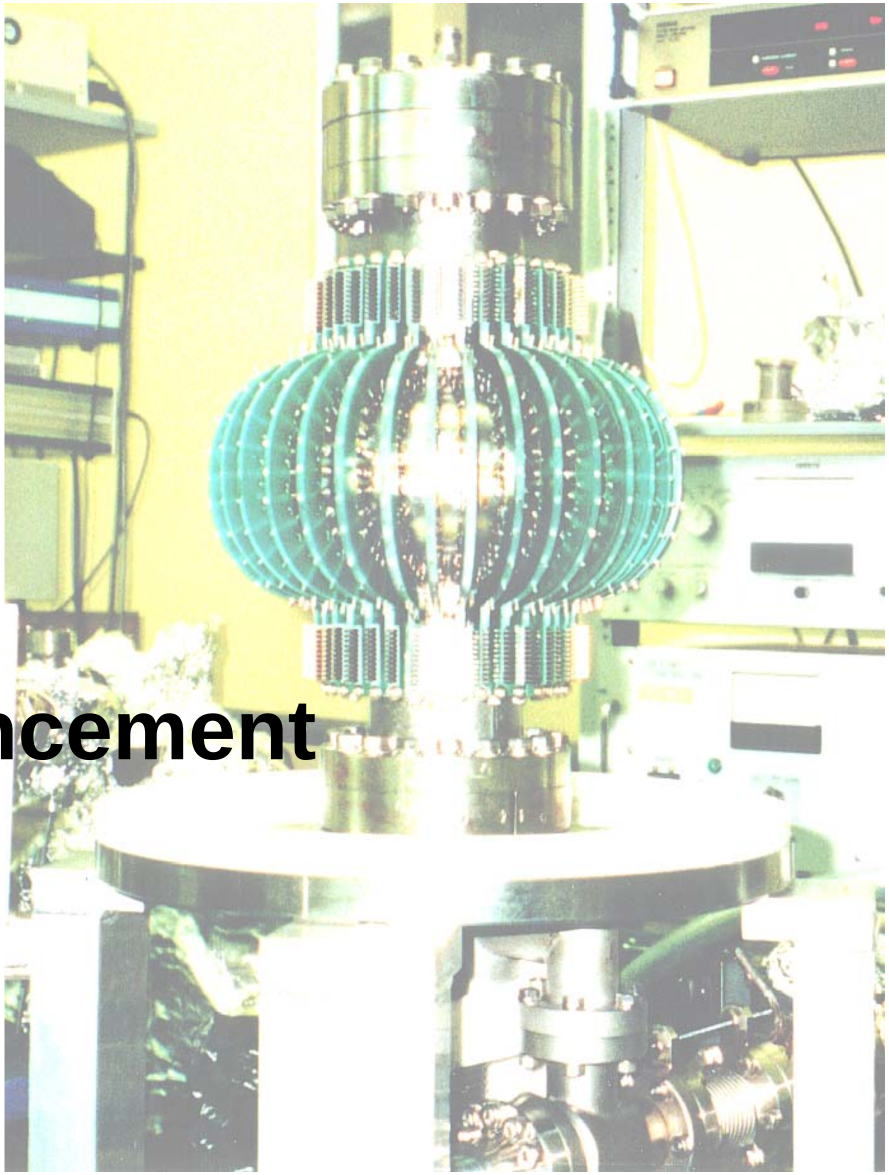
Superconducting RF II
- Basics for SRF Cavity -

K.Saito, KEK

8. Performance Limitations and Cures
9. Surface Preparation
10. Performance Measurement (Vertical Test)
11. Cavity Dressing
12. Cavity R&D for ILC

8. Performance Limitations and Cure



8.1 Multipacting

8.2 Field Emission

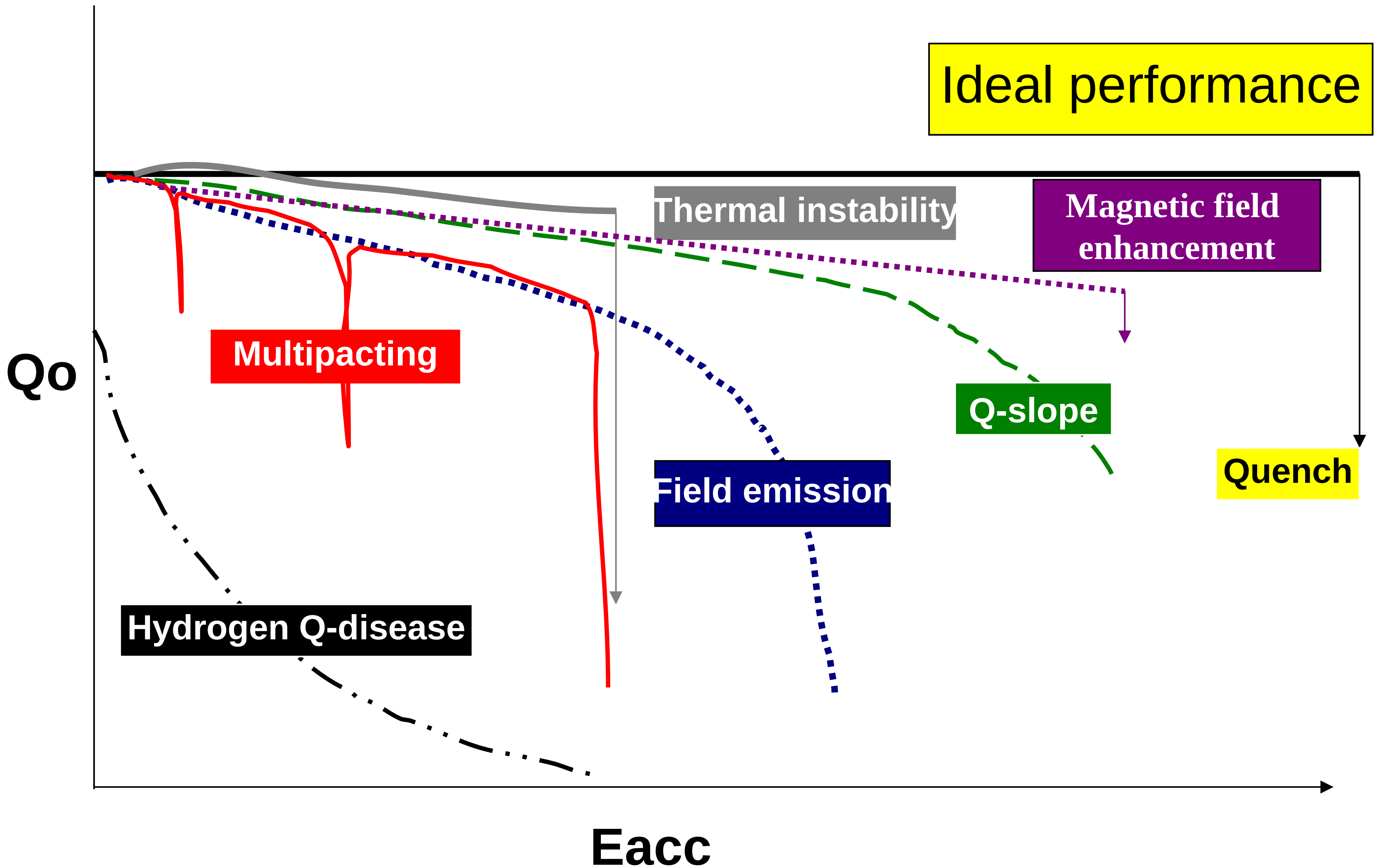
8.3 Thermal Instability

8.4 Hydrogen Q-Disease

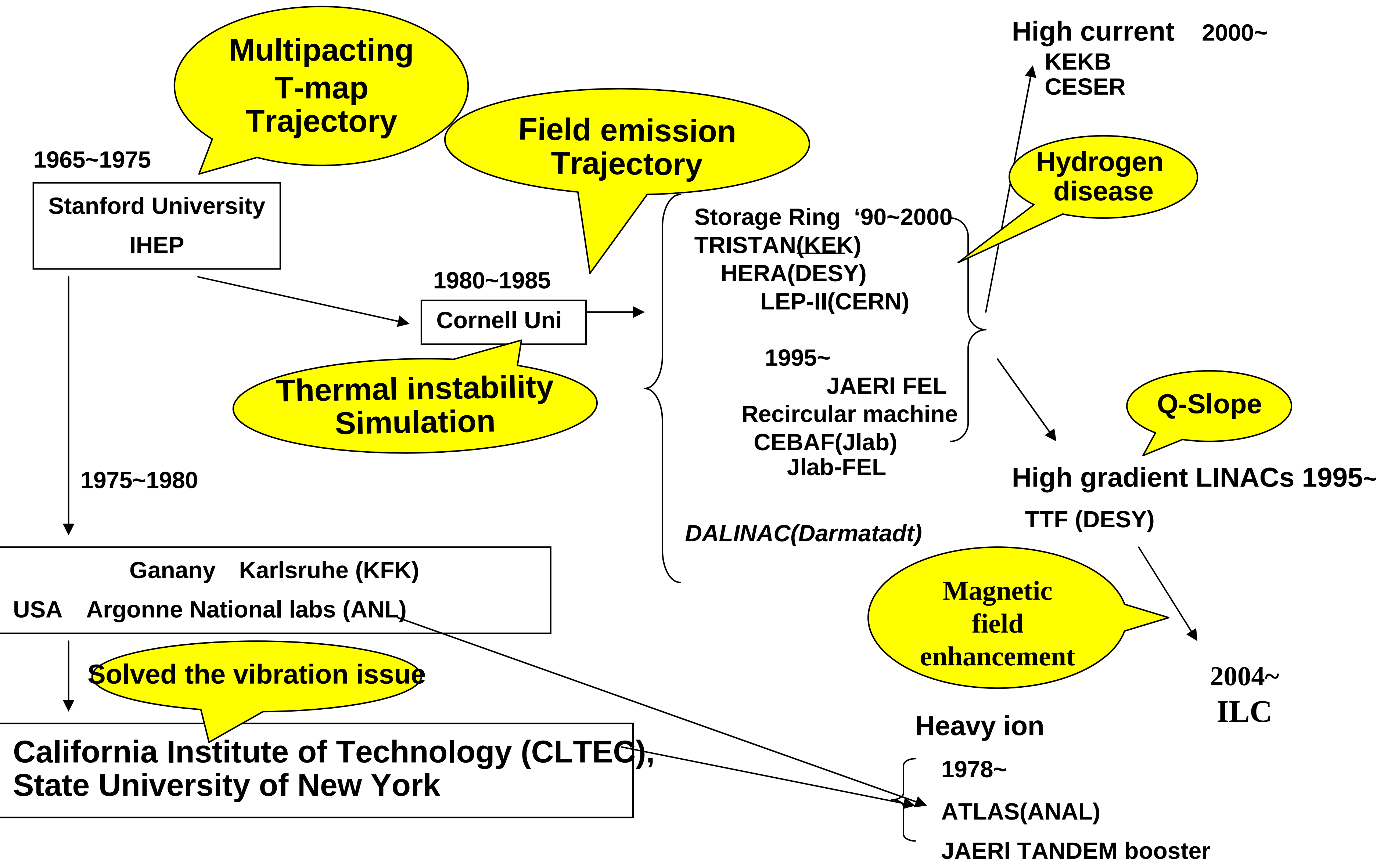
8.5 Q-Slope

8.6 Magnetic Field Enhancement

Various Performance Limitations in SRF Cavity



History of the Understanding of limitations

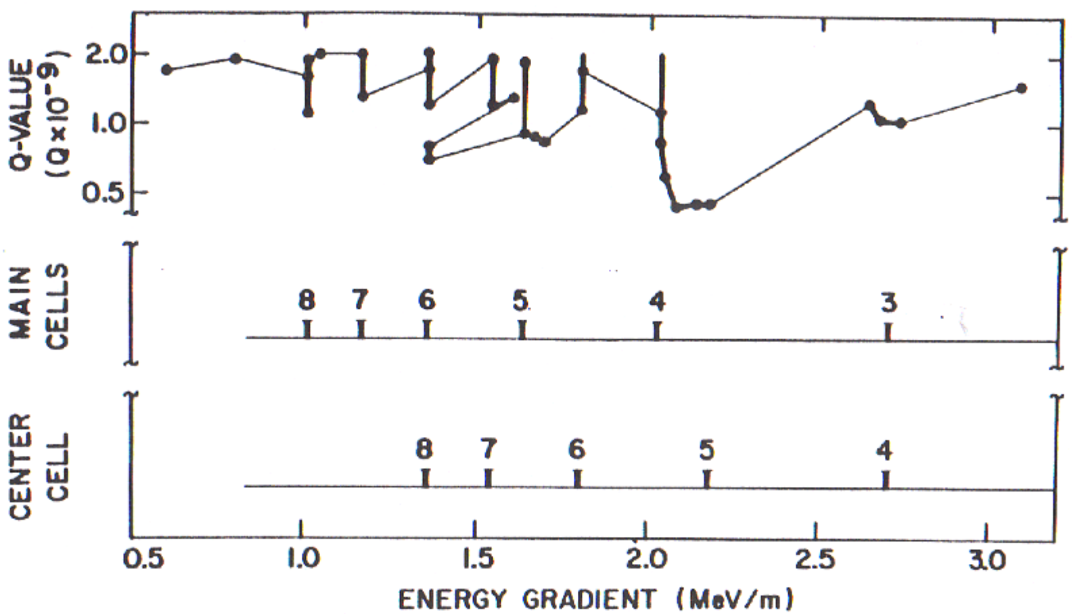


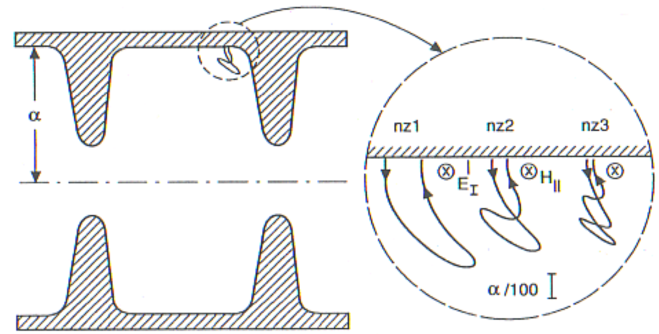
8.1 Multipacting

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

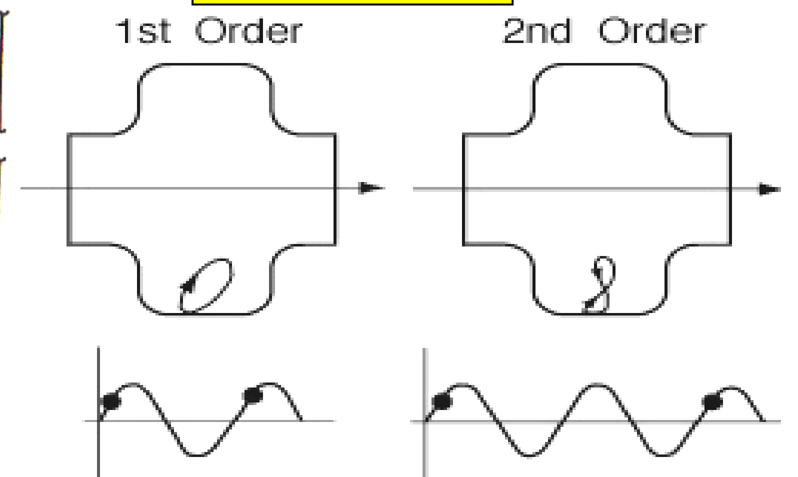
Seriously Limited by 1PM or 2PM

One point multipacting





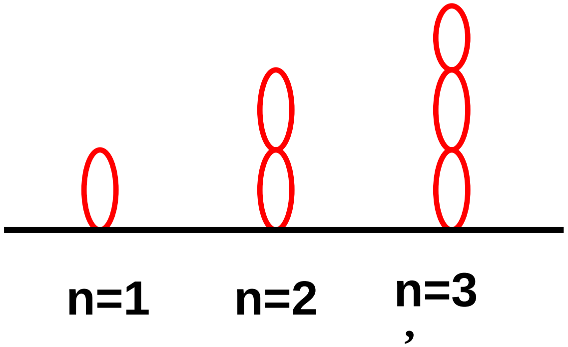
1 point MP



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

Scale law on RF frequency with the maltipacting levels



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

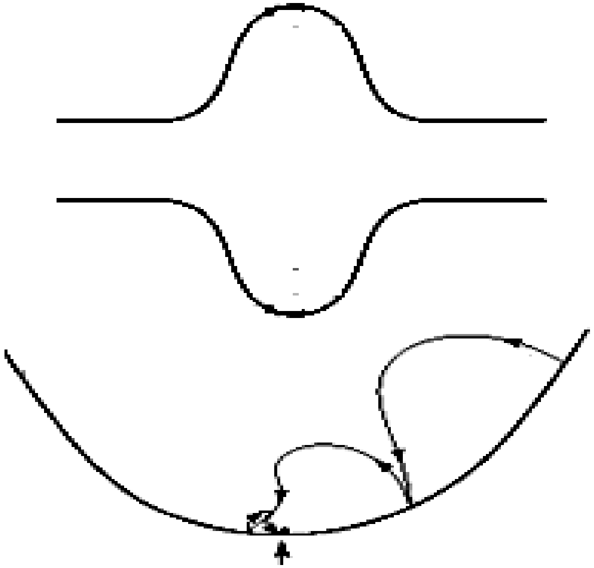
$$2\pi \cdot f(1P-nth) = \frac{e \cdot H(1P-nth)}{c \cdot m}$$

