

7. Various Cavity Performance Limitation

7.1 Multipacting

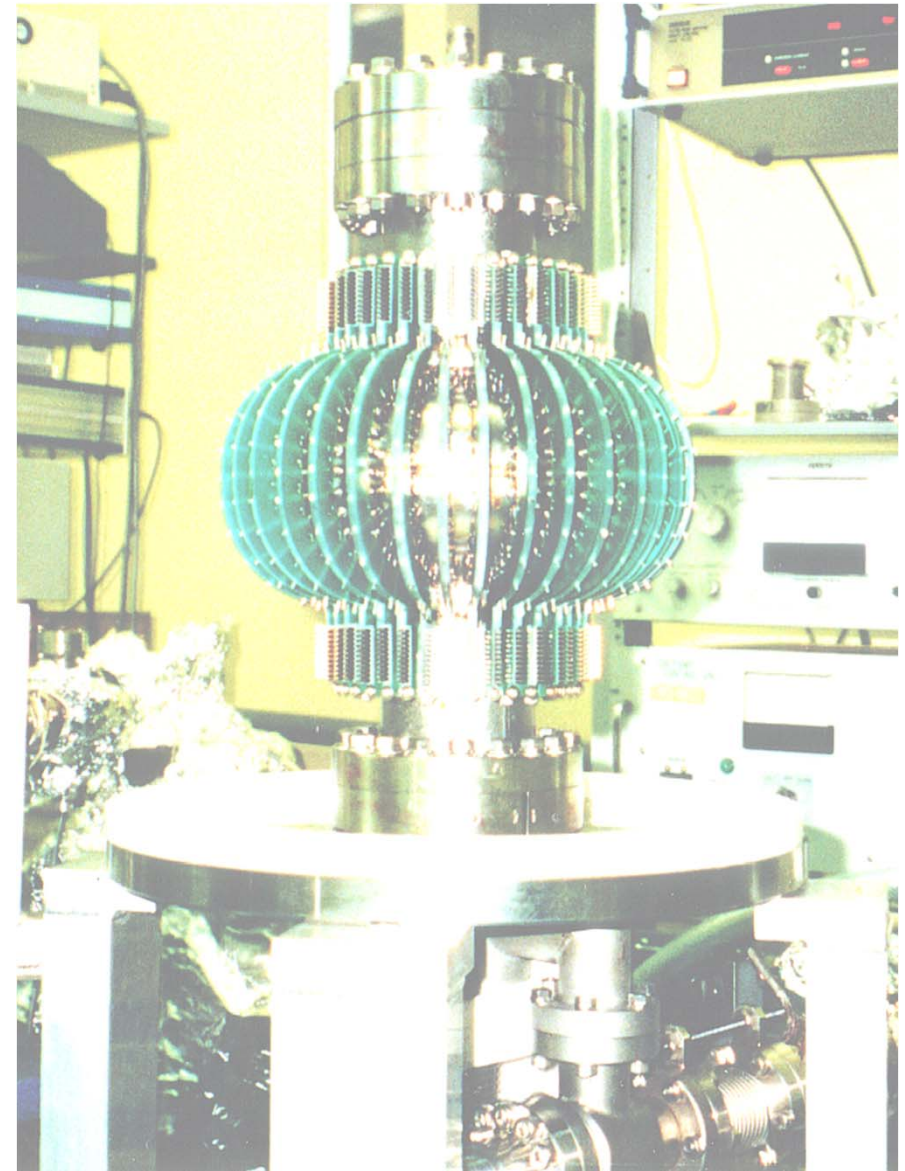
7.2 Field Emission

7.3 Thermal Instability

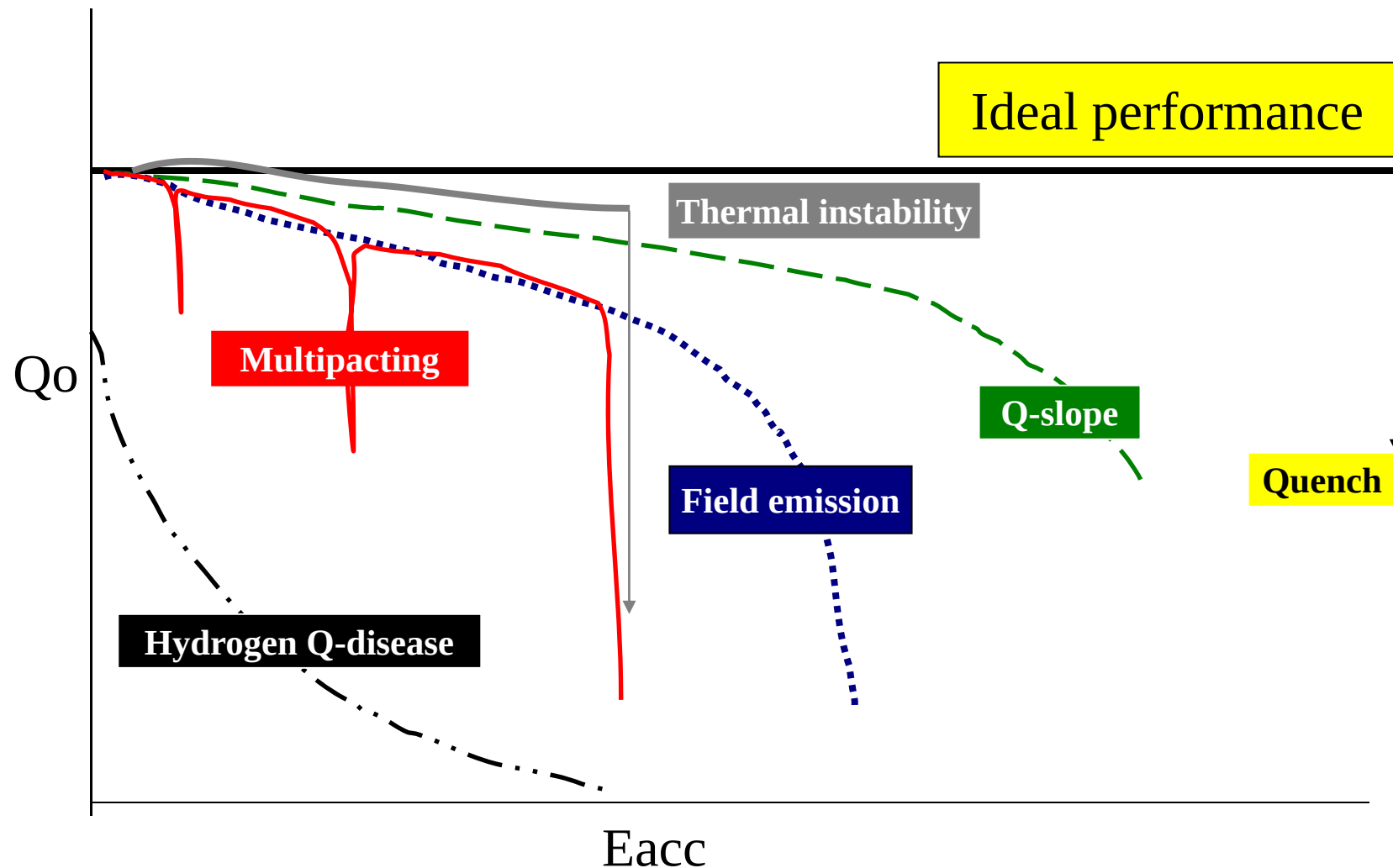
7.4 Hydrogen Q-Disease

7.5 Q-Slope

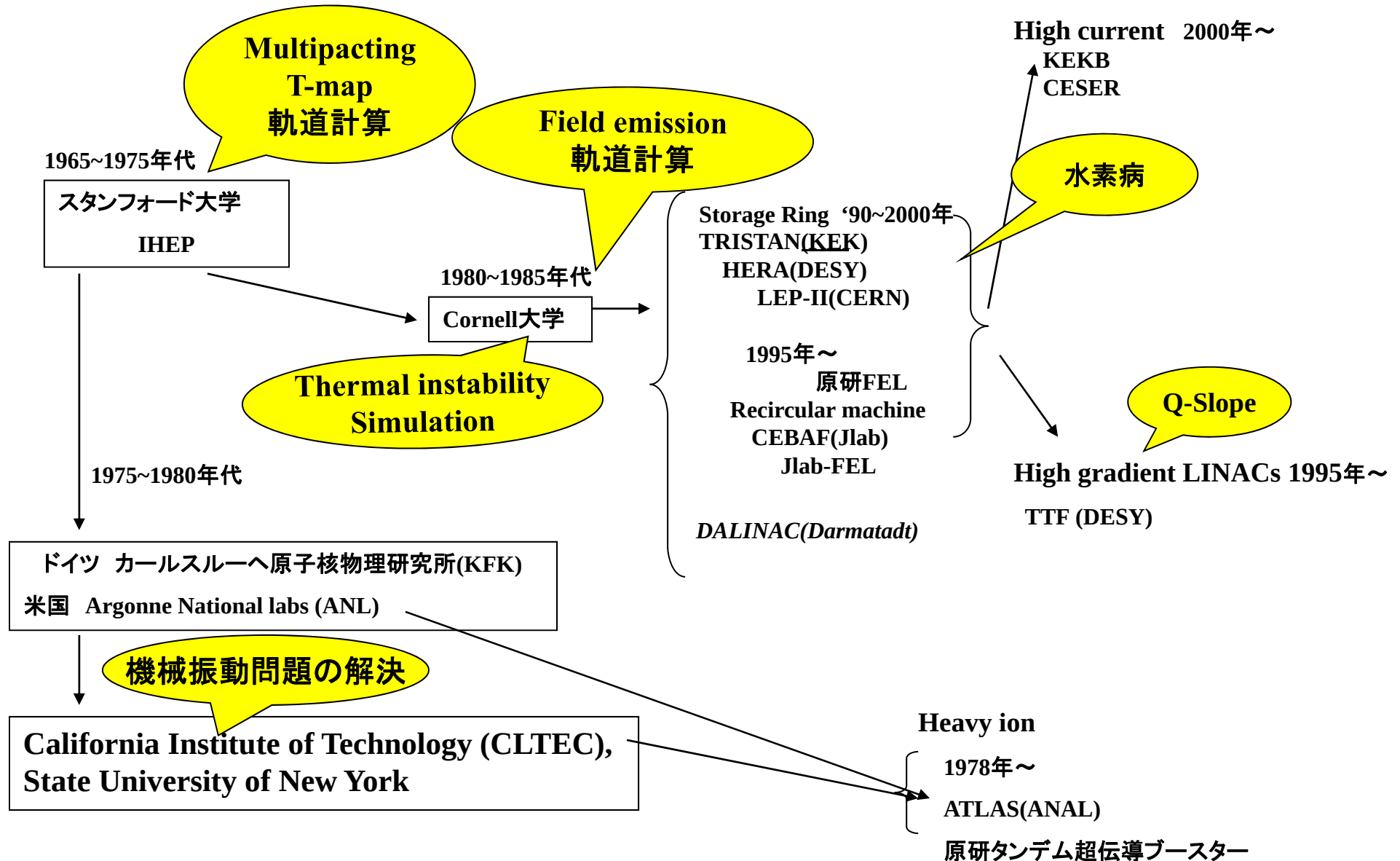
7.6 Magnetic Field Enhancement



Real SRF Cavity Performance



History of the Understanding

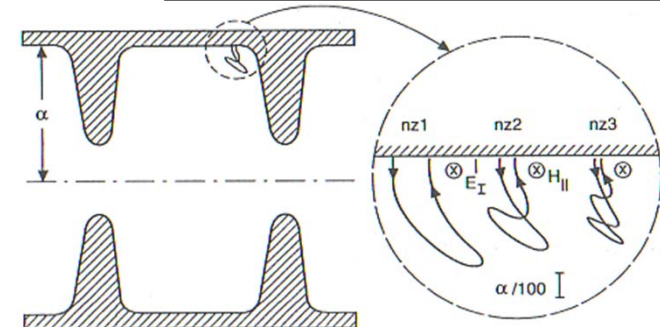
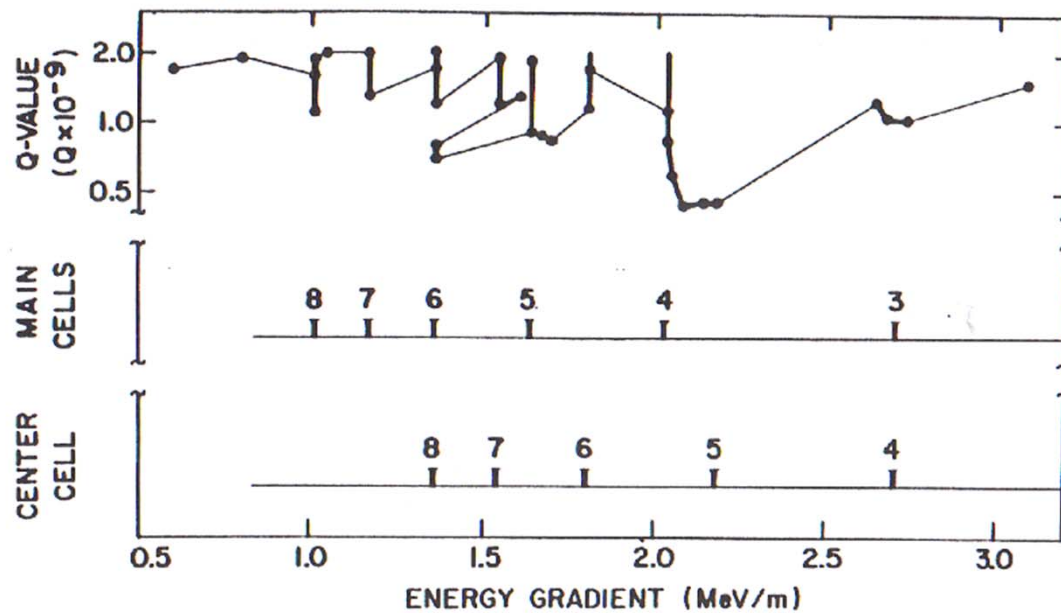


7.1 Multipacting

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

1PM or 2PMが性能を著しく制限した。

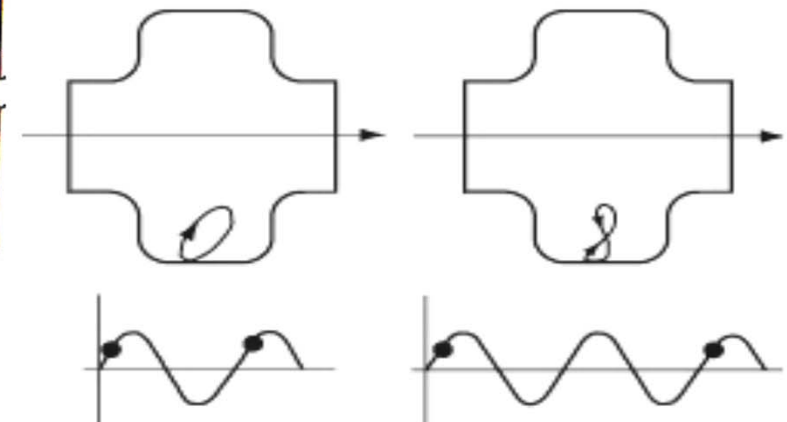
One point multipacting



1 point MP

1st Order

2nd Order



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 multipacting levels

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

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

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

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

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

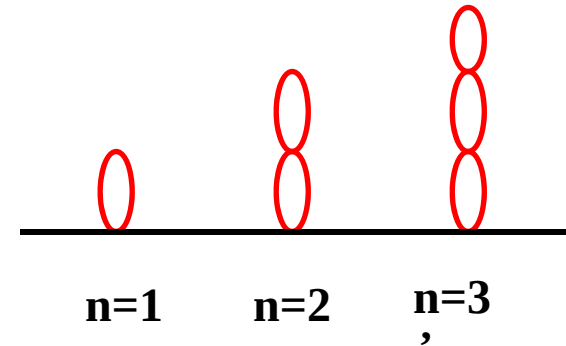
Example ;

1300MHz, $H_p/E_{acc} = 43.8 [\text{Oe}/(\text{MV/m})]$

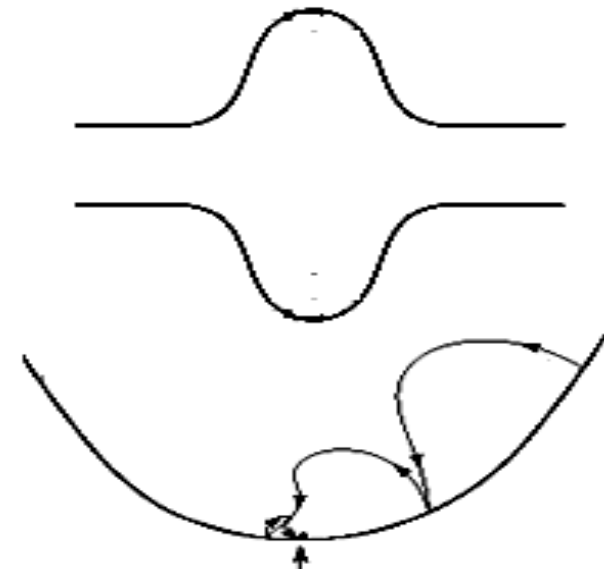
1P-1st order $\dots H_{RF}(1P-1^{st}) = 0.3 \times 1300 = 390 \text{ Oe}$

$E_{acc}(1P-1^{st}) = 390/43.8 = 8.9 \text{ MV/m}$

1P-2nd order $\dots E_{acc}(1P-2^{nd}) = 4.5 \text{ MV/m}$



Spherical shape suppresses the one point multipacting.



Two-point MP

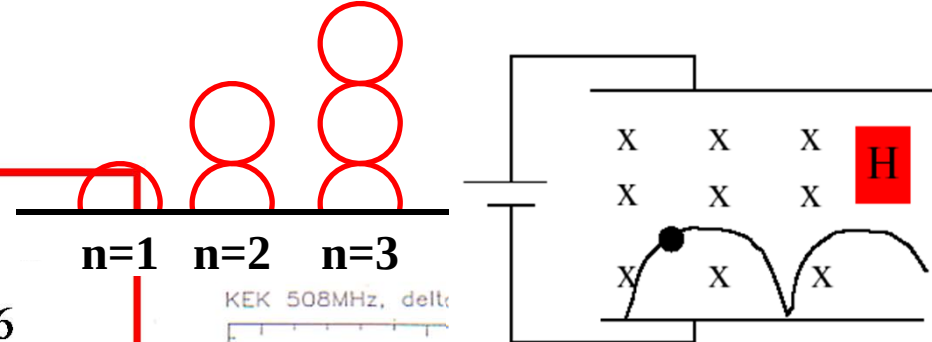
Two-point multipacting

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

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

Experiment : Onset field

$$\frac{H(2P - nth, [\text{Oe}])}{f_{RF} [\text{MHz}]} = \frac{0.6}{2n - 1}$$



Examples ;

508MHz , $H_p/E_{acc} = 40.6 [\text{Oe}/(\text{MV}/\text{m})]$

2P-1 order $H_p(2p-1) = 0.6 \times 508 = 304.8 \text{ Oe}$

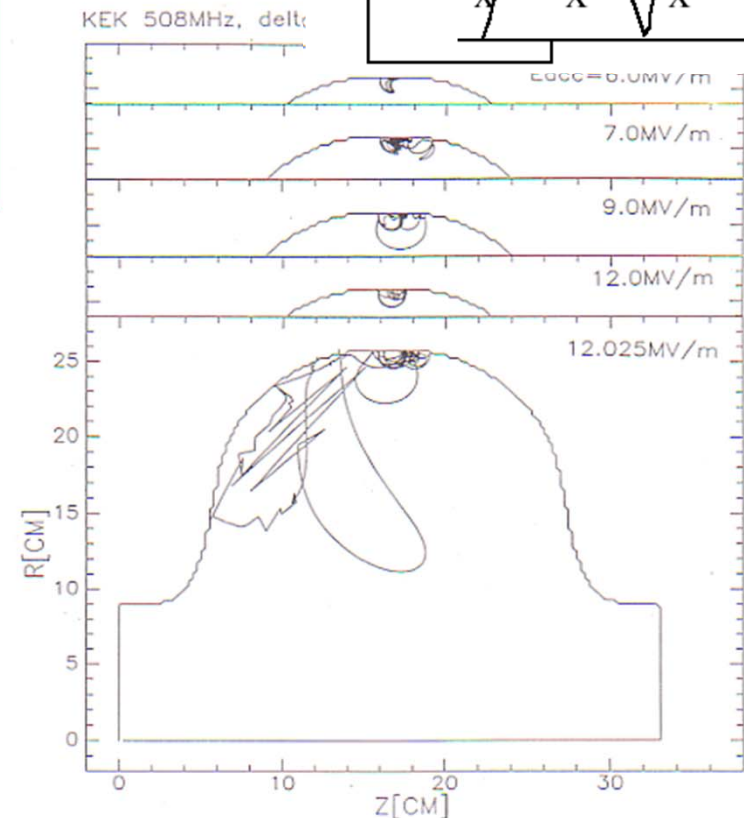
$E_{acc}(2P-1) = 304.8 / 40.6 = 7.5 \text{ MV}/\text{m}$

1300MHz, $H_p/E_{acc} = 43.8 [\text{Oe}/(\text{MV}/\text{m})]$

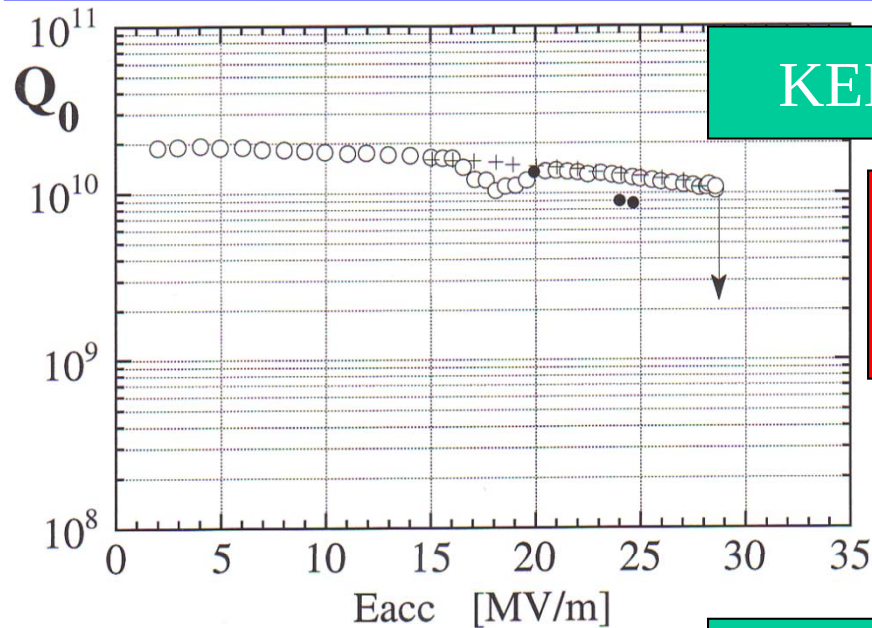
2P-1 order $H_p(2p-1) = 0.6 \times 1300 = 780 \text{ Oe}$

$E_{acc}(2P-1) = 780 / 43.8 = 17.8 \text{ MV}/\text{m}$

2P-2 order $E_{acc}(2P-2) = 17.8 / 3 = 5.9 \text{ MV}/\text{m}$



T-mapping of Tow-point MP

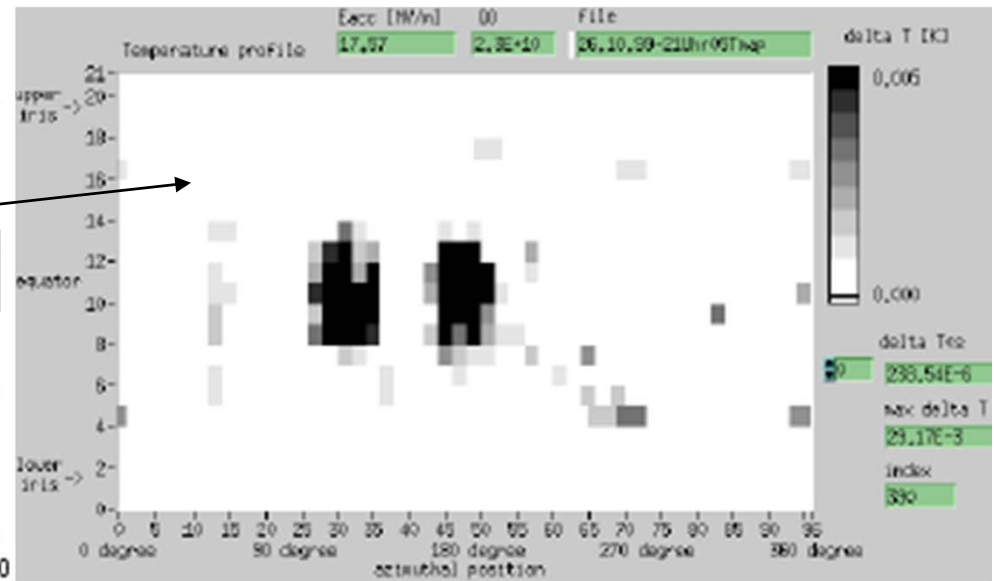
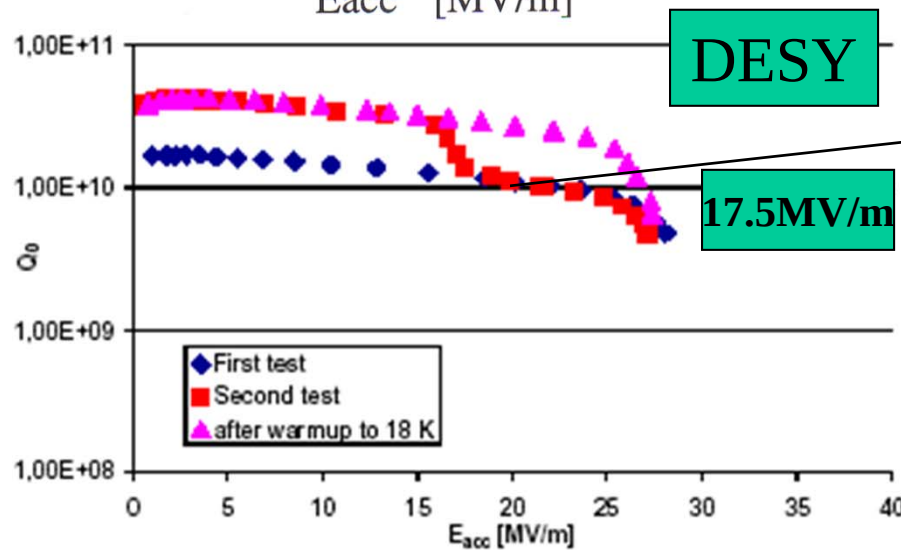


