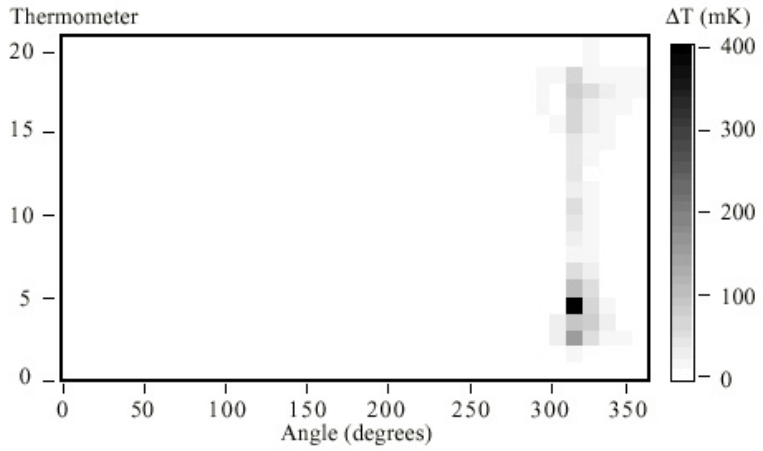
Field emitted electrons ionized helium gas

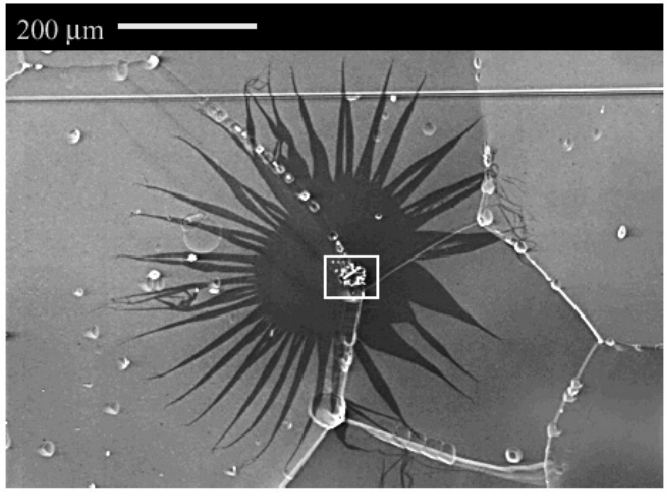
Helium ions stream back to emitting site

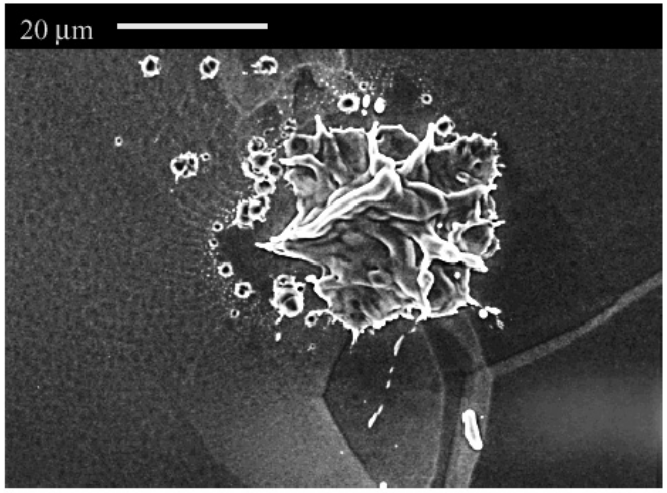
- Cleans surface contamination
- Sputters sharp protrusions

