7. Performance Limitations and Cure

7.1 Field Emission

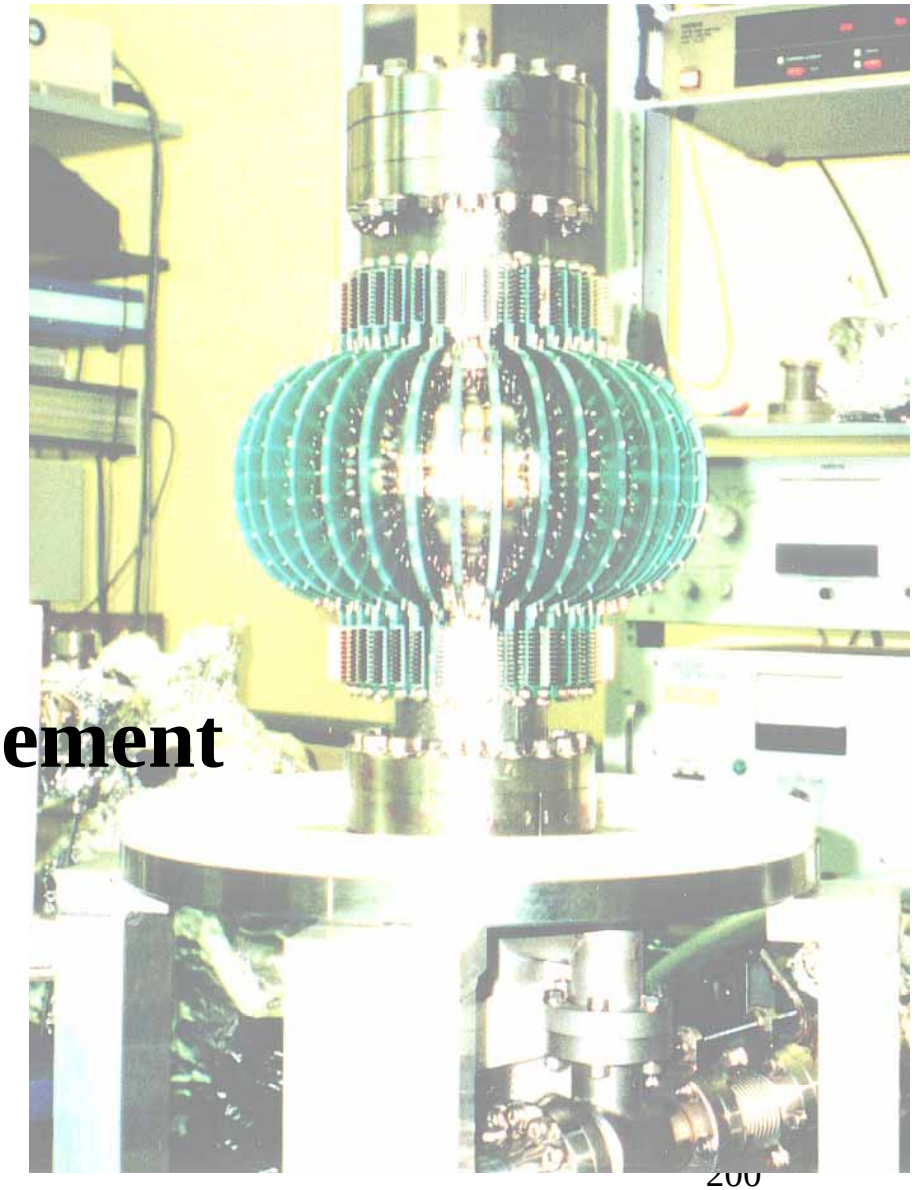
7.2 Multipacting

7.3 Thermal Instability

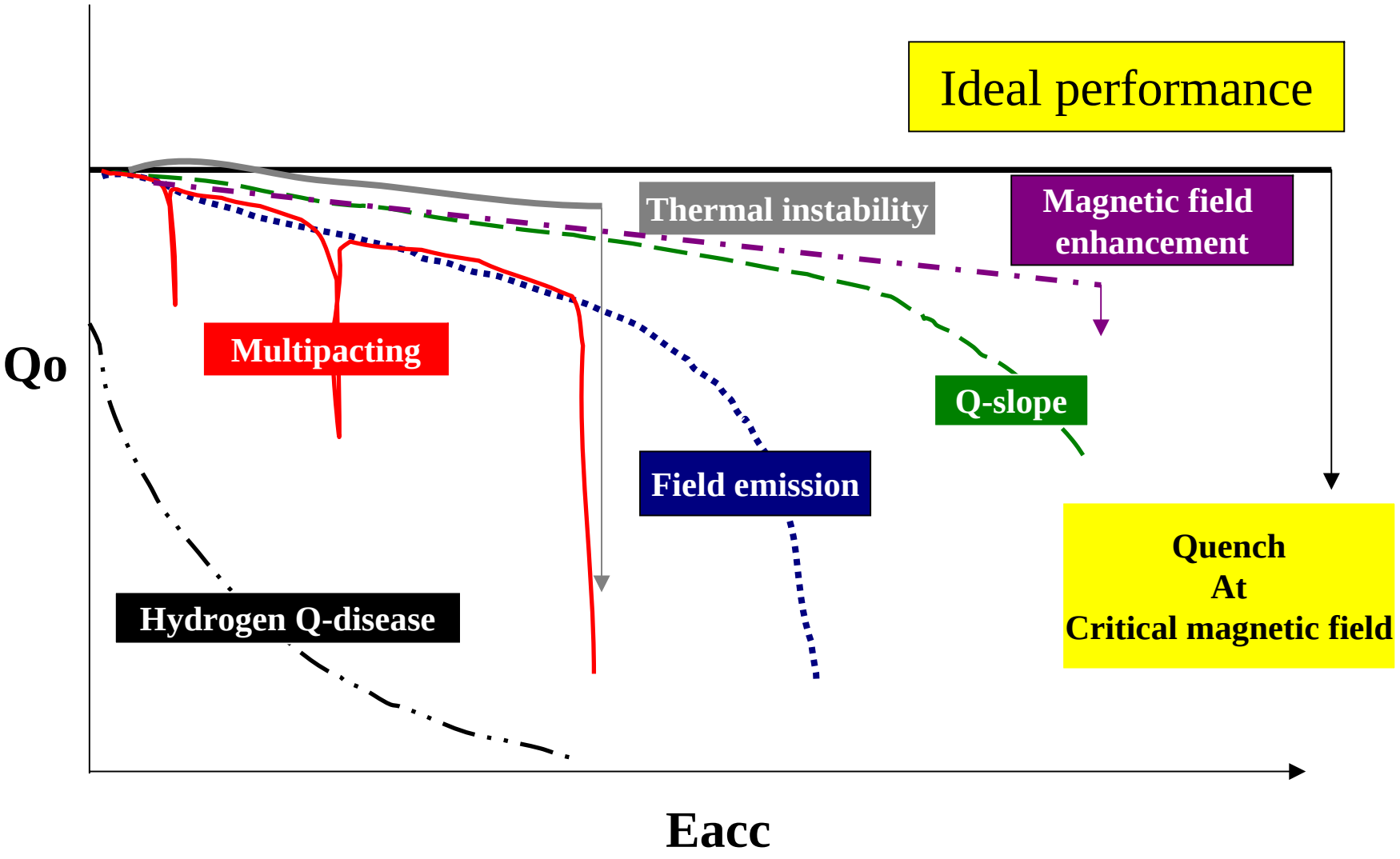
7.4 Hydrogen Q-Disease

7.5 Q-Slope

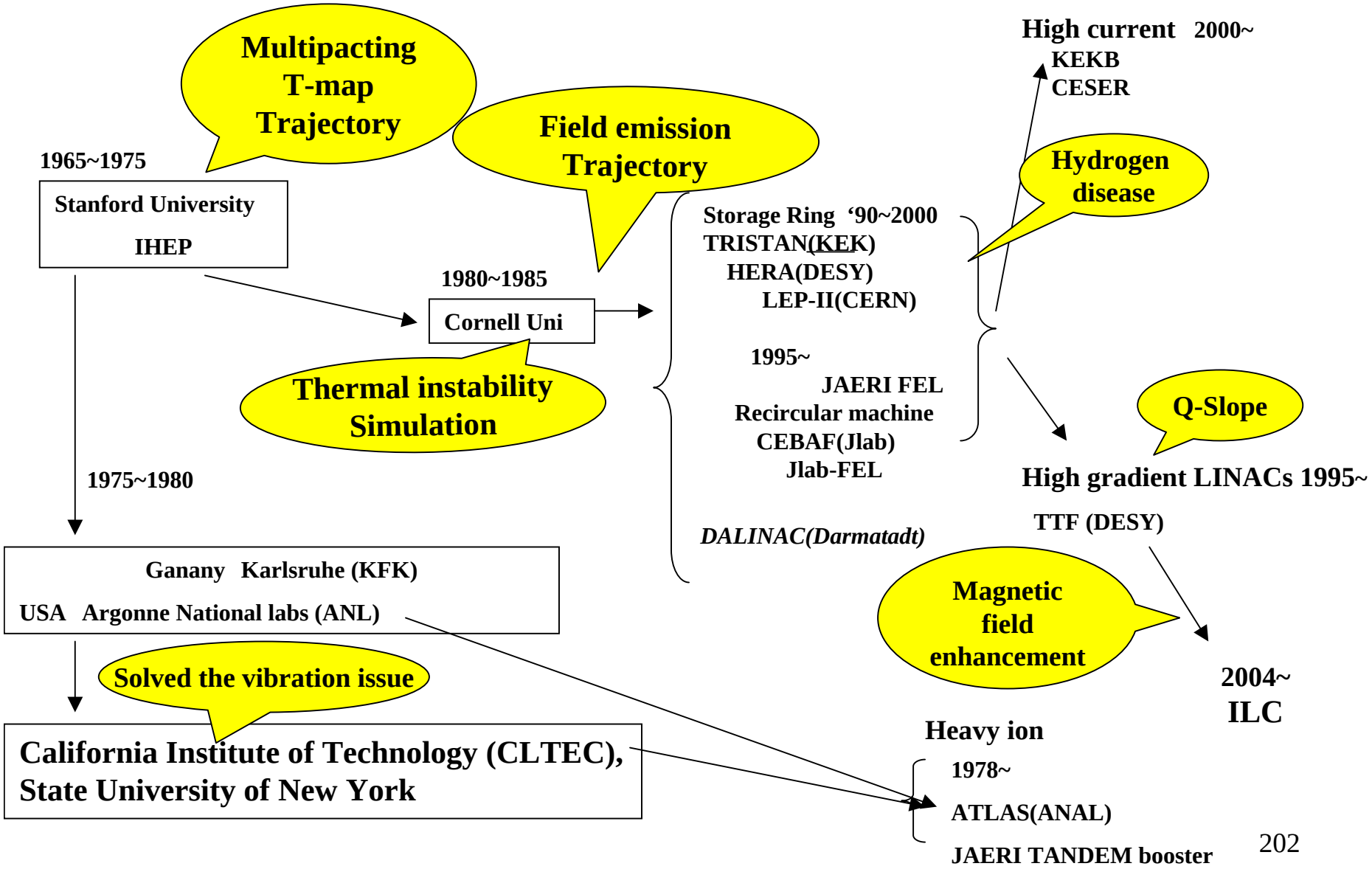
7.6 Magnetic Field Enhancement



Various Performance Limitations in SRF Cavity

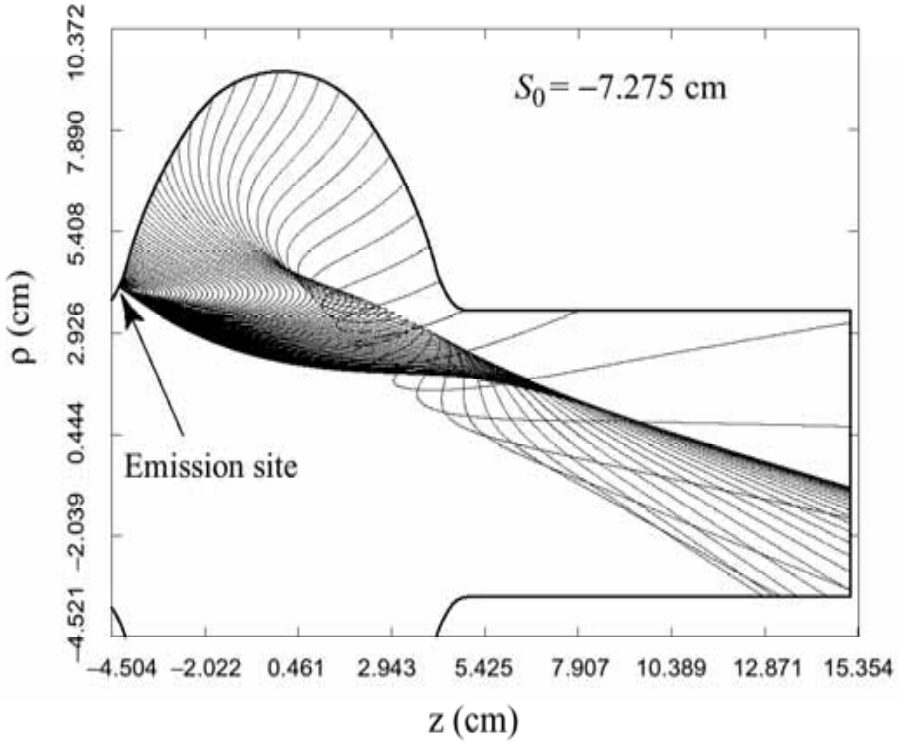


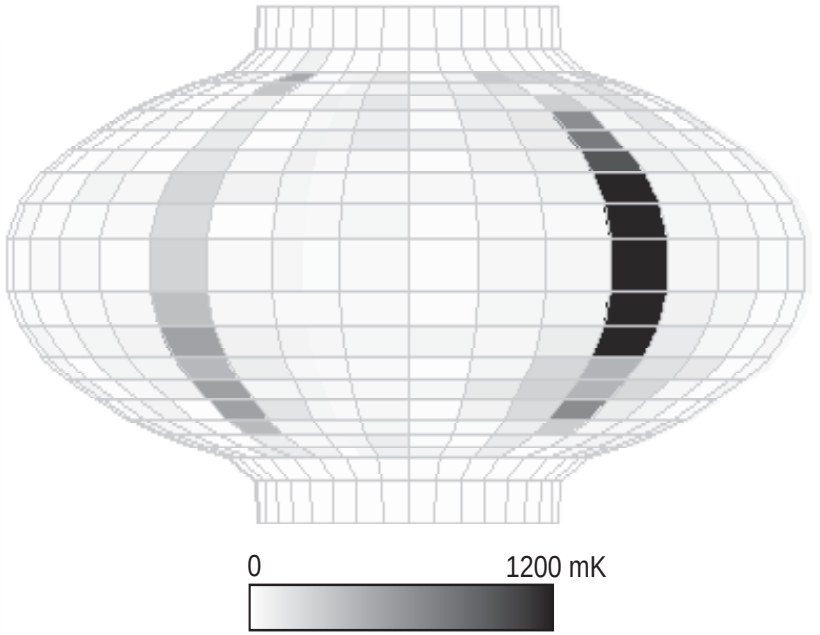
History of the Understanding of limitations



7.1 Field Emission

Non-resonant electron loading due to field emitted electrons by tunneling effect





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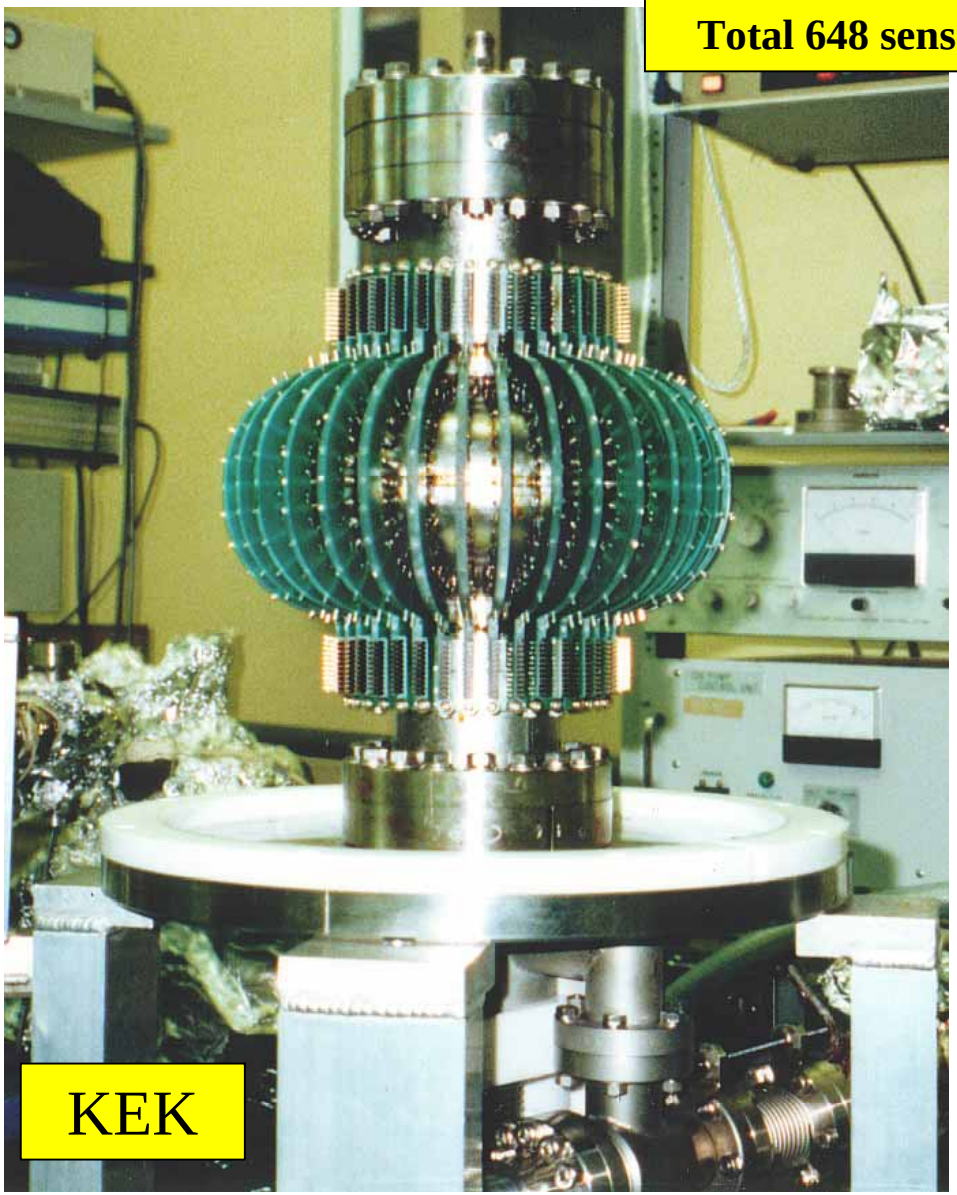
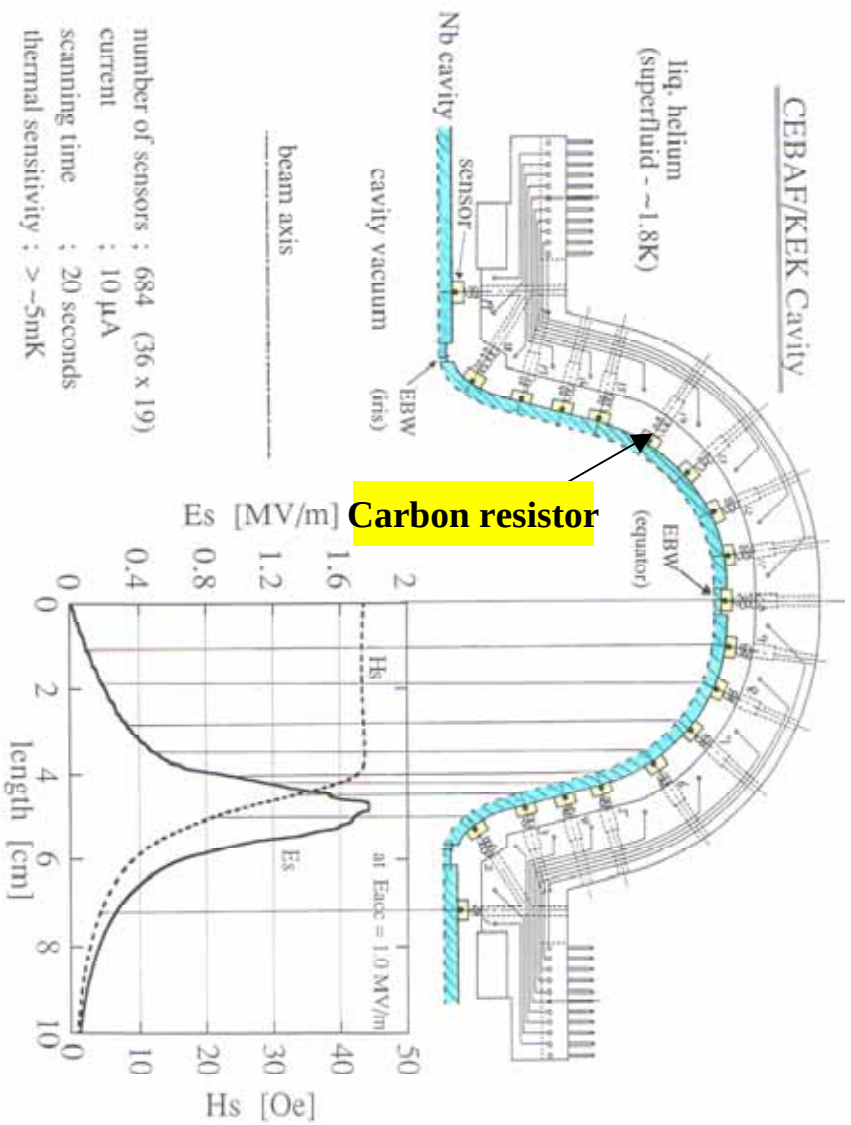
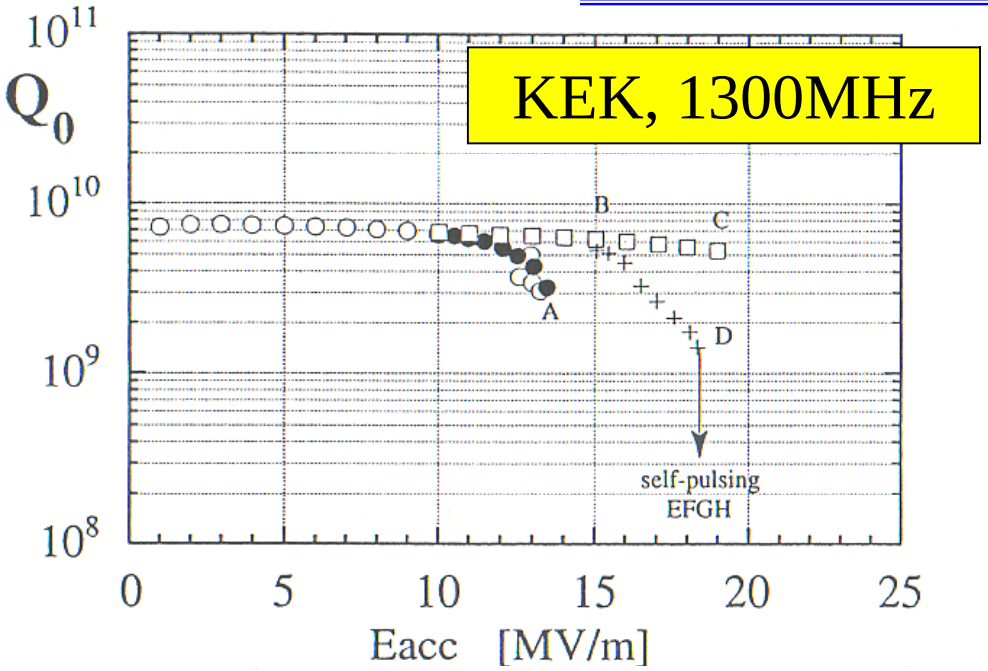
T-mapping System

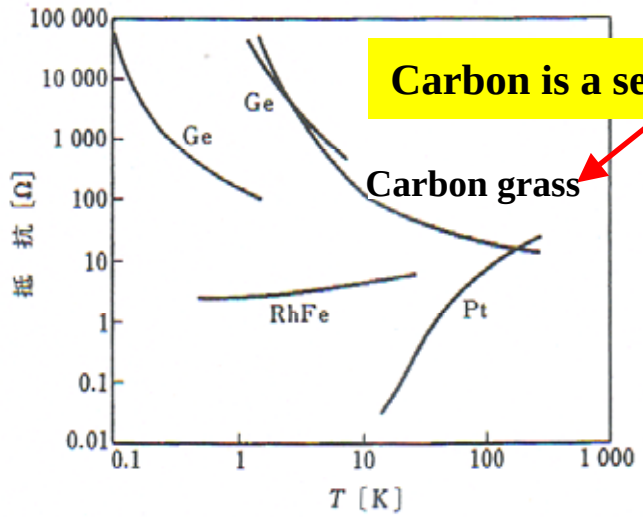
19 sensors at every 10 degree.
Total 648 sensors on outer cavity surface (360x19=684)





T-mapping KEK

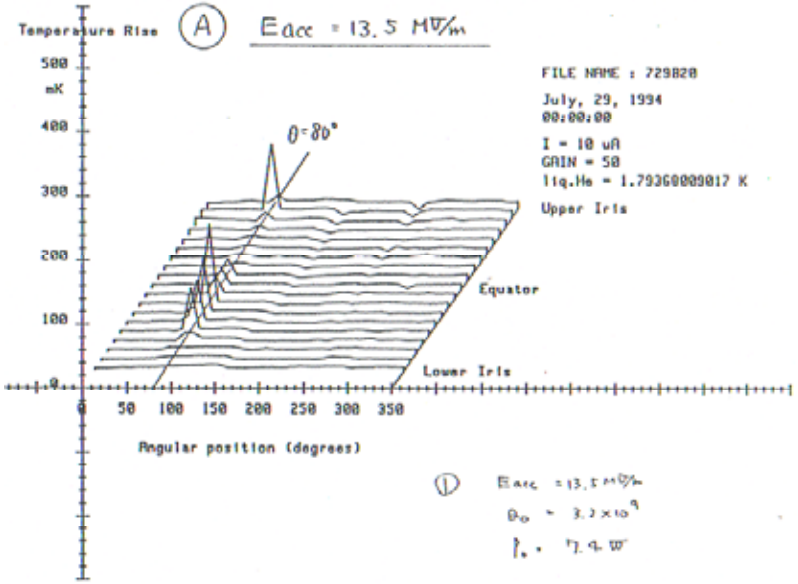


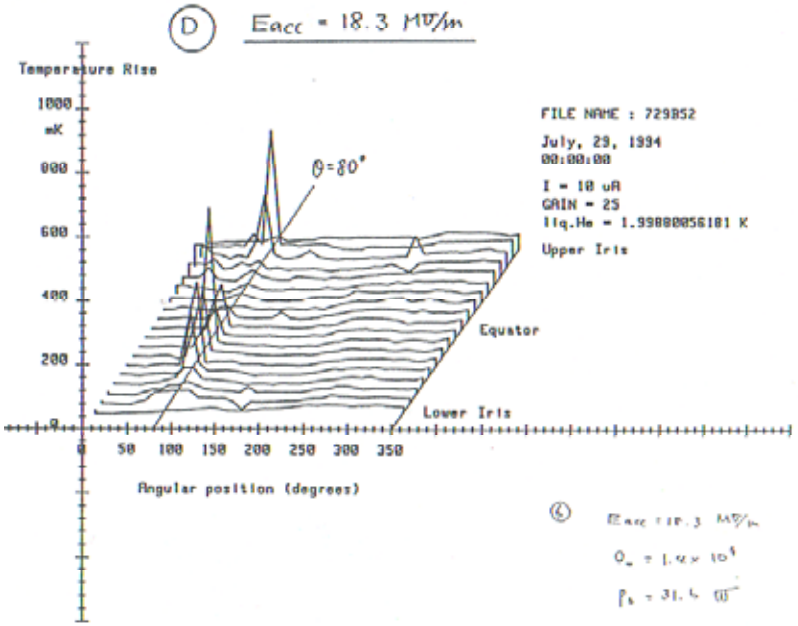


Carbon is a semiconductor.