MP → Frozen flux trapping → Warm-up $T > T_c$

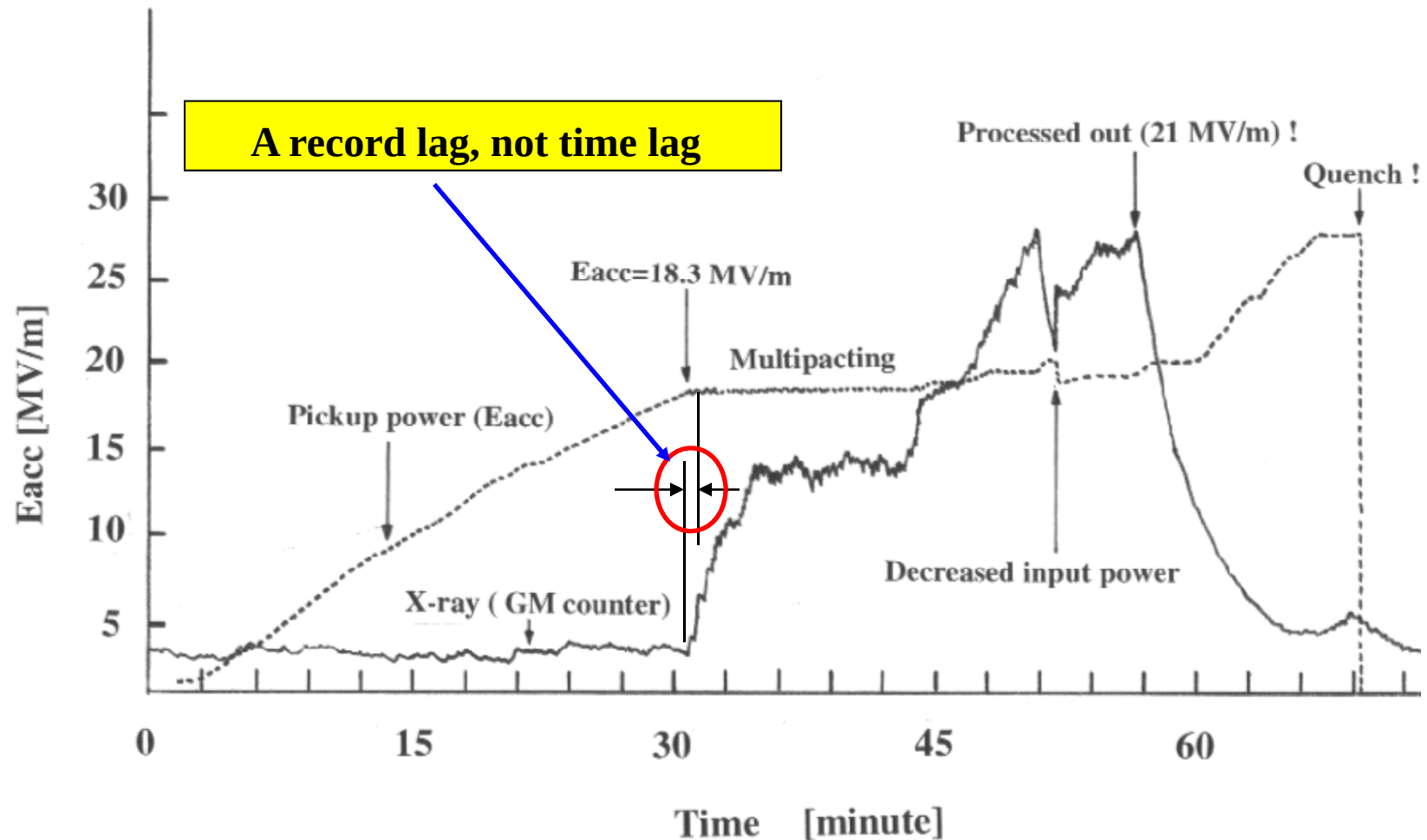
↓

Disappear of the heating spots

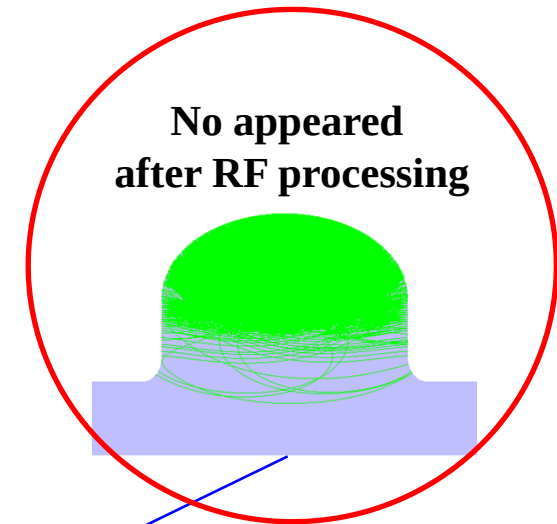
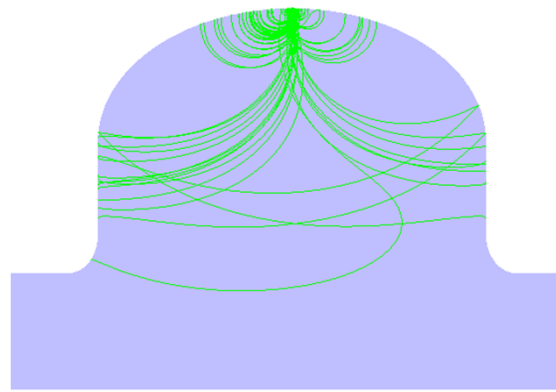
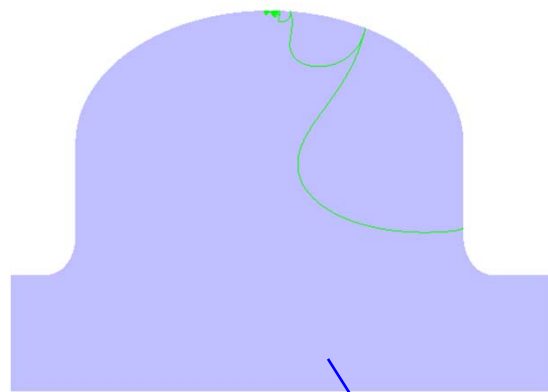
T-mapping at 17.5 MV/m



Processing of Two-point MP

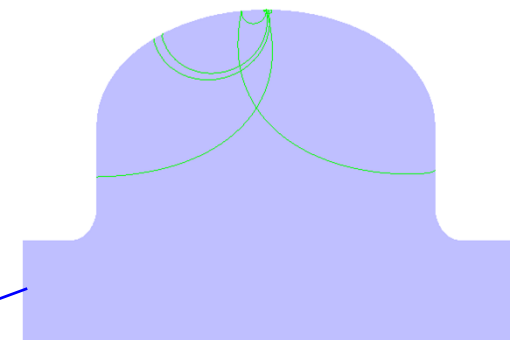
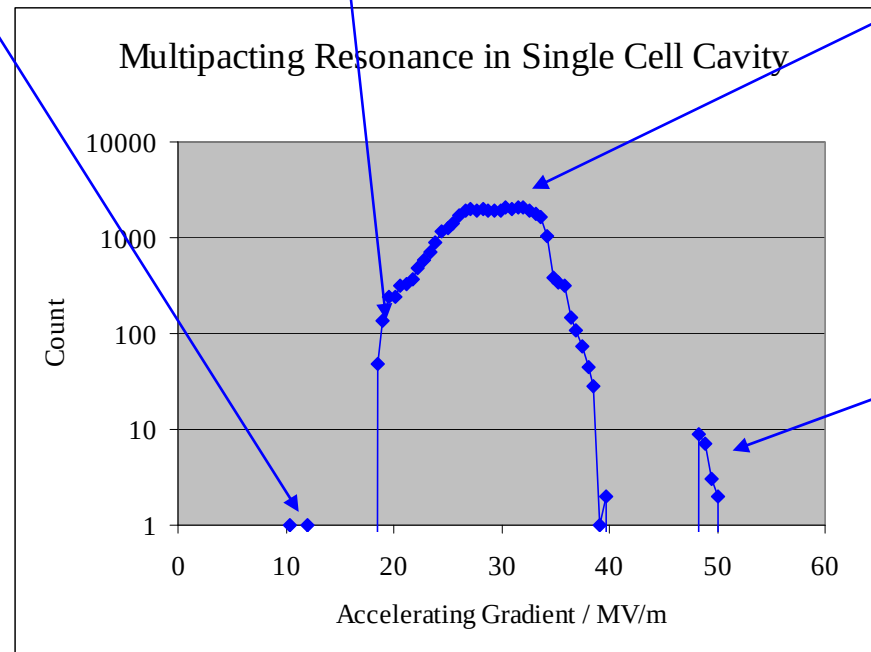


Multipacting in Ichiro Regular center Cell



by Morozumi

Be careful for
the multipacting



Simulation of KEK Cavity by INFN Genova

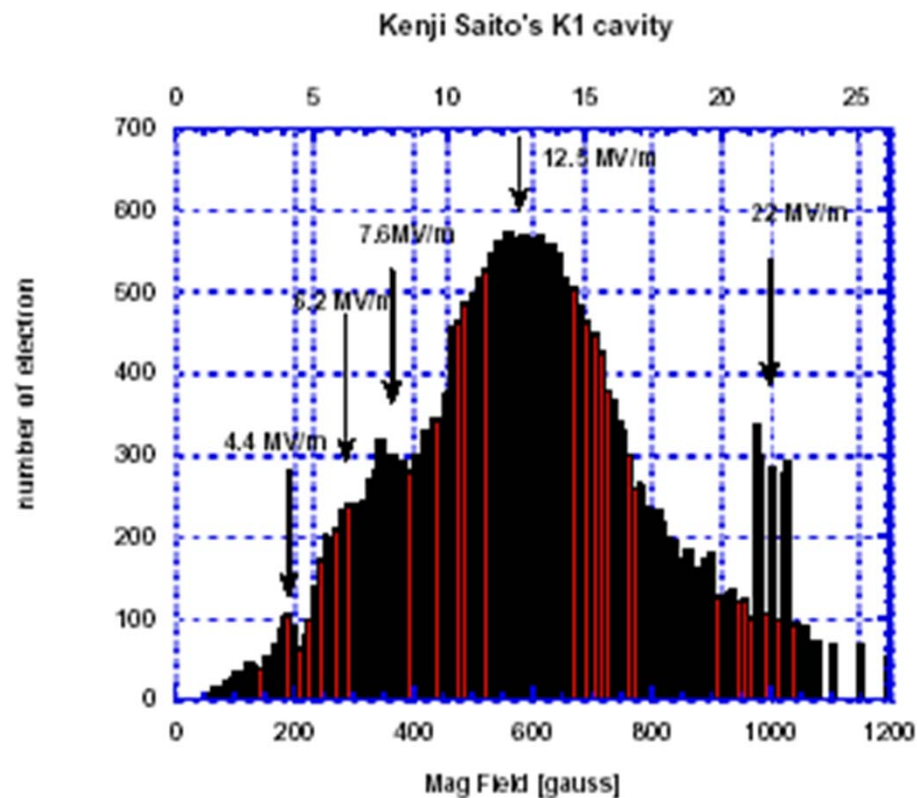


Figure 5 Surviving electrons versus RF Fields. ,

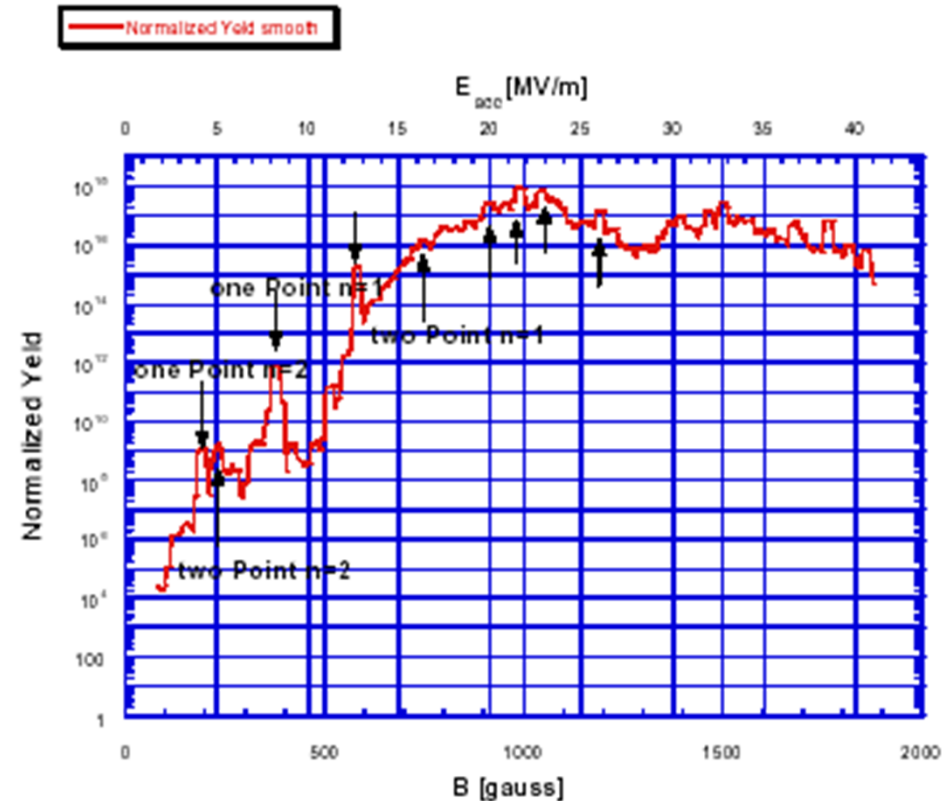
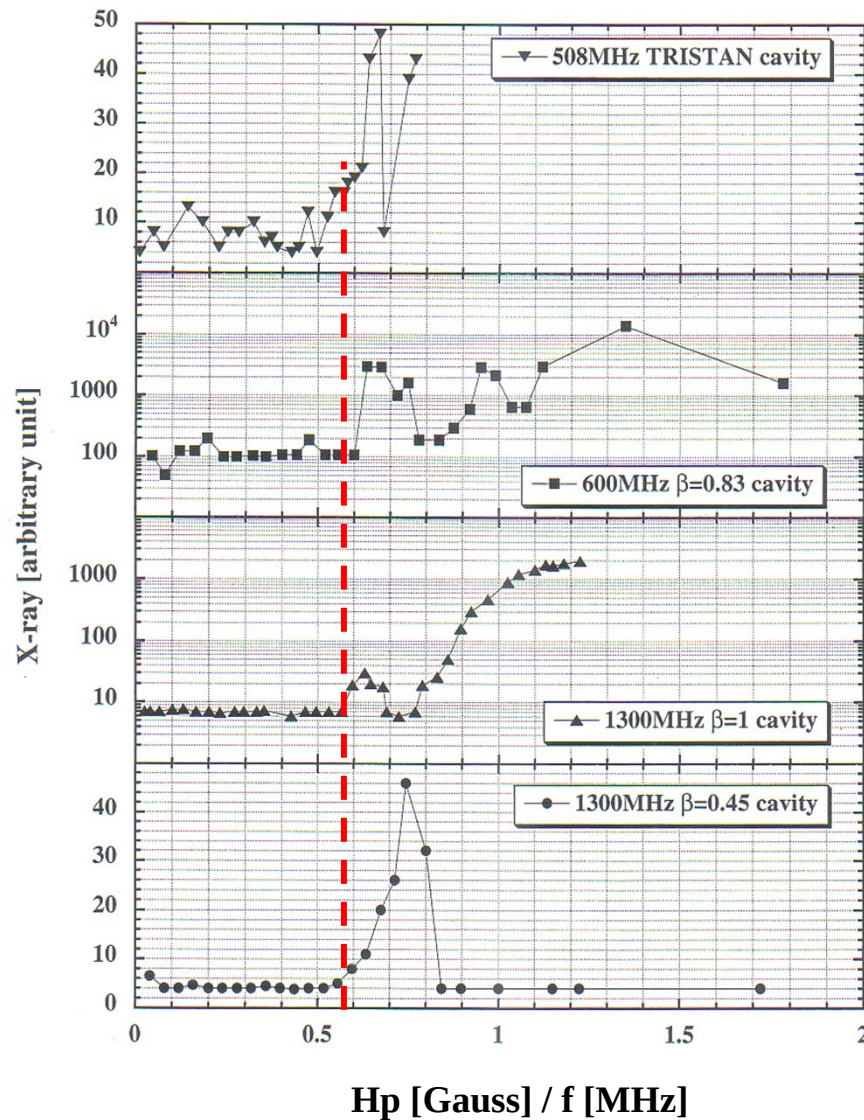


Figure 6 Mean Yield versus field for electron trajectories in the K1 cavity

Onset Field of Two-point MP



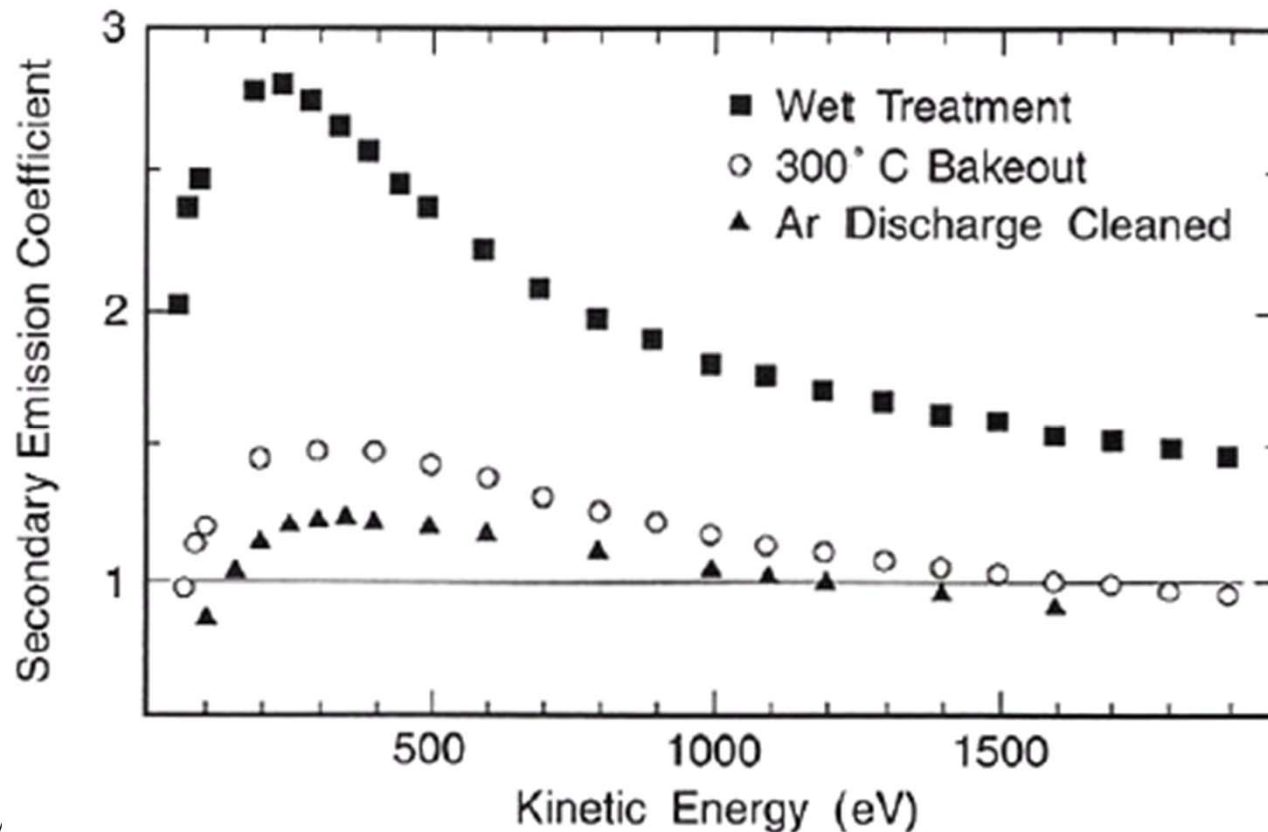
$$2P - onset = \frac{H_p [\text{Gauss}]}{f [\text{MHz}]} \approx \frac{0.6}{2n - 1}$$

Multipactingは
RF processingのmemory effectを持つ。

200K程度までWarm-upすると
memoryが消え、再びRF processingが
必要となる。

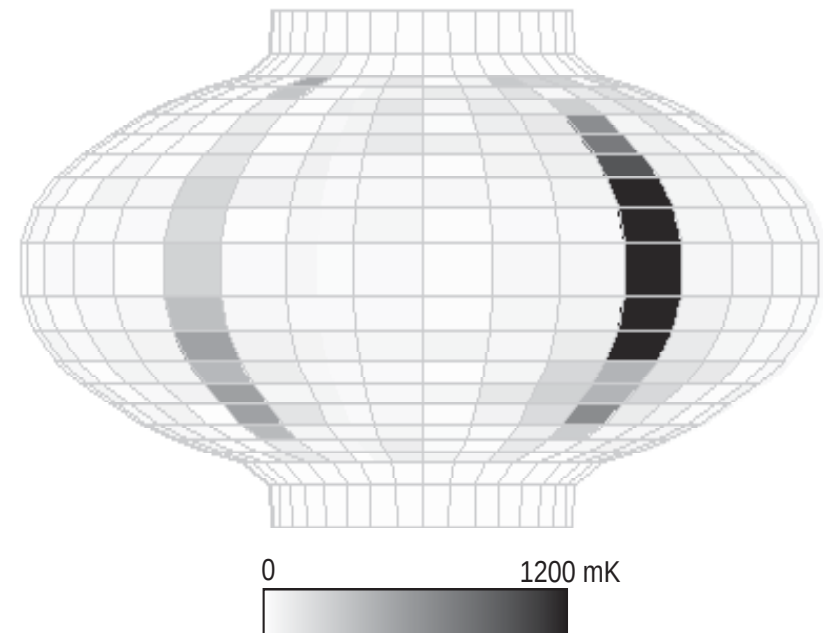
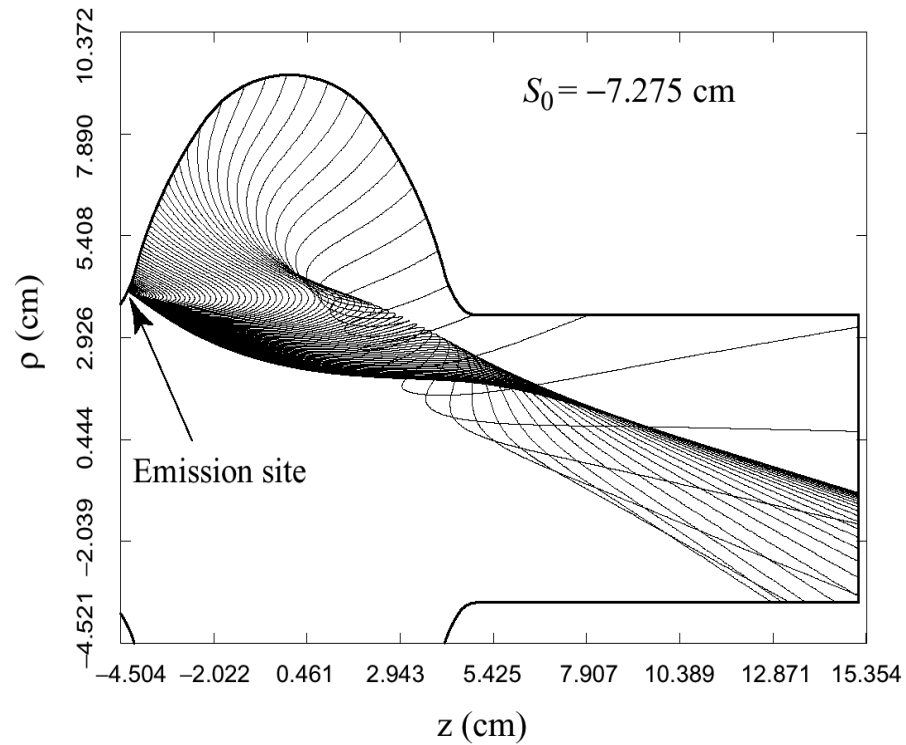
Cures against MP

- 1) Cavity shape $\longrightarrow$ Spherical or Elliptical shape
(effective for one point multipacting)
- 2) $\delta < 1$: Clean surface $\longrightarrow$ Surface preparation
High pressure water rinsing
Argon gas or Helium gas discharge cleaning

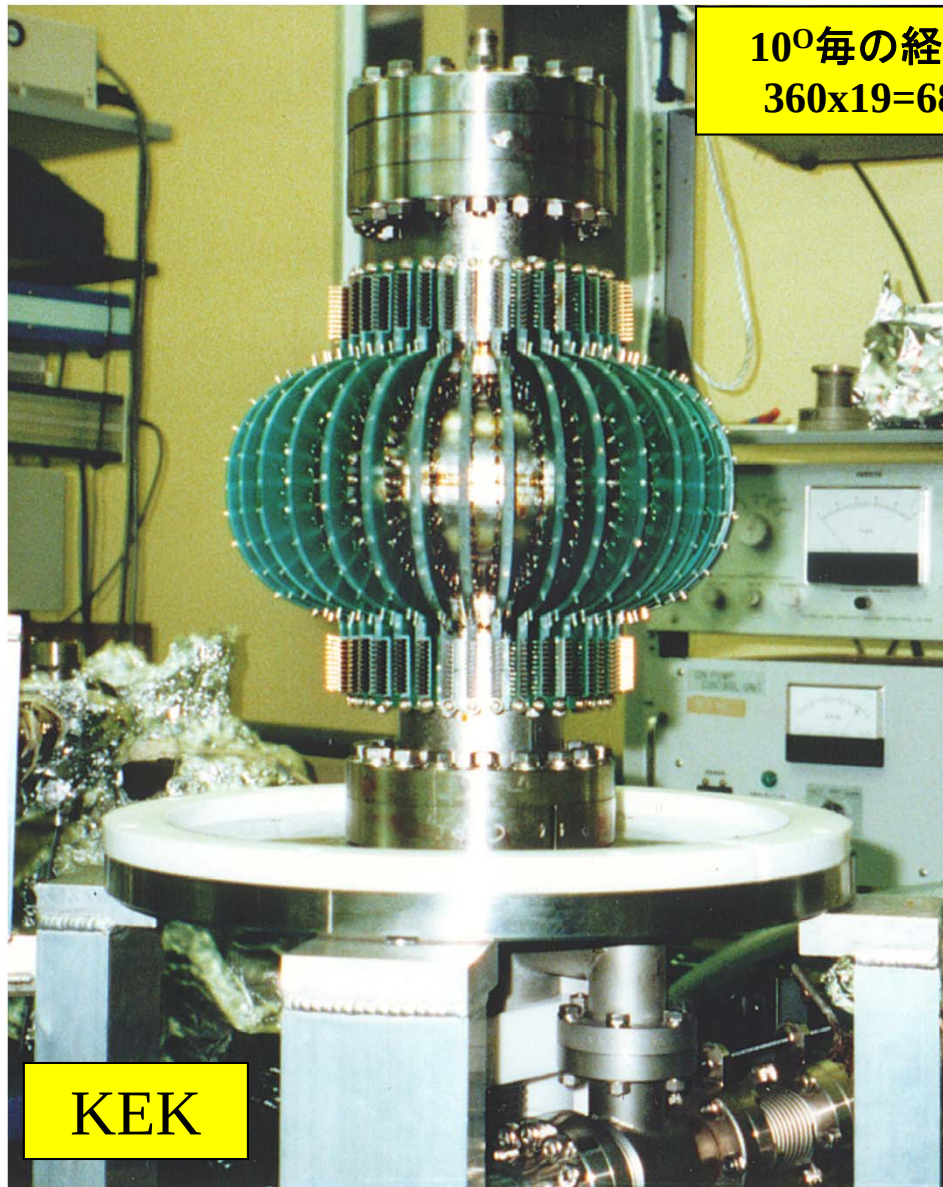


7.2 Field Emission

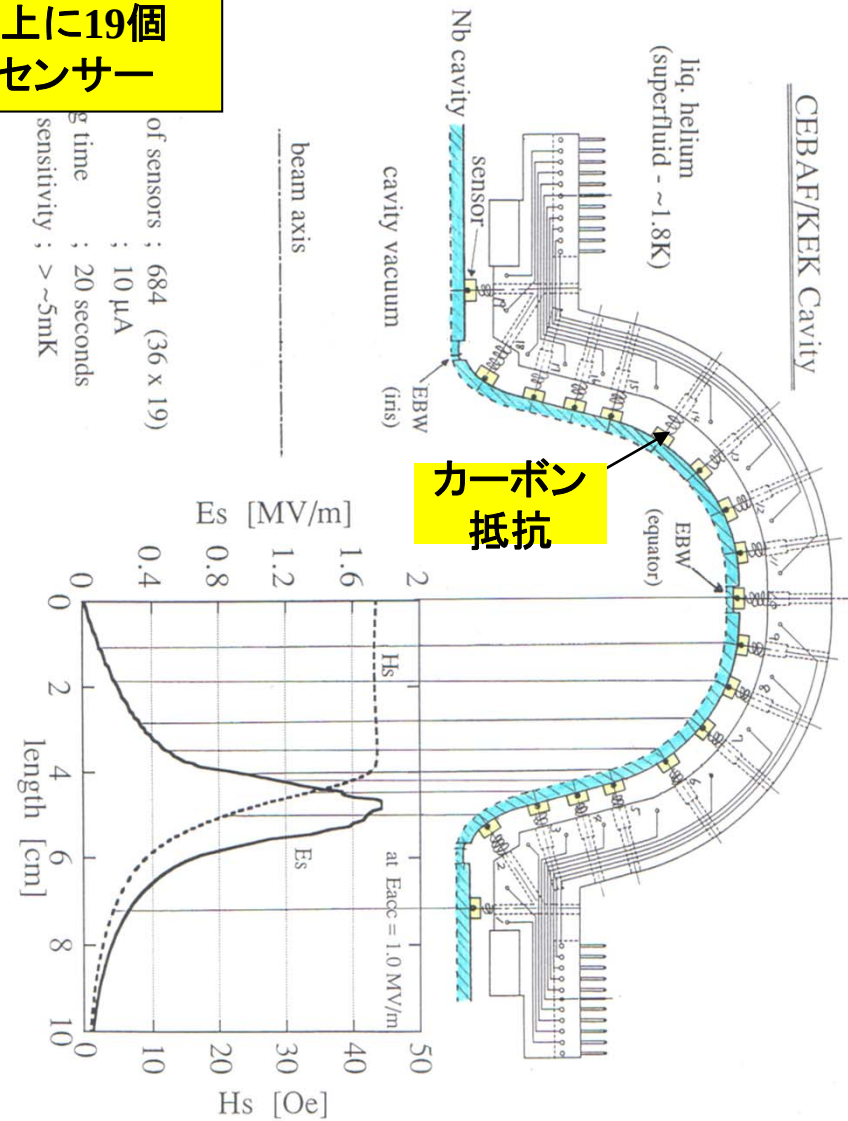
Non-resonant electron loading due to field emitted electrons by tunneling effect