Helium Processing

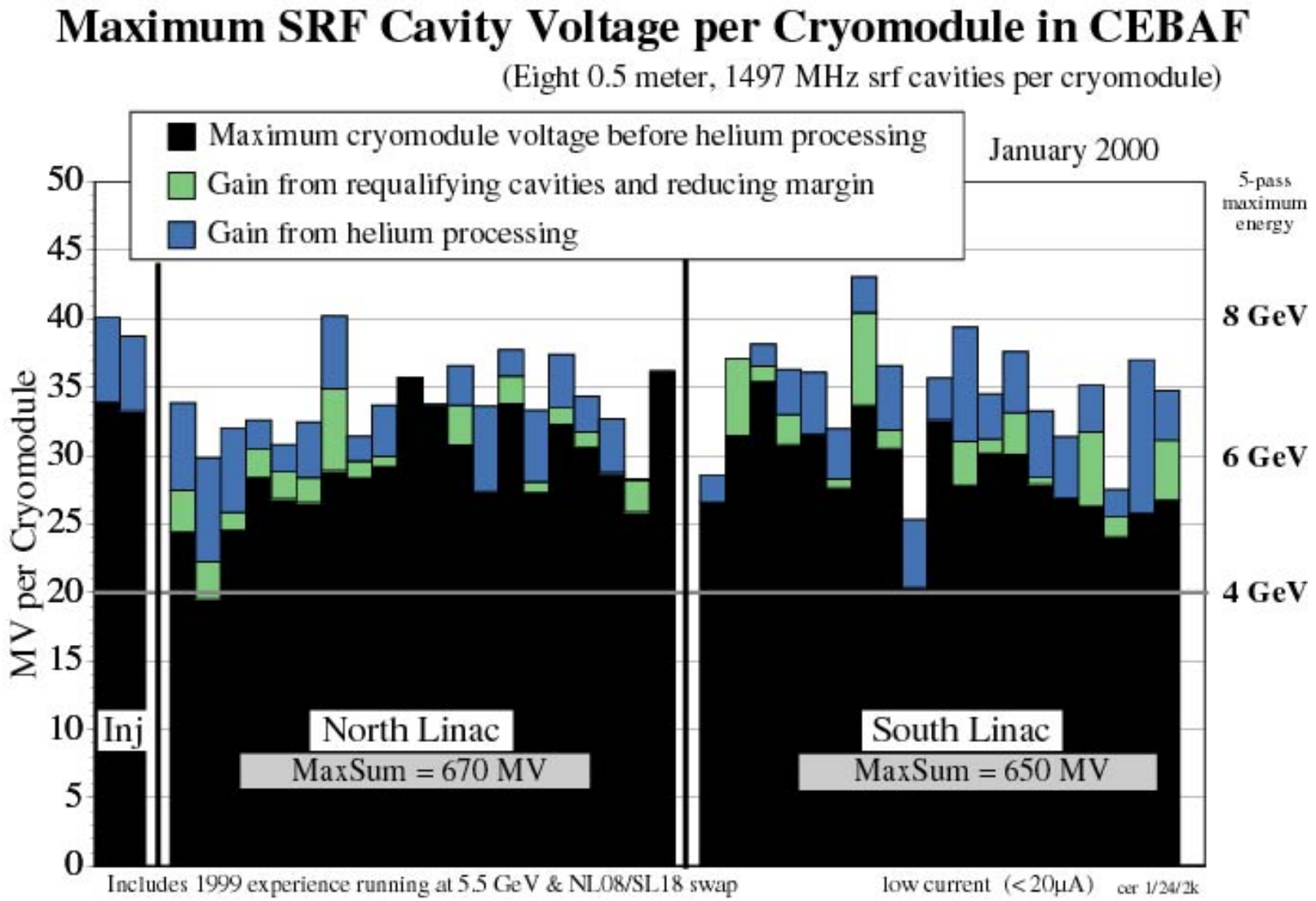








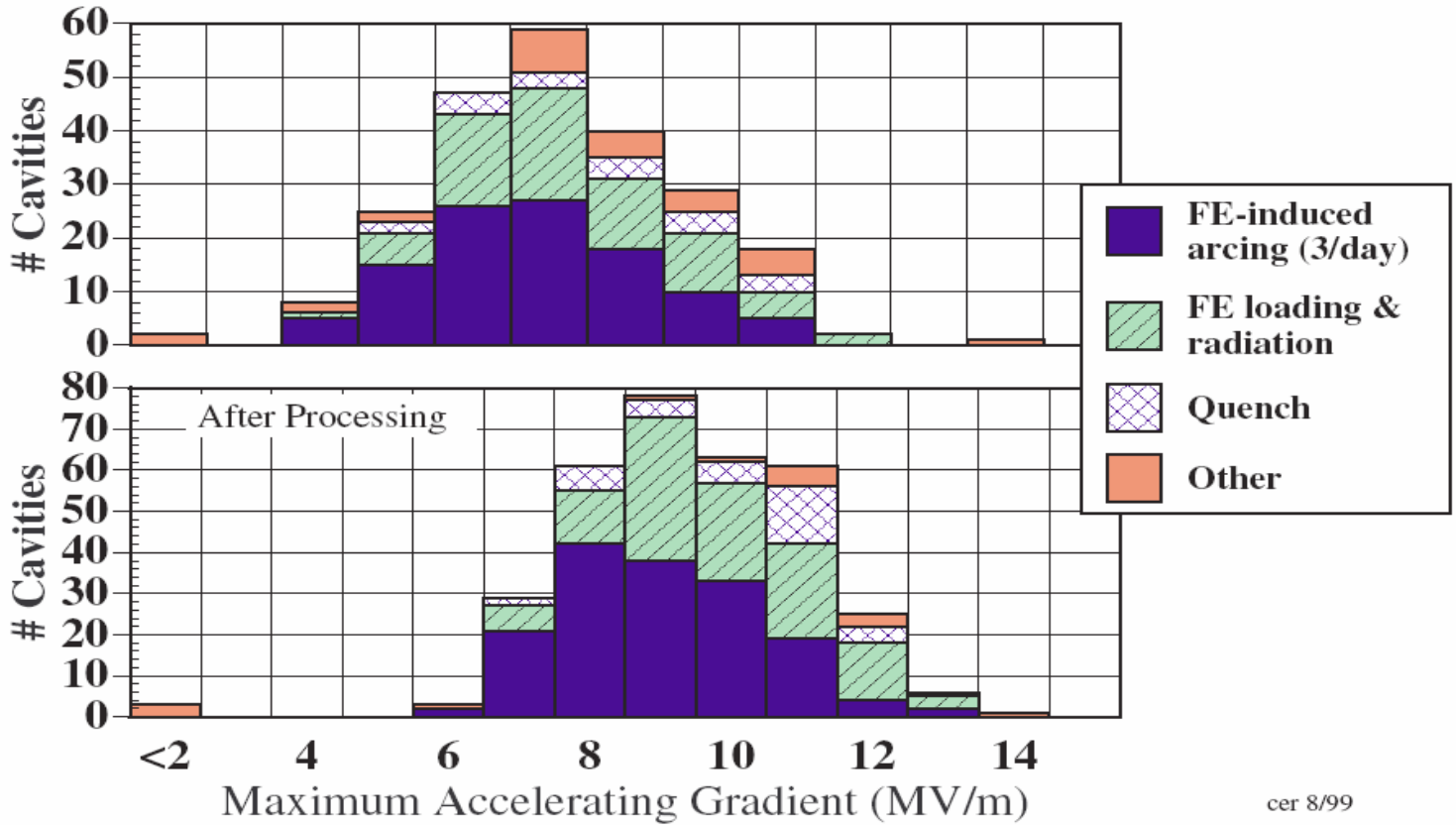