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

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

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

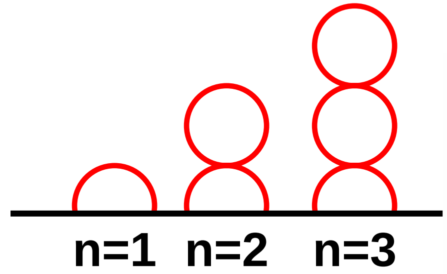
Eacc(1P-1st) = 390/43.8=8.9 MV/m

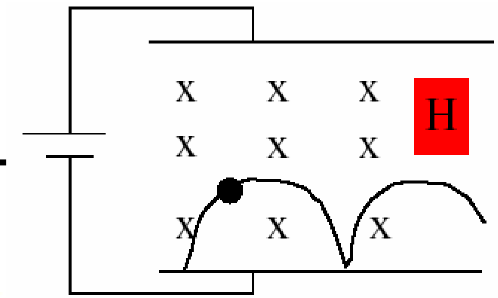
1P-2nd order・・・Eacc(1P-2nd) = 4.5 MV/m

Two-point MP

Two-point multipacting

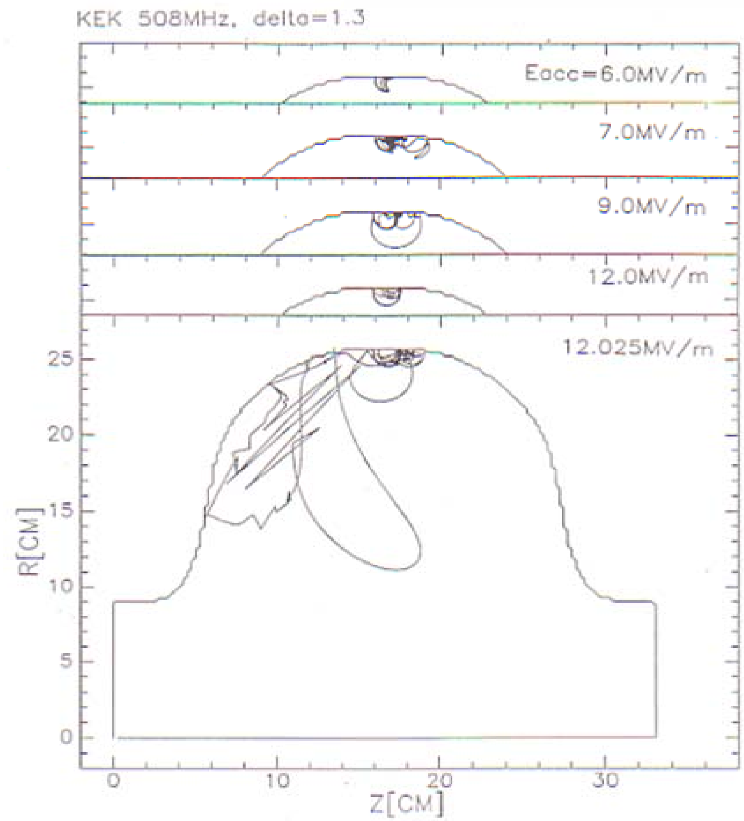
$$T(2P-nth)=(2n-1)T_{RF}$$





$$\frac{H(2P-nth)}{f_{RF}}=\frac{constant}{2n-1}$$, **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

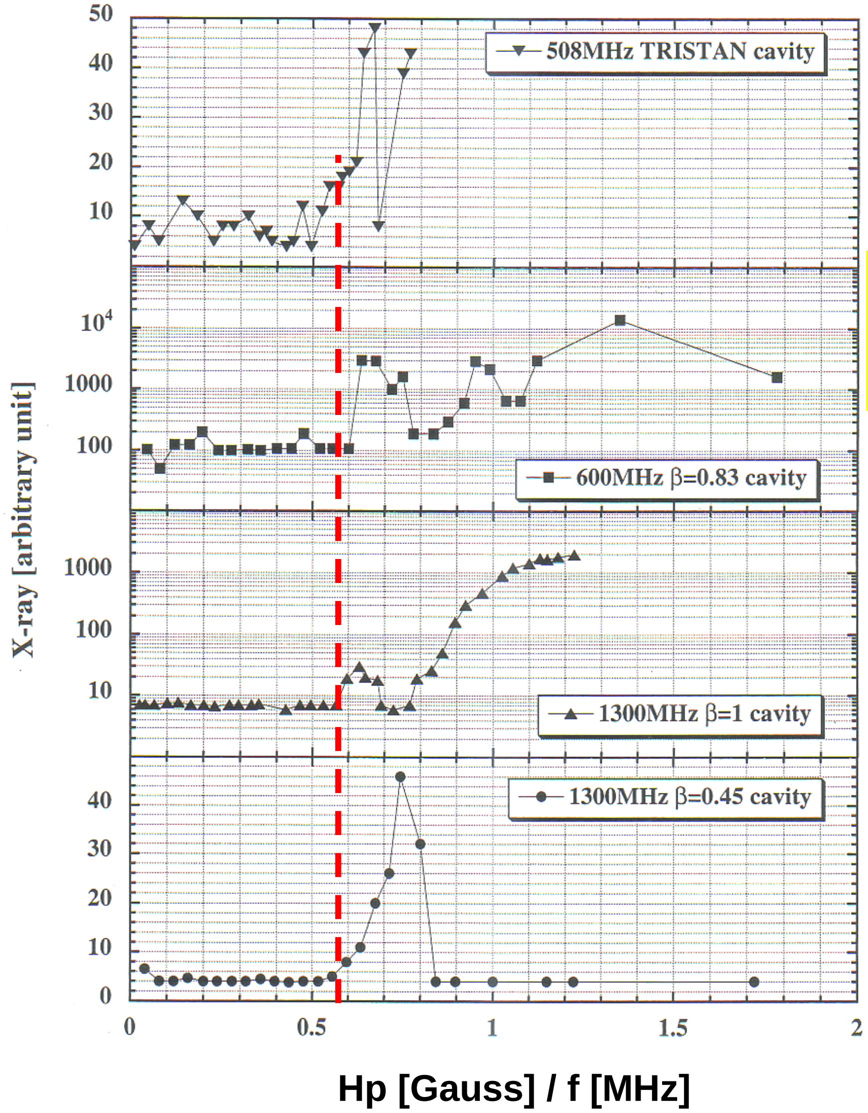
1300MHz, Hp/Eacc=43.8 [Oe/(MV/m)]

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

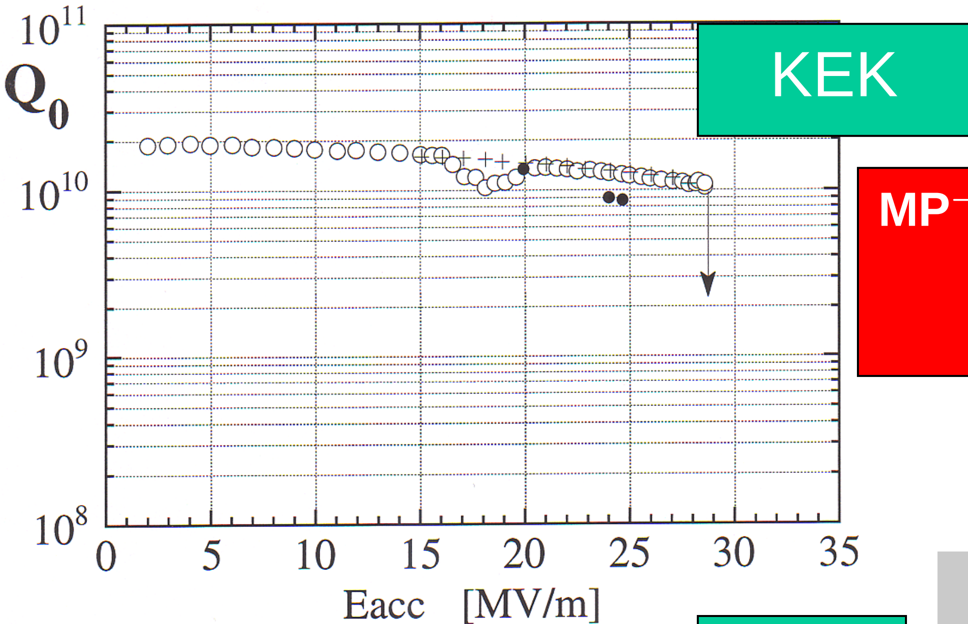
Onset Field of Two-point MP



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

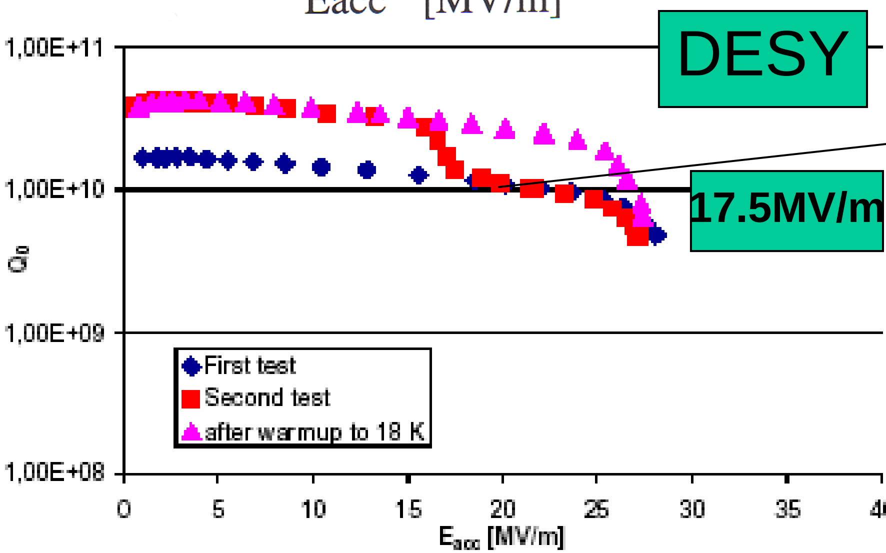
Multipacting keeps RF processing memory effect up to 200K warm up.

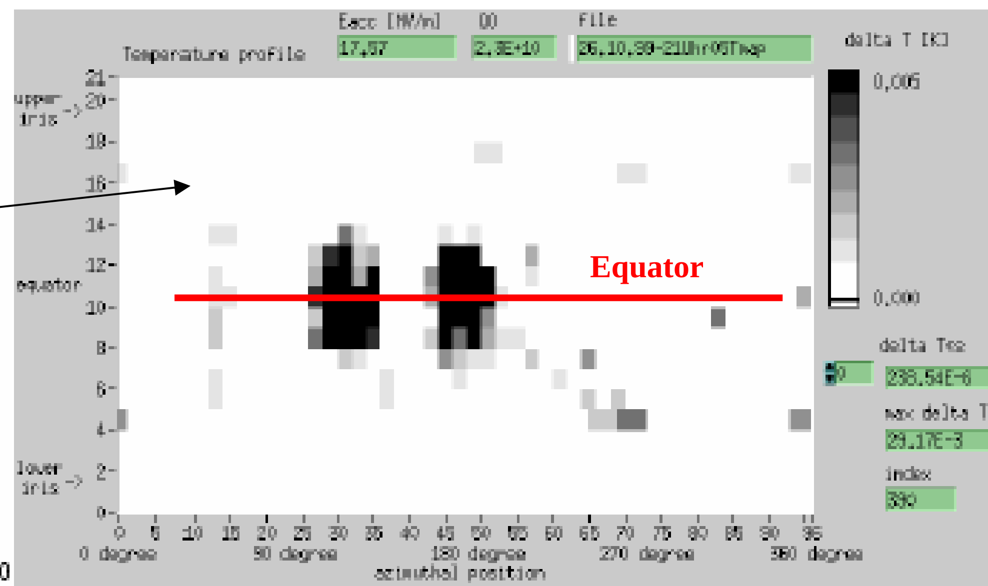
T-mapping of Tow-point MP



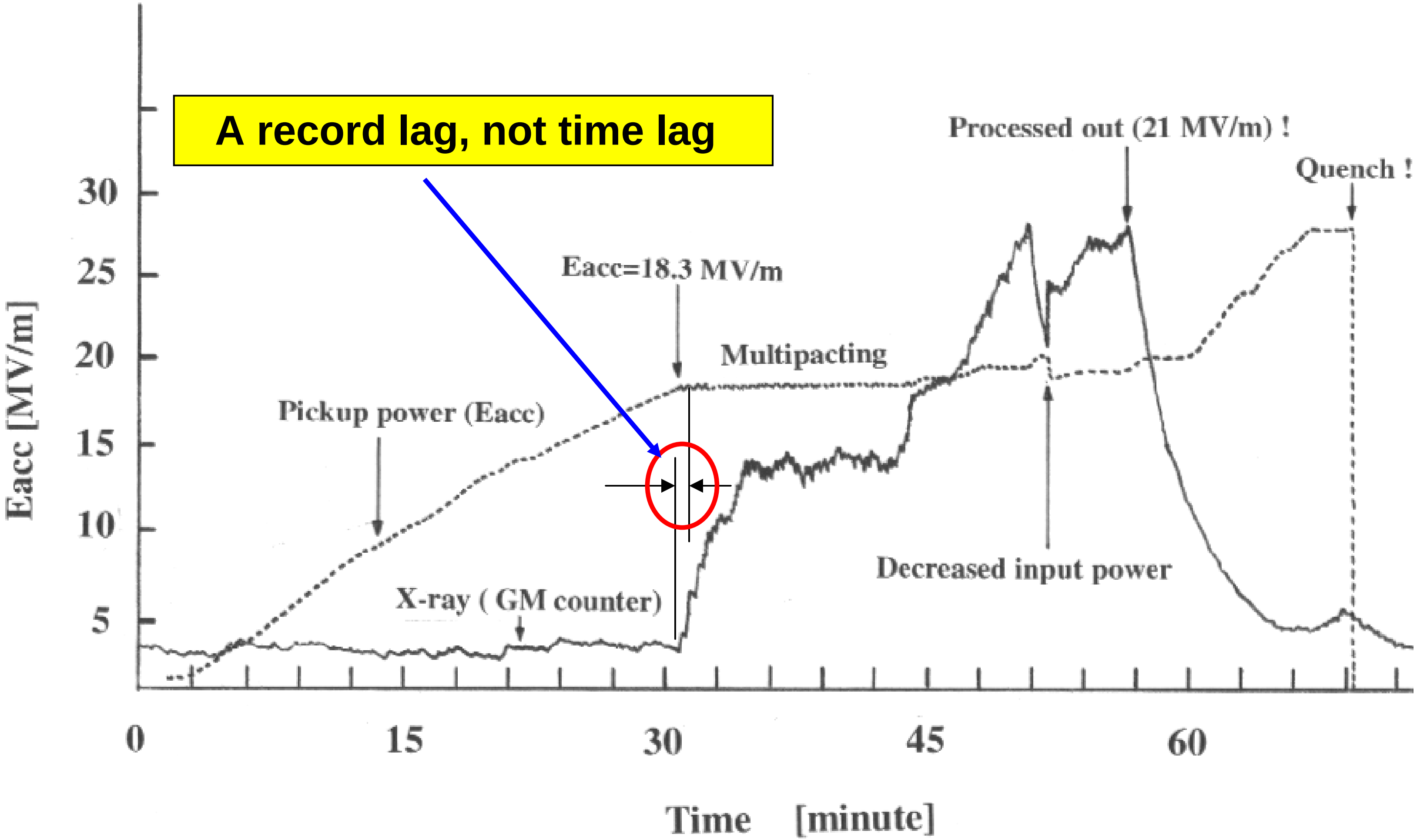
MP → Frozen flux trapping → Warm-up T >Tc → Disappear of the heating spots

T-mapping at 17.5MV/m

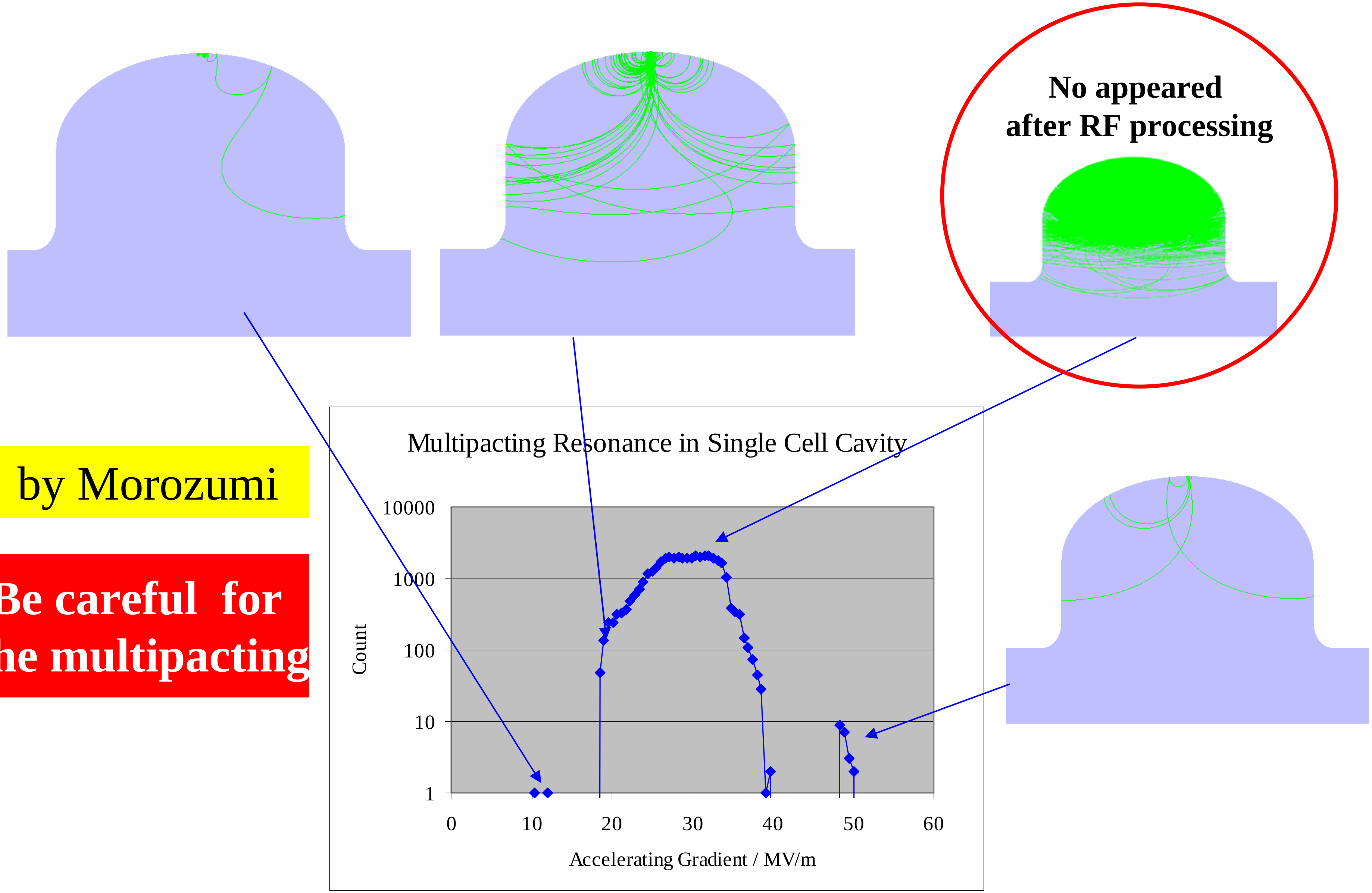




Processing of Two-point MP



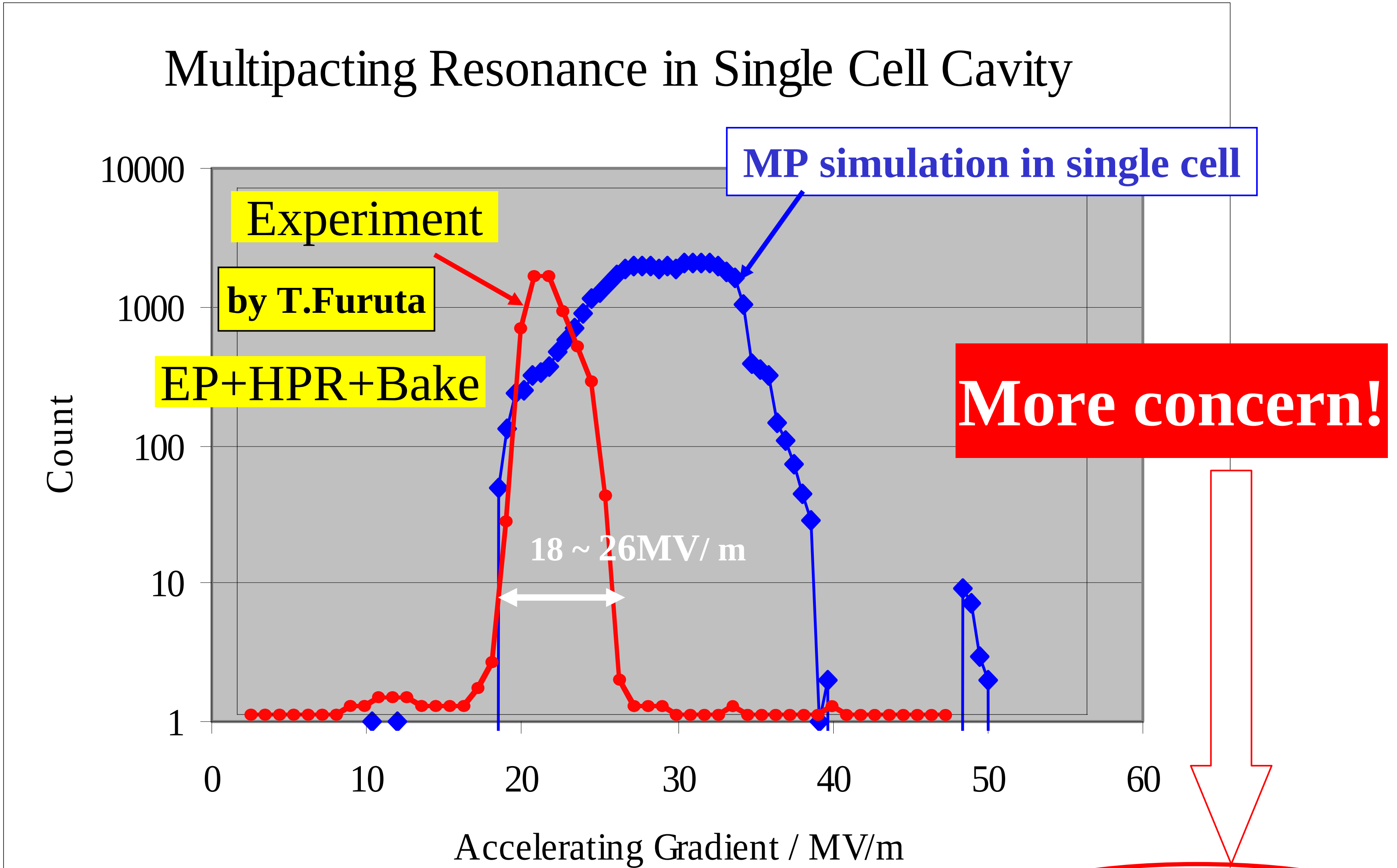
Multipacting in Ichiro Regular center Cell