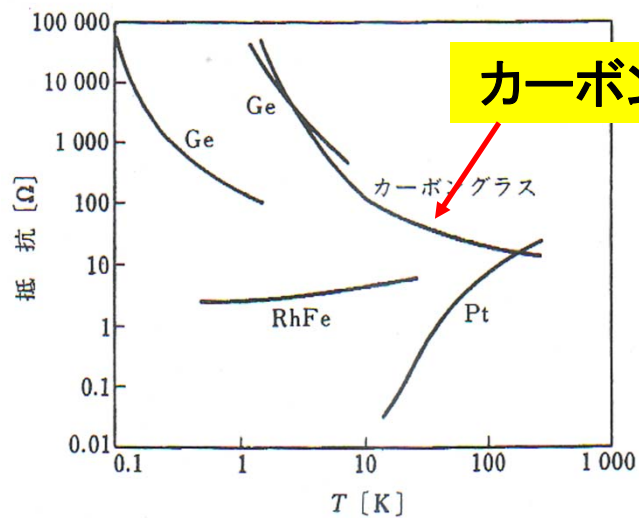
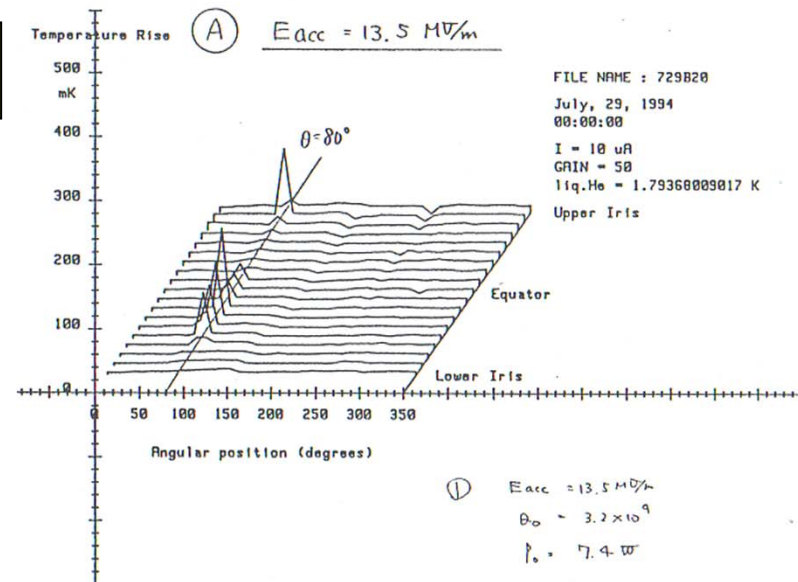
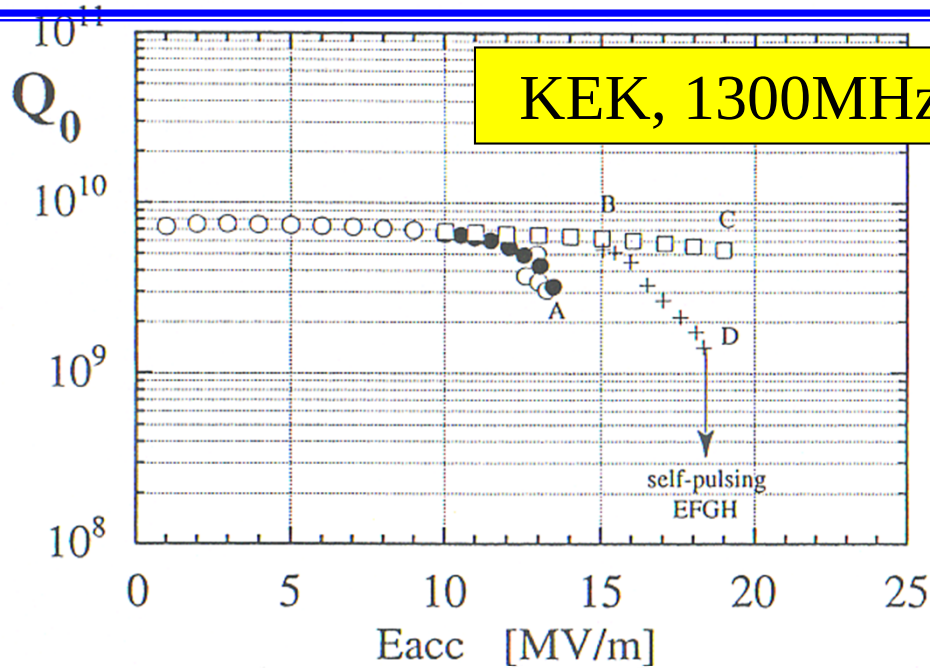
T-mapping Sensor



10°毎の経度上に19個
360x19=684センサー

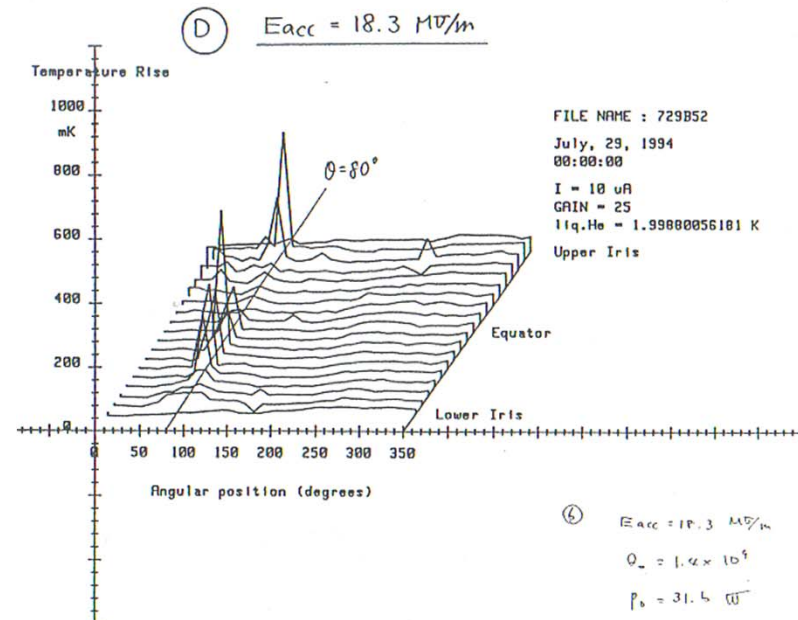


T-mapping KEK

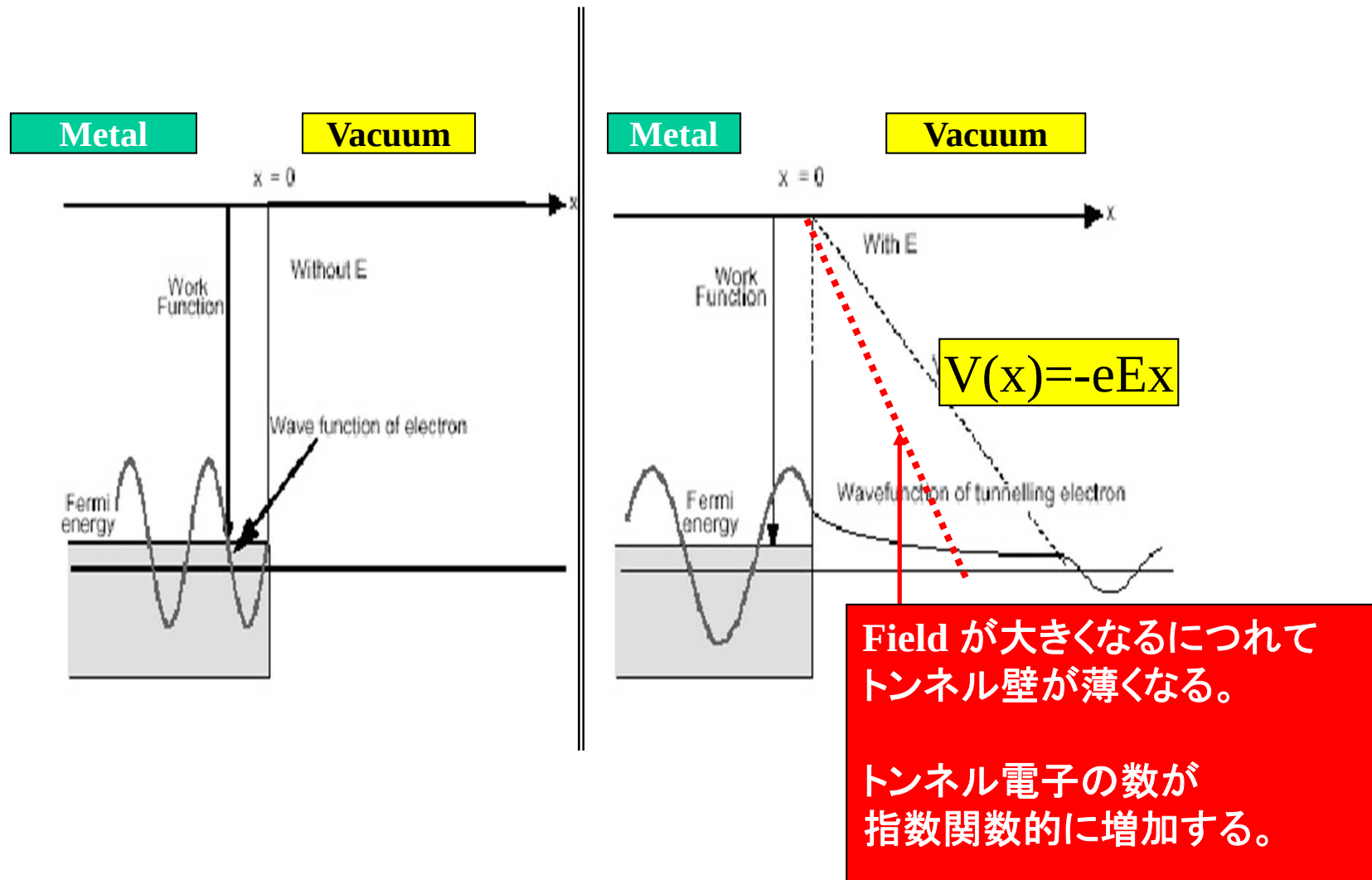


カーボンは半導体

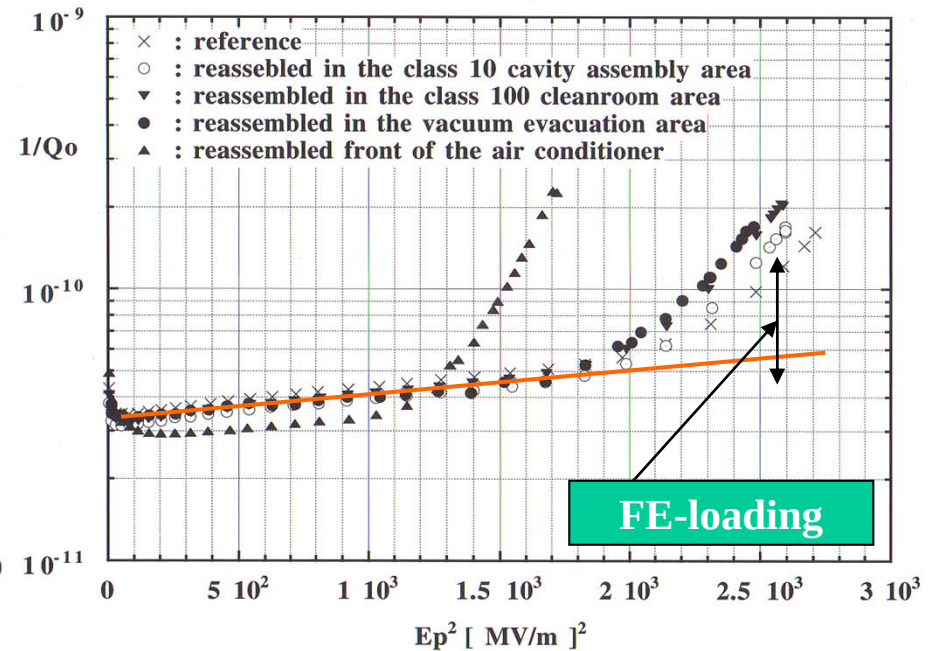
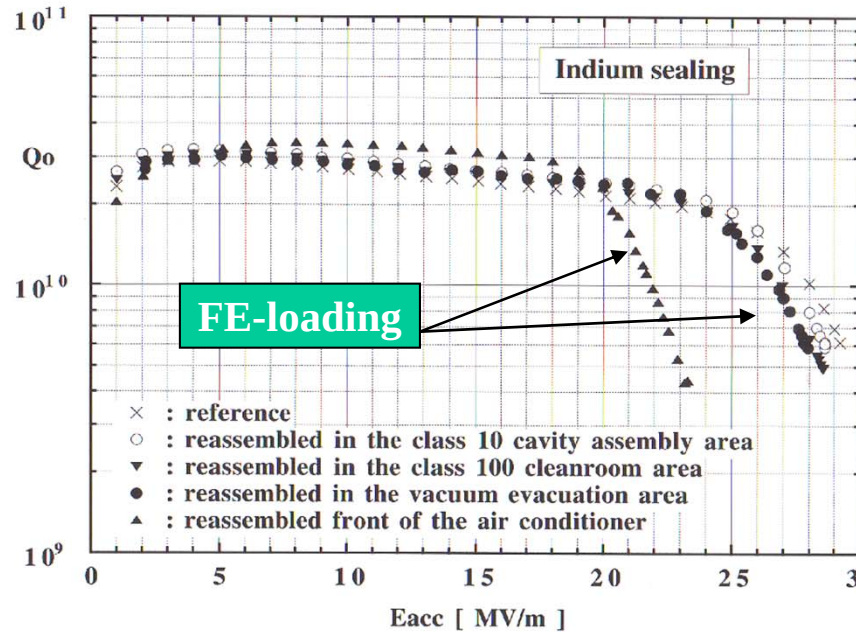
図 8-2 温度センサーの抵抗-温度特性^[1]



Mechanism of Field Emission



Field Emission Analysis



$$\frac{1}{Q_0} = A + B \cdot E_p [MV/m]^2, \Delta\left(\frac{1}{Q_0}\right) = \frac{1}{Q_0(E_p^2)} - (A + B \cdot E_p [MV/m]^2)$$

$$\Delta\left(\frac{1}{Q_0}\right) = S \cdot E_p^{1.5} \cdot \exp\left(-\frac{\phi}{\beta \cdot E_p}\right) = S \cdot E_p [MV/m]^{1.5} \cdot \exp\left(-\frac{5.46E + 4}{\beta \cdot E_p [MV/m]}\right)$$

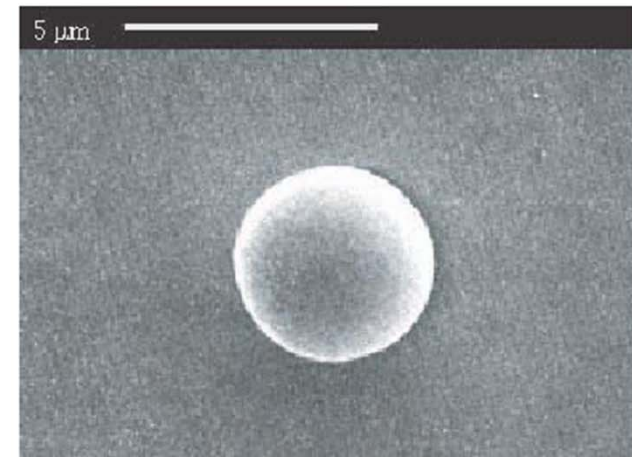
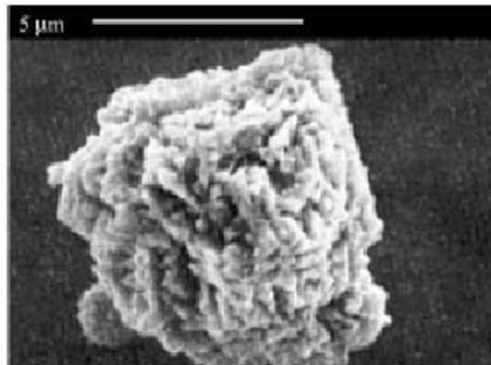
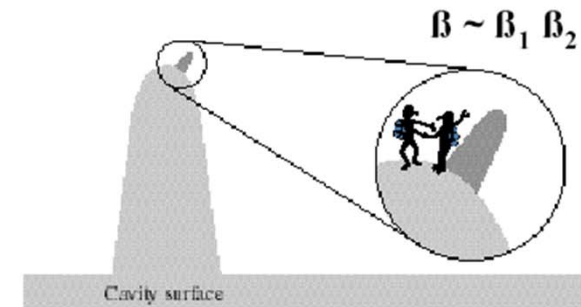
Field Enhancement Factor β

Field enhancement factor β ; 50 ~ 1000

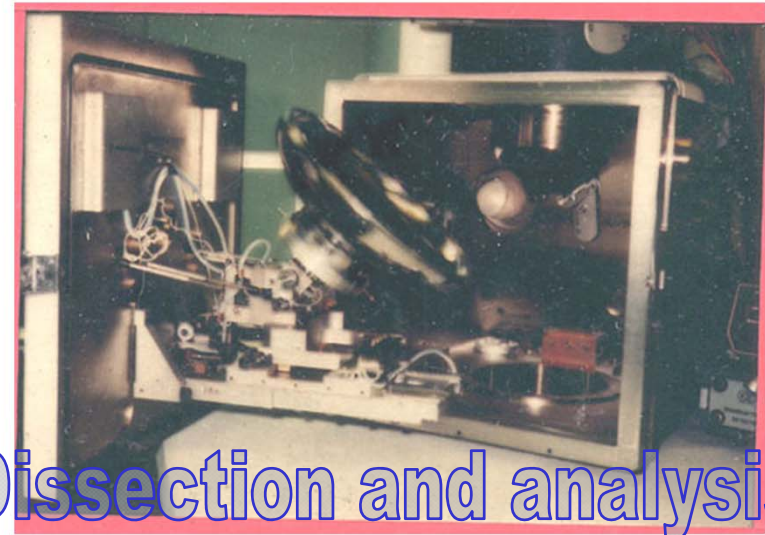
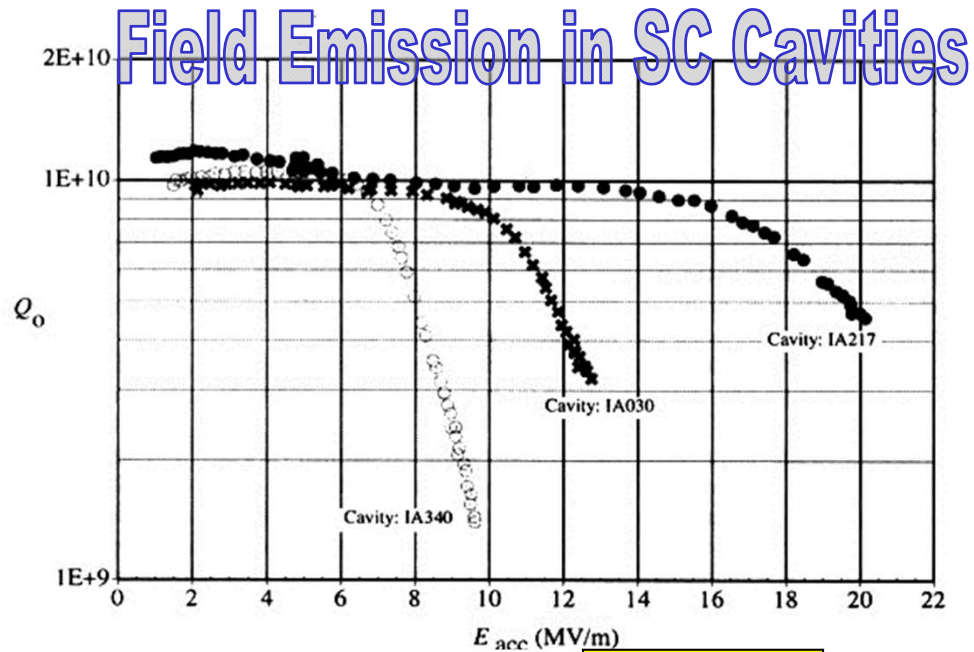
Projection model :

何故、 β がそんなに
大きいのか？

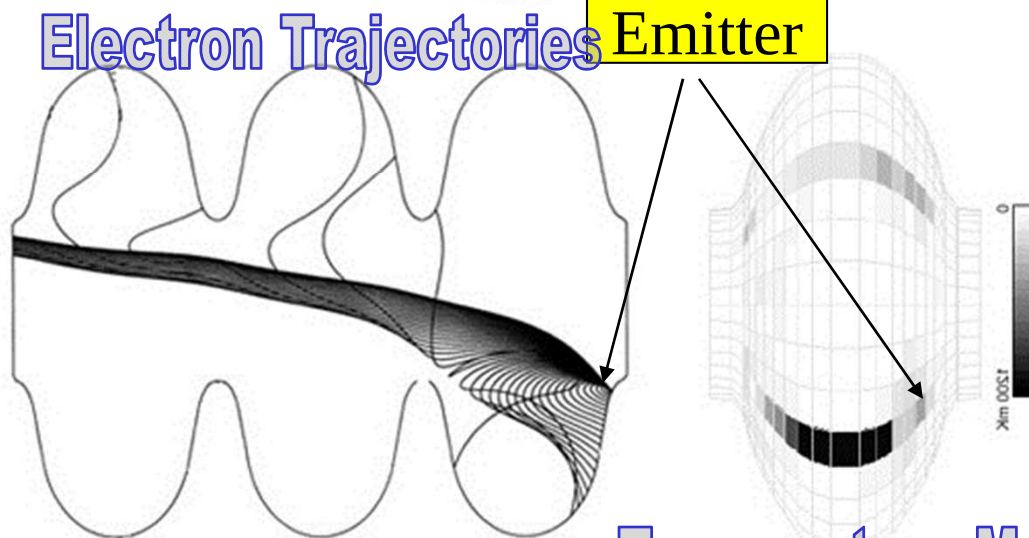
- *Tip-on-tip* model is one explanation
- Smooth particles don't emit.



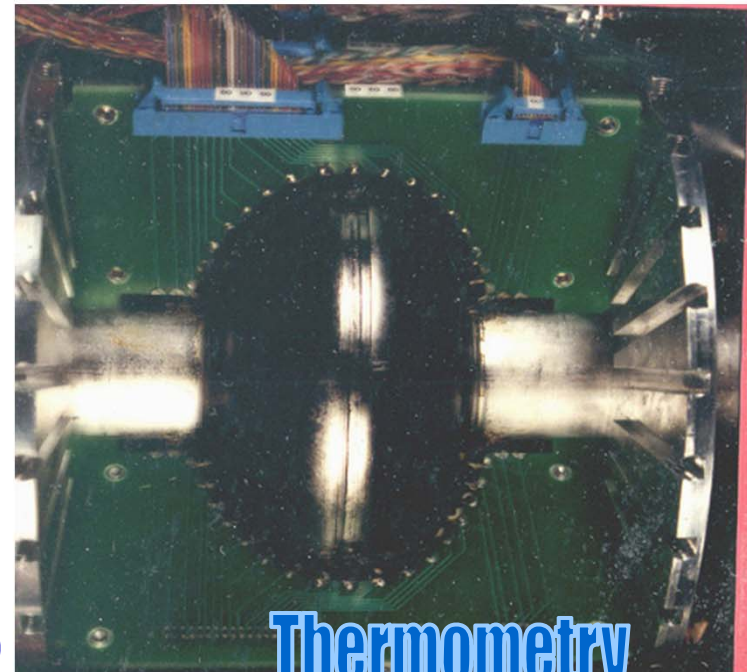
Cornell Study on FE



Dissection and analysis

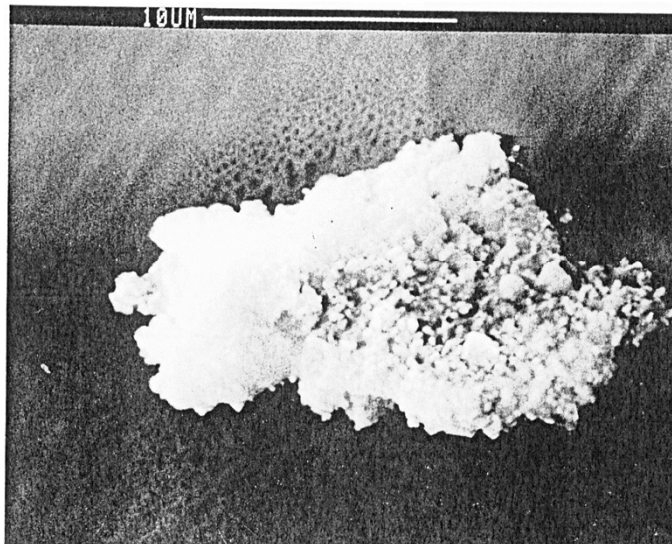


Temperature Map



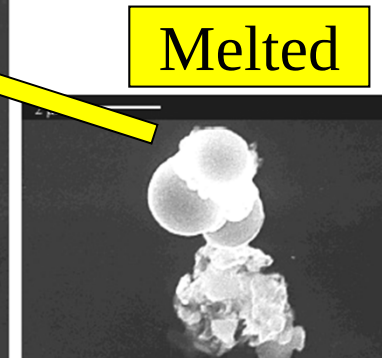
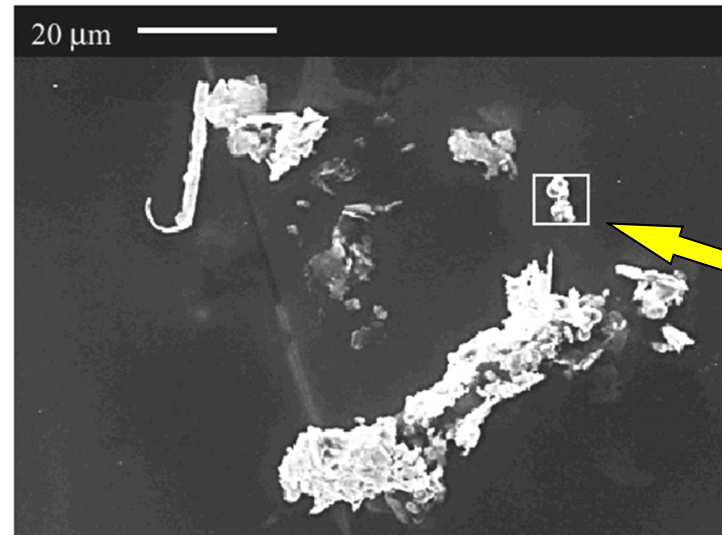
Thermometry