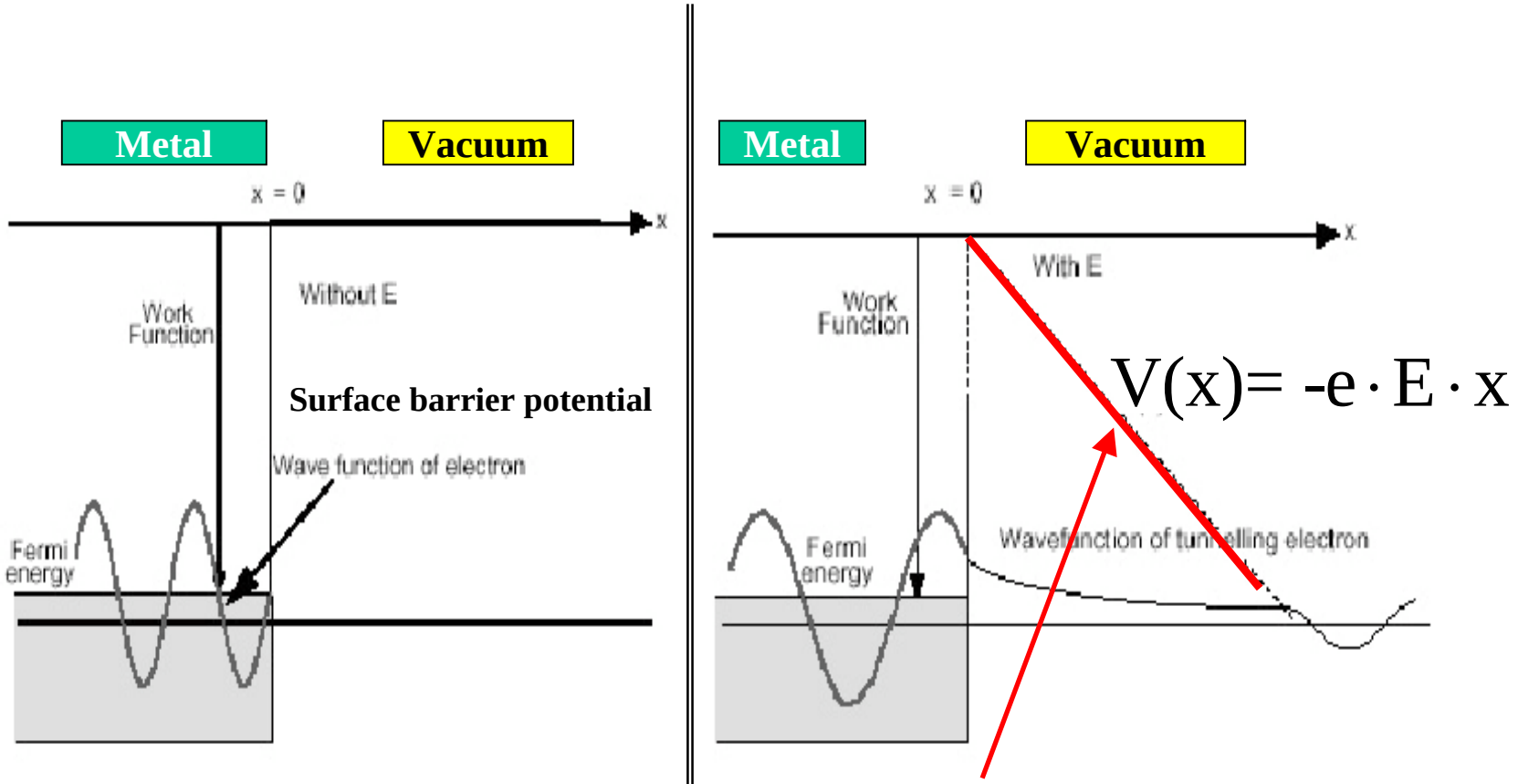
Carbon grass

Characteristics of T-sensitivity for various material





Field Emission Mechanism



A potential: -eEx is added to the surface barrier potential by applying E-field.
The surface barrier becomes thinner with the added potential.
The number of tunneling electrons is increased exponentially with the thinner barrier potential and lot of electrons are emitted from the surface.

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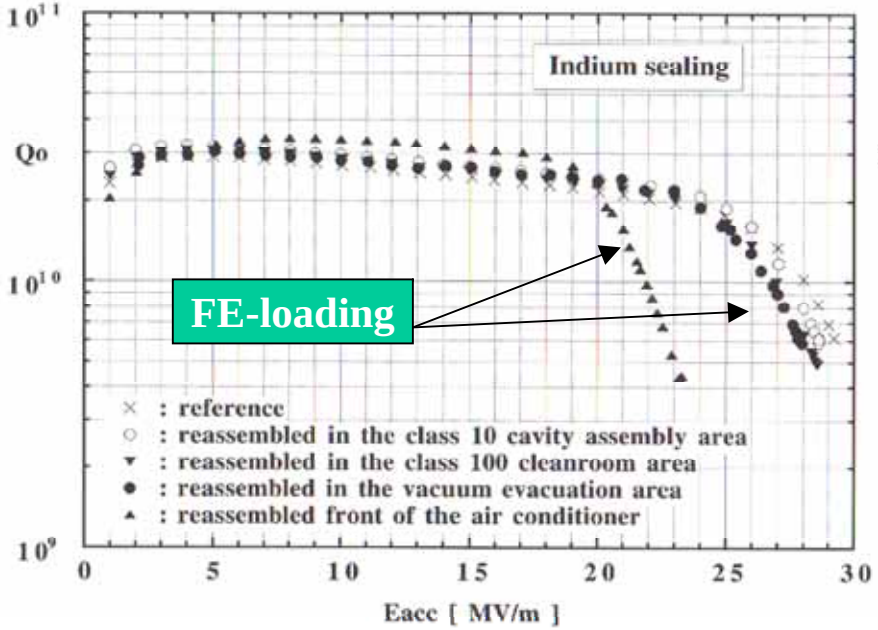
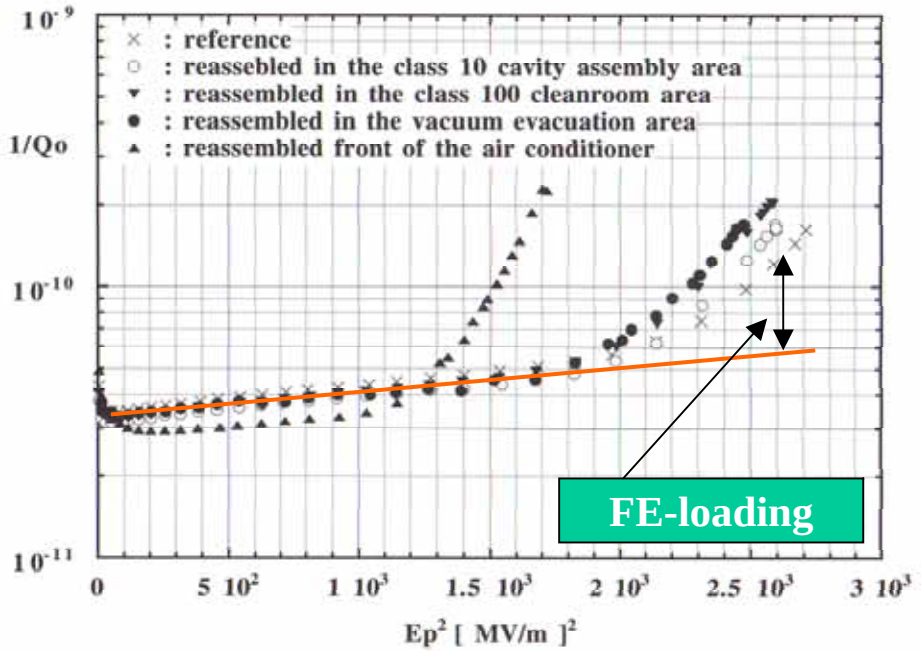
Field Emission Analysis





$$\frac{1}{Q_o} = A + B \cdot E_p[MV/m]^2, \quad \Delta\left(\frac{1}{Q_o}\right) = \frac{1}{Q_o(E_p^2)} - (A + B \cdot E_p[MV/m]^2)$$

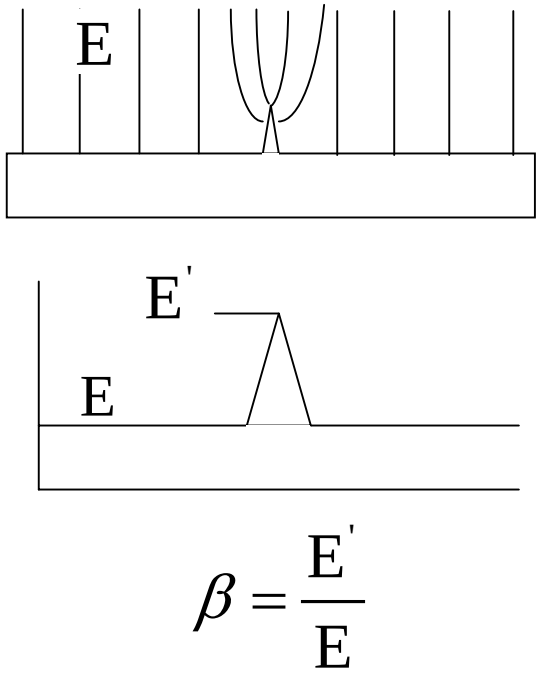
$$\Delta\left(\frac{1}{Q_O}\right) = S \cdot E_p^{1.5} \cdot \exp\left(-\frac{\phi}{\beta \cdot E_P}\right) = S \cdot E_p[MV/m]^{1.5} \cdot \exp\left(-\frac{5.46E+4}{\beta \cdot E_P[MV/m]}\right)$$

Field Enhancement Factor β

Field enhancement factor ß: 50 ~ 1000

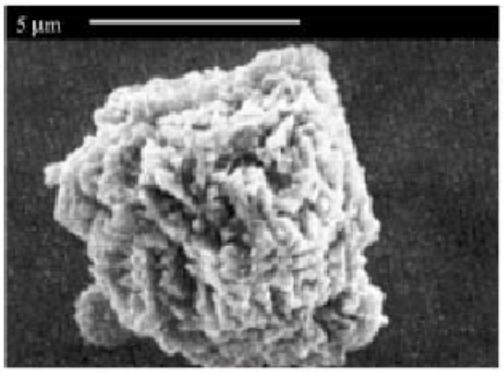
Why field enchantment is so large?

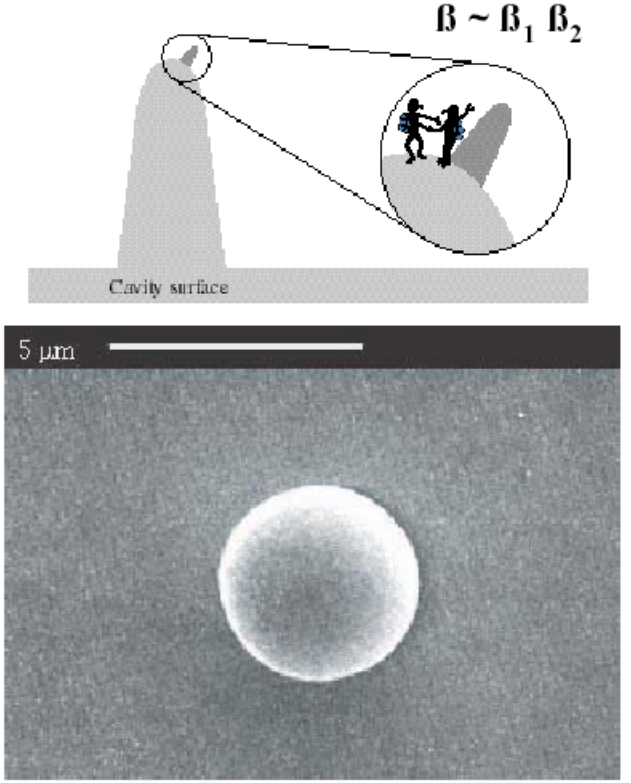
Projection model :



$$\beta = \frac{E'}{E}$$

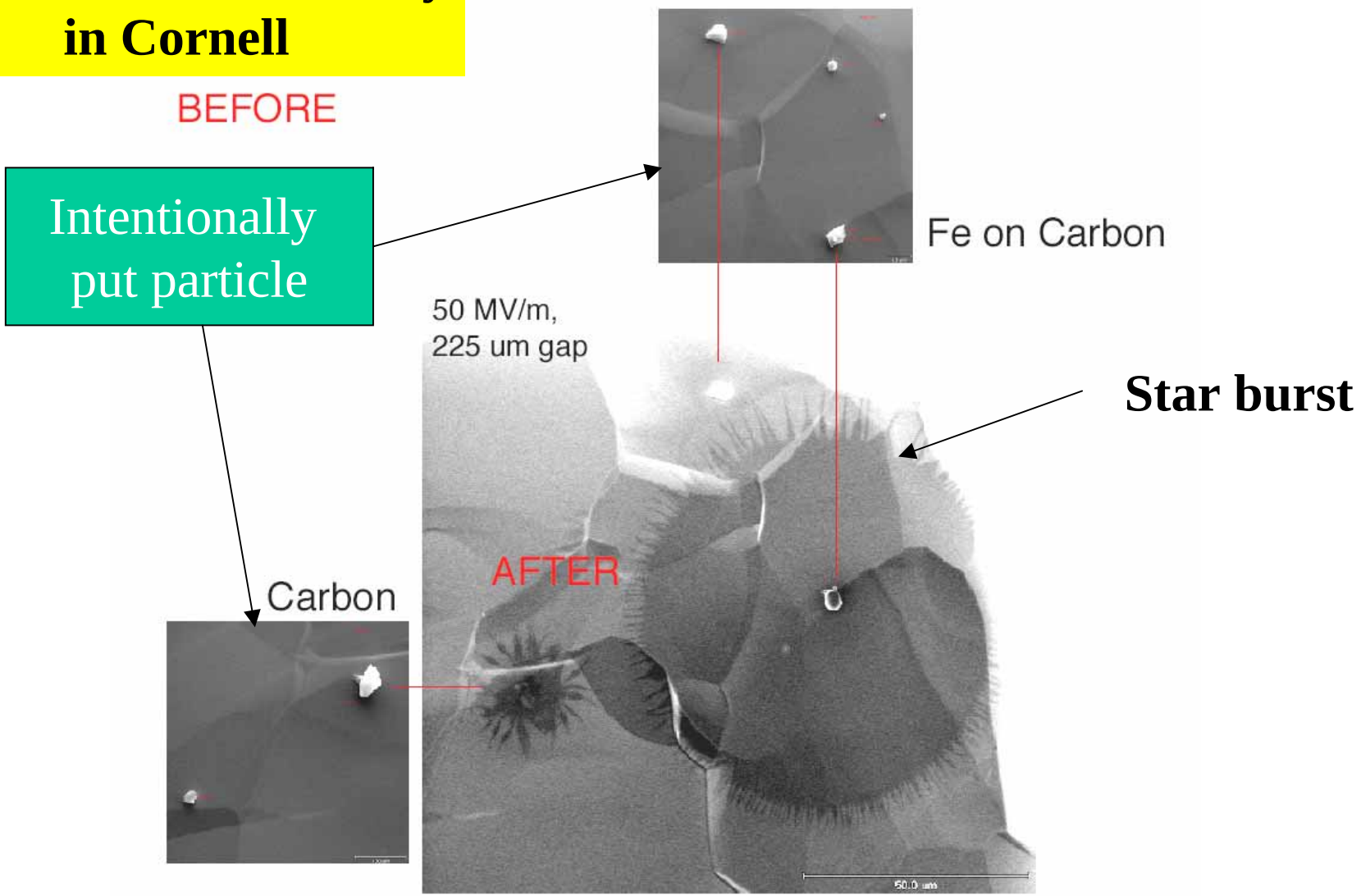
- *Tip-on-tip* model is one explanation
- Smooth particles don't emit.





Particle Contamination produces field emission

DC Field emission study in Cornell



Particle is a seed of field emission.

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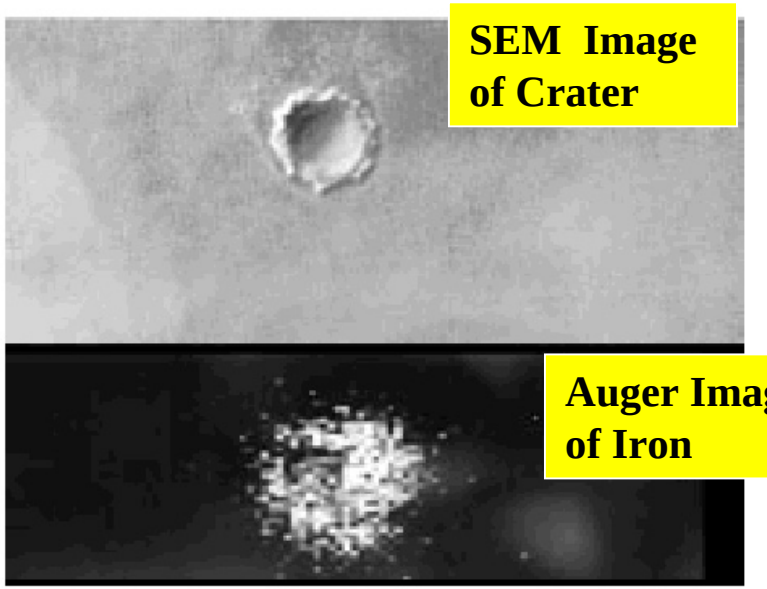
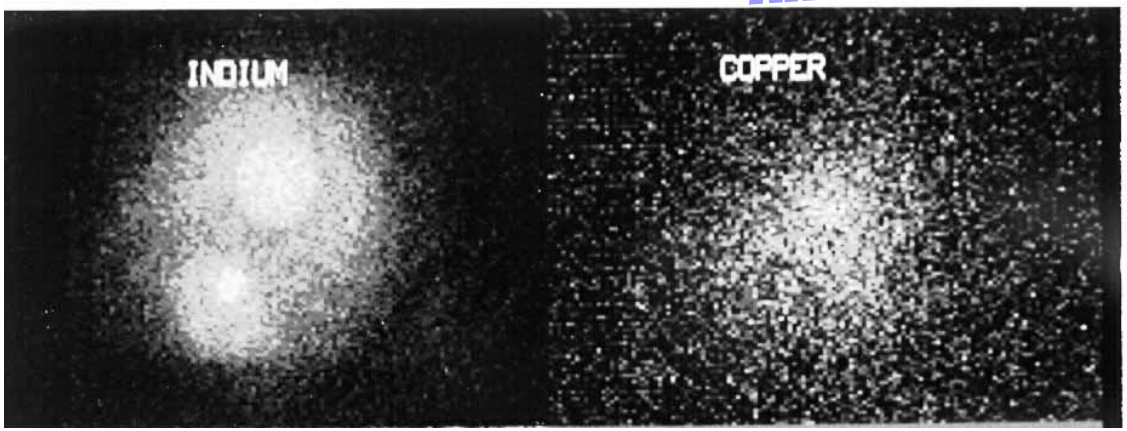
Foreign Elements



Nothing with EDX

But - With Auger Analysis
Almost all craters show foreign material



Auger Images of Craters

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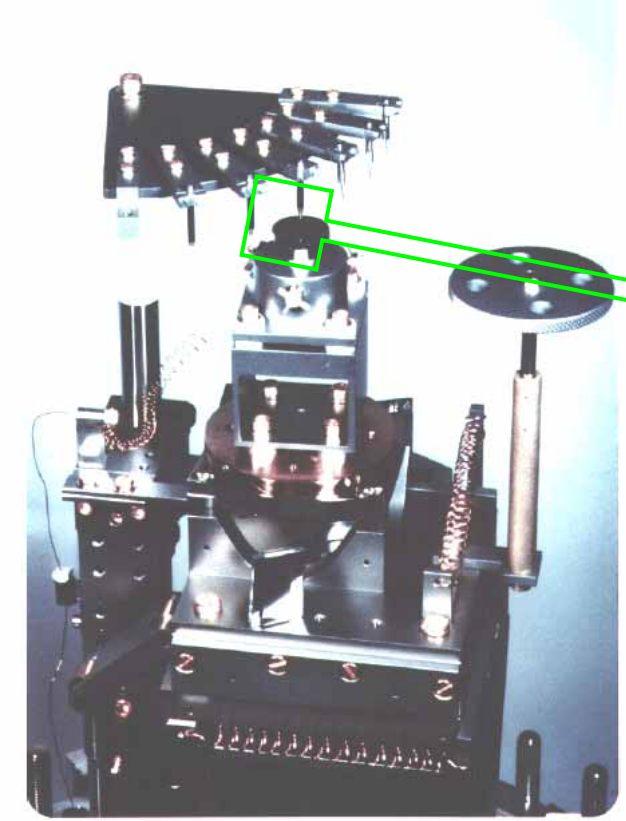
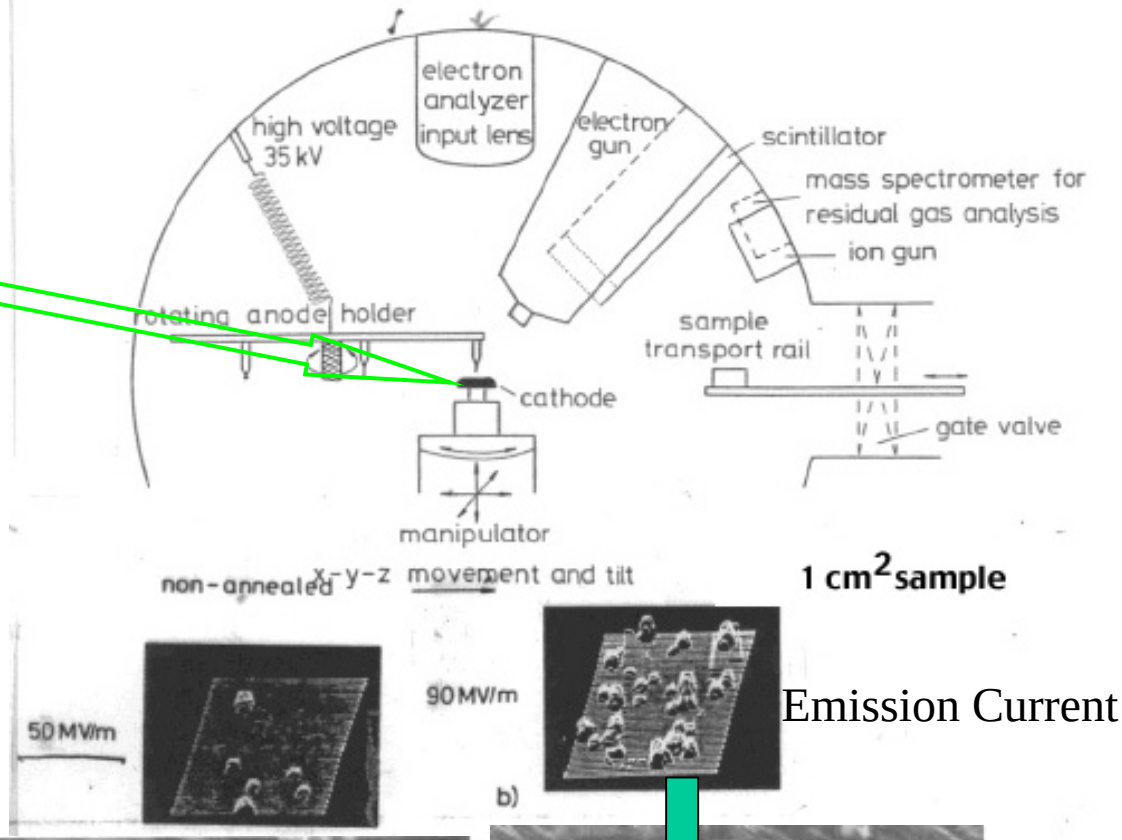
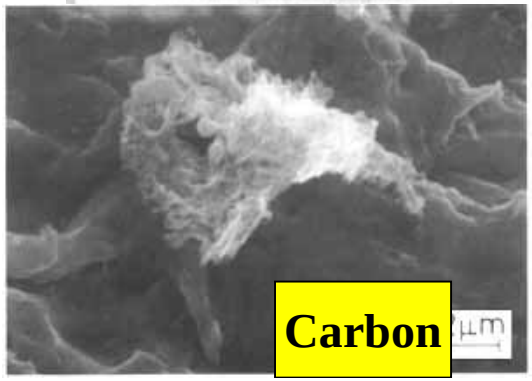
Foreign material is another seed of the filed emission.