by Morozumi

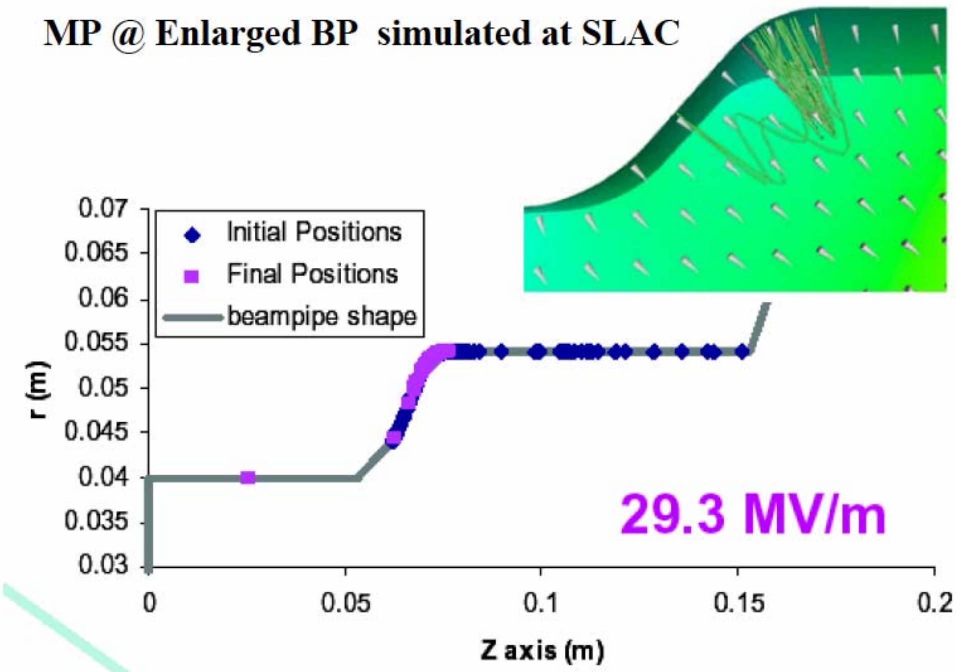
Be careful for the multipacting

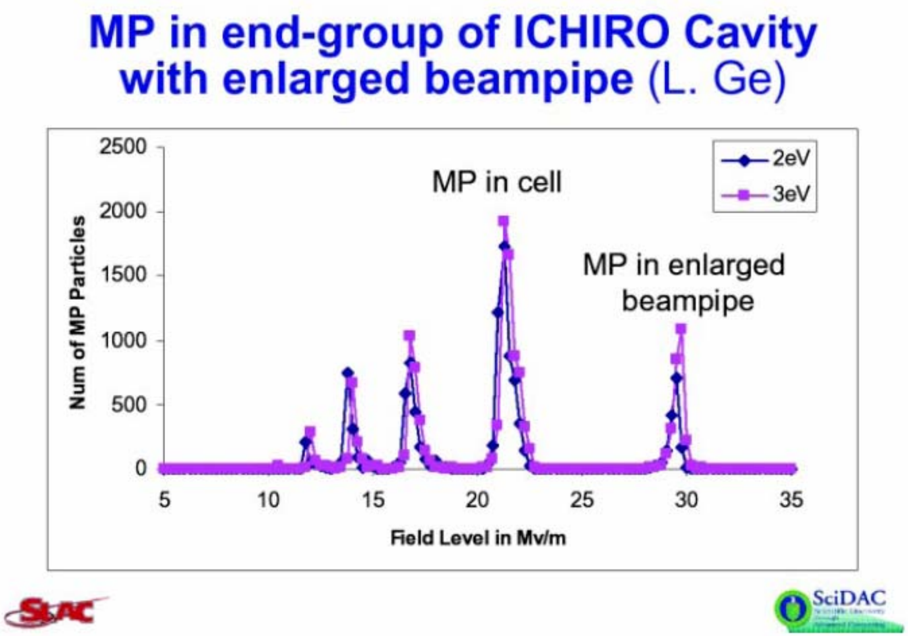
Need more concern on the multipacting



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

Multipacting @ enlarged beam pipe

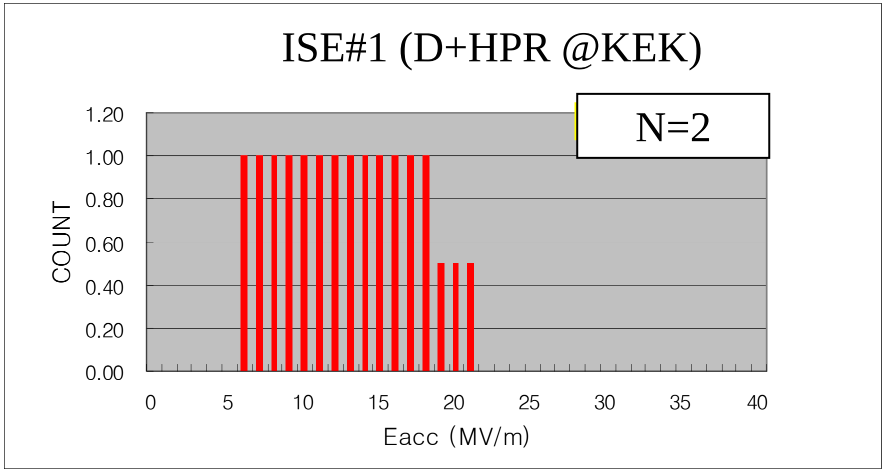




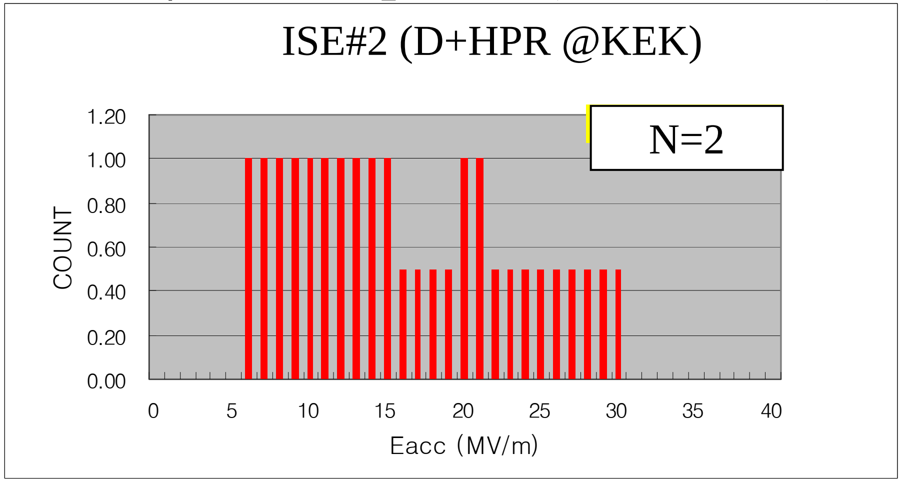
MP @ BP could be overcome by EP+Degreasing+HPR.

Multipacting in the END-cell

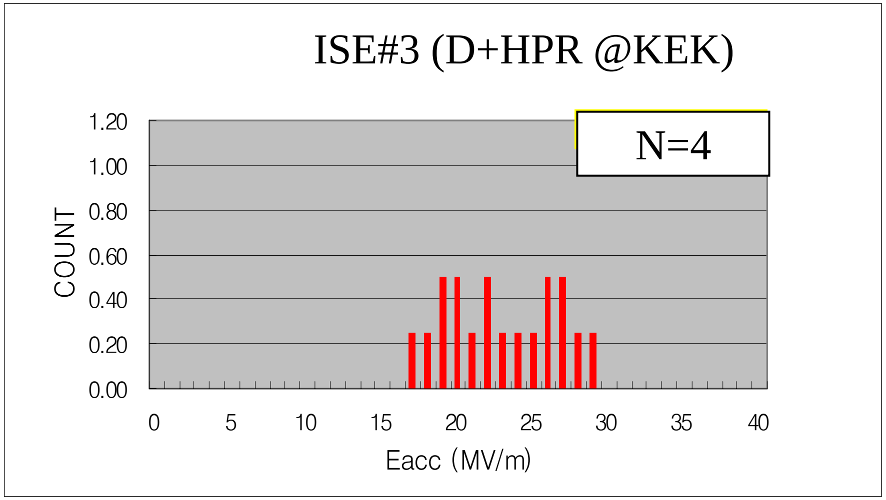
108ϕ BP, Straight



108ϕ BP, Tapered (Old Ichiro)



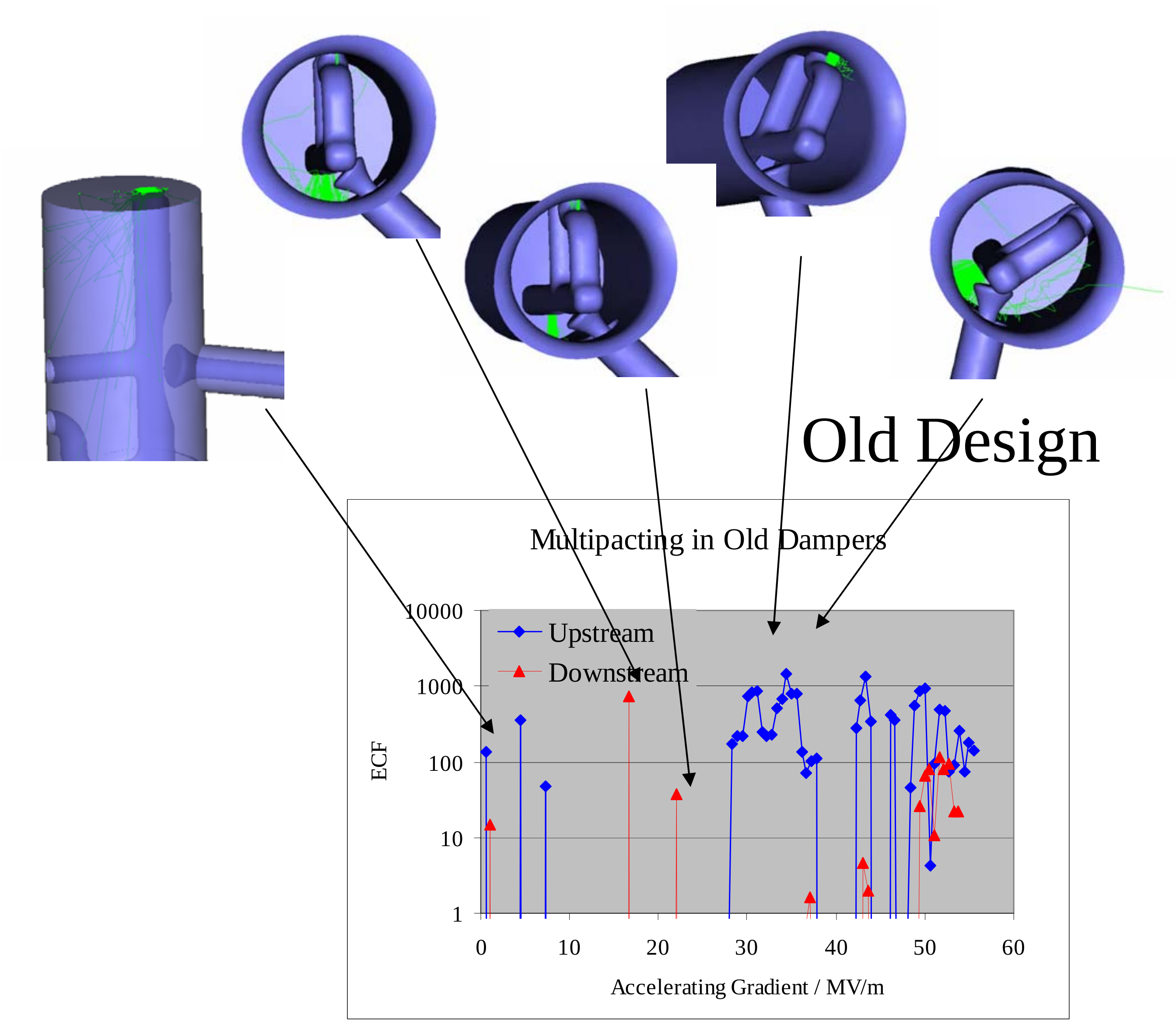
80ϕ BP, Straight (New Ichiro)



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)

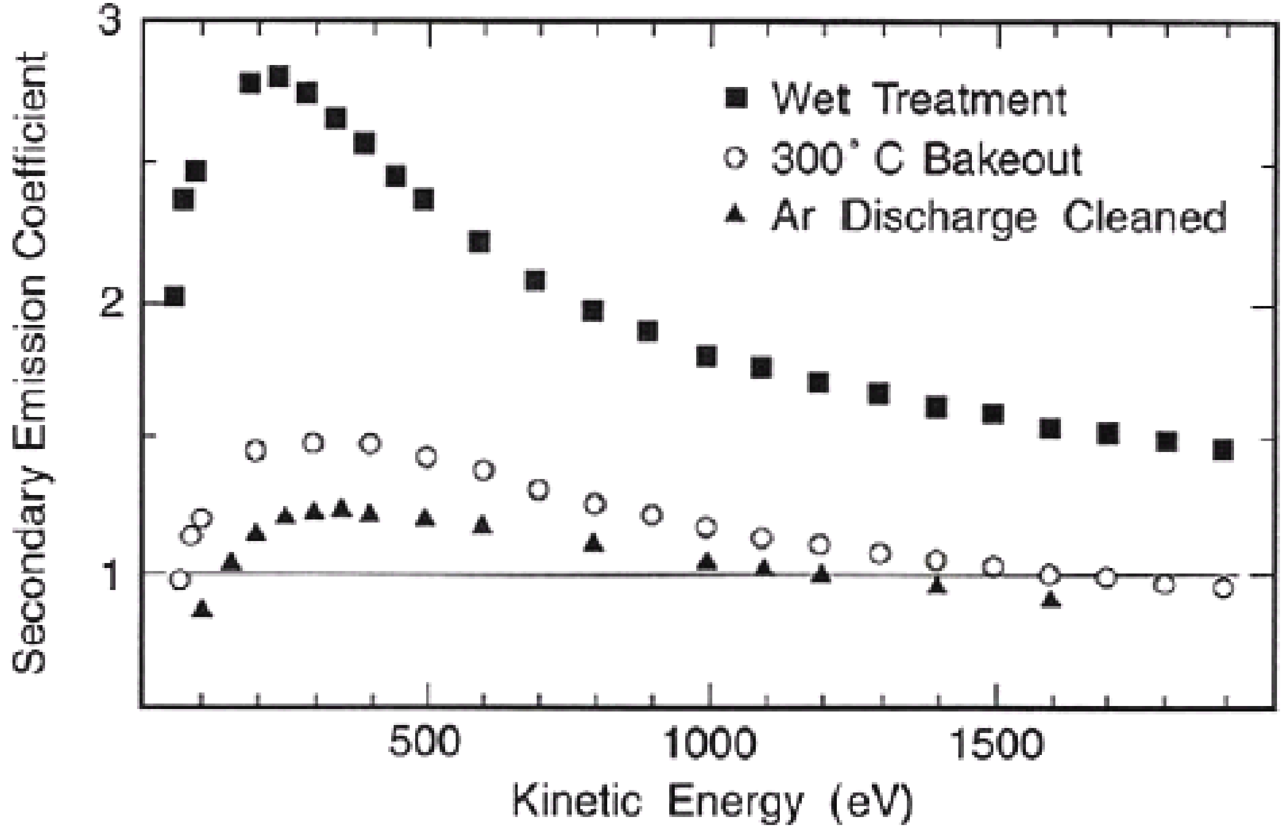


Cures against MP

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

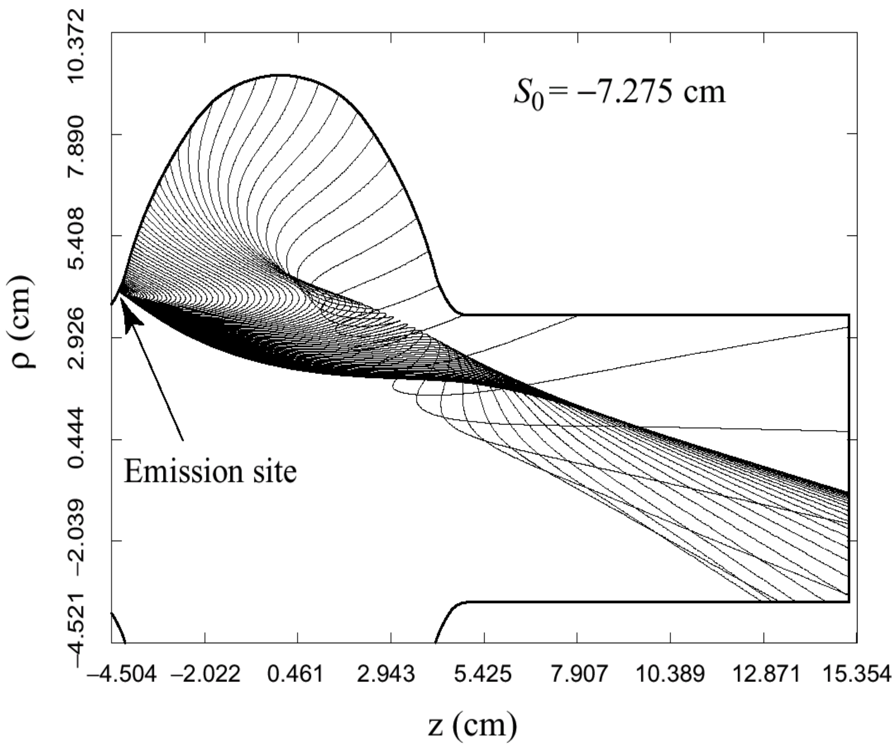
2) δ< 1 : Clean surface ⟶ Surface preparation