Emitter of FE : Particles



CORNELL
UNIVERSITY

Melted



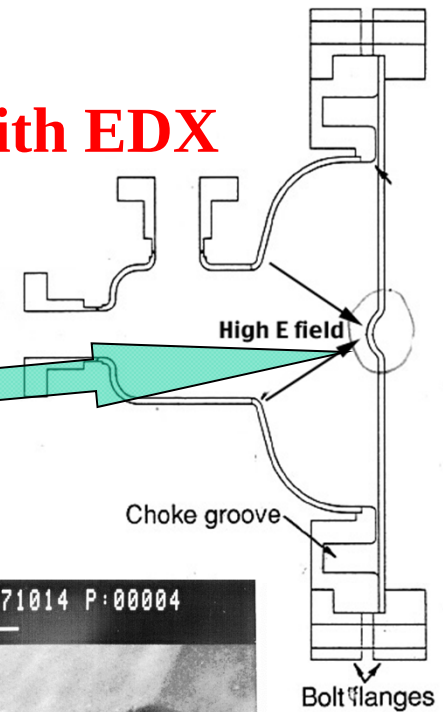
Melted

Emitters Found
in Niobium SC Cavities
Particles - often melted

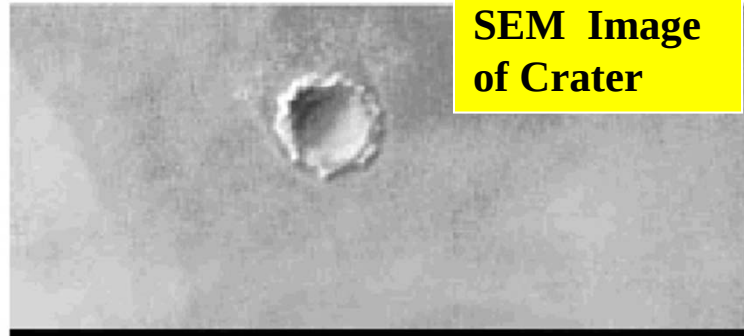
Intentionally Introduced Particles



After RF
No silicon found with EDX

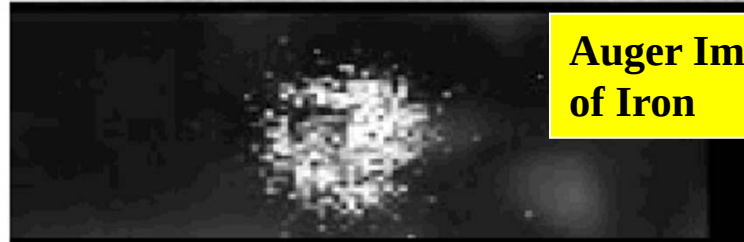


Crater shows Foreign Elements



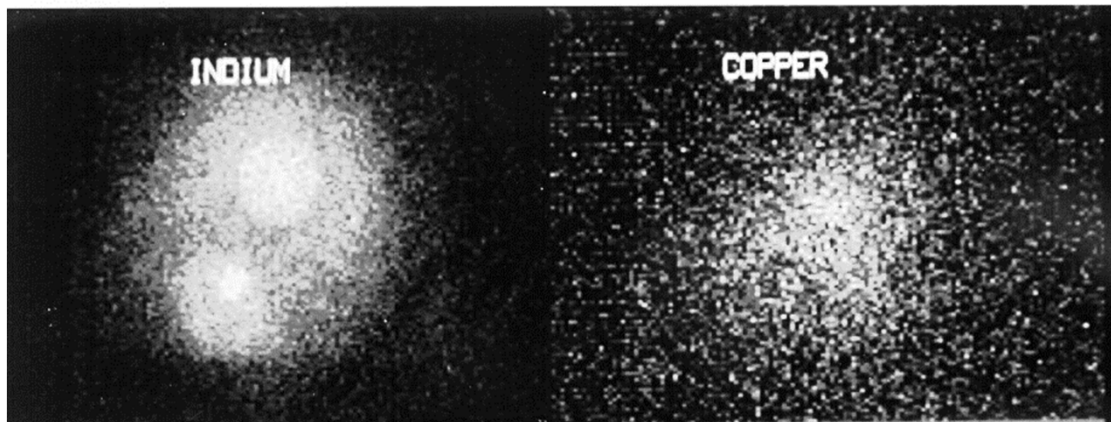
SEM Image
of Crater

Nothing with EDX



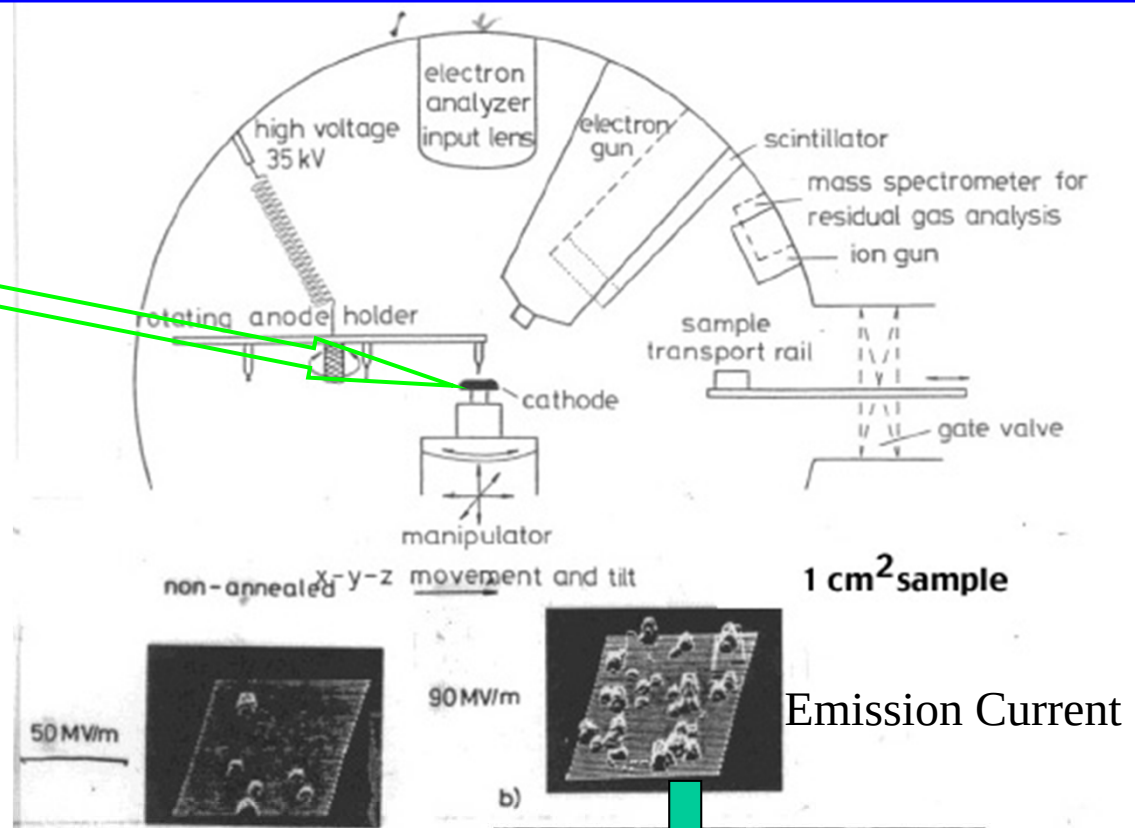
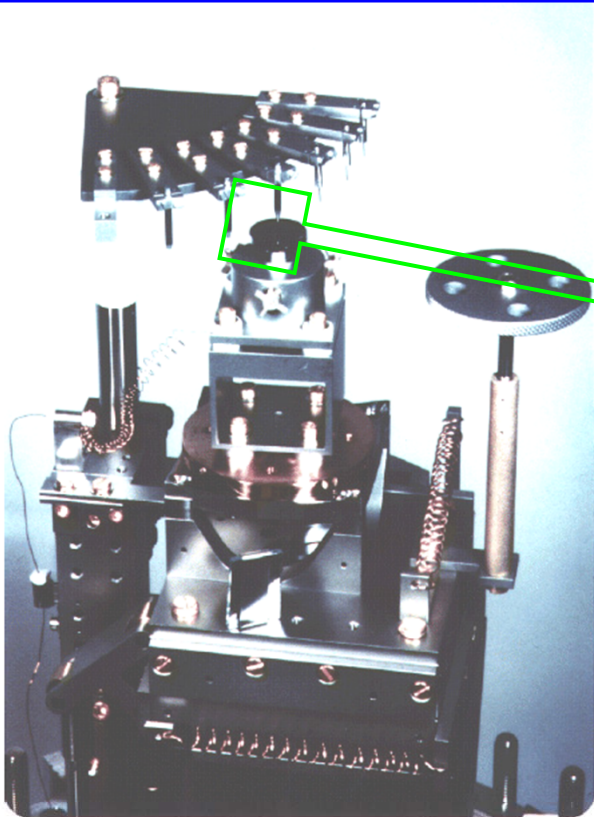
Auger Image
of Iron

But - With Auger Analysis
Almost all craters show foreign material



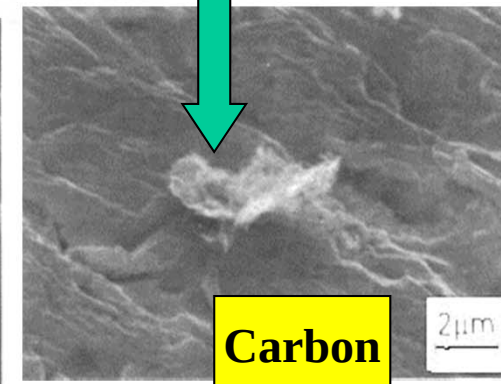
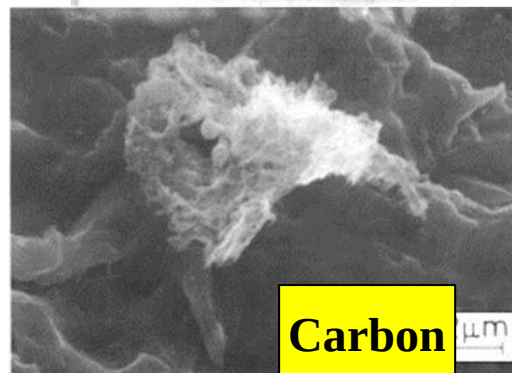
Auger Images
of Craters

DC Field Emission Study in U.Geneva and Wuppertal

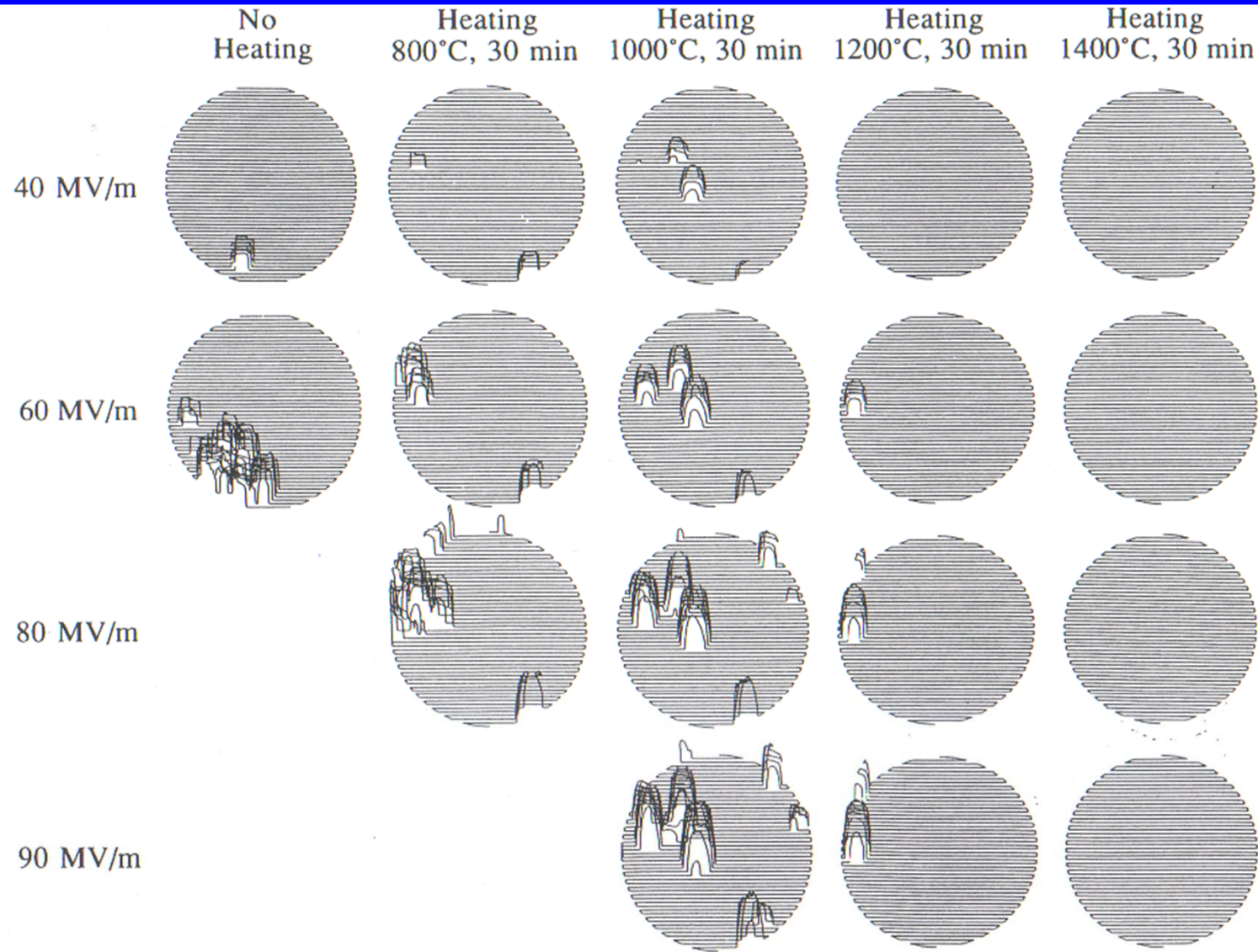


1 cm² sample

Emission Current

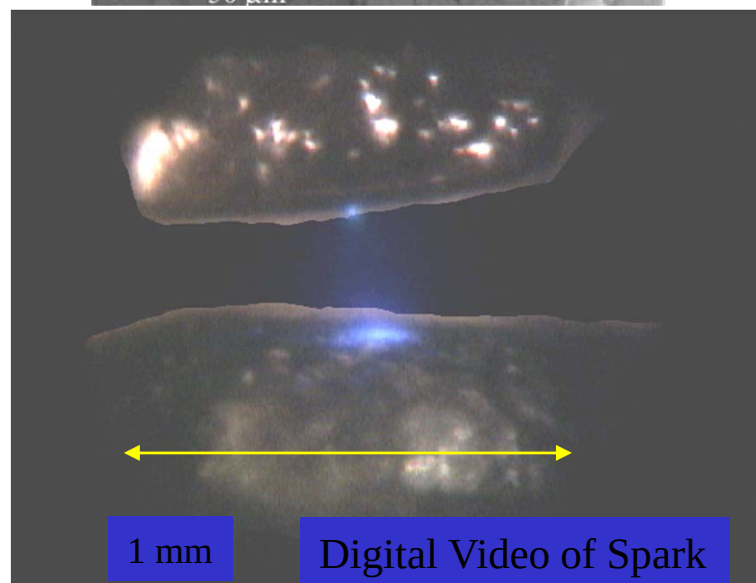
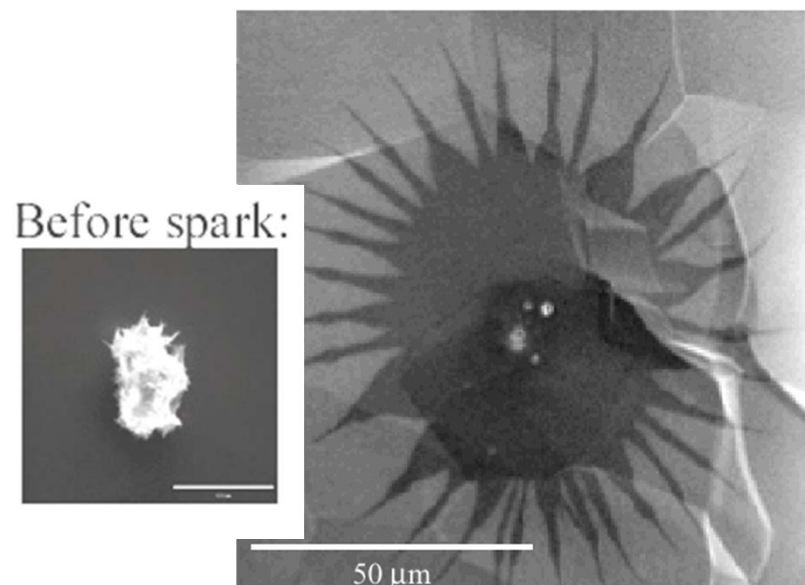


Wuppertal Result



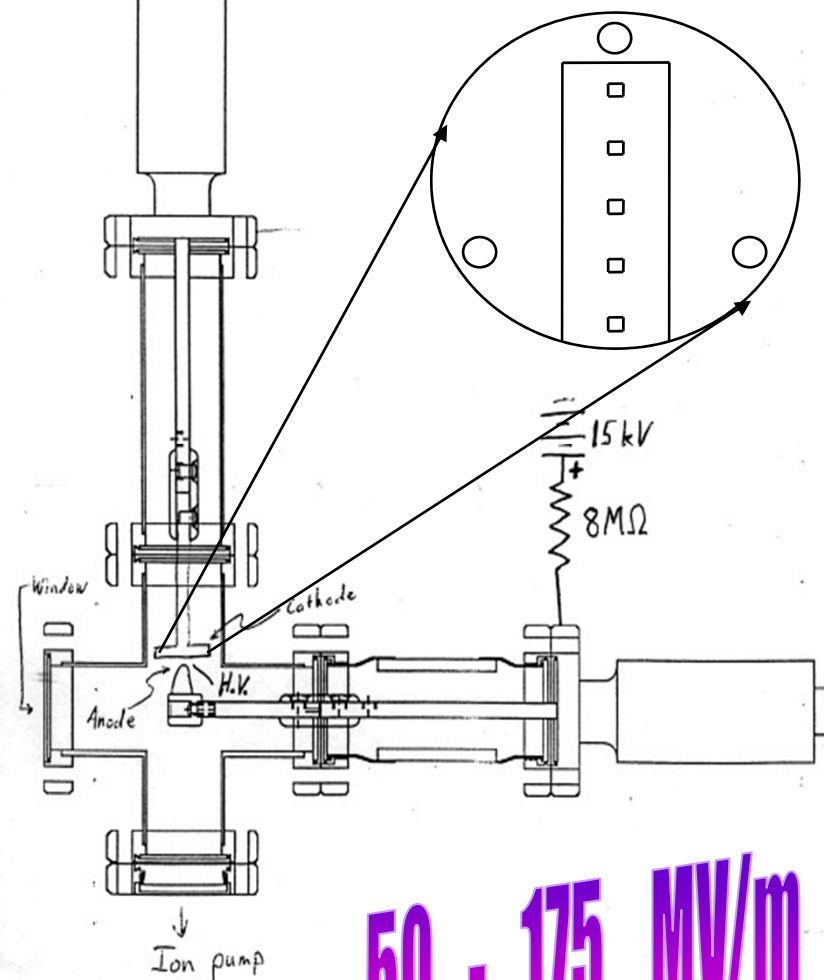
**High Temp. Annealing is very effective to eliminate FE seeds.
DESYが1400°C annealingを採用している一つの理由。**

DC Field Emission Study in Cornell



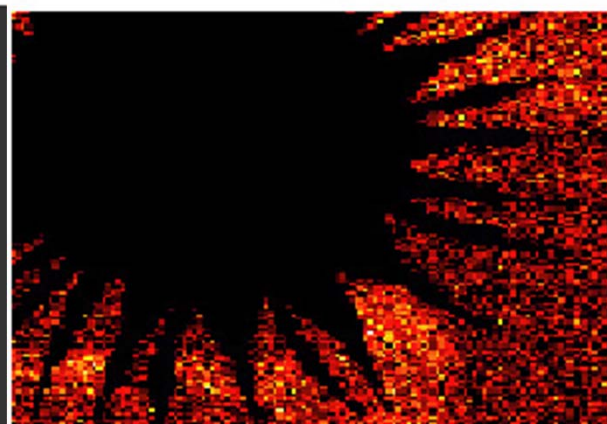
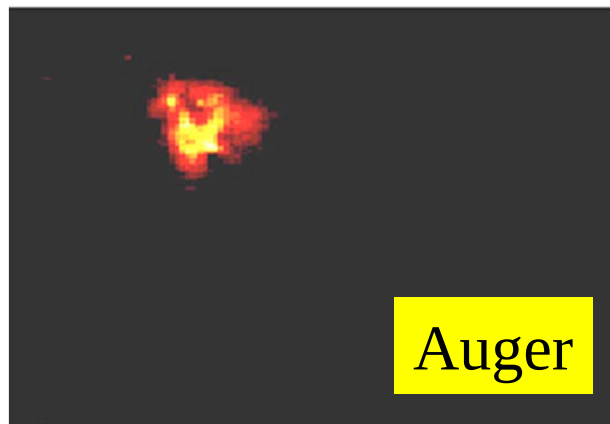
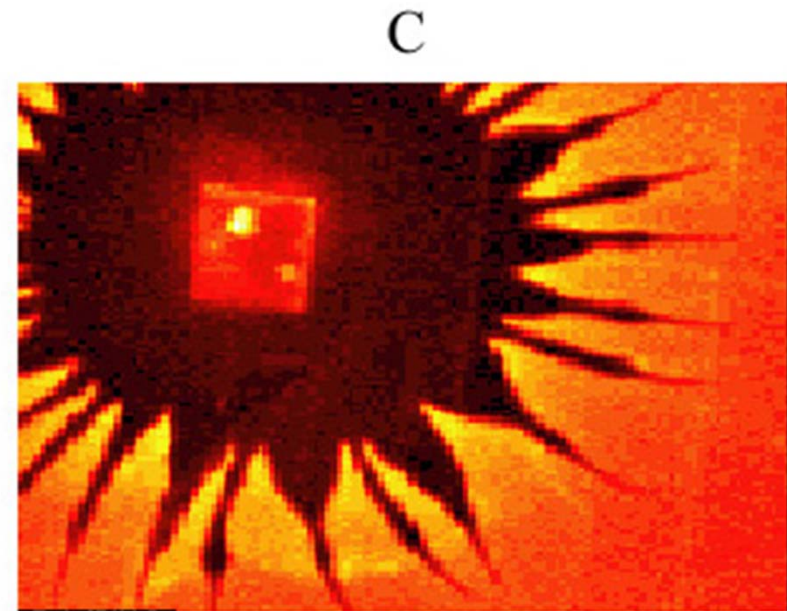
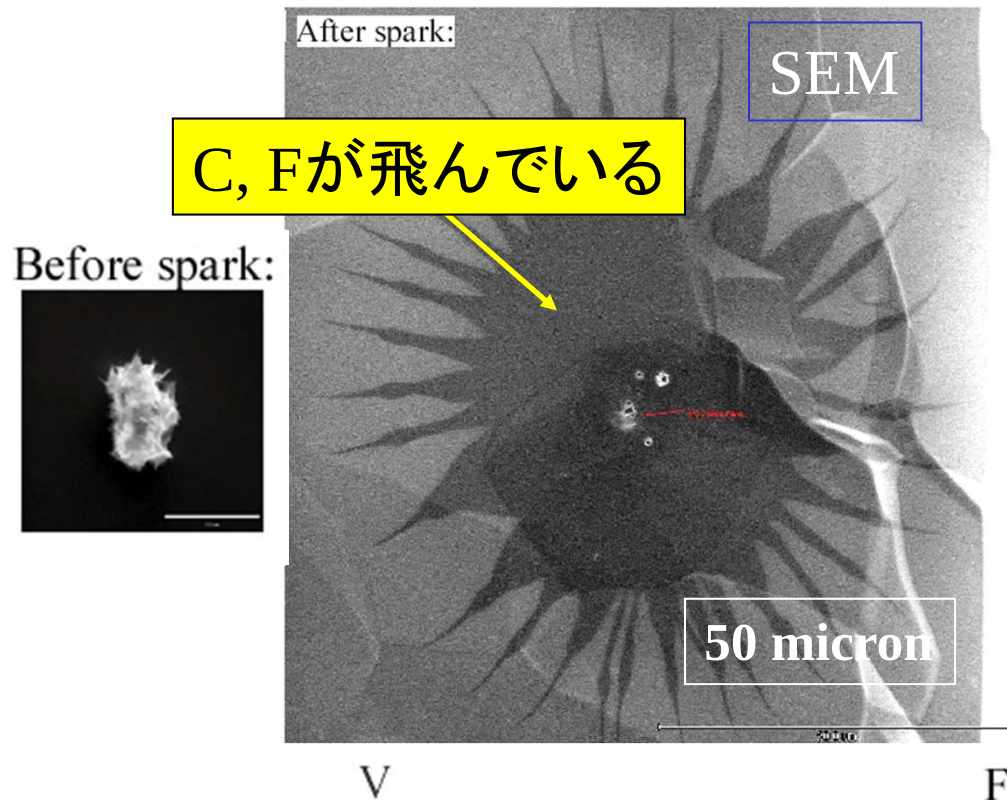
Nb

DC Field Emission



50 - 175 MV/m

Intentionally Introduced Vanadium Particles on Nb

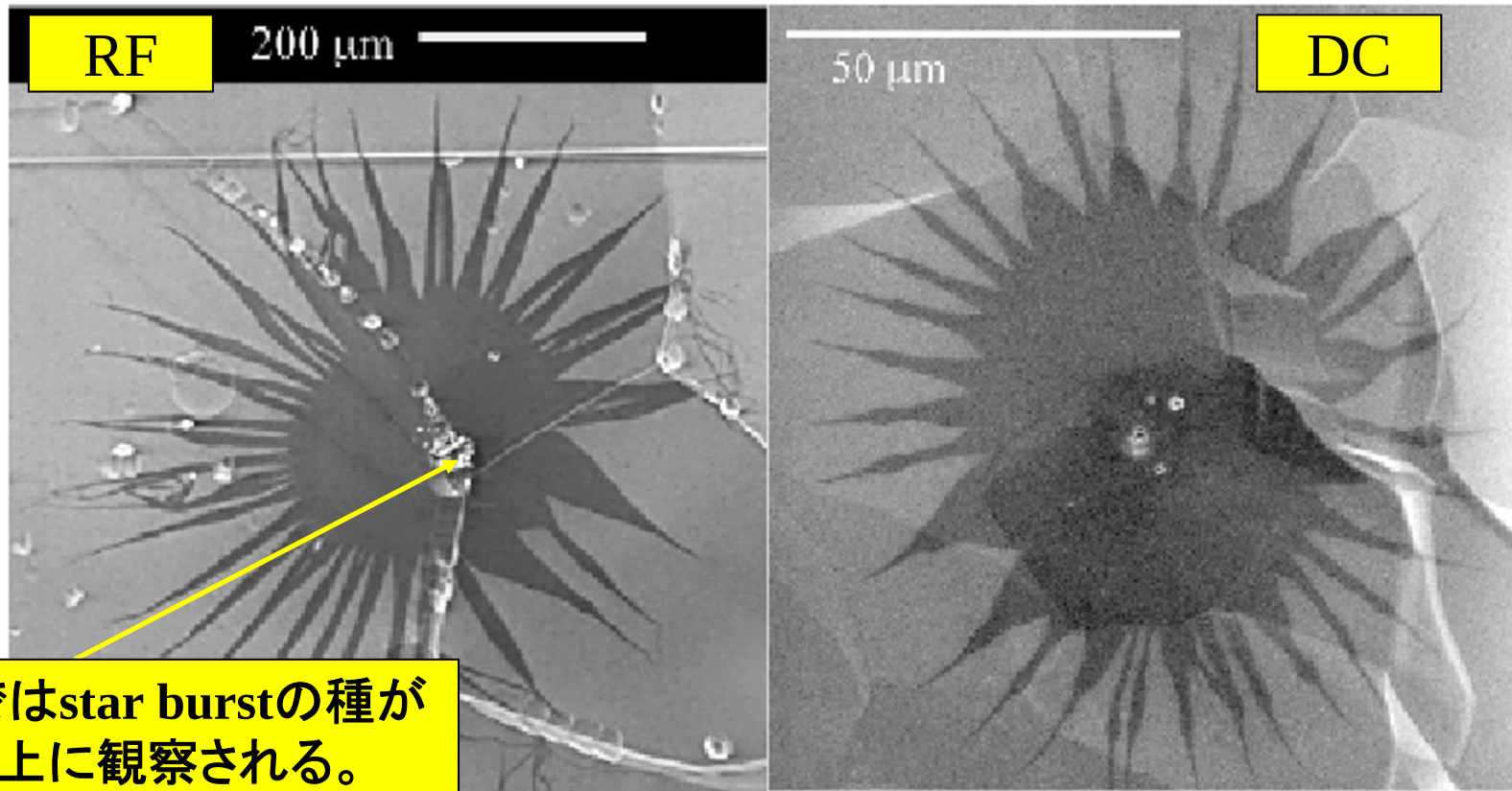


What removes C and F?