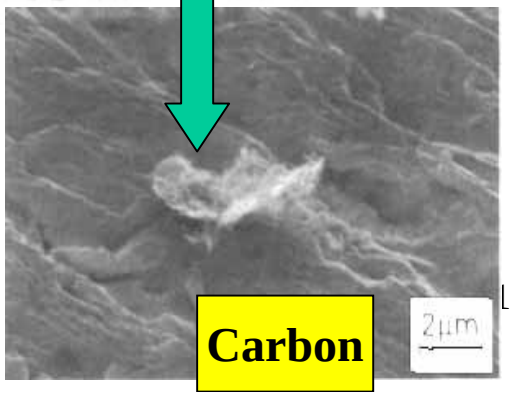
DC Field Emission Study in Geneva Uni. and Wuppertal Uni.



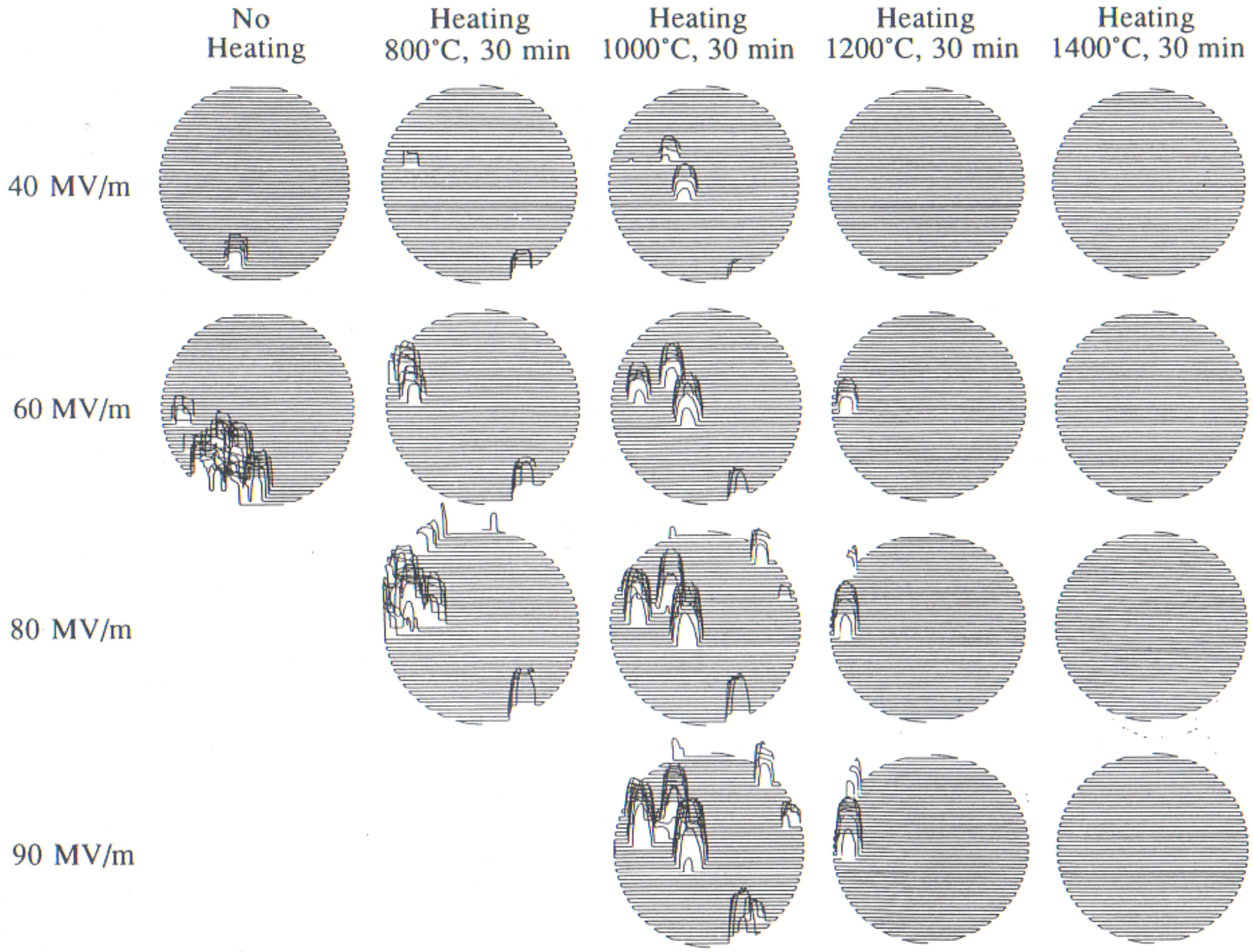


Emission Current



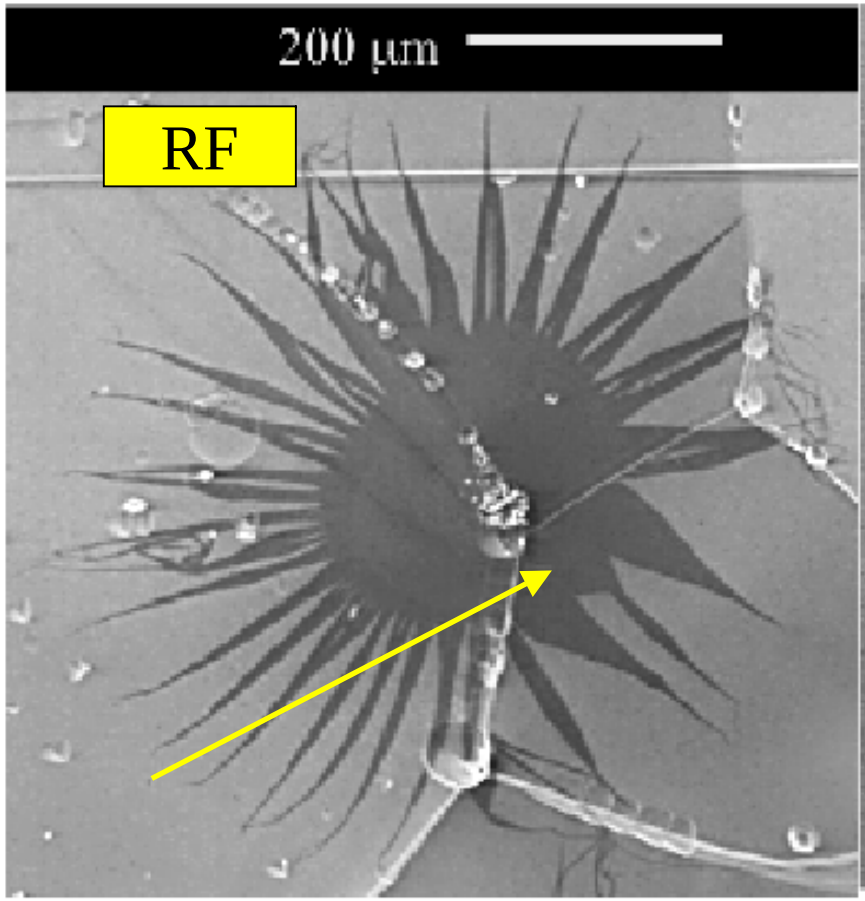


Wuppertal Result

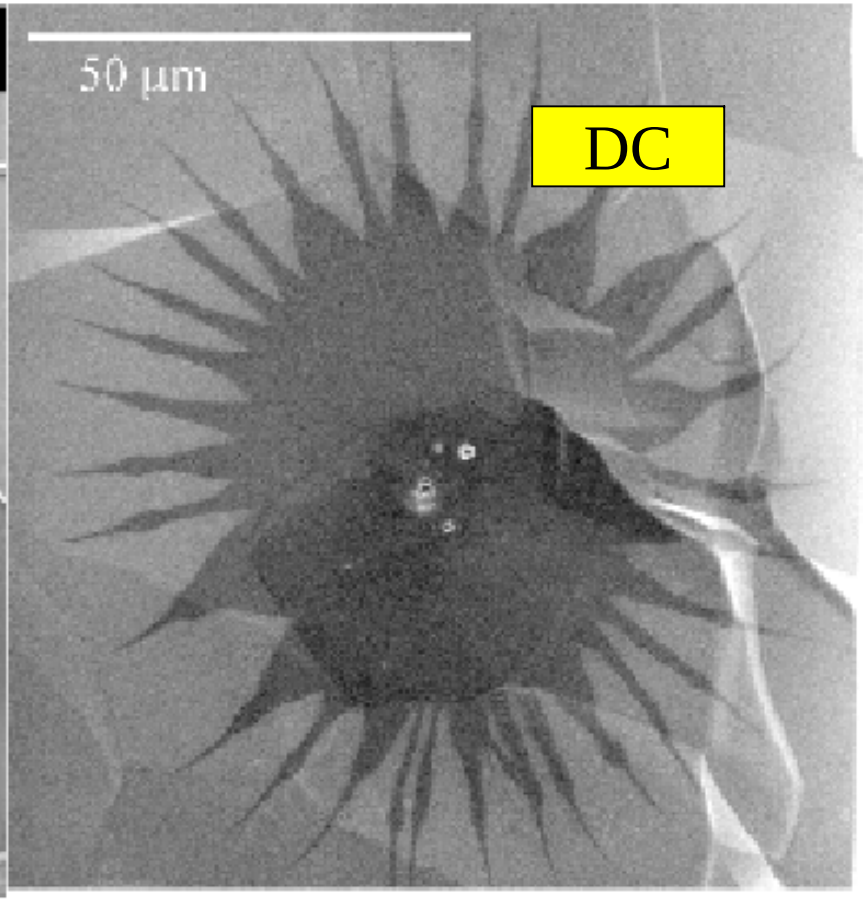


High Temp. Annealing evaporates or diffuses FE emitters.

Difference between DC and RF



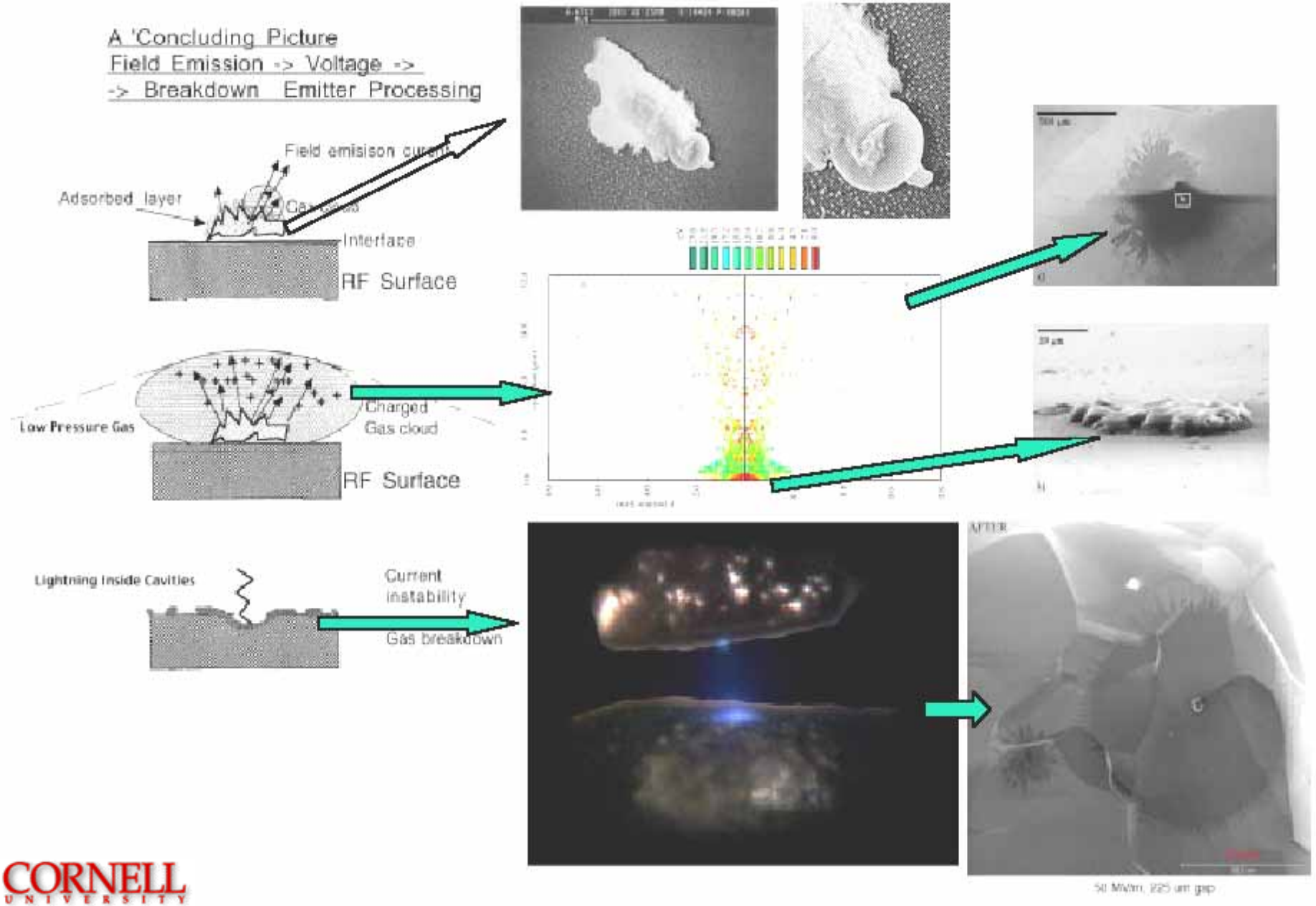
Starburst in a 1.5GHz Nb cavity



Starburst on a DC cathode (Nb)

Emitter sites are observed on grain boundary in RF case,
that suggests magnetic field enhancement there:
the enhanced Joule heating promotes evaporating gas and results in star burst.

Cornell Model for FE



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Cures against Field Emission

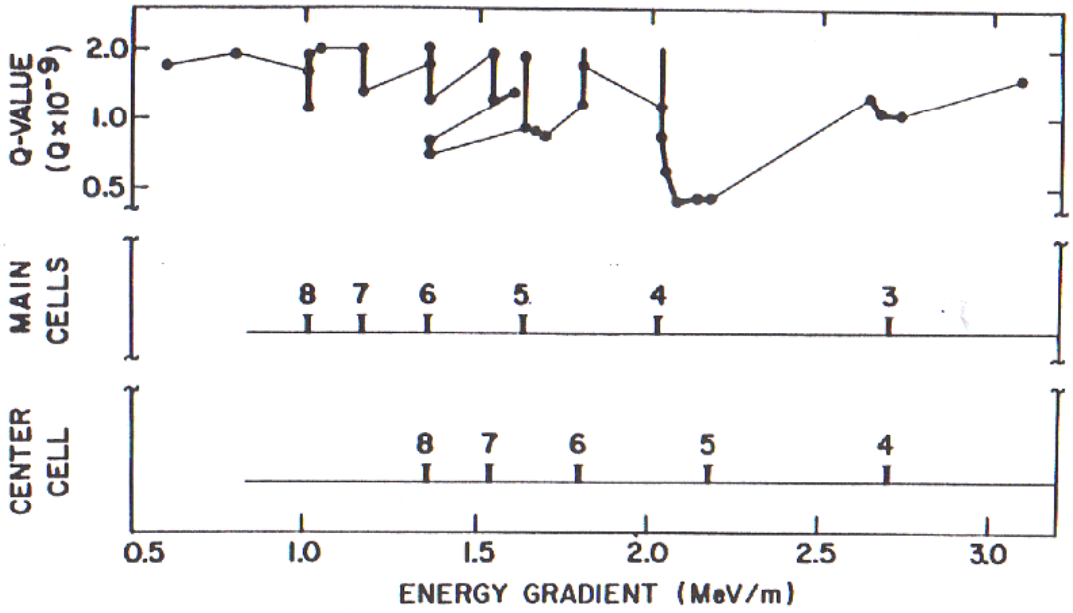
1) Make dust free clean surface
   - Use ultra-pure water in the rising process
   - High Pressure water Rinsing to remove particle contamination on the SRF surface
   - Use clean-room in the cavity assembly
2) Make smooth surface
   - Electropolishing
3) Cavity design
   - Lower Ep/Eacc

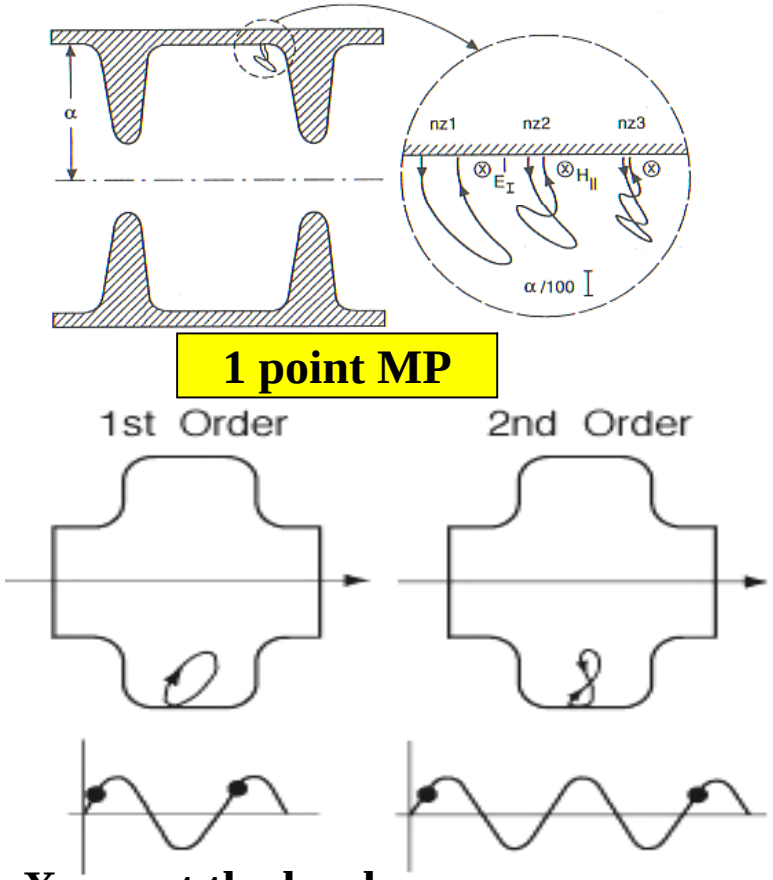
7.2 Multipacting

Multipacting : Resonant electron loading due to secondary electrons
(synchronized electron motion with RF)

Seriously Limited by 1PM or 2PM

One point multipacting



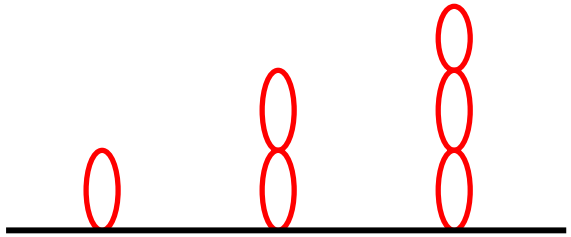


Characteristic: Q-drop at some discrete field levels, X-ray at the levels,
Diagnostics: Temperature mapping & X-ray mapping

Onset Field of One-point MP

Scale law on RF frequency with the maltipacting levels

Cyclotron frequency : $\omega = \dfrac{e \cdot H}{c \cdot m}$



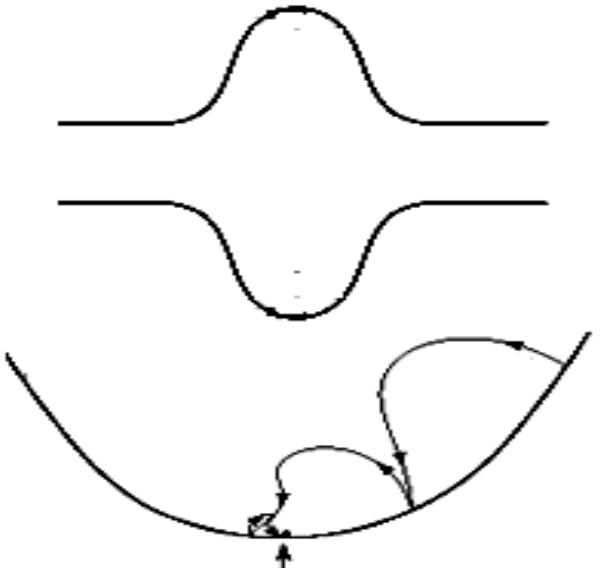
$$2\pi \cdot f(1P-nth) = \frac{e \cdot H(1P-nth)}{c \cdot m}$$

$$T(1P-nth) = \frac{1}{f(1P-nth)} = \frac{2\pi \cdot c \cdot m}{e \cdot H(1P-nth)} = n \cdot T_{RF} = \frac{n}{f_{RF}}$$

$$\frac{H(1P-nth)}{f_{RF}} = \frac{constant}{n}, \quad \text{n=1, 2, 3 } \cdots \quad \text{[Oe/Hz]}$$

Experiment : Onset field $\dfrac{H(1P-nth,[Oe])}{f_{RF}[MHz]} = \dfrac{0.3}{n}$ **[Oe/MHz]**

Spherical shape suppresses the one point multipcting.



Example ;

1300MHz, Hp/Eacc = 43.8 [Oe/(MV/m)]

1P-1st order ··· H_{RF}(1P-1st) =0.3 x 1300 = 390 Oe

Eacc(1P-1st) = 390/43.8=8.9 MV/m

1P-2nd order ··· Eacc(1P-2nd) = 4.5 MV/m

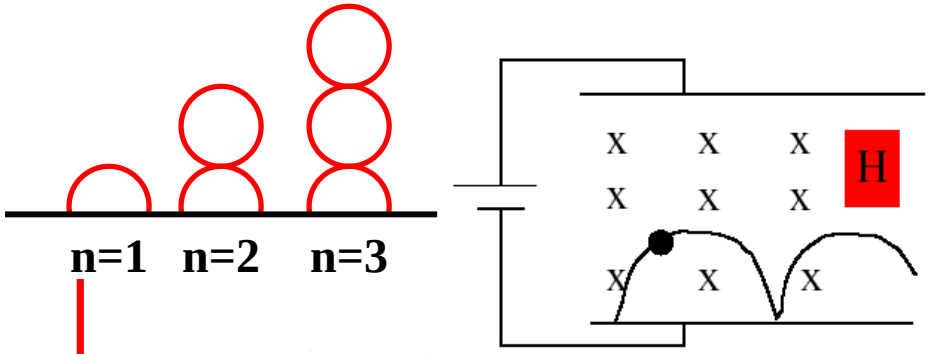
Two-point MP

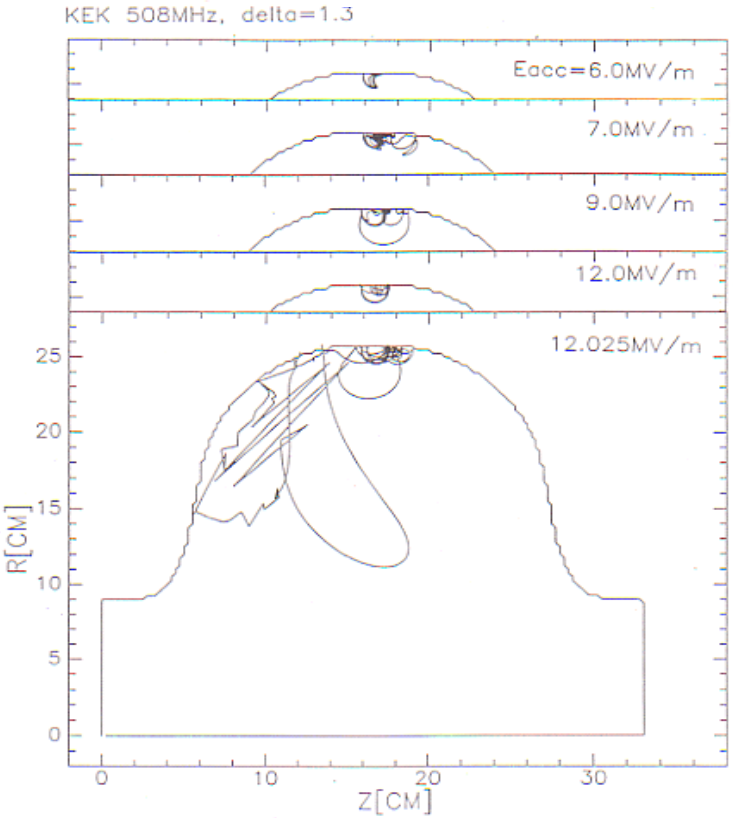
Two-point multipacting

$$T(2P-nth)=(2n-1)T_{RF}$$

$$\frac{H(2P-nth)}{f_{RF}}=\frac{constant}{2n-1}\text{, n=1, 2, 3 ‘‘‘ [Oe/Hz]}$$

Experiment :Onset field $\dfrac{H(2P-nth,[Oe])}{f_{RF}[MHz]}=\dfrac{0.6}{2n-1}$





Examples ;

508MHz , Hp/Eacc=40.6 [Oe/(MV/m)]

2P-1st order Hp(2p-1st) = 0.6 x 508 = 304.8 Oe

Eacc(2P-1st) = 304.8/40.6 = 7.5 MV/m

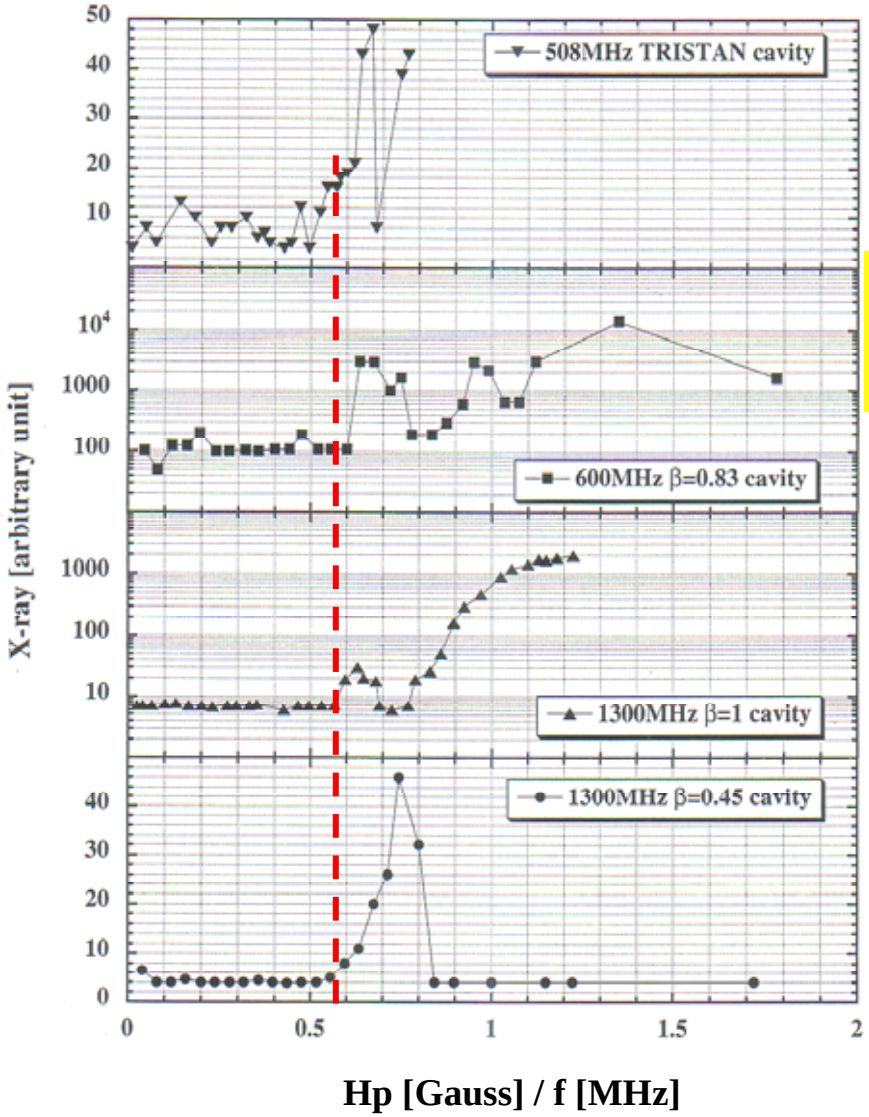
1300MHz, Hp/Eacc=43.8 [Oe/(MV/m)]

2P-1st order Hp(2p-1st) = 0.6 x 1300 = 780 Oe

Eacc(2P-1st) = 780/43.8 = 17.8 MV/m

2P-2nd order Eacc(2P-2nd) = 17.8/3 = 5.9 MV/m

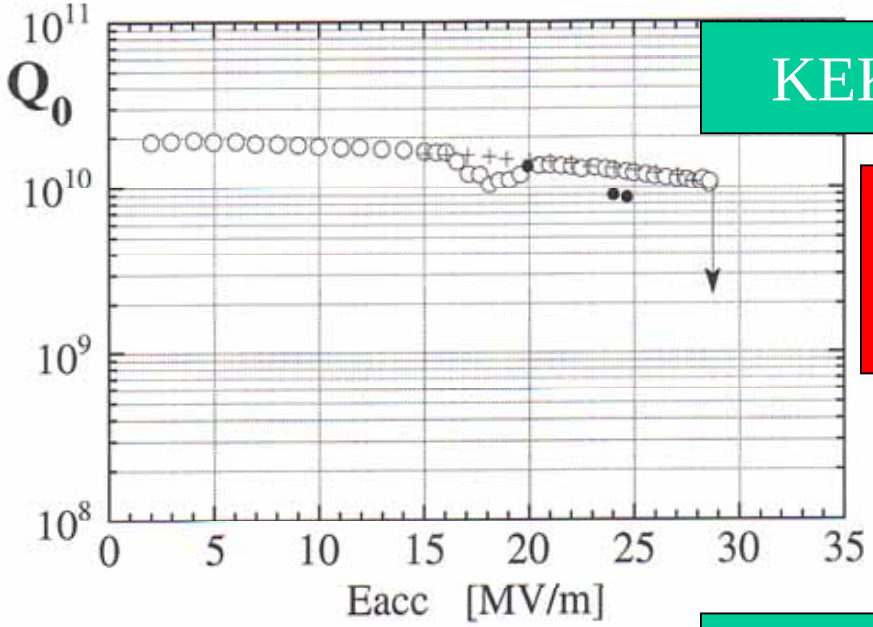
Onset Field of Two-point MP



$$2P-onset = \frac{Hp[Gauss]}{f\,[MHz]} \approx \frac{0.6}{2n-1}$$

Multipacting keeps RF processing memory effect up to 200K warm up.

