PHY905 Section 4
Ion Accelerator Technology
Lecture 15
- SRF Cavity Performance Limitations -

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15. SRF Cavity Performance Limitations

15.1 SRF cavity performance limitation summary

15.2 History of understanding the limitation

15.3 Multipacting

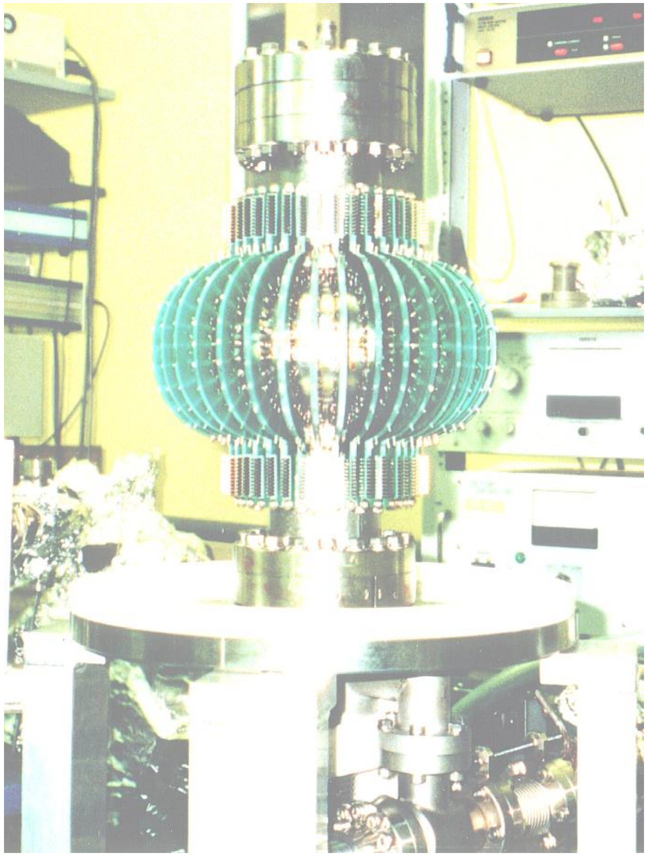
15.4 Field Emission

15.5 Thermal Instability

15.6 Hydrogen Q-Disease

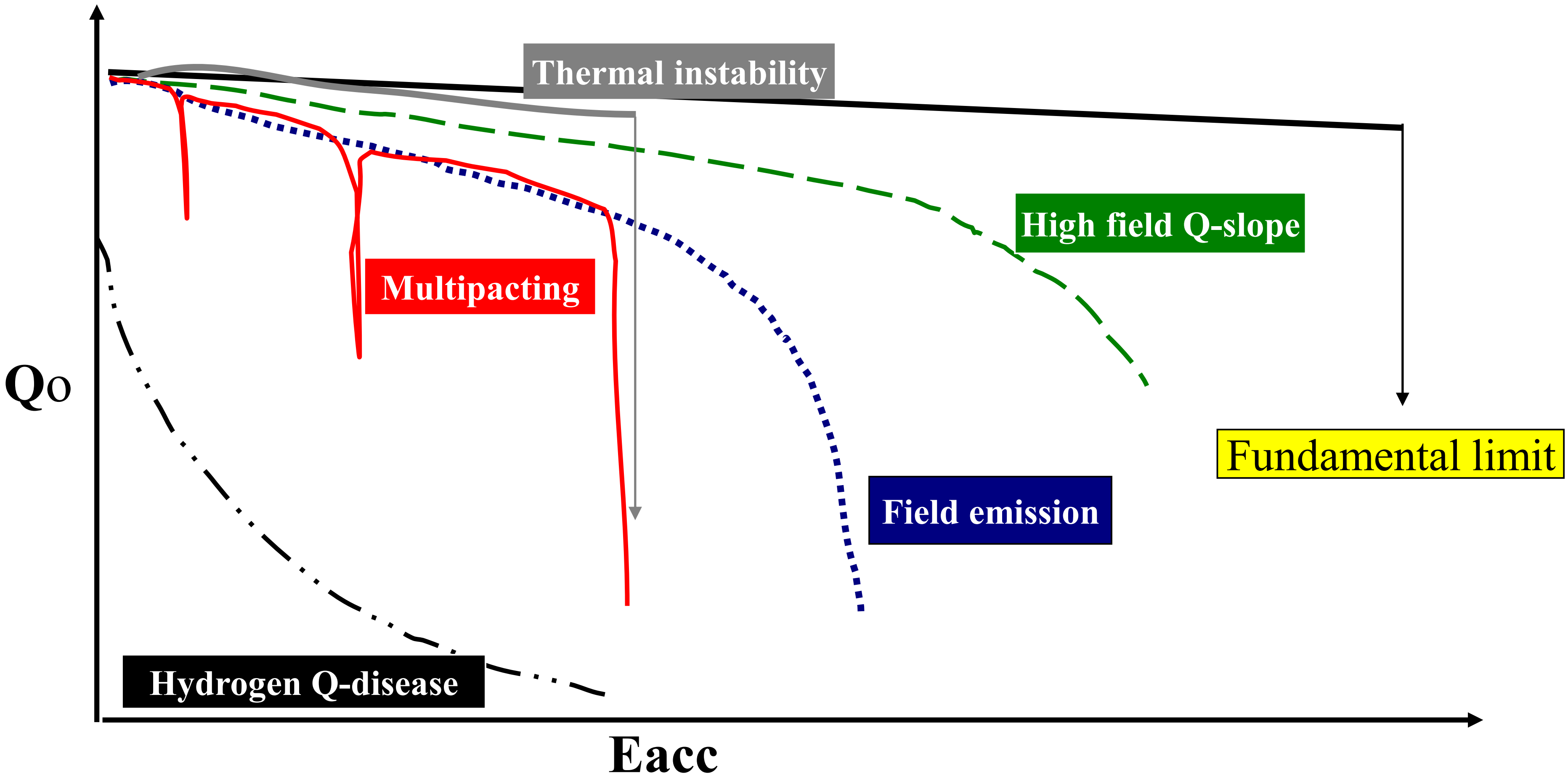
15.7 High Field Q-Slope

15.8 Magnetic Field Enhancement

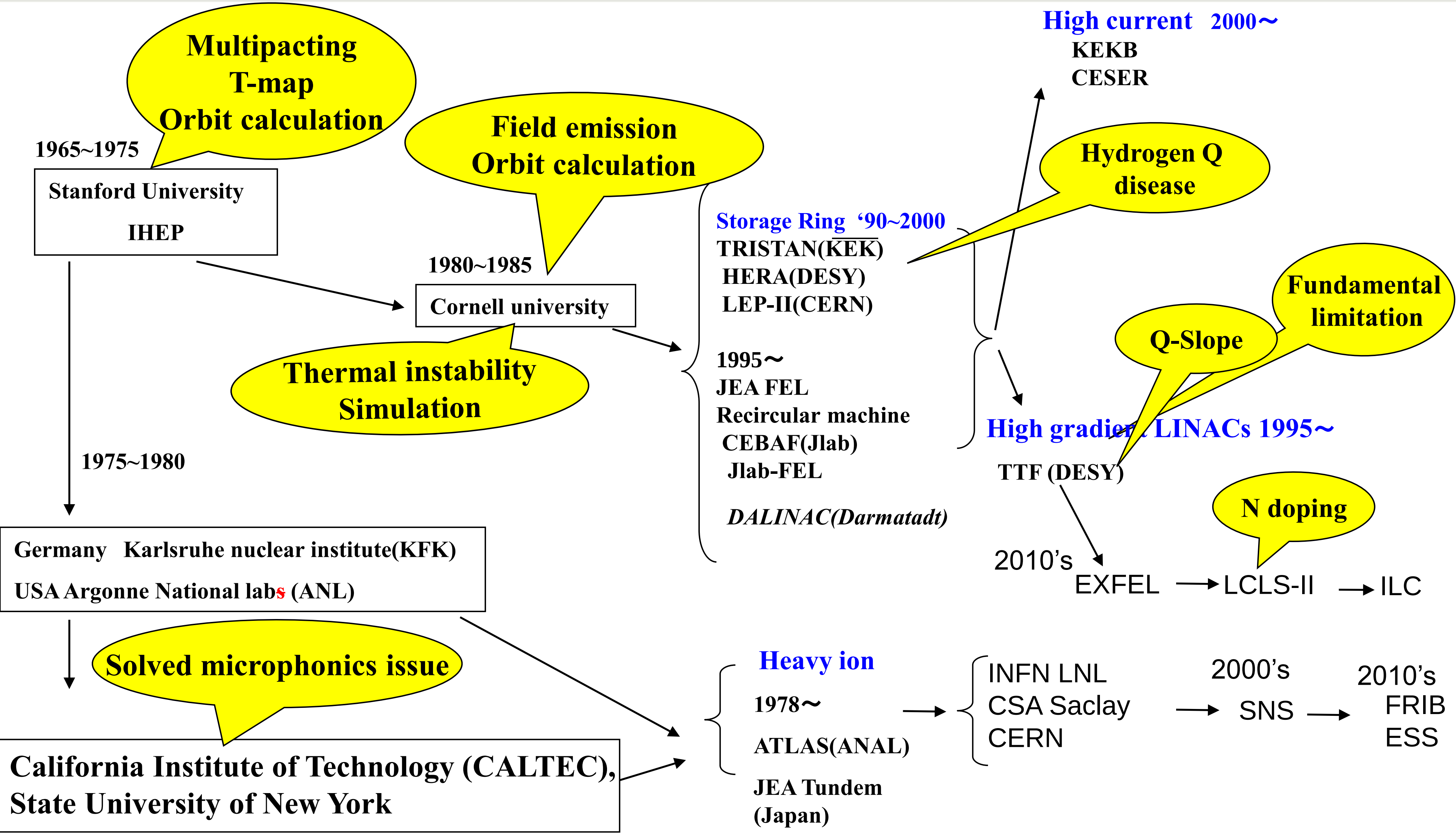


15.1 SRF Cavity Performance Limitations Summary

- Below are 6 major phenomena that are well known as the SRF cavity performance limitations so far.



15.2 History of Understanding of the Phenomenon

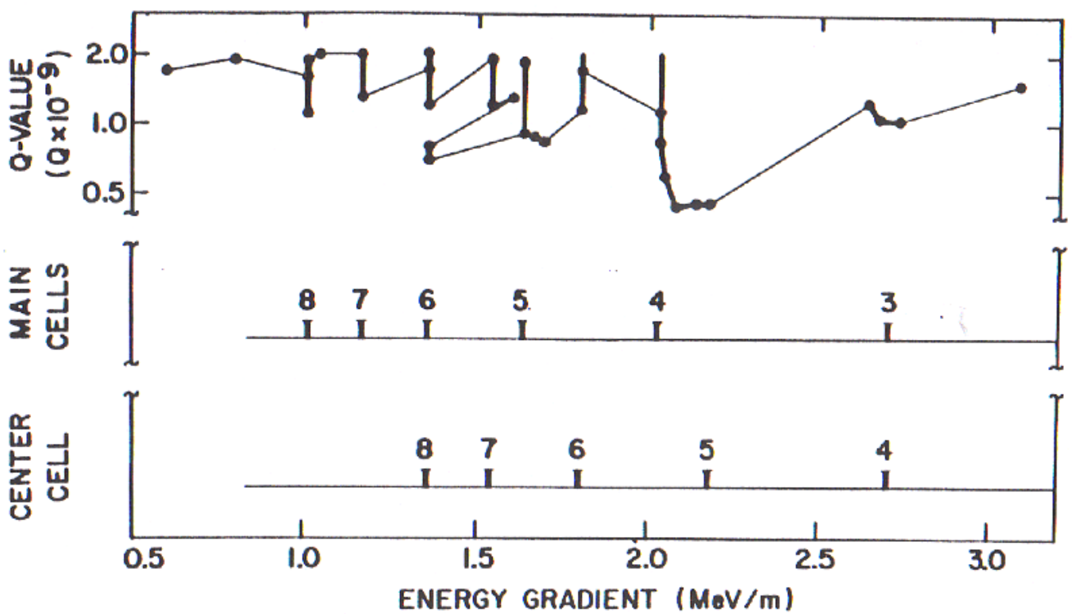


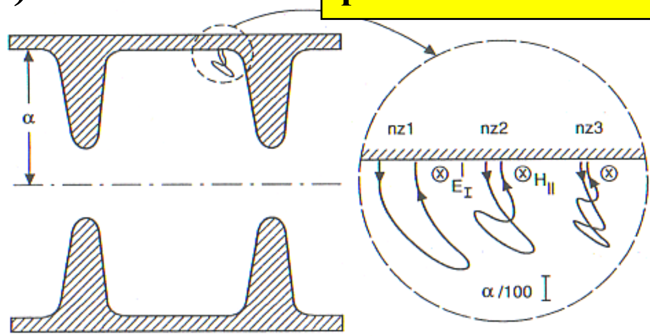
15.3 Multipacting

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

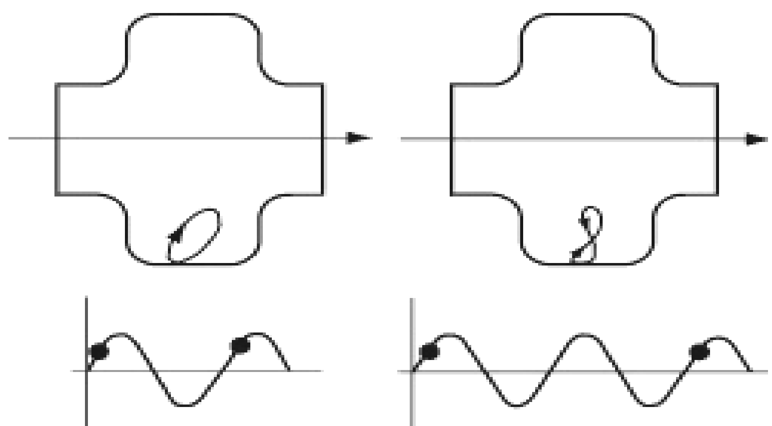
Multipacting limited the cavity performance remarkably.

One point multipacting





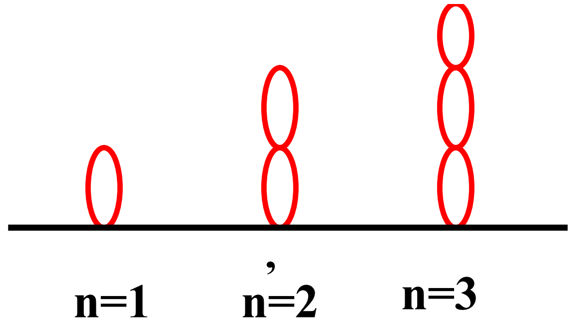
1 point MP



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

Resonant with RF frequency !!



Scale law on RF frequency with the maltipacting levels

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

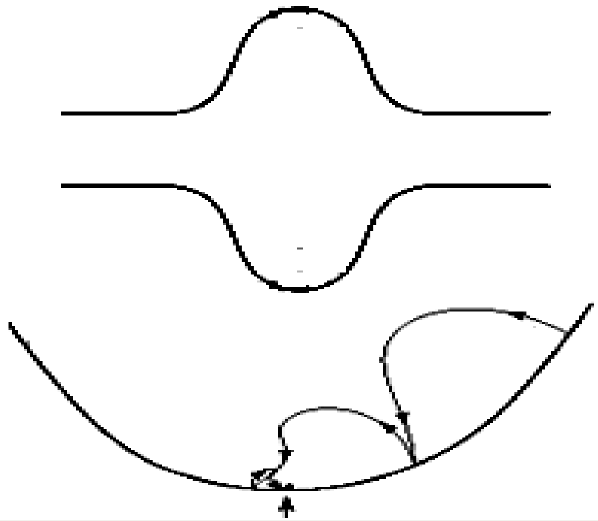
$$2\pi \cdot f(1P - nth) = \frac{e \cdot H(1P - nth)}{c \cdot m}$$

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

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

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

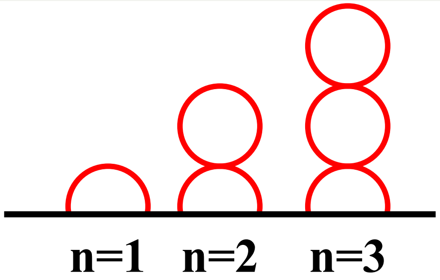
Two-point MP

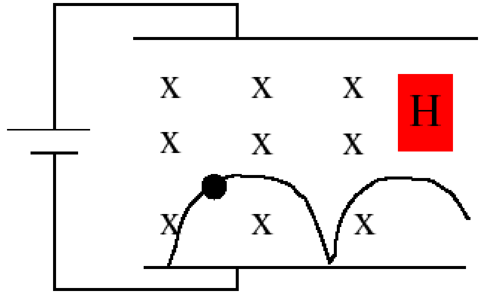
Two-point multipacting

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

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

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

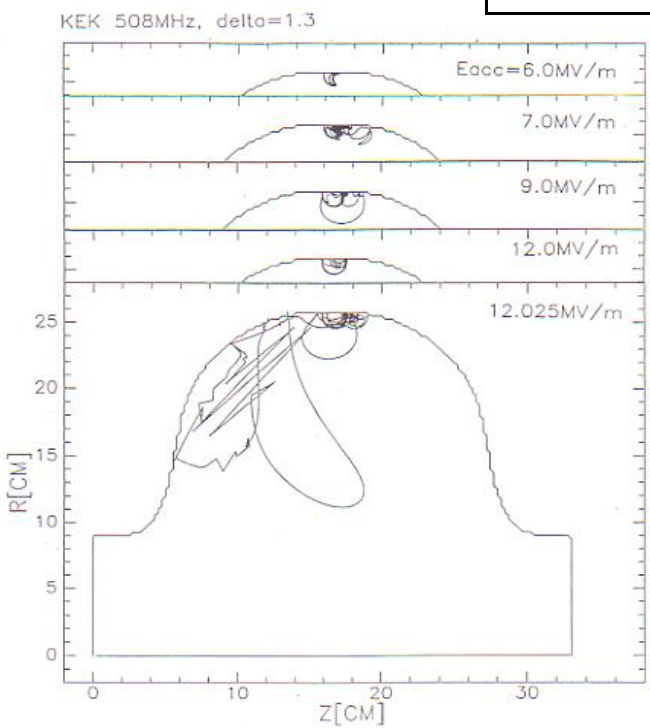




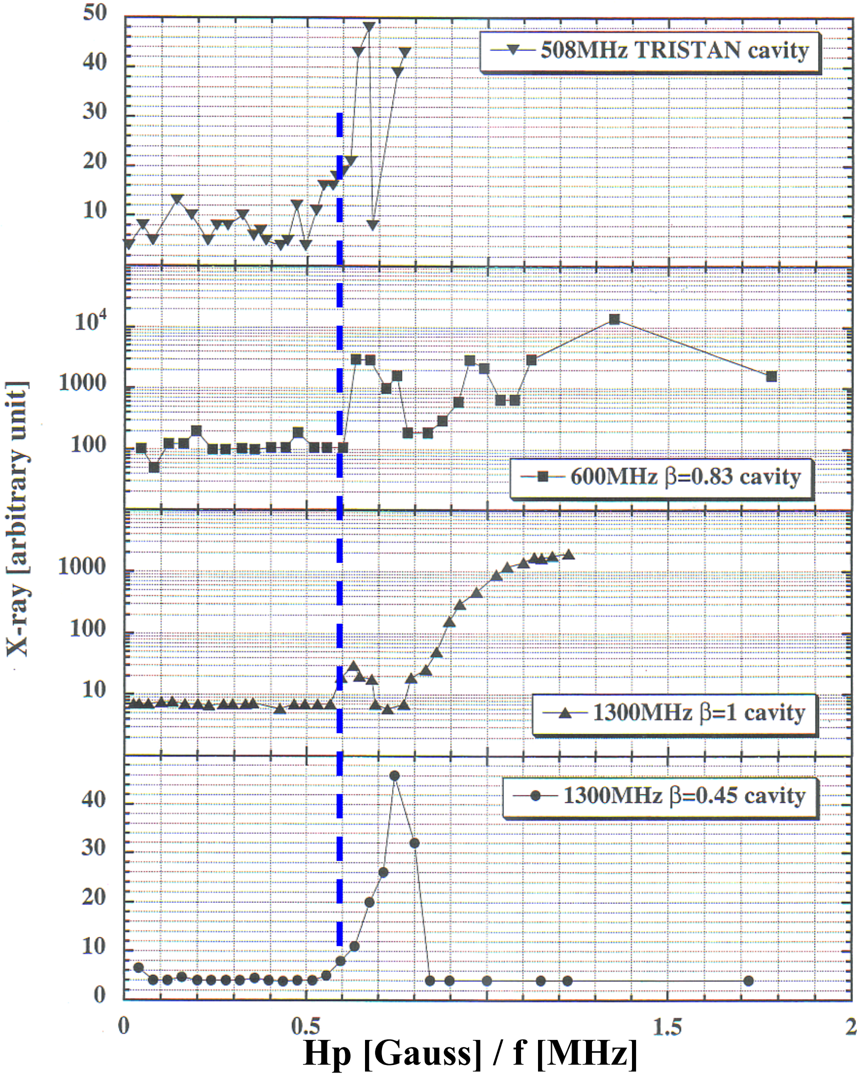
Examples ;
508MHz , Hp/Eacc=40.6 [Oe/(MV/m)]
2P-1st order Hp(2p-1st) = 0.6 x 508 = 304.8 Oe
Eacc(2P-1st) = 304.8/40.6 = 7.5 MV/m

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: measurement

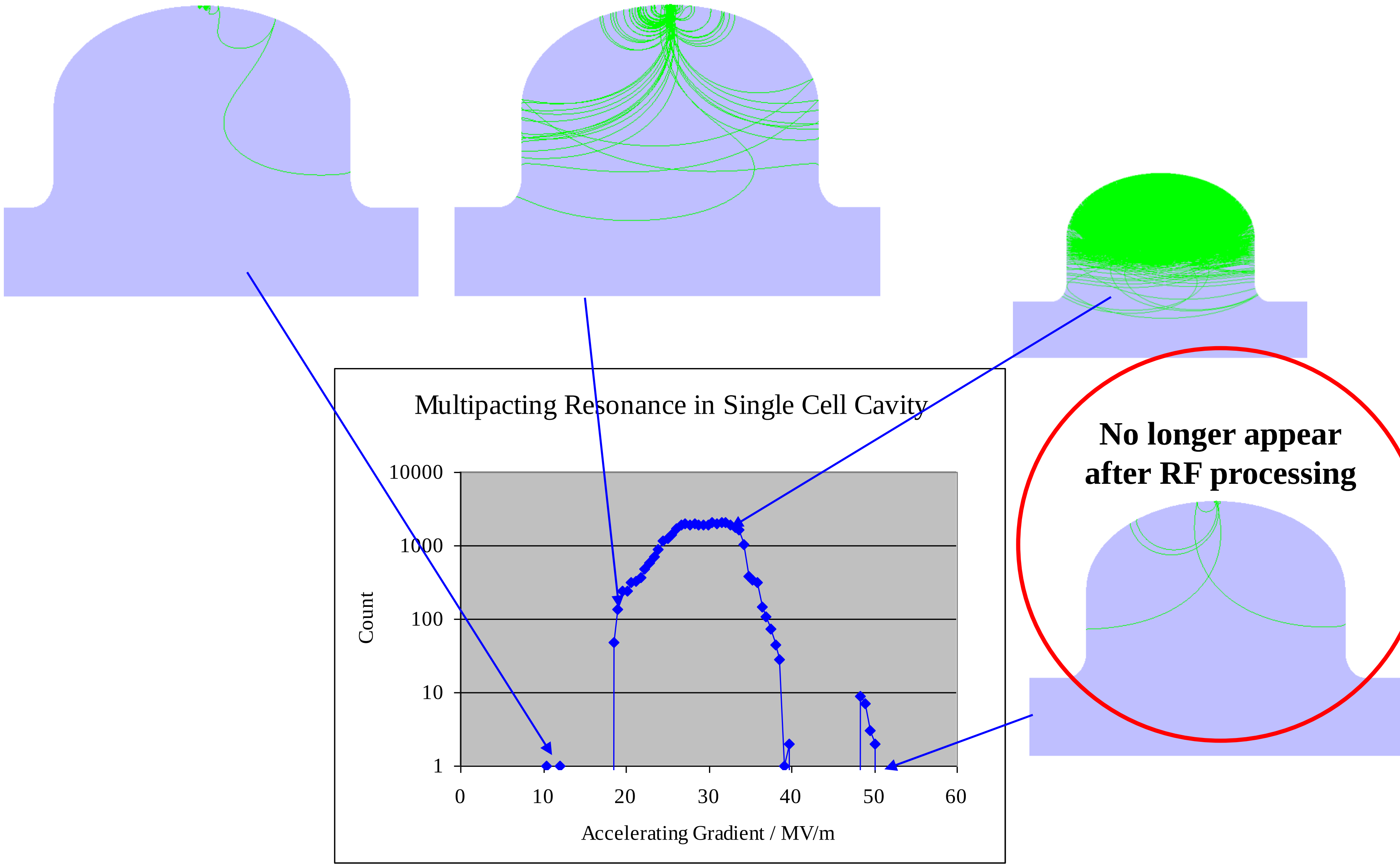


$$2P-onset = \frac{Hp[Gauss]}{f\,[MHz]} \approx \frac{0.6}{2n-1}$$

- Onset of MP is well scaled by Hp/f.
- RF processing of MP has a memory effect.
- The memory has gone when cavity warmed up T > 200K, then needs re-RF processing in the further cooling.