Ion bombardment

There must be gas present during the arc

Difference in RF and DC



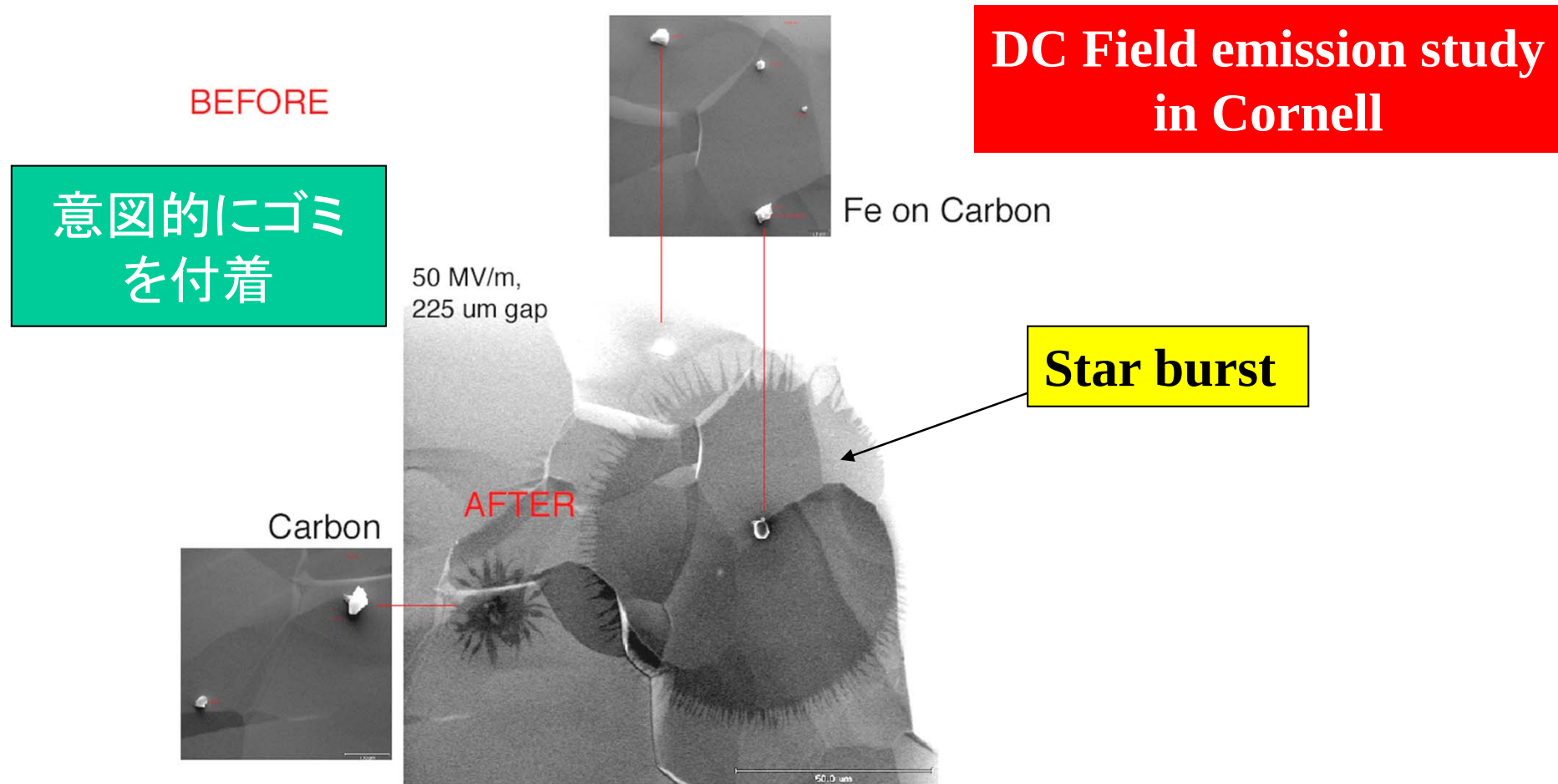
RFではstar burstの種が
粒界上に観察される。

Starburst in a 1.5GHz Nb cavity

Starburst on a DC cathode (Nb)

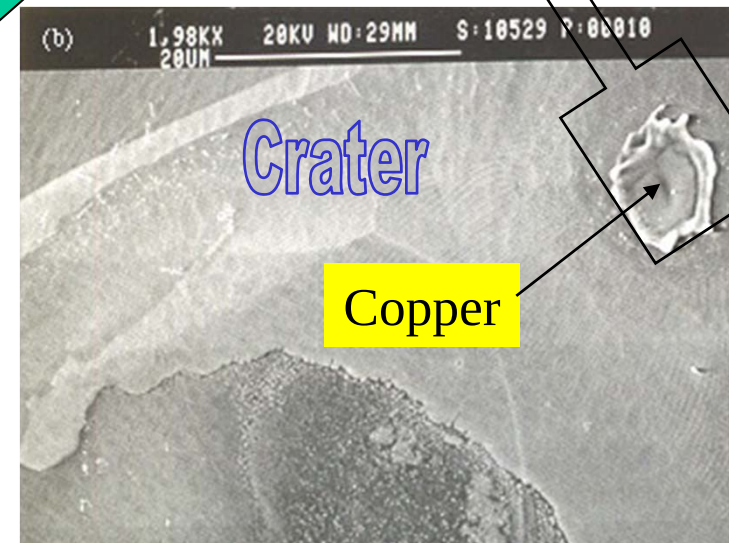
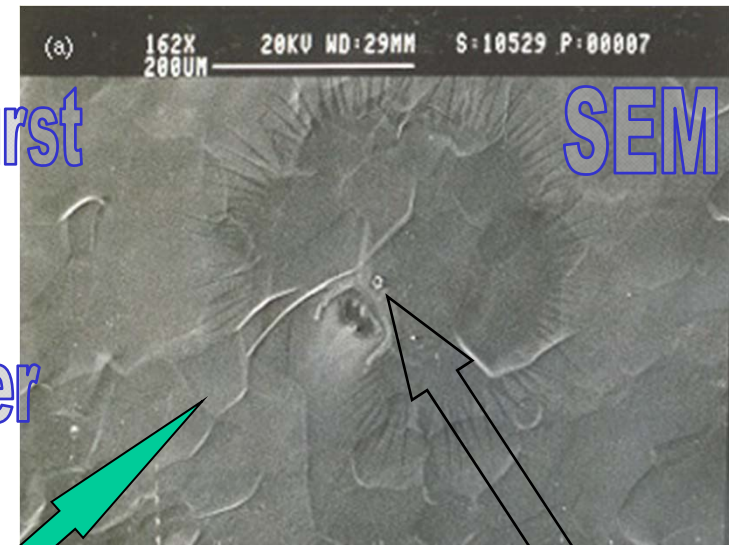
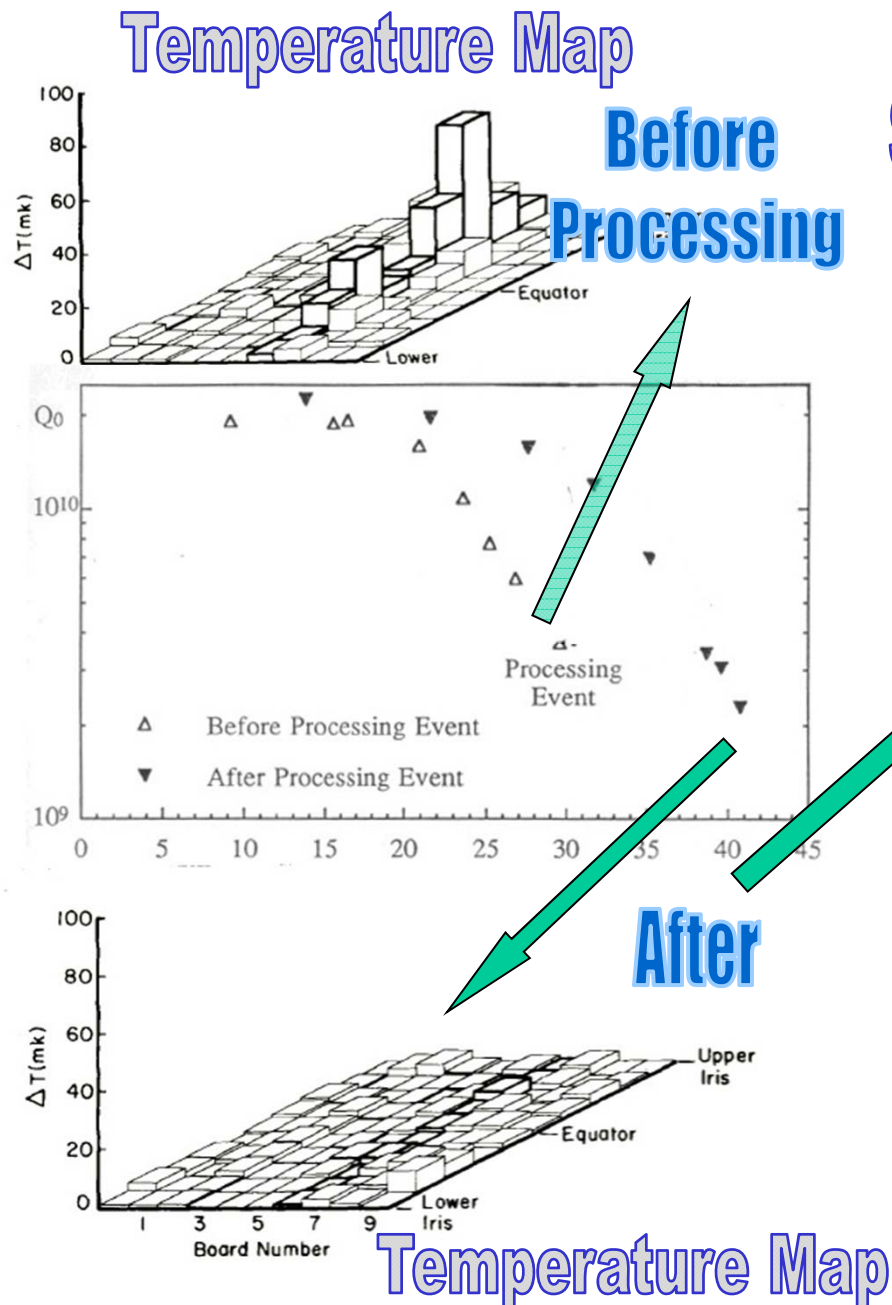
RF は electric and magnetic fieldの両効果を見るが、
DC は主として electric effectを見る。例えば、Grain boundaryでの現象は、
magneticつまり表面電流による効果であり、DCでは研究しづらい。

Particulate Contamination produces field emission

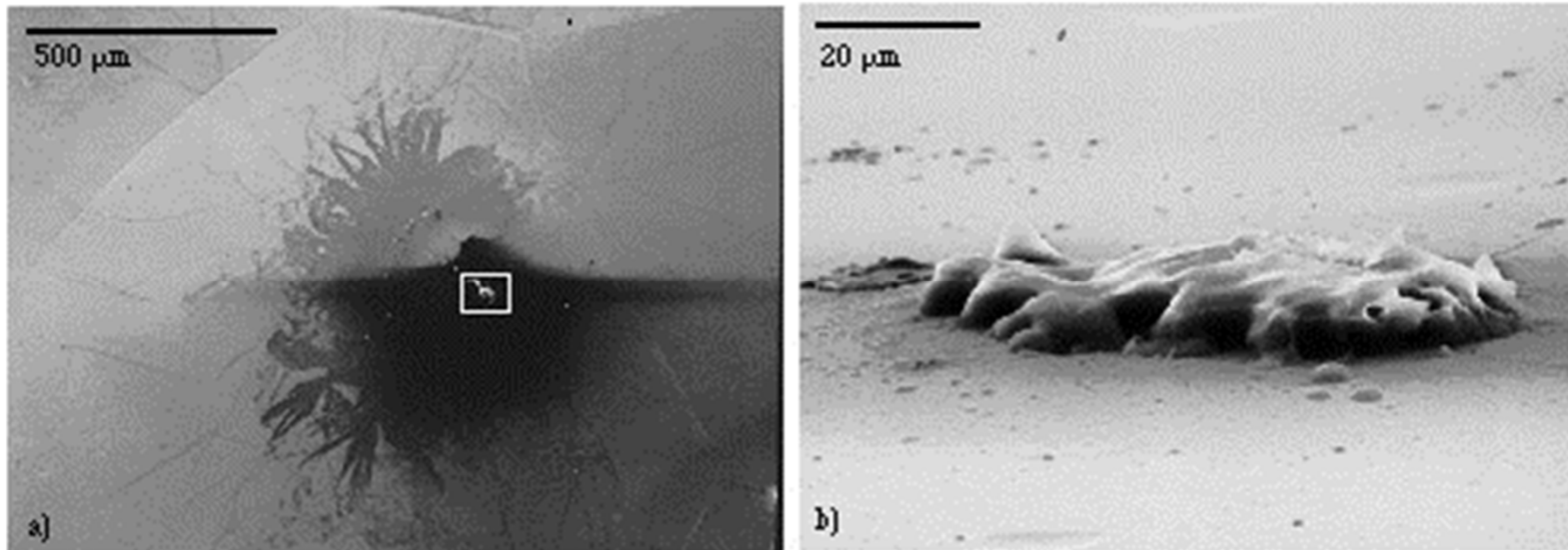


Particulate contaminations cause field emission.

High Peak Power Processing: HPP



Too Large Molten Region

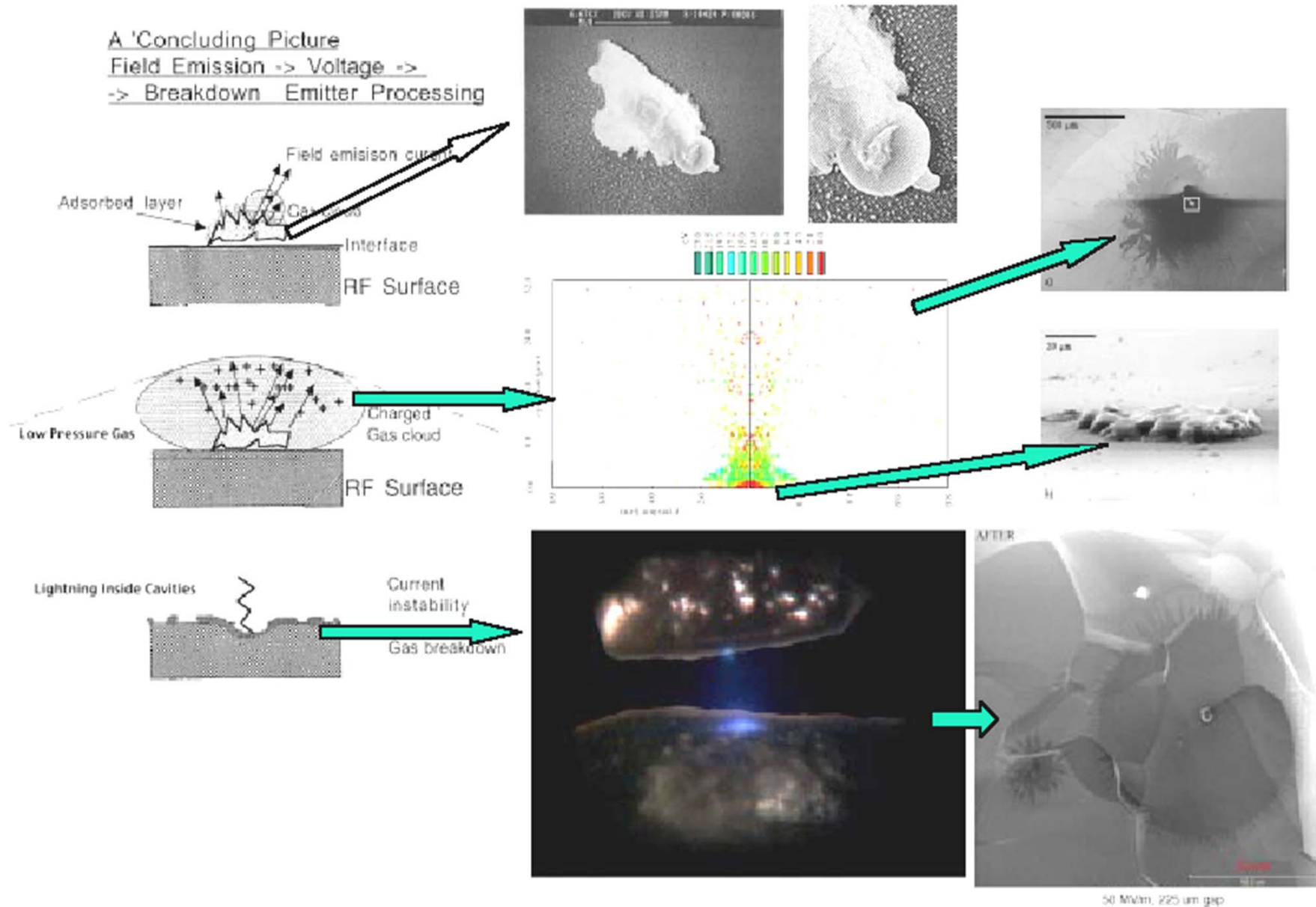


This **active** emitter shows large melted region
And dark cloud around it

Calculations show that FE current alone cannot
Produce this much melting

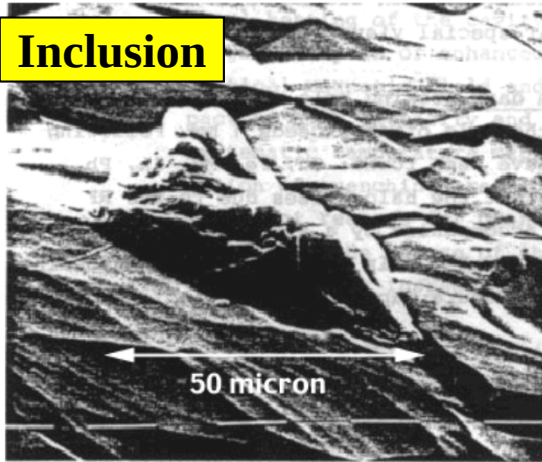
Gas is involved...
metal vapor + desorbed surface layers?

Cornell Model for FE



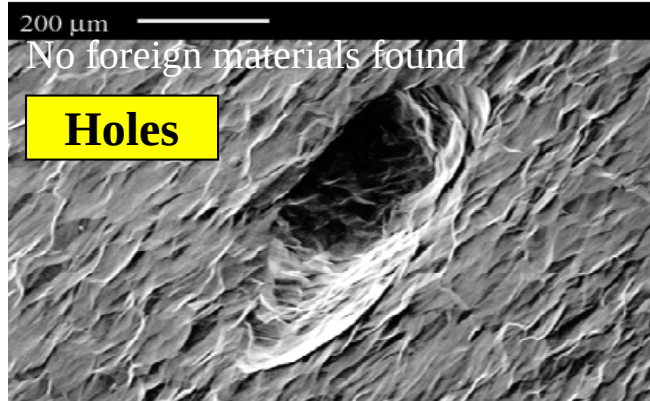
Various Surface Defects

Inclusion



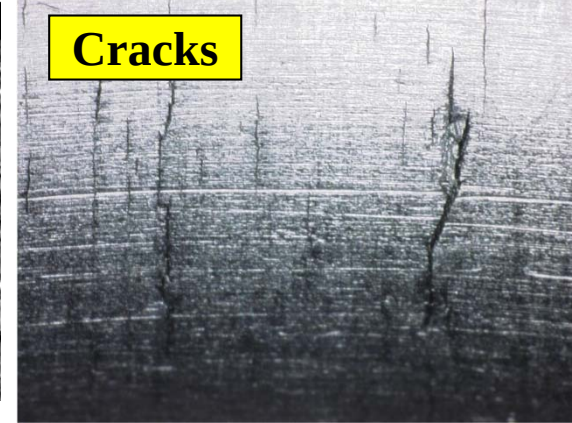
200 μm
No foreign materials found

Holes

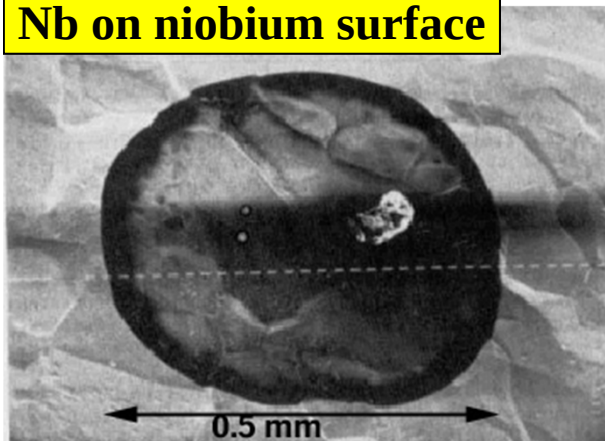


Surface defects, holes can also cause TB

Cracks

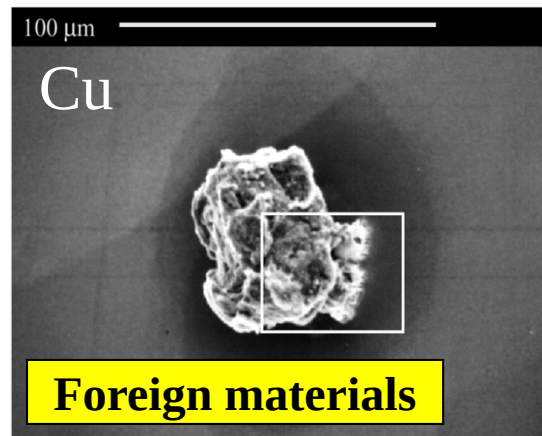


Nb on niobium surface

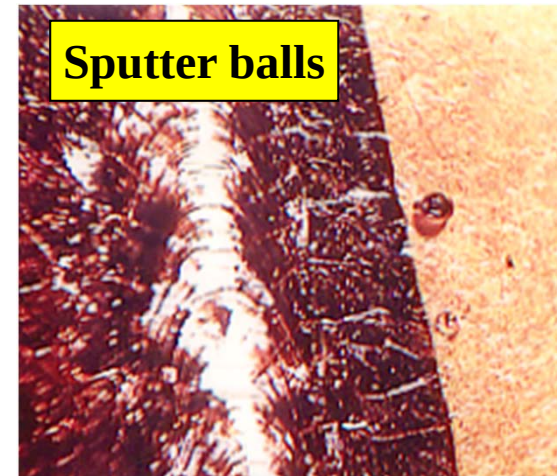


Cu

Foreign materials

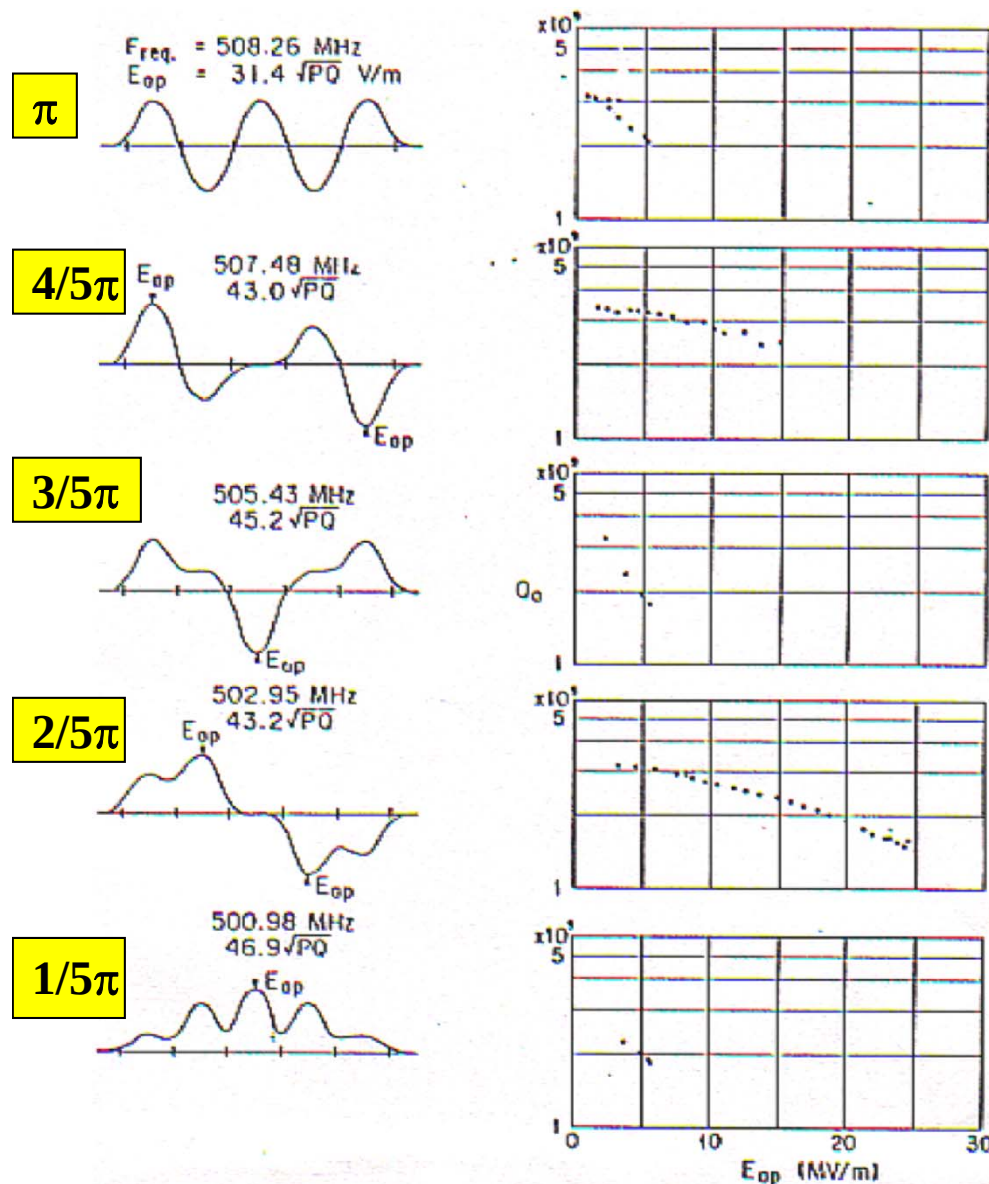


Sputter balls

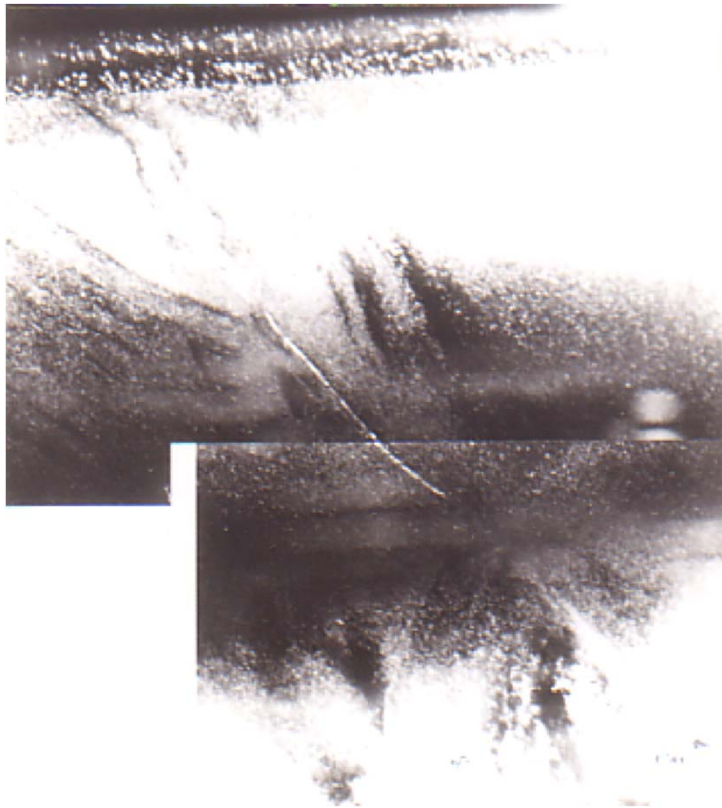


材料表面欠陥および加工時に発生するキズを機械研磨で十分に除去することが重要。

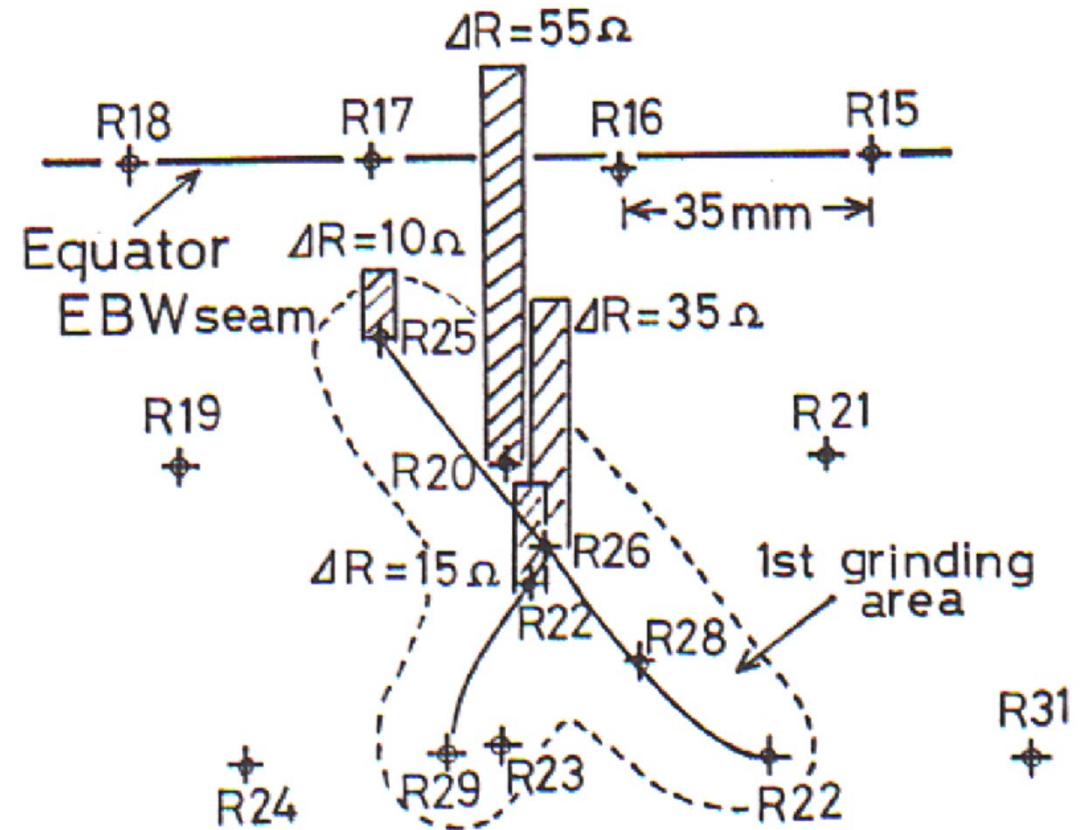
7.3 Thermal Instability : Example in A TRISTAN SC Cavity