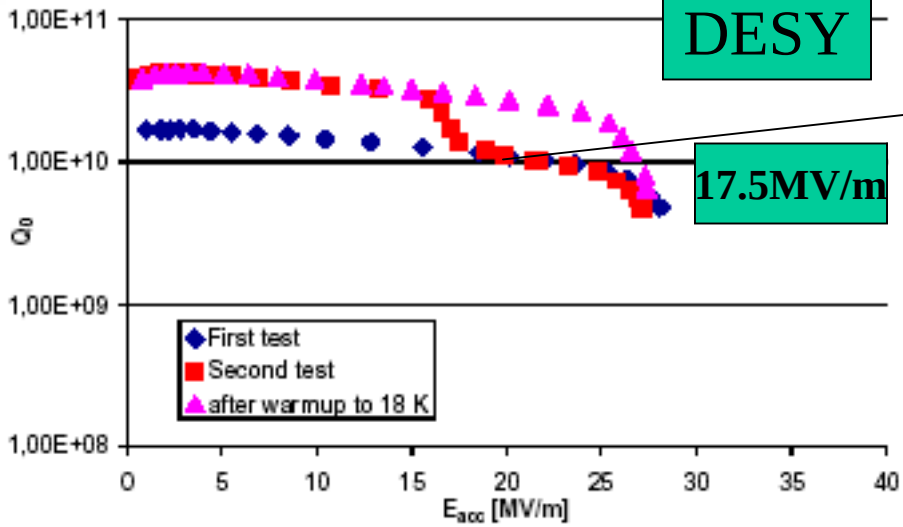
T-mapping of Tow-point MP

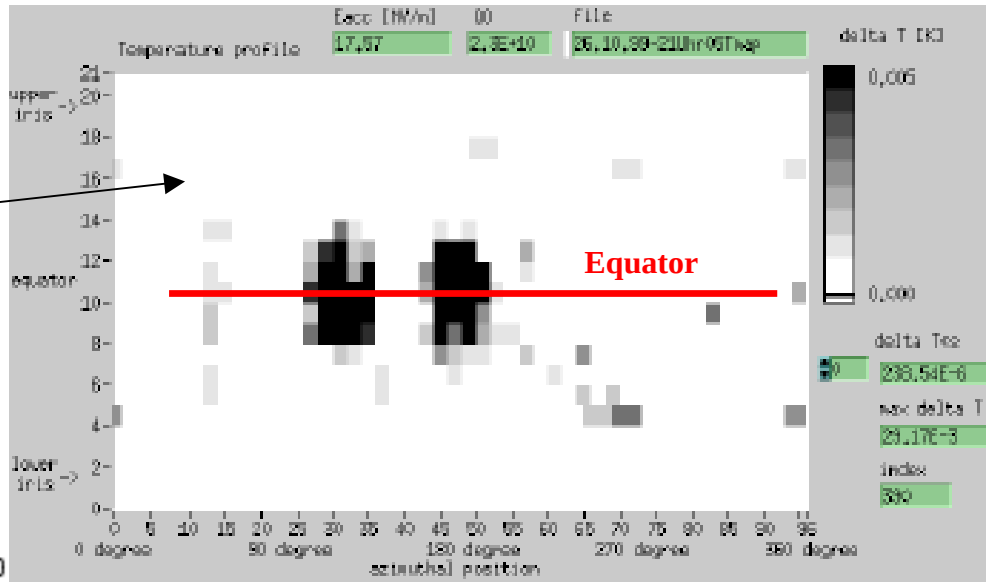


MP → Frozen flux trapping → Warm-up T >Tc

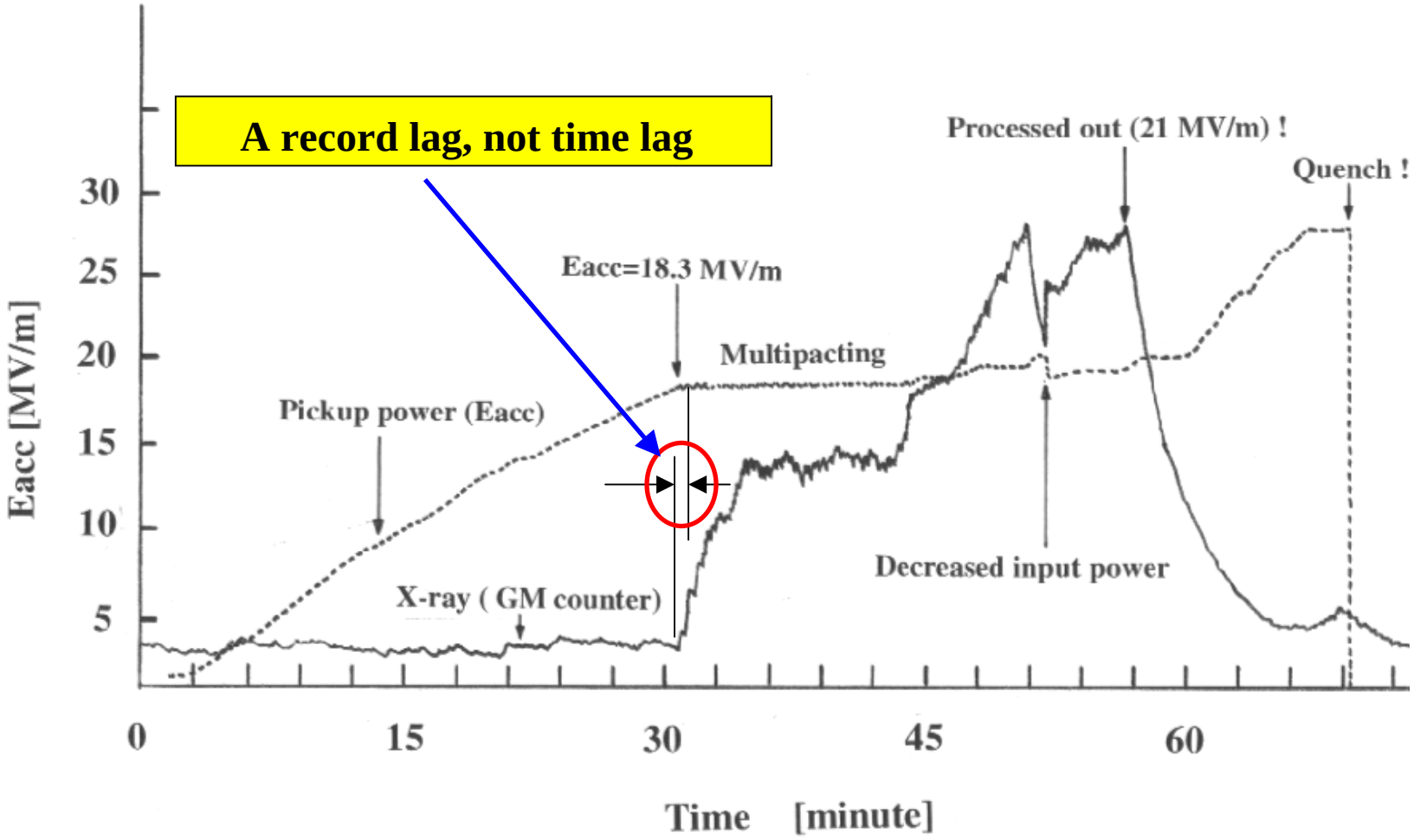
Disappear of the heating spots

T-mapping at 17.5MV/m

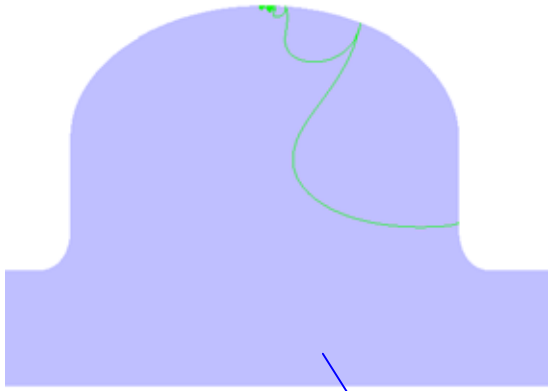


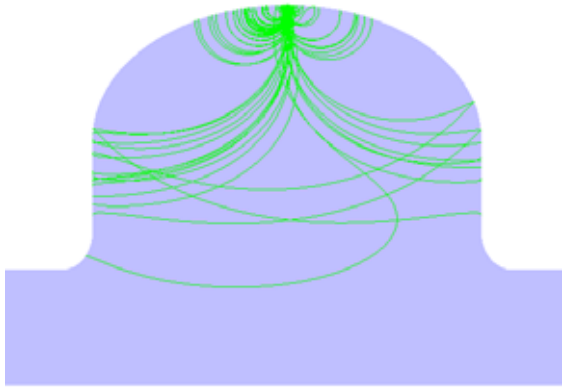


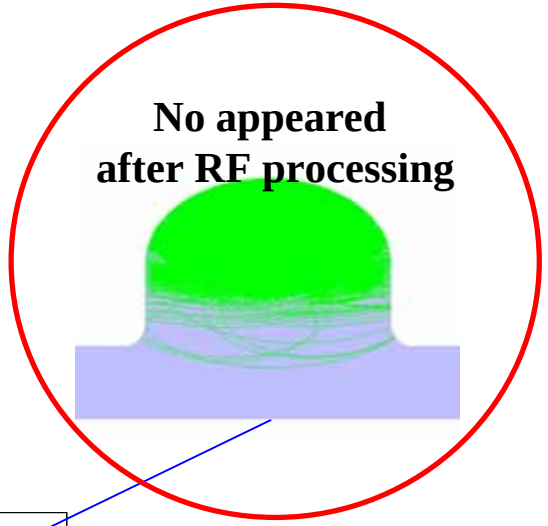
Processing of Two-point MP



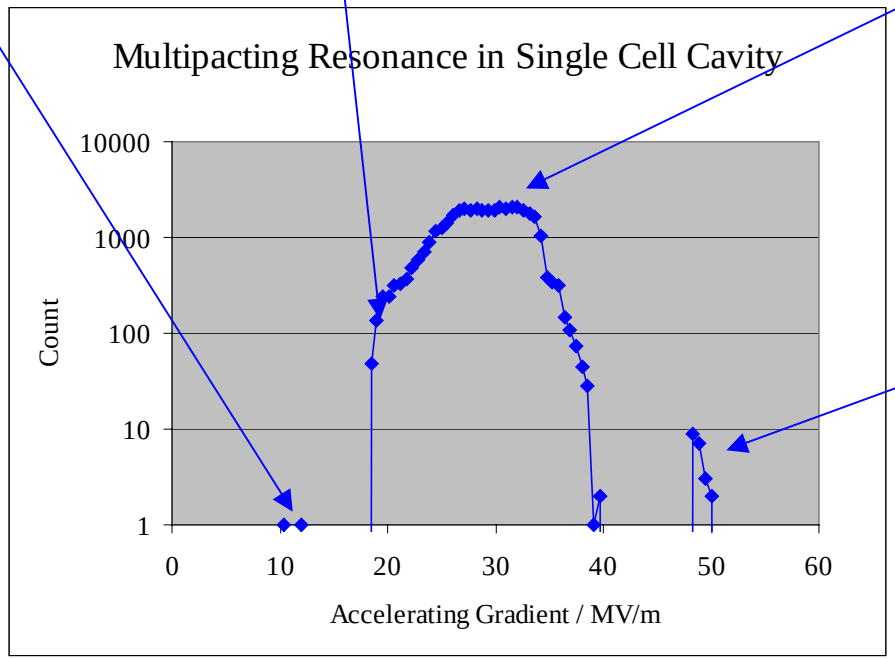
Multipacting in LL shape cavity

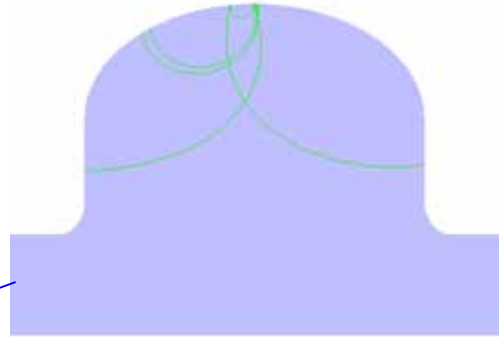




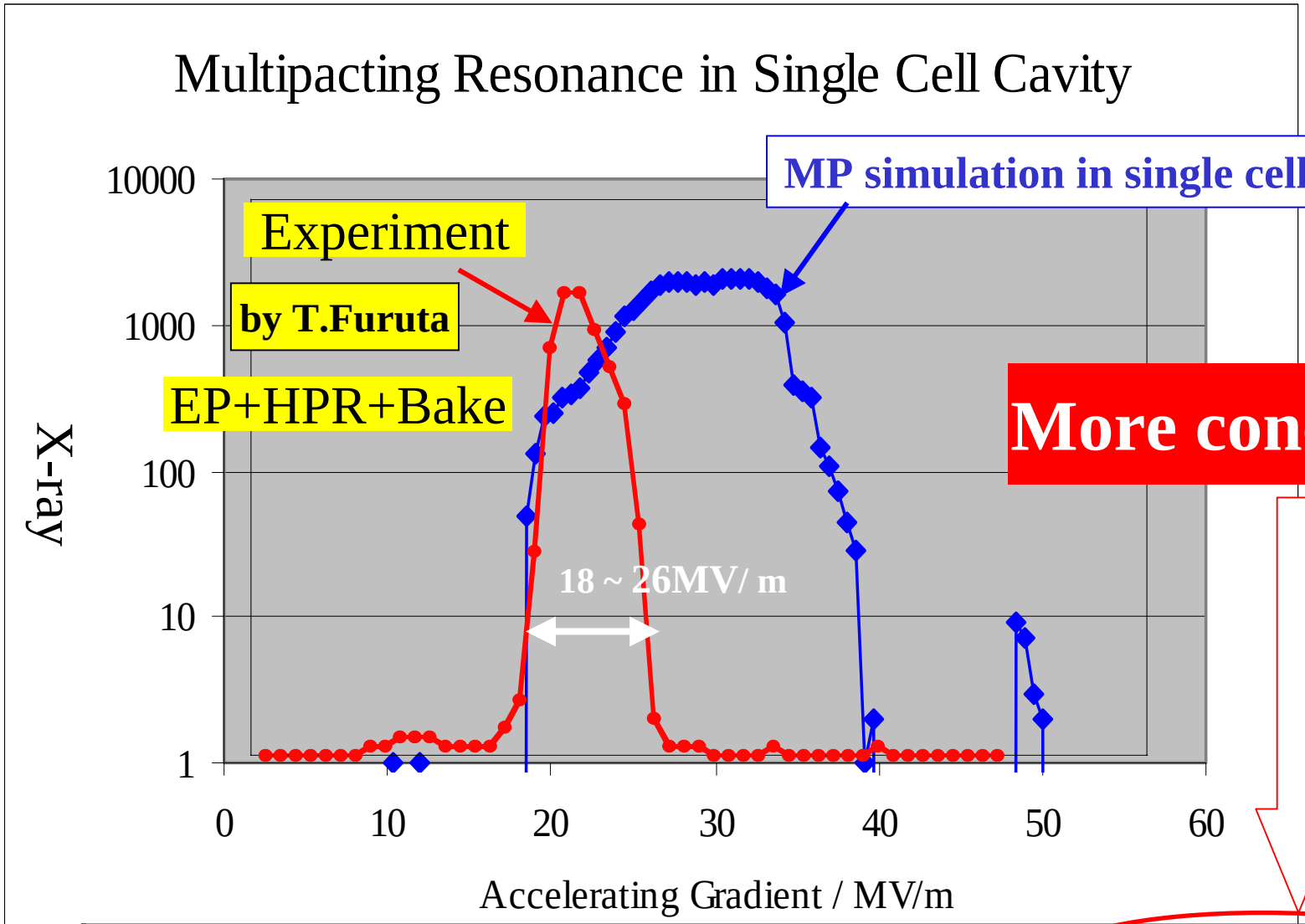


by Morozumi



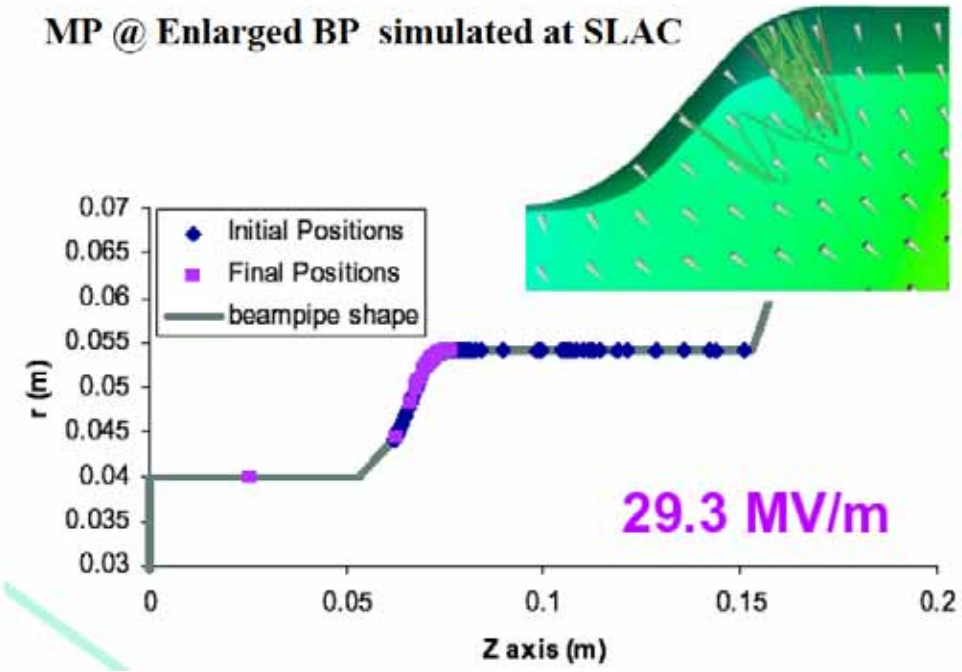


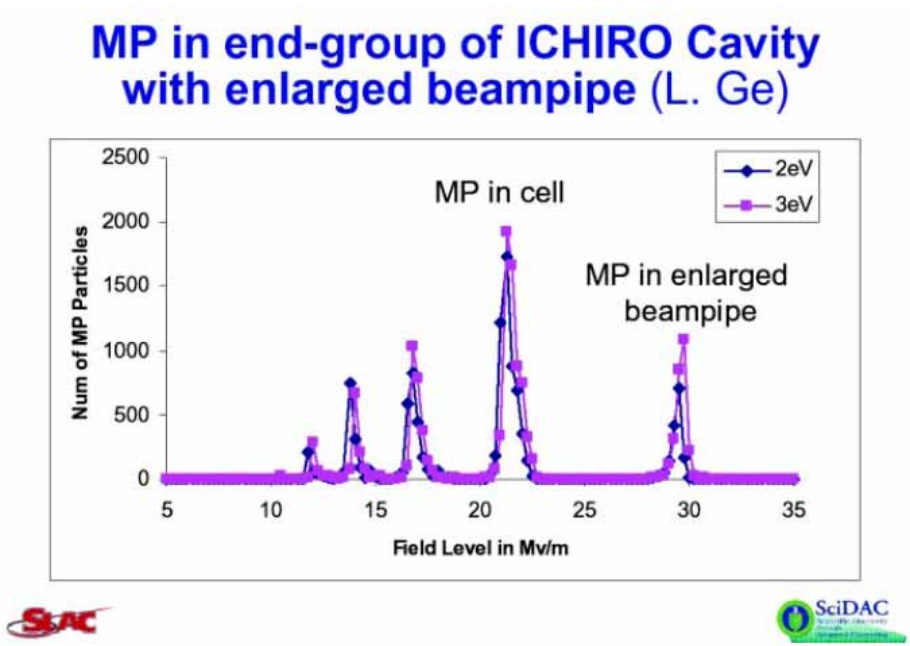
Comparison with Experiment



	V.T.	MP process out	No-MP	Couldn't process (FE)
Total times	69	53	2	14 (20%)

Multipacting @ Beam pipe

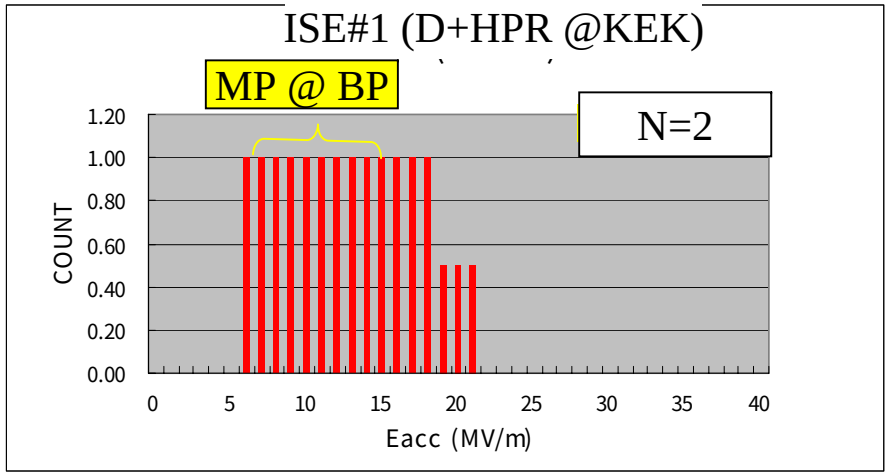




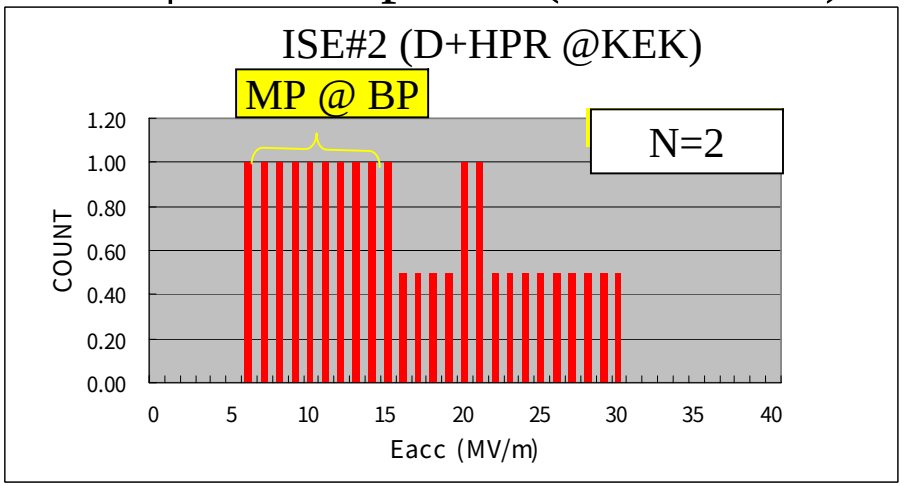
MP @ BP could be overcome by EP+Degreasing+HPR.