MP Simulation (Two point MP)
Some wide barrier

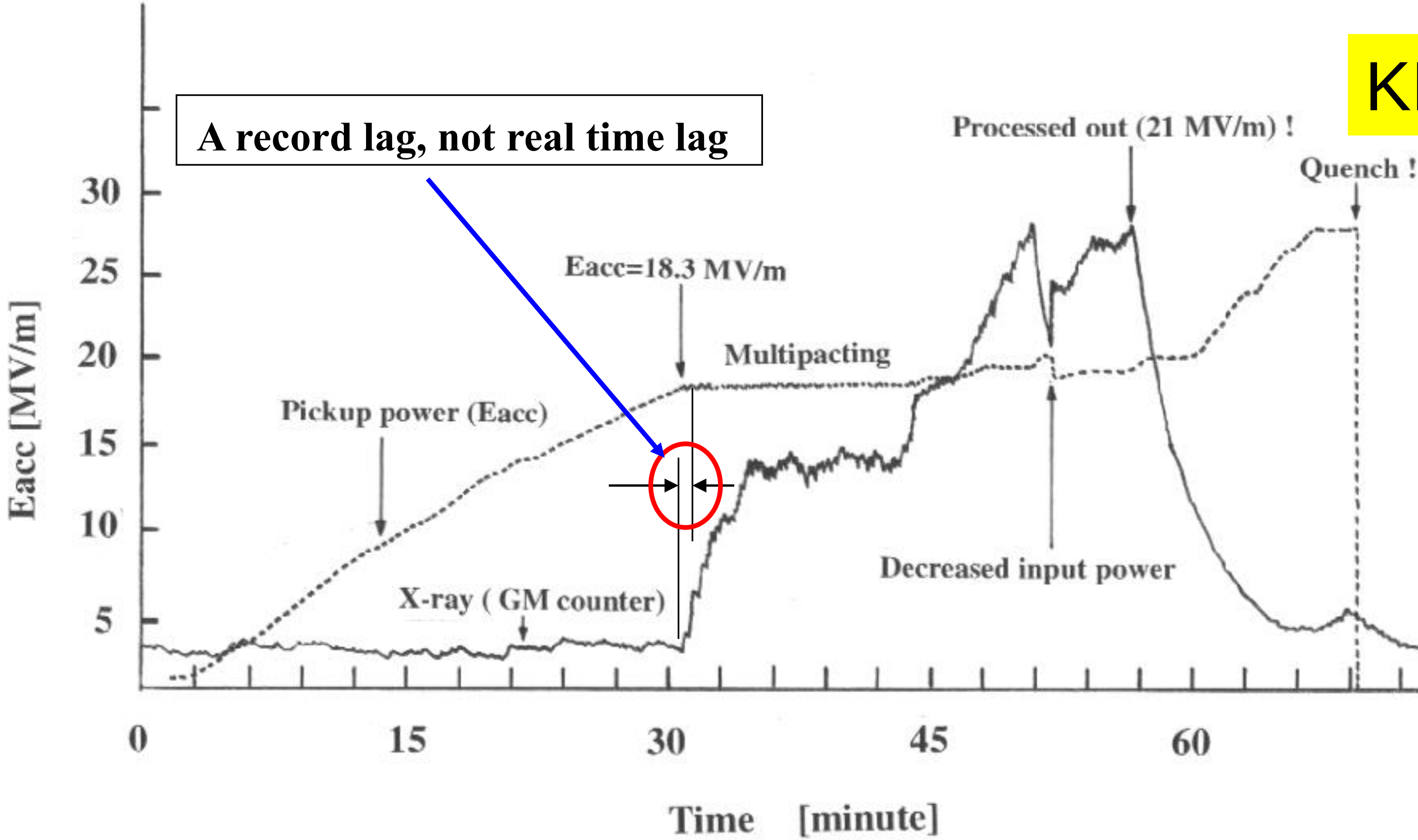
by Morozumi



RF Condition of MP Barrier: Example for 1.3 GHz Single Cell Cavity

- MP can be processed out by RF conditioning but the conditioning period depends on the contamination level

KEK



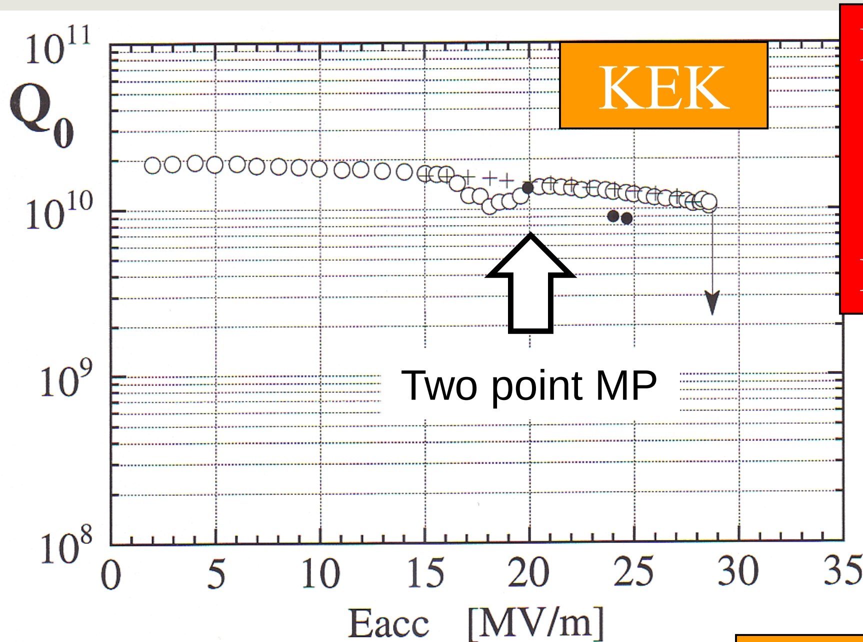
Phenomena of Tow-point MP

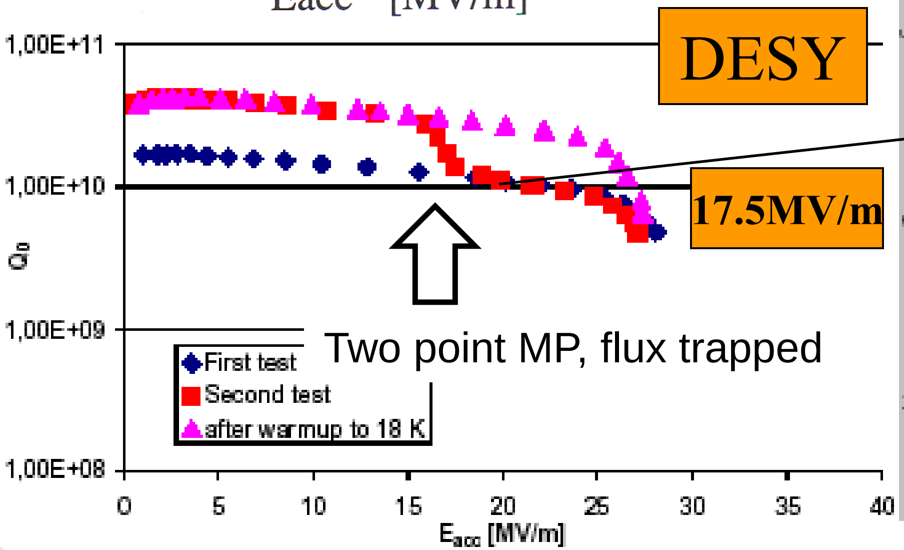
MP → Electron bombardments (local heating) → Frozen flux trapping

⇩ Warm-up T > T_c

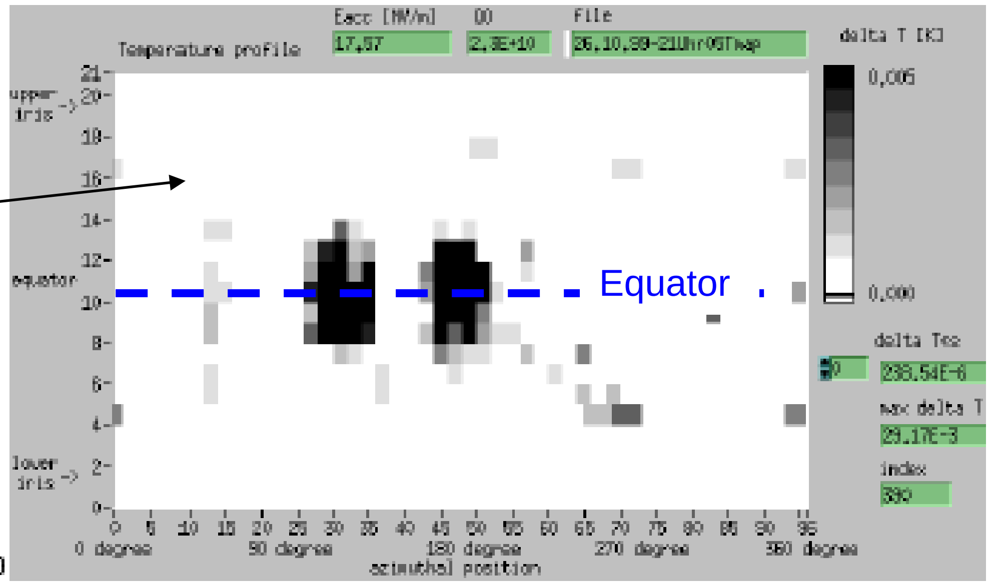
⇩ Release flux trapp

Disappearance of the heating spots





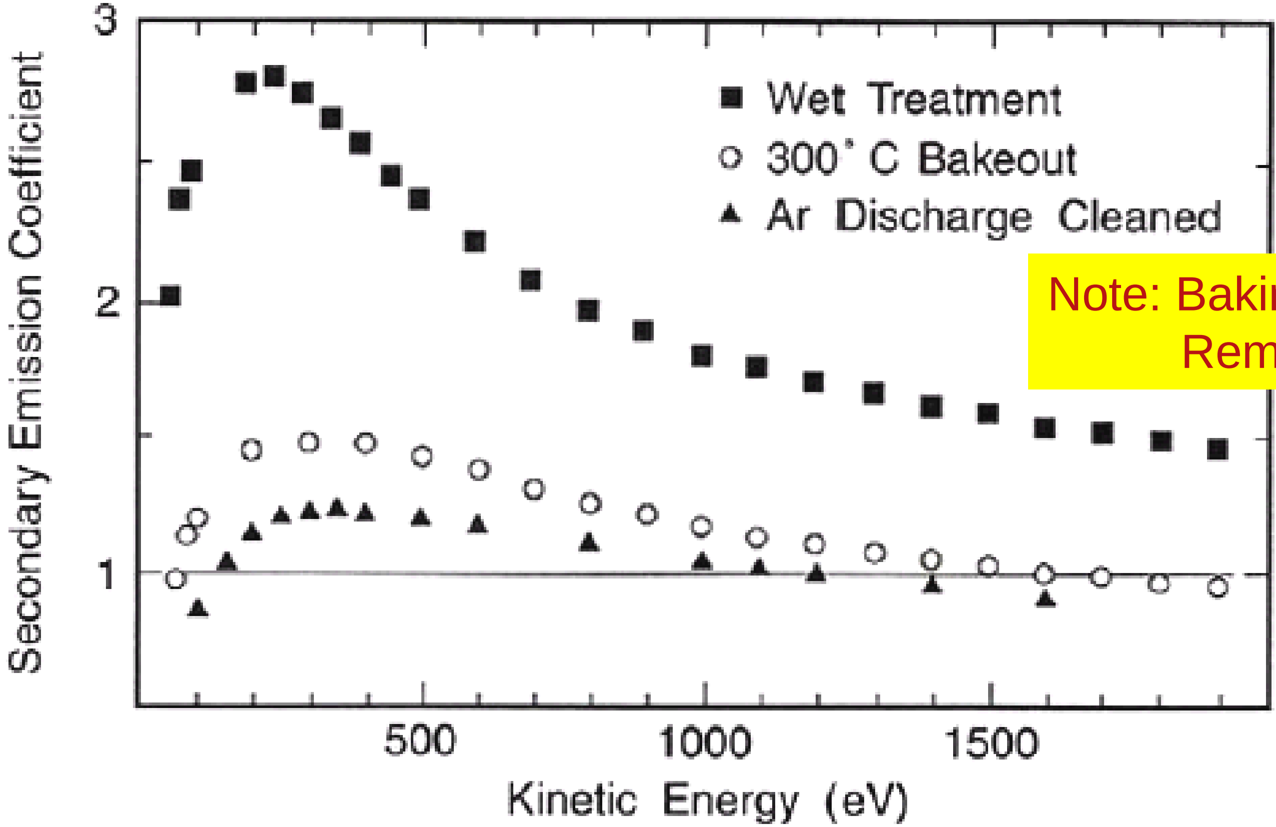
T-mapping at 17.5MV/m



Cures Against MP

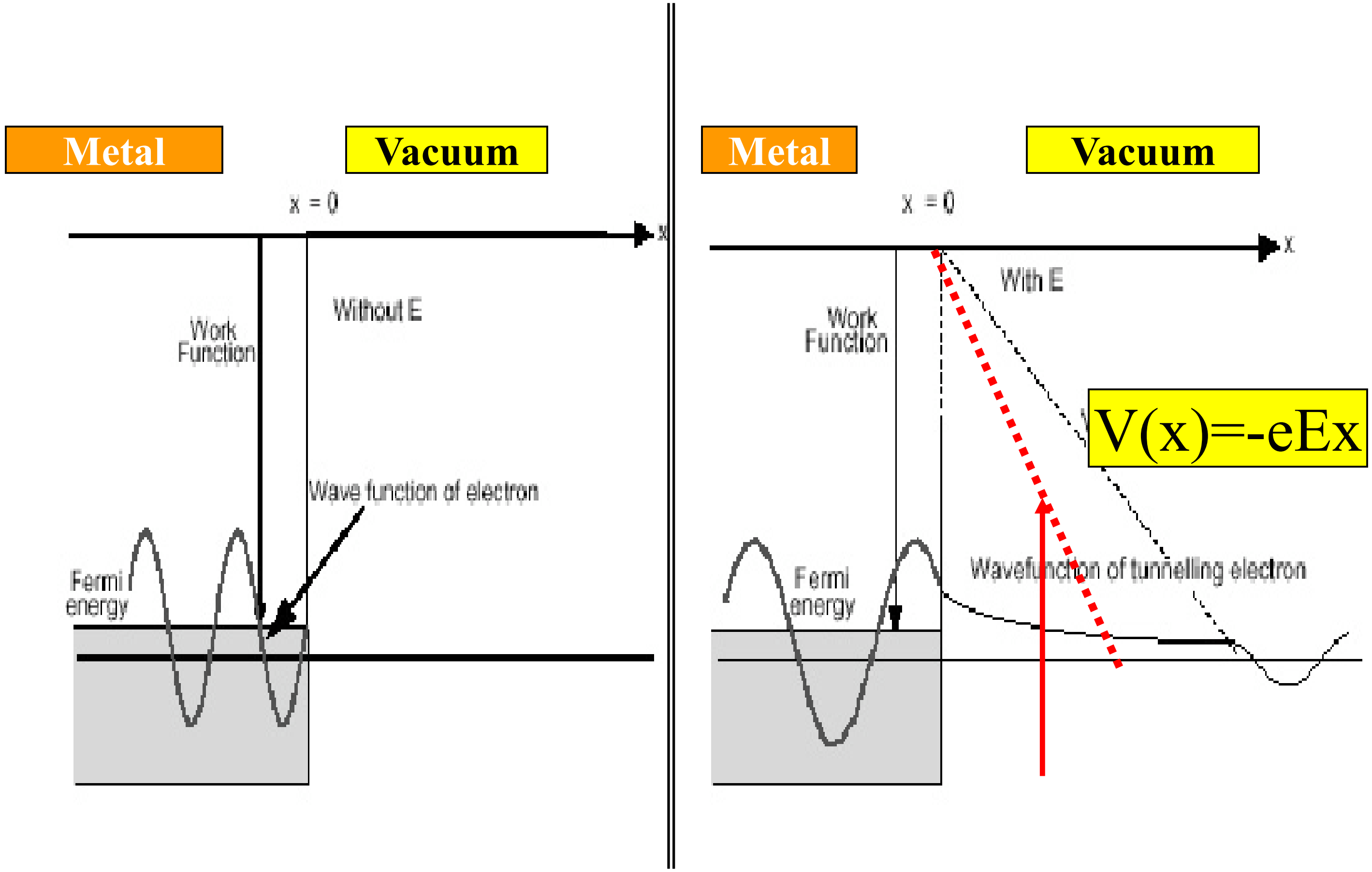
1) Cavity shape ⟶ Spherical or Elliptical shape
(effective for one point multipacting)

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



Note: Baking is effective !!
Remove H_2O

15.4 Field Emission

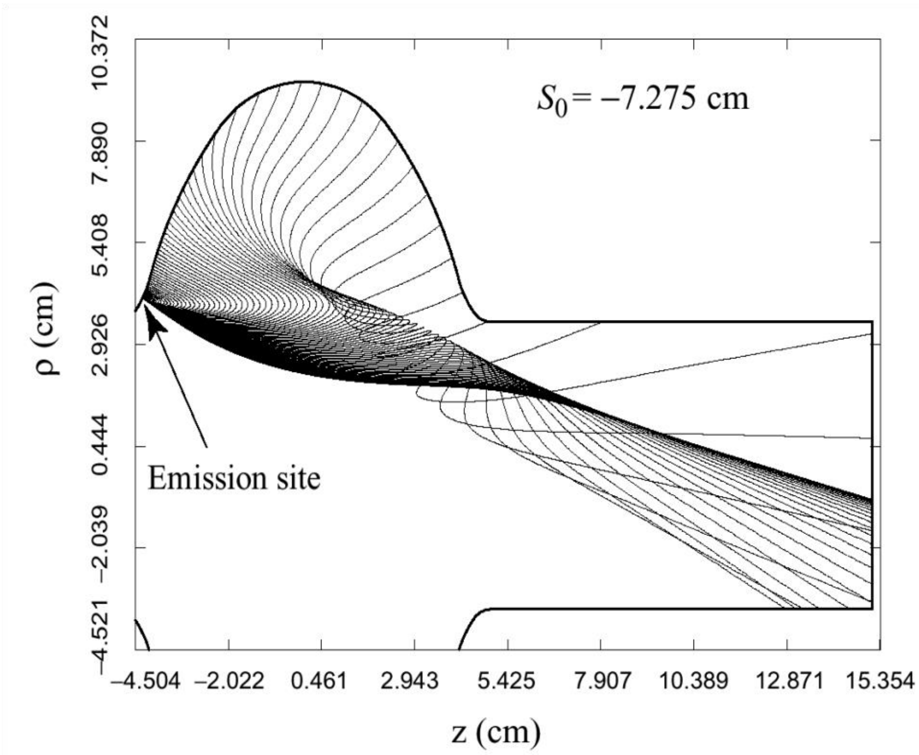


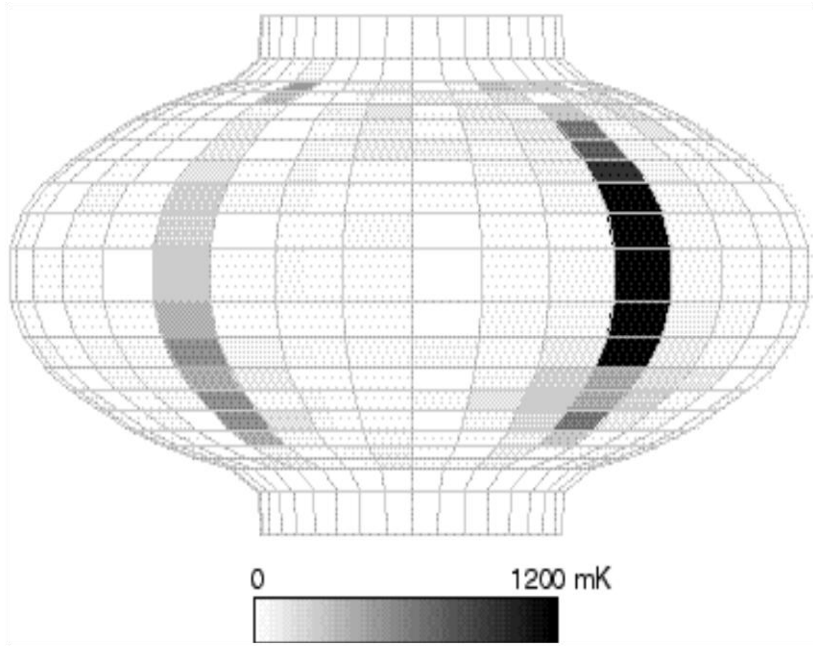
The tunnel thickness becomes thin when the field amplitude is getting larger. Penetrated tunnel electron increases exponentially with increased field amplitude.

Field Emission Trajectory

None resonant with RF frequency

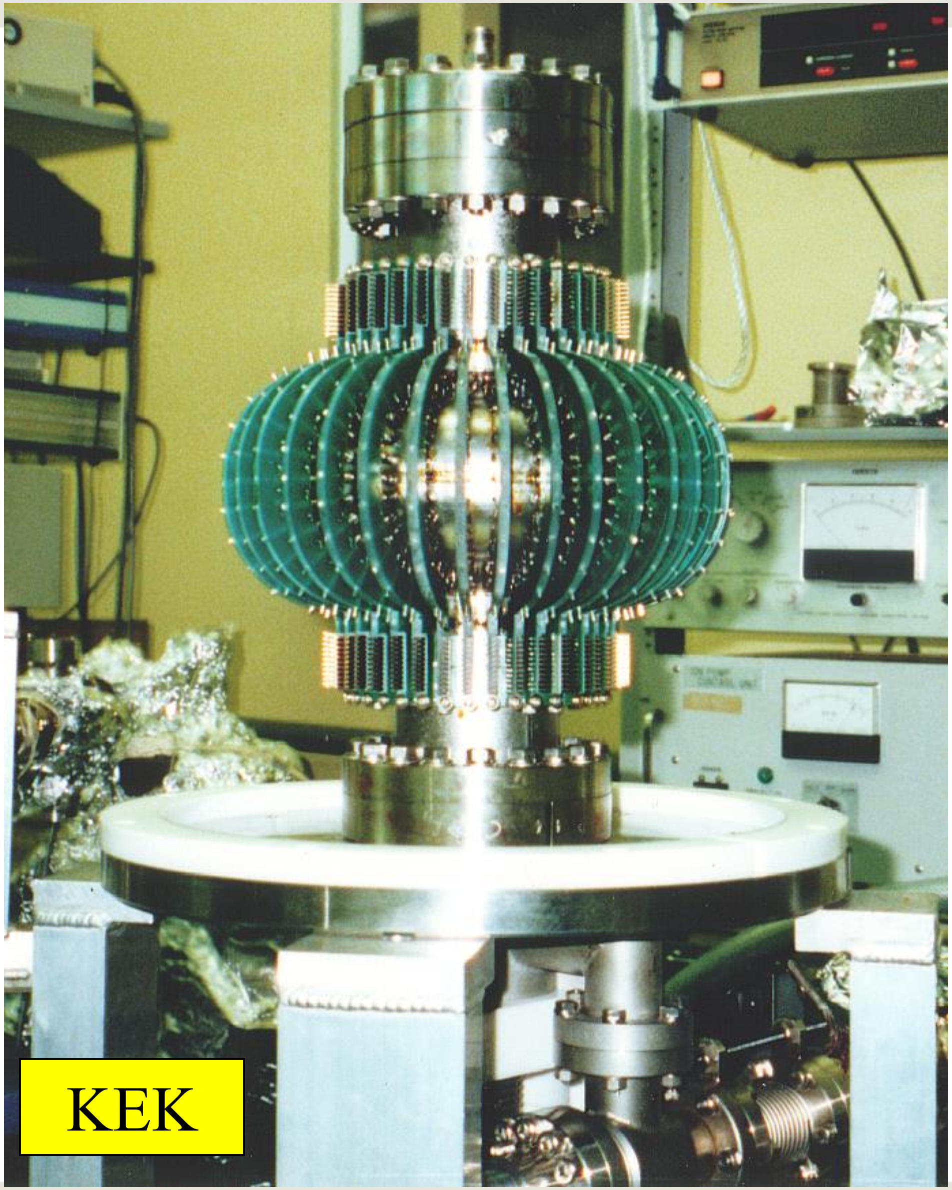
Non-resonant electron loading due to field emitted electrons by tunneling effect

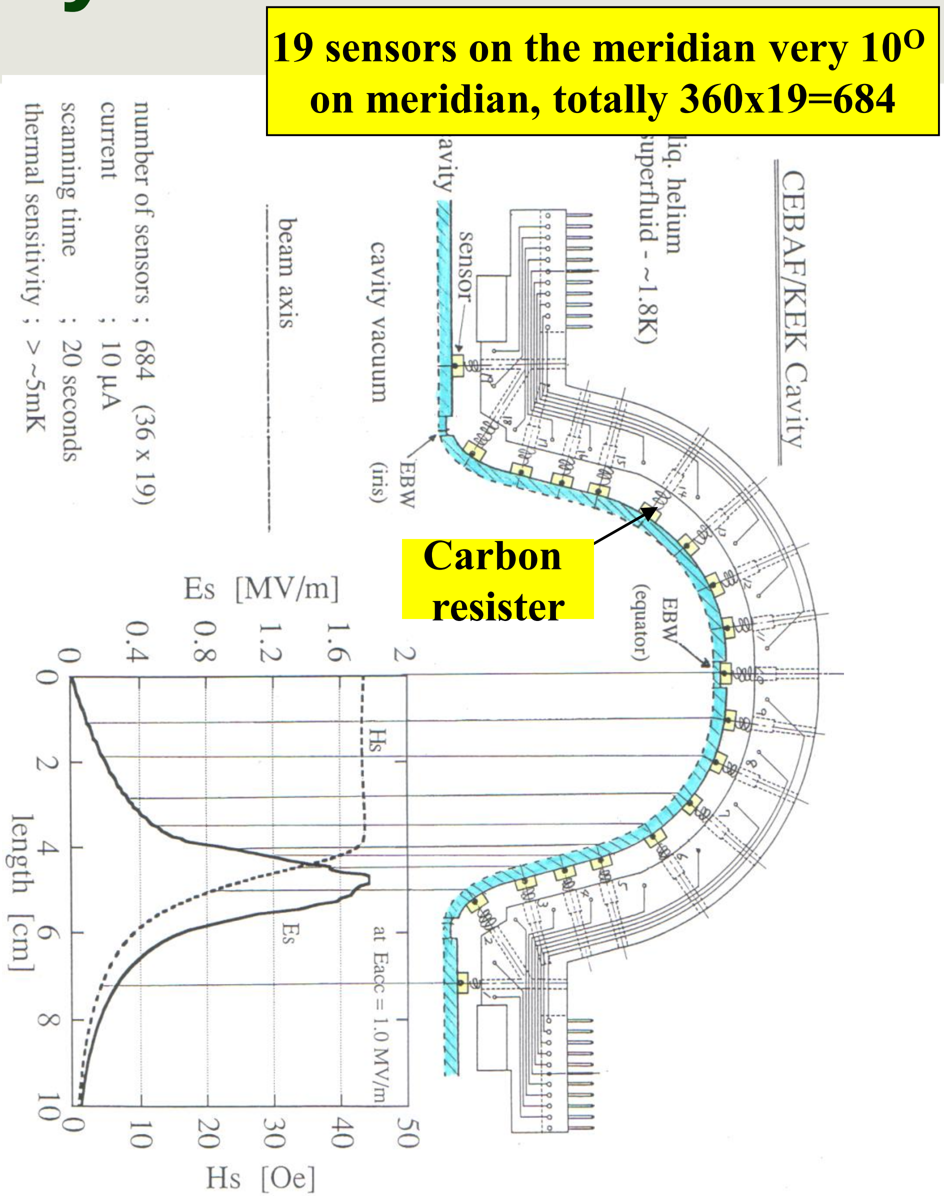




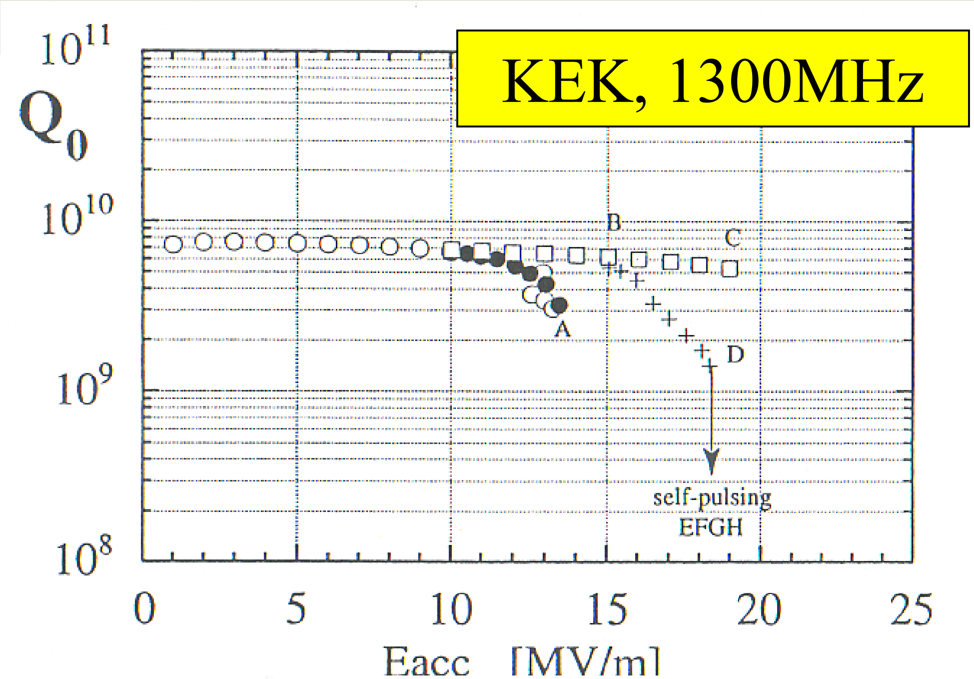
Heating spots appears on one meridian.