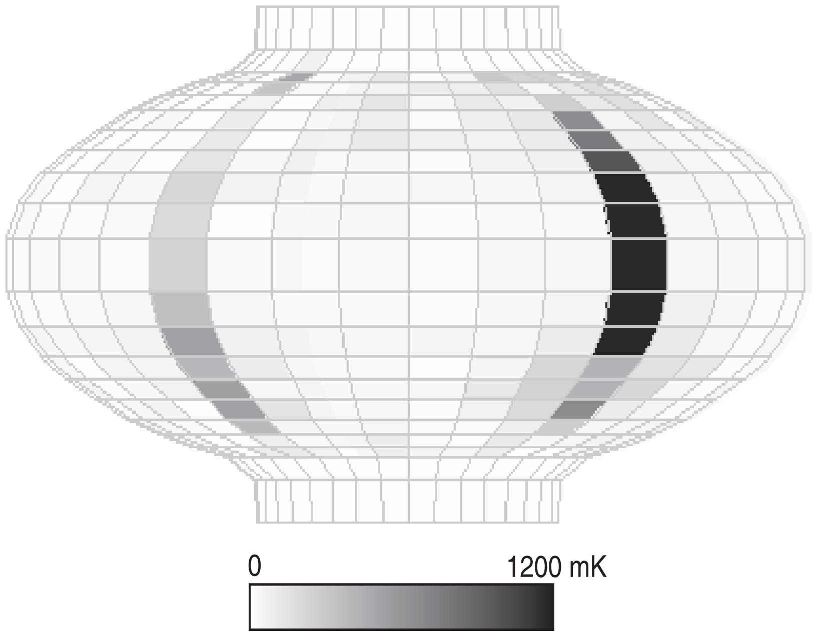
High pressure water rinsing
Argon gas or Helium gas discharge cleaning



8.2 Field Emission

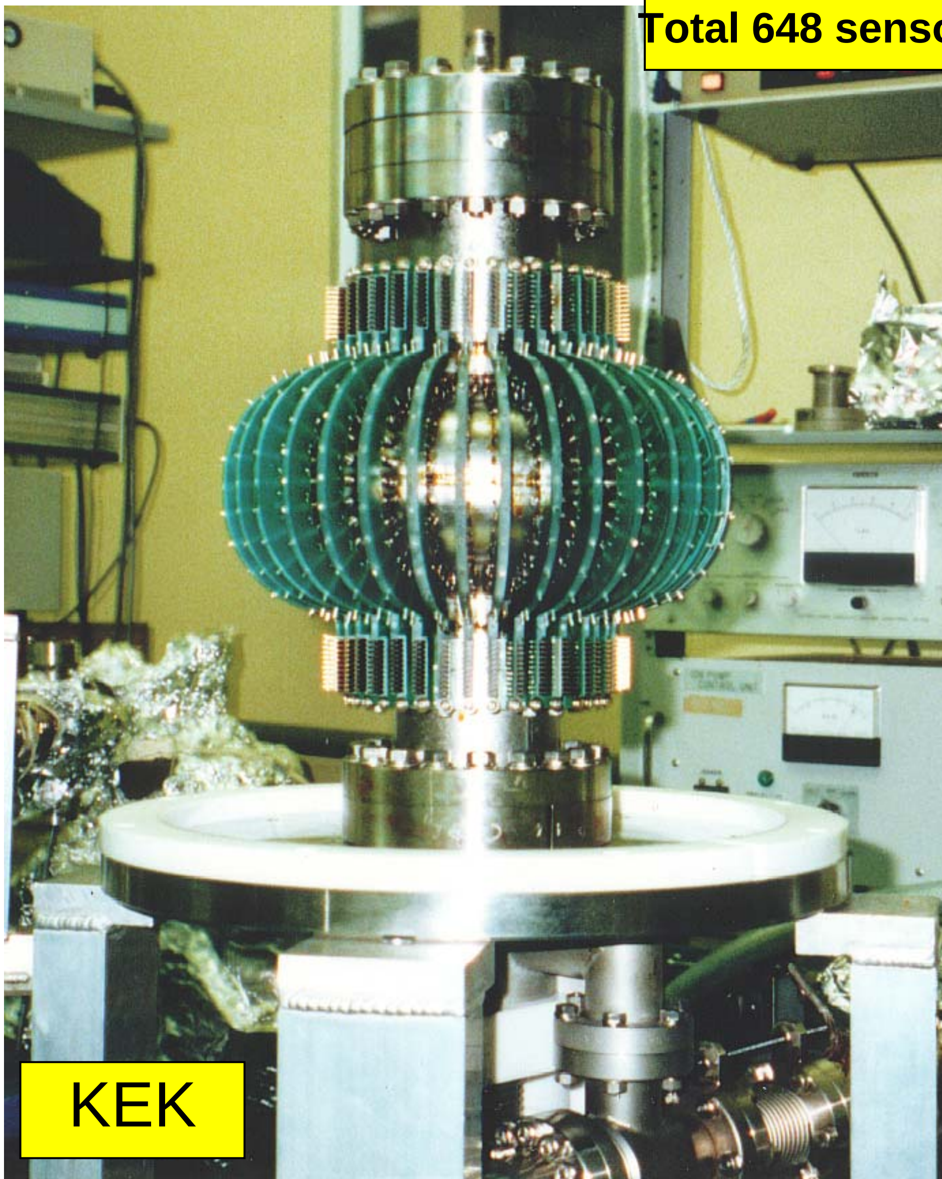
Non-resonant electron loading due to field emitted electrons by tunneling effect

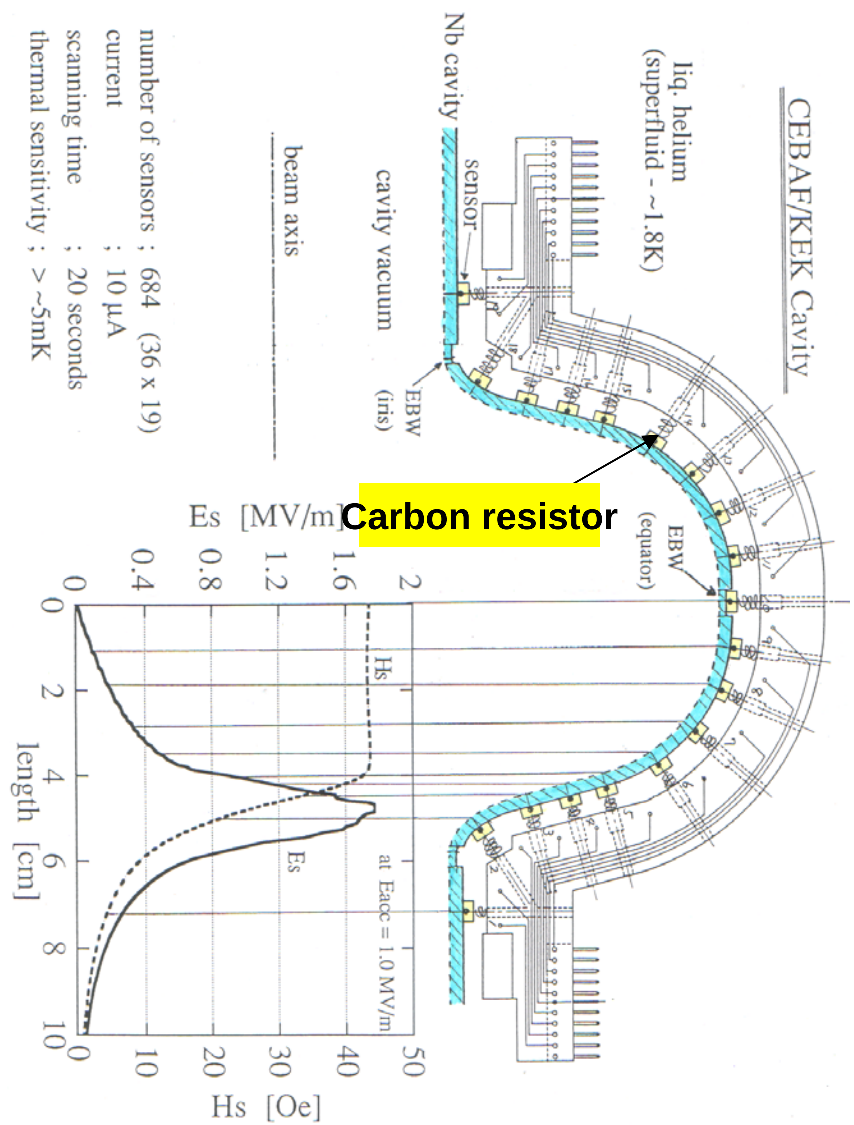




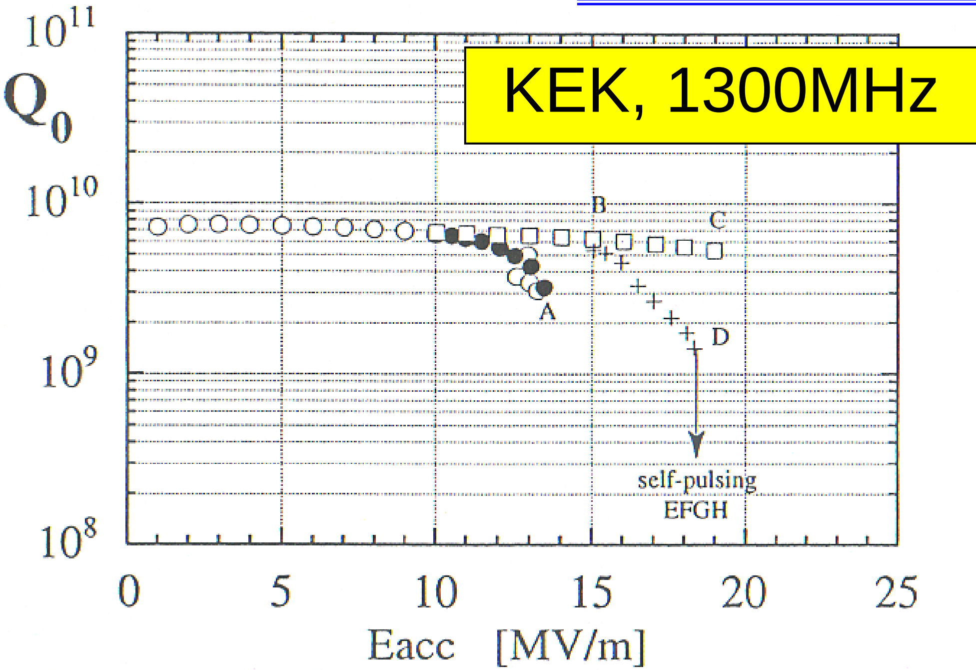
T-mapping System

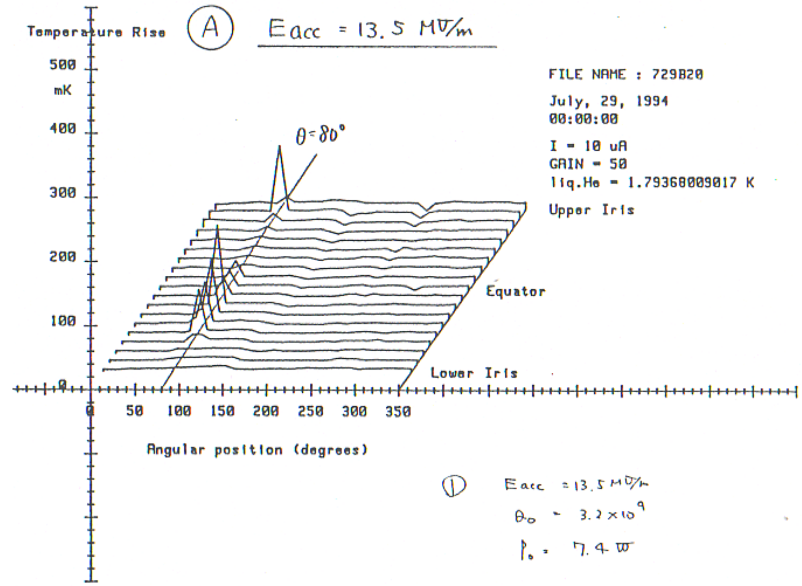
19 sensors at every 10 degree.
Total 648 sensors on outer cavity surface (360x19=684)