Multipacting in the large BP

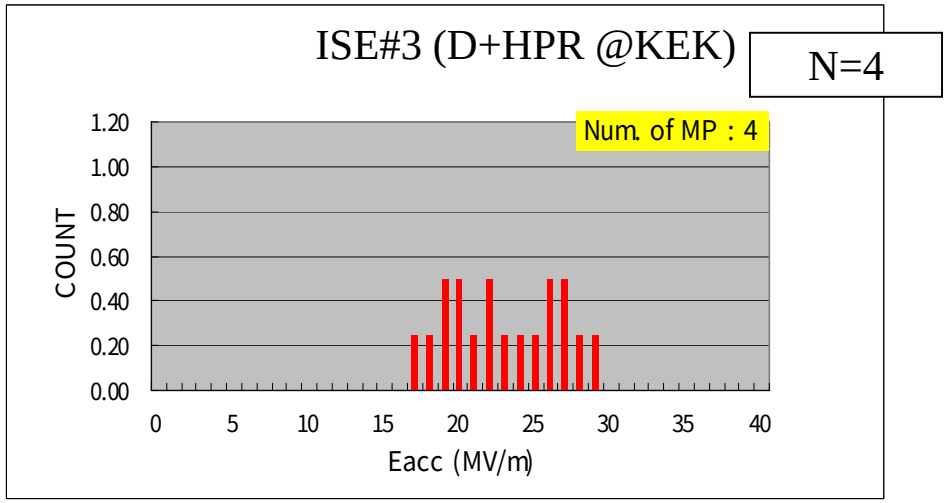
108ϕ BP, Straight



108ϕ BP, Tapered (Old Ichiro)



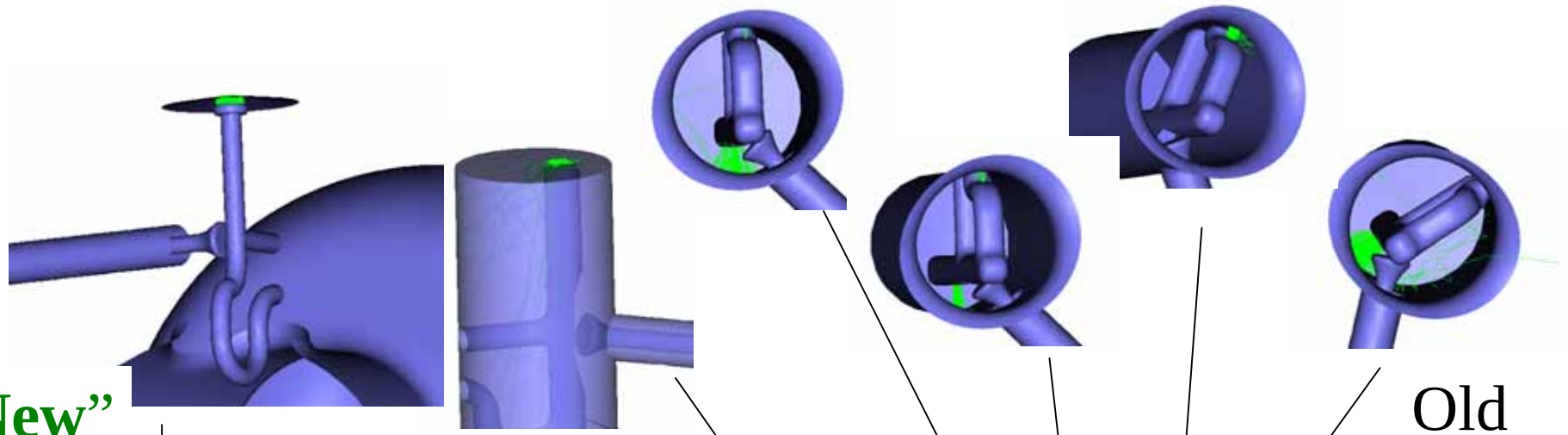
80ϕ BP, Straight (New Ichiro)

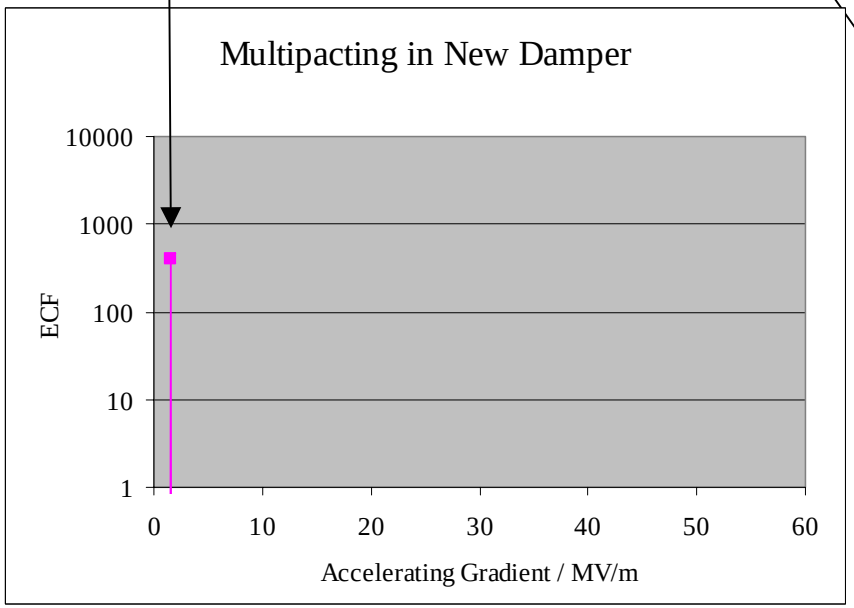


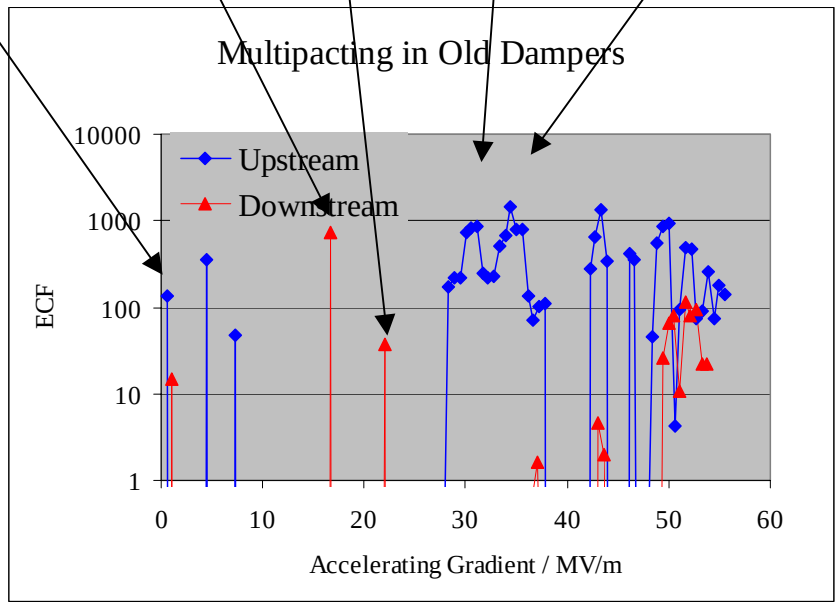
End cell cavity with Large BP:
ϕ108 mm diameter has multipacting at BP for both cases: Straight and Tapered BP.

When changed to ϕ80mm diameter BP, No multipacting happens at BP.

Multipacting in HOM Cylinder (Simulation)



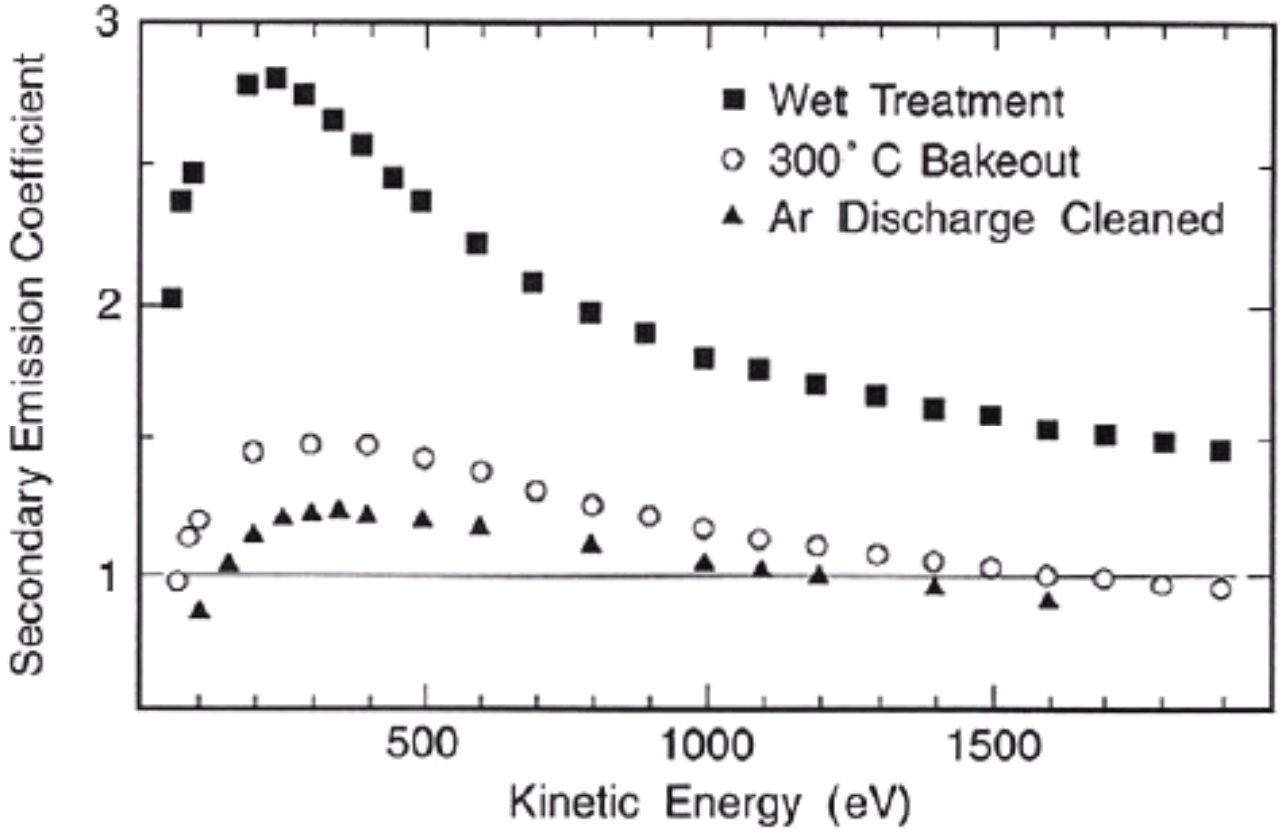




Cures against MP

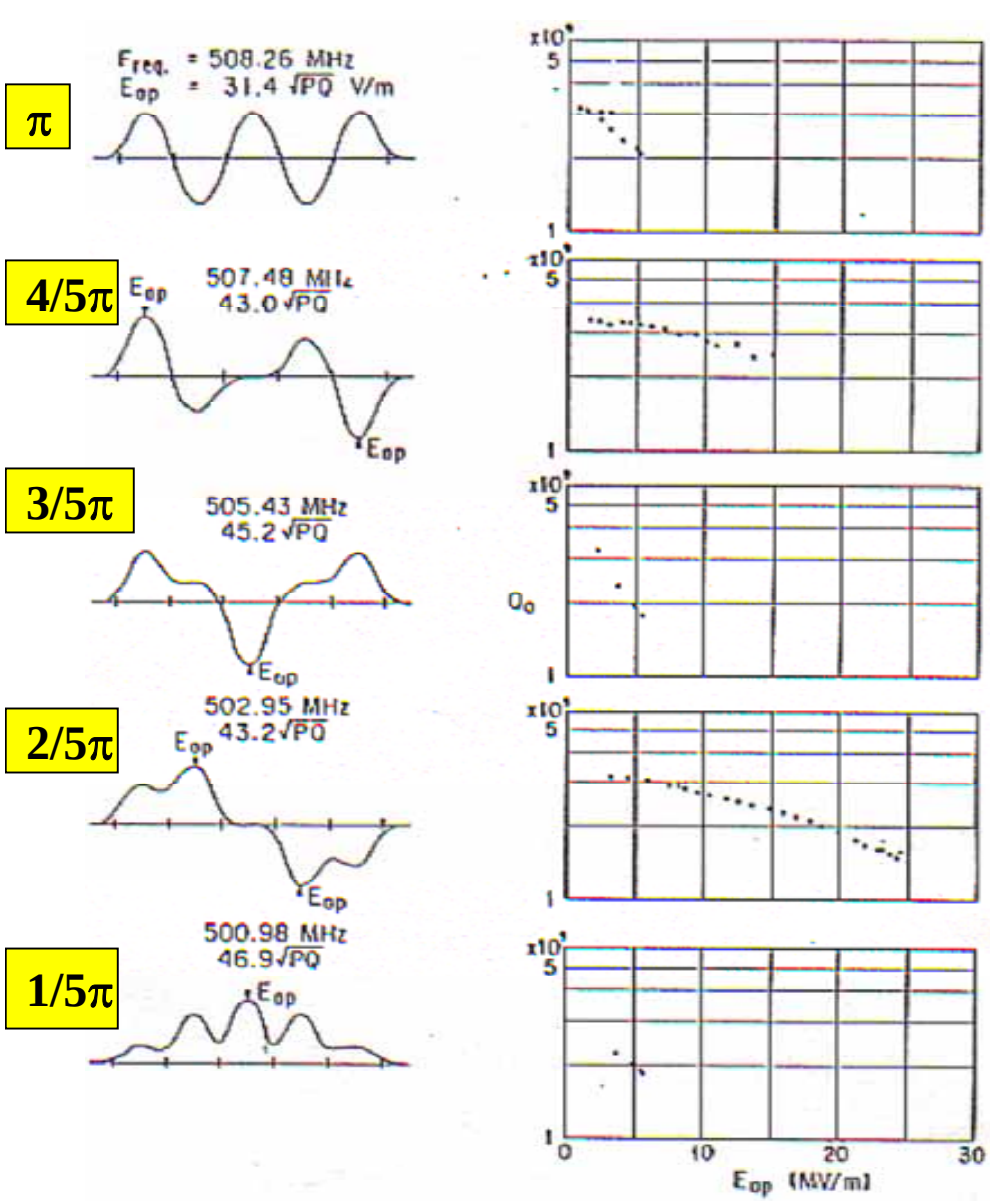
1) Cavity shape ⟶ Spherical or Elliptical shape
(effective for one point multipacting)

2) $\delta < 1$: Clean surface ⟶ Surface preparation
High pressure water rinsing
Degreasing
Argon gas or Helium gas discharge cleaning



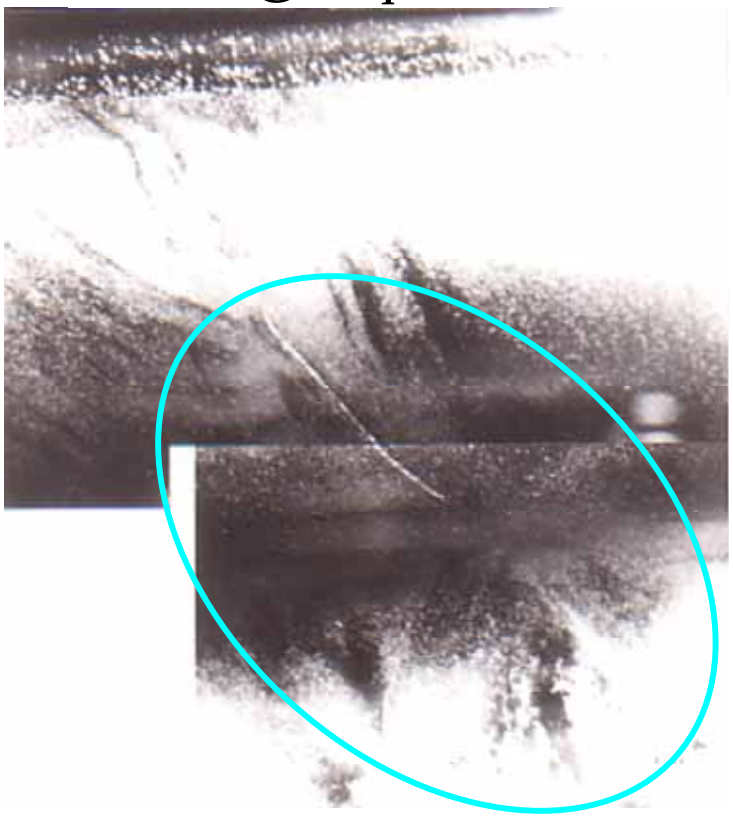
7.3 Thermal Instability

- An Example in A TRISTAN SC Cavity -

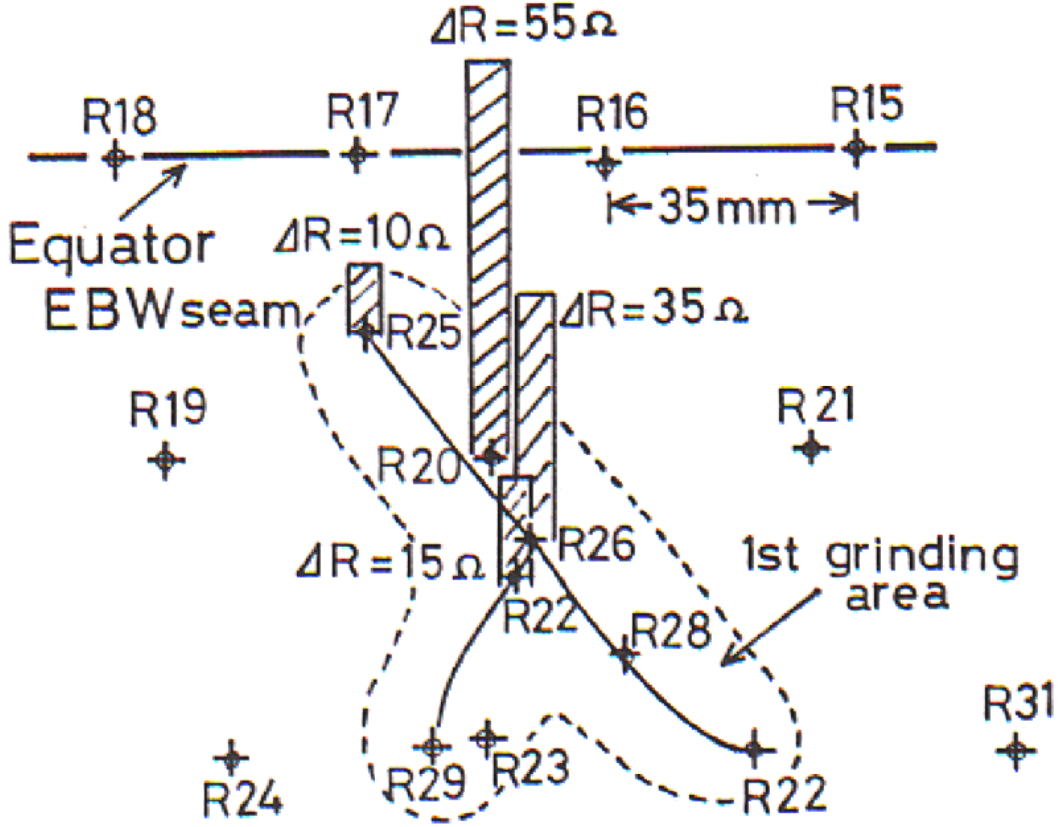


Surface Defect of the quench location

EBW @ Equator

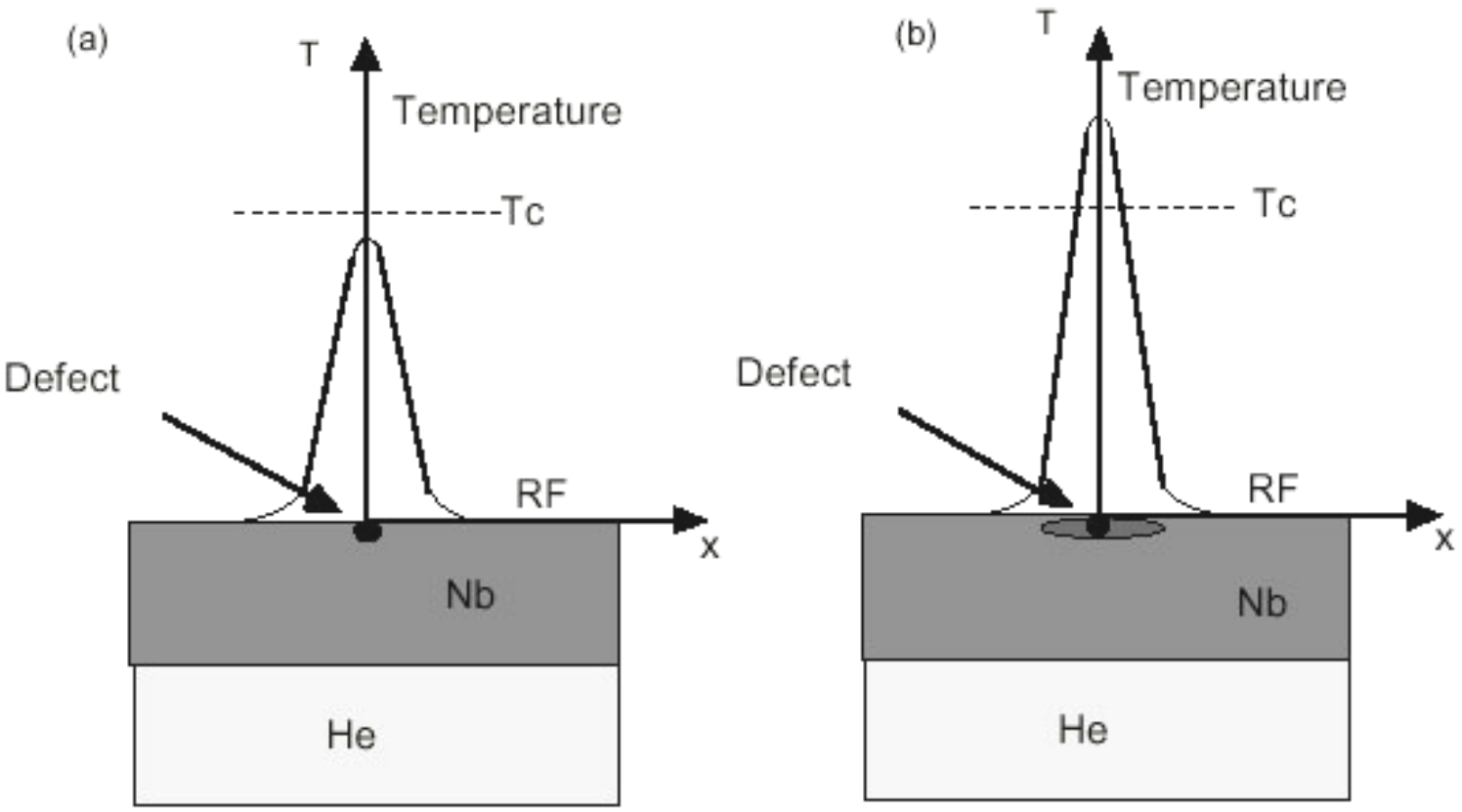


Picture of the defect area



T-mapping on the defect

Mechanism of Thermal Instability

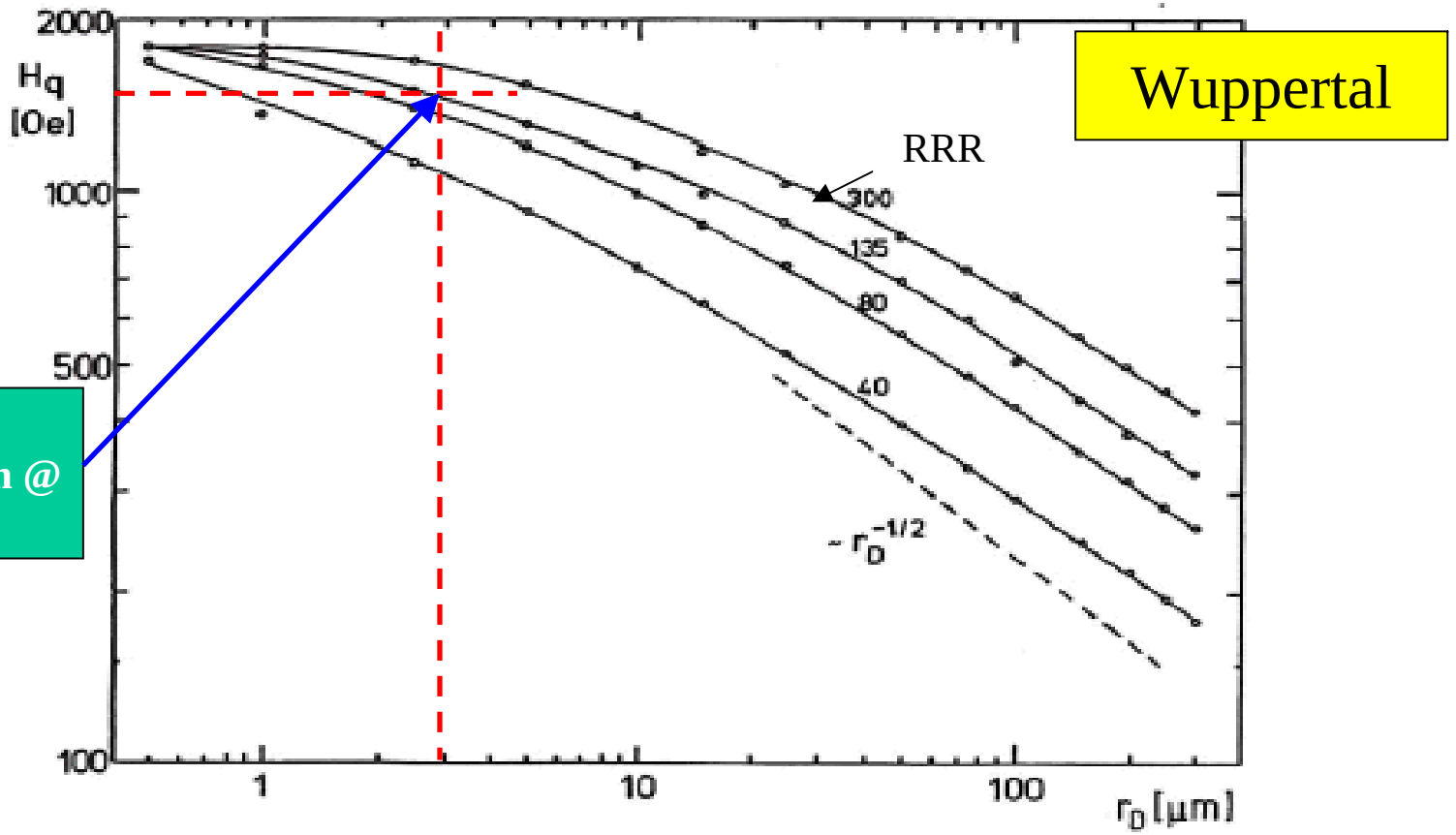


Thermal conductivity of the niobium material is concerned
In order to suppress the thermal instability.