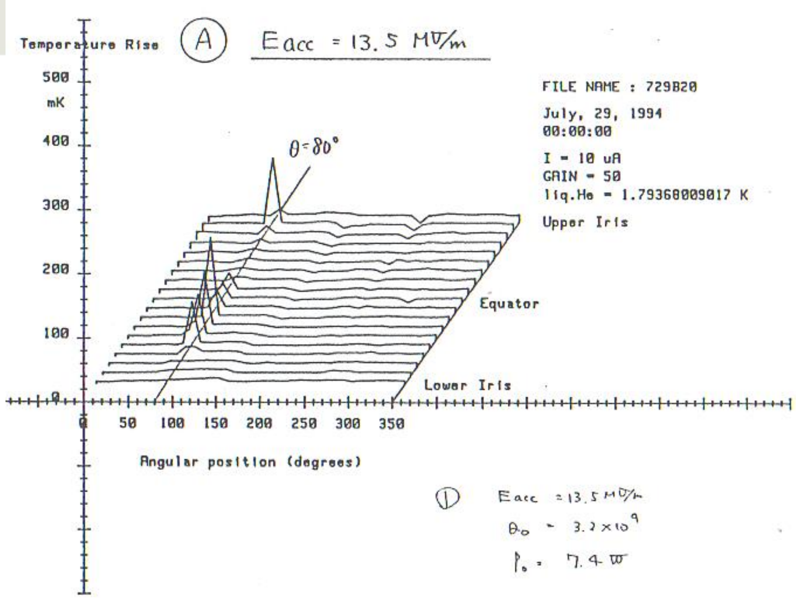
T-mapping System

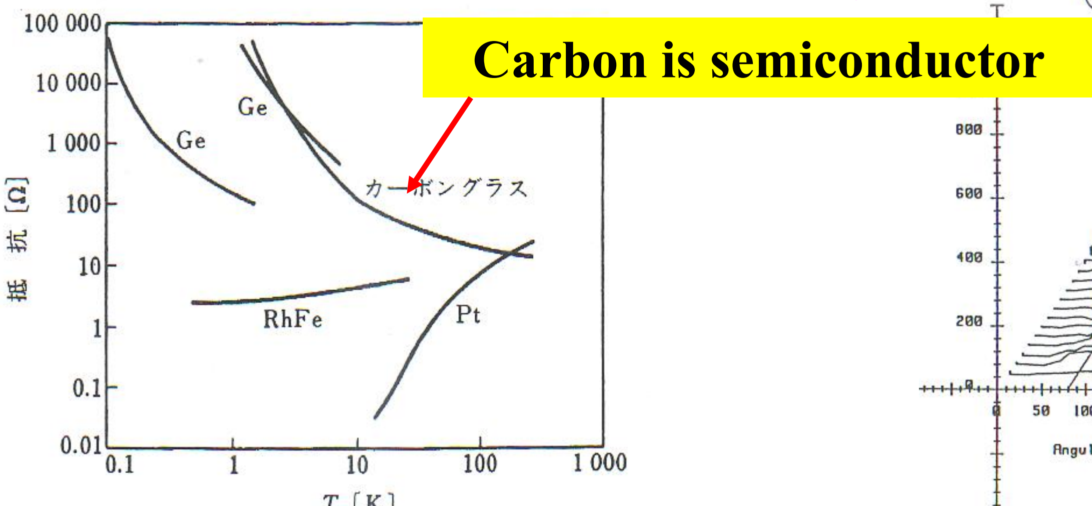


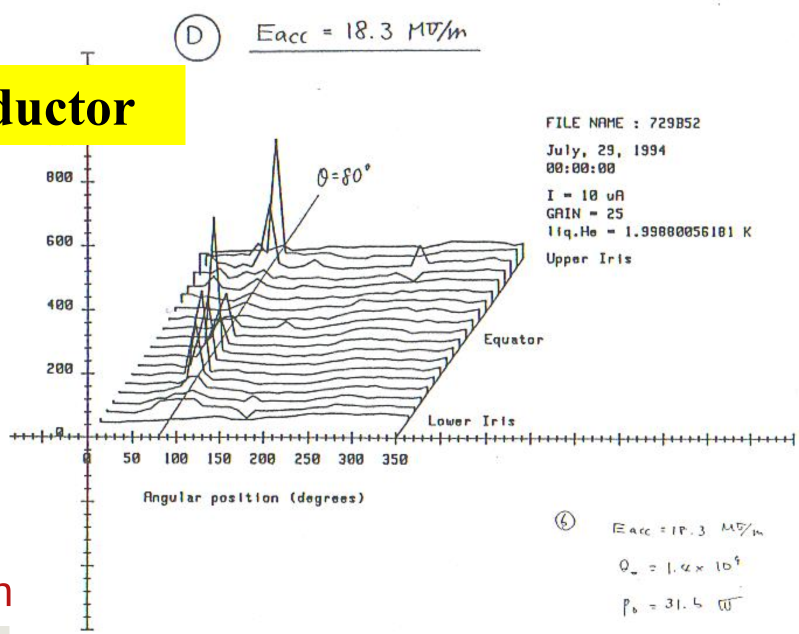


T-mapping Measurement at KEK





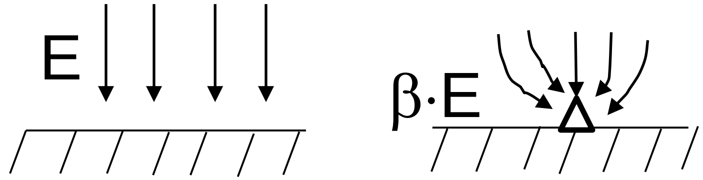


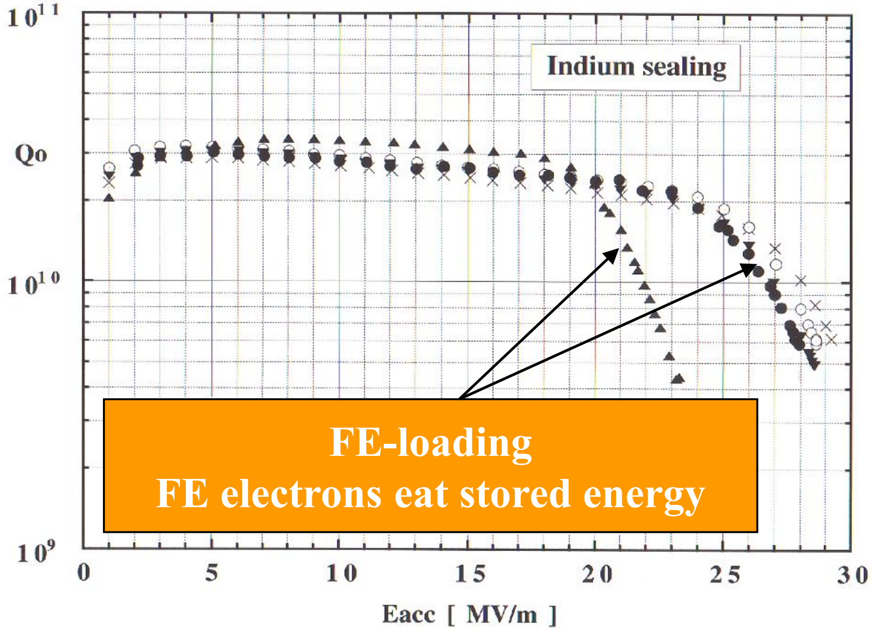


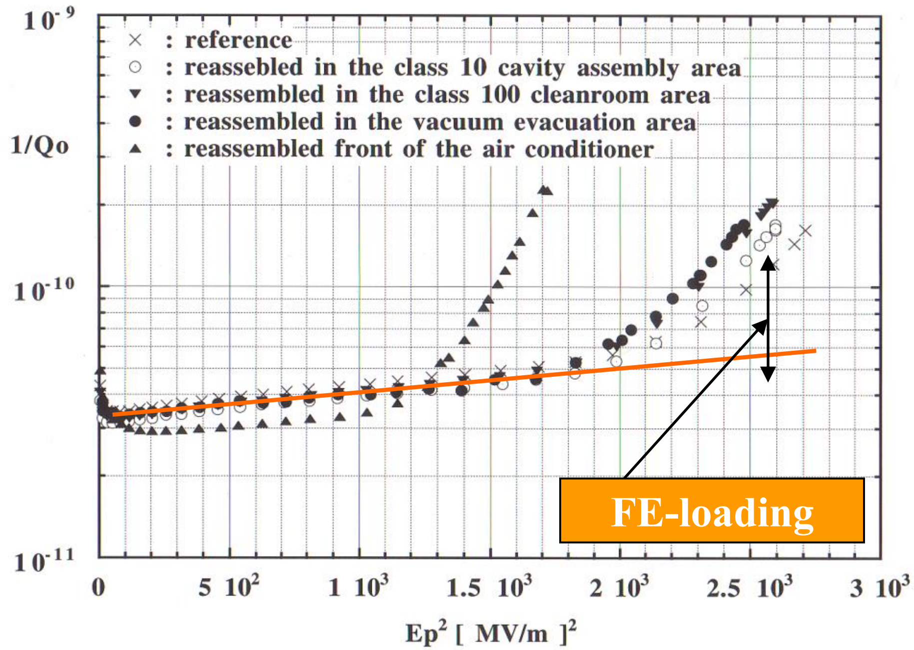
Resistance-Temperature characteristics of carbon

Field Emission Analysis

- Field emission onset
- Field enhancement factor β







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

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

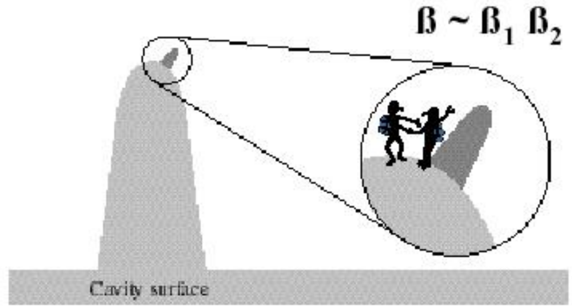
Projection Model of Field Enhancement Factor

Field enhancement factor β ; 50 ~ 1000

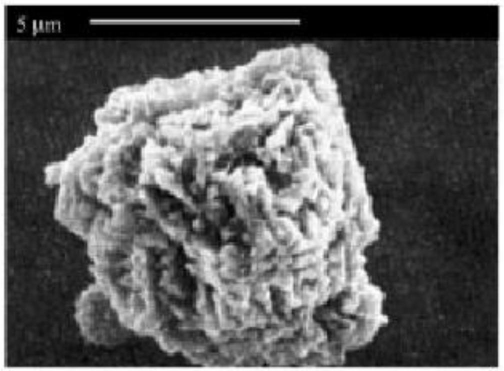
Projection model :

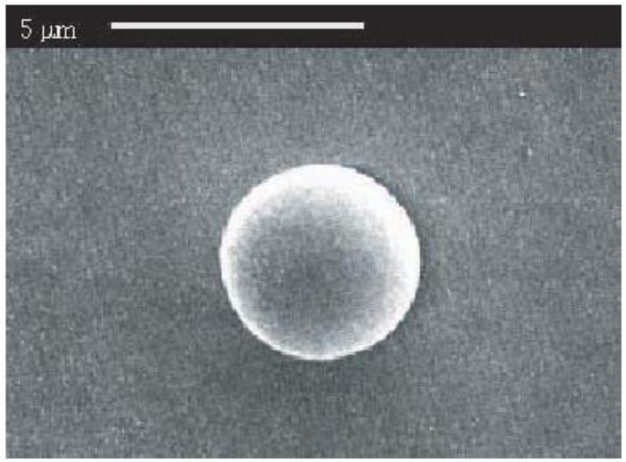
Why β is so large?

- *Tip-on-tip* model is one explanation



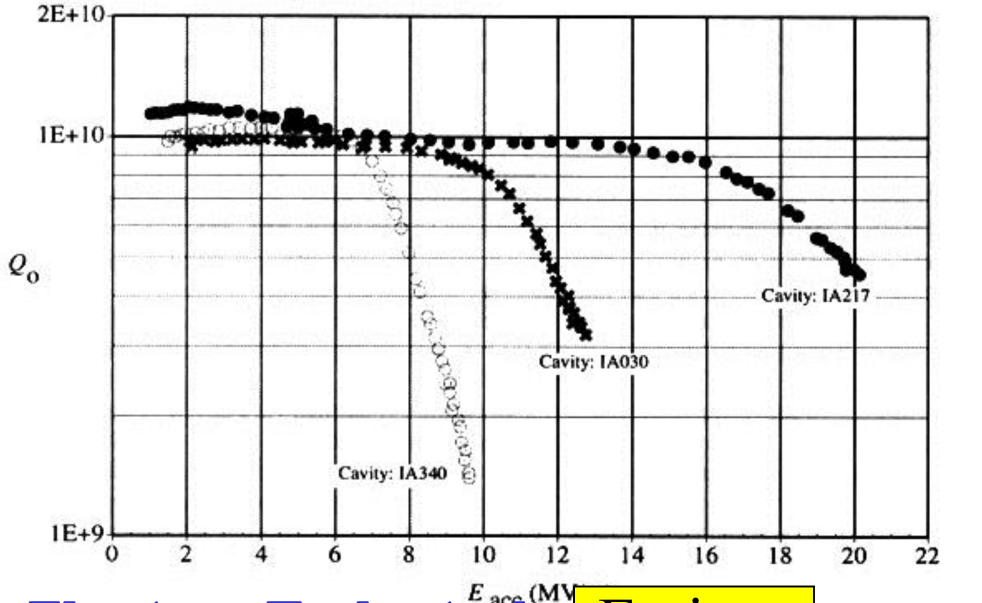
- Smooth particles don't emit.

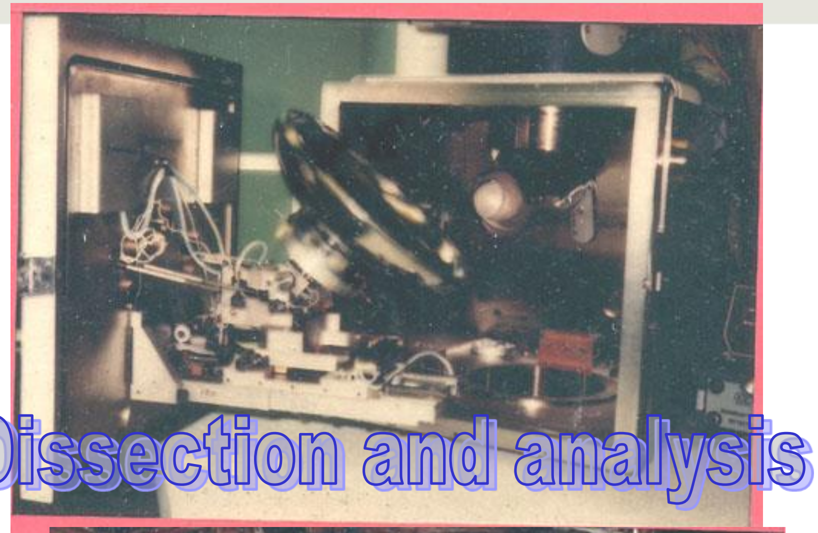




Cornell Studies on FE

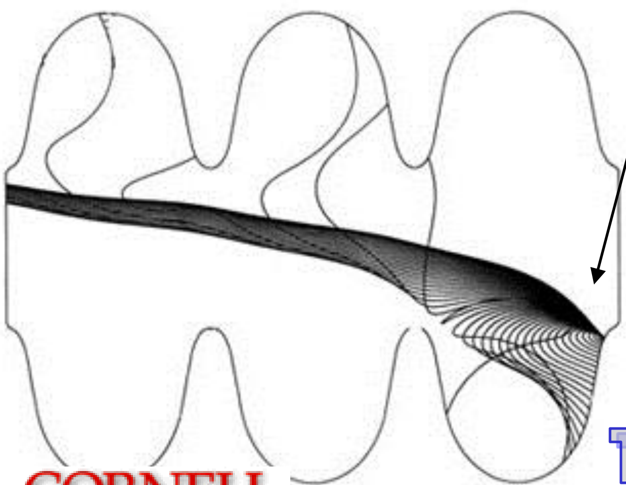
T-mapping, Trajectory calculation, Site analysis

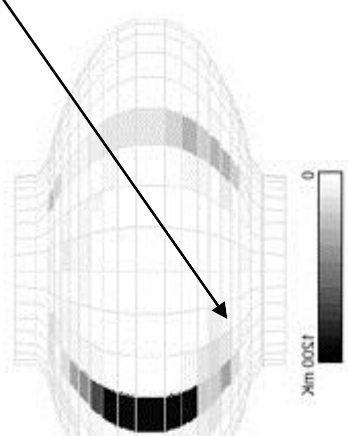




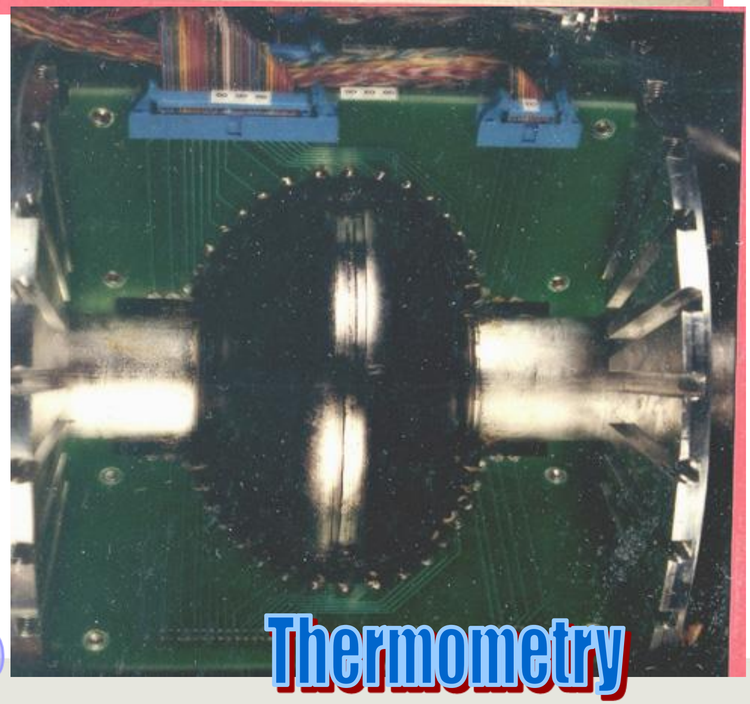
Electron Trajectories

Emitter

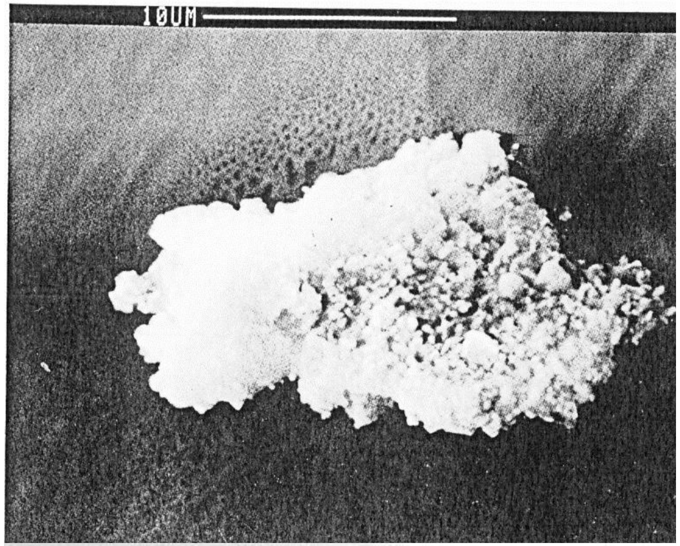


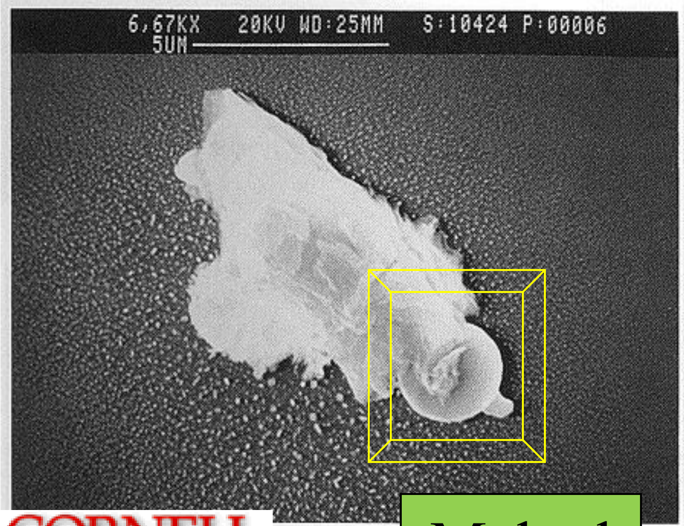


Temperature Map



Emitter of FE : Particles





Melted

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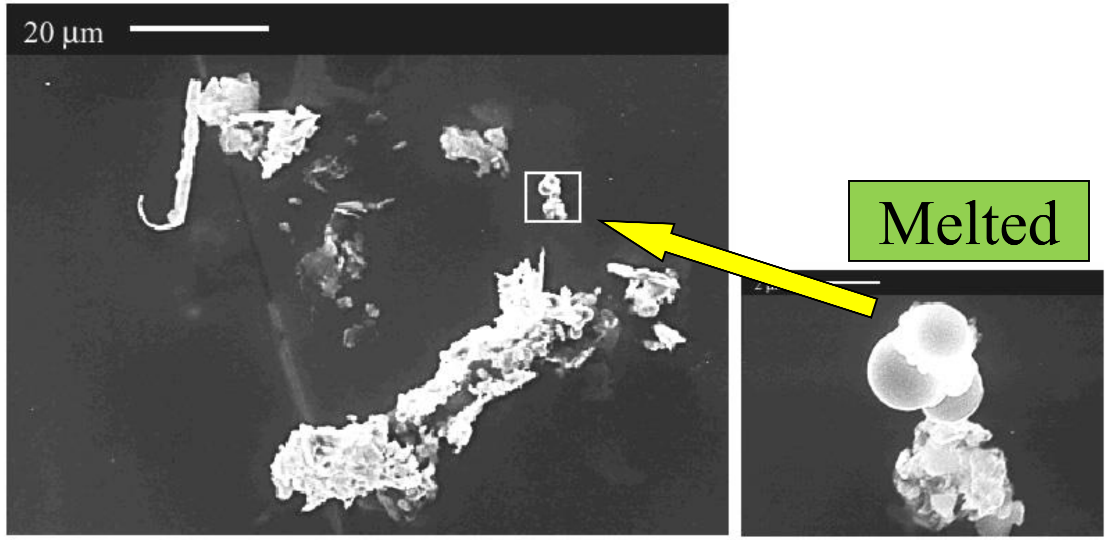


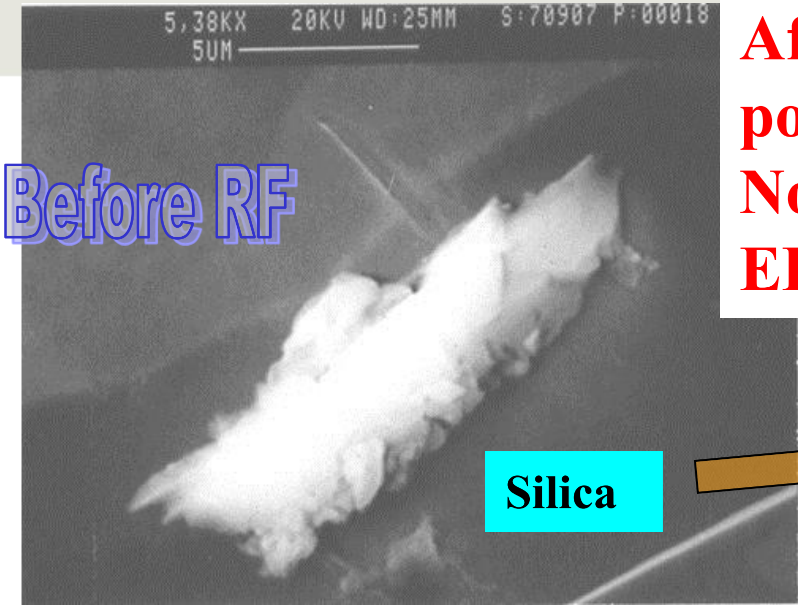
Emitters Found

in Niobium SC Cavities

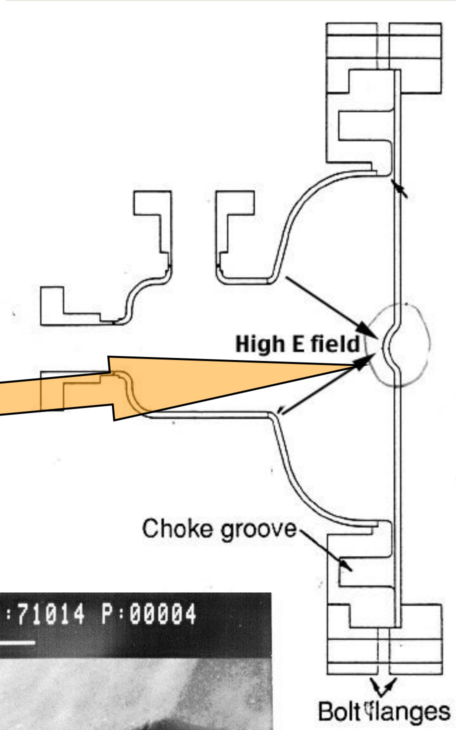
Particles - often melted

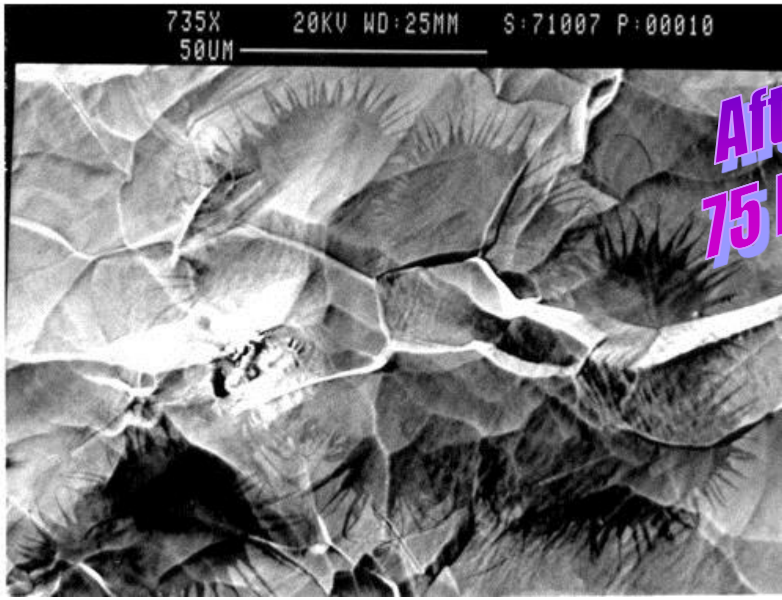
Particle free clean surface !!

Intentionally Introduced Particles

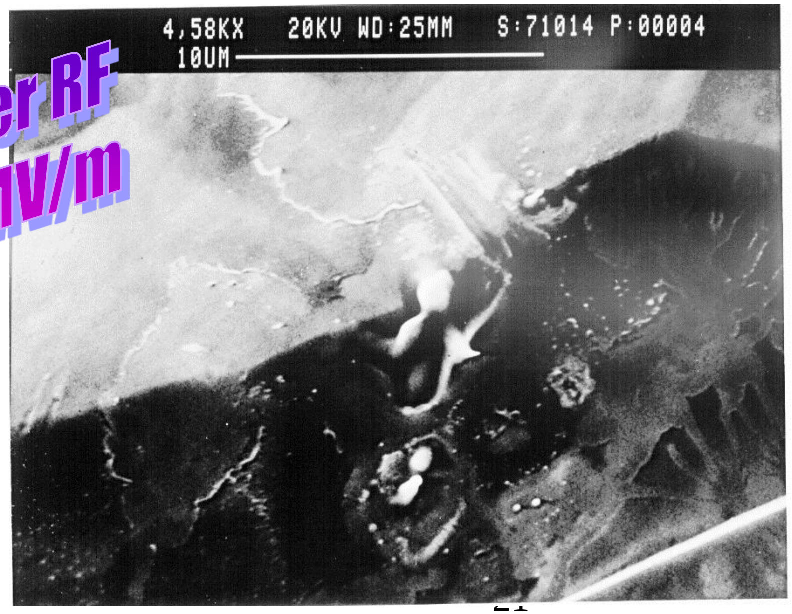


After RF high peak power processing. No silicon found by EDX, evaporated.

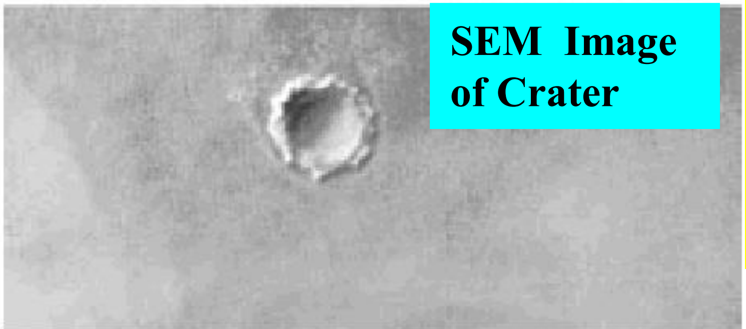




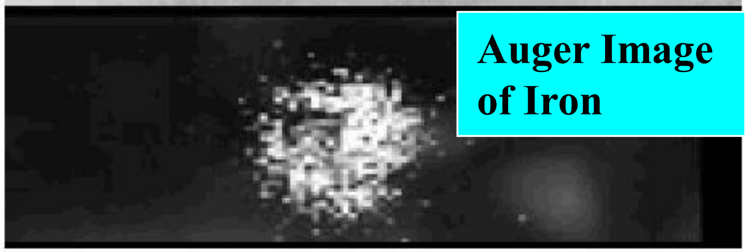
After RF 75 MV/m



Crater Shows Foreign Elements



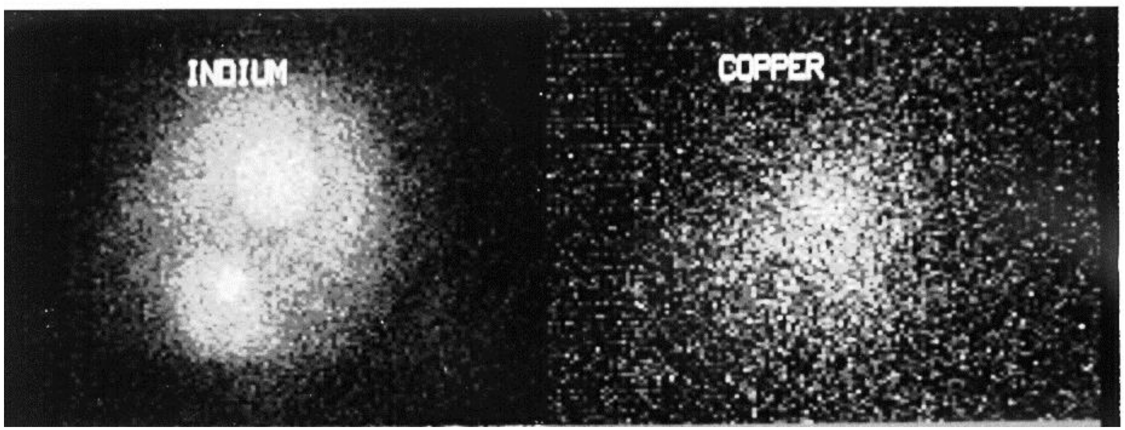
SEM Image of Crater



Auger Image of Iron

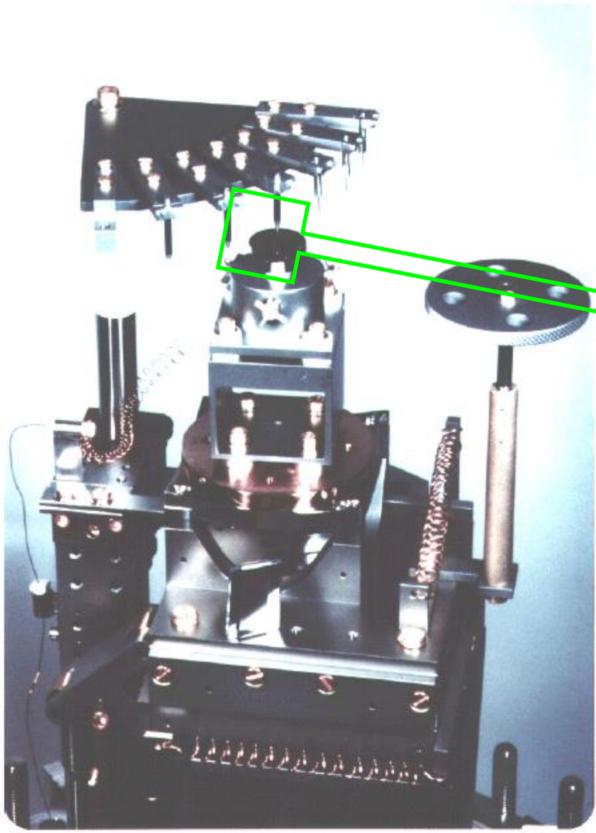
Edge geometry makes a field enhancement (recent understanding) !! Smooth surface is important.