Helium Processing in CEBAF



Helium Processing in CEBAF

Improvement of Cavity Performance with Helium Processing

Distribution of Maximum Gradients by Type of Limitation



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Helium Processing in CEBAF

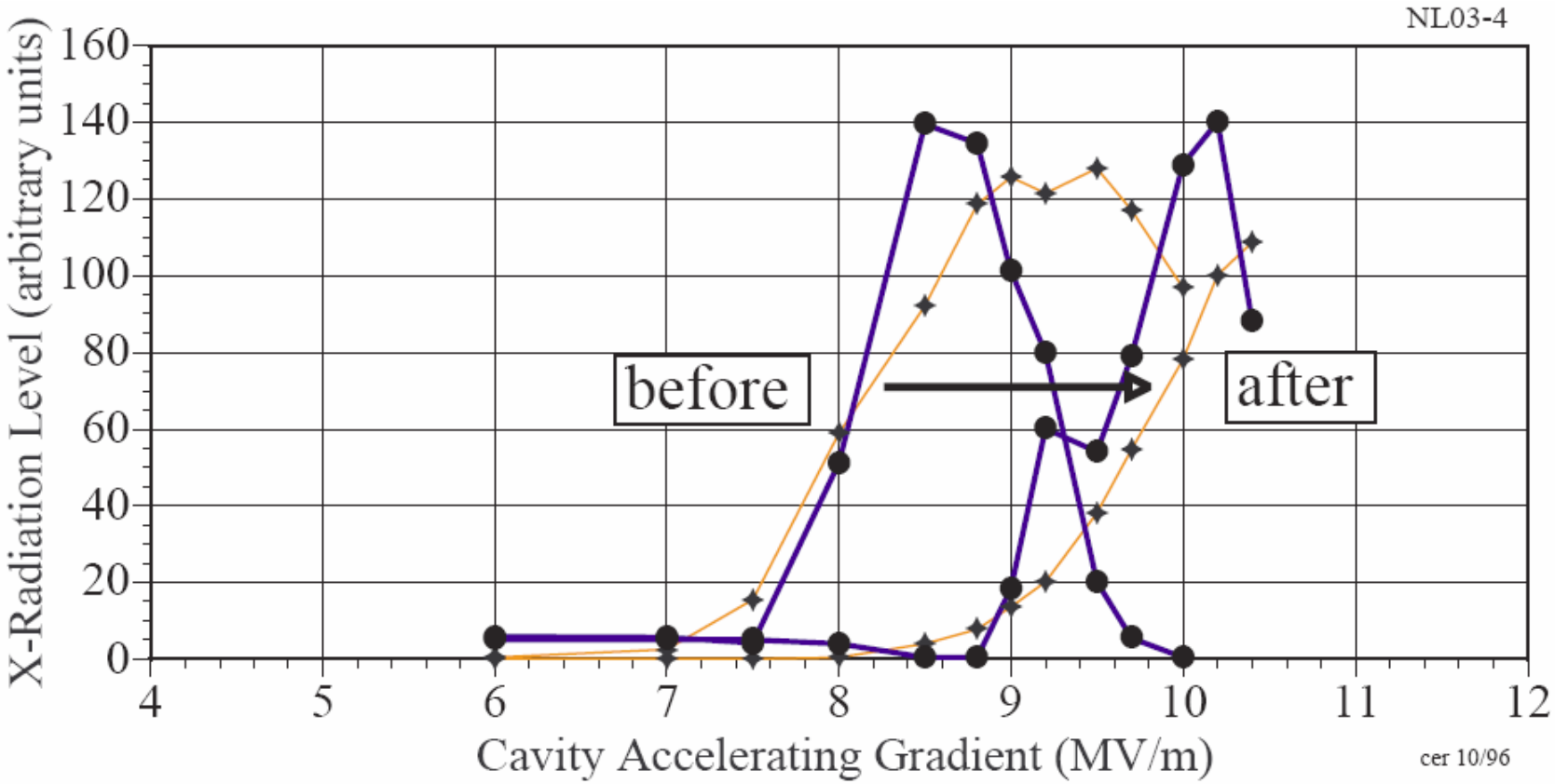
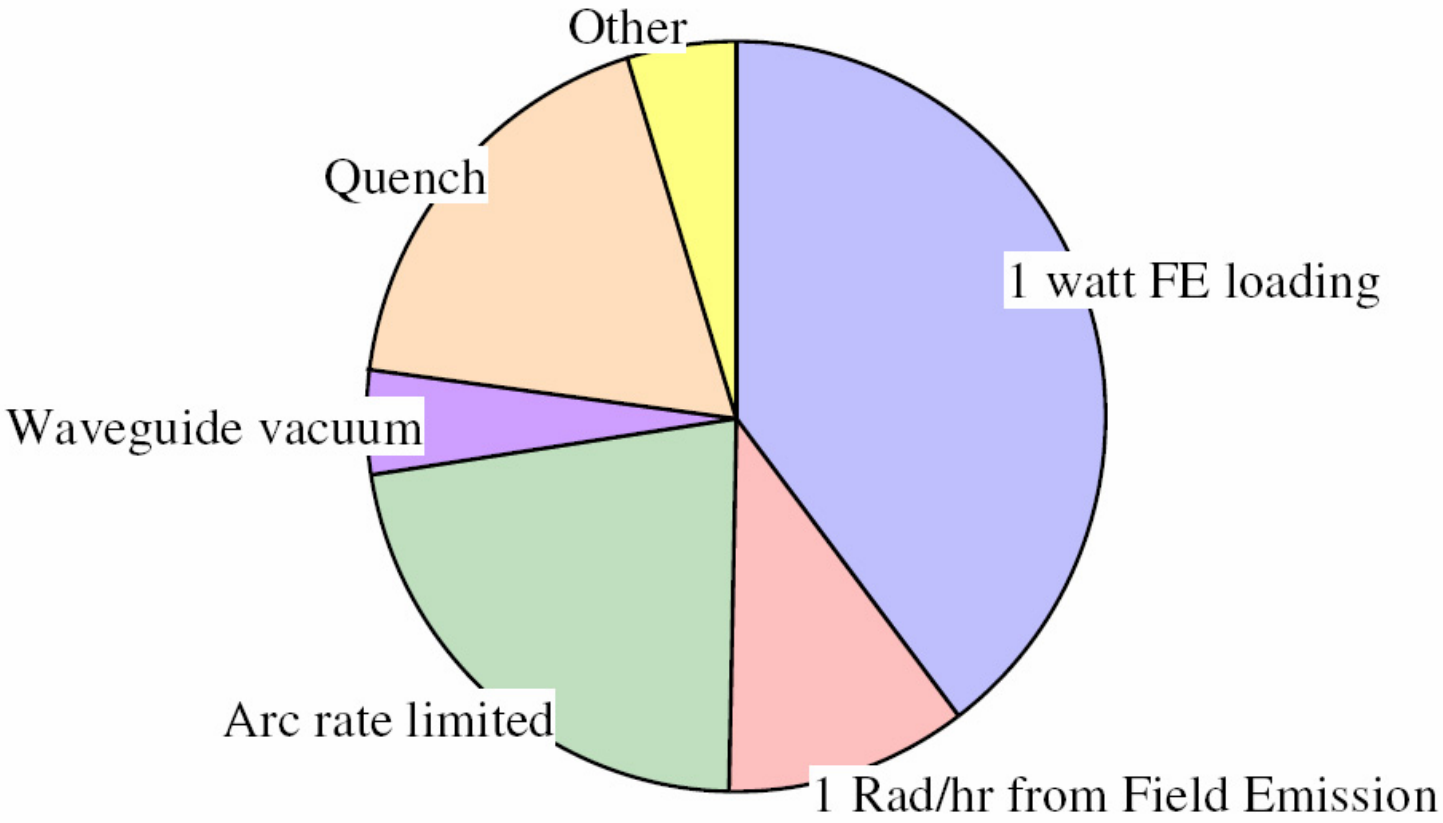
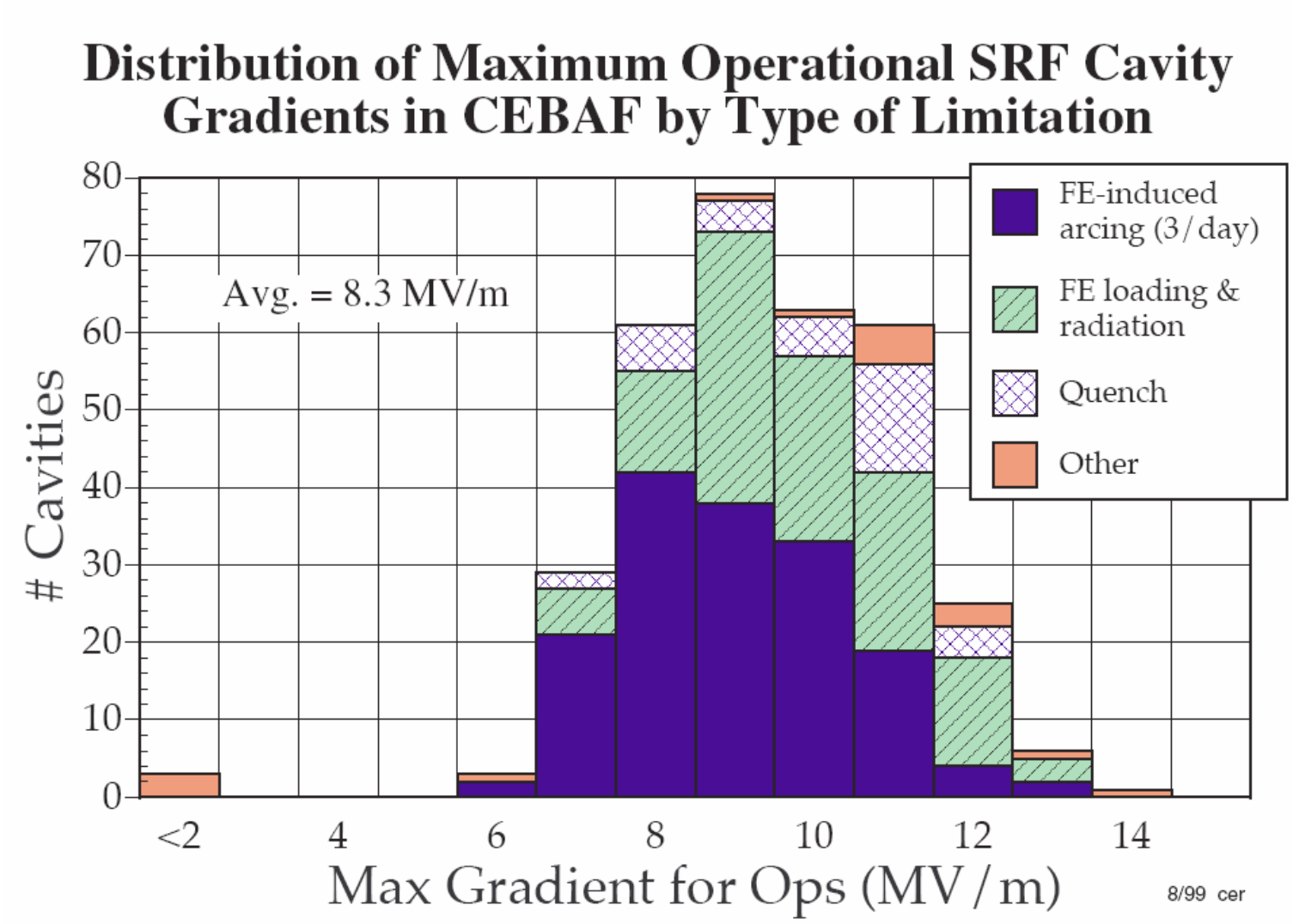