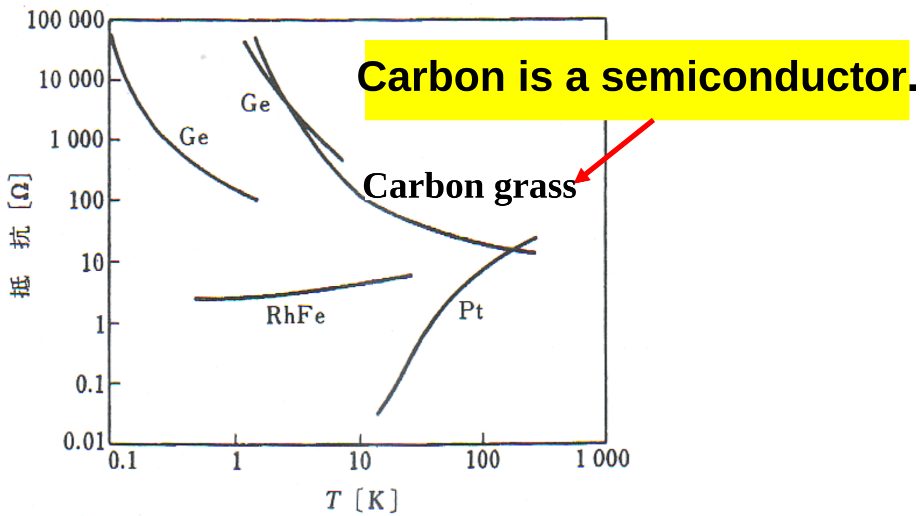


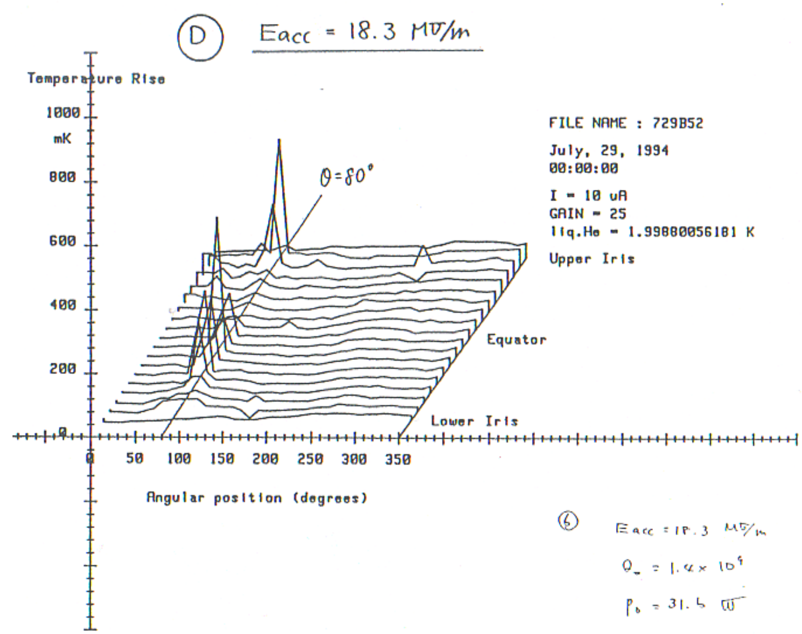


T-mapping KEK



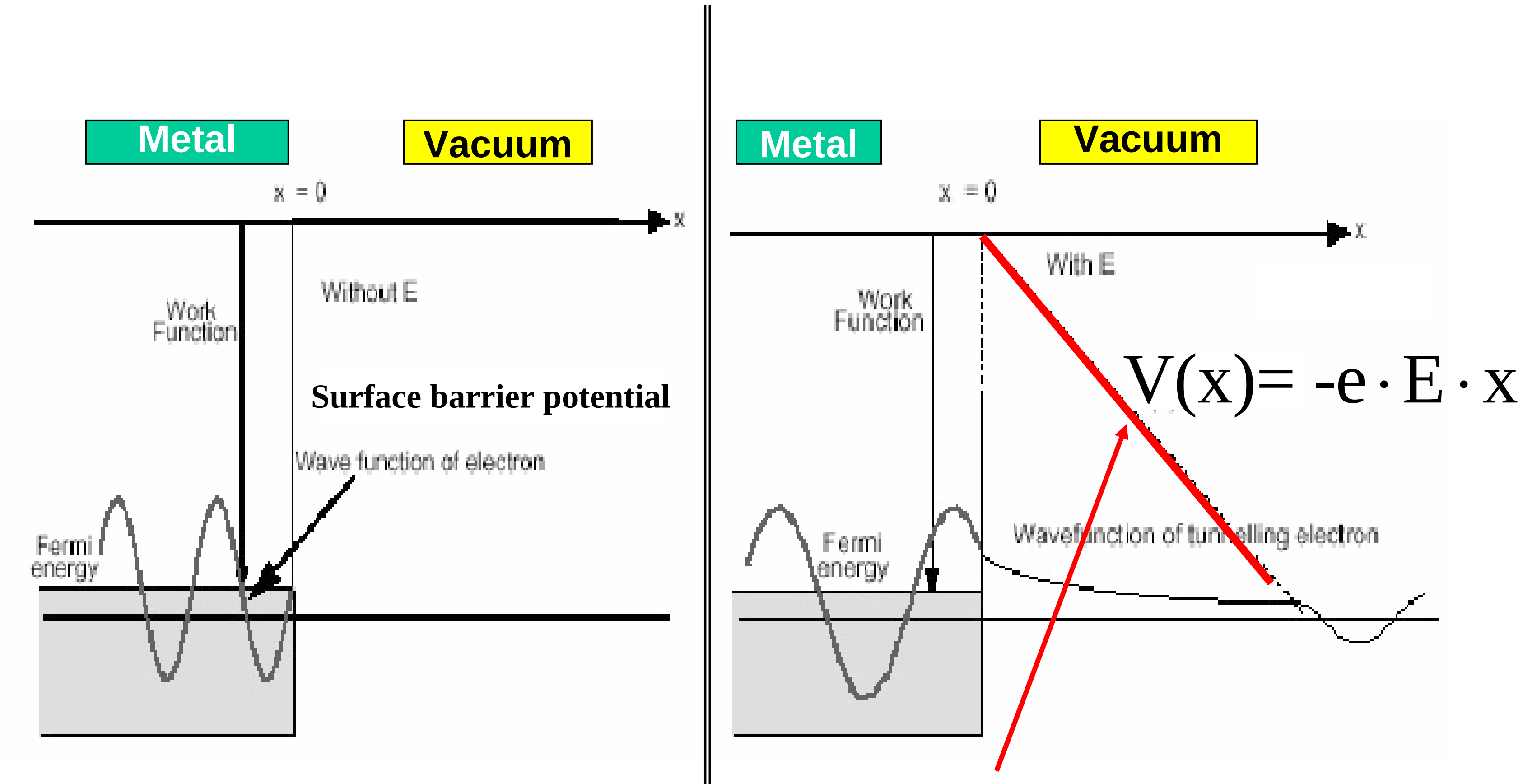






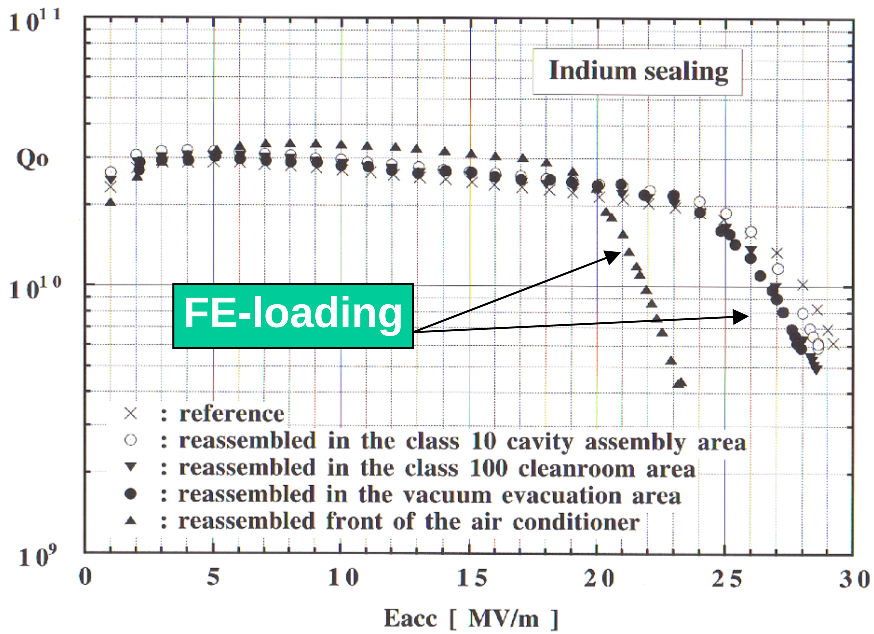
Characteristics of T-sensitivity for various material

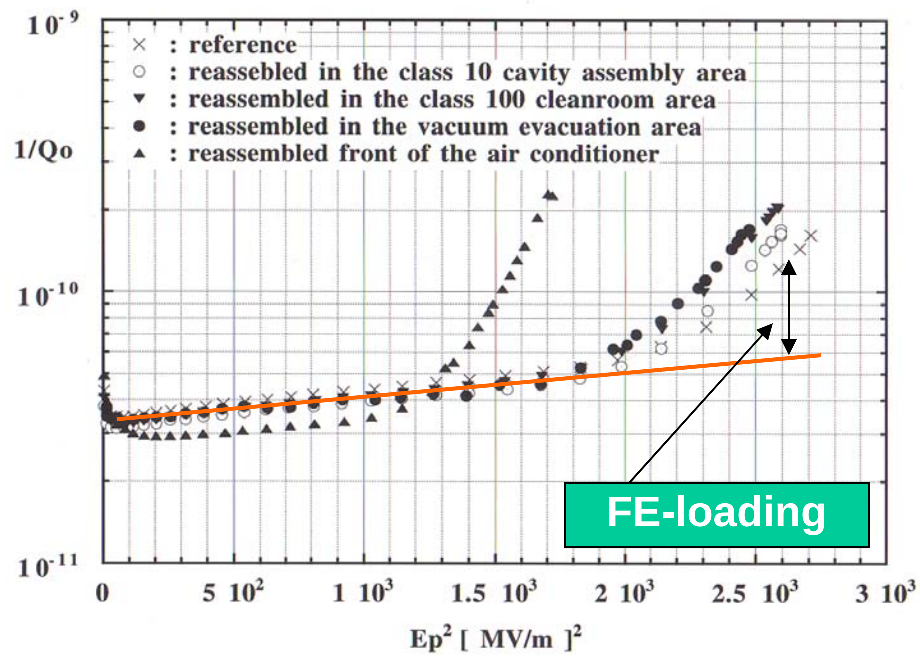
Field Emission Mechanism



A potential: -eEx is added to the surface barrier potential by applying E-fi
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.

Field Emission Analysis





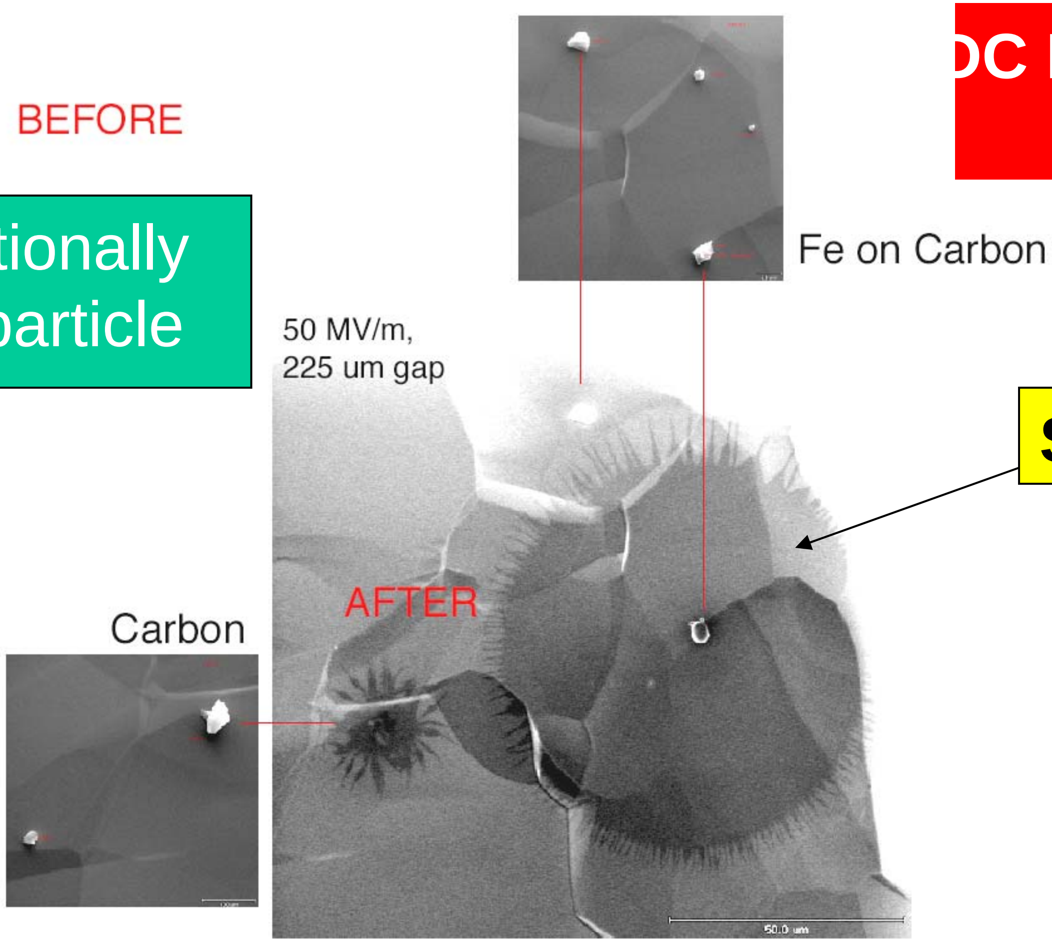
$$\frac{1}{Q_o} = A + B \cdot E_p[MV/m]^2, \quad \Delta\left(\frac{1}{Q_o}\right) = \frac{1}{Q_o(E_p^2)} - (A + B \cdot E_p[MV/m]^2)$$

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

Particulate Contamination produces field emission

DC Field emission study in Cornell

Intentionally put particle



Star burst

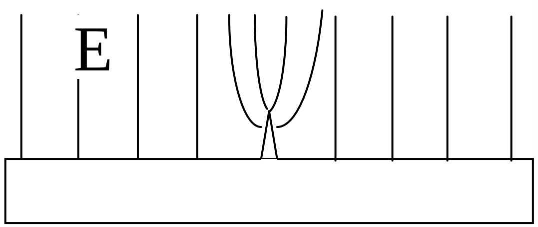
Particulate contaminations cause field emission.

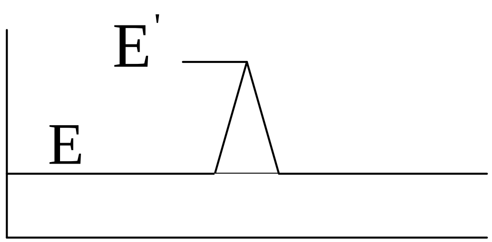
Field Enhancement Factor β

Field enhancement factor ß: 50 ~ 1000

Why field enchantment is so large?

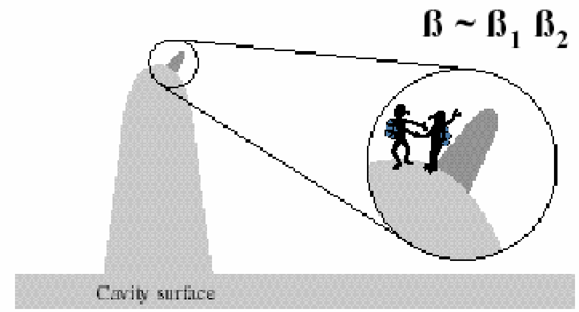
Projection model :



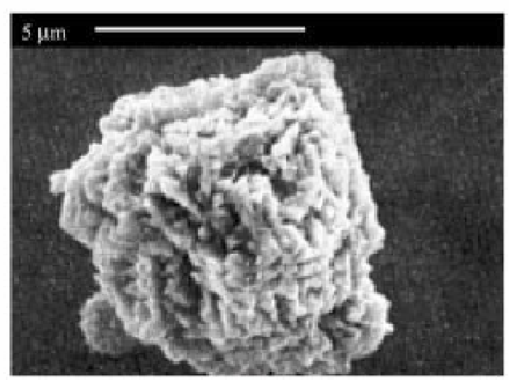


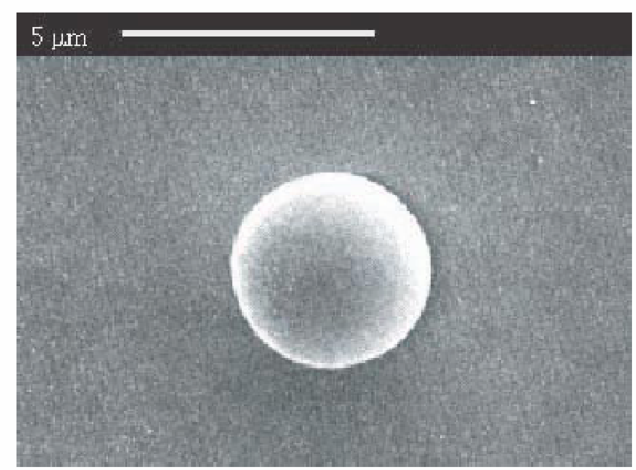
$$\beta = \frac{E'}{E}$$

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

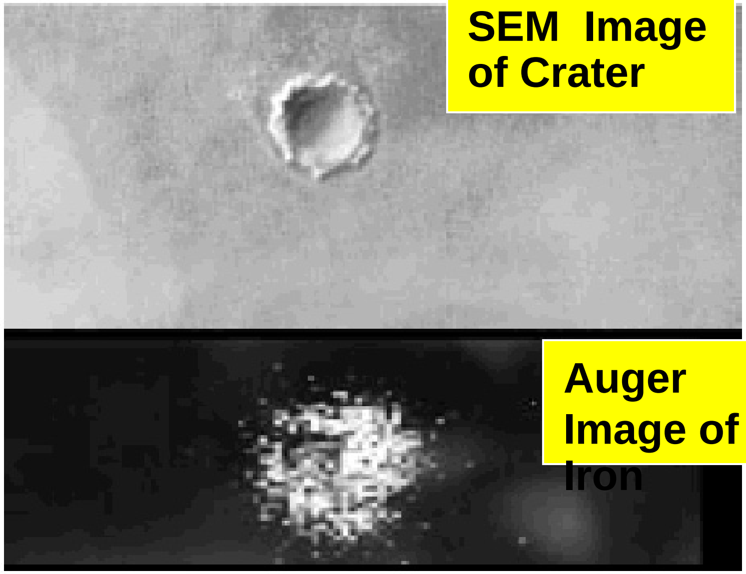


- Smooth particles don't emit.





Crater shows Foreign Elements

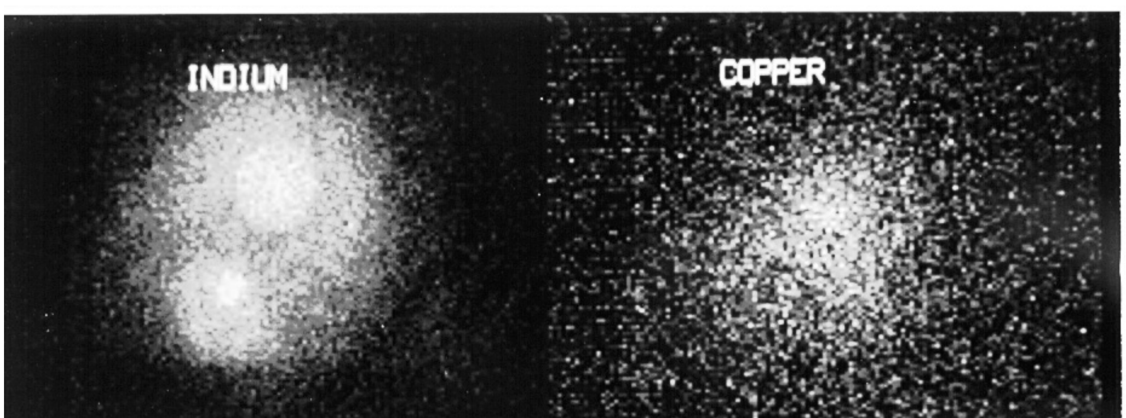


SEM Image of Crater

Auger Image of Iron

Nothing with EDX

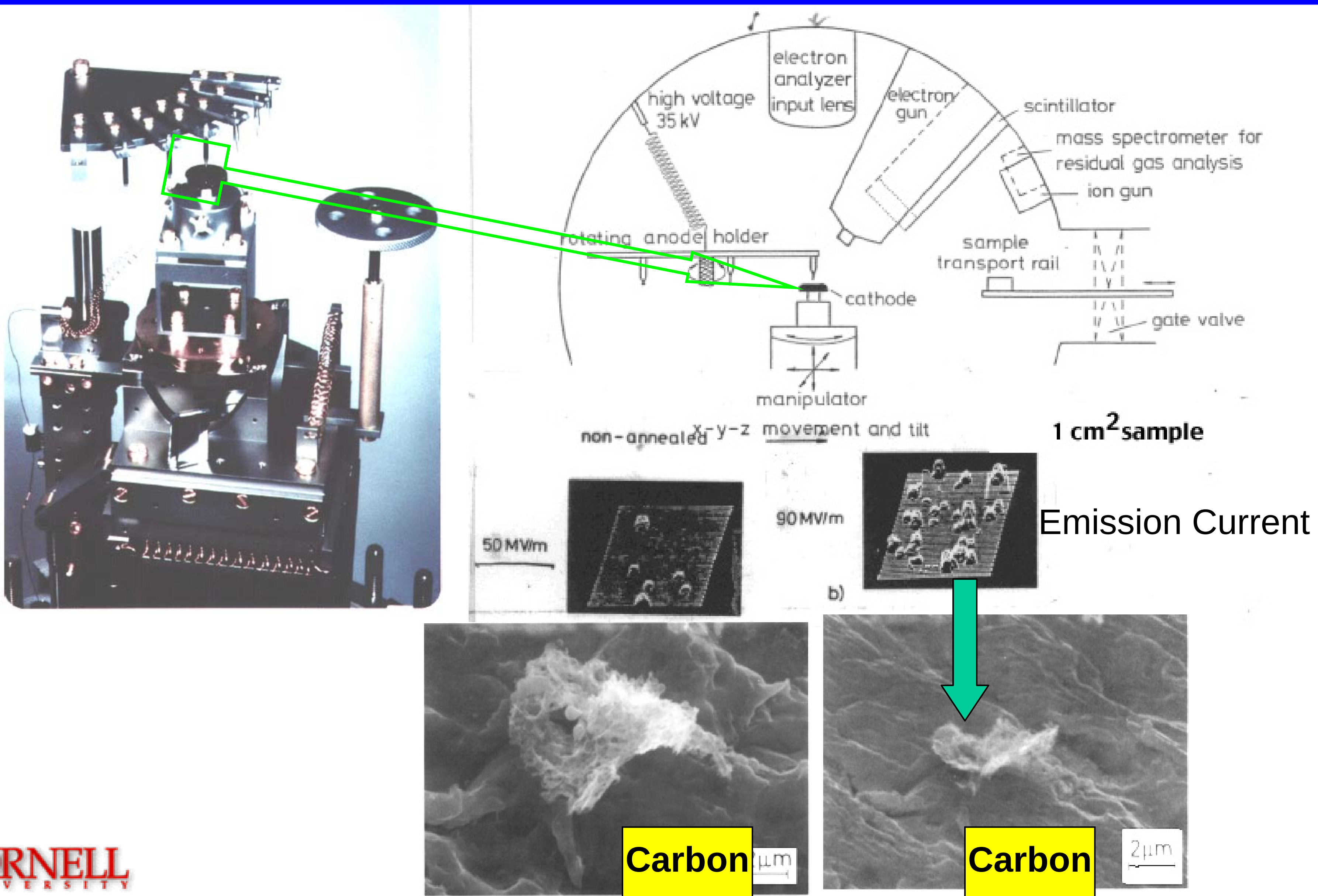
But - With Auger Analysis
Almost all craters show foreign material