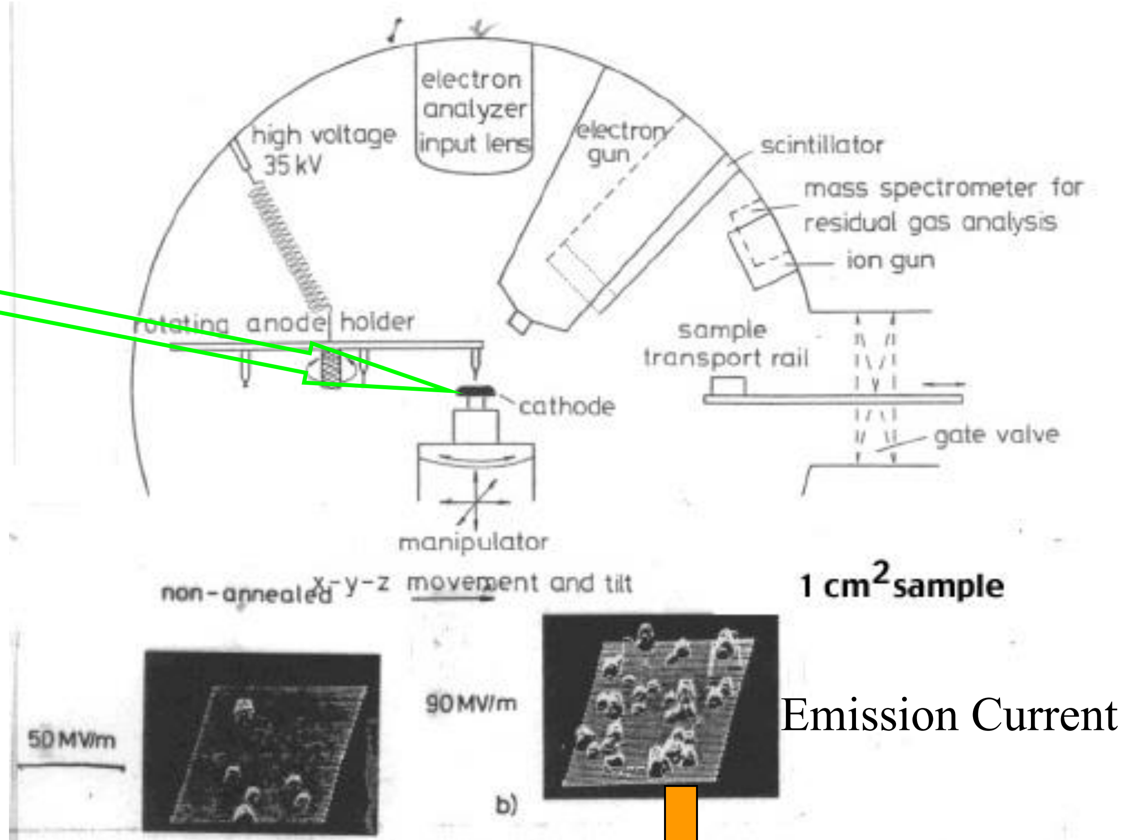
But - With Auger Analysis
Almost all craters show foreign material

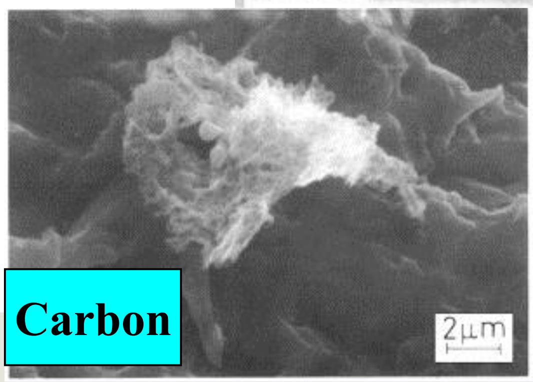


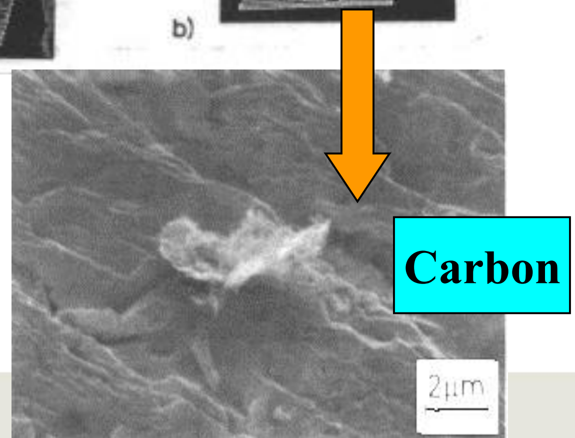
Auger Images of Craters

DC Field Emission Studies in University Geneva and Wuppertal

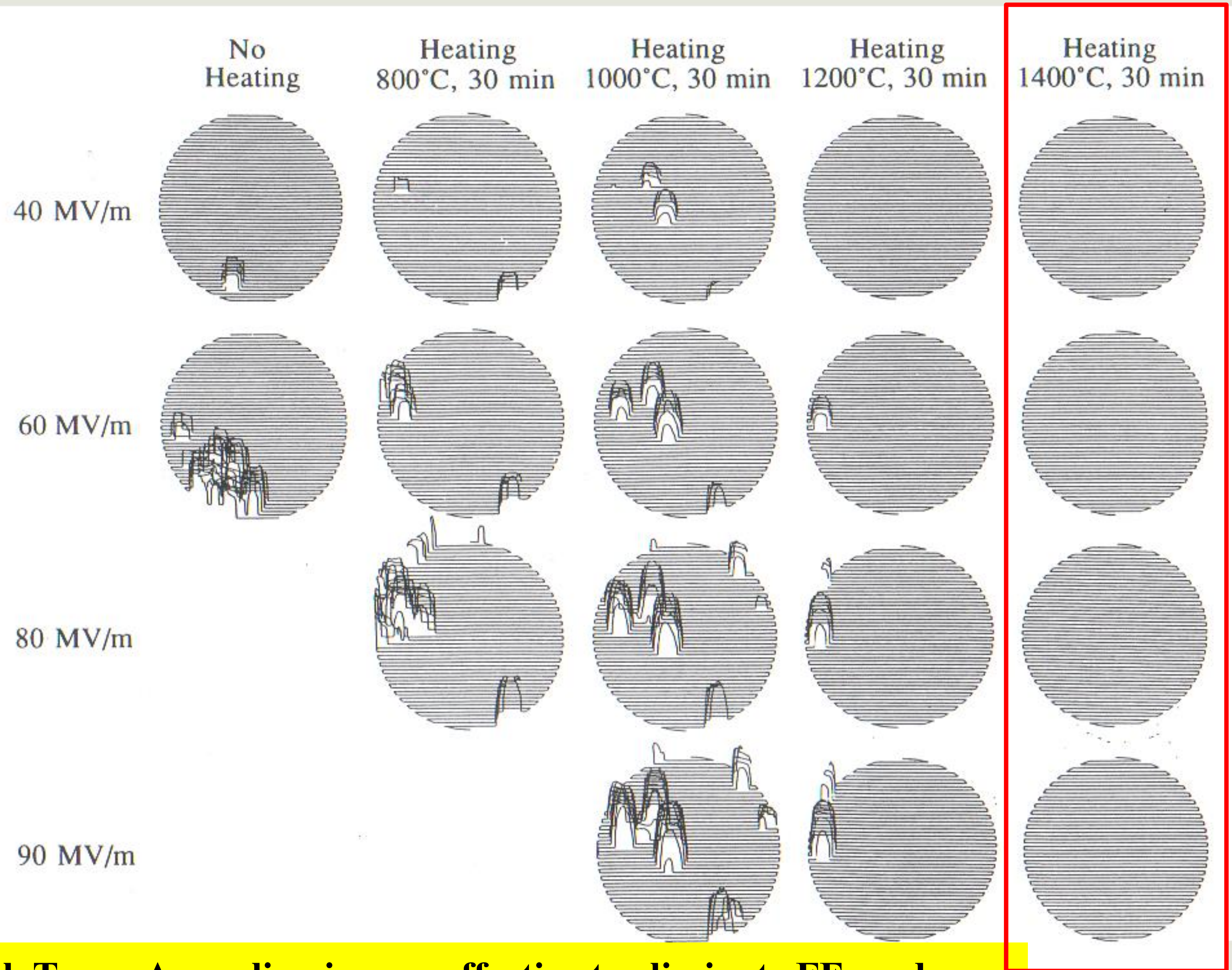






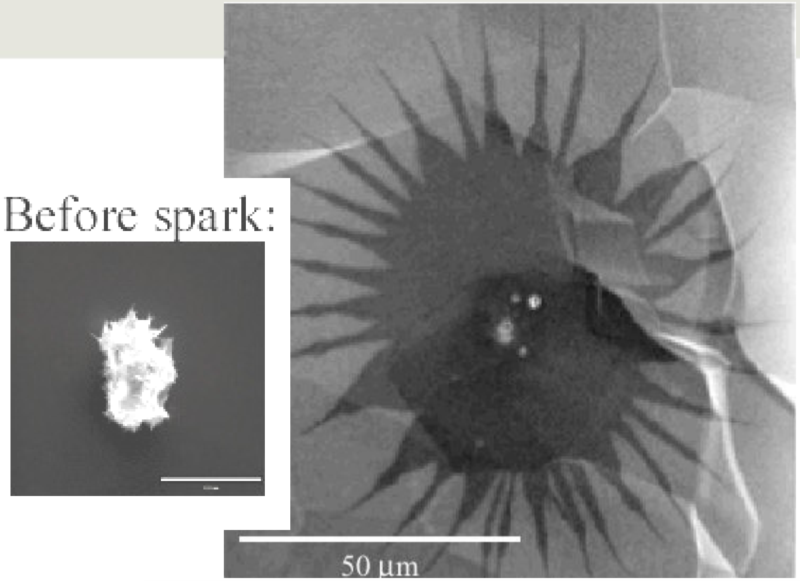


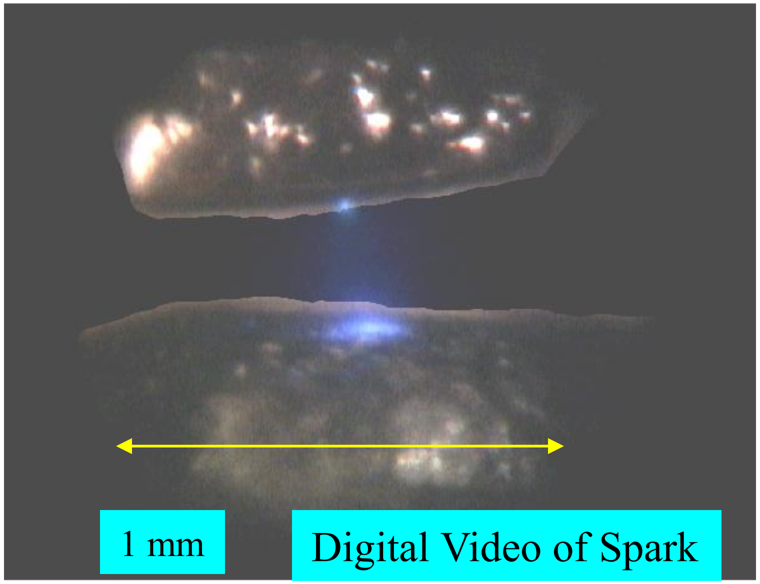
Wuppertal Result: High Temperature Annealing

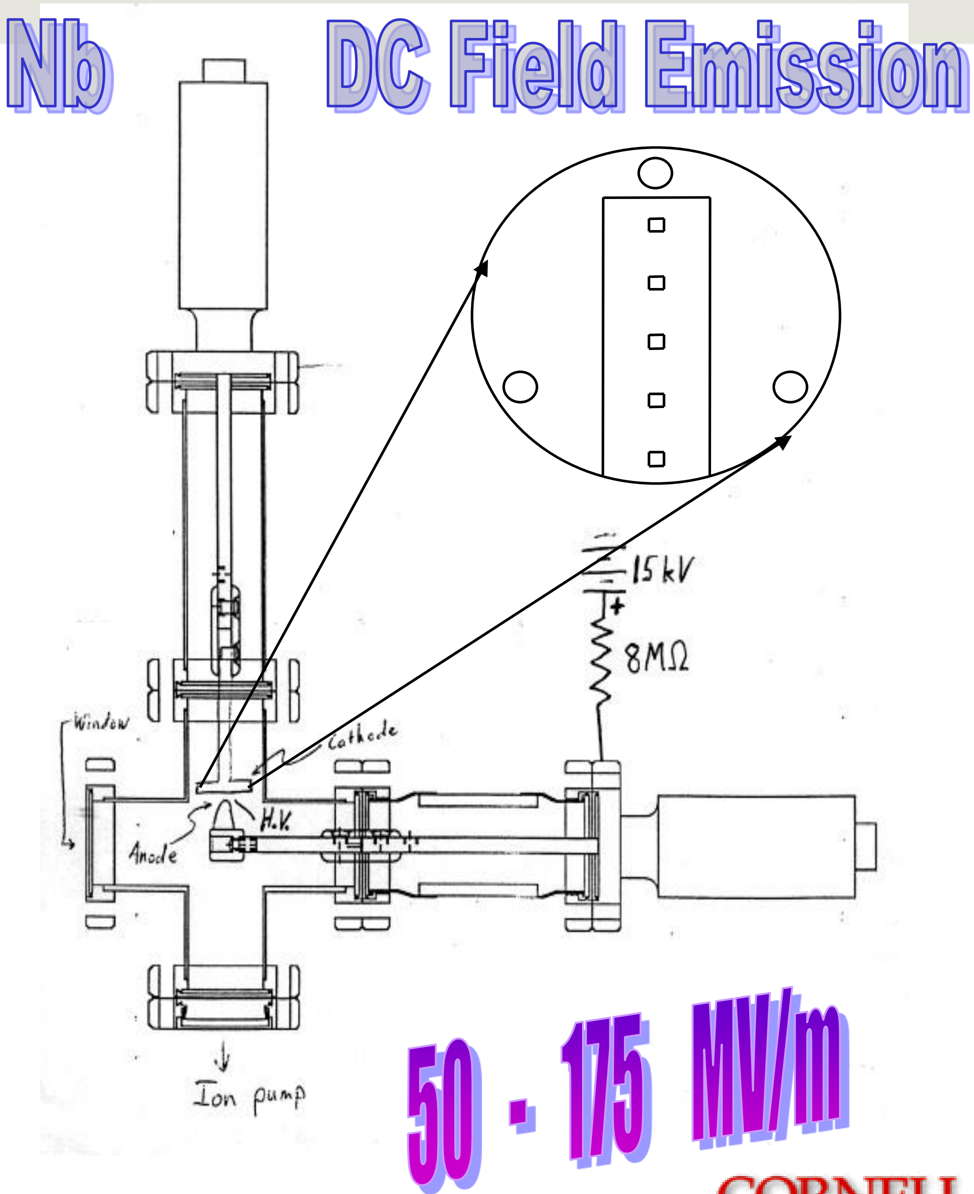


High Temp. Annealing is very effective to eliminate FE seeds. DESY once wanted to apply 1400^{O}C annealing for ILC cavities.

DC Field Emission Studies in Cornell







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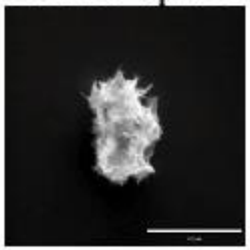
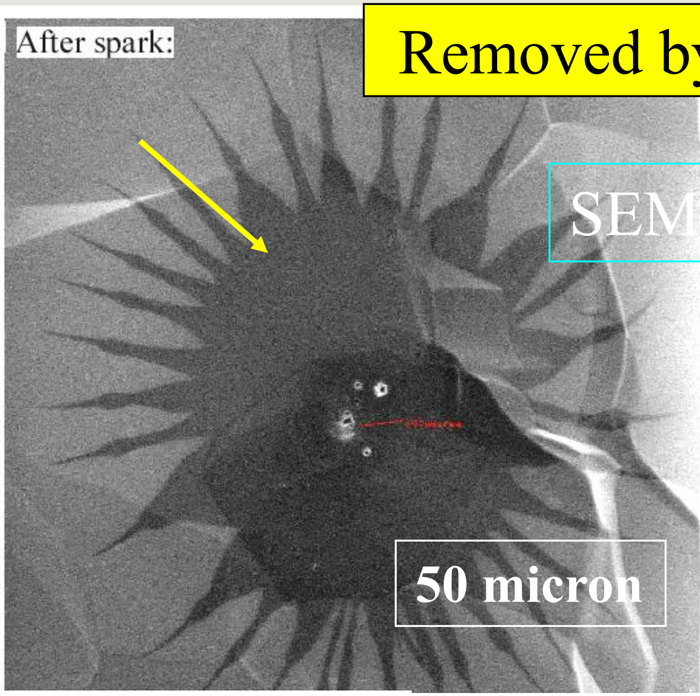
Intentionally Introduced Vanadium Particles on Nb Surface

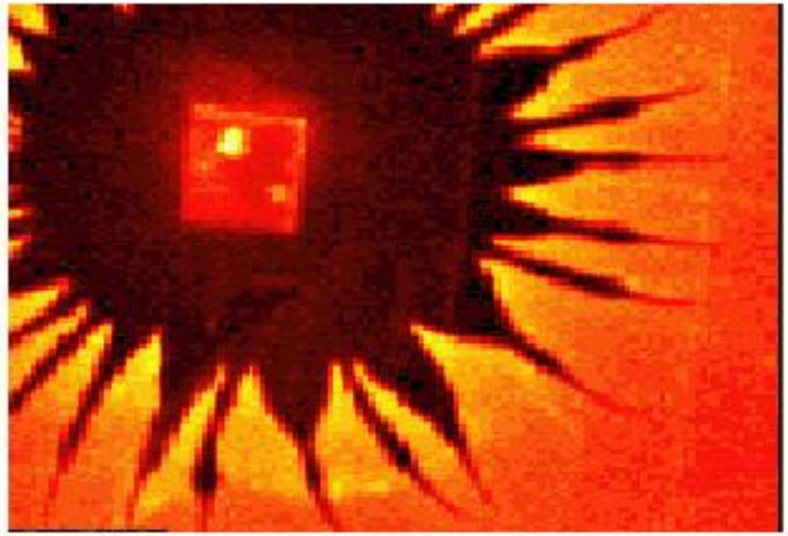
Removed by C, F

Before spark:

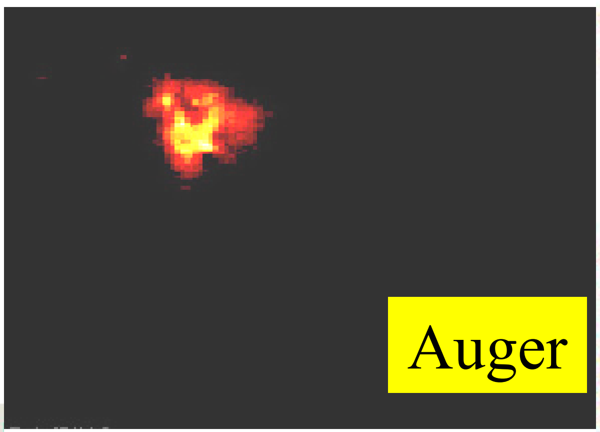




C



V



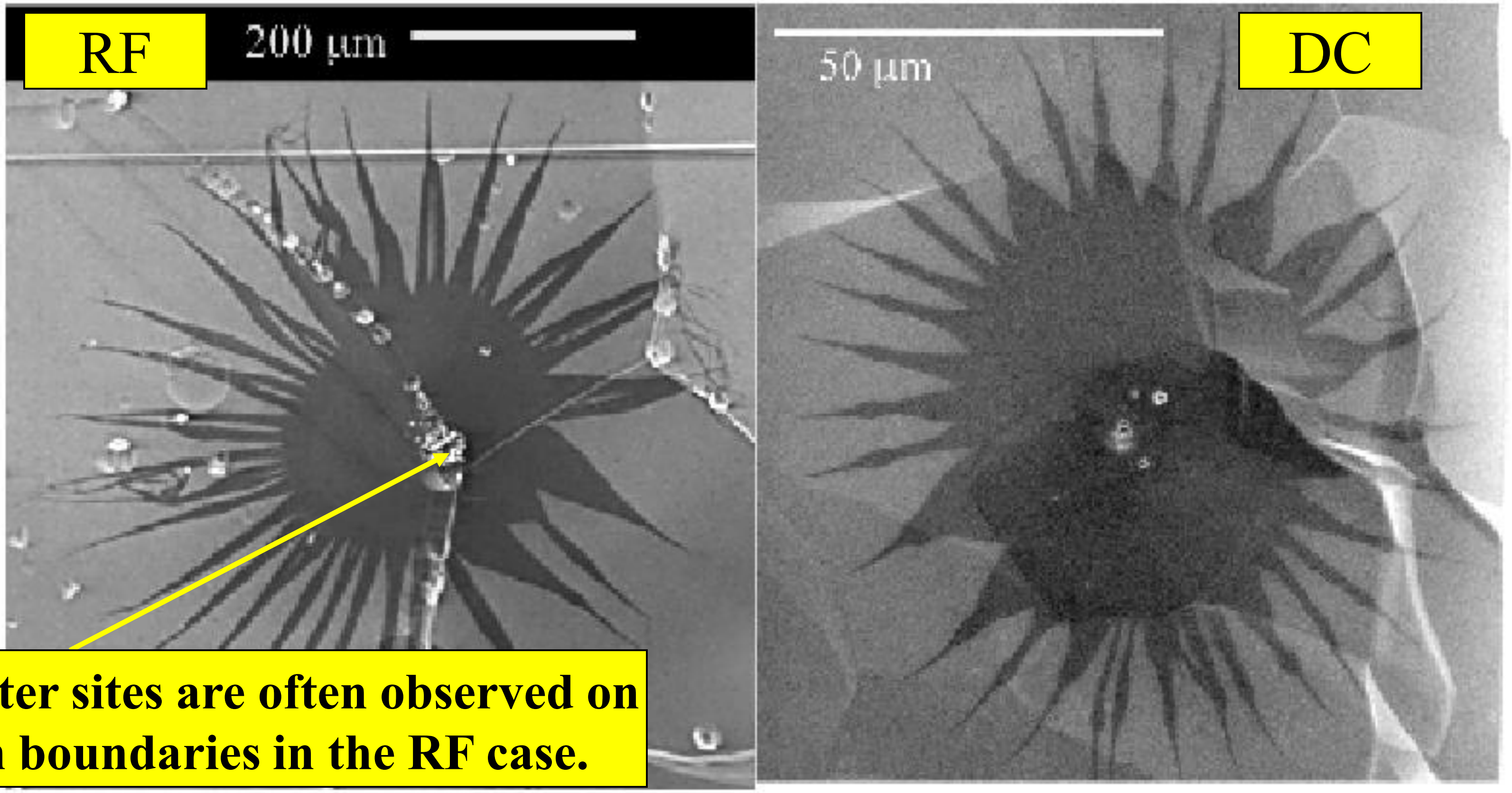
F

What removes C and F?

Ion bombardment

There must be gas present during the arc

Difference Between RF and DC



Emitter sites are often observed on grain boundaries in the RF case.

Starburst in a 1.5GHz Nb cavity

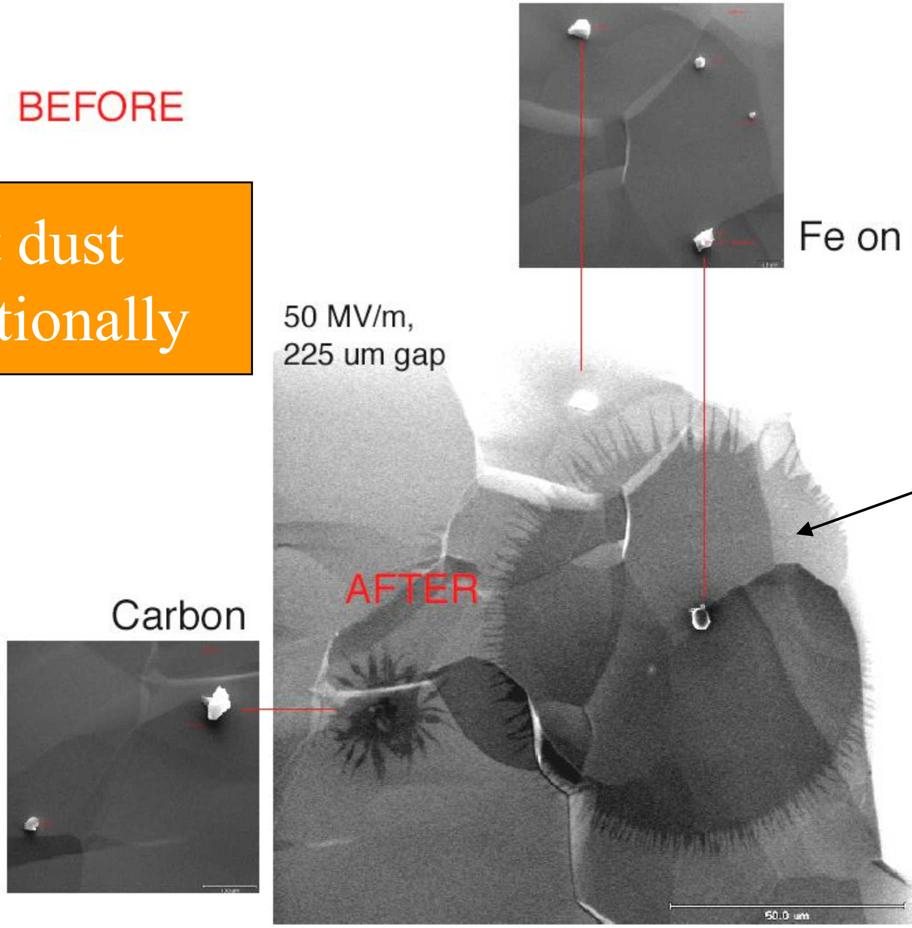
Starburst on a DC cathode (Nb)

RF can observe both effects of electric and magnetic field (surface current)
DC looks only electric effect. DC is difficult to investigate the grain boundary effect.

Particulate Contamination IS a Field Emission Source

DC Field emission study in Cornell

Put dust intentionally

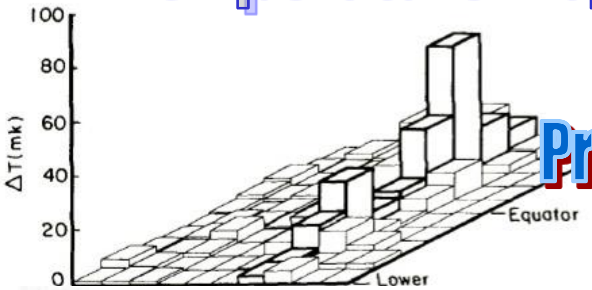


Star burst

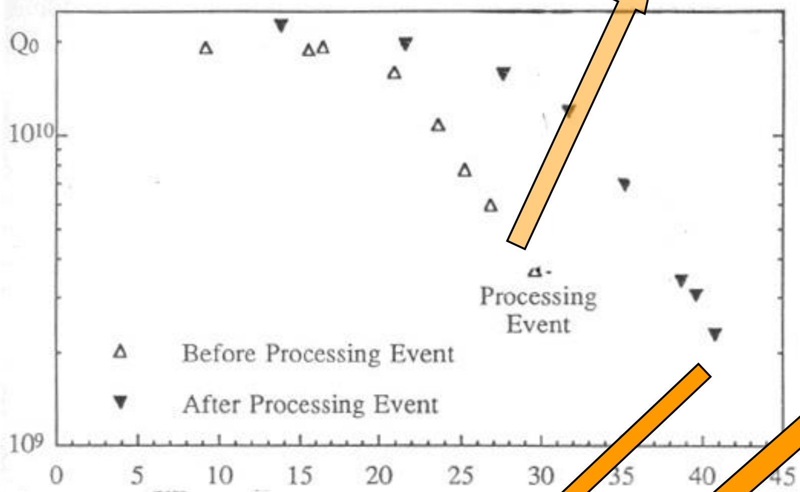
Particulate contaminations cause field emission.