Figure 1. Radiation reduction with He processing.

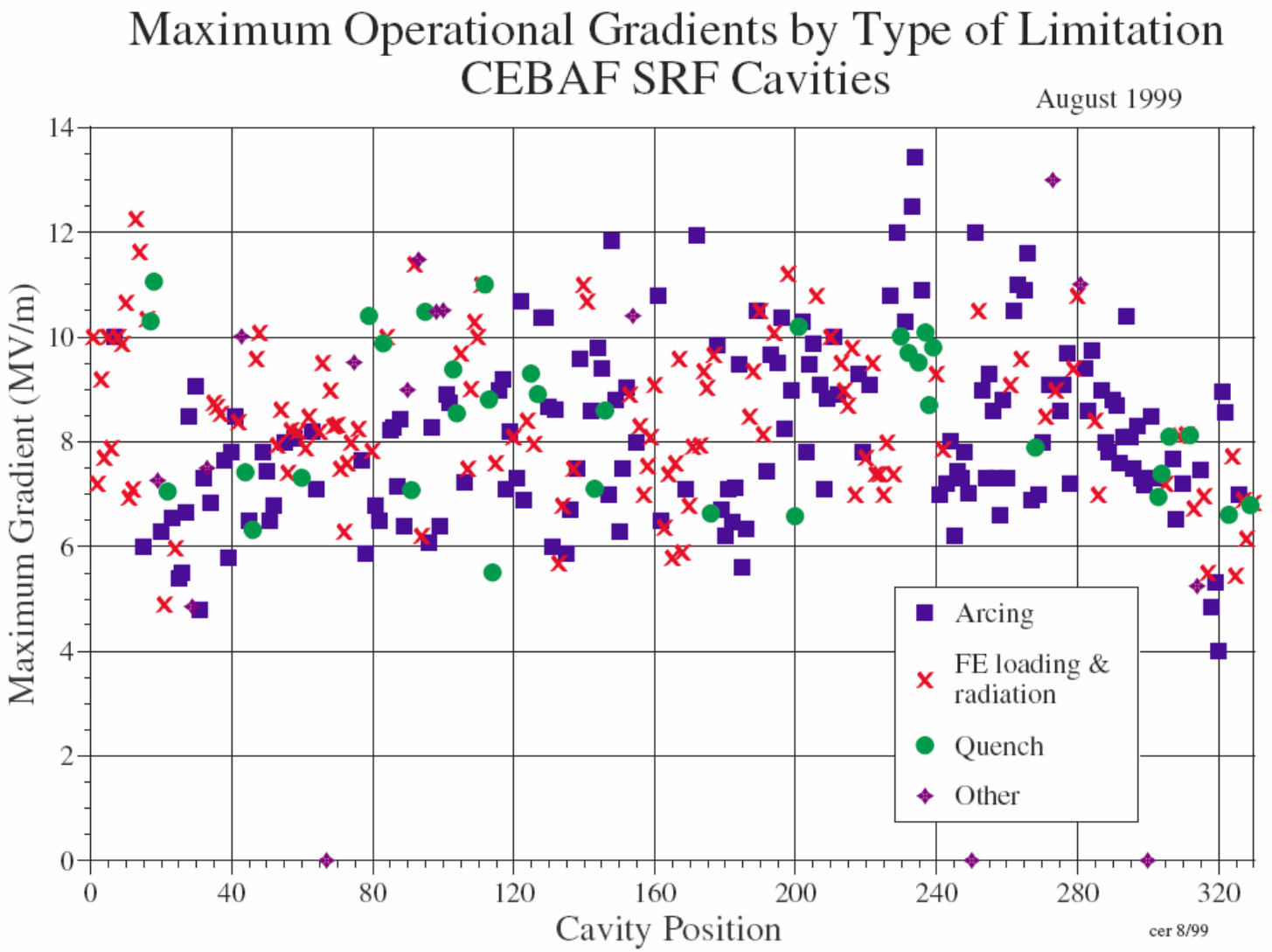
Practical Limitations (CEBAF)