Thermal conductivity has linear relationship with RRR.
RRR is used instead of the thermal conductivity.

RRR Dependence of Quench Field

$$\text{Quench Field : } Hq = \sqrt{\frac{4\kappa(Tc - Tb)}{r_D \cdot R_s(Tb)}} \propto RRR^{\frac{3}{4}} \cdot \sqrt{\frac{(Tc - Tb)}{r_D \cdot Rs(300K)}}$$

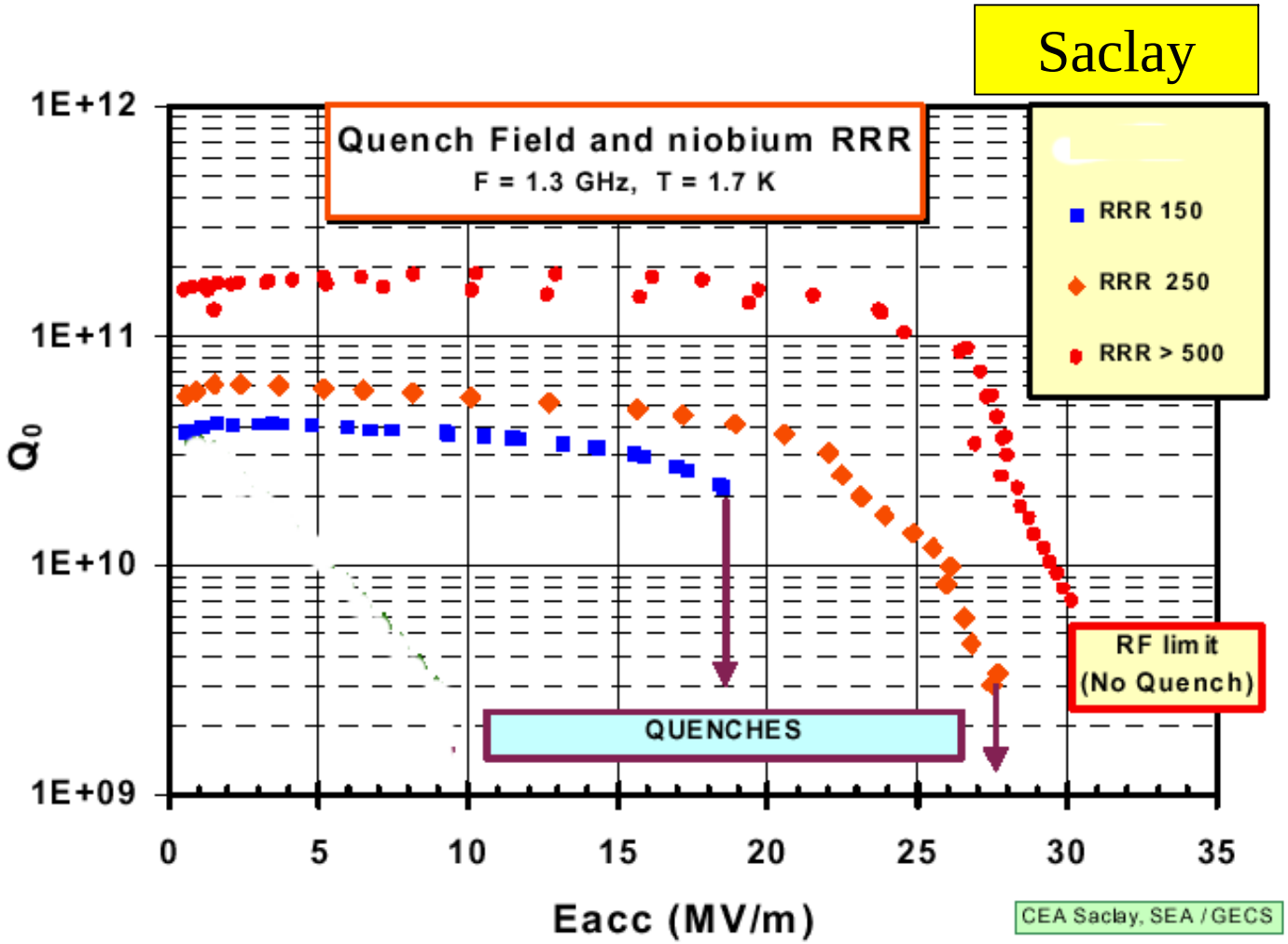


Hq~1500Oe,
Eacc,max ~34MV/m @
RRR=135, r_D=3μm

Defect radius

Need to remove 1μm size defects. Use high purity niobium with RRR>200.

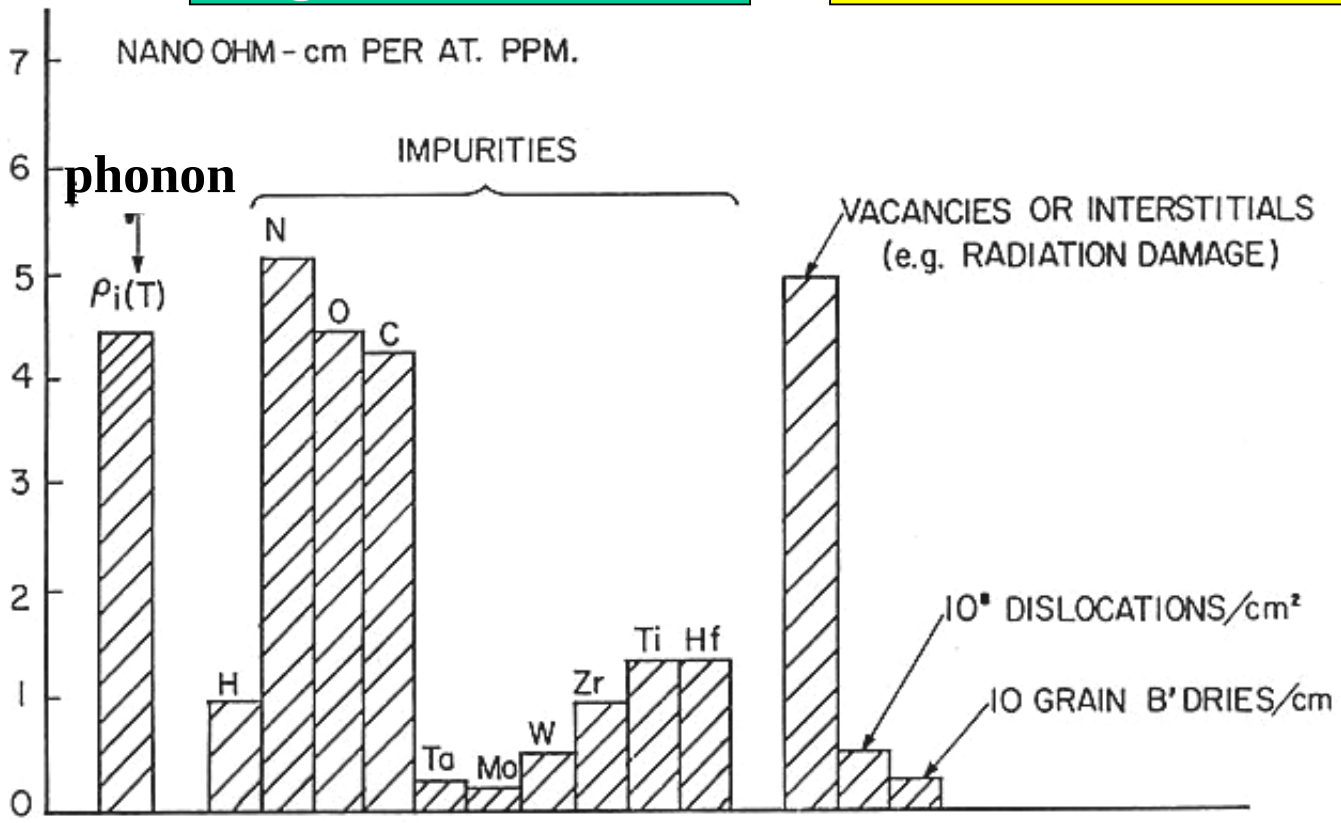
Field Improvement by High RRR Material



Effect of Various Scattering Mechanisms on Electric Resistivity

High purity + **Homogeneity**

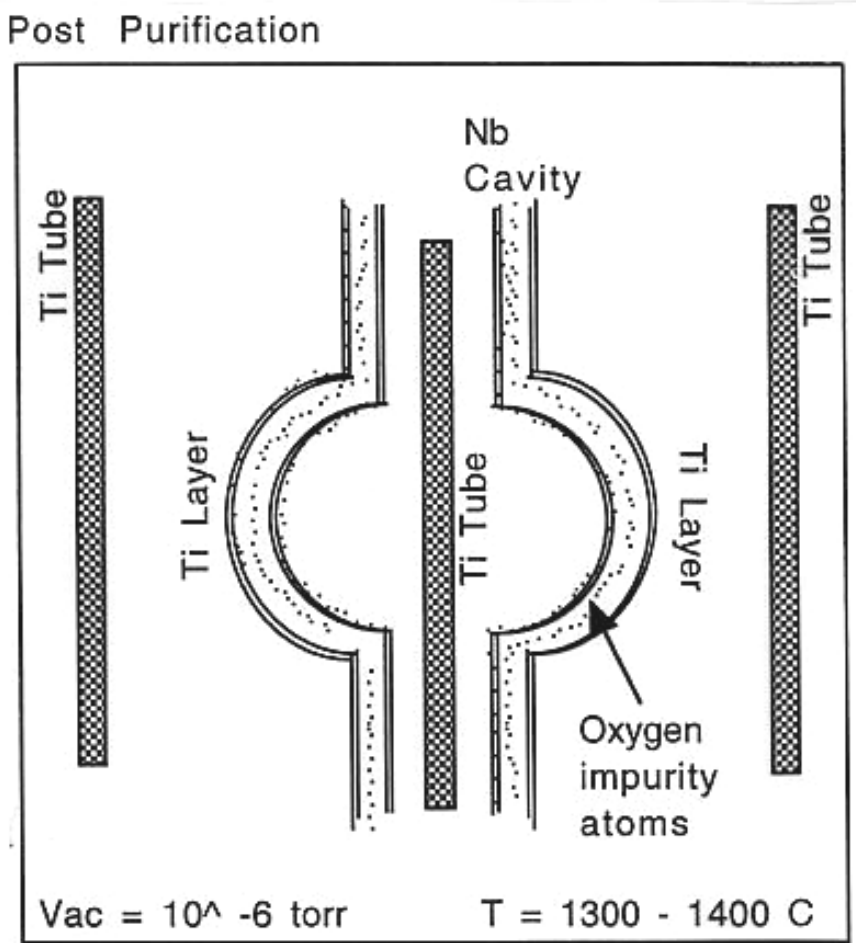
Nb → High RRR material → Vacuum annealing



$$\text{E-Resistivity} = \sum (\text{mechanism})_i$$

$$= \text{e-phonon scat.} + \text{e-imprity scat.} + \text{e-inhomogenety scat.} + \cdots$$

Cure : Post Purifying of Niobium



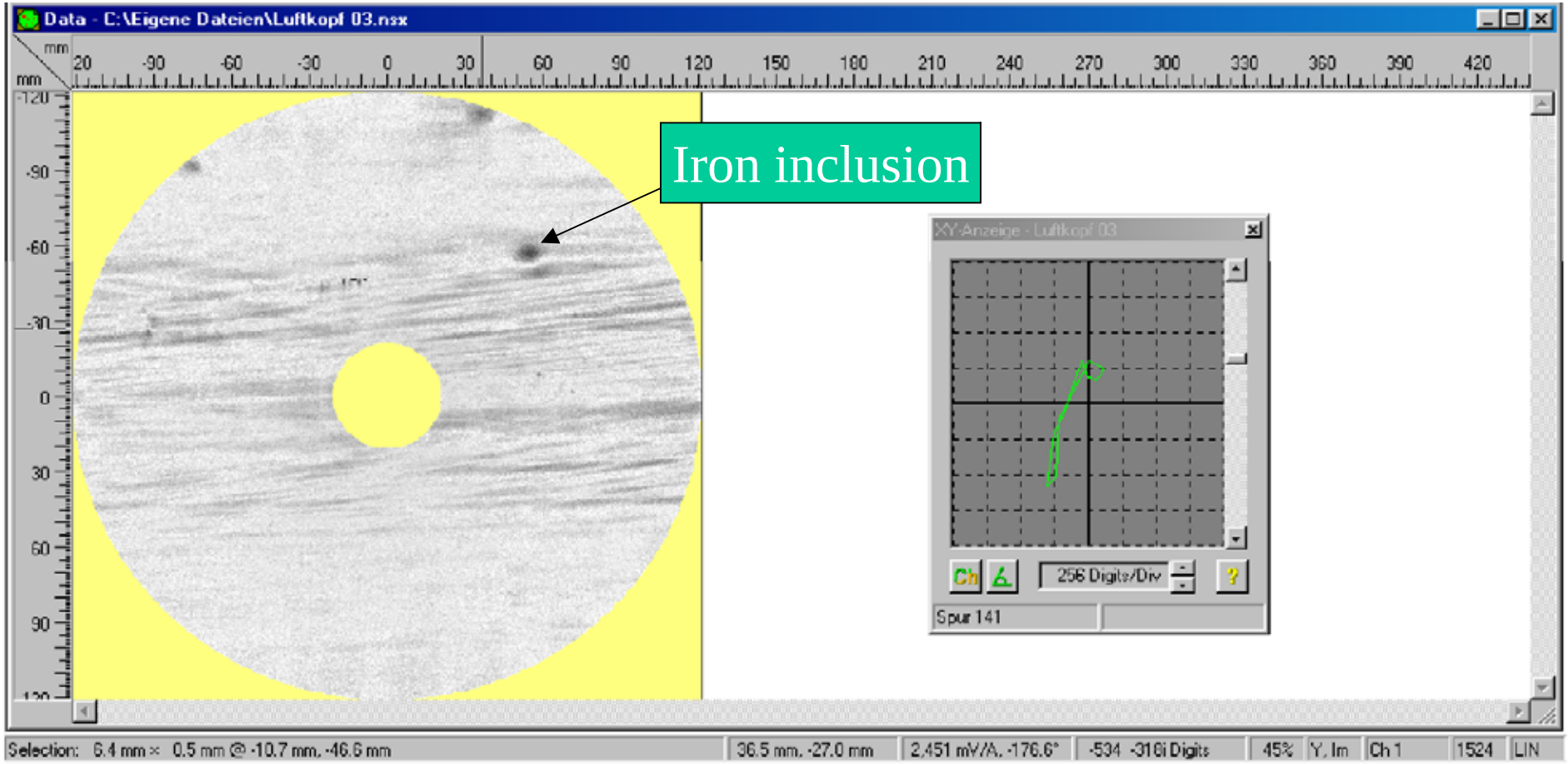
After cavity or half-cell is produced

- **Heat in vacuum furnace to ~ 1350 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)**

Cure : Inspection of Nb Sheet and Cavity Surface

Defect free material : Quality control

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



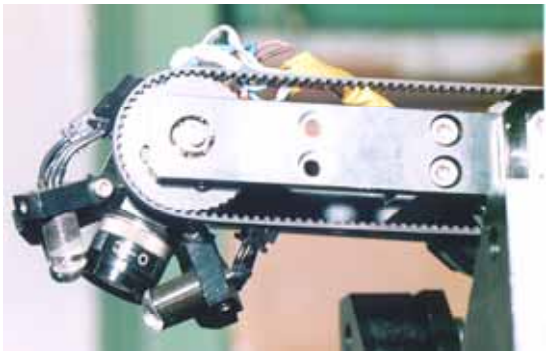
Global view, rolling marks and defect areas can be seen

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

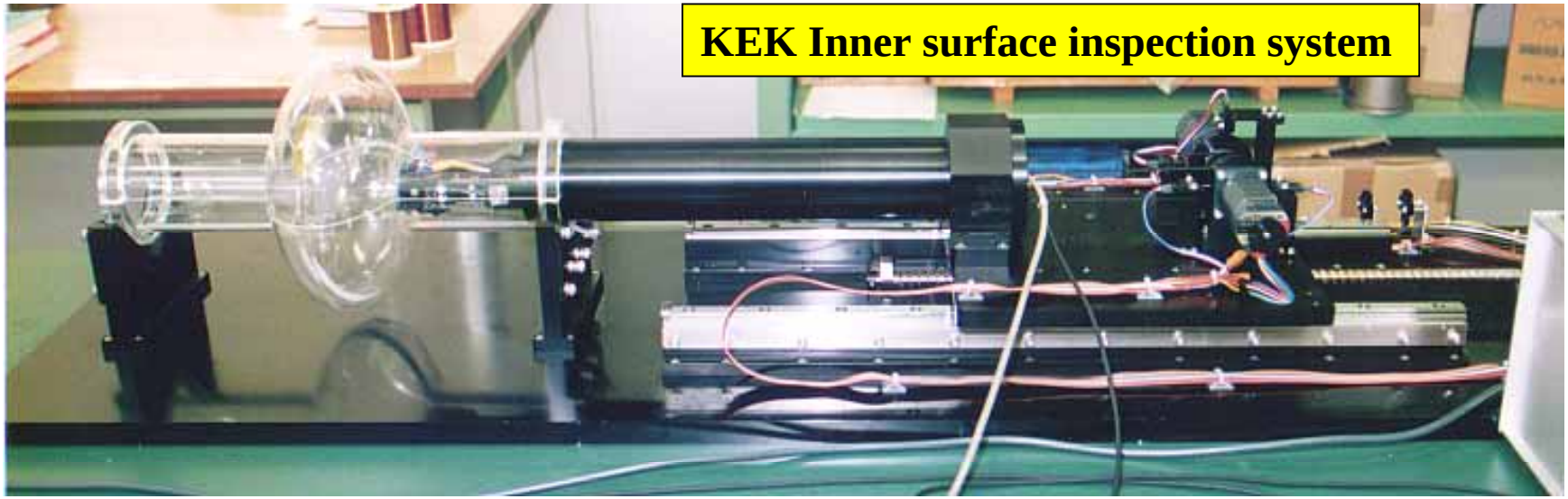
Eddy current scanning system DESY

Cavity Inner Surface Inspection System : KEK

Small CCD camera



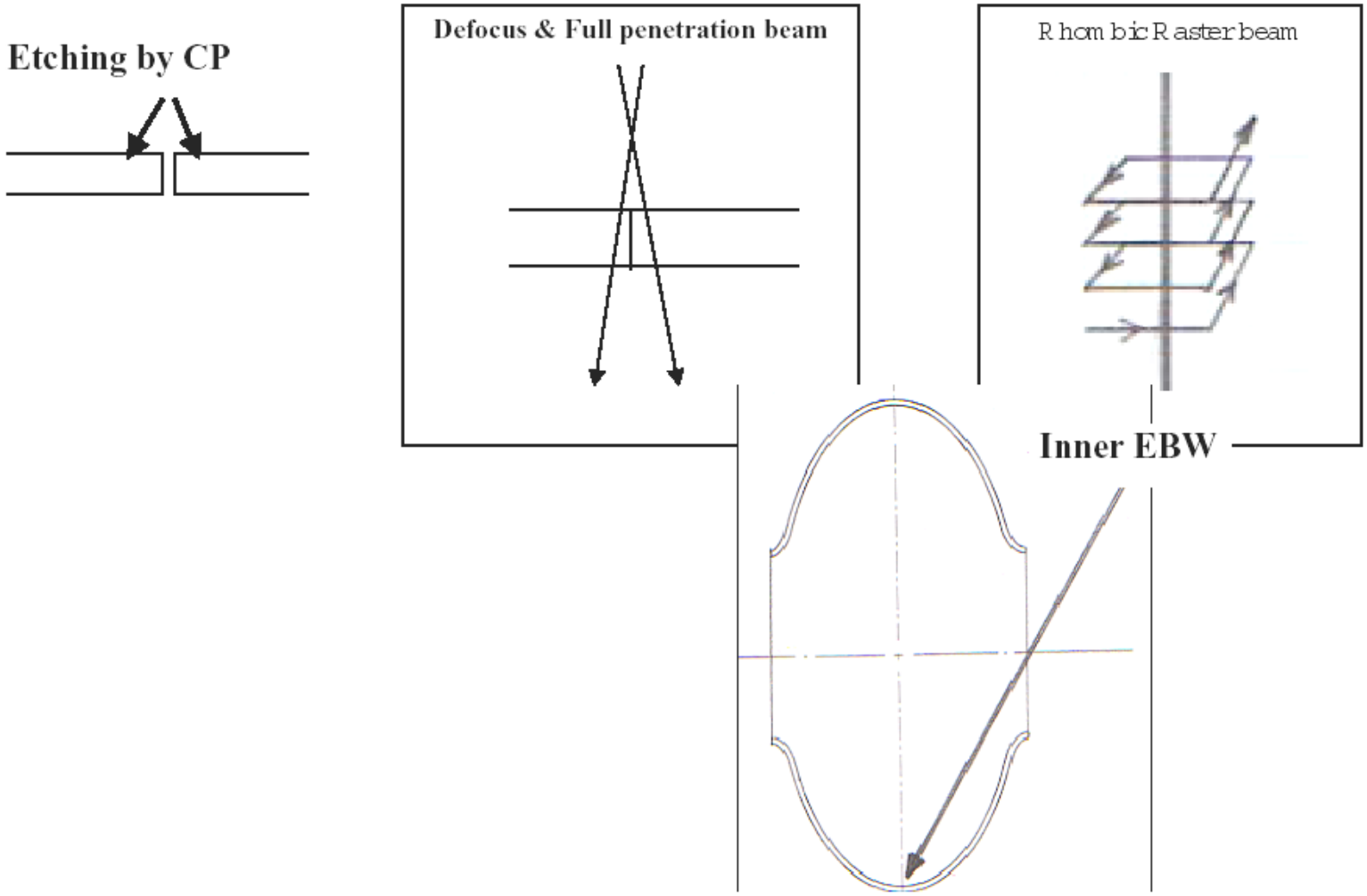
CRT monitor
Magnification ~13



KEK Inner surface inspection system

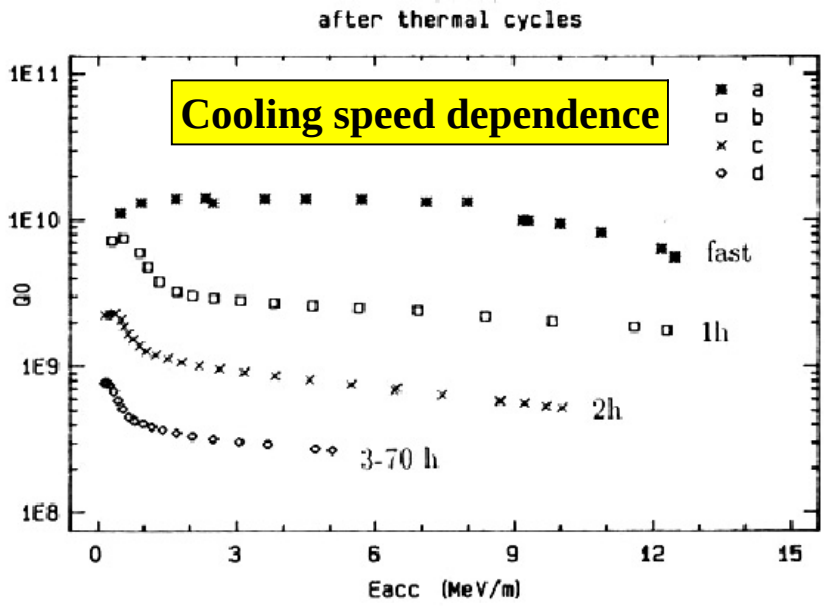
Cure : High Quality EB-welding

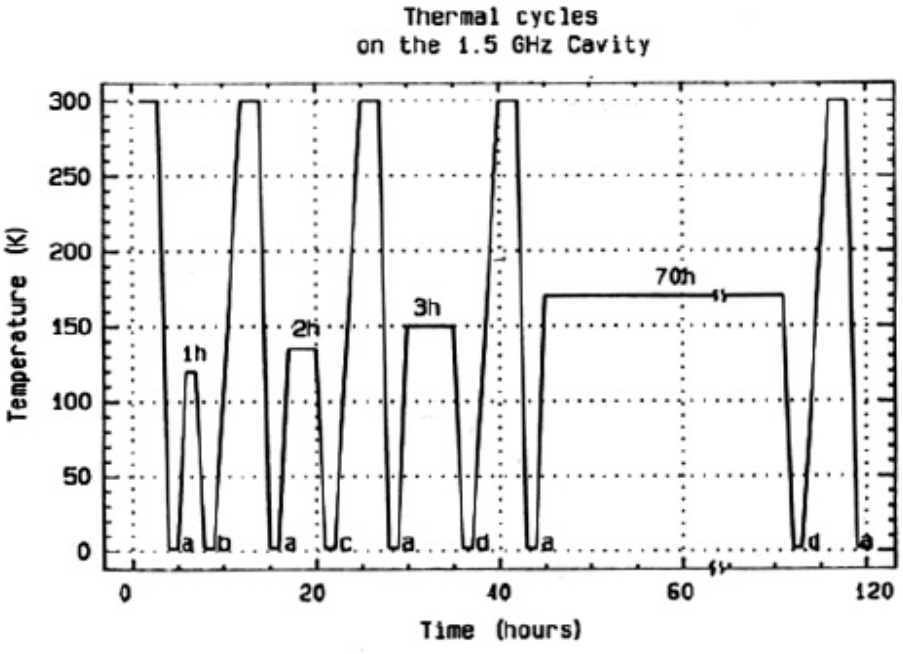
Better EBW



7.4 Hydrogen Q-Disease

Q_o-value strongly depends on cooling down speed.