High Peak Power Processing: HPP

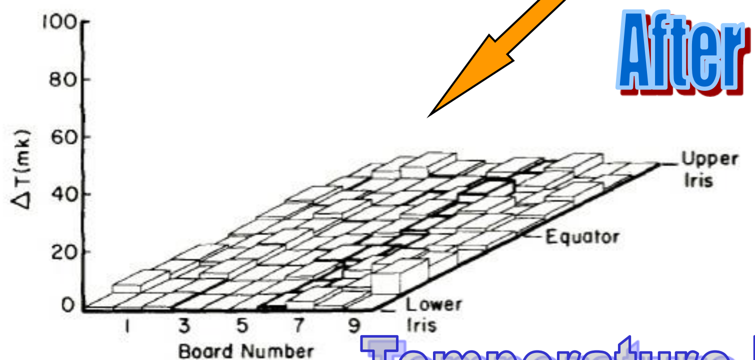
Temperature Map



Before Processing



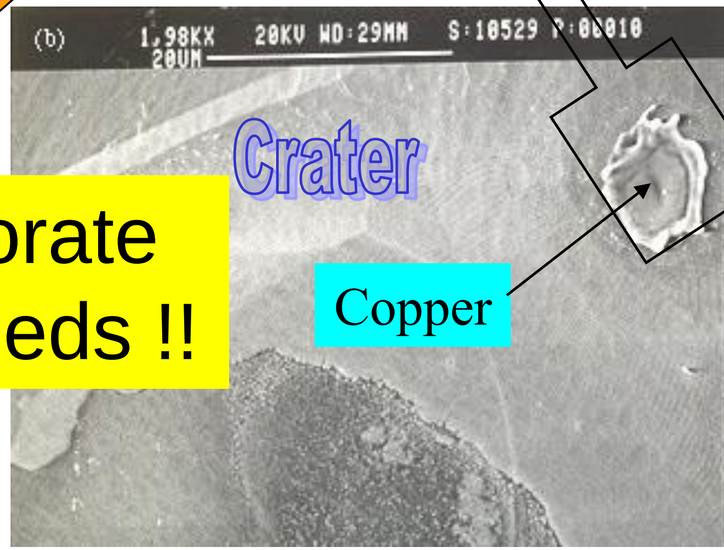
After



Temperature Map

Starburst & Crater

SEM



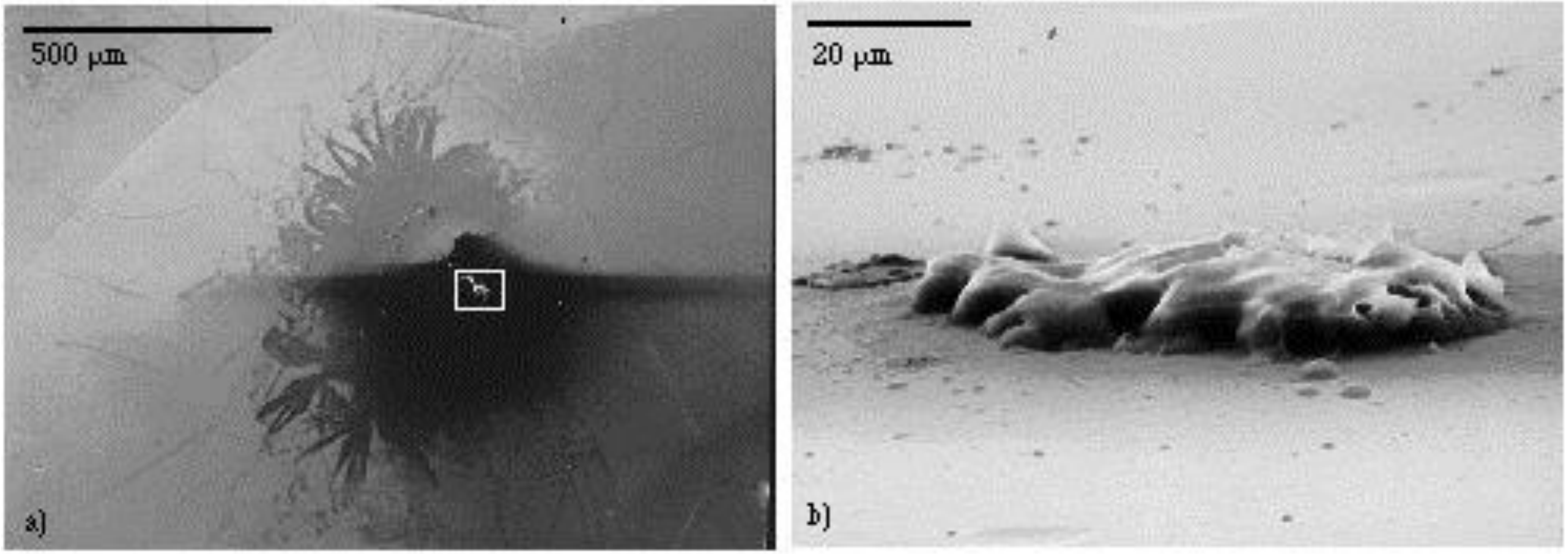
Crater

Copper

Evaporate FE seeds !!

CORNELL UNIVERSITY

Large Molten Region after HPP



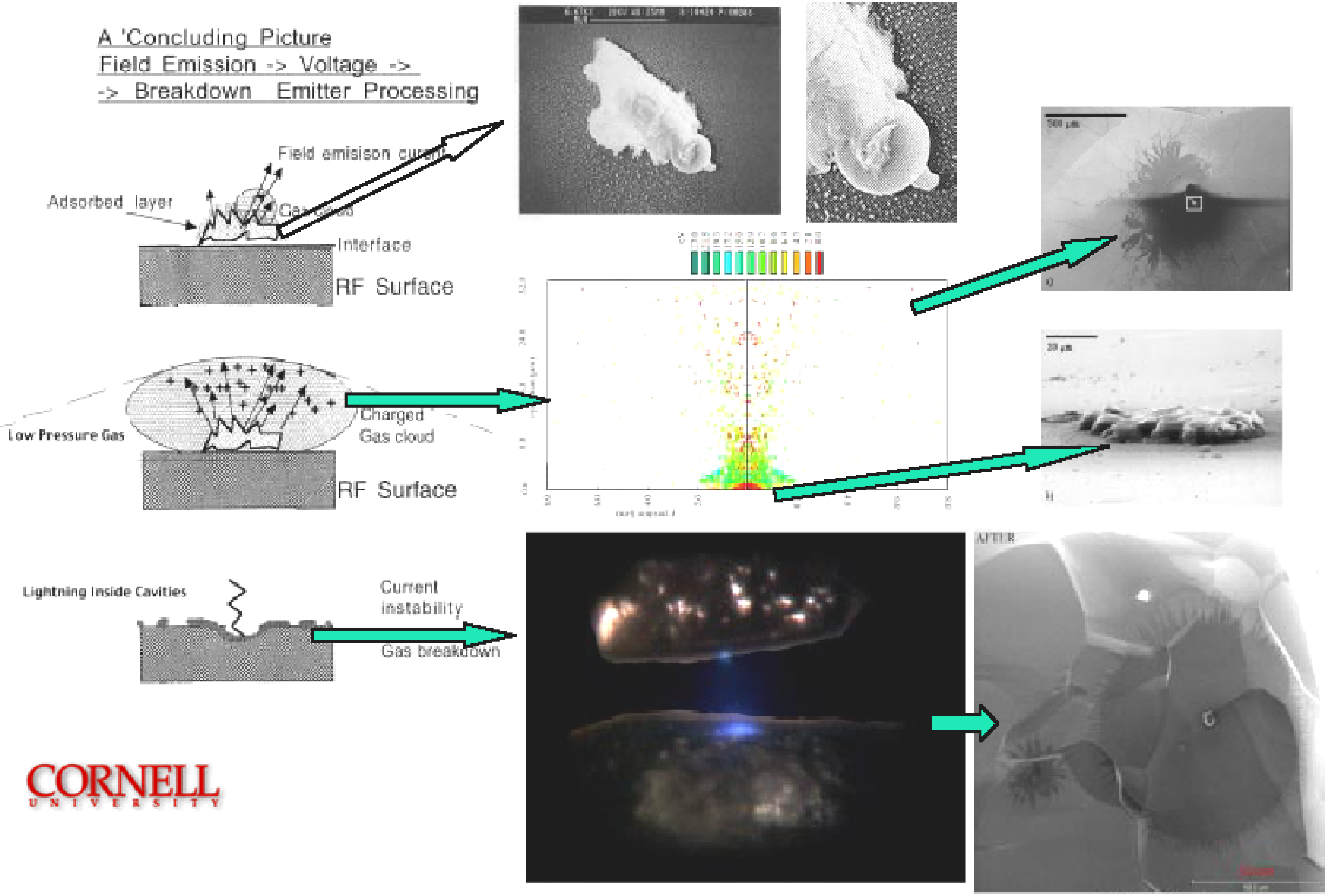
CORNELL UNIVERSITY

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

Calculations show that FE current alone cannot
Produce this much melting

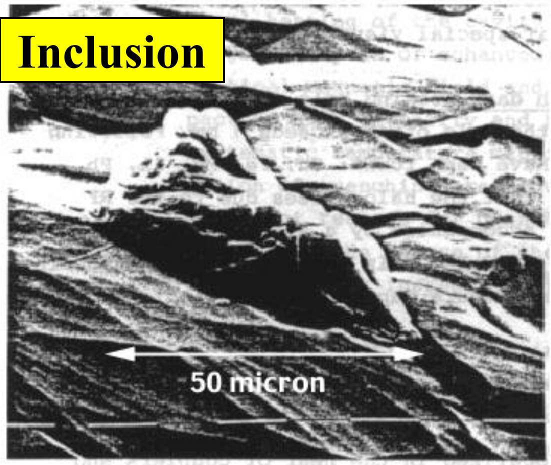
Gas is involved…
metal vapor + desorbed surface layers?

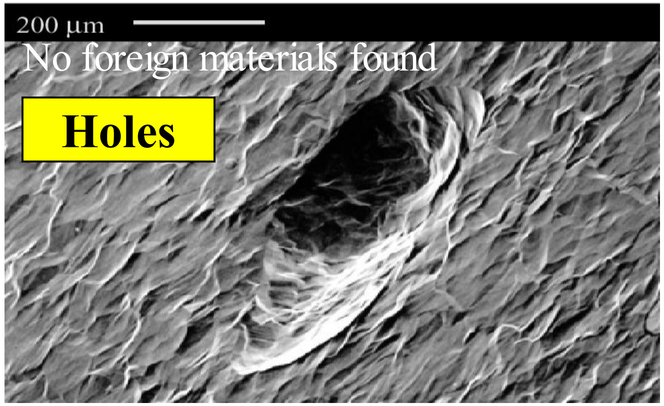
Cornell Model for RF Conditioning



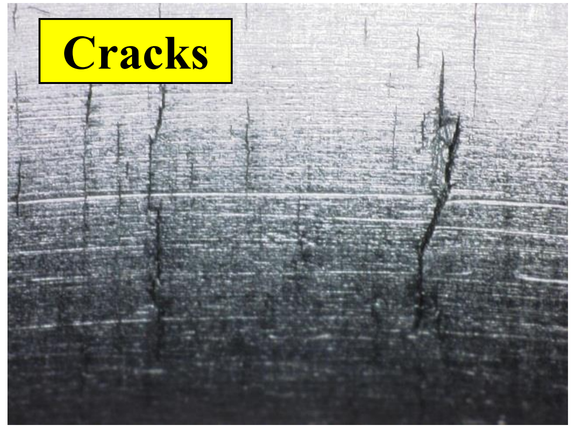
15.5 Thermal Instability (Quench at low field)

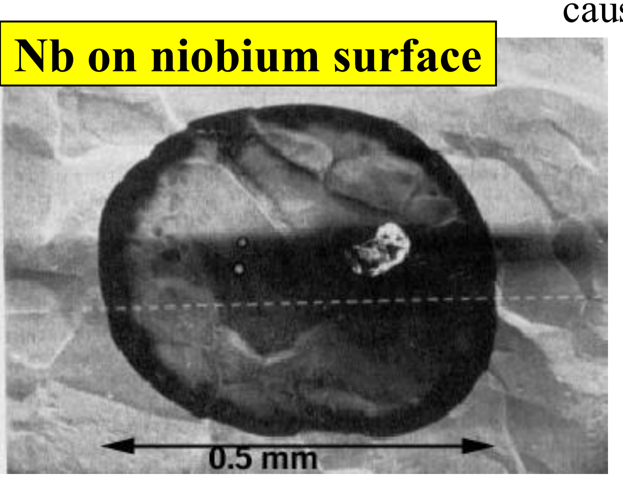
Various surface defects produce RF heating source

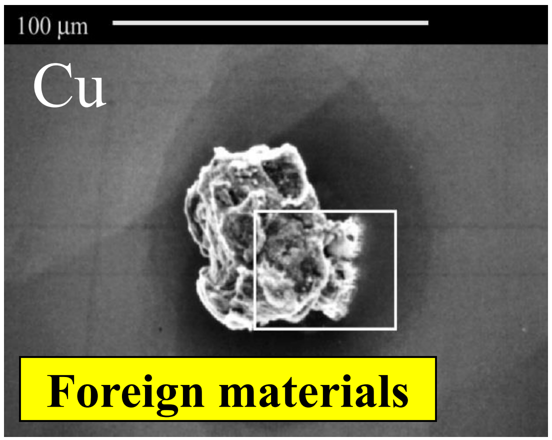




Surface defects, holes can also cause TB

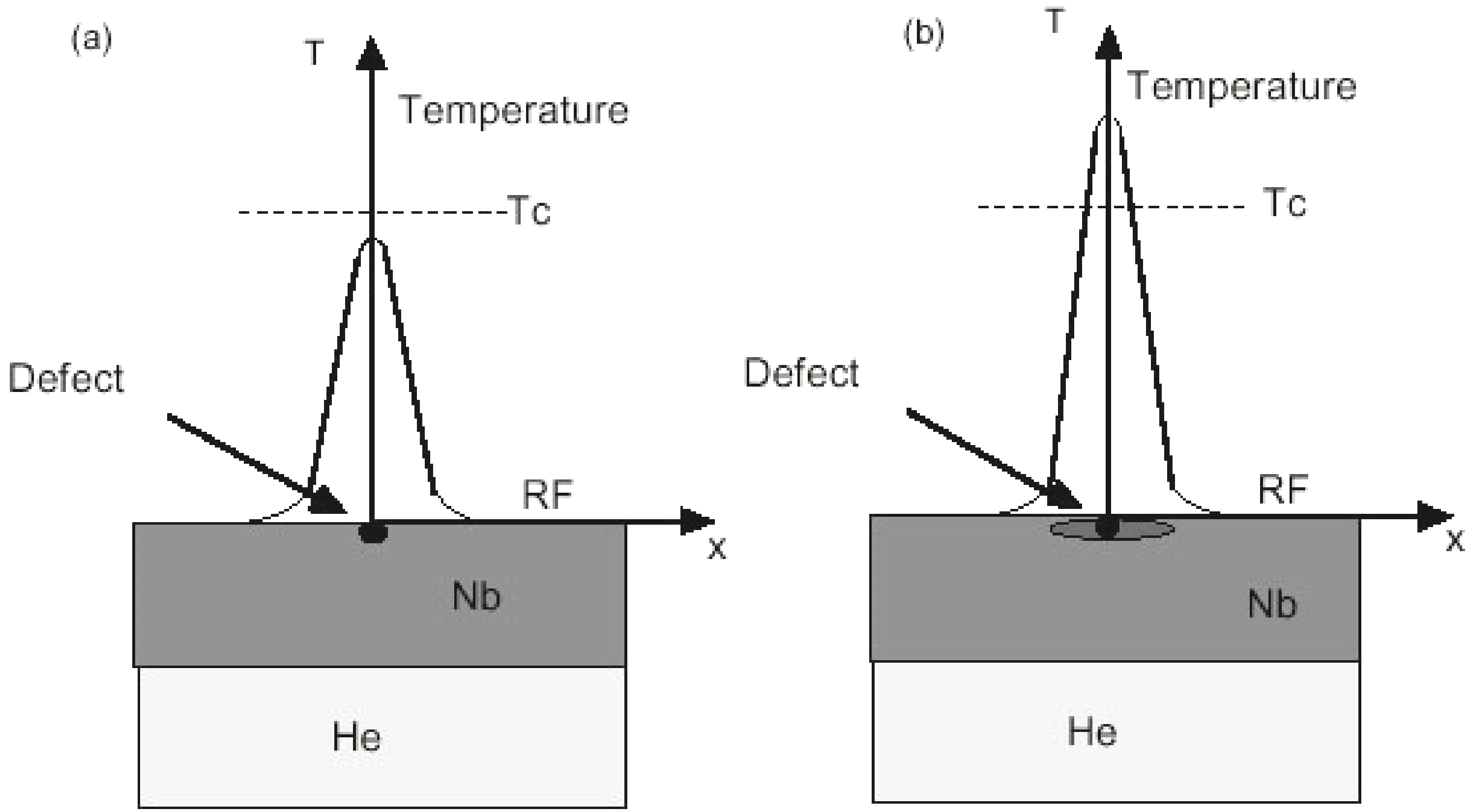




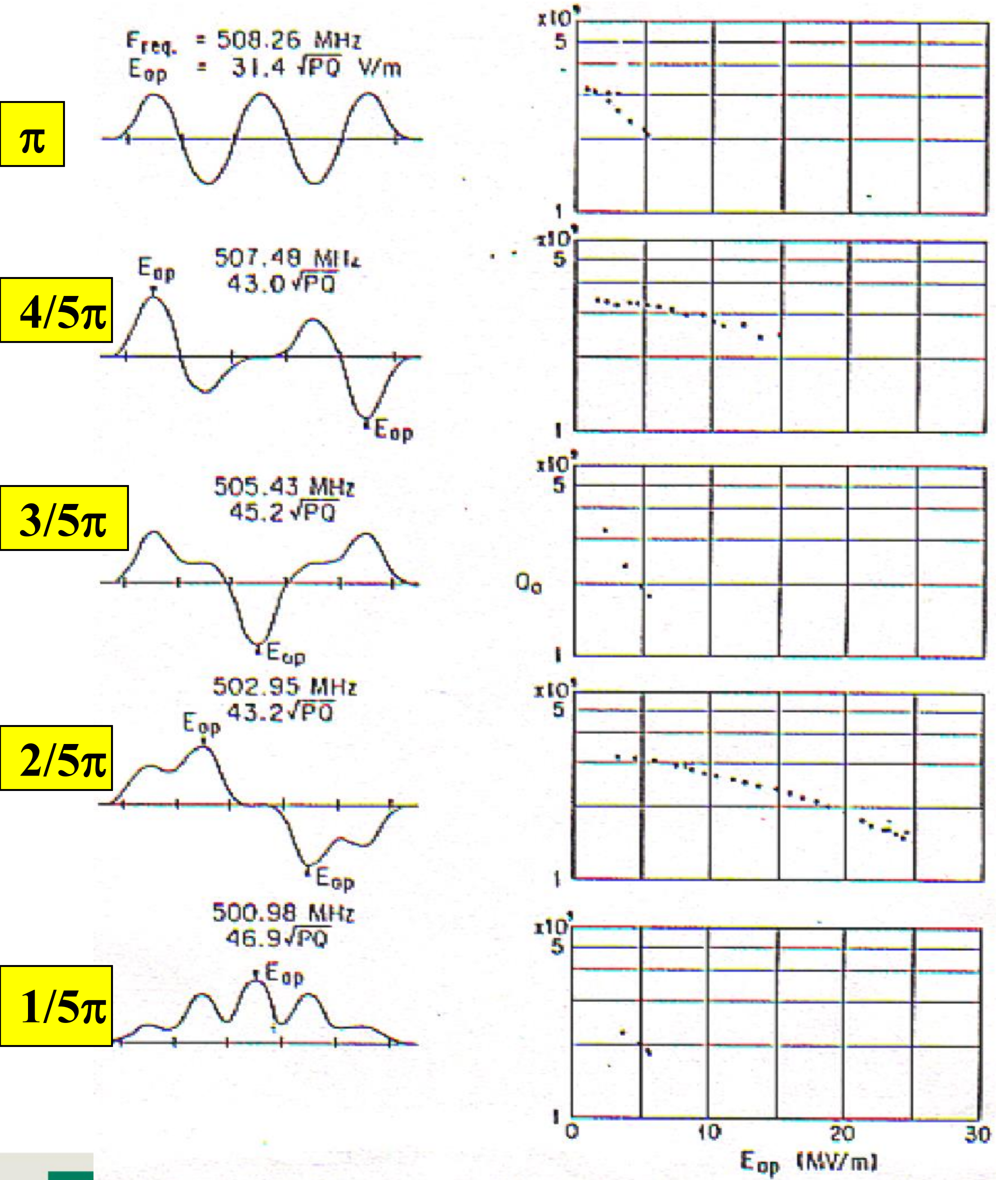


Polishing off such a defect before chemical/electrical treatment is very important.

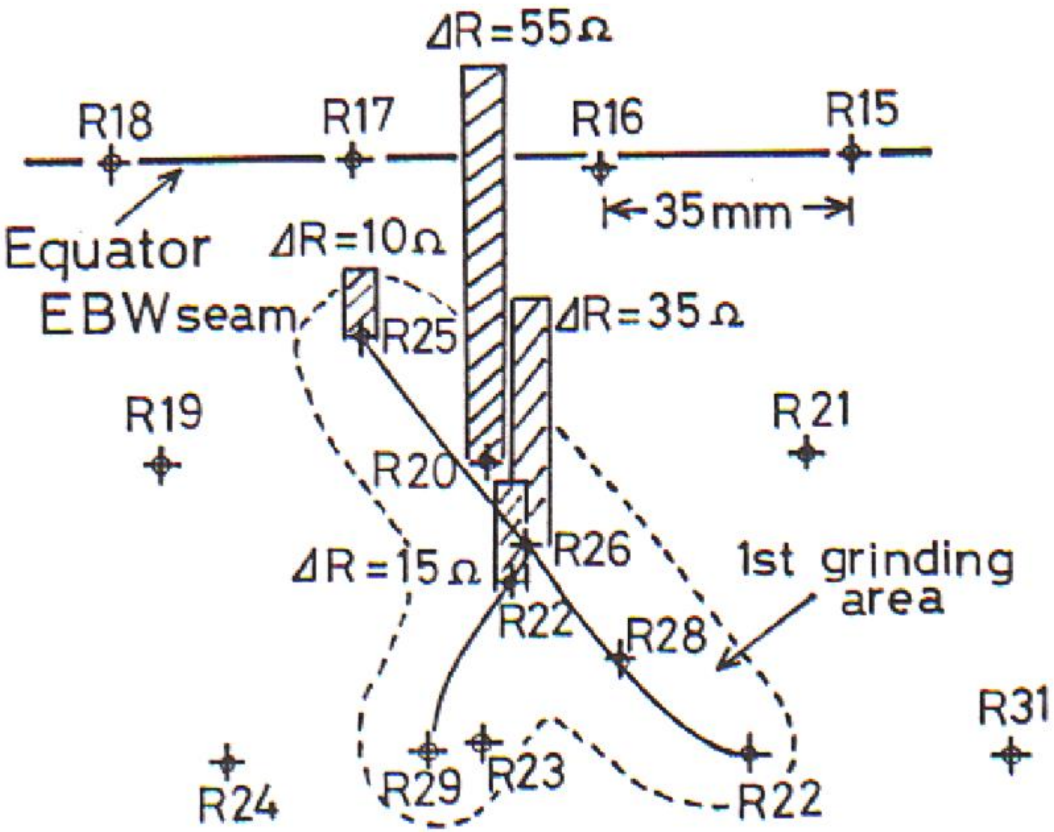
Mechanism of Thermal Instability



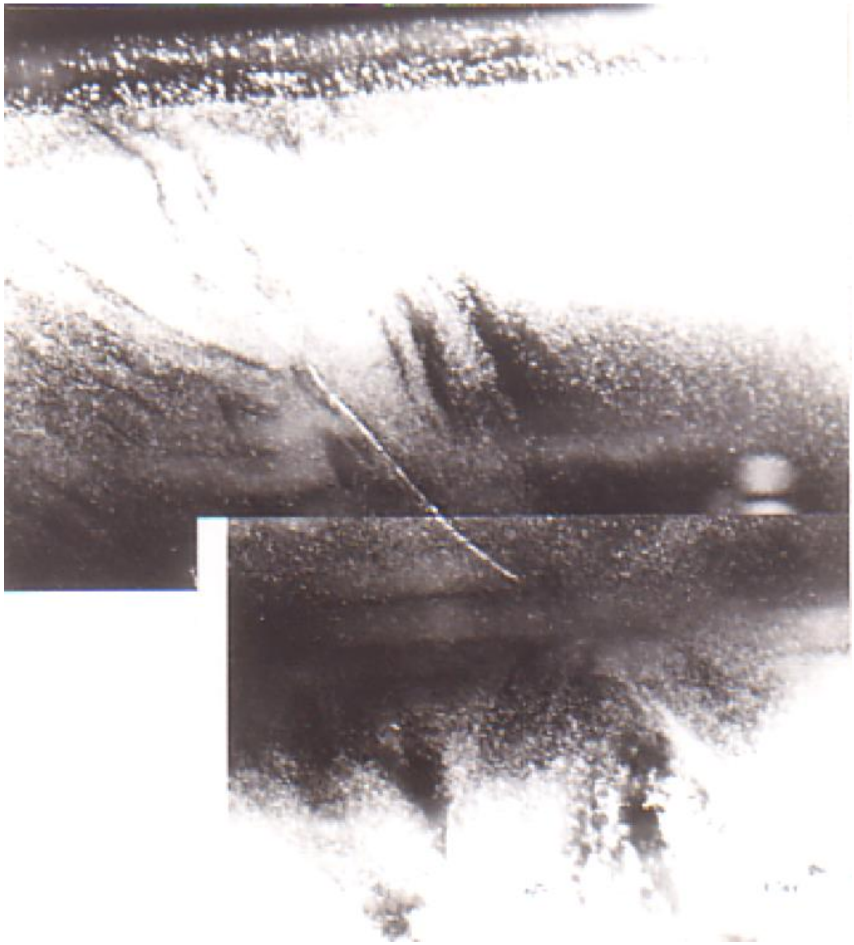
Thermal Instability: Example in a TRISTAN SC Cavity(508MHz 5-cell Cavity)



T-mapping and Surface Defect Visually Observed



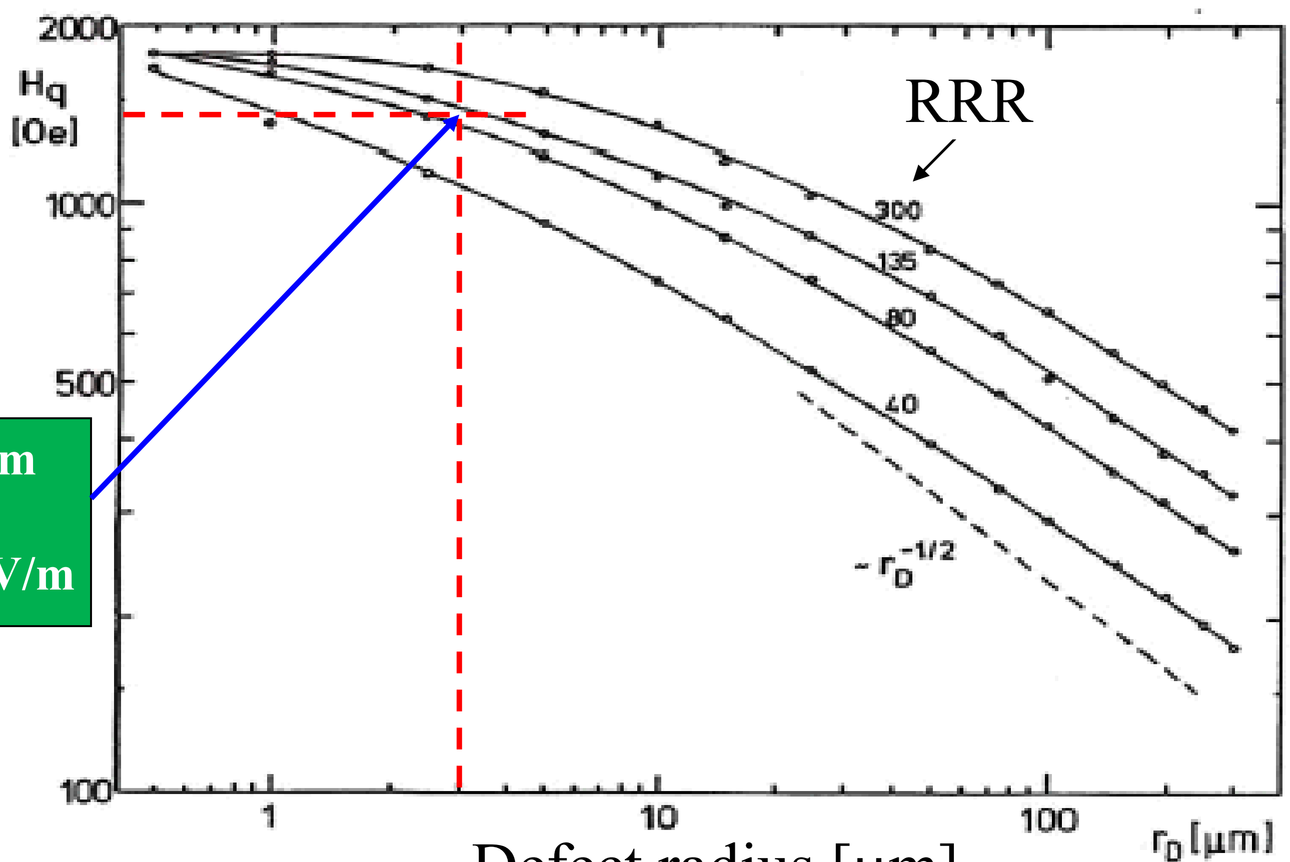
T-mapping on the defect



Picture of the defect area

RRR Dependence of Quench Field due to Thermal Instability

Wuppertal University



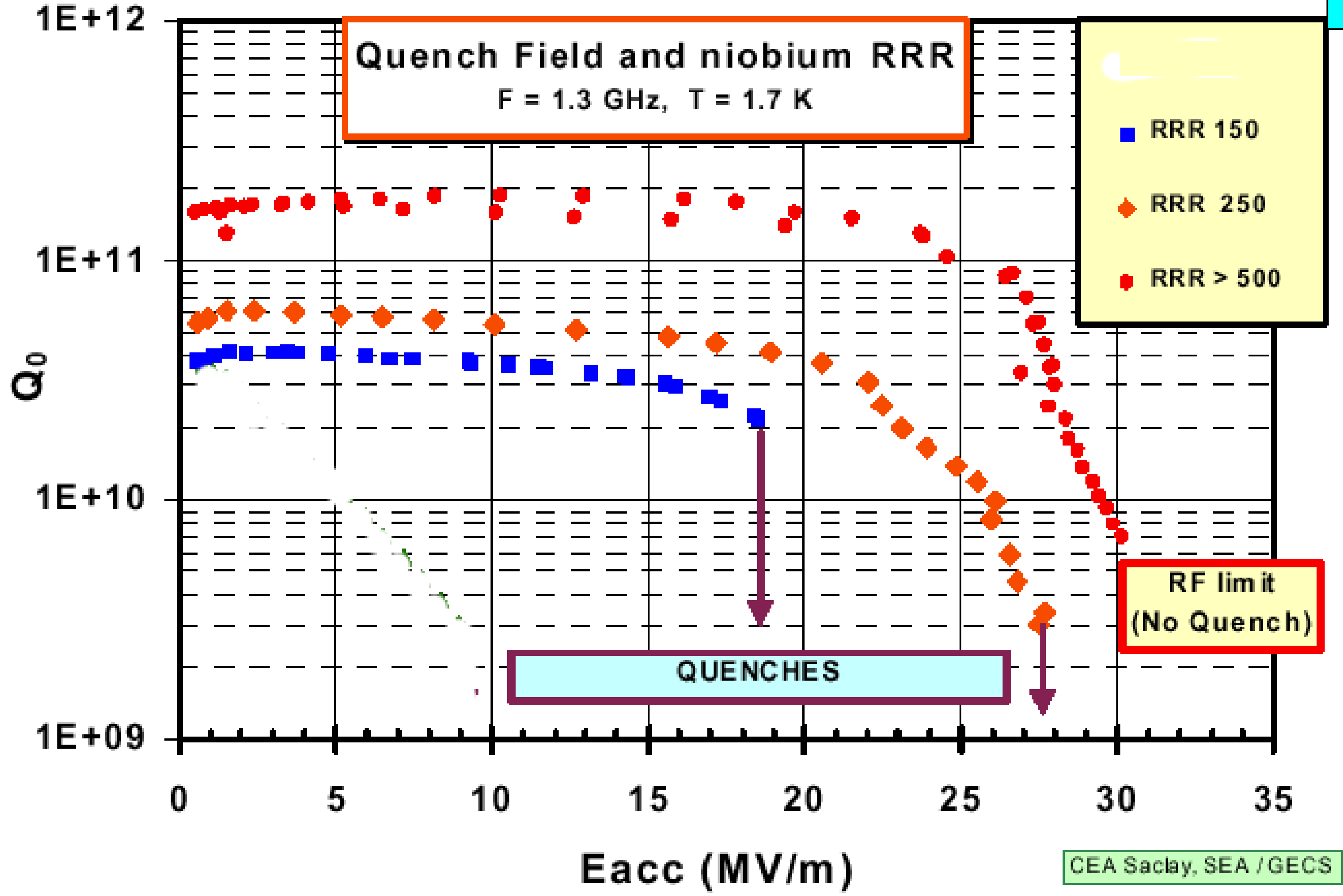
Defect radius [μm]

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

Needs to control the defect > 1μm.
Use the Nb material with RRR > 200.