Surface Defect

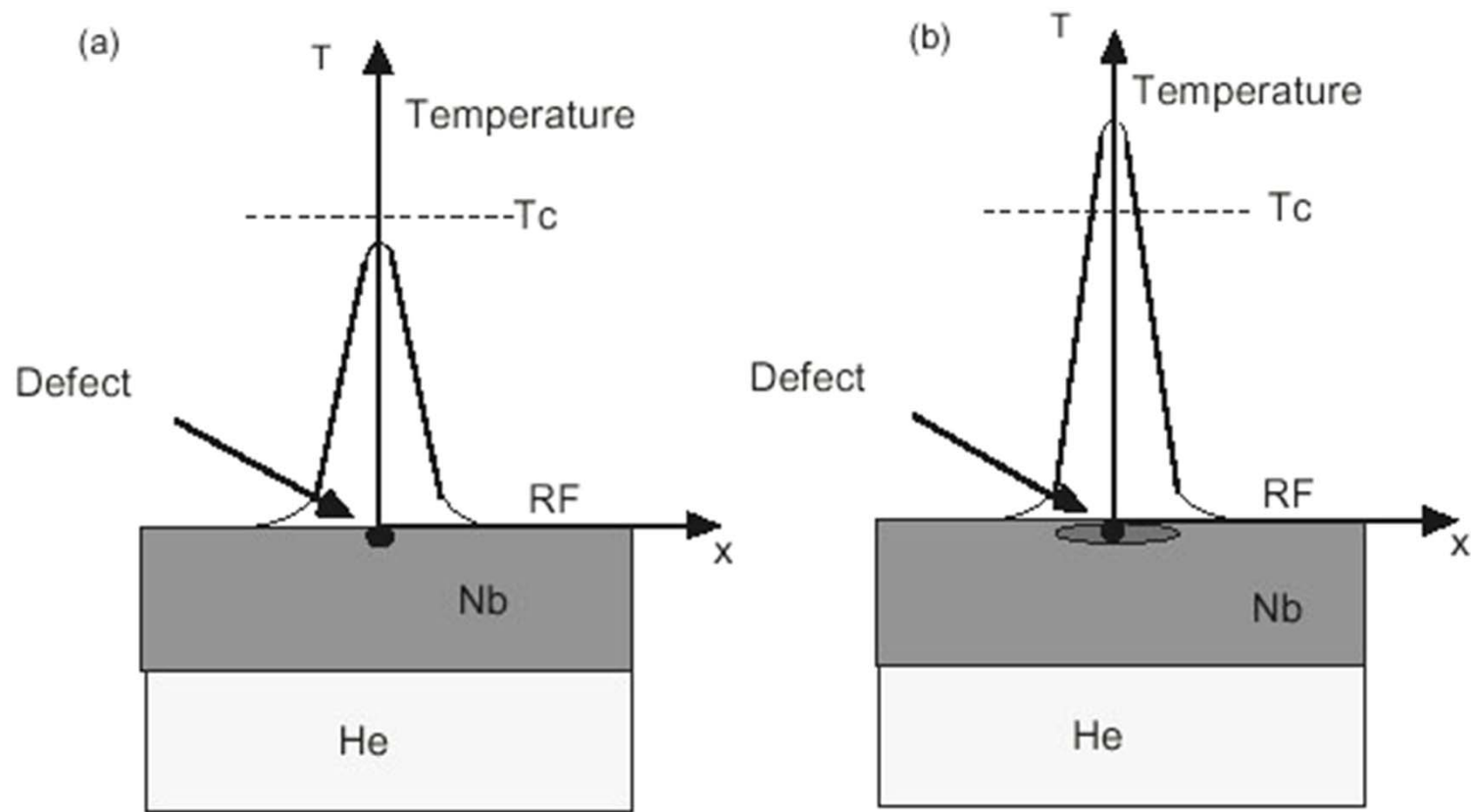


Picture of the defect area



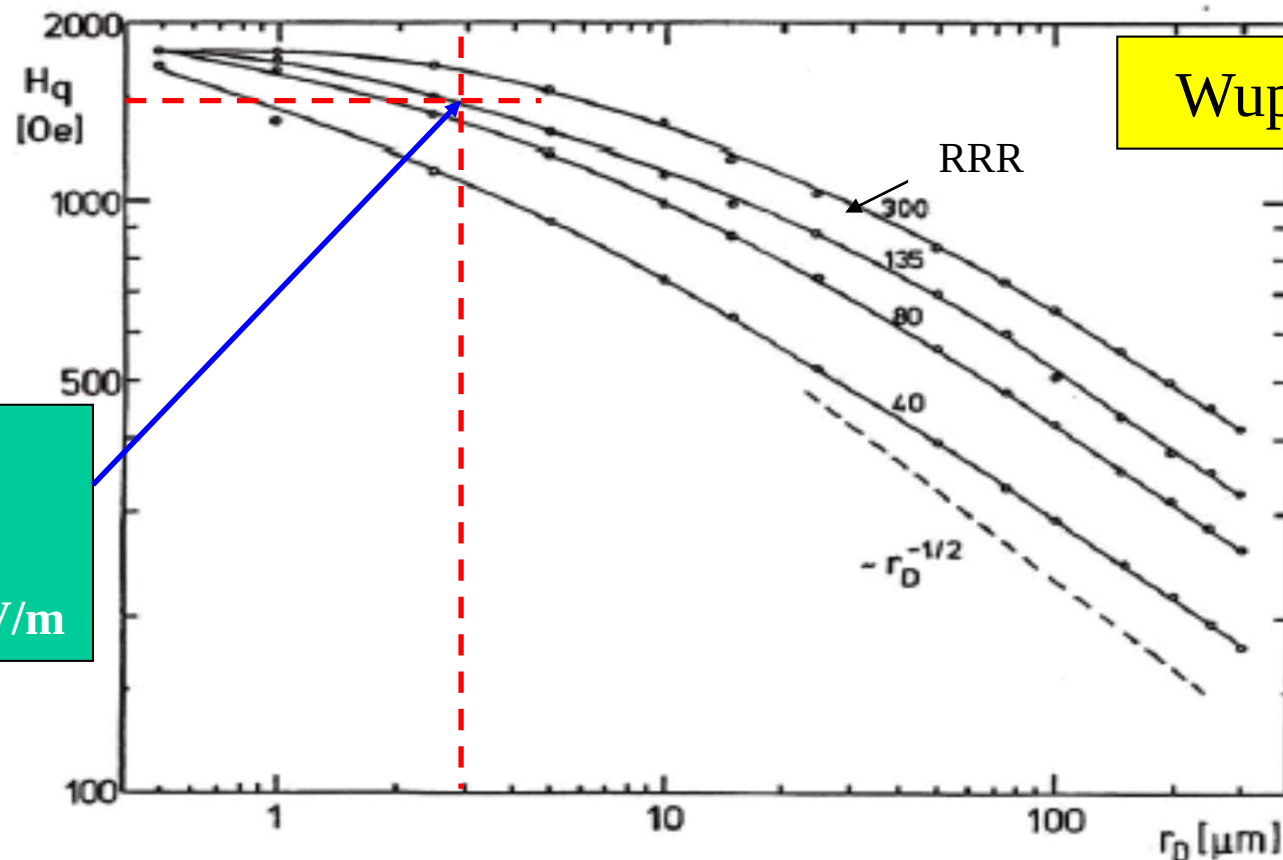
T-mapping on the defect

Mechanism of Thermal Instability



RRR Dependence of Quench Field

$$\text{Quench Field : } H_q = \sqrt{\frac{4\kappa(T_c - T_b)}{r_D \cdot R_s(T_b)}} \propto RRR^{\frac{3}{4}} \cdot \sqrt{\frac{(T_c - T_b)}{r_D \cdot R_s(300K)}}$$



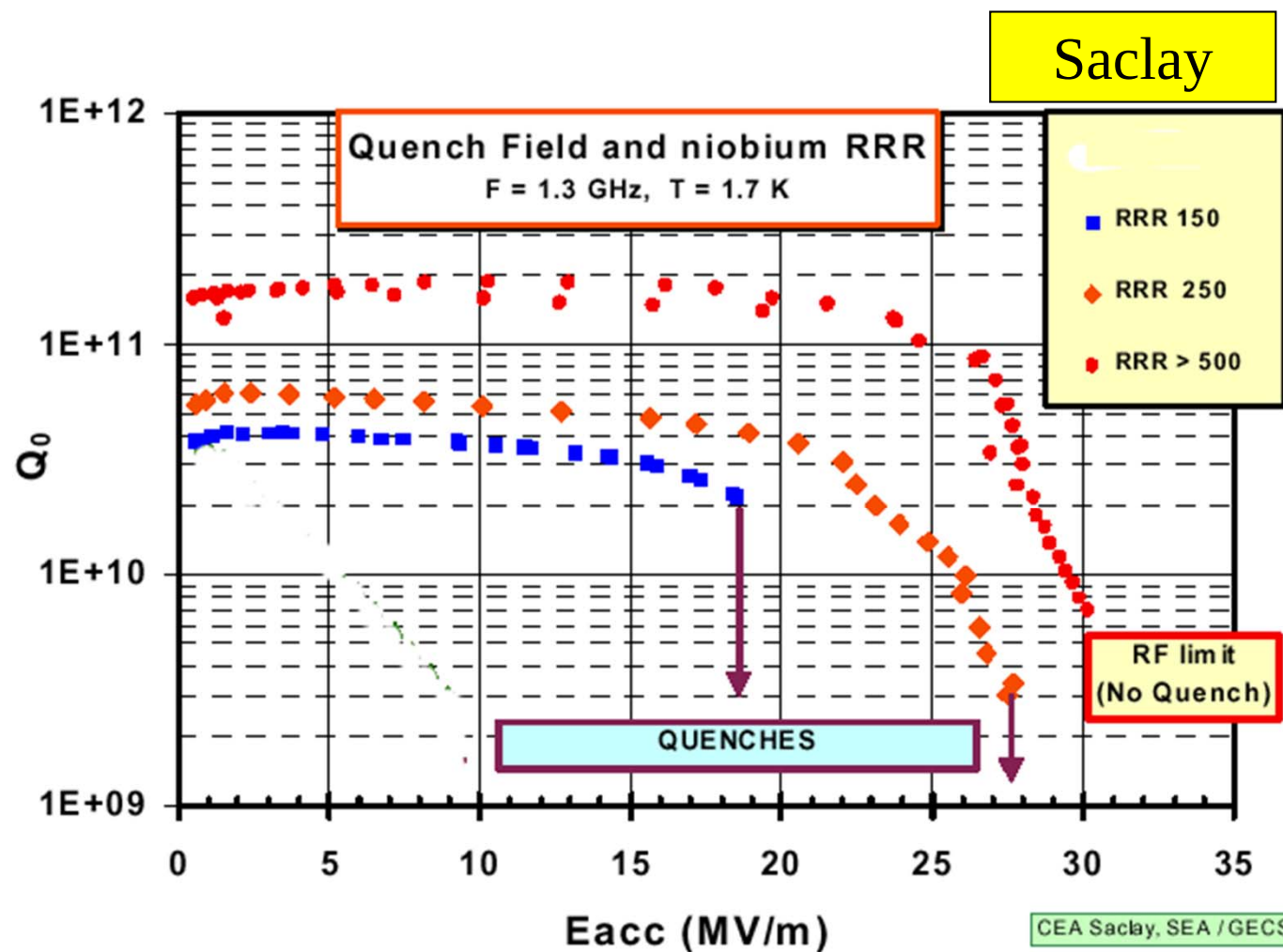
Wuppertal

RRR=135,
 $r_D=3\mu m$ では
 $H_q \sim 1500 Oe$
 $E_{acc,max} \sim 34 MV/m$

Defect radius

1 μm 以上の欠陥をコントロールする必要がある。RRR>200の材料を使え。

Field Improvement by High RRR Material



Effect of Various Scattering Mechanisms on Electric Resistivity

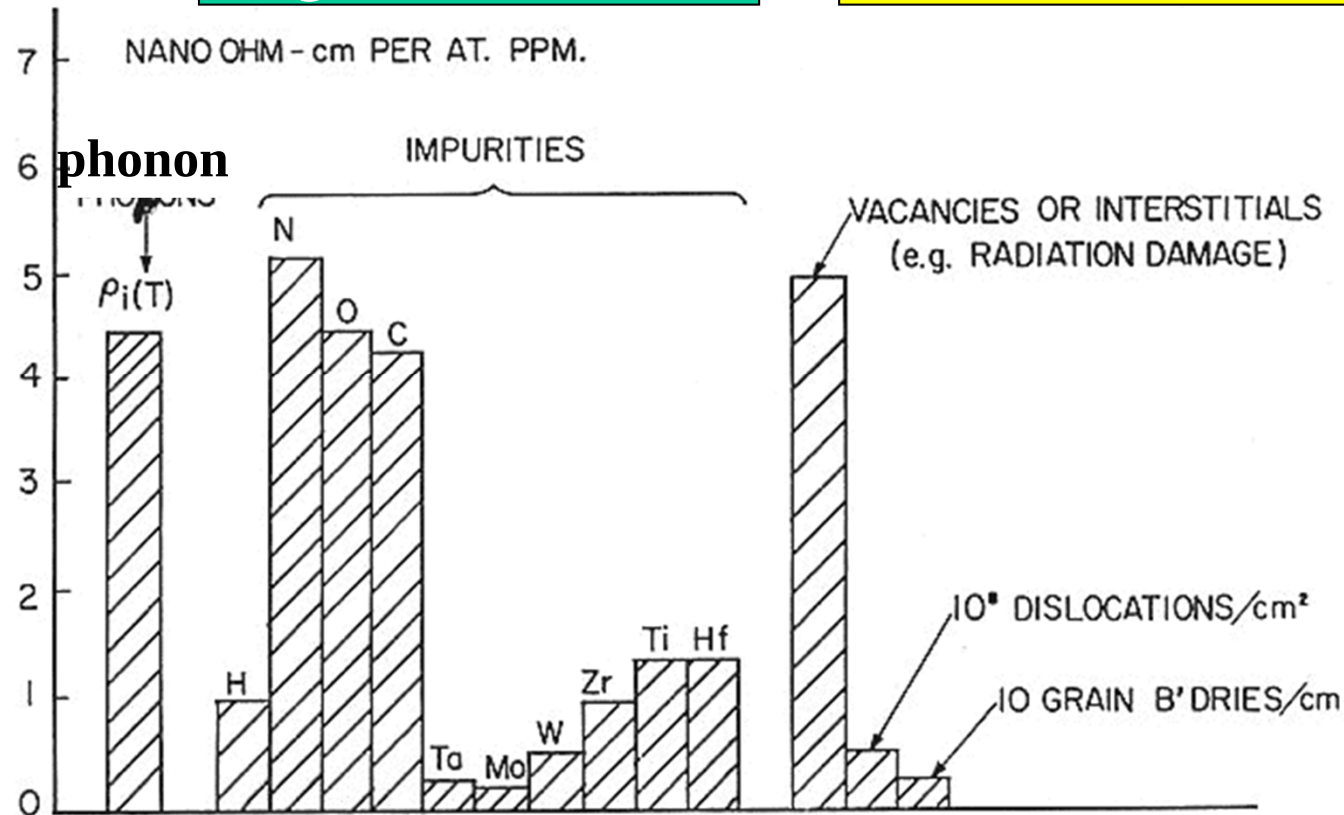
High purity + Homogeneity



Nb

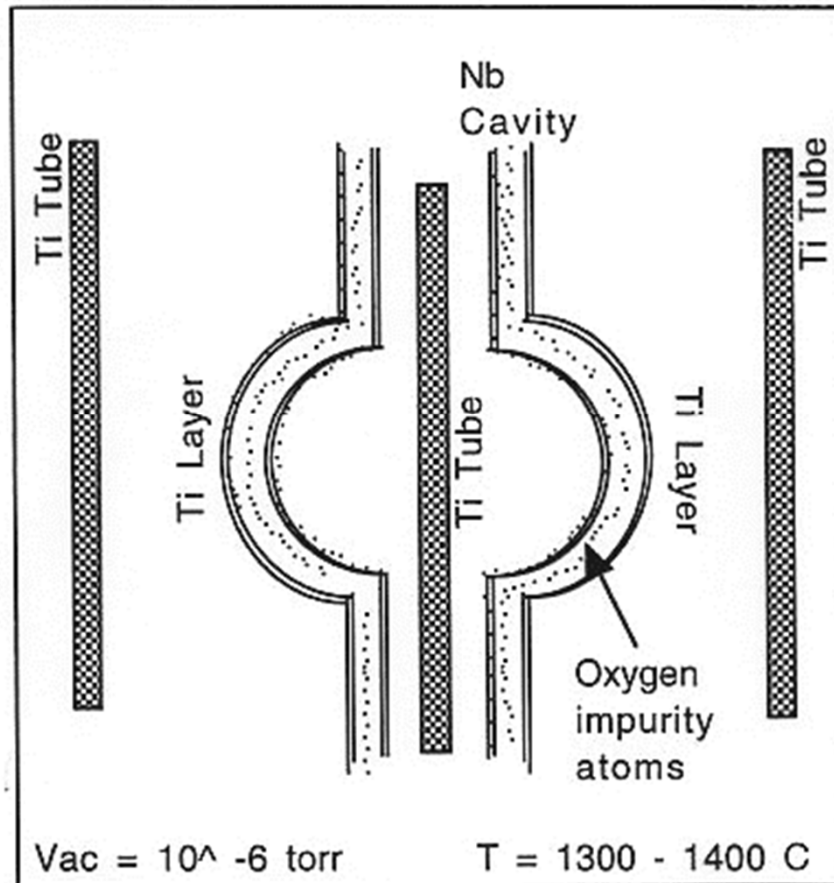
High RRR material

Vacuum annealing



Cure : Post Purifying of Niobium

Post Purification



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)

DESYが 1400° annealingを採用している
もう一つの理由。

Cure : Inspection of Nb Sheet and Cavity Surface

Defect free material : Quality control

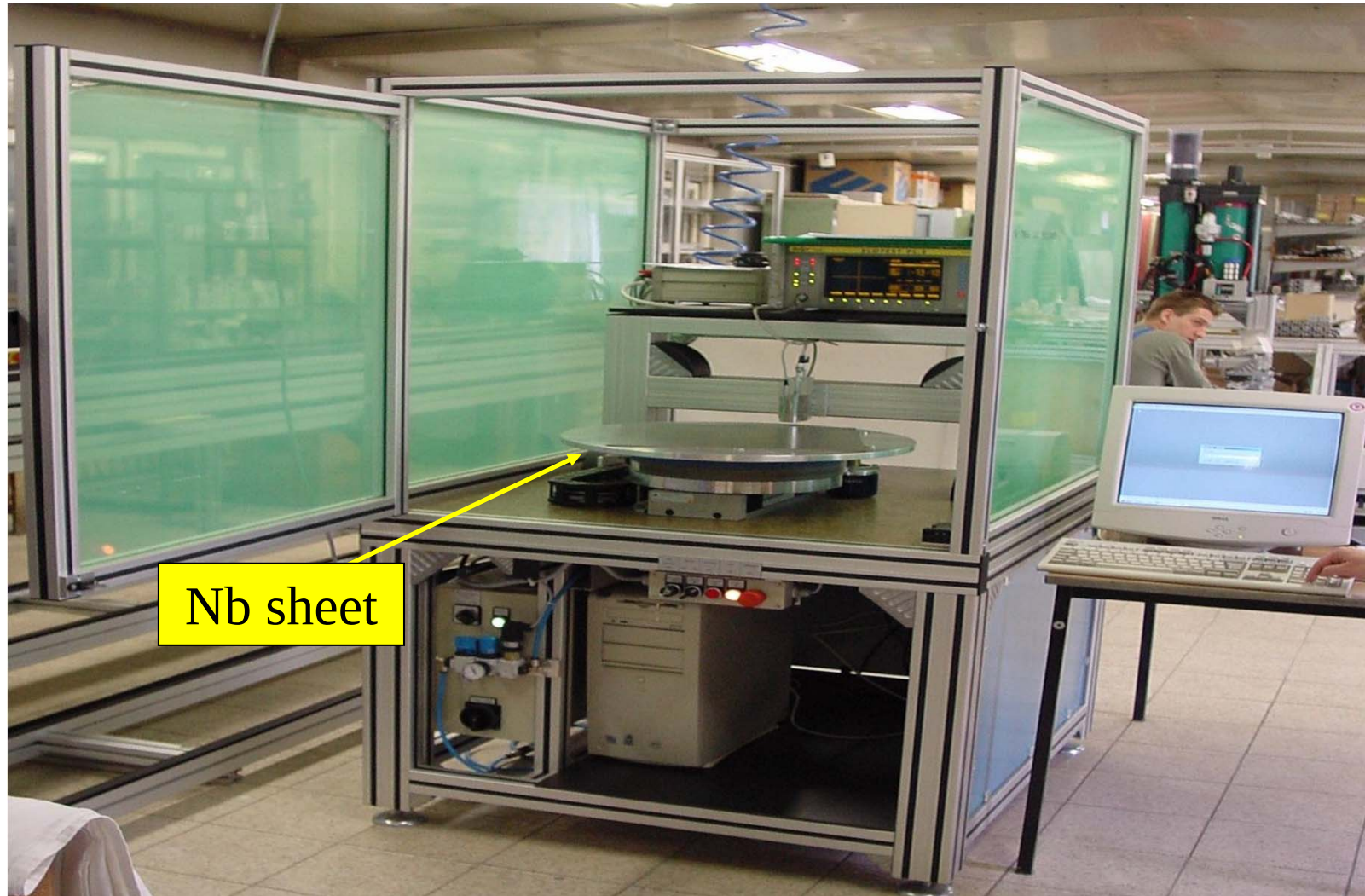
Result of eddy current scanning a Nb disc, dia. 265 mm at DESY



Global view, rolling marks
and defect areas can be seen

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

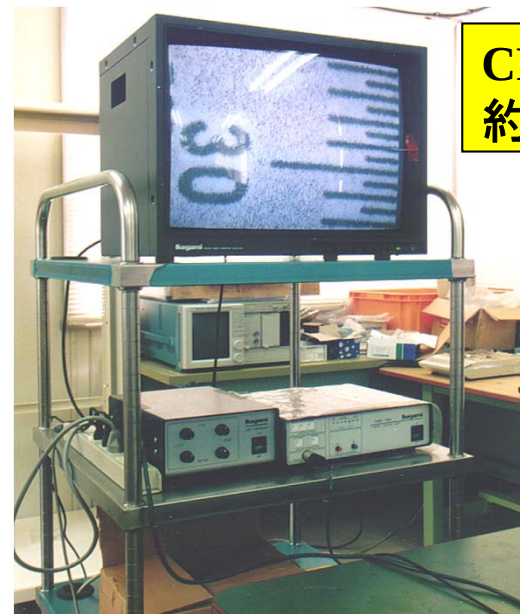
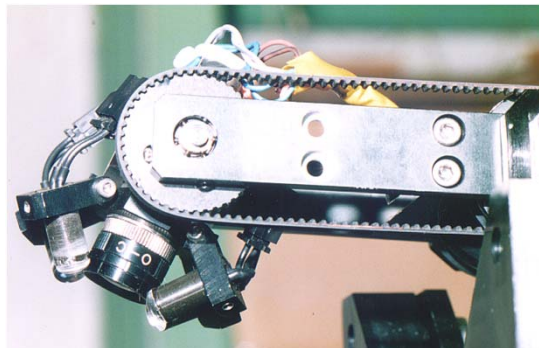
Eddy current scanning system DESY



Cavity Inner Surface Inspection System : KEK



超小型CCDカメラ



CRTモニター
約13倍

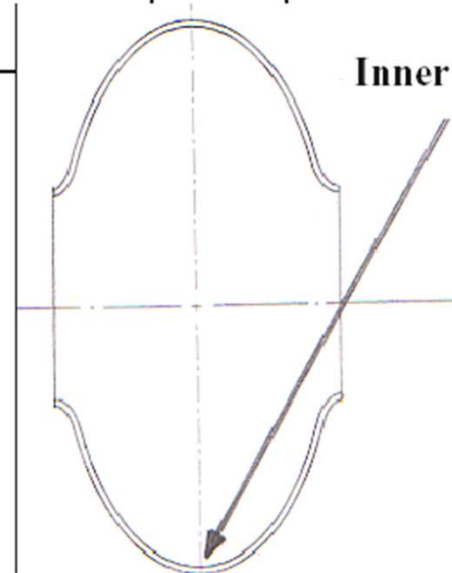
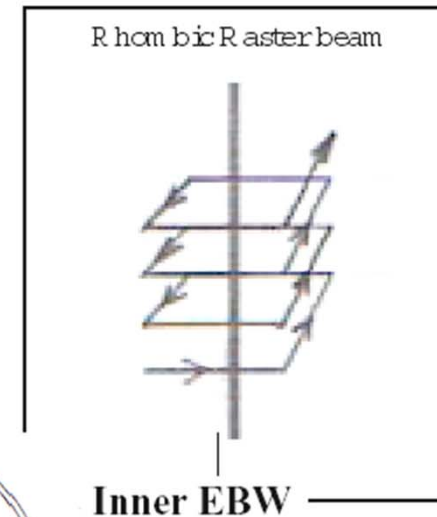
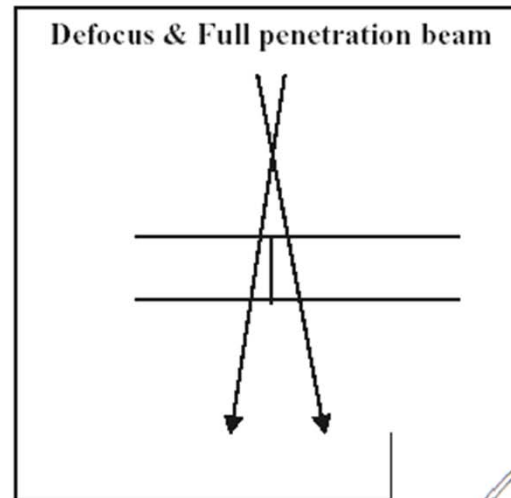
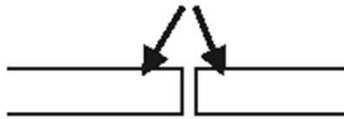