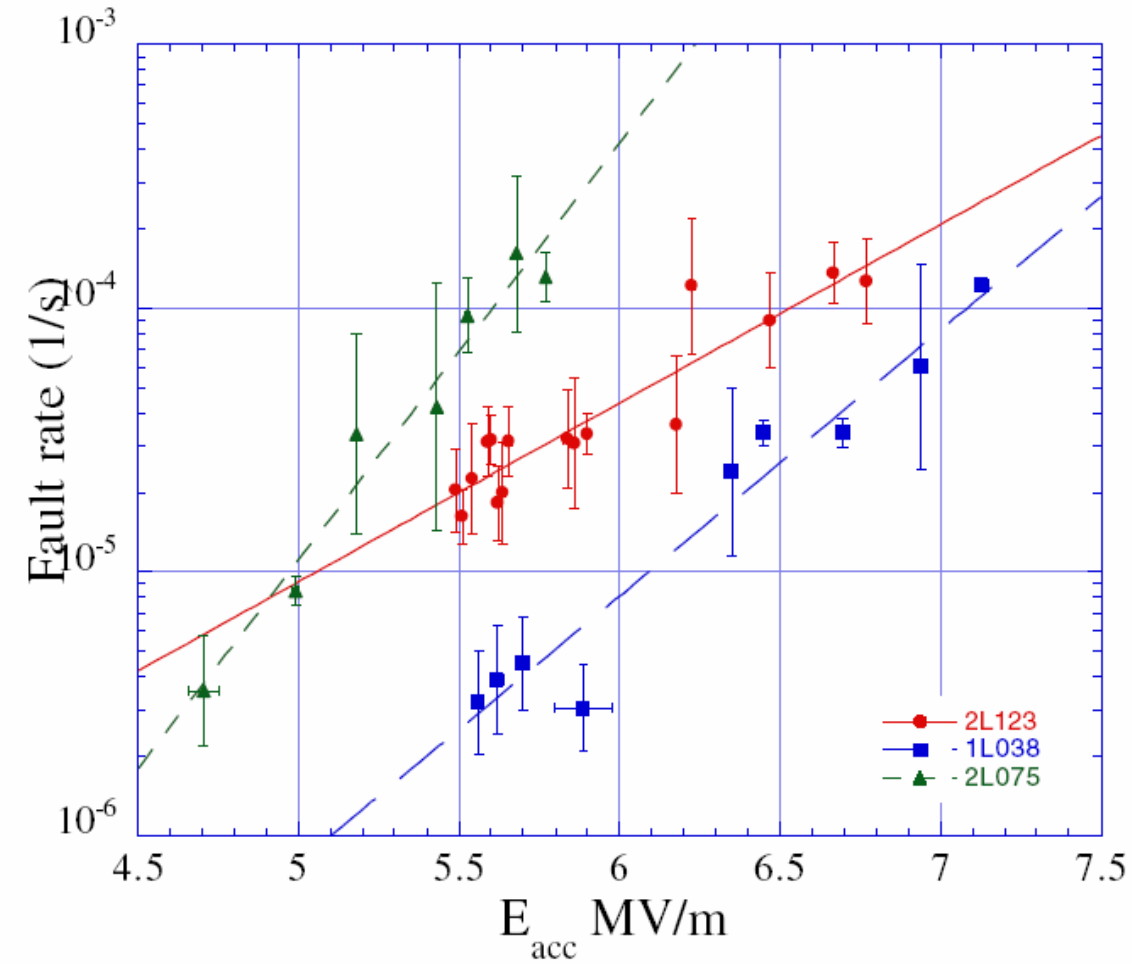
Practical Limitations (CEBAF)