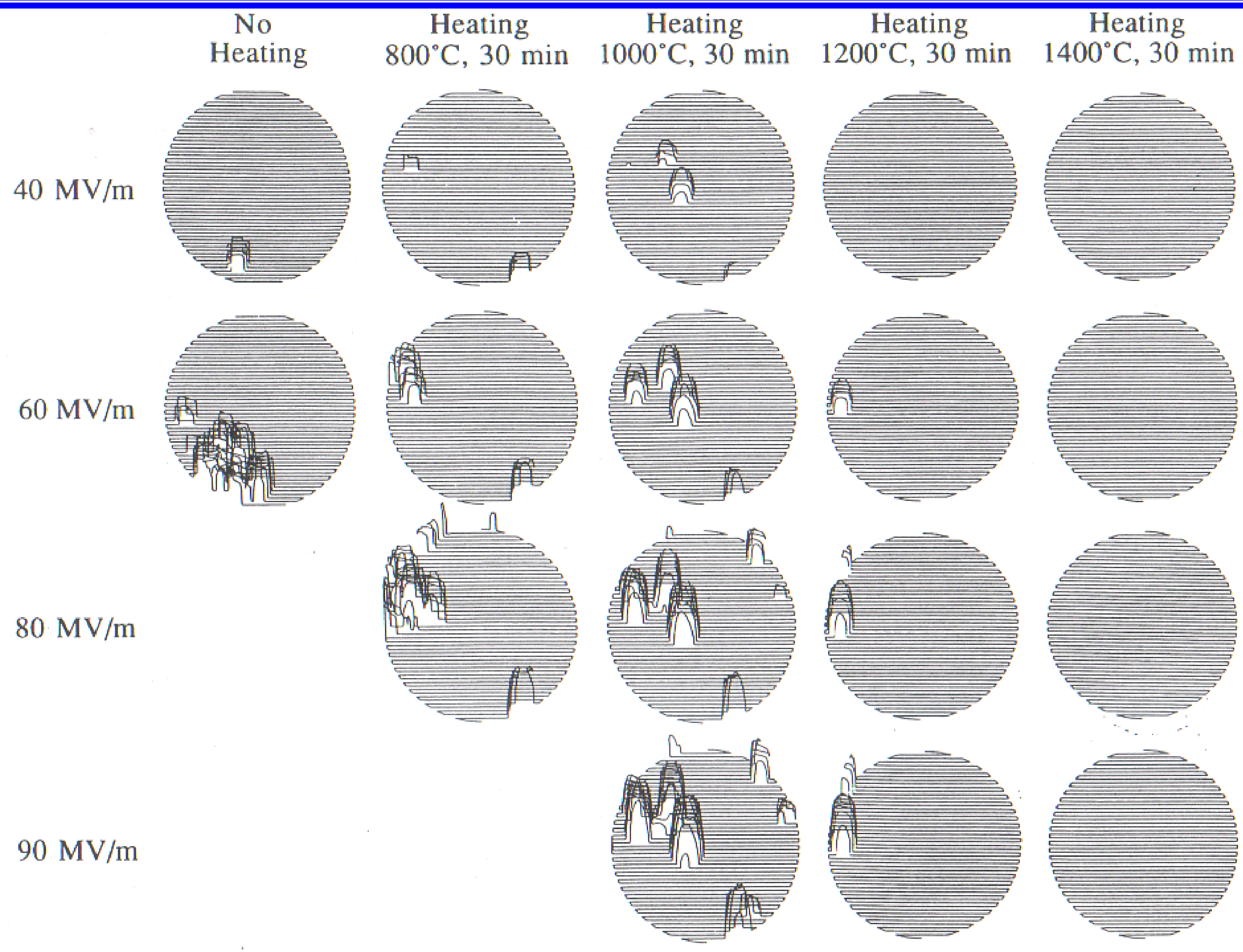
Auger Images of Craters

CORNELL UNIVERSITY

DC Field Emission Study in U.Geneva and Wuppertal

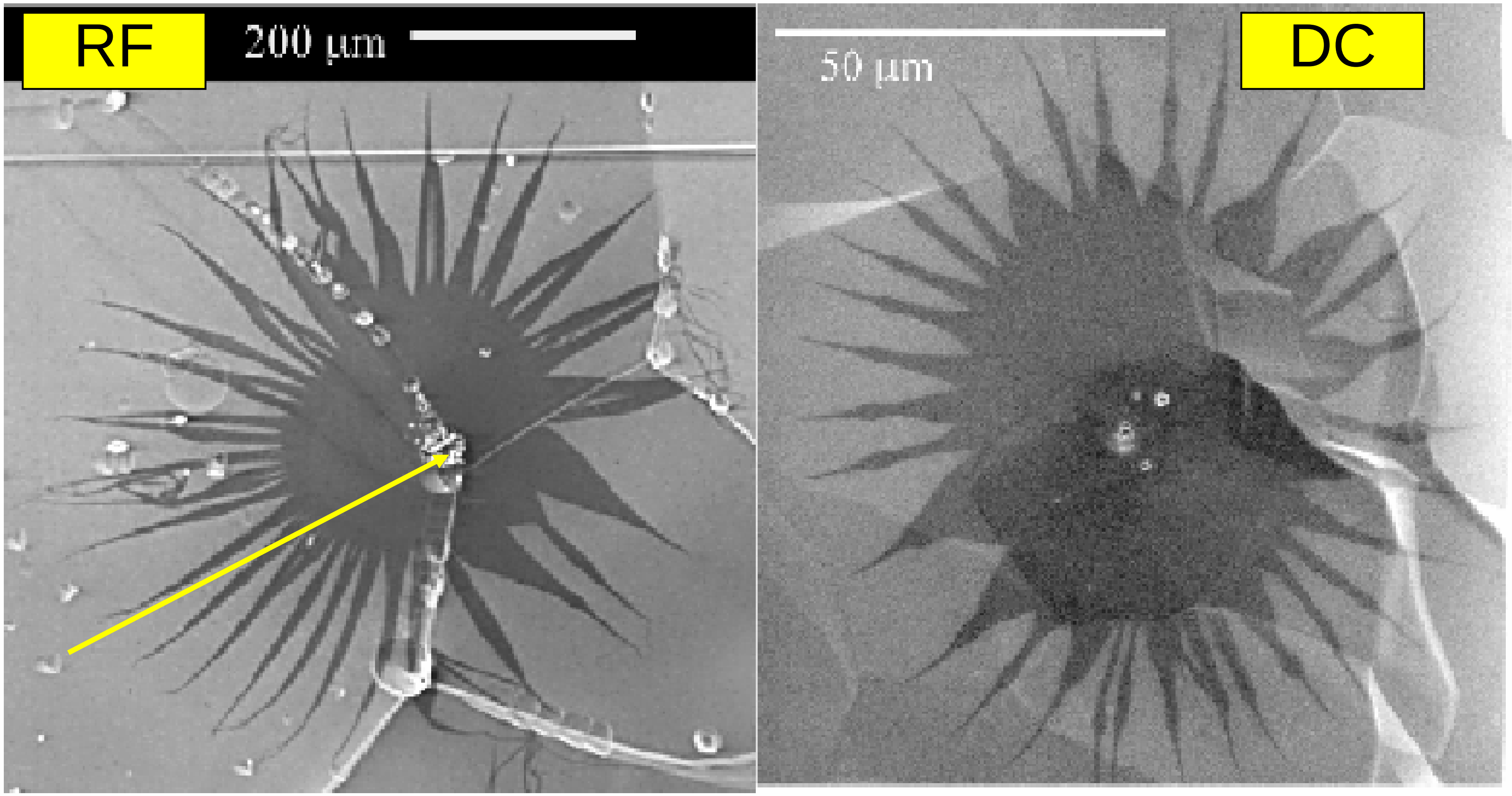


Wuppertal Result



High Temp. Annealing is very effective to eliminate FE seeds.

Difference in RF and DC

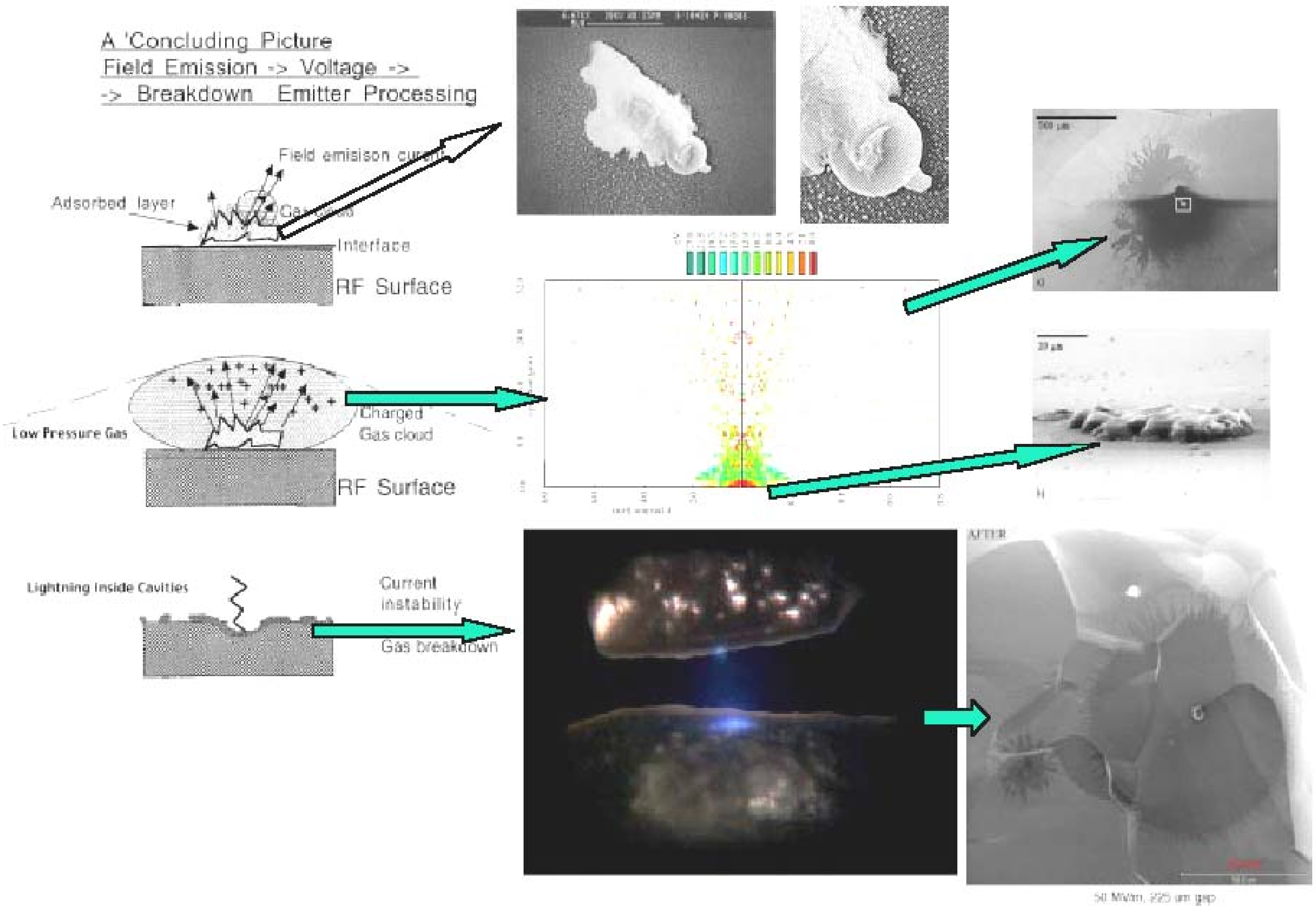


Starburst in a 1.5GHz Nb cavity

Starburst on a DC cathode (Nb)

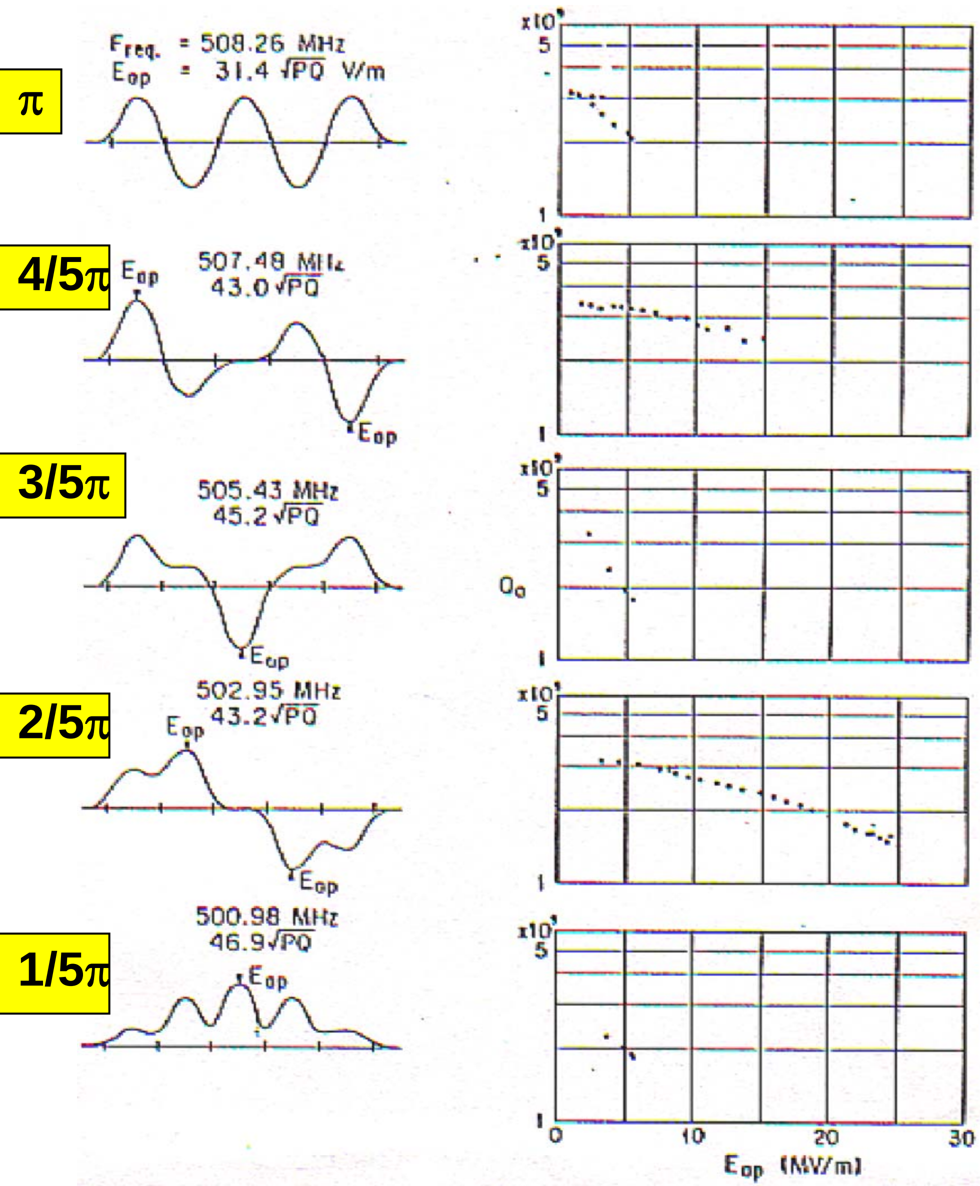
Emitter sites are observed on grain boundary in RF case,
that might suggest magnetic field enhancement there: Joule heating mi
Promotes evaporating gas and results in star burst.