KEK 内面検査システム

Cure : High Quality EB-welding

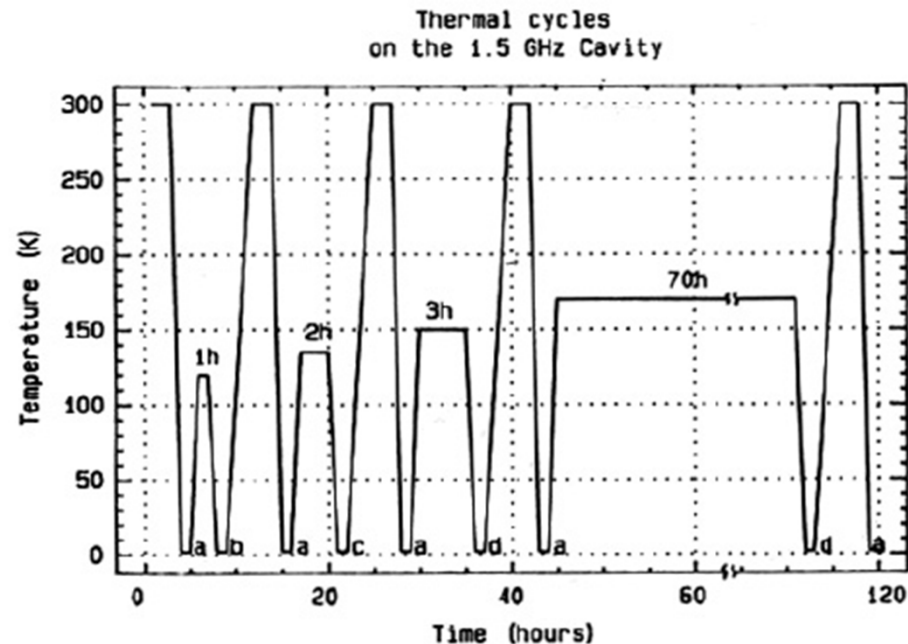
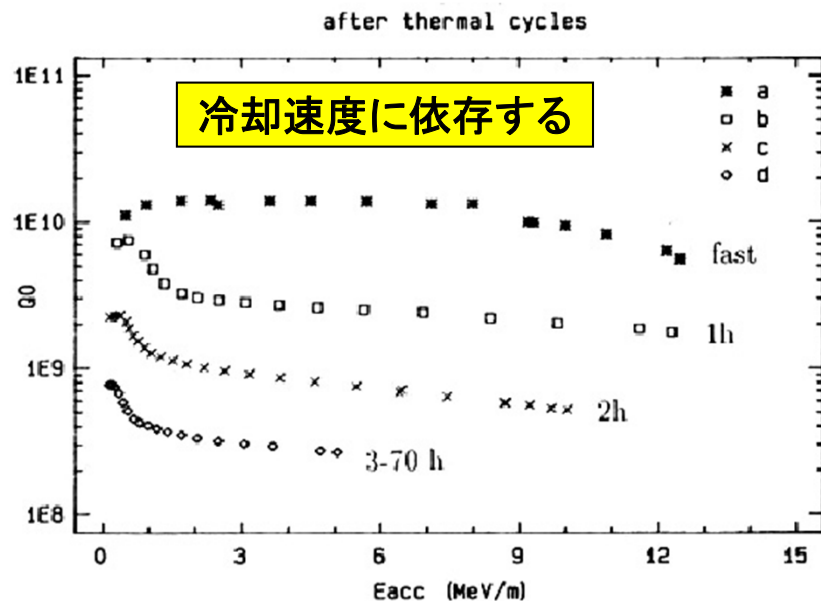
Better EBW

Etching by CP



7.4 Hydrogen Q-Disease

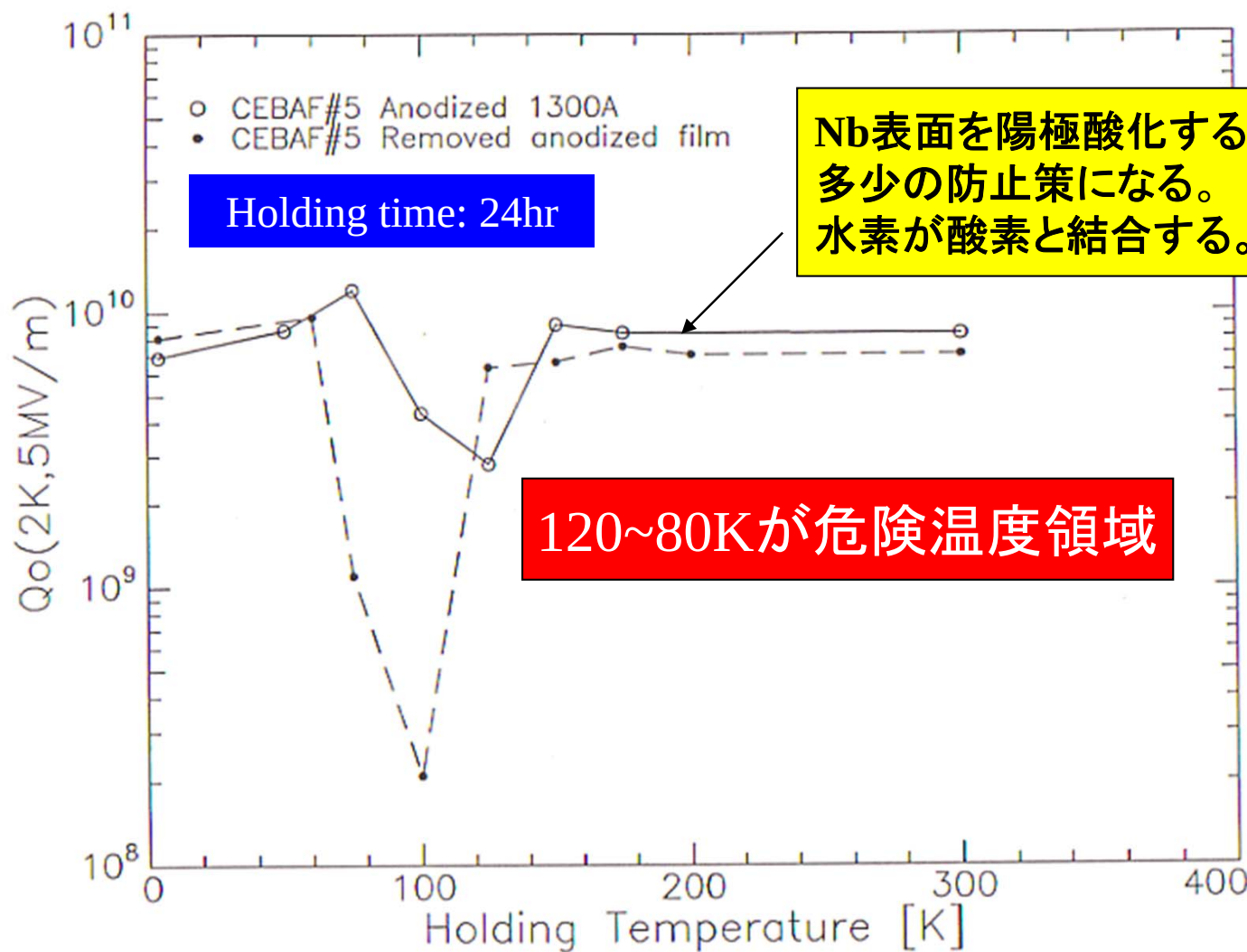
空洞をゆっくり冷却すると Q-値がとんでもなく低い！



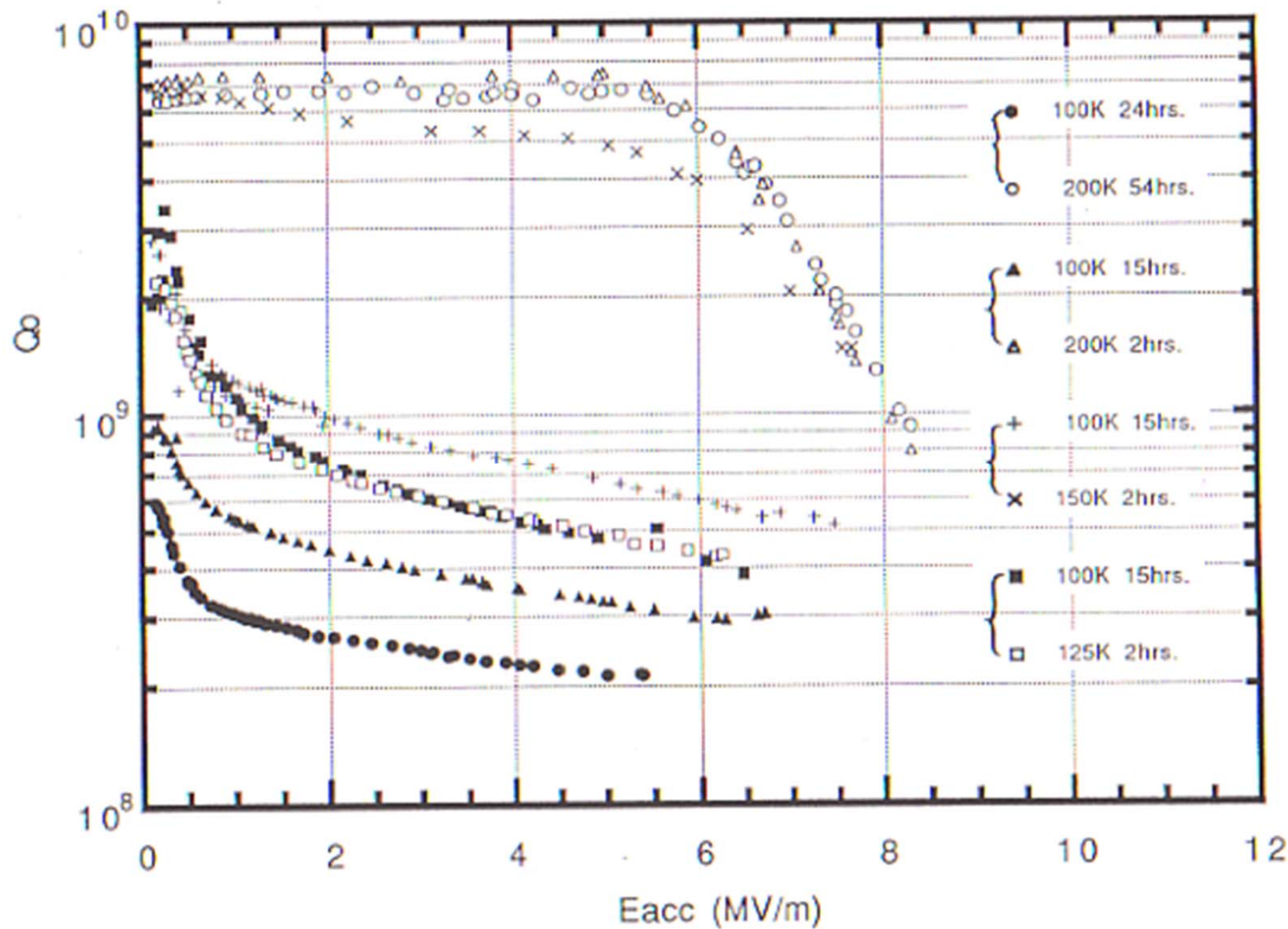
化学研磨したニオブ空洞で
1990年Saclayで発症

欧米では、化学研磨が主流で、
水素脱ガス真空熱処理を行っていなかった。
これは、化学研磨を採用する一つの理由でも
あった。

Dangerous Temperature



Recovery of Hydrogen Q-Disease



200Kまでwarm up
すると回復する。

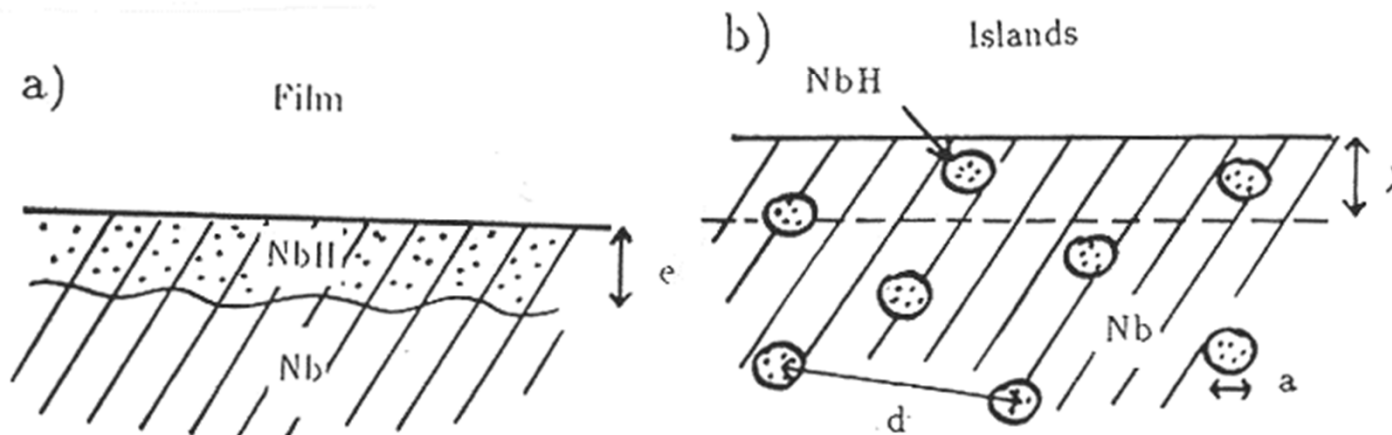
Mechanism of Hydrogen Q-disease

Mechanism and Explanation of Symptoms

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

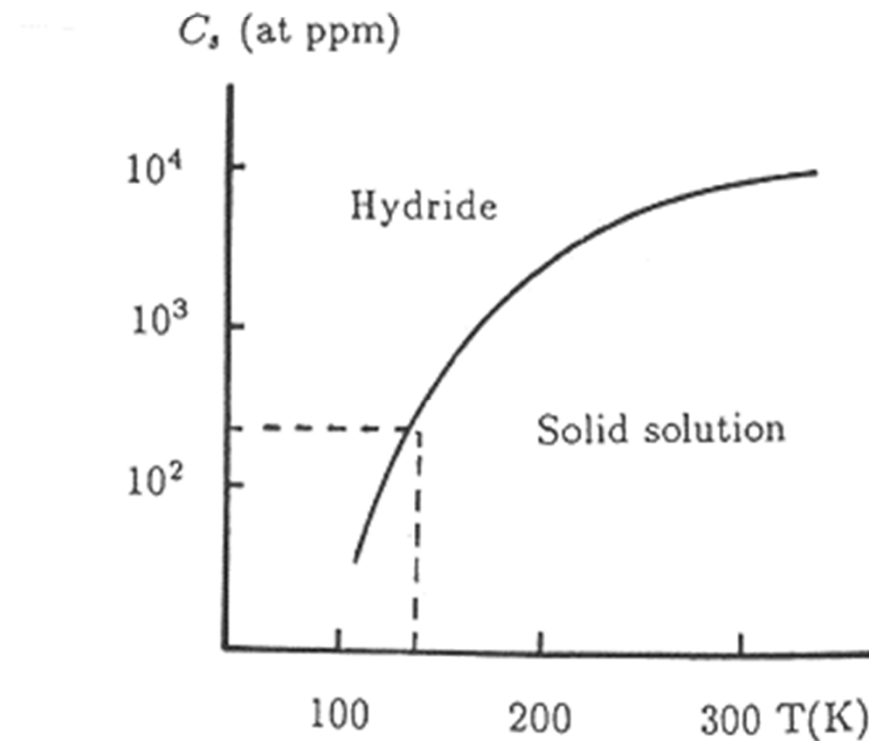
When a cavity is cooled the dissolved hydrogen
precipitates as a hydride phase that has high rf loss
 T_c of hydride = 2.8 K, $H_c = 60$ Oersted

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

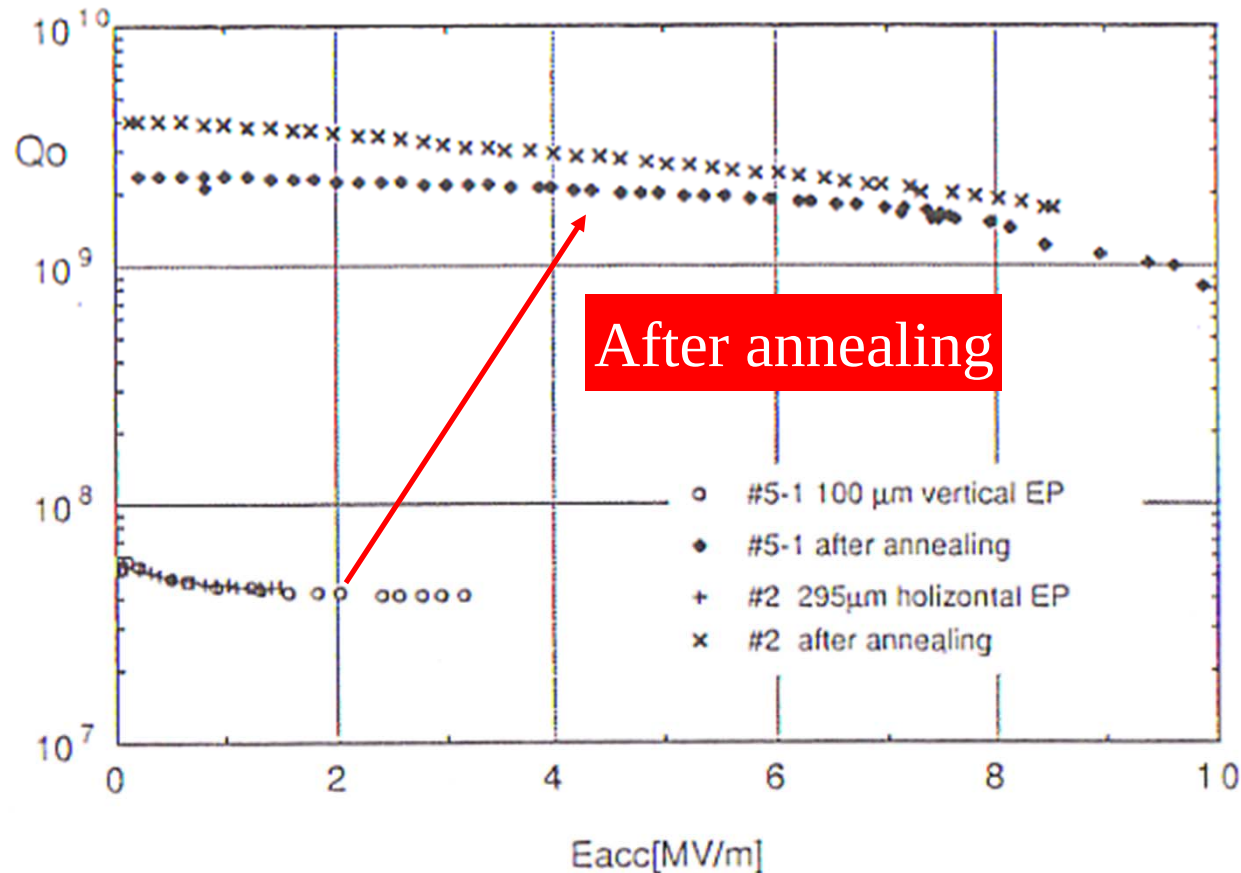


At room temperature the required conc. to form hydride phases is very high, e.g 4600, 7400 wt ppm

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



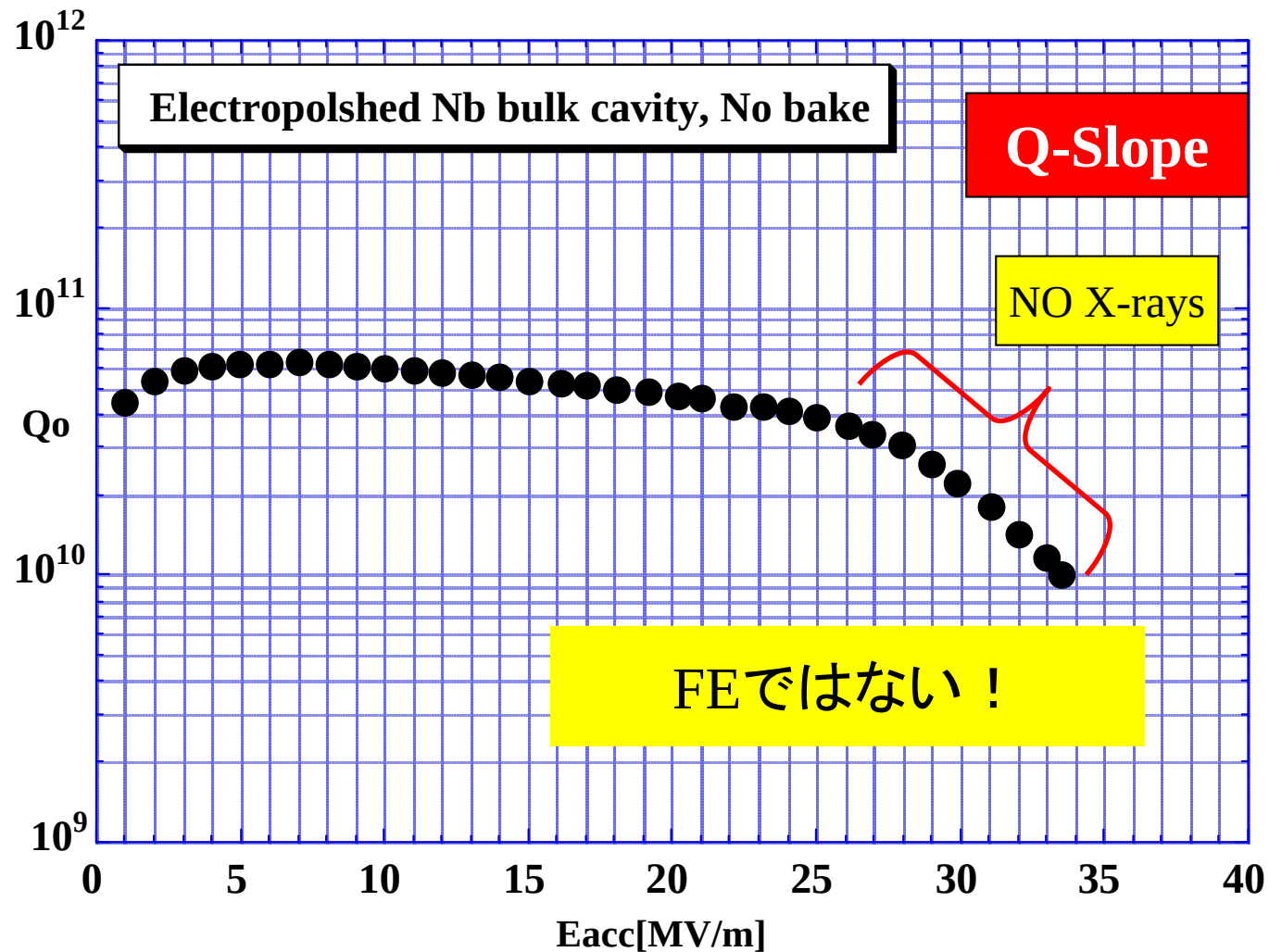
TRISTAN's Experience and its Cure



TRISTAN空洞では
水素病との大きな
闘いあり。

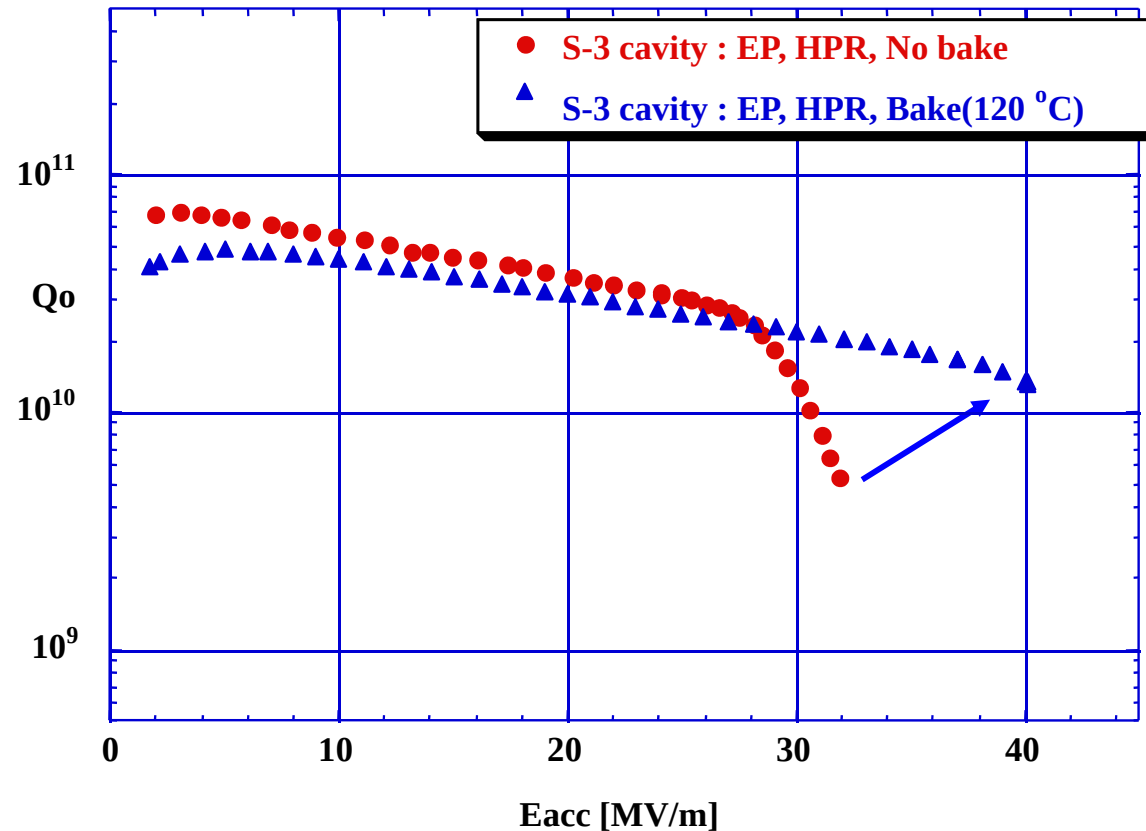
- ・電解研磨では、水素の吸蔵が起こり、Q-値が著しく低下することをよく分かっていた。
- ・750°Cの真空熱処理を施し、その問題を解決した。
- ・ただその現象が空洞の冷却速度に依存することは知らなかった。
- ・KEKでは液体ヘリウムの消費量を減らすために、一晩液体窒素による予冷(~100K)を習慣的に行っていた。