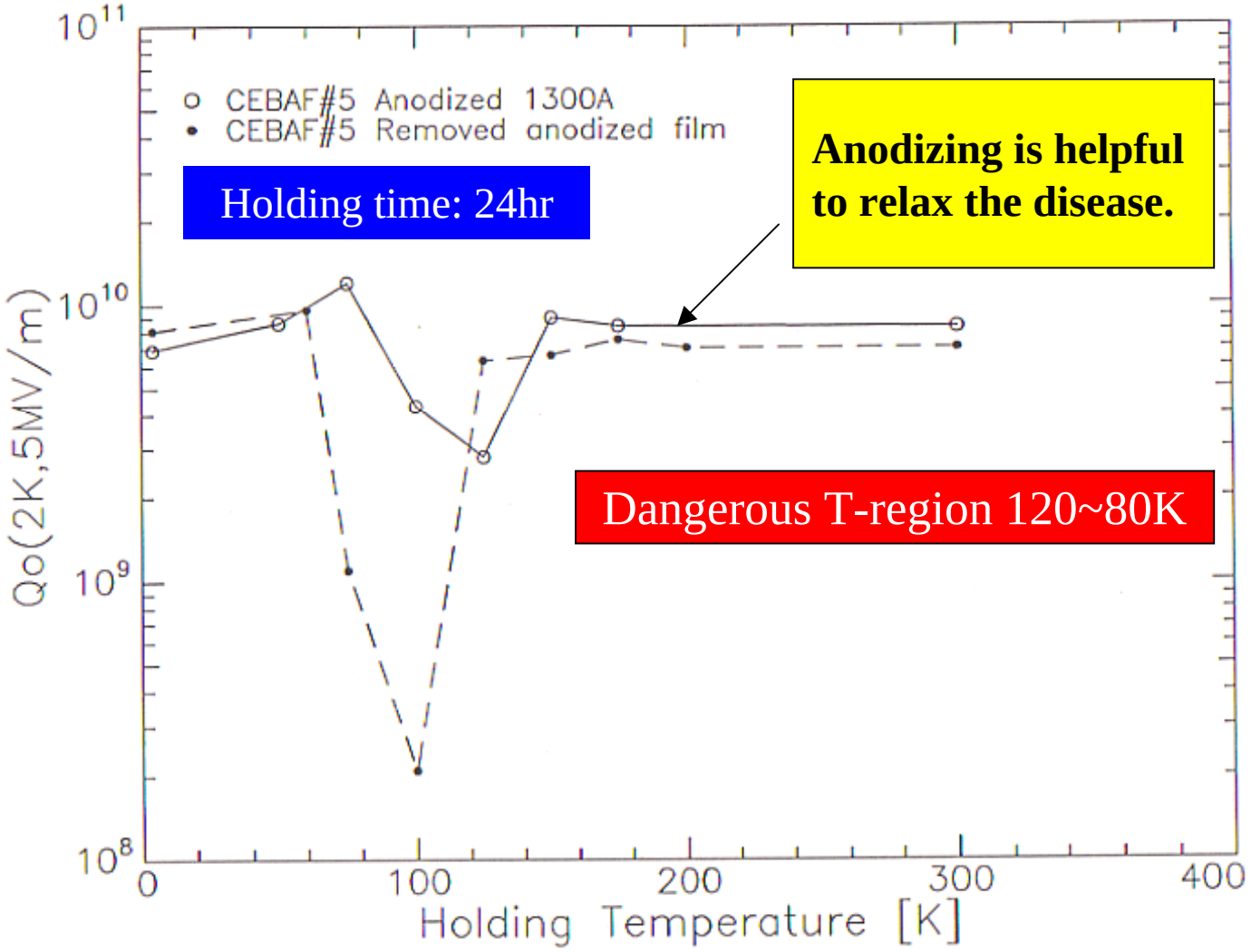




In 1990, Discovered
with chemically polished niobium cavity

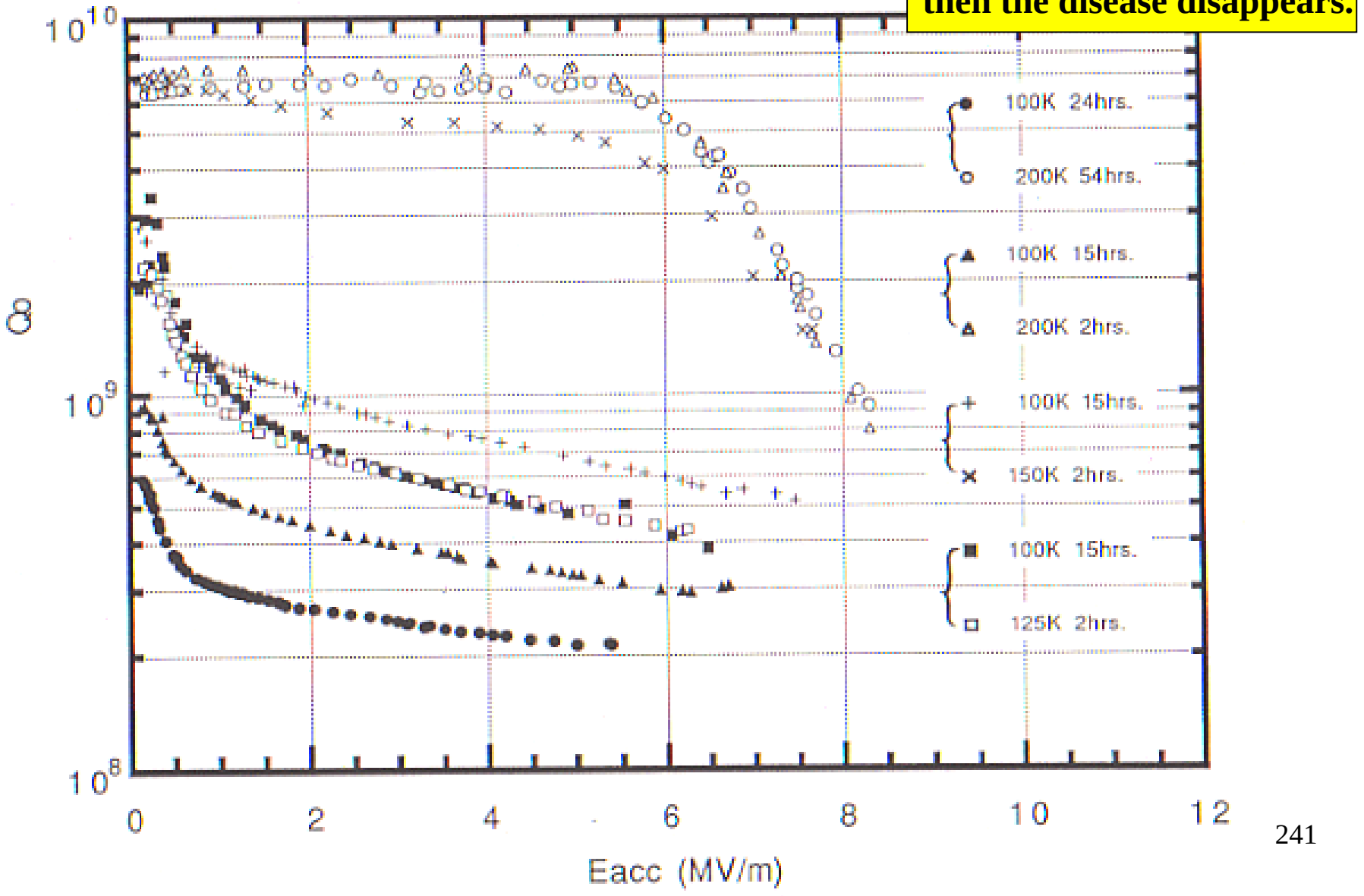
At those days, all labs in Europe and US have been used chemical polishing, because it is simple and no needs hydrogen degassing annealing.

Dangerous Temperature



Recovery of Hydrogen Q-Disease

Warm up to 200K,
then the disease disappears.



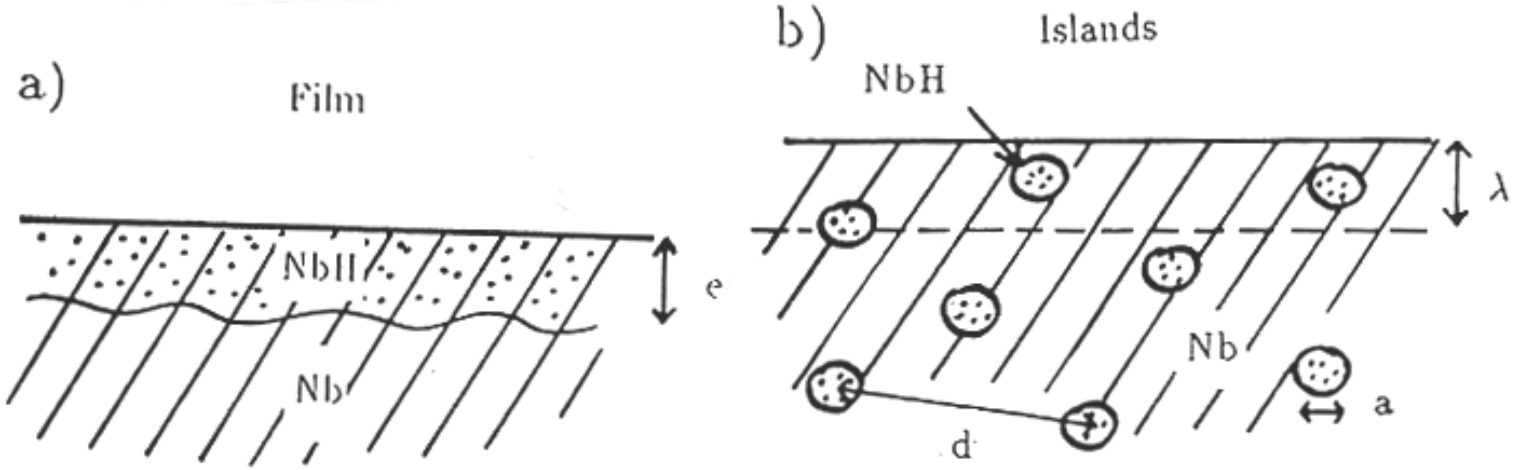
Mechanism of Hydrogen Q-disease

Mechanism
and Explanation of Symptons

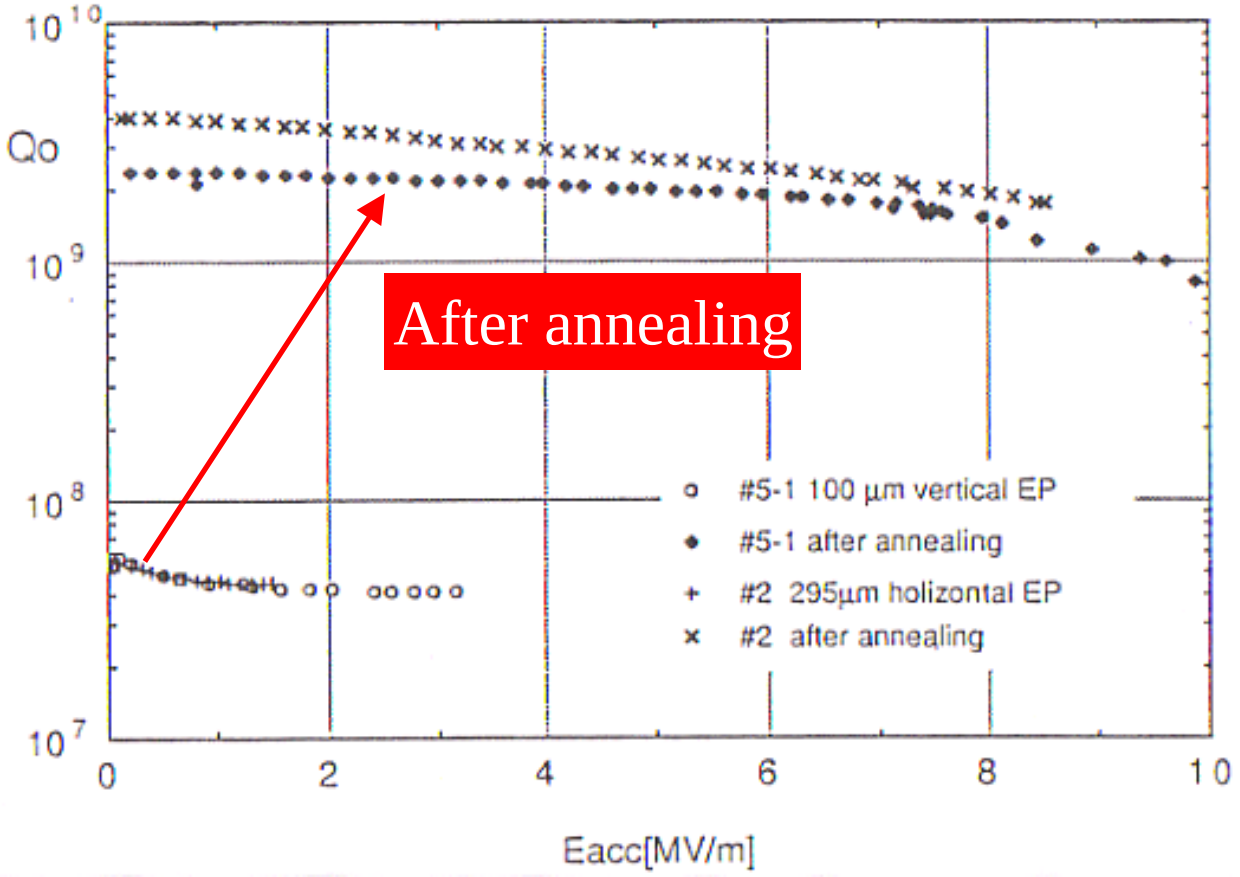
At room temperature H moves freely,
there is some evidence of surface enrichment

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

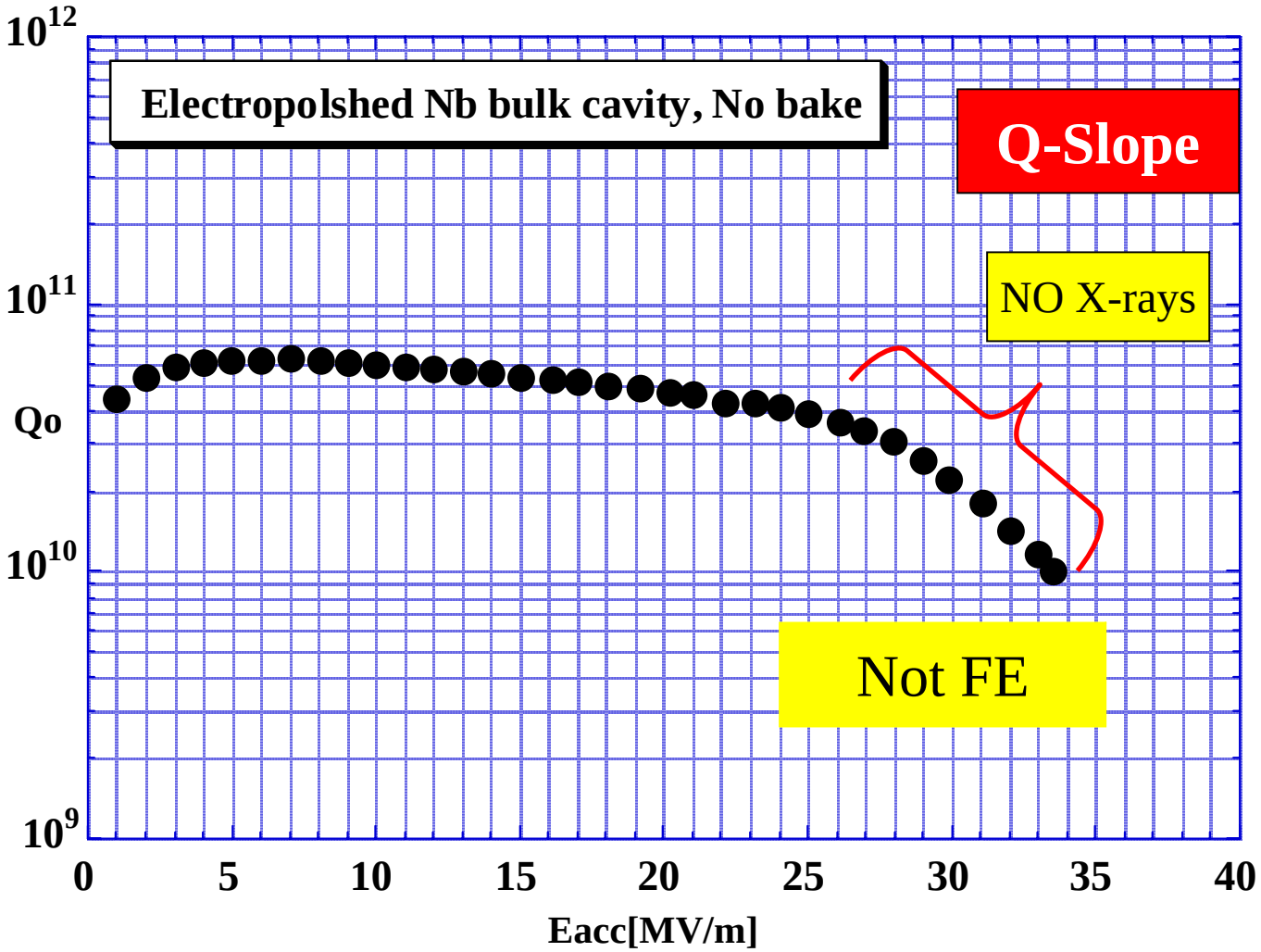


Hydrogen Q-disease in electropolished cavity



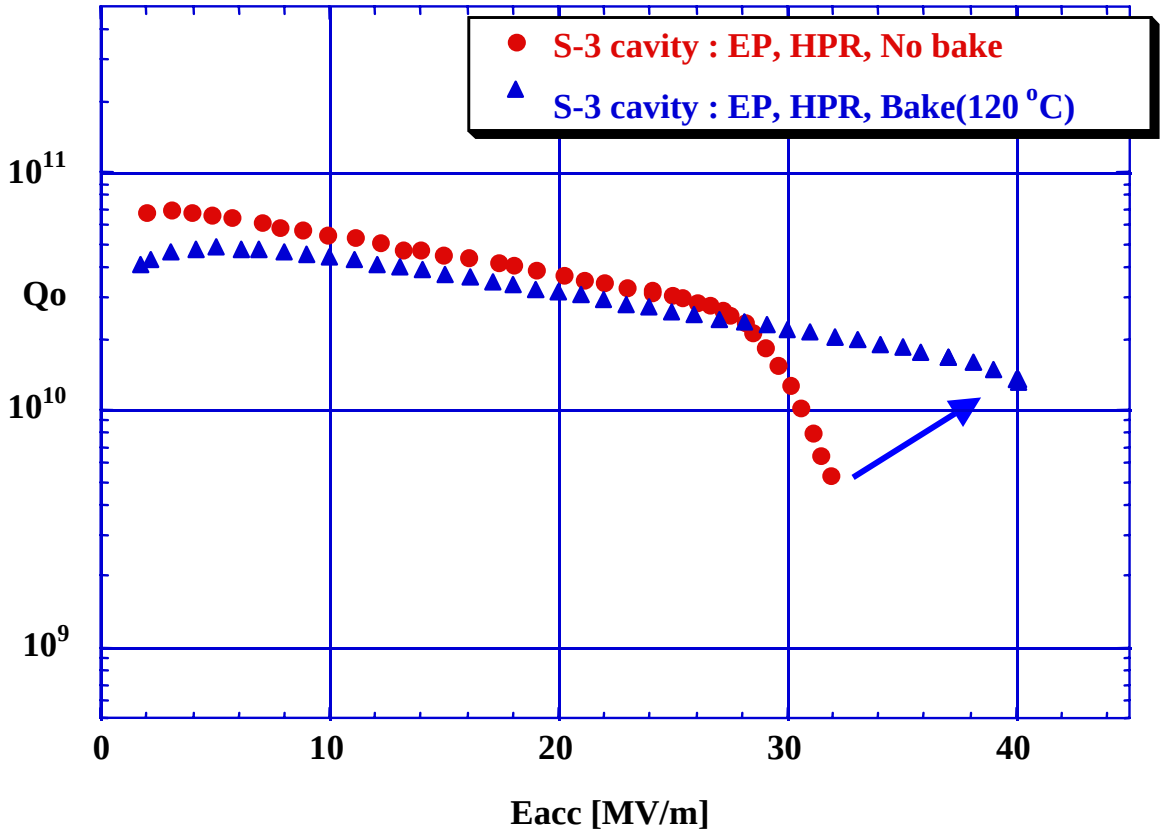
Hydrogen Q-disease is much serious on electropolished cavity.
Hydrogen degassing has been routinely done by annealing.
In those days, pre-cooling with liquid nitrogen had been used and nobody knew the disease depends on cooling down speed.

7.5 Q-Slope



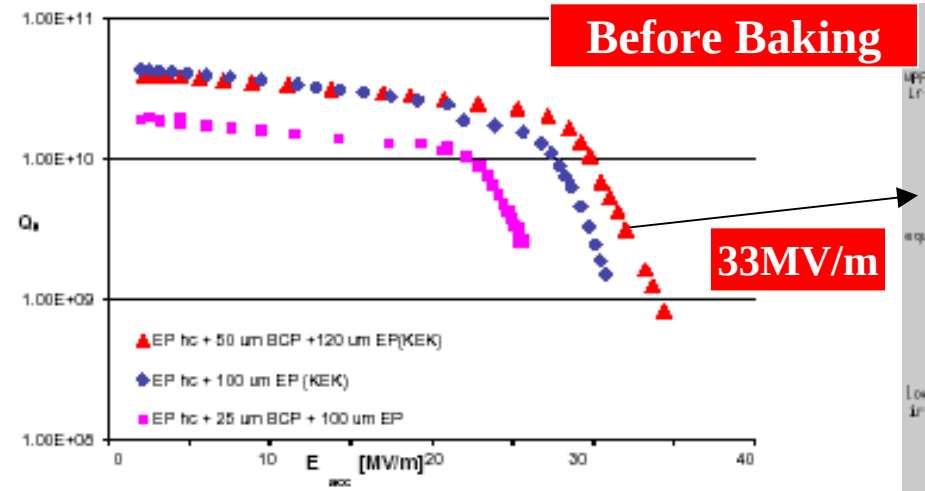
Discovered in 1998

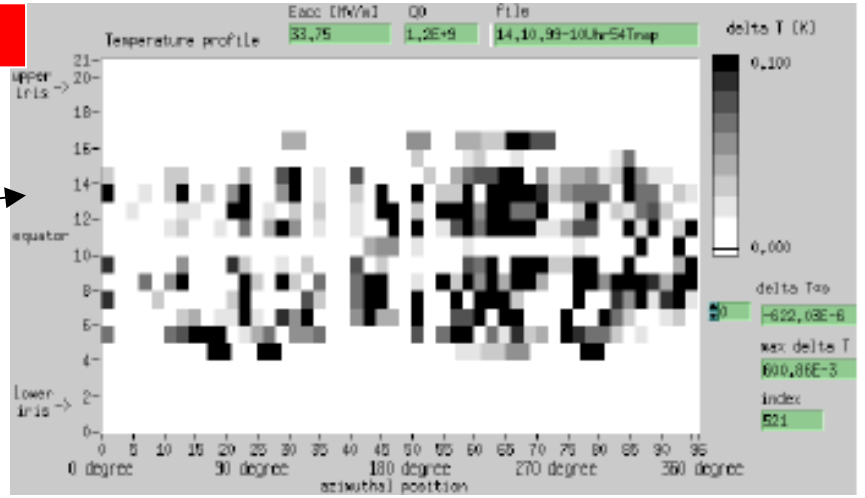
Crucial Baking Effect on EP Cavity



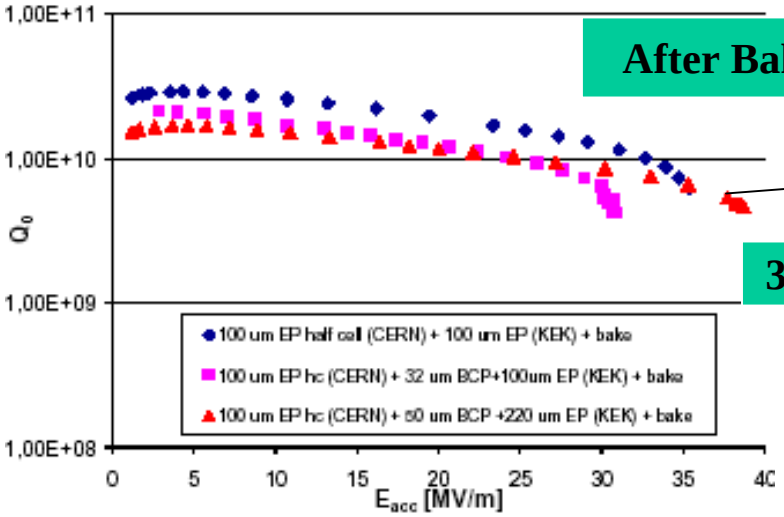
When took baking, Q-slope disappears in case of electropolished cavity.
KEK has been used baking and thought that it gets better vacuum.
They did not notice the Q-slope.