Cornell Model for FE



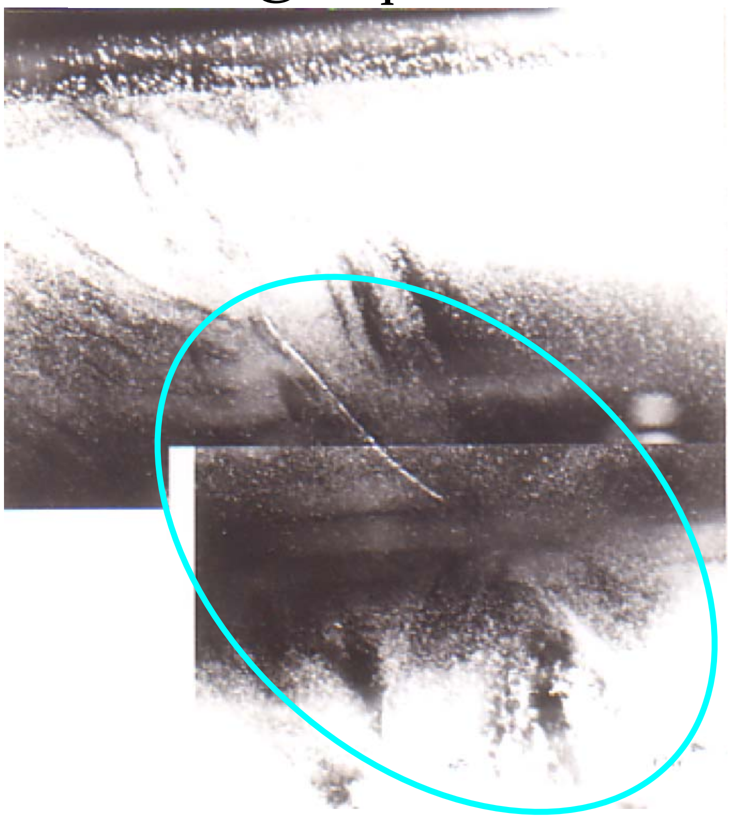
8.3 Thermal Instability

- An Example in A TRISTAN SC Cavity -

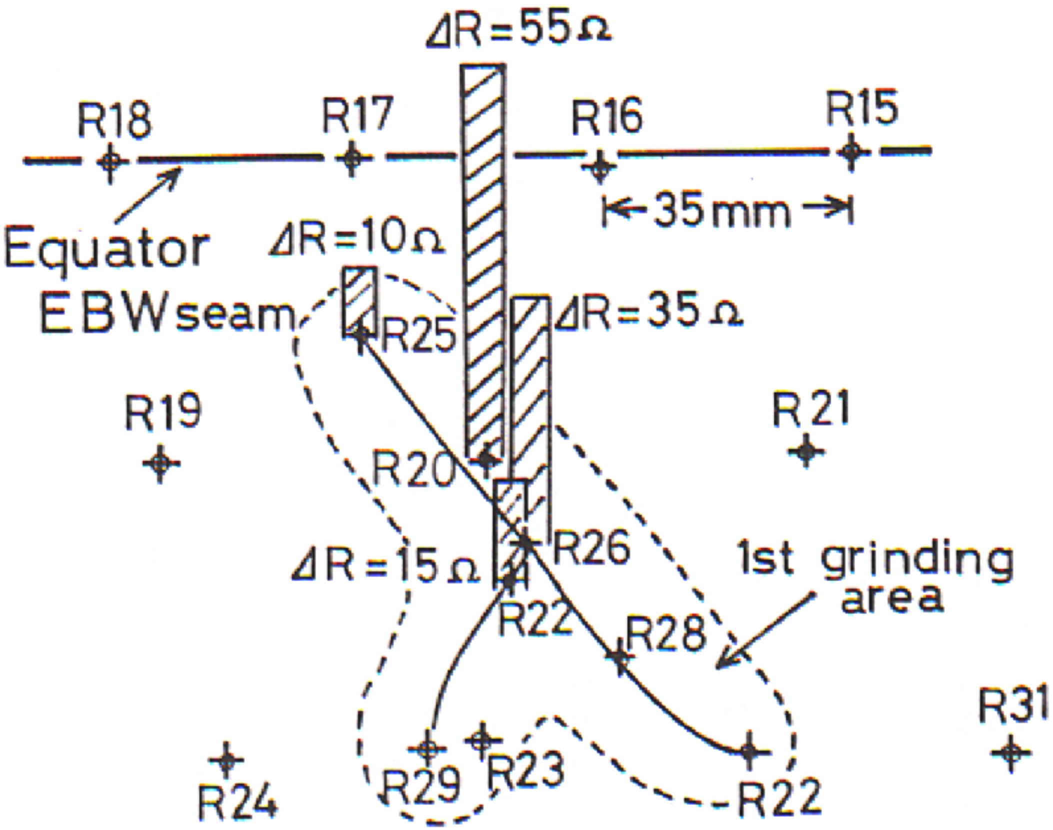


Surface Defect

EBW @ Equator

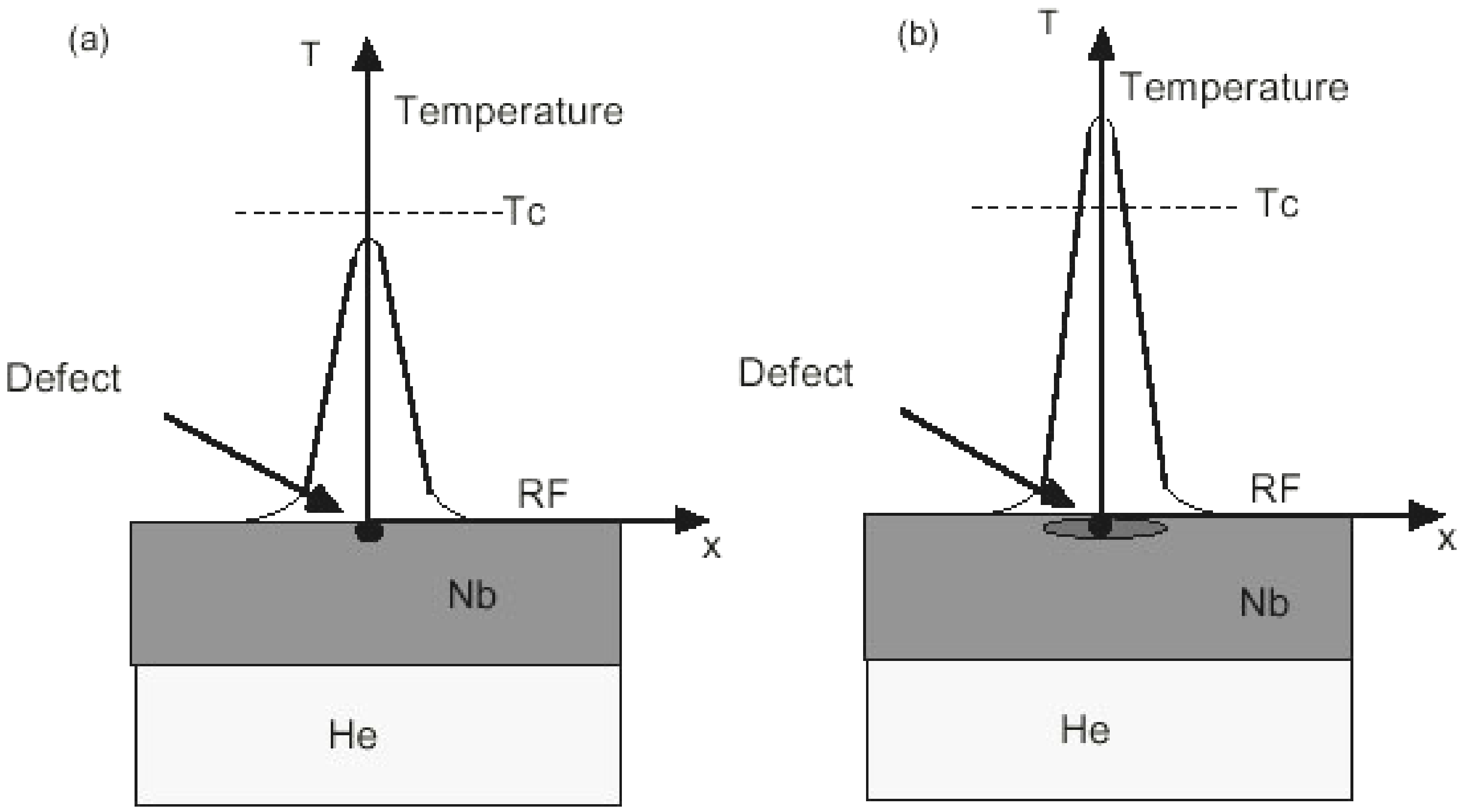


Picture of the defect area



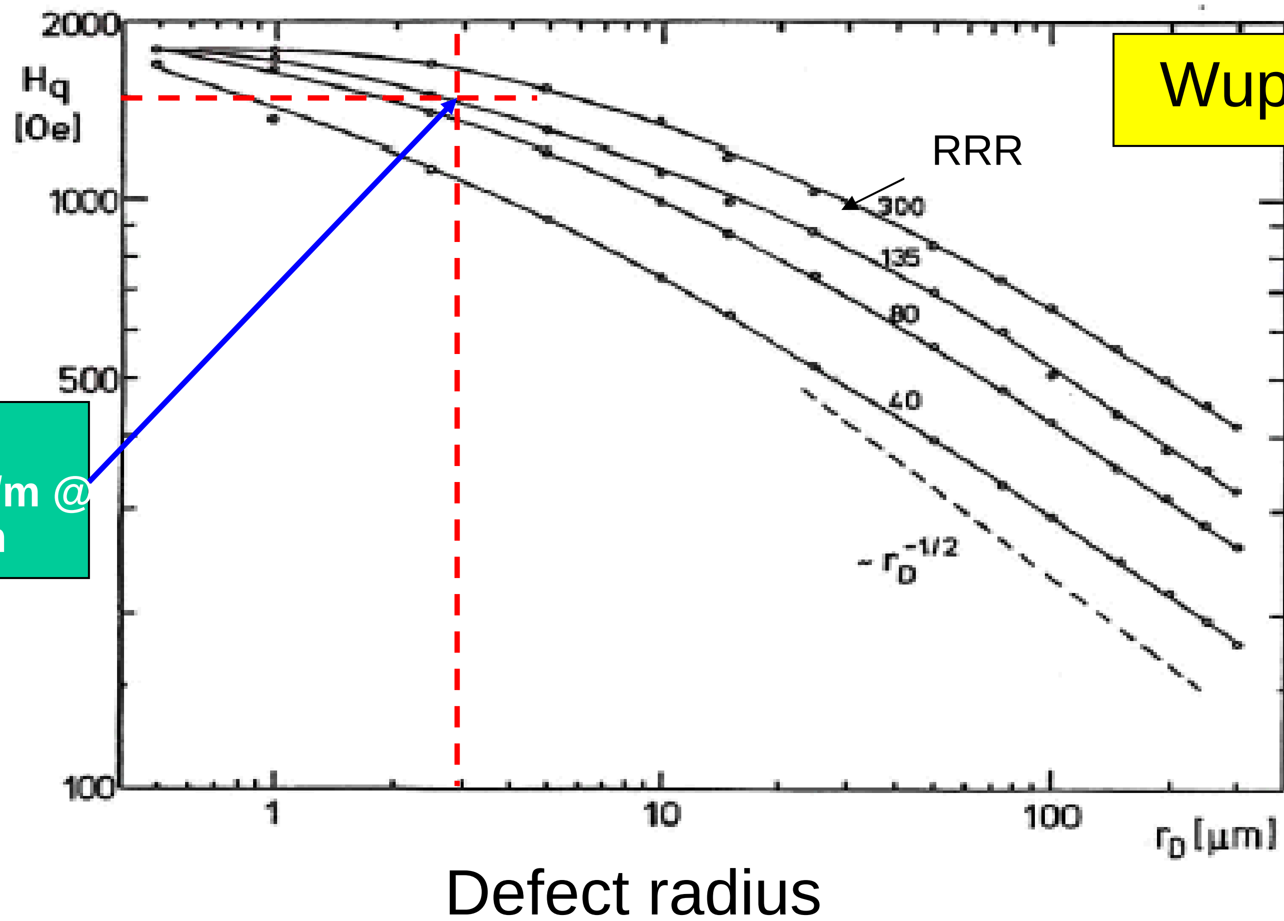
T-mapping on the defect

Mechanism of Thermal Instability



RRR Dependence of Quench Field

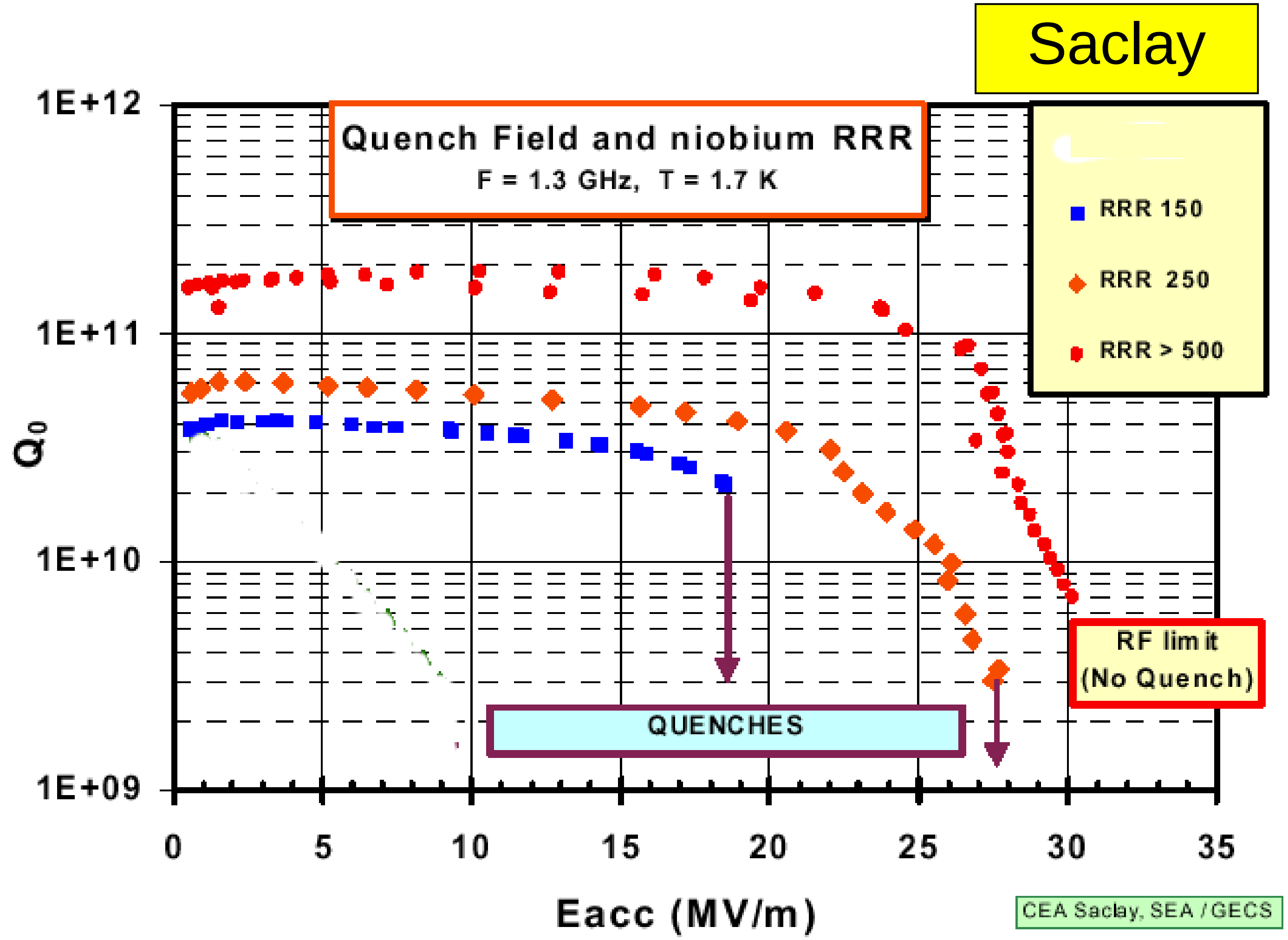
$$\text{Quench Field : } Hq = \sqrt{\frac{4\kappa(Tc - Tb)}{r_D \cdot R_s(Tb)}} \propto RRR^{\frac{3}{4}} \cdot \sqrt{\frac{(Tc - Tb)}{r_D \cdot Rs(300K)}}$$