7.5 Q-Slope



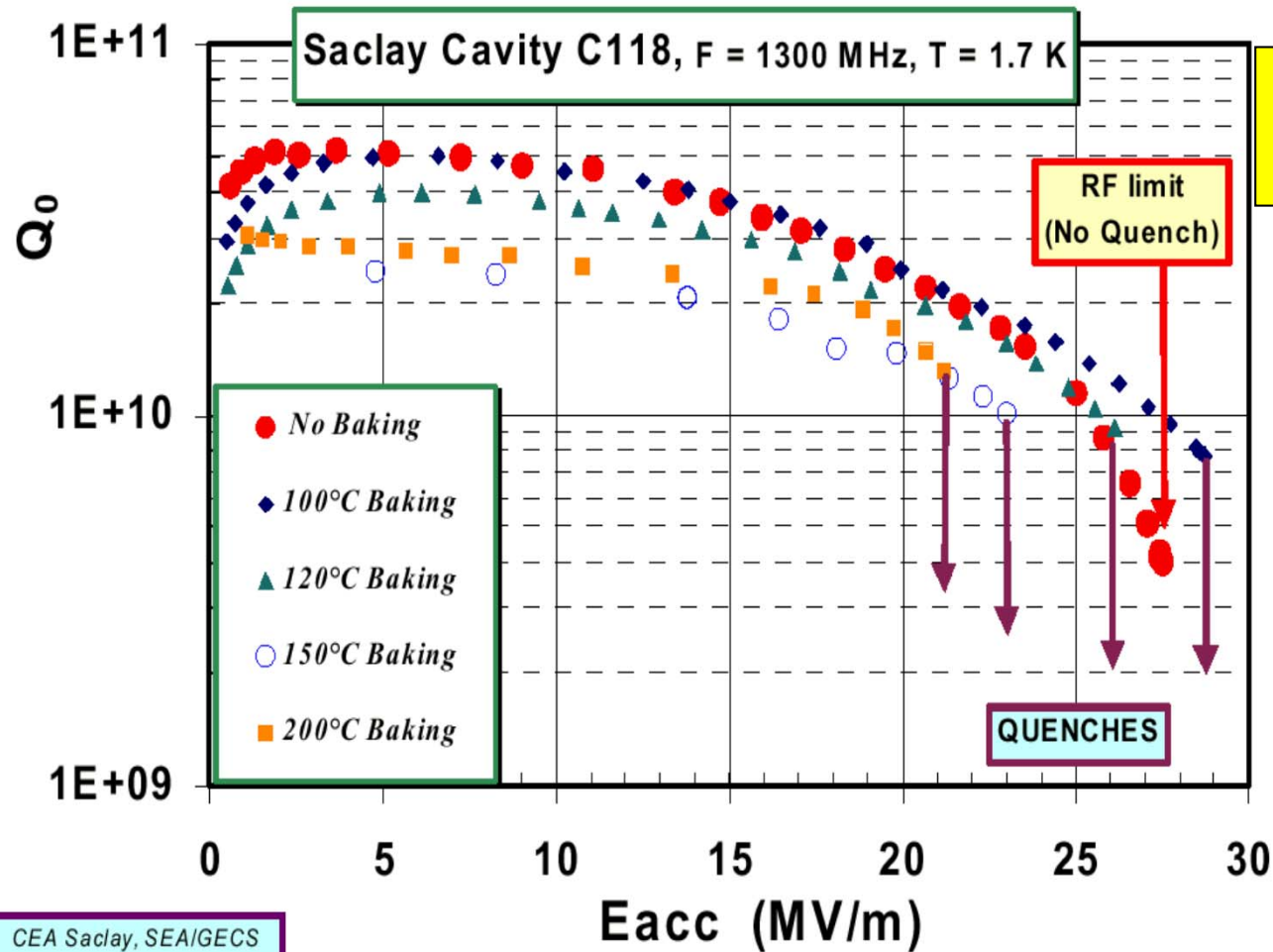
1998年に発見

Crutial Baking Effect on EP Cavity



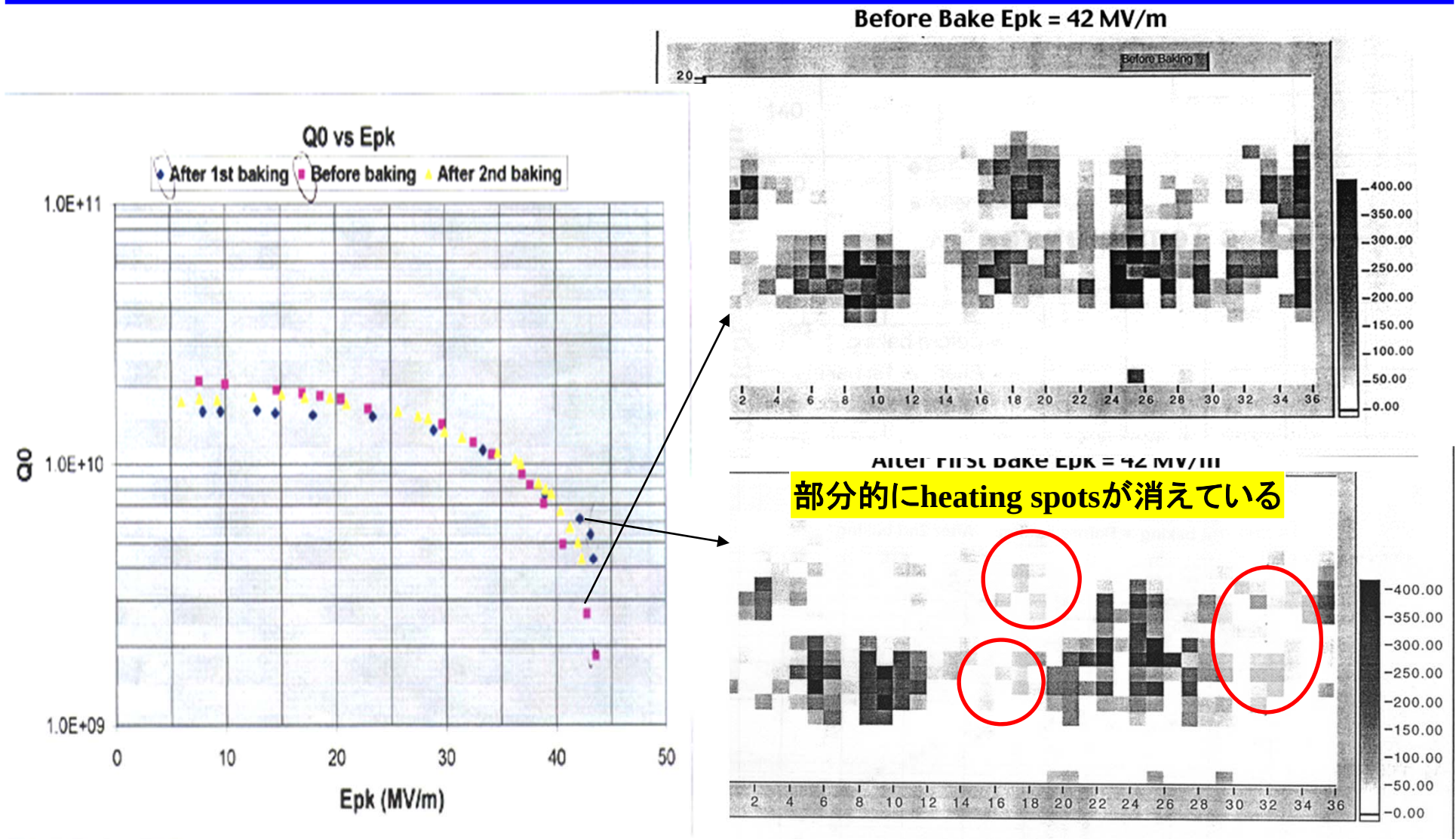
電解研磨した空洞ではベーキングでQ-Slopeのが消え、
電界が向上する！

Small Baking Effect on CP Cavities

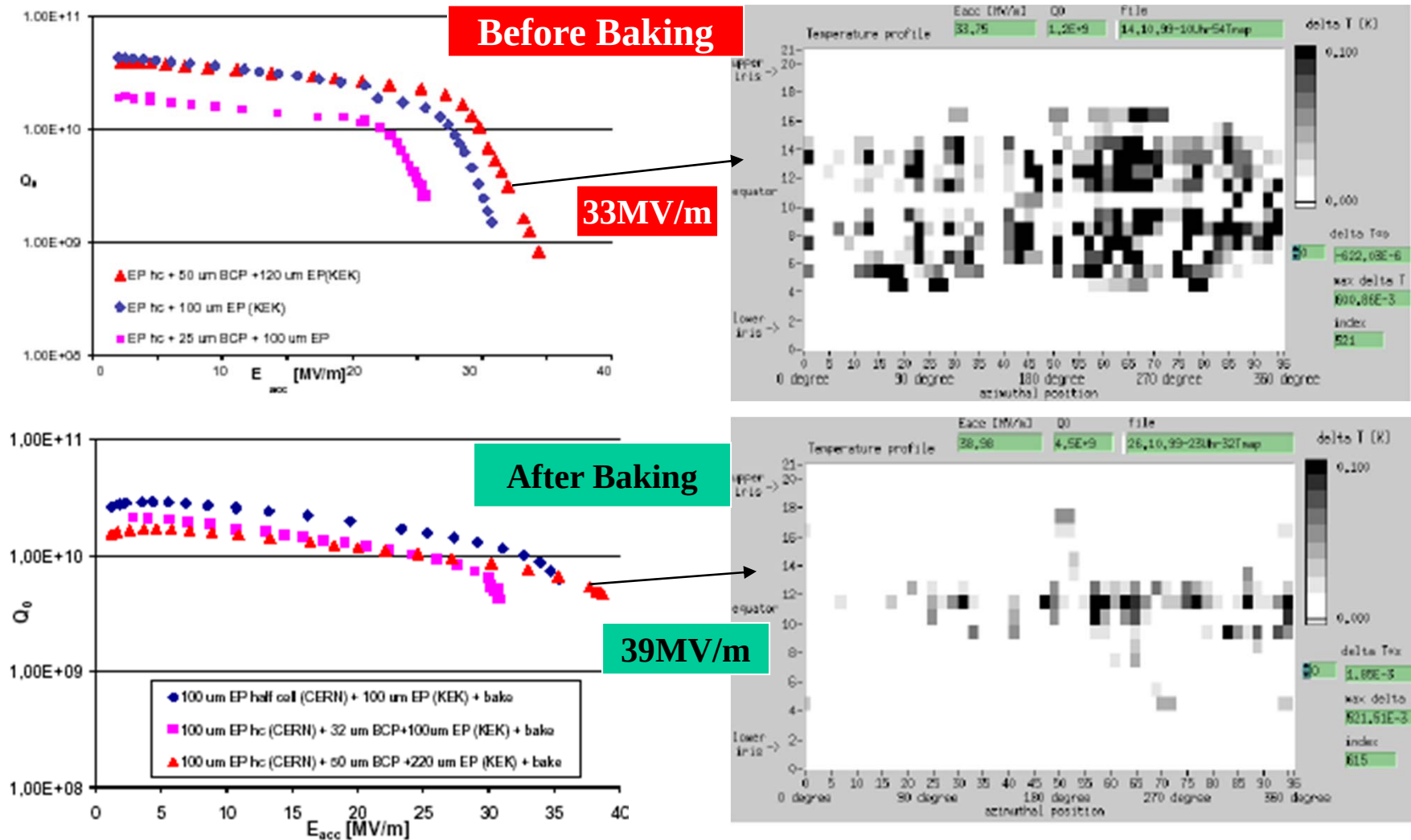


化学研磨した空洞では、
baking効果は顕著でない。

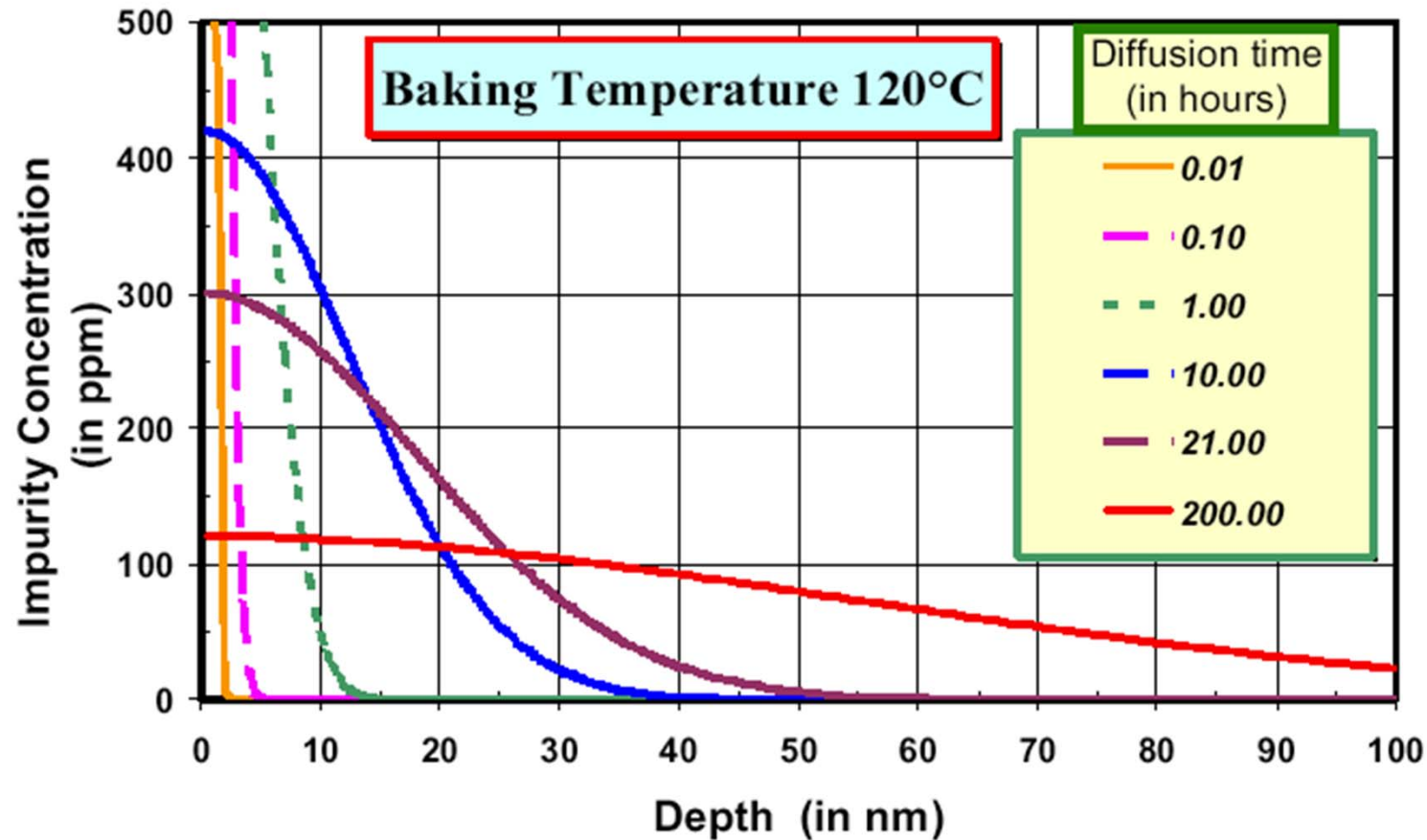
Partially Disappeared Heating Spots by Baking on CP Cavity



Disappeared Heating Spots by Baking on EP Cavity



Oxygen Diffusion



Baking effectはニオブ表面に存在する酸素のバルク中への拡散によると考えられる。

Loss Mechanism

Interface Tunnel Exchange(ITE Model) By J.Halbritter

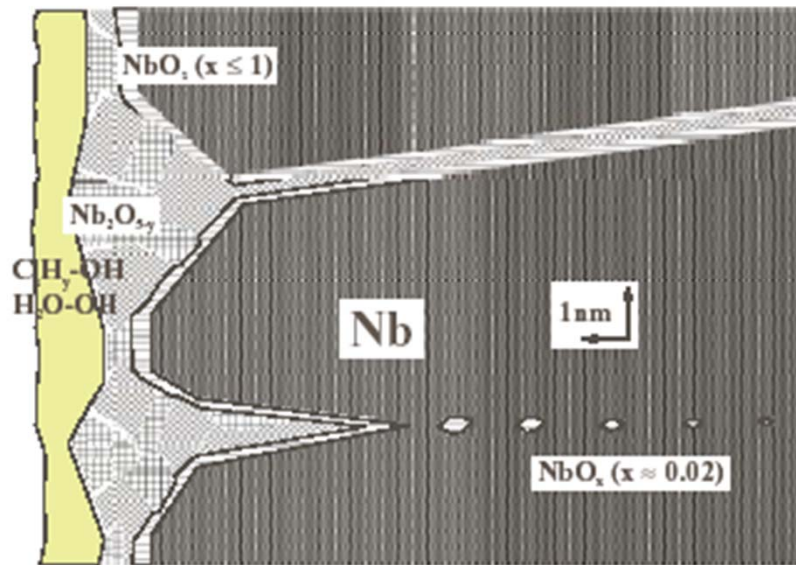


Fig. 1: Nb surface with crack corrosion by oxidation by Nb_2O_5 volume expansion (factor 3). $\text{Nb}_2\text{O}_{5-y}$ - NbO_x weak links/segregates ($y, x < 1$) extend up to depths between $0.01 - 1/1-10 \mu\text{m}$ for good – bad Nb quality and weak - strong oxidation [8]. Embedded in the adsorbate layer of $\text{H}_2\text{O}/\text{C}_x\text{H}_y\text{OH}$ ($\geq 2 \text{ nm}$) being chemisorbed by hydrogen bonds to $\text{NbO}_x(\text{OH})_y$, adsorbate covered dust is found. This dust yields enhanced field emission (EFE [7]) summarized in Sect. 3.1.

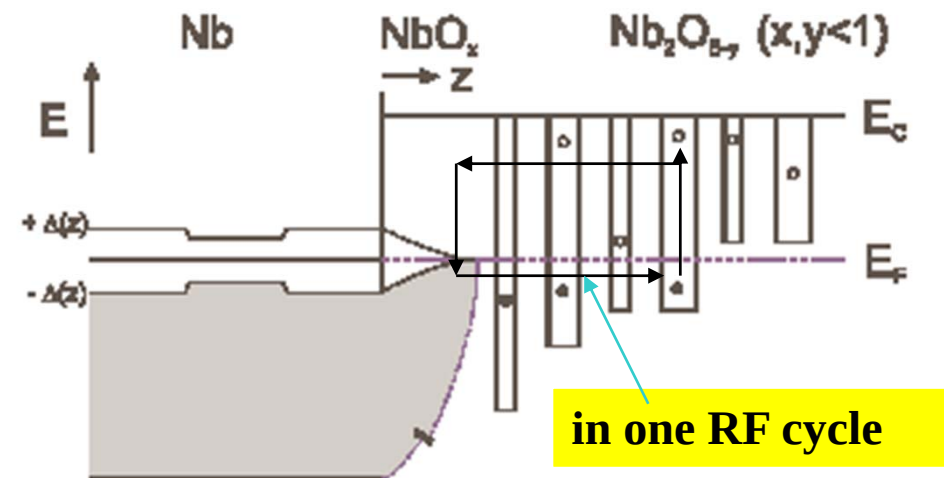
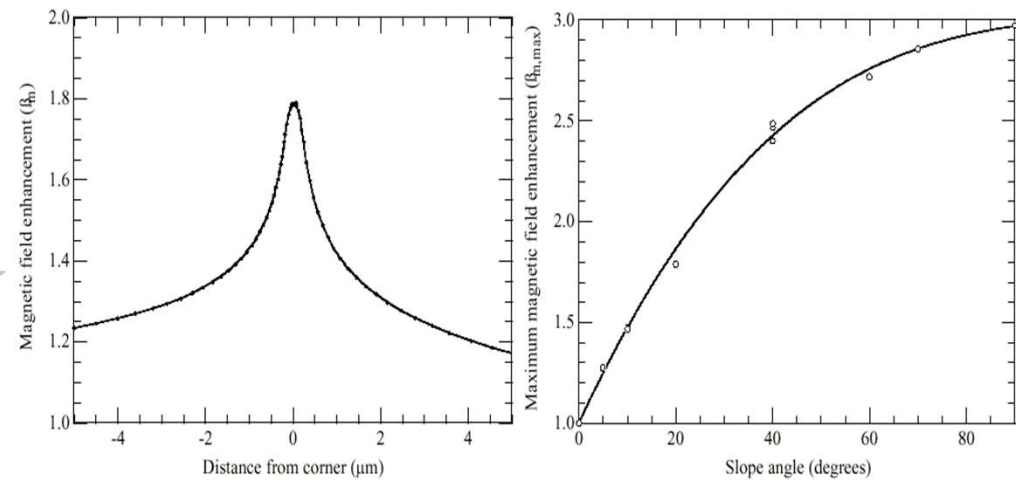
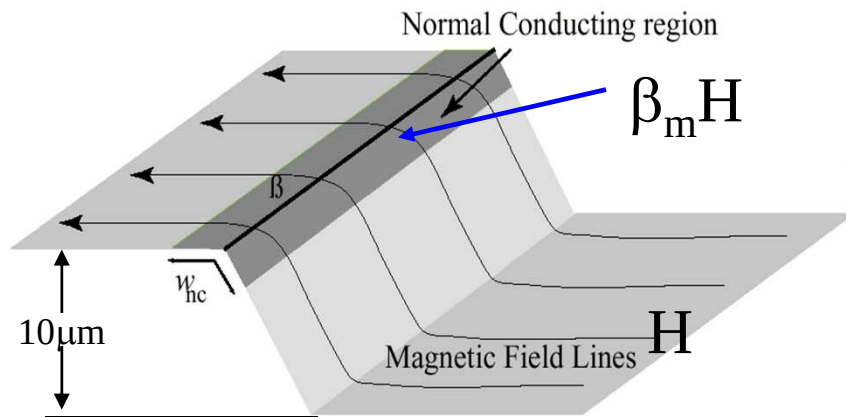
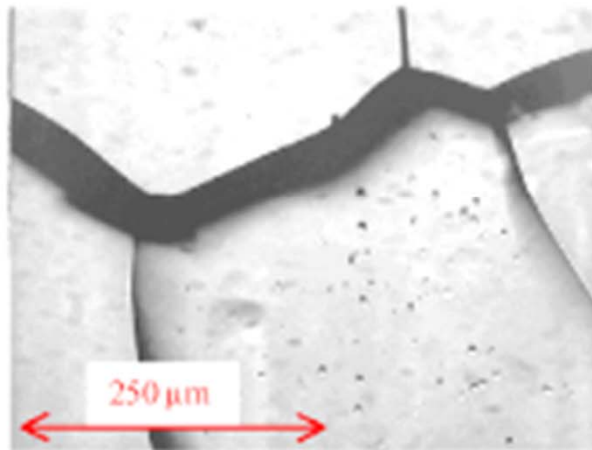


Fig. 3: Band structure at Nb-NbO_x-Nb₂O_{5-y} interfaces with $E_c - E_f = \phi \approx 0.1 - 1 \text{ eV}$ as barrier heights for tunneling along crystallographic shear planes ($\sim 0.1 \text{ eV}$) or of $\text{Nb}_2\text{O}_{5-y}$ crystallites ($\sim 1 \text{ eV}$). Added is the superconducting energy gap $\Delta^*(z) < \Delta_0$ being reduced in NbO_x clusters or interfaces and being normal conducting Δ^* ($z_L \geq 0.5 \text{ nm}$) in localized states of $\text{Nb}_2\text{O}_{5-y}$. By their volume expansion those clusters locally enhance T^* and $\Delta^* > \Delta_0$ in adjacent Nb by the uniaxial strain yielding a smeared BCS DOS.

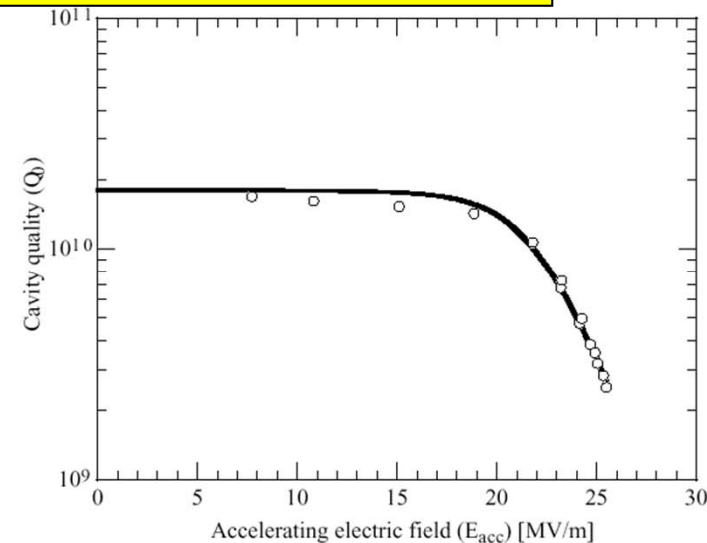
Magnetic Field Enhancement on Sharp Edges



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



Baking effectを説明できない。

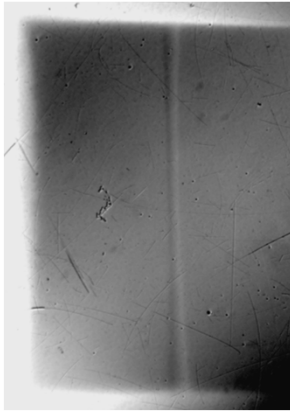


$$\beta_m \cdot H_{RF} \geq H_C = \frac{\sqrt{2} \cdot H_C(0)}{\kappa(0)} \cdot (1 - t^4)$$

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

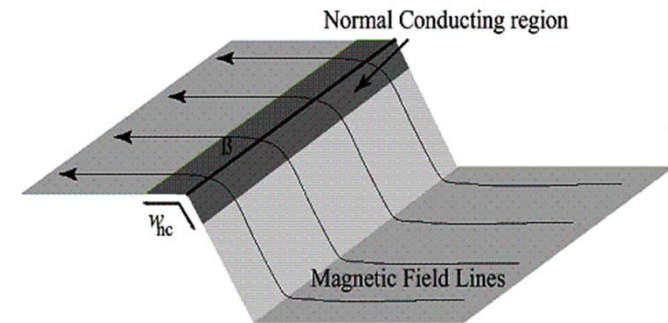
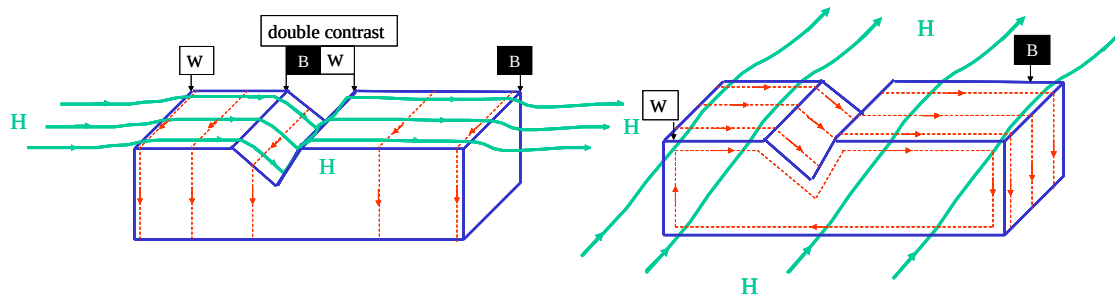
Monograph effect on Magnetic field

By C.Antone

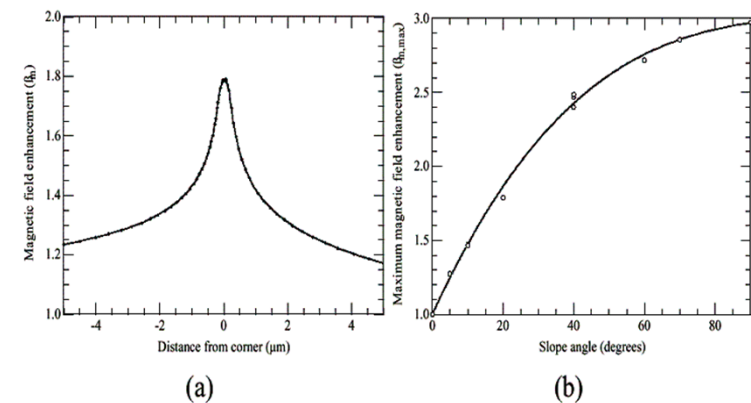


CBP is right way to eliminate the monograph effect !!

J.Knobloch



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



11-13/May/2011
K.Saito

7 Summary

- 超伝導空洞の性能を制限する現象には、1) Multipacting, 2) Field emission, 3) Thermal instabilityの三つが過去に置いては、主であった。
- 上記の最初二つについては、コンタミの無い清浄表面を製作する事が重要である。
- Thermal instabilityに対しては、製作過程で発生する表面欠陥の除去、また使用材料中に欠陥が無いように材料の品質管理が重要である。
- また、熱伝導率の高い高純度ニオブ材料の使用が不可欠である。
- 最近では、Q-Slopeのような細かな空洞性能劣化原因が問題になっている。
- これは、今後のさらなる研究が必要である。