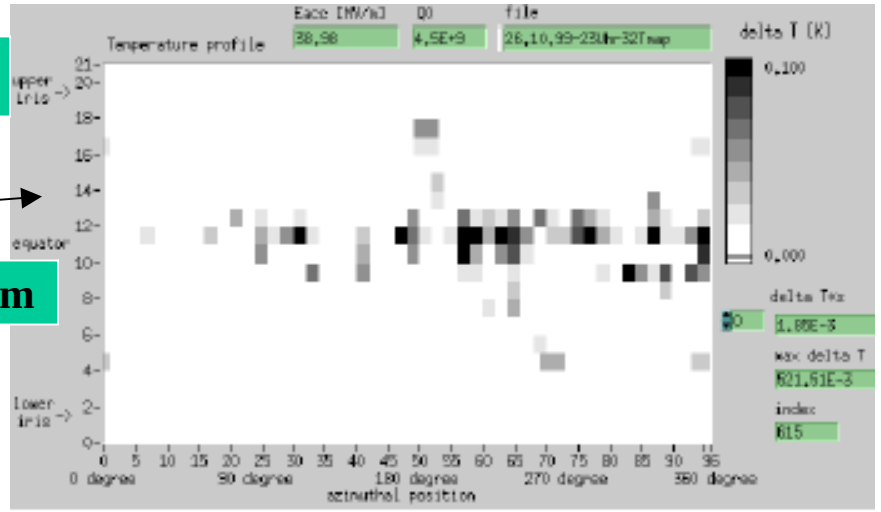
Disappeared Heating Spots by Baking on EP Cavity





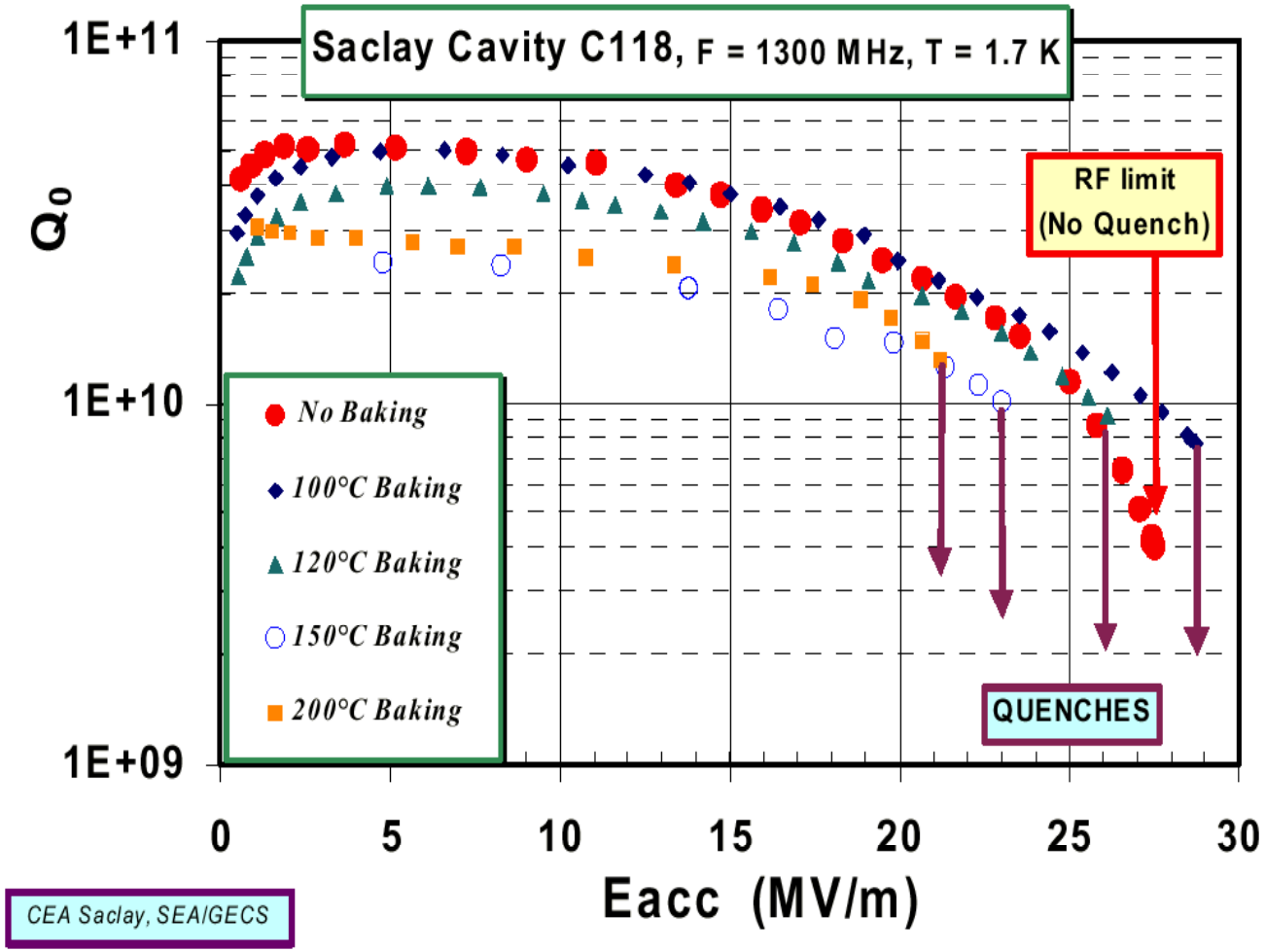
33MV/m





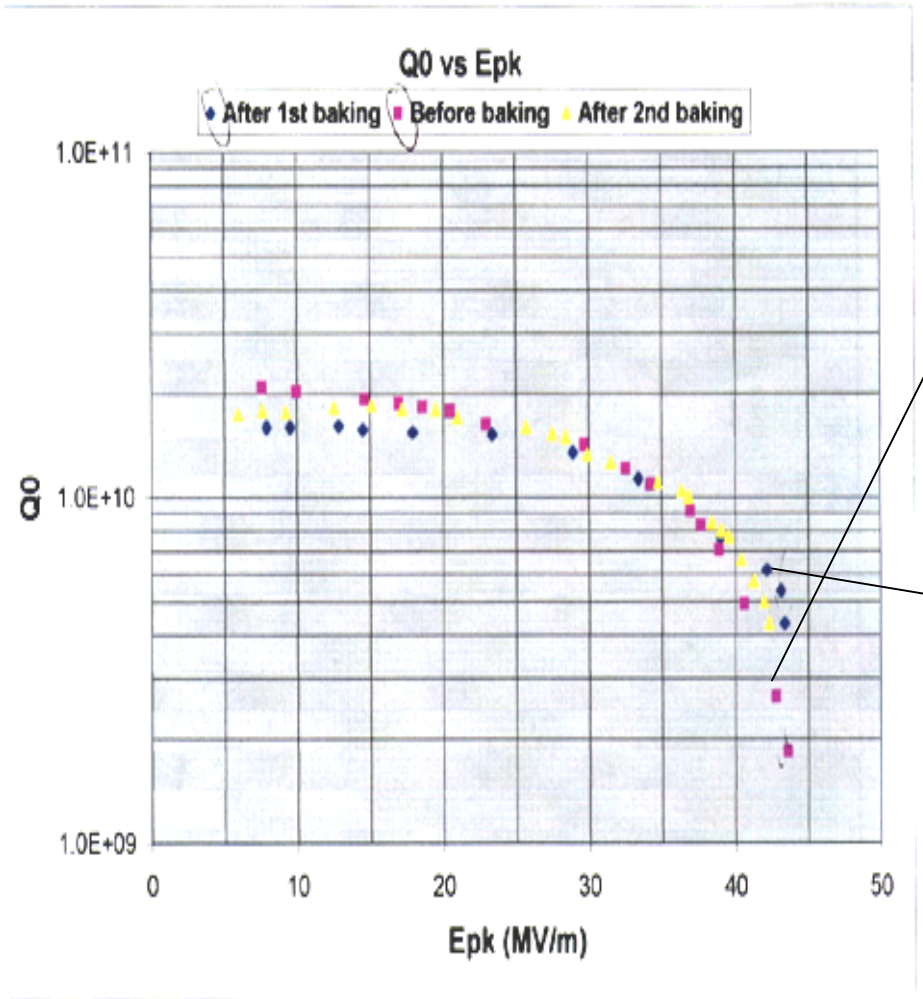
39MV/m

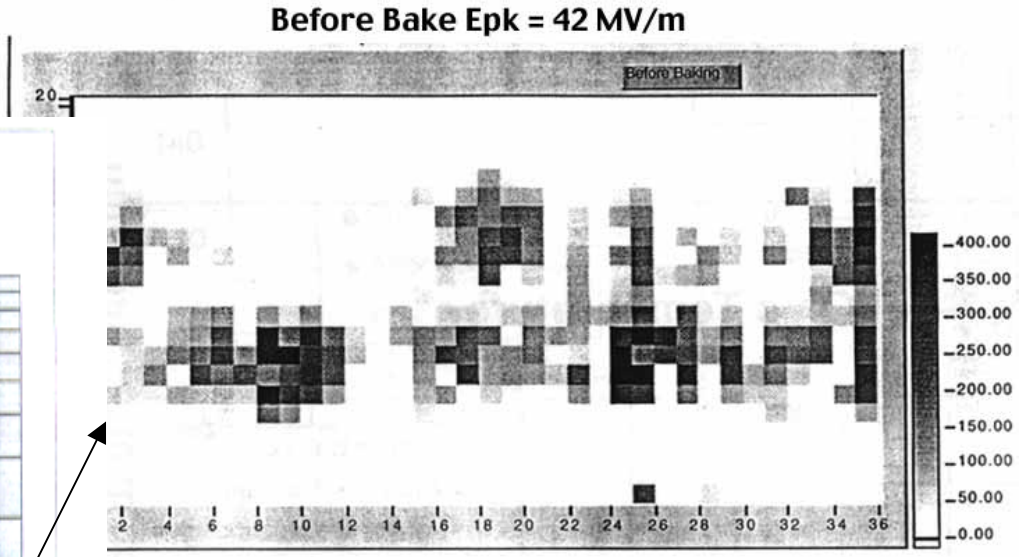
Small Baking Effect on CP Cavities (polycrystalline)

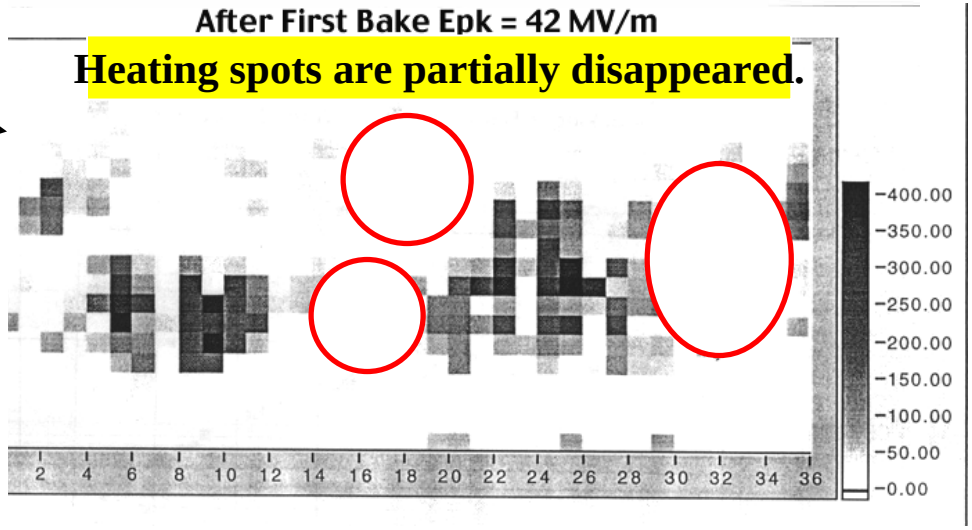


Baking effect on the Q-slope looks small on chemically polished polycrystalline cavity.

Partially Disappeared Heating Spots by Baking on CP Cavity







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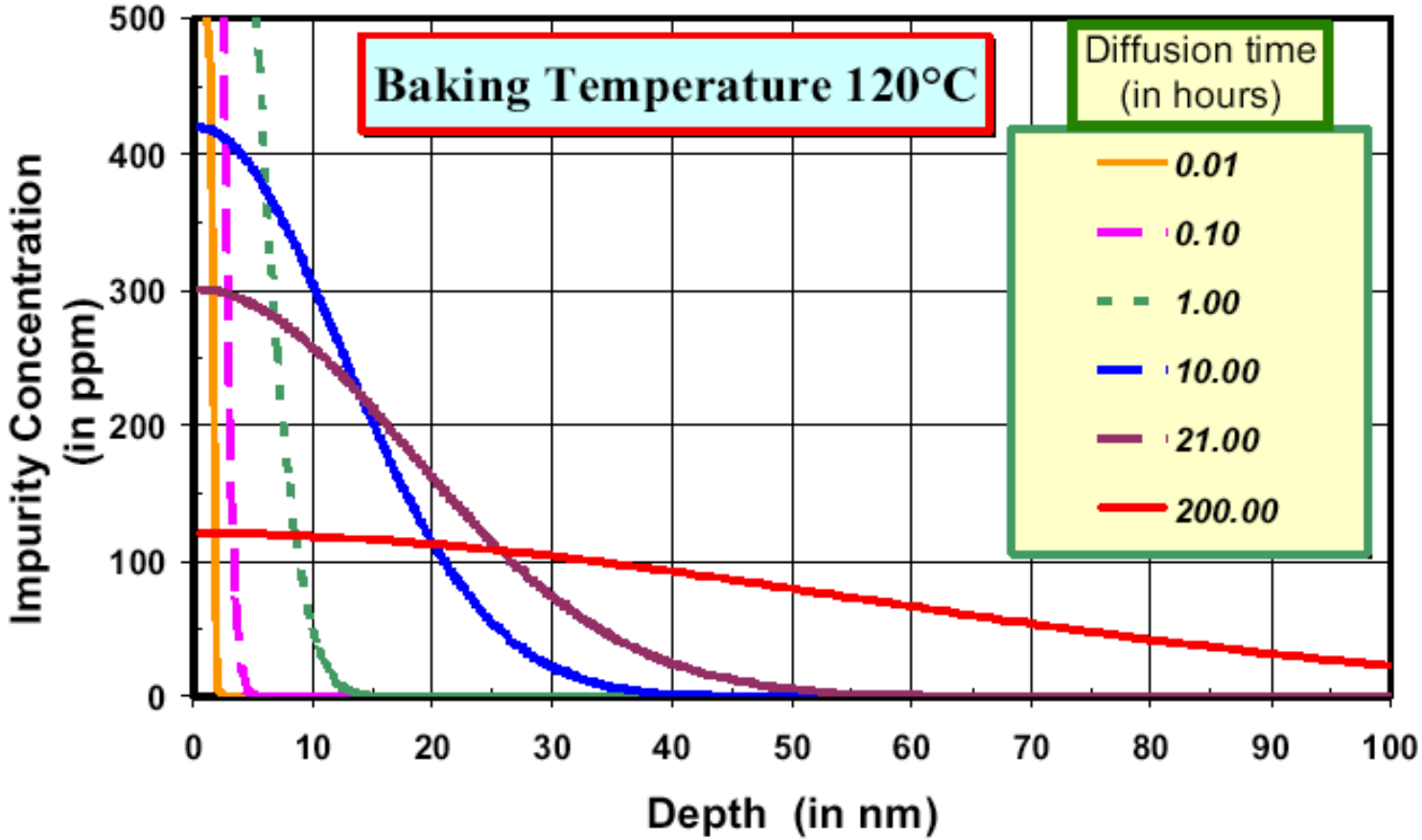
Oxygen Diffusion



Baking could defuse the oxygen contamination on the top into the bulk and the niobium RF penetration surface could be become clean.

Loss Mechanism

Interface Tunnel Exchange(ITE Model) By J.Halbritter

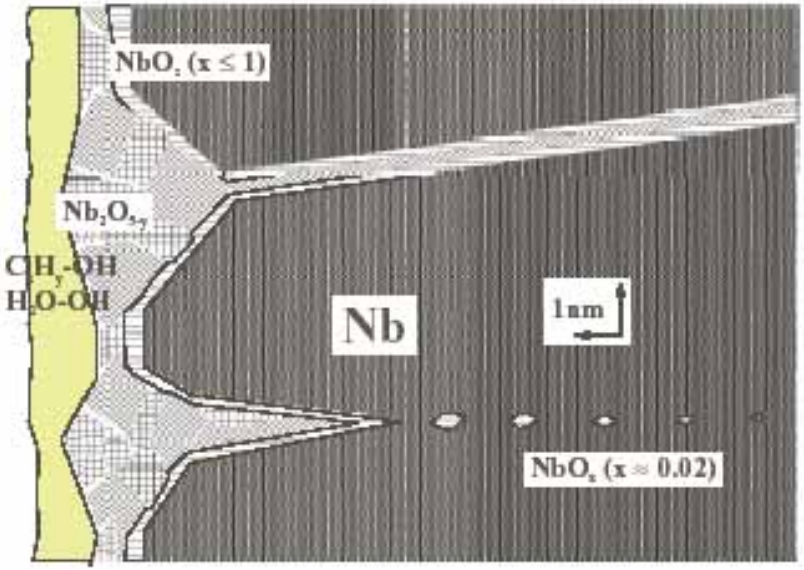


Fig. 1: Nb surface with crack corrosion by oxidation by Nb_2O_5 volume expansion (factor 3). Nb_2O_{5-y}-NbO_x weak links/segregates (y, x < 1) extend up to depths between 0.01 – 1/ 1-10 µm for good – bad Nb quality and weak - strong oxidation [8]. Embedded in the adsorbate layer of H_2O/C_xH_yOH (≥ 2 nm) being chemisorbed by hydrogen bonds to $NbO_x(OH)_y$, adsorbate covered dust is found. This dust yields enhanced field emission (EFE [7]) summarized in Sect. 3.1.

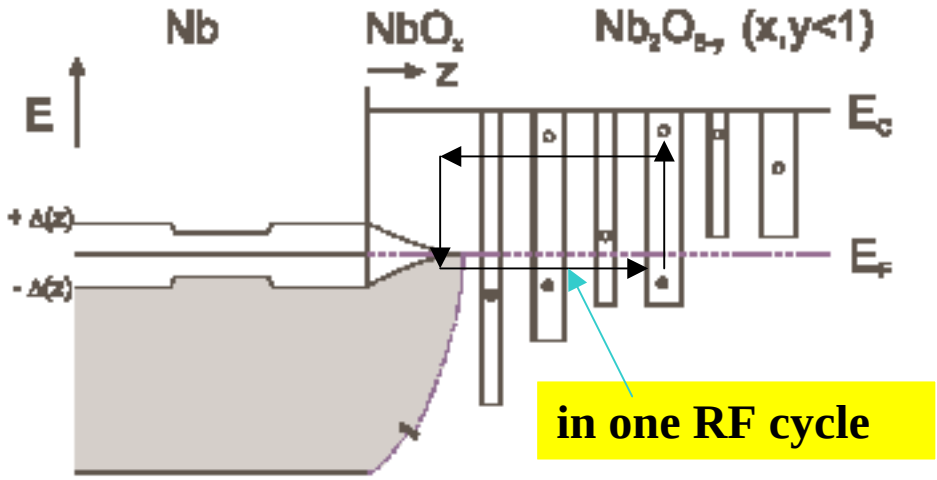
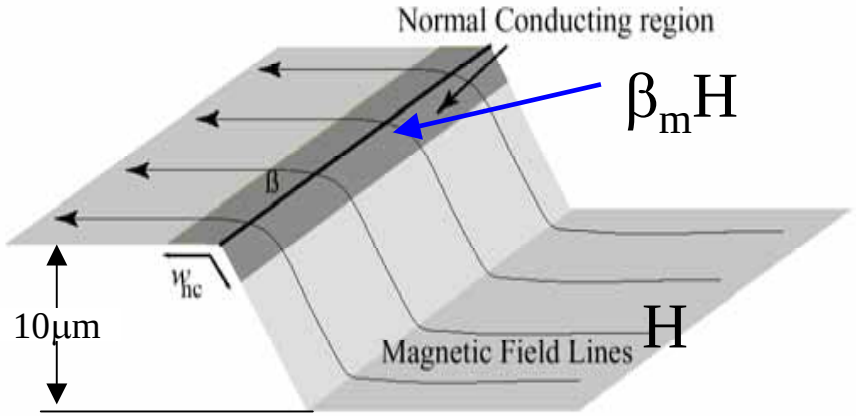
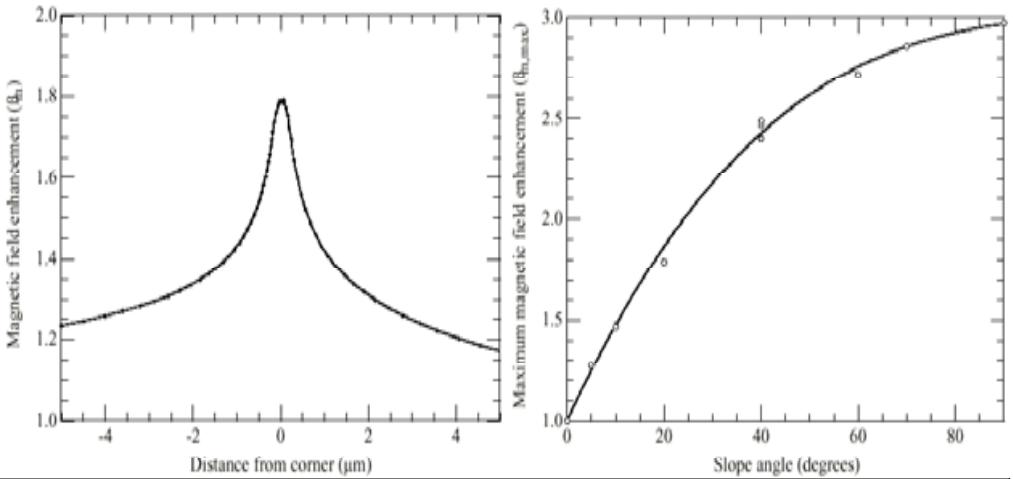


Fig. 3: Band structure at Nb-NbO_x-Nb_2O_{5-y} interfaces with E_c-$E_F = \phi \approx 0.1 - 1$ eV as barrier heights for tunneling along crystallographic shear planes (~ 0.1 eV) or of Nb_2O_{5-y} crystallites (~ 1 eV). Added is the superconducting energy gap $\Delta^*(z) < \Delta_o$ being reduced in NbO_x clusters or interfaces and being normal conducting Δ^* ($z_L \geq 0.5$ nm) in localized states of Nb_2O_{5-y}. By their volume expansion those clusters locally enhance T* and $\Delta^* > \Delta_o$ in adjacent Nb by the uniaxal strain yielding a smeared BCS DOS.

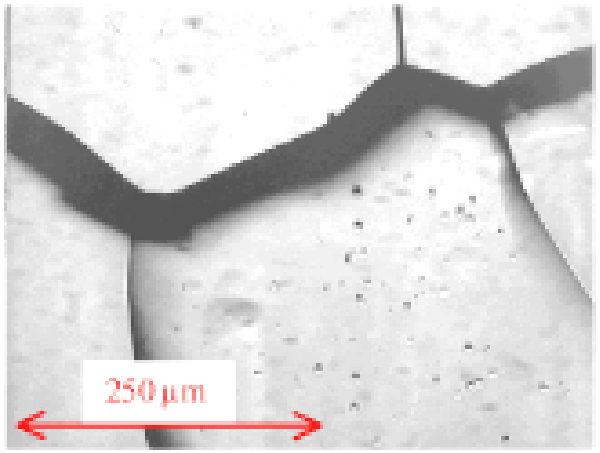
7.6 Magnetic Field Enhancement on Sharp Edges

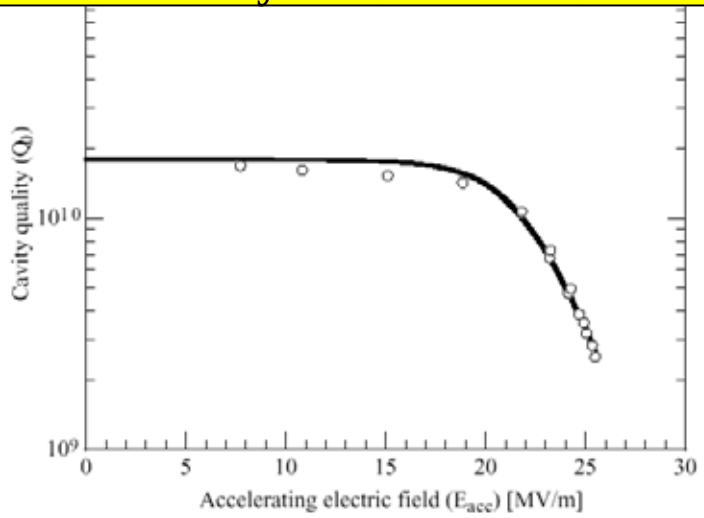




Standard BCP Chemistry on niobium :
Sharp boundary edges are clearly visible

Why the gradient can not be improved after baking in chemically polished cavity ?





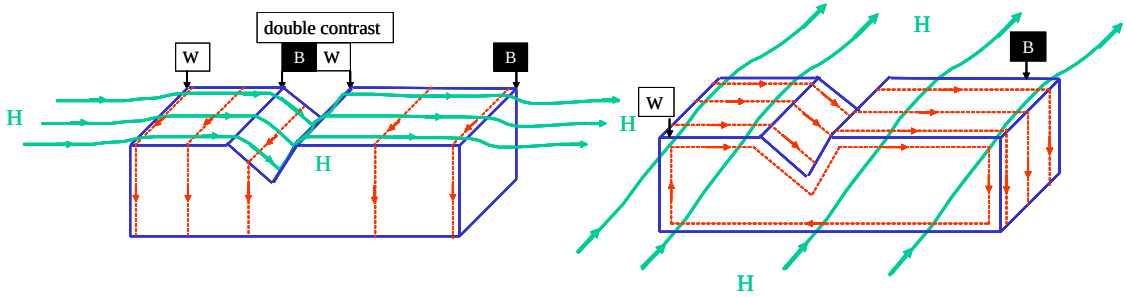
$$\beta_m \cdot H_{RF} \geq H_C = \frac{\sqrt{2} \cdot H_C(0)}{\kappa(0)} \cdot (1 - t^4)$$

Figure 19: Comparison of the measured cavity quality (Test C) with that calculated by (25) using $H_{crit} = 1875$ Oe.

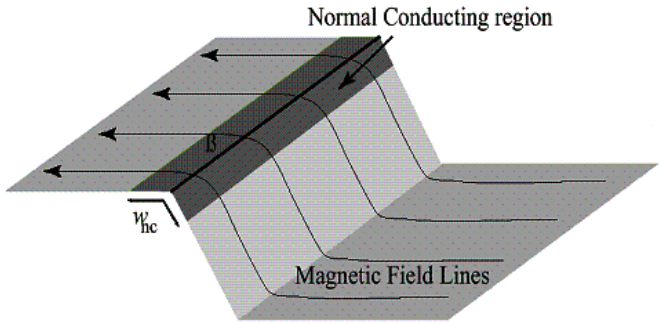
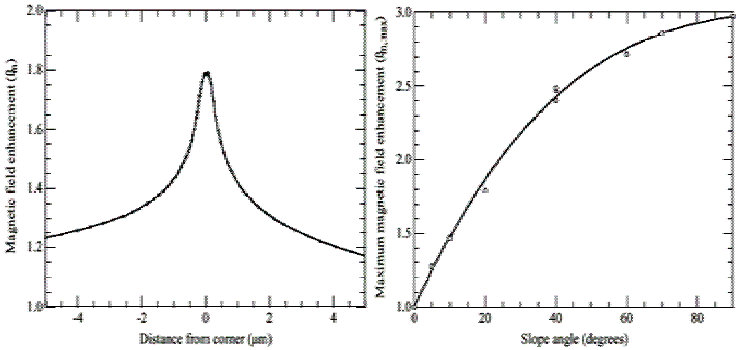
Monograph effect on Magnetic field

By C.Antone

CBP is right way to eliminate the monograph effect !!



J.Knobloch



Flux trapping happens on the steps perpendicular to the magnetic flux !