High RRR Material Mitigates Thermal Instability

Saclay



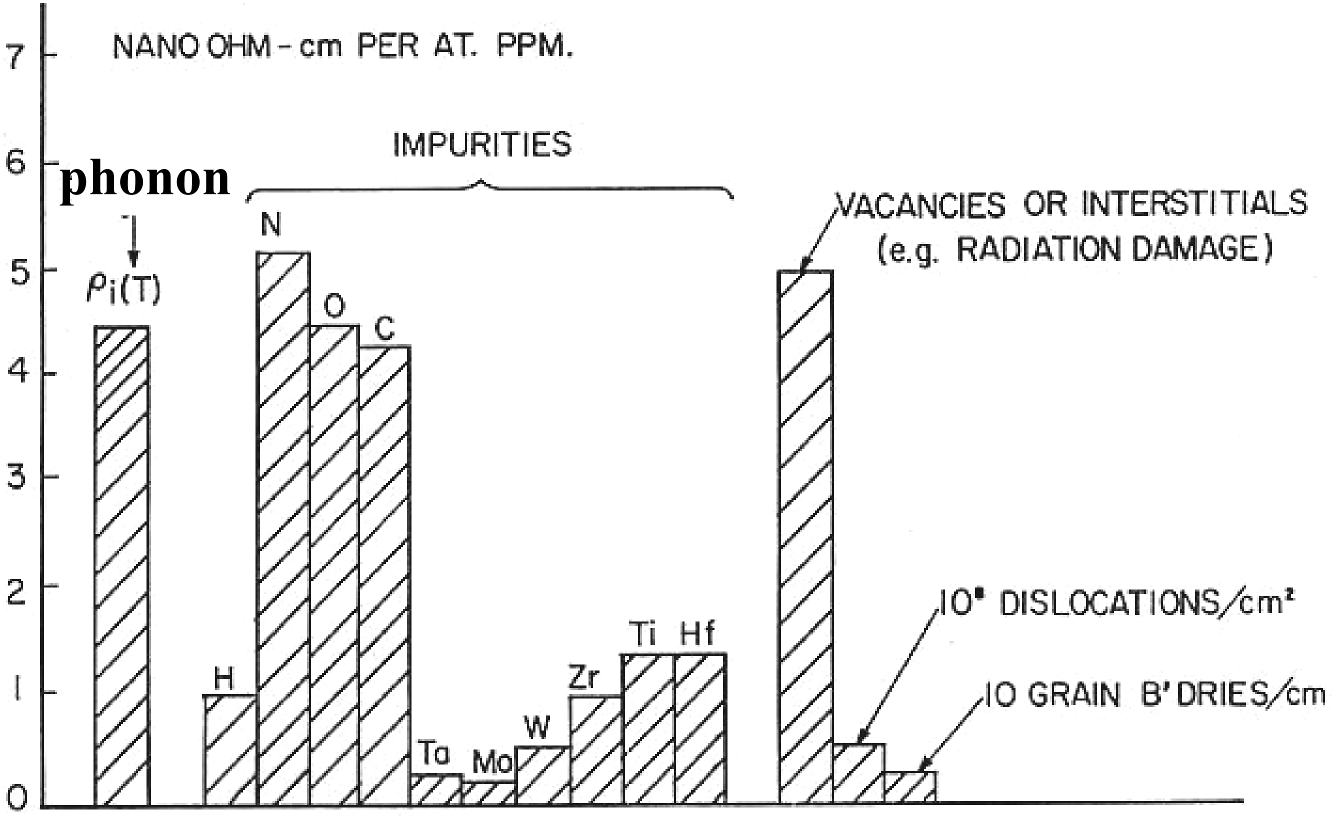
Thermal Resistance by Impurities

High purity + Homogeneity

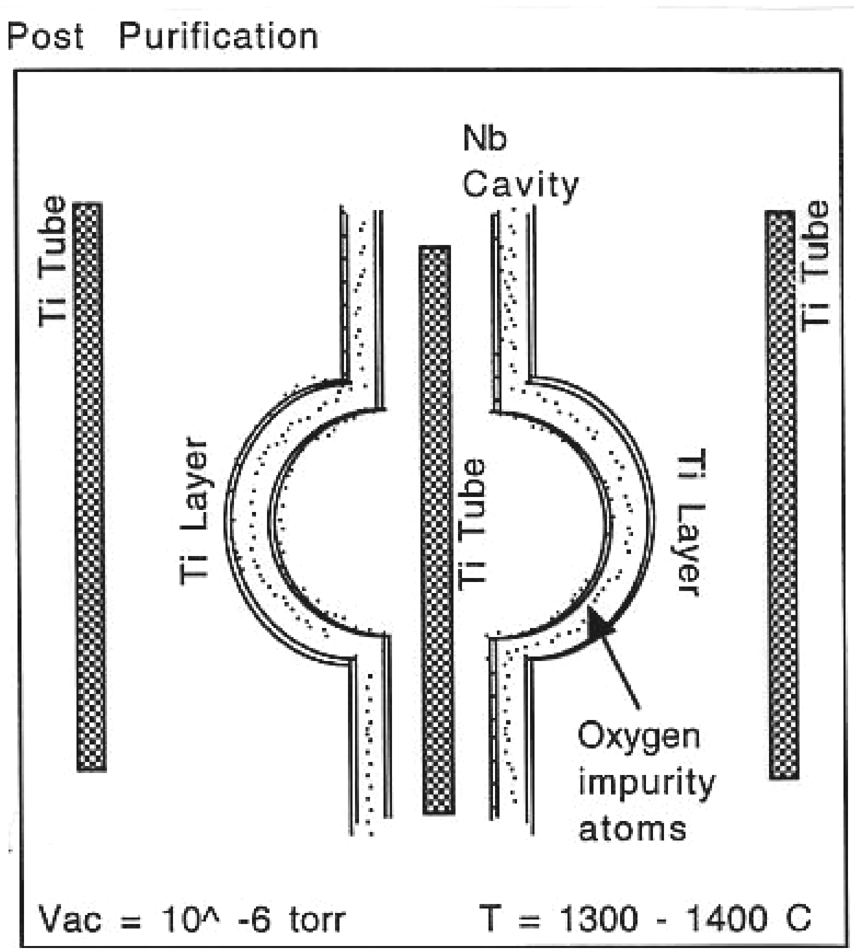
High RRR material

Vacuum annealing

Nb



Cure-I : Post Purifying of Niobium



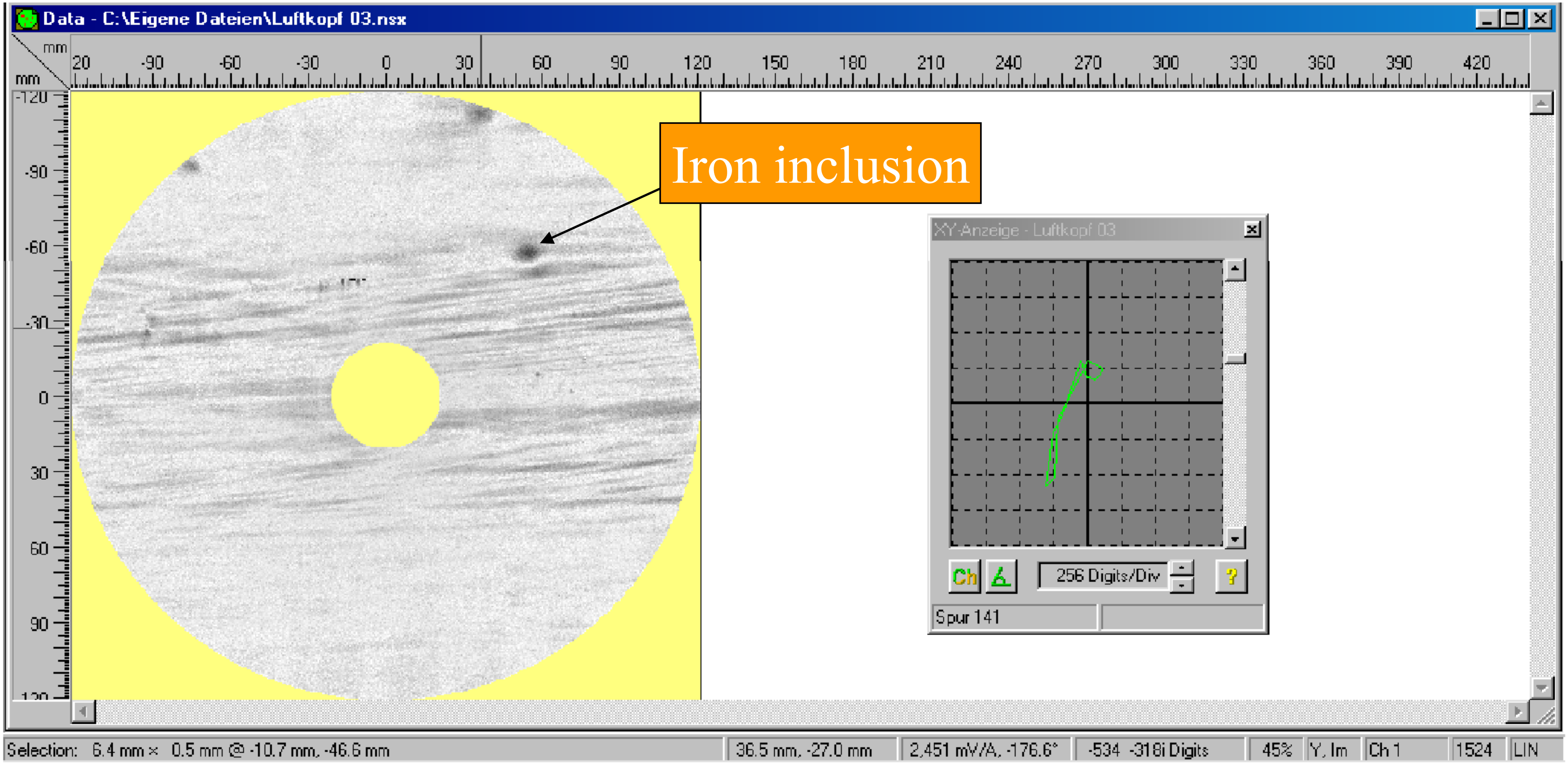
After cavity or half-cell fabrication

- **Heat in vacuum furnace to ~ 1350 ^{O}C**
- **Evaporate Ti vapor on the niobium surface**
- **Use titanium as "getter" to pick up impurities**
- **Later etch away the titanium**
- **Doubles the purity**
- **(RRR ~ 600 if originally RRR = 300)**

Cure-II : Careful Inspection of Nb Sheets and Cavity Surface

Defect free material : Quality control

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



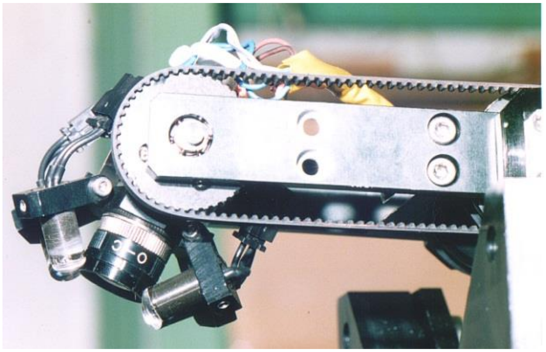
Global view, rolling marks and defect areas can be seen

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

Eddy Scanning System at DESY

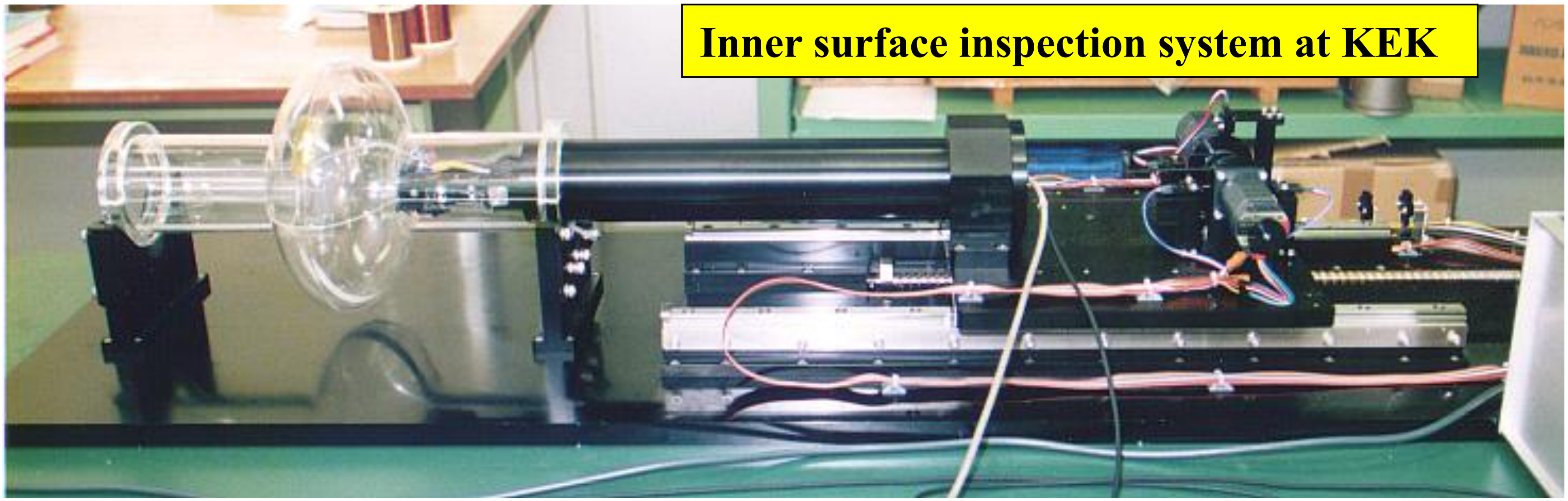
Cavity Inner Surface Inspection System: KEK

Small CCD camera

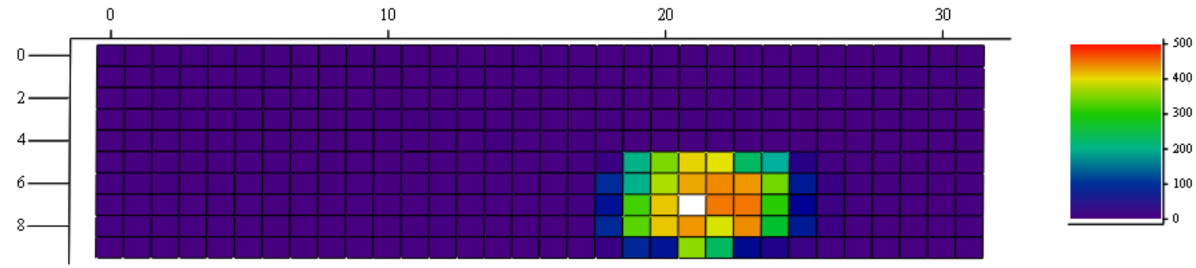


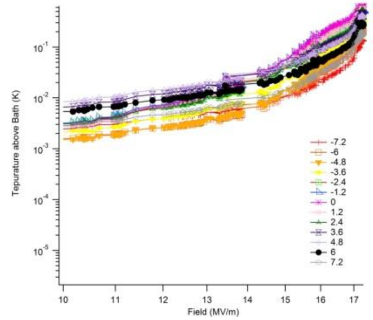
CRT monitor
Magnification x 13

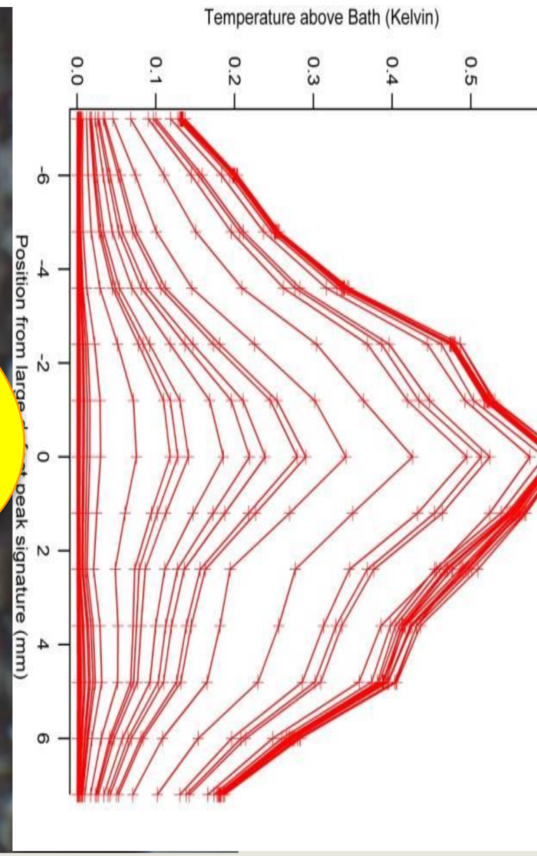
Inner surface inspection system at KEK



EBW Defects Limiting Gradient around 20MV/m



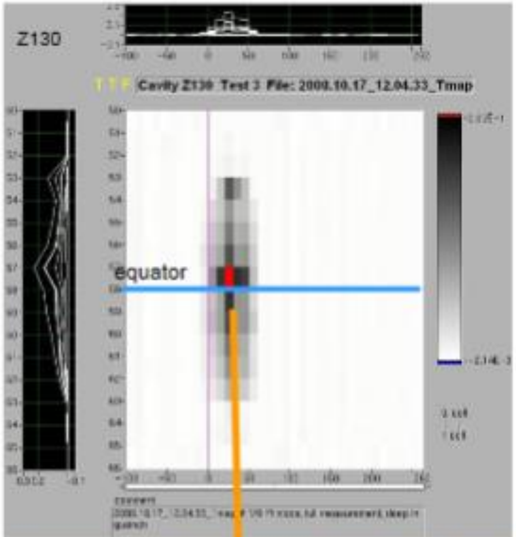




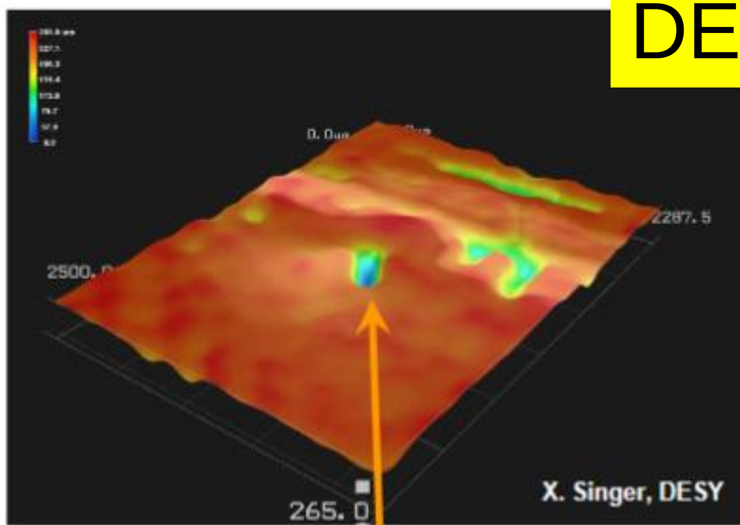
Visual Surface Inspection used High Resolution Camera (Kyoto Camera)

DESY/KEK

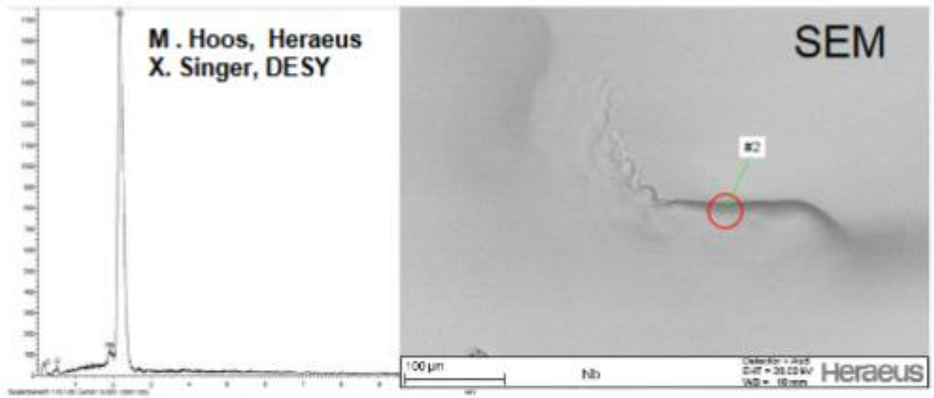
Cell 5, Quench at 23 MV/m on equator



hole in the equator weld



3D image, bump and hole up to 200 µm deep



No foreign material inclusions detected by EDX

… 22nd, 2009, 14th International Conference on RF Superconductivity, Berlin
D. Möller, DESY, Hamburg, Germany

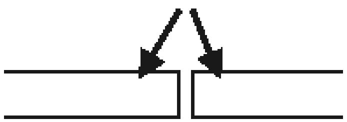
Poster :TUPPO073 Singer W., Singer X. et al

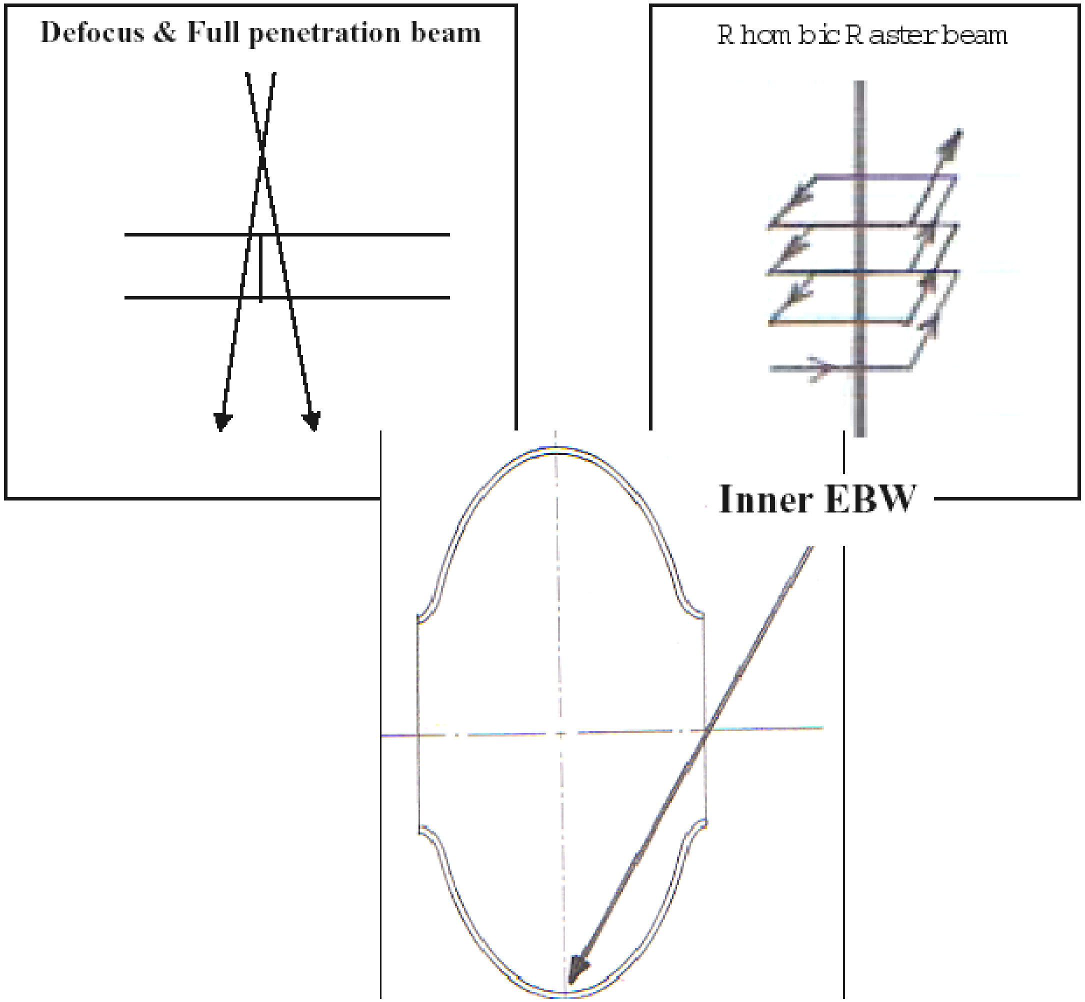
8

Cure-III : High Quality EB-Welding

Better EBW

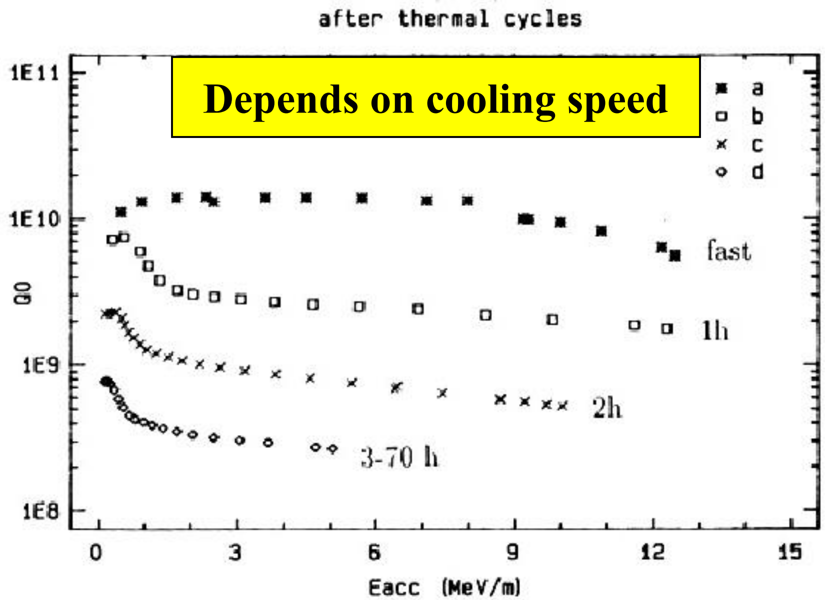
Etching by CP

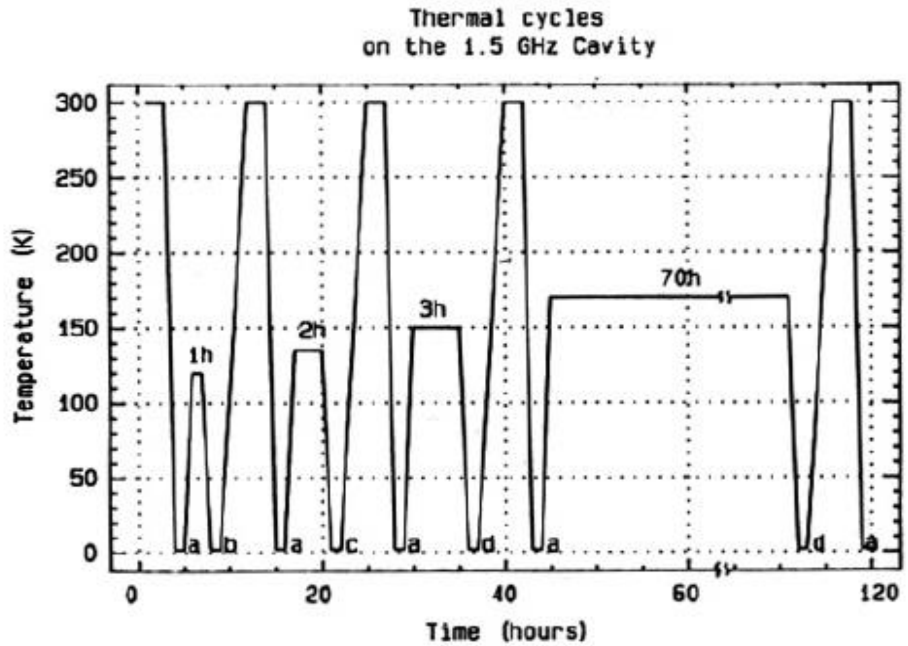




15.6 Hydrogen Q-disease

When cavity is cooled down slowly, Q_O is remarkably low.