Practical Limitations (CEBAF)

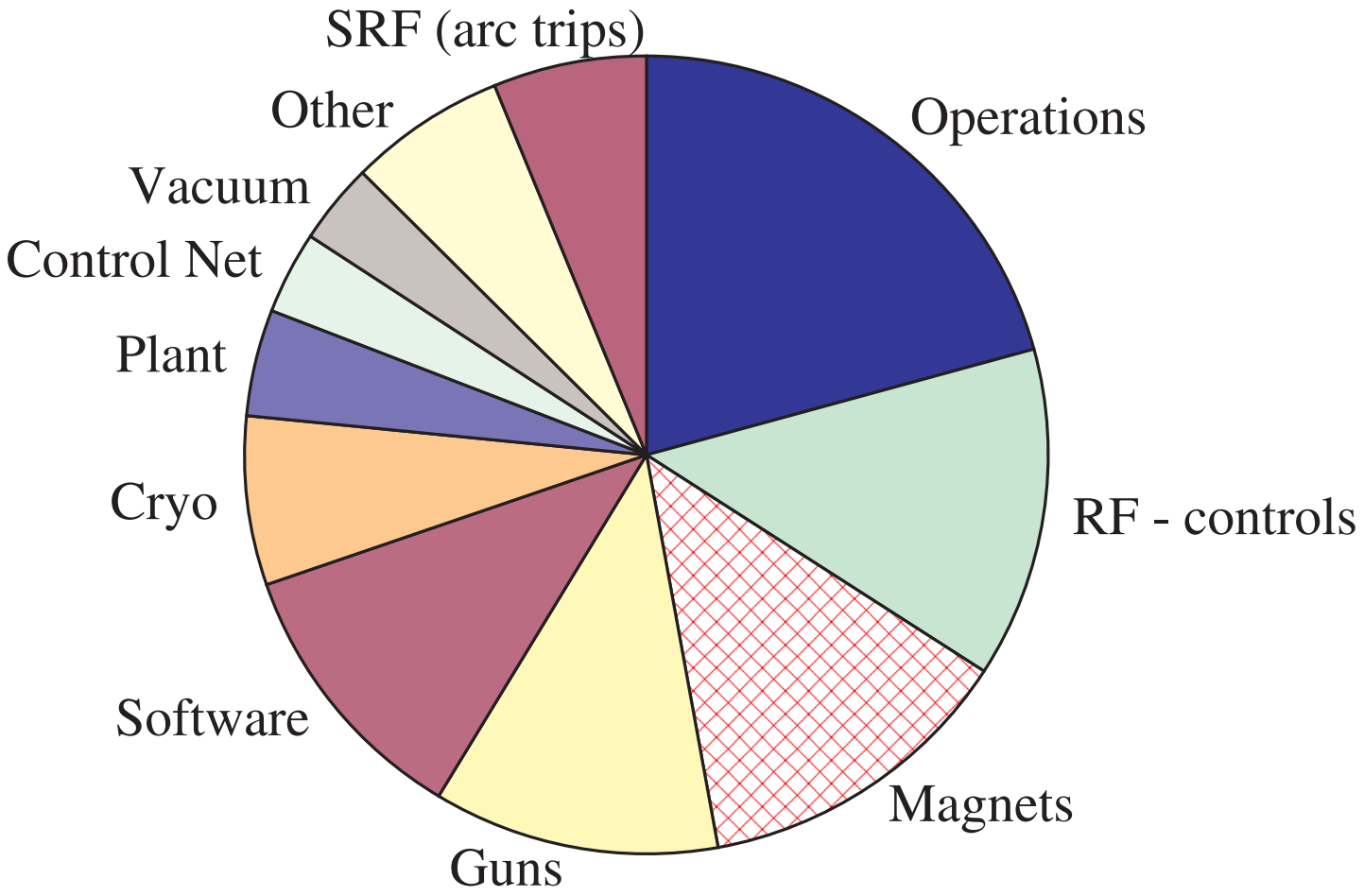


Practical Limitations (CEBAF)



CEBAF Downtime Distribution

CEBAF Downtime Contribution by System - FY99



Time Evolution of Performance (DESY)