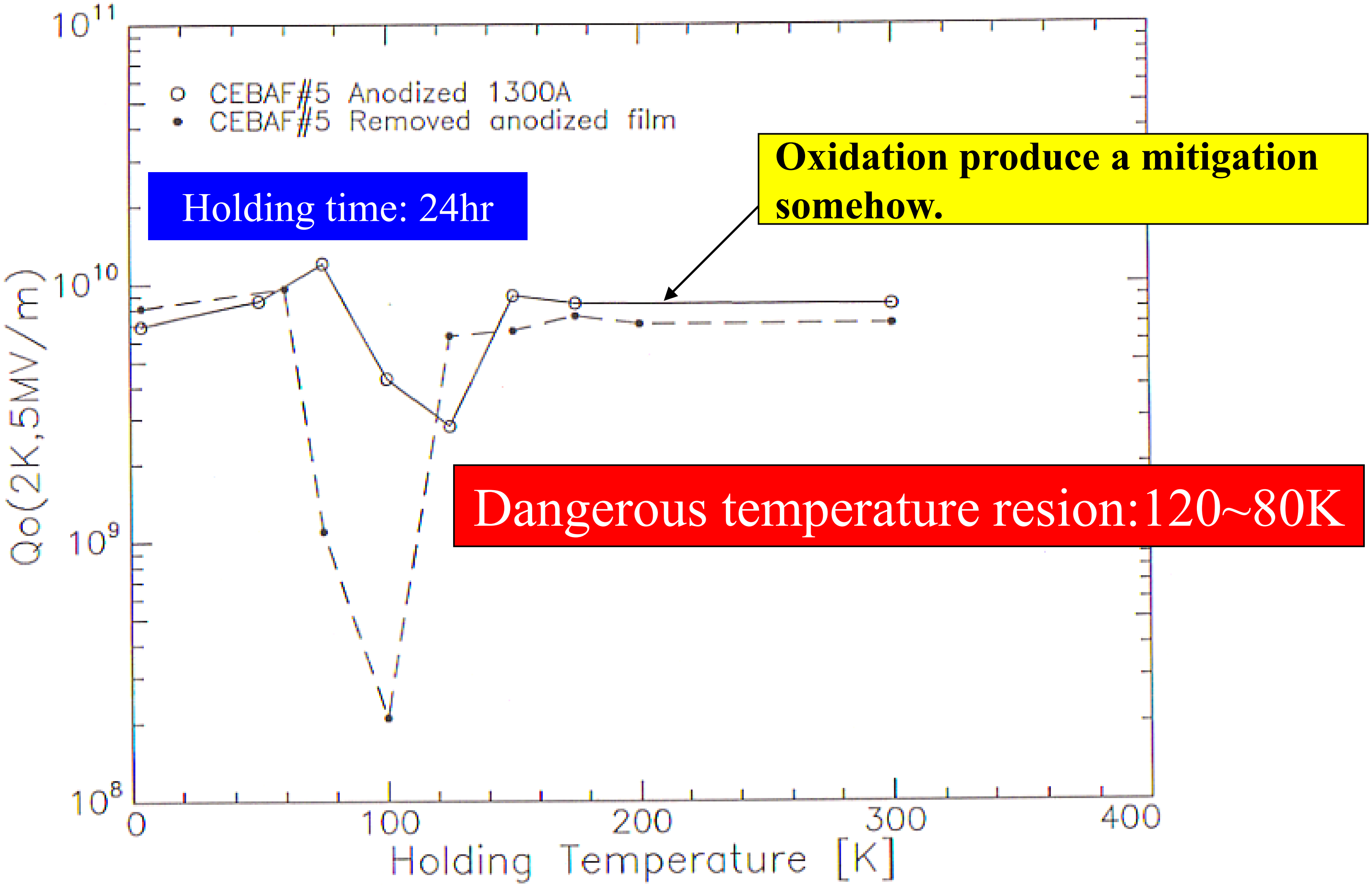




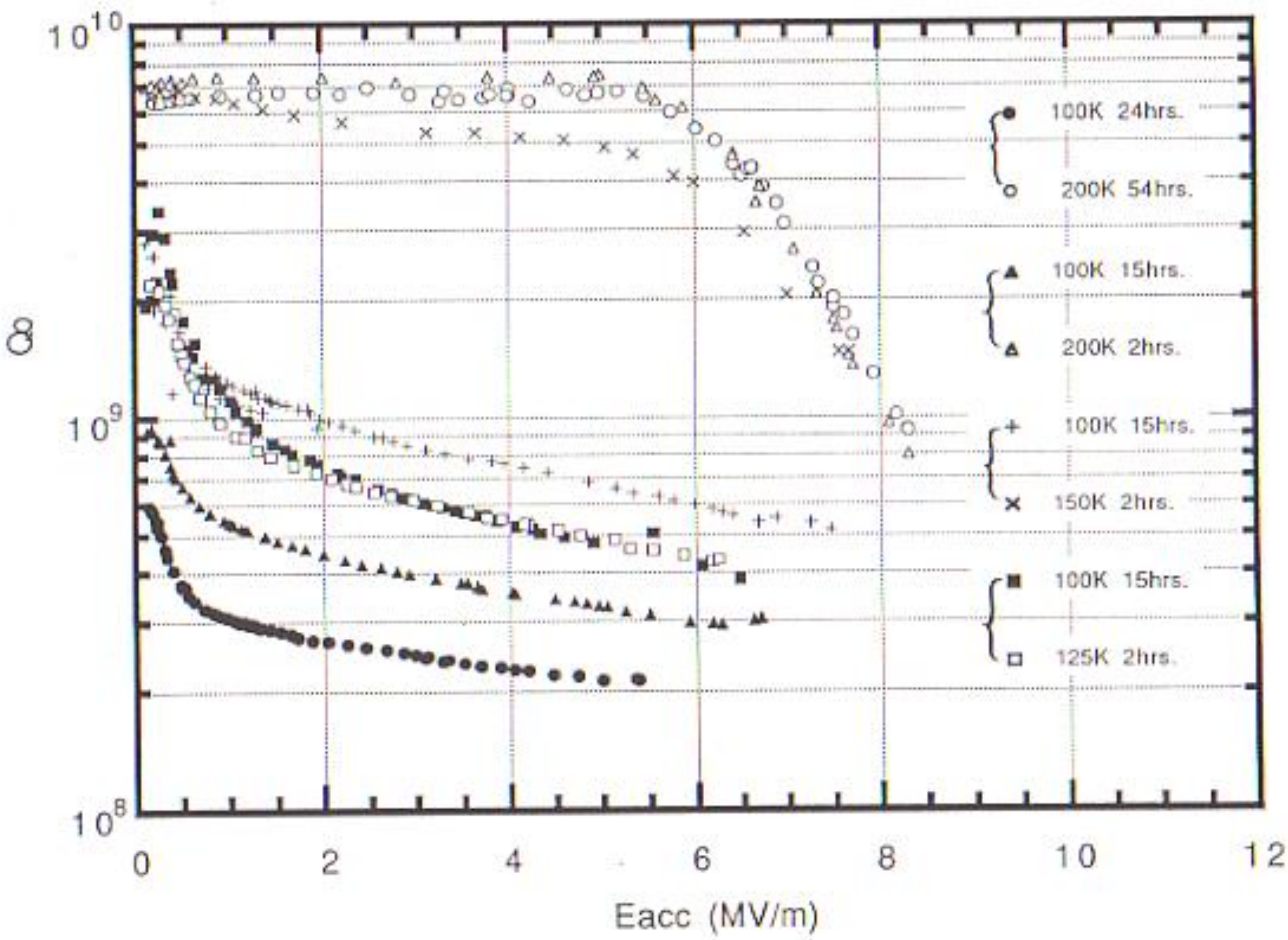
Discovered with BCP'ed cavity in 1990's at Saclay

By end of 1990's chemical polishing was mostly used in Europe and north America, and they did not make hydrogen degassing by annealing.

Dangerous Temperature Region



Recovery of Hydrogen Q-disease



Hydrogen Q disease recover when warmed up T > 200K.

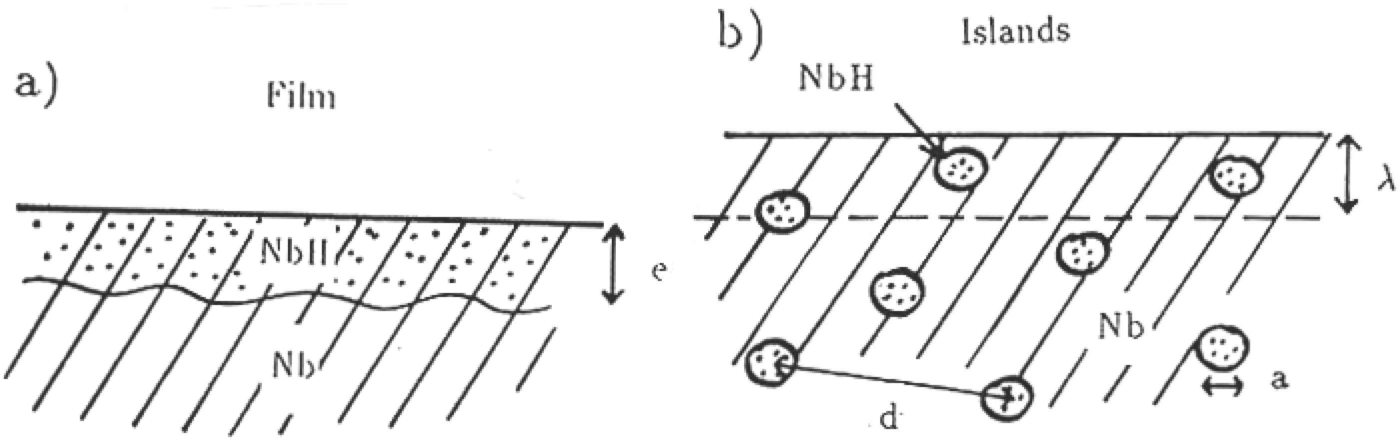
Mechanism of Hydrogen Q-disease

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

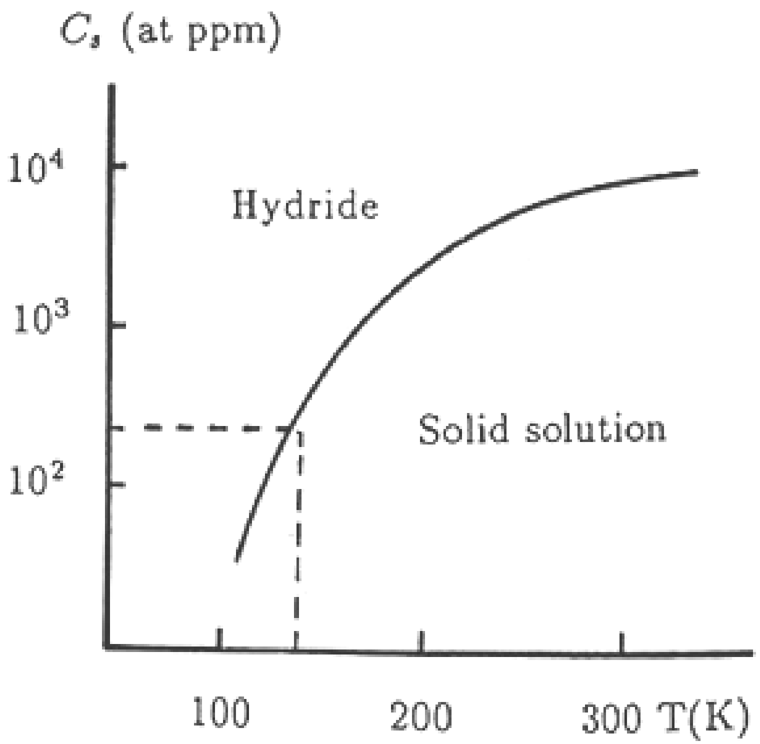
This explains shape of Q vs E curves
of Q-disease cavities



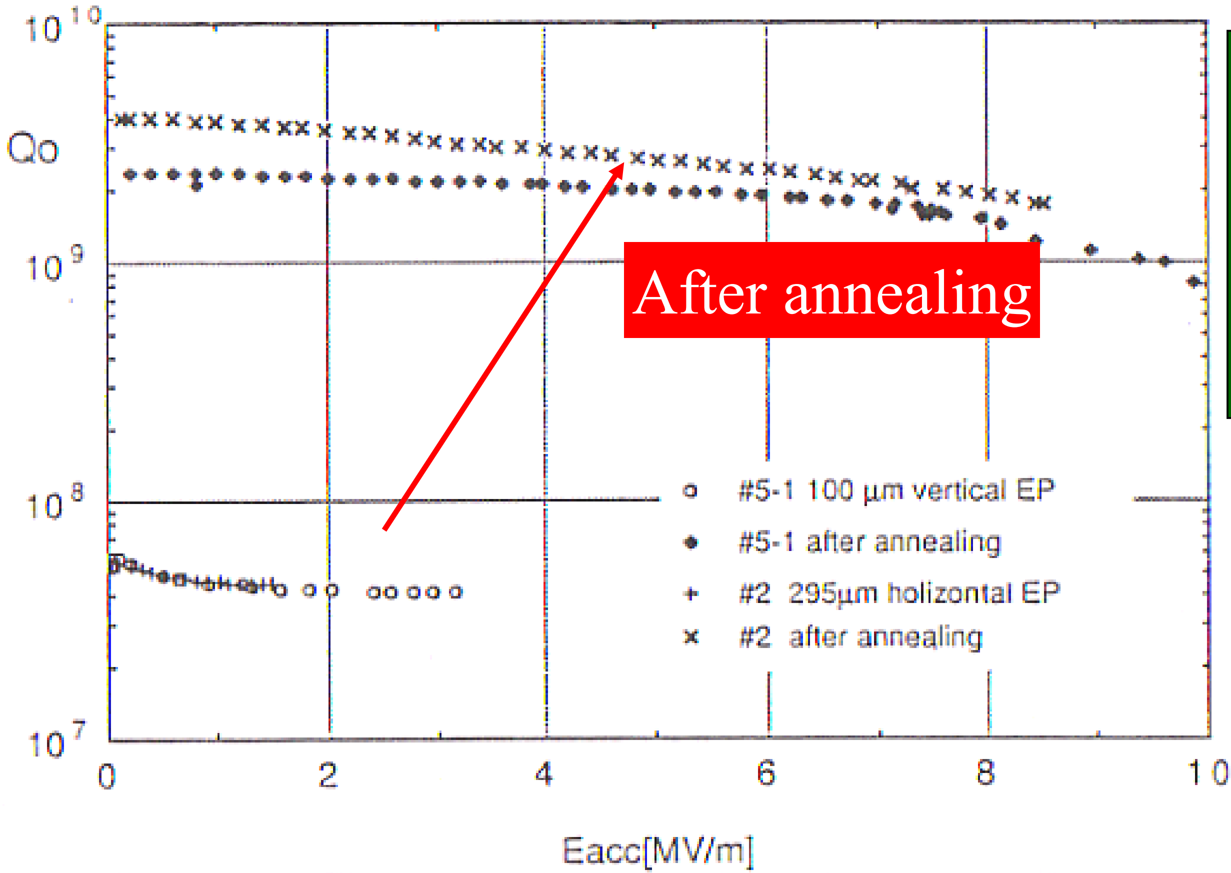
Hydride Formation

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.



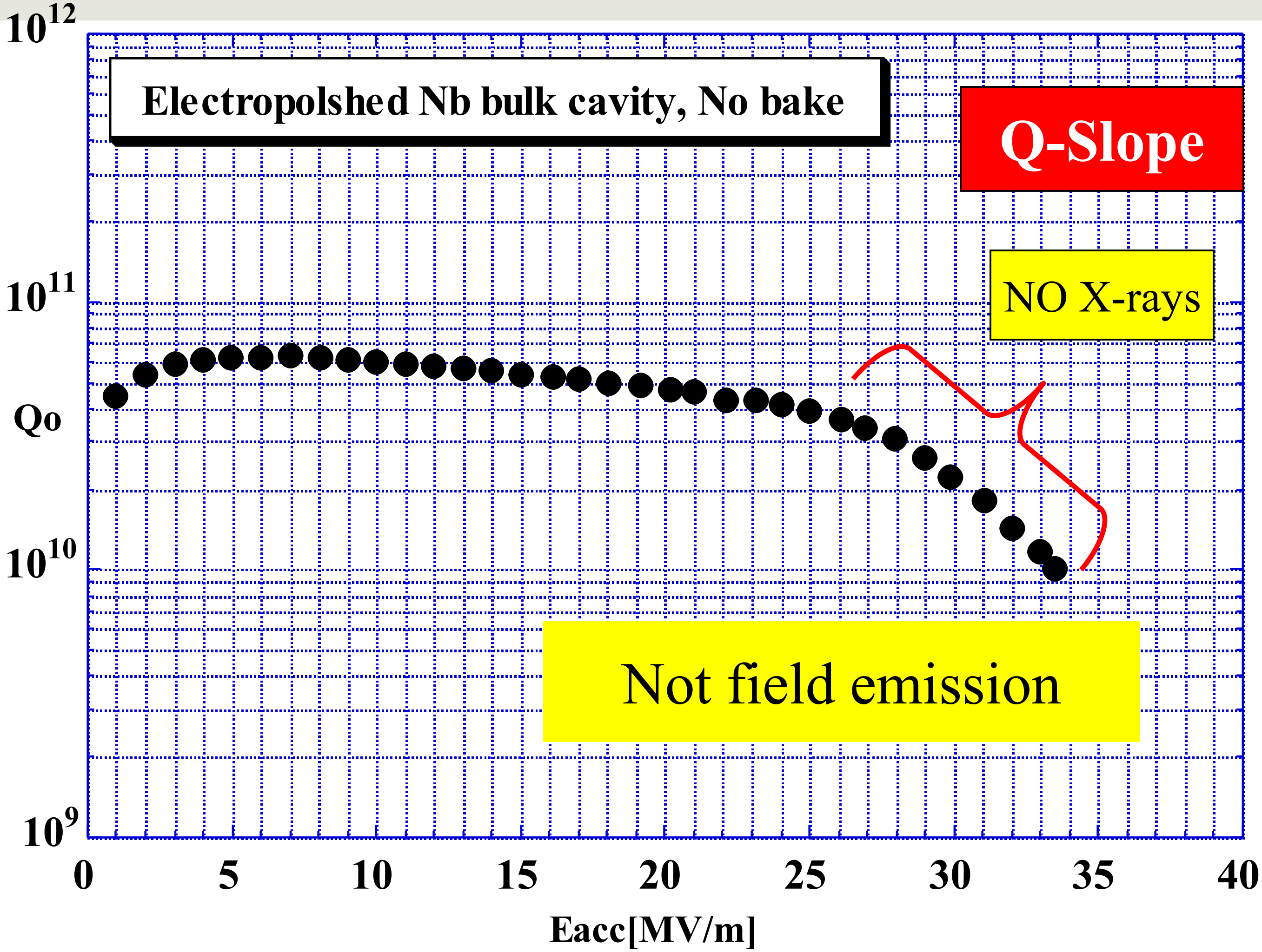
KEK's Experience against Hydrogen Q-disease and the Cure



KEK battled hydrogen Q-disease with EP'ed cavities.
They took hydrogen degassing at 710^{O}C for TRISTAN cavities.
No problem happened for the TRISTAN cavities.

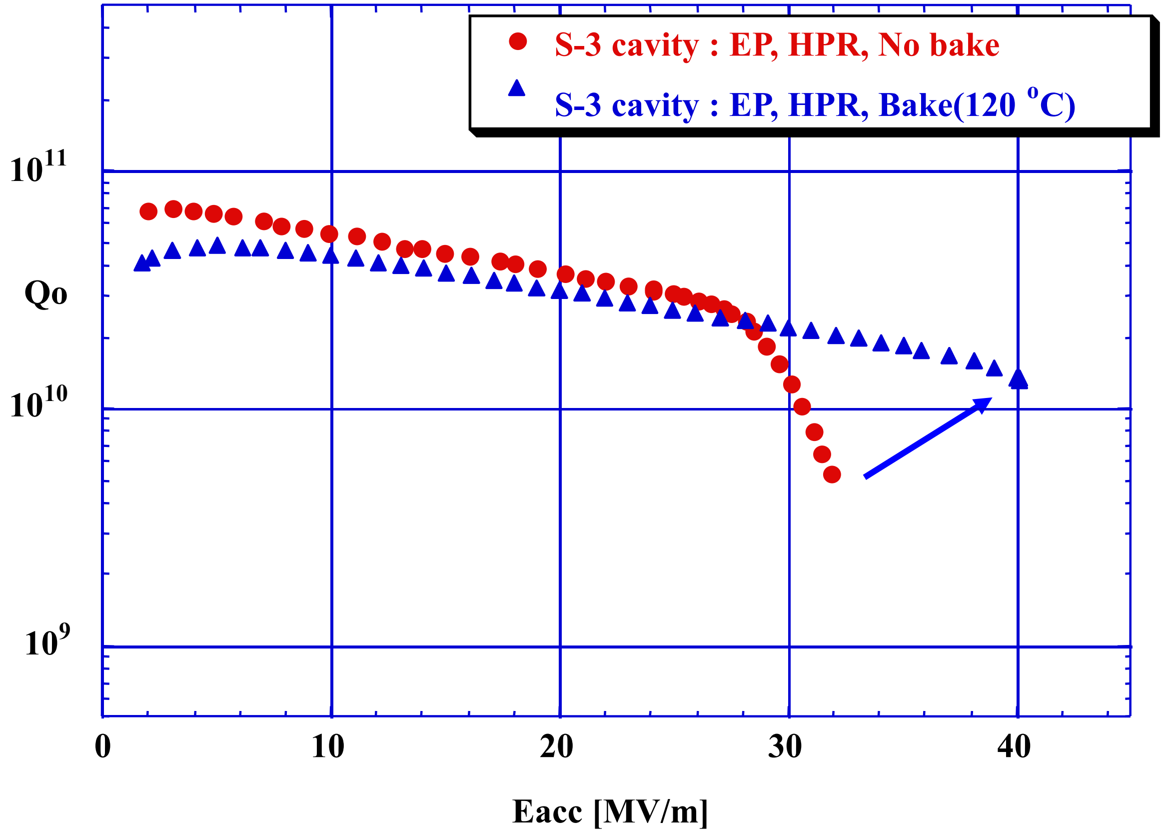
- Hydrogen Q-disease with electric polished cavity is well known since 1980's.
- Heat treatment at 710 -750^{O}C (depend on mechanical property) could solve this issue.
- From the present understanding point of view, the pre-cooling (~ 100K) by liquid nitrogen could make the problem, which was done to save liquid helium.

15.7 High Field Q-slope



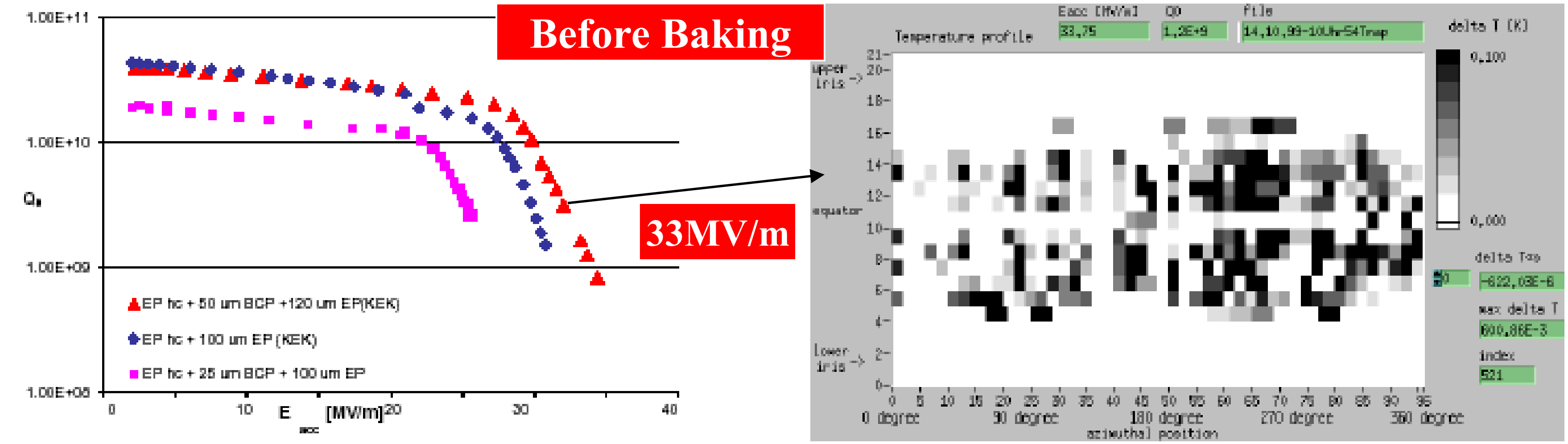
Discovered in 1998 at KEK/DESY

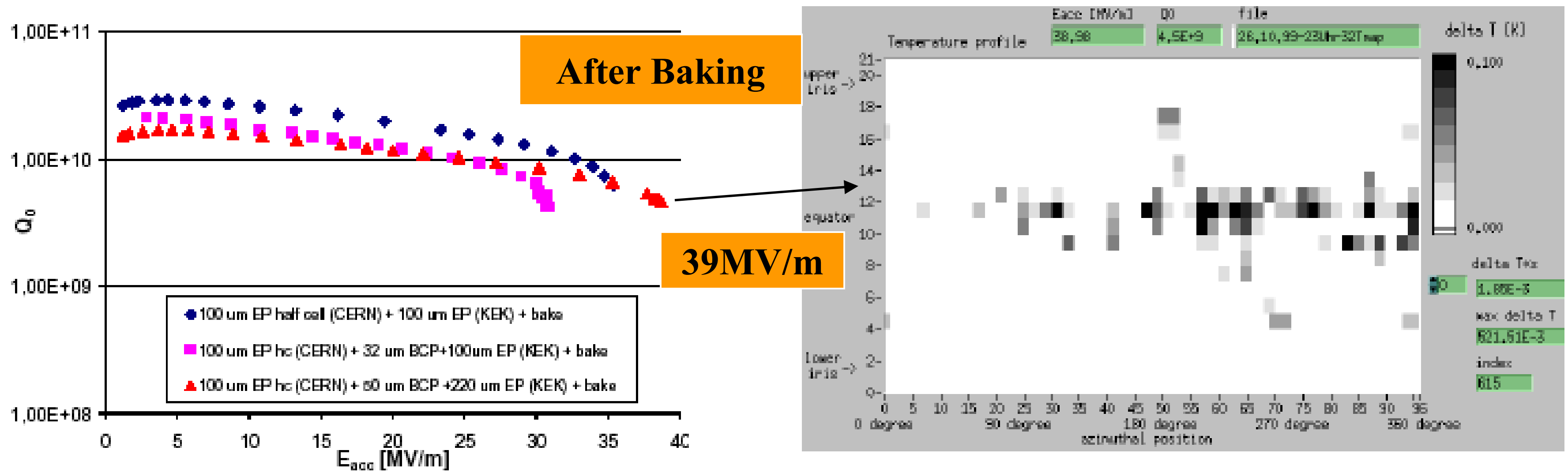
Baking Effect with EP'ed Cavities



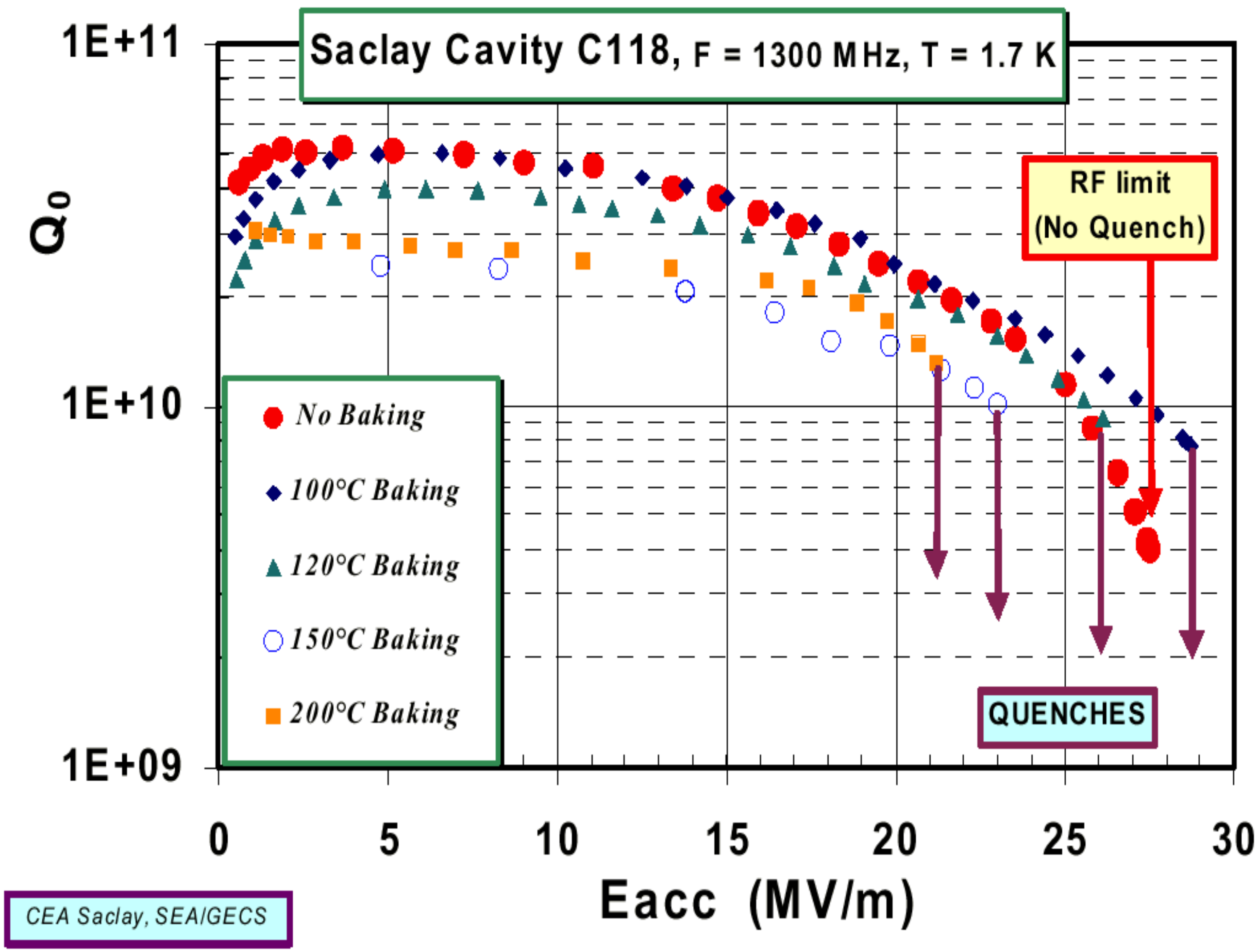
- **EP'd cavities have HFQS but it disappears by baking.**
- **KEK was routinely making bake to improve the vacuum quality in the cavity but did not noticed the effect on HFQS.**
- **DESY found this phenomena.**

Heating Spots Dramatically Disappears by Baking on EP'ed Cavities





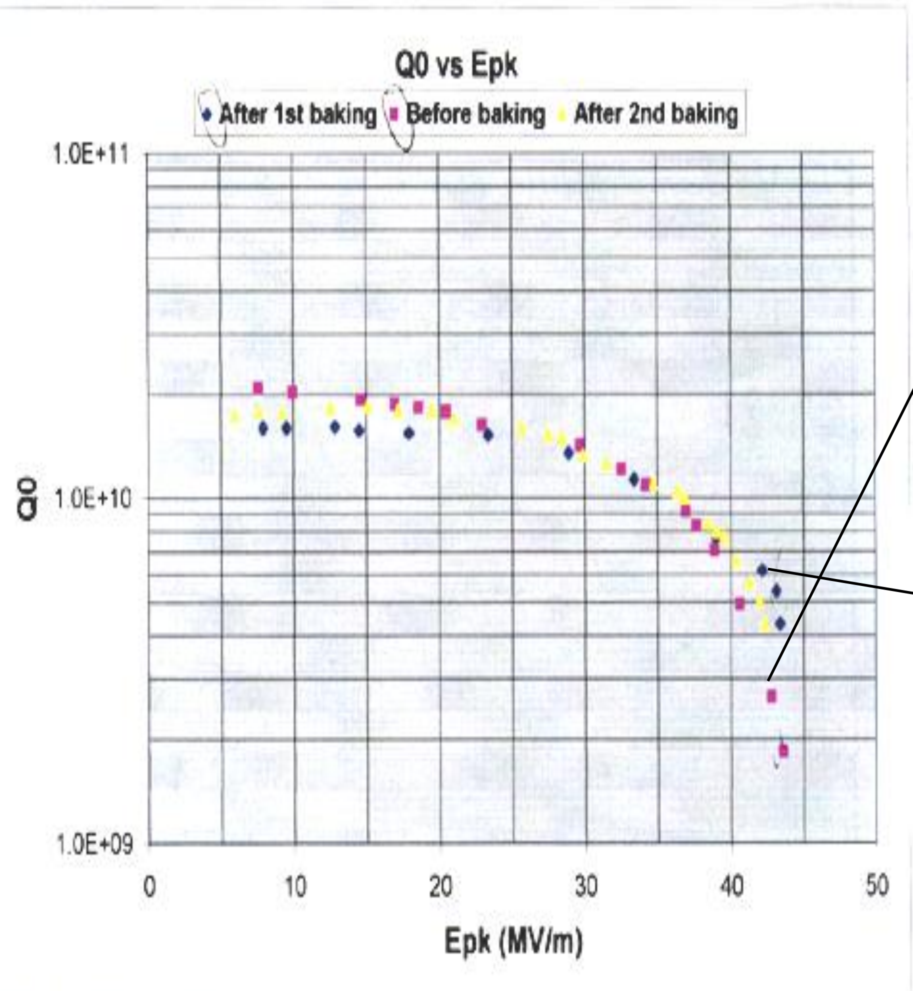
Baking Effect on CP'ed Cavities



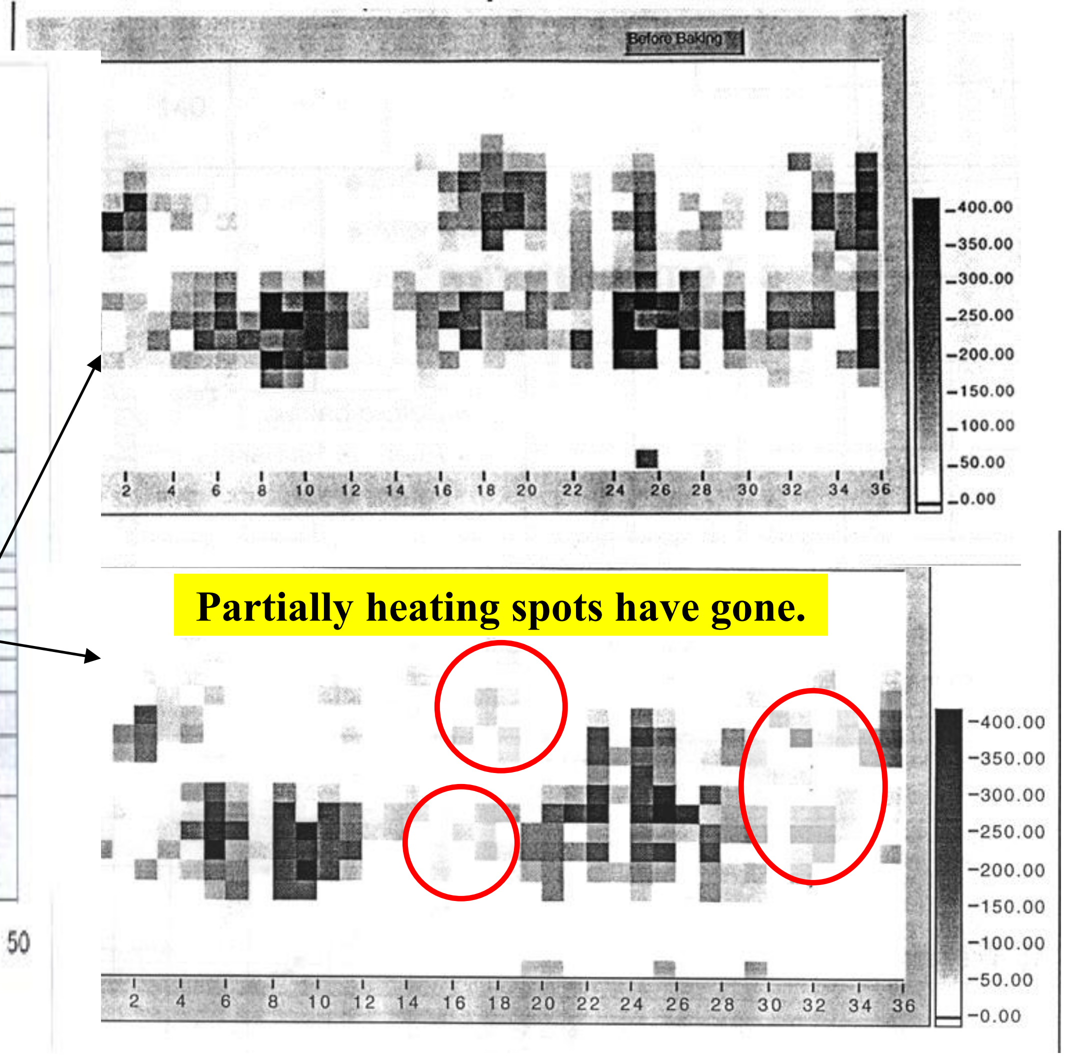
Baking effect is small with the chemically polished cavities.

CEA Saclay, SEA/GECS

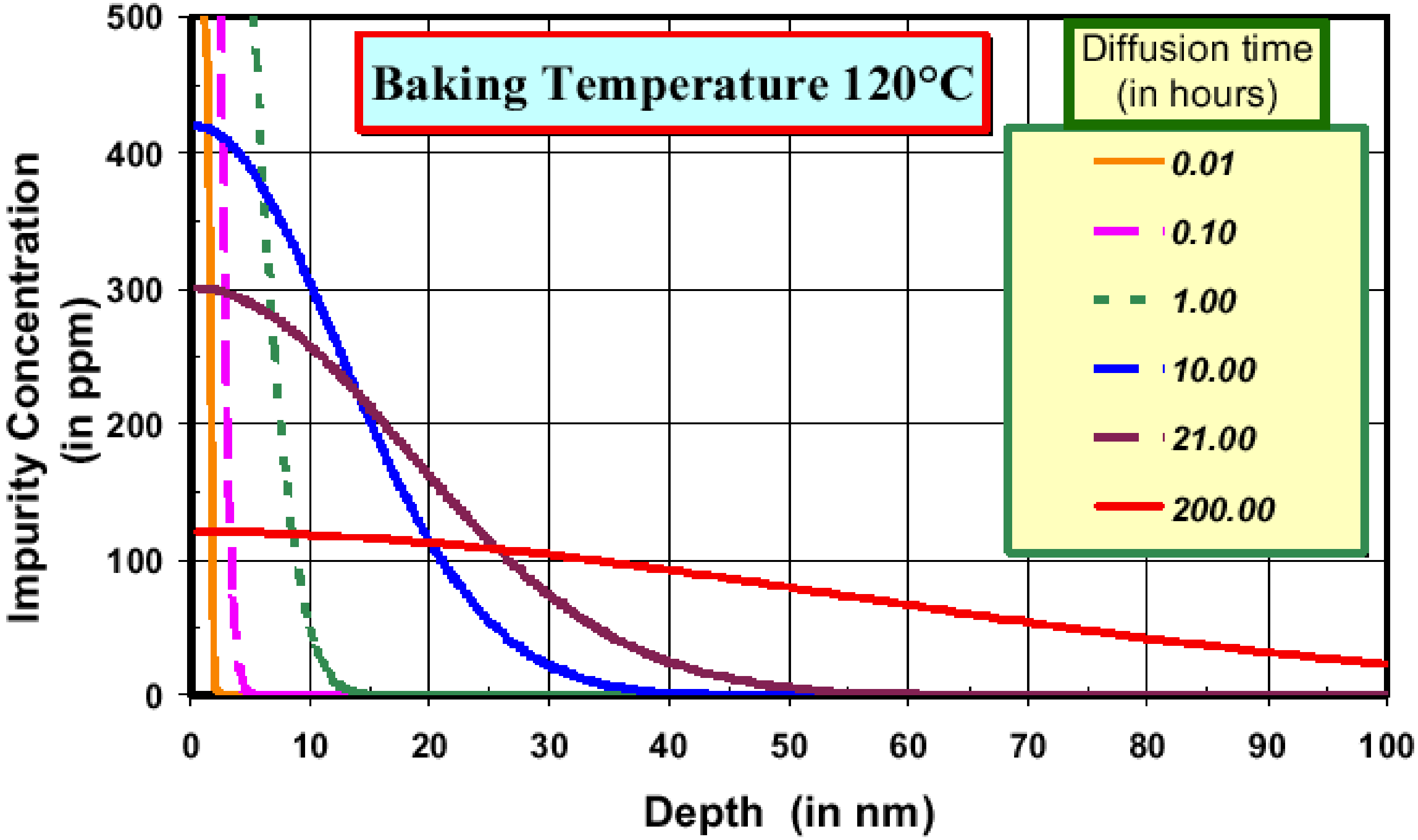
Heating Spots Partially Disappeared by Baking on BCP'ed



Before Bake Epk = 42 MV/m

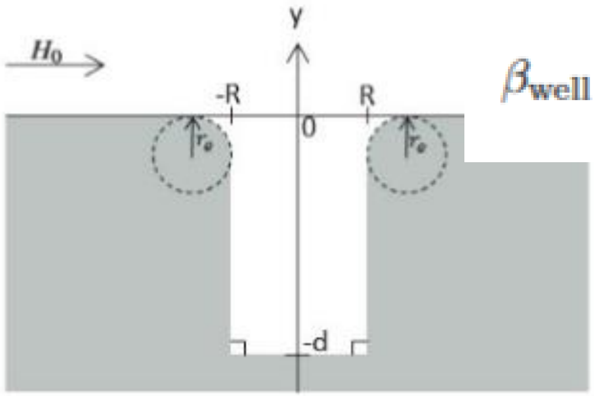


Oxygen Diffusion by Baking



- **Baking effect is expected by Oxygen diffusion underneath deeper and top surface (RF penetration depth) becomes clean.**

15.8 Magnetic Field Enhancement at Defect Surface



$$\beta_{\text{well}}(r) = \left(\frac{2}{3\pi}\frac{R}{r}\right)^{\frac{1}{3}}$$

Figure 3: A two-dimensional well with round edges. A gray region represents a superconductor in the Meissner state, R is half a width, $d\,(\gg R)$ is a depth of the well and r_e is a round-edge radius.

$$\beta^*_{\text{tri}} = P(\alpha)\left(\frac{R}{r_e}\right)^{\frac{\alpha}{1+\alpha}}$$

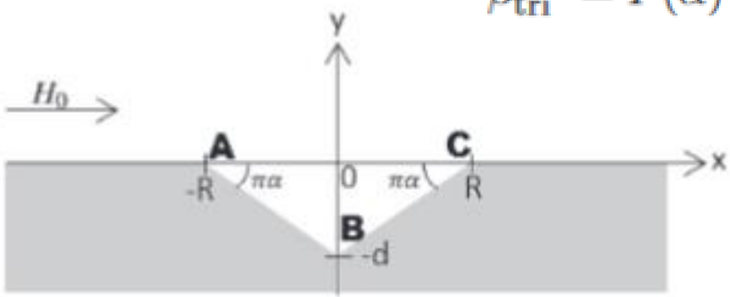


Figure 4: A two-dimensional triangular pit with sharp edges. A gray region corresponds to a superconductor in the Meissner state, $\pi\alpha\,(0 < \alpha < 1/2)$ is a slope angle and R is half a width of the open mouth. Note that a relation between a depth, d, and half a width of the open mouth, R, is given by $d = R\tan\pi\alpha$.

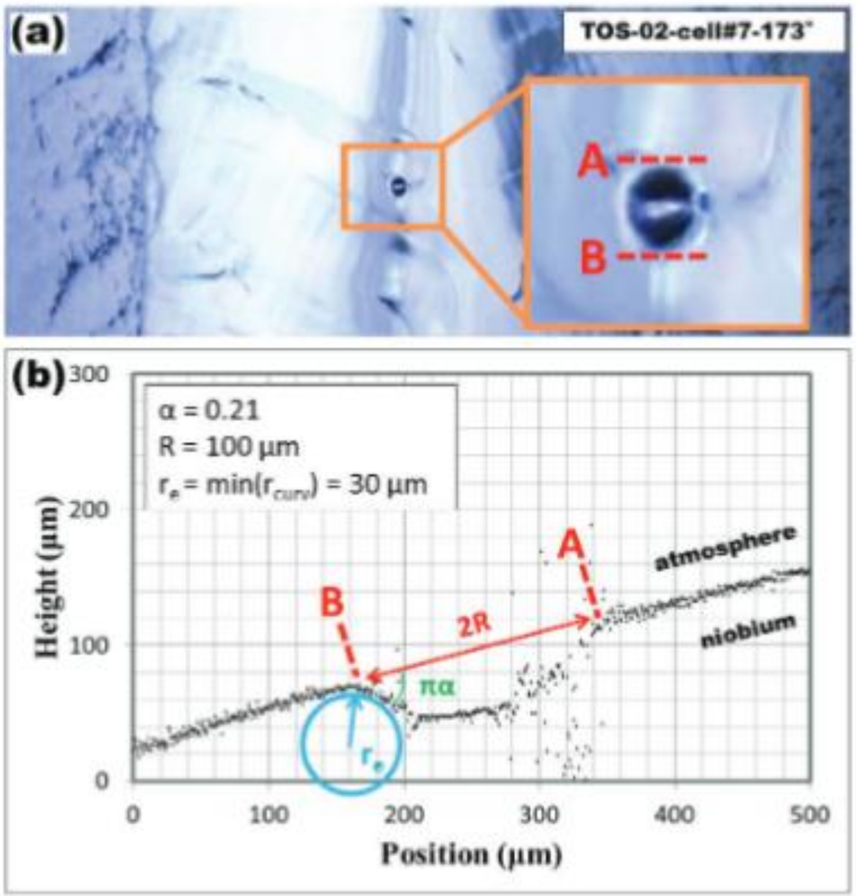
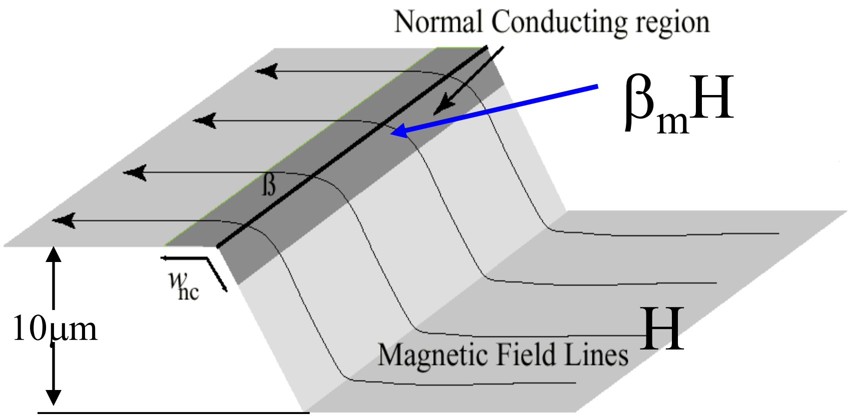
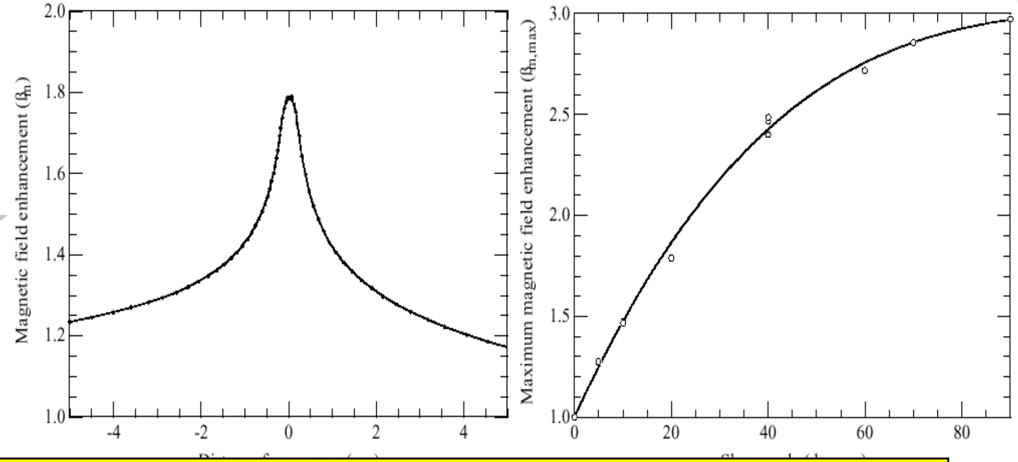


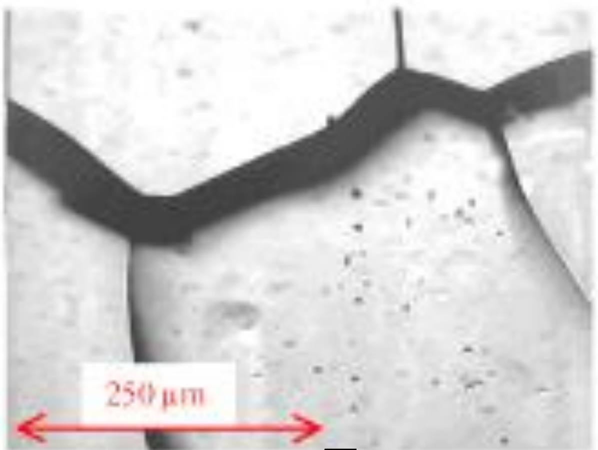
Figure 7: A pit found at the surface of TOS-02 cavity. (a) An optical image of the pit [4]. (b) Results of profilometry by a laser microscope.

Magnetic Field Enhancement at Grain Boundary Steps

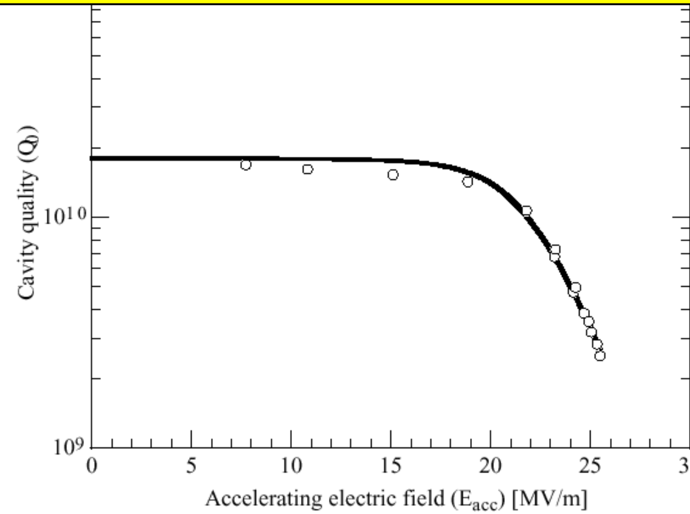




Standard BCP Chemistry on niobium :
Sharp boundary edges are clearly visible



This model can not explain baking effect.

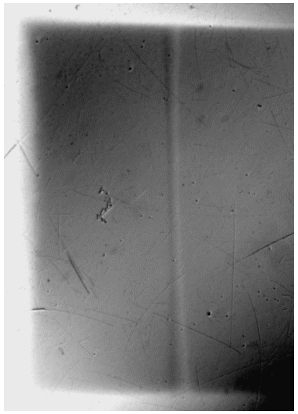


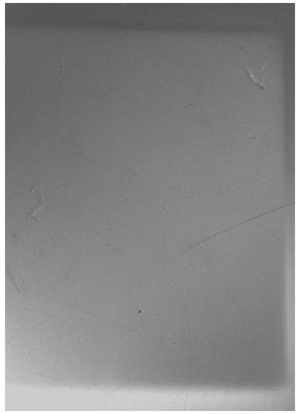
$$\beta_m \cdot H_{RF} \geq H_C = \frac{\sqrt{2} \cdot H_C(0)}{\kappa(0)} \cdot (1 - t^4)$$

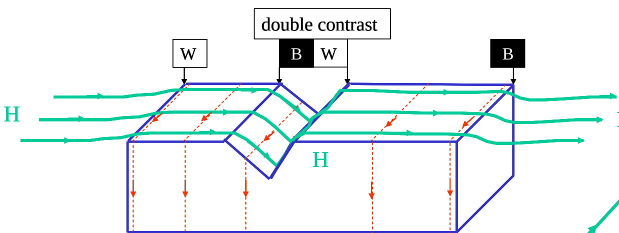
Figure 19: Comparison of the measured cavity quality (Test C) with that calculated by (25) using $H_{crit} = 1875$ Oe.

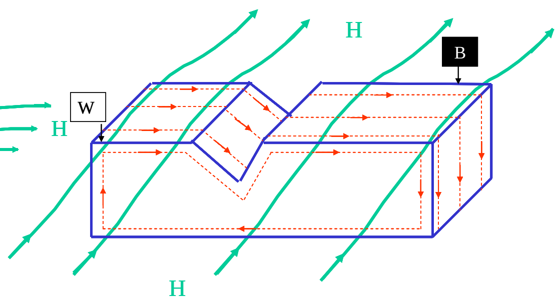
Monograph Effect on Magnetic Field Enhancement

By C.Antone





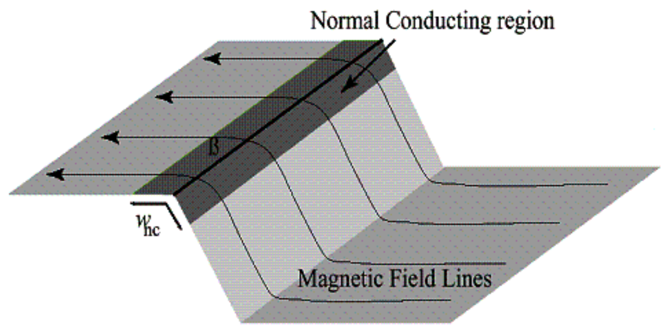


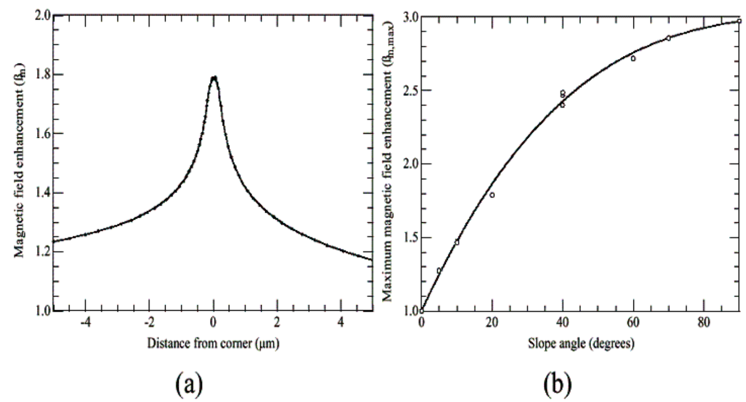


Flux trapping happens on the steps perpendicular to the magnetic flux !

CBP is right way to eliminate the monograph effect !!

J.Knobloch





Homework

▪ Homework 16.1

- SRF niobium cavity performance is getting close to the fundamental limitation, however still multipcating and field emission are concerned as the current major performance limitation. In this homework, explain below.

  1) Describe the phenomena of the multipcating.
  2) Describe the phenomena of the field emission.
  3) Both are happed by similar causes, but they have a difference. Explain it.
  4) Describe cures for these problem.