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

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

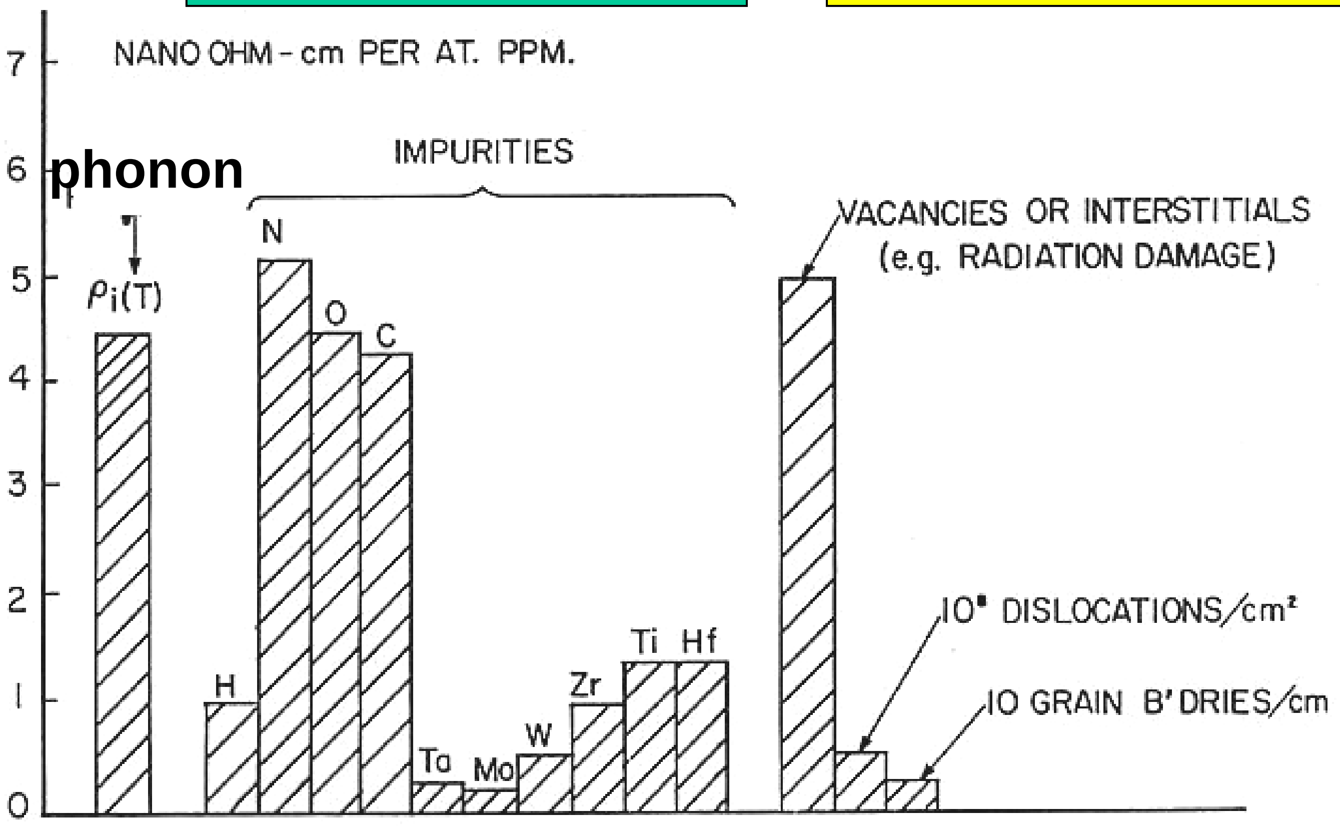
High purity **+**
Homogeneity

High RRR material

Vacuum annealing

Nb

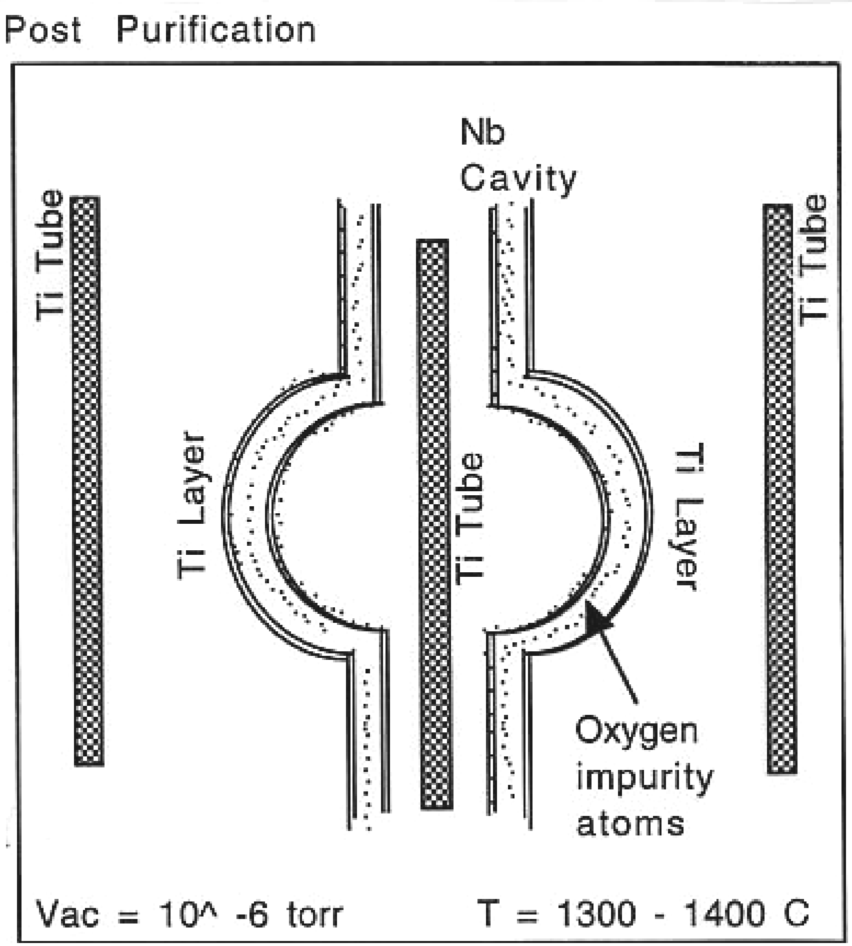
phonon



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

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

Cure : Post Purifying of Niobium



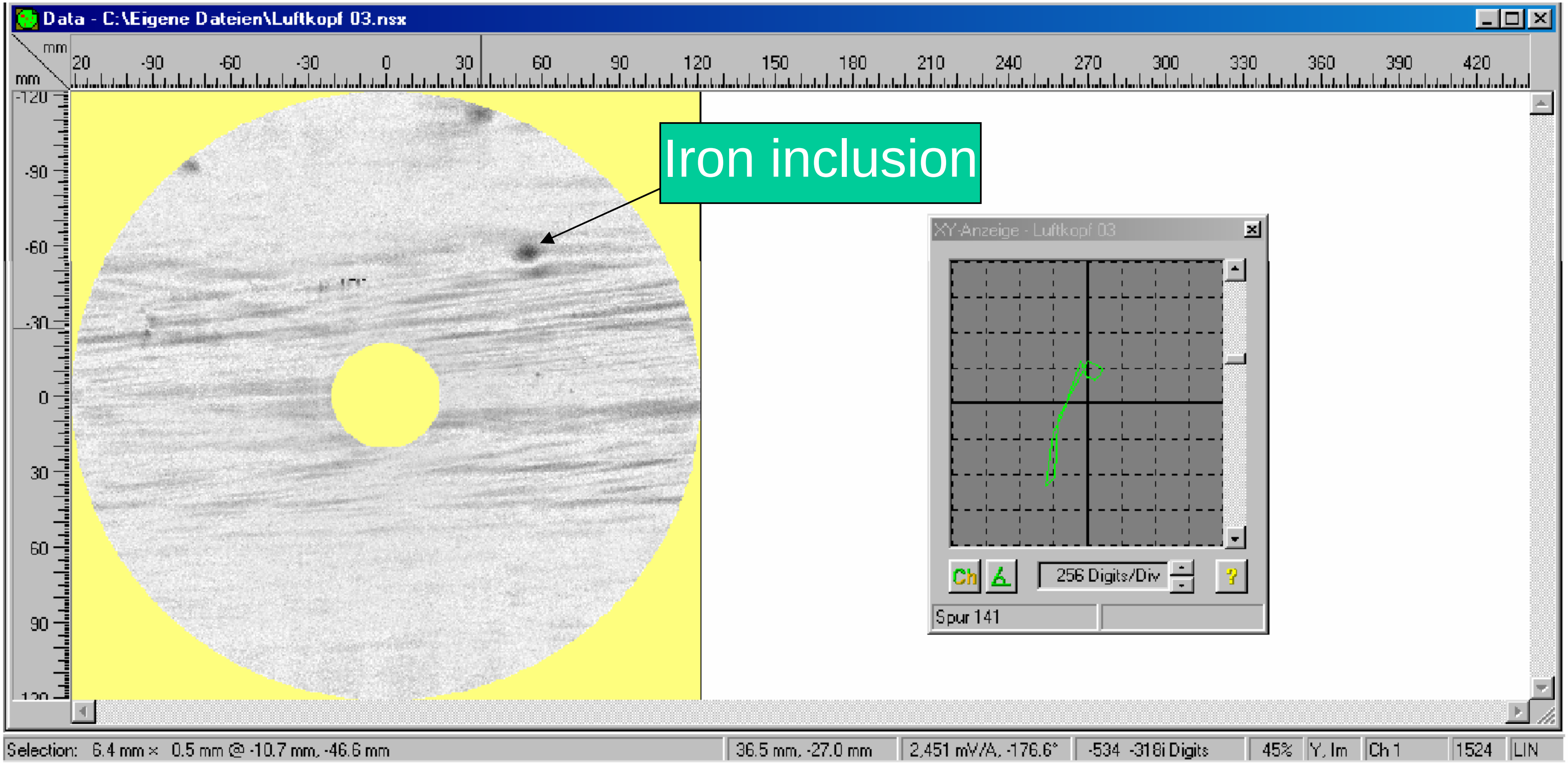
After cavity or half-cell is produced

- **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

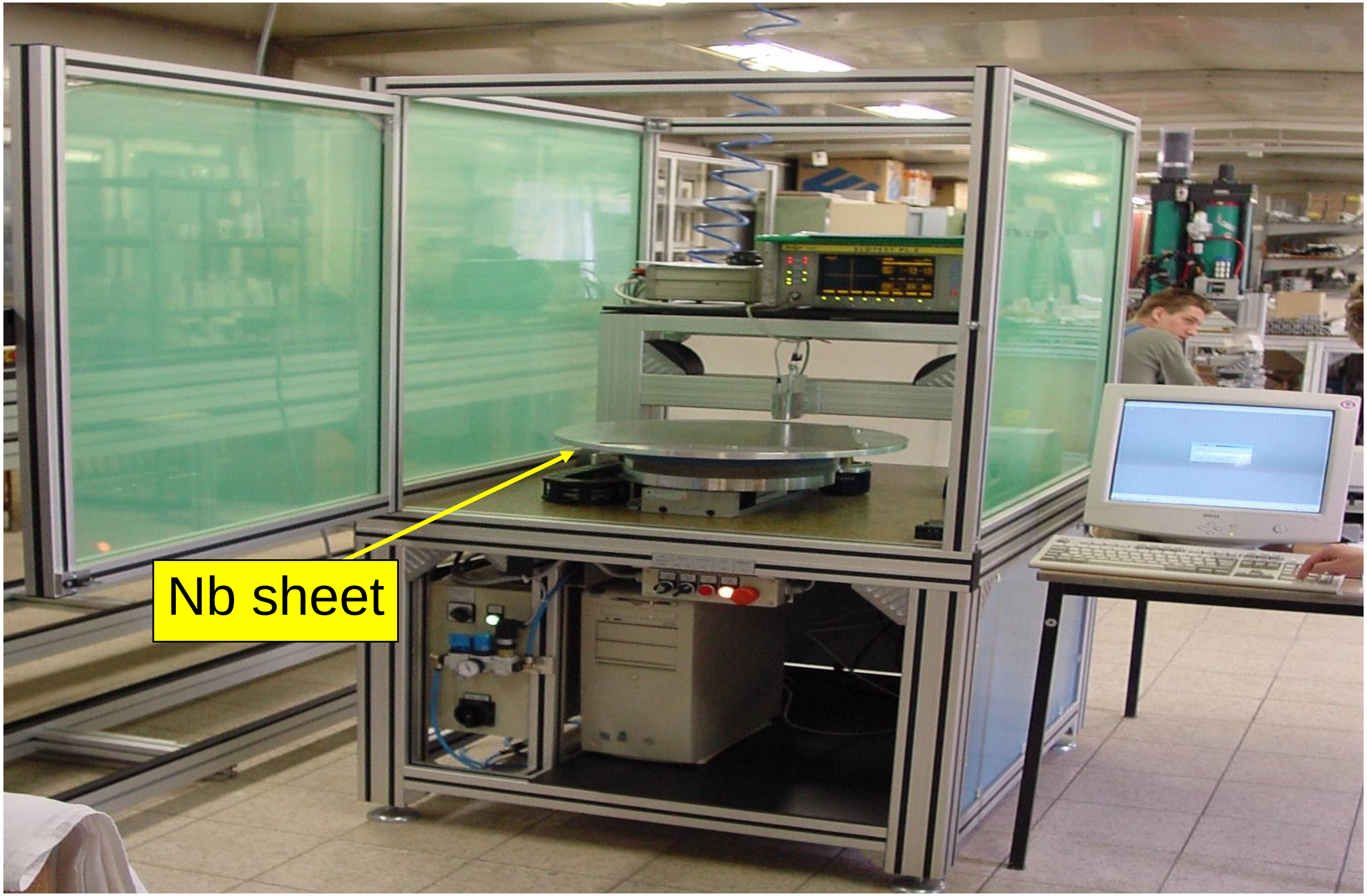
Result of eddy current scanning a Nb disc, dia. 265 mm at DESY



Global view, rolling marks and defect areas can be seen

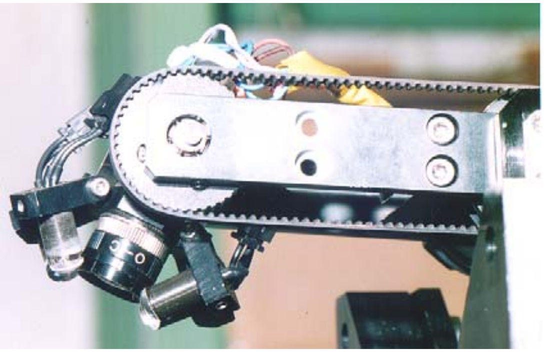
Real and imaginary part of conductivity at defect, typical Fe signal

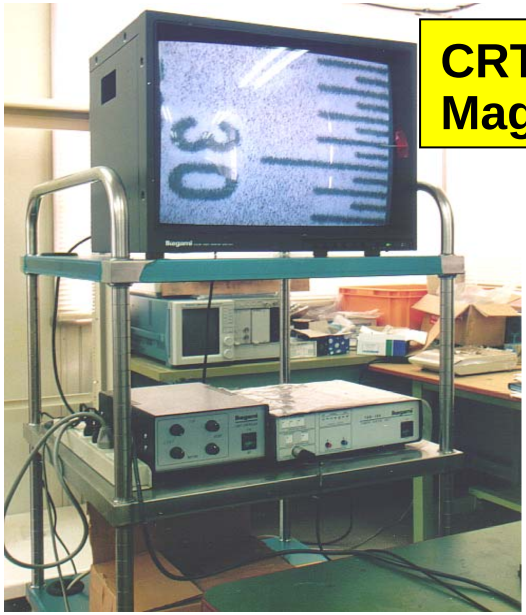
Eddy current scanning system DESY



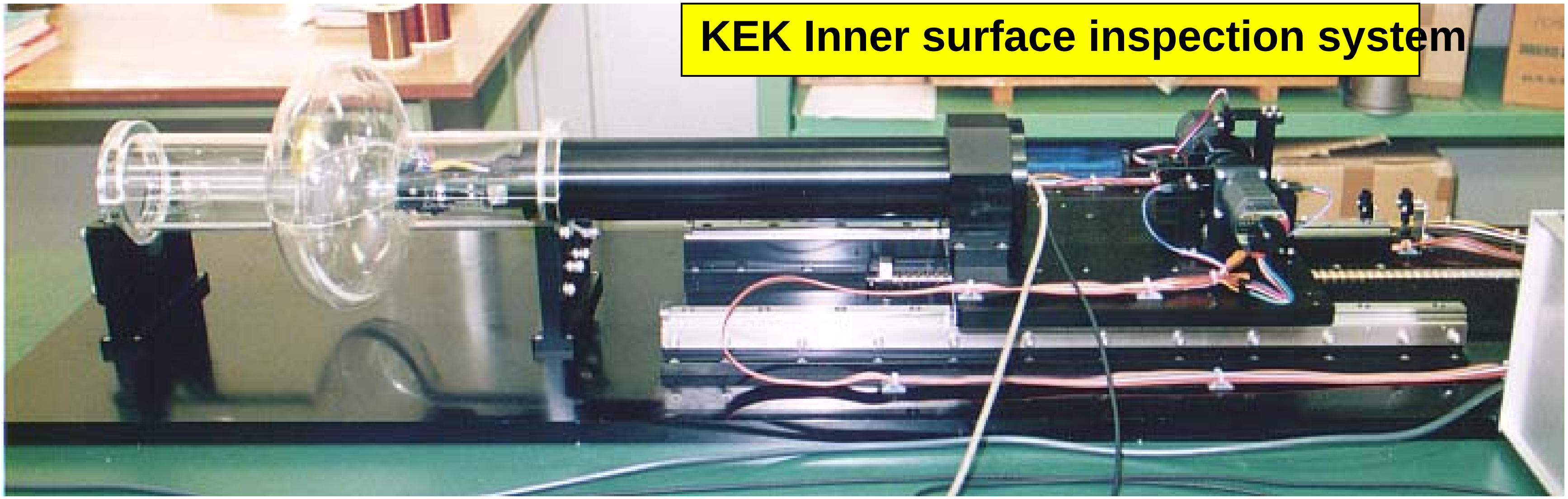
Cavity Inner Surface Inspection System : KEK

Small CCD camera





CRT monitor
Magnification ~13

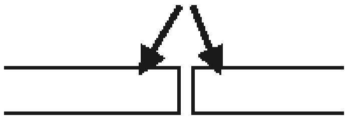


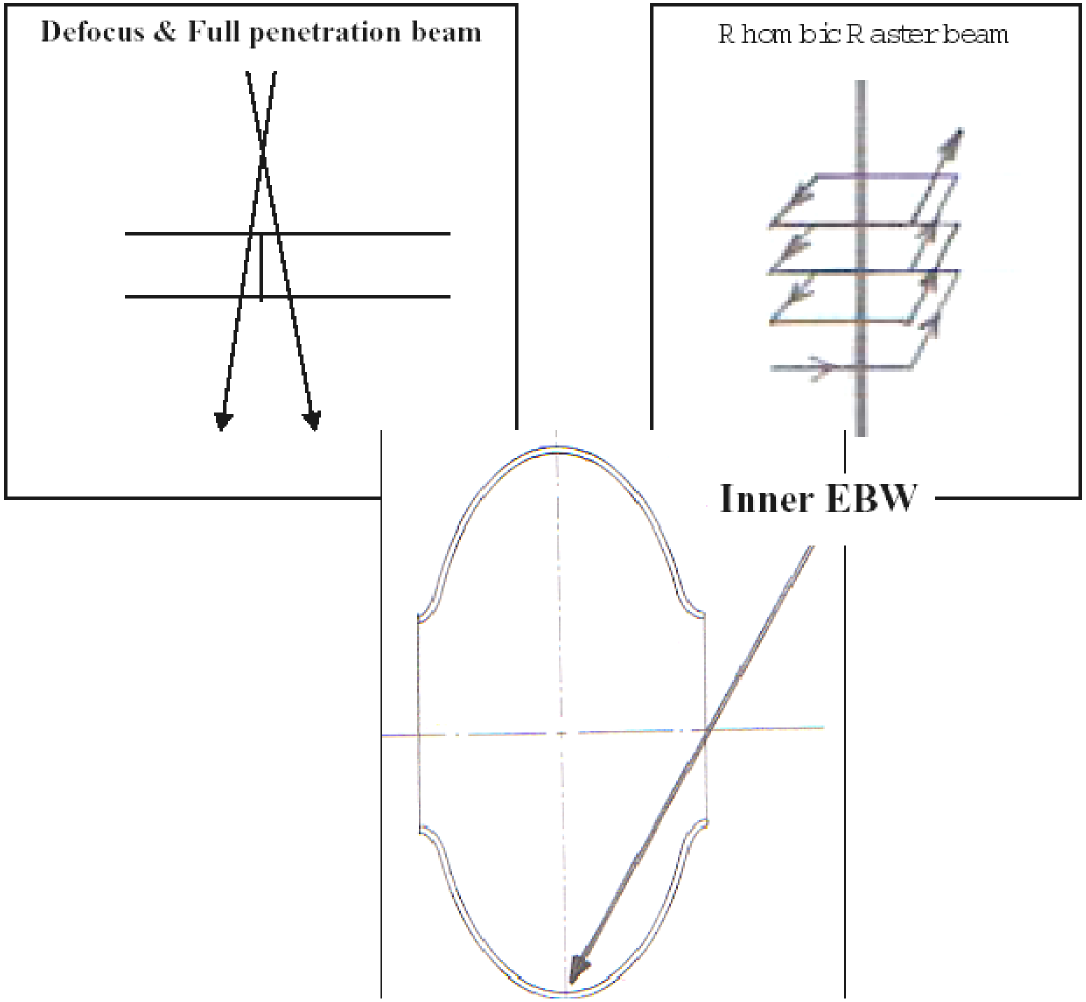
KEK Inner surface inspection system

Cure : High Quality EB-welding

Better EBW

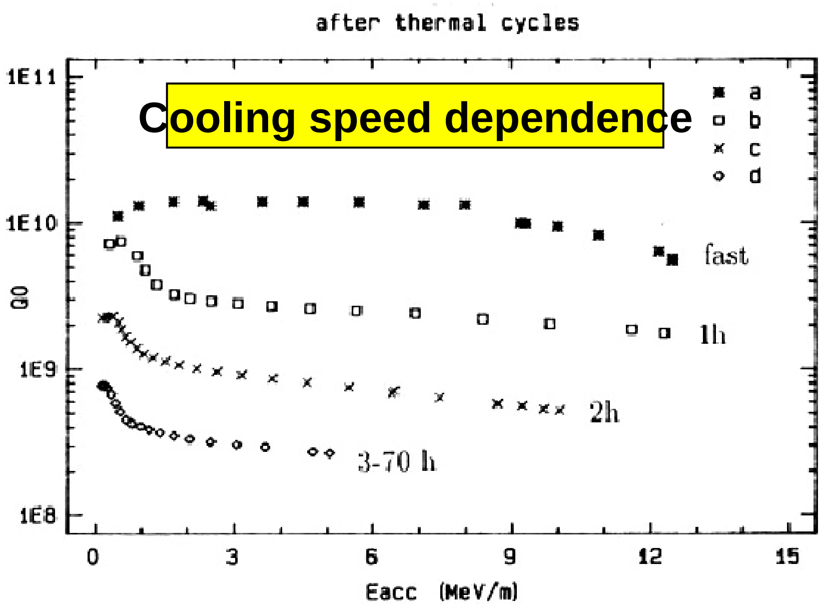
Etching by CP

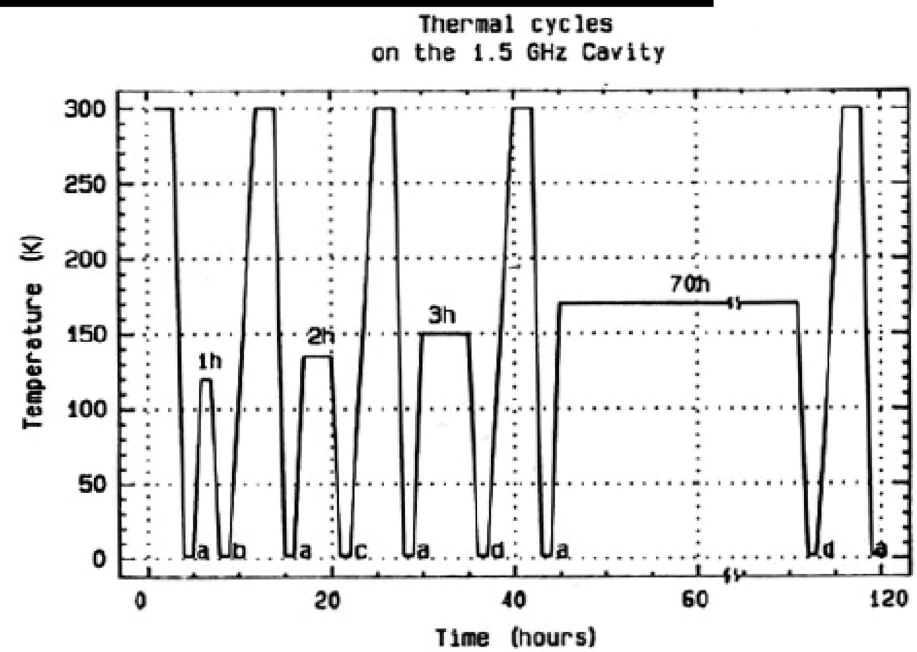




8.4 Hydrogen Q-Disease

Q_o-value strongly depends on cooling down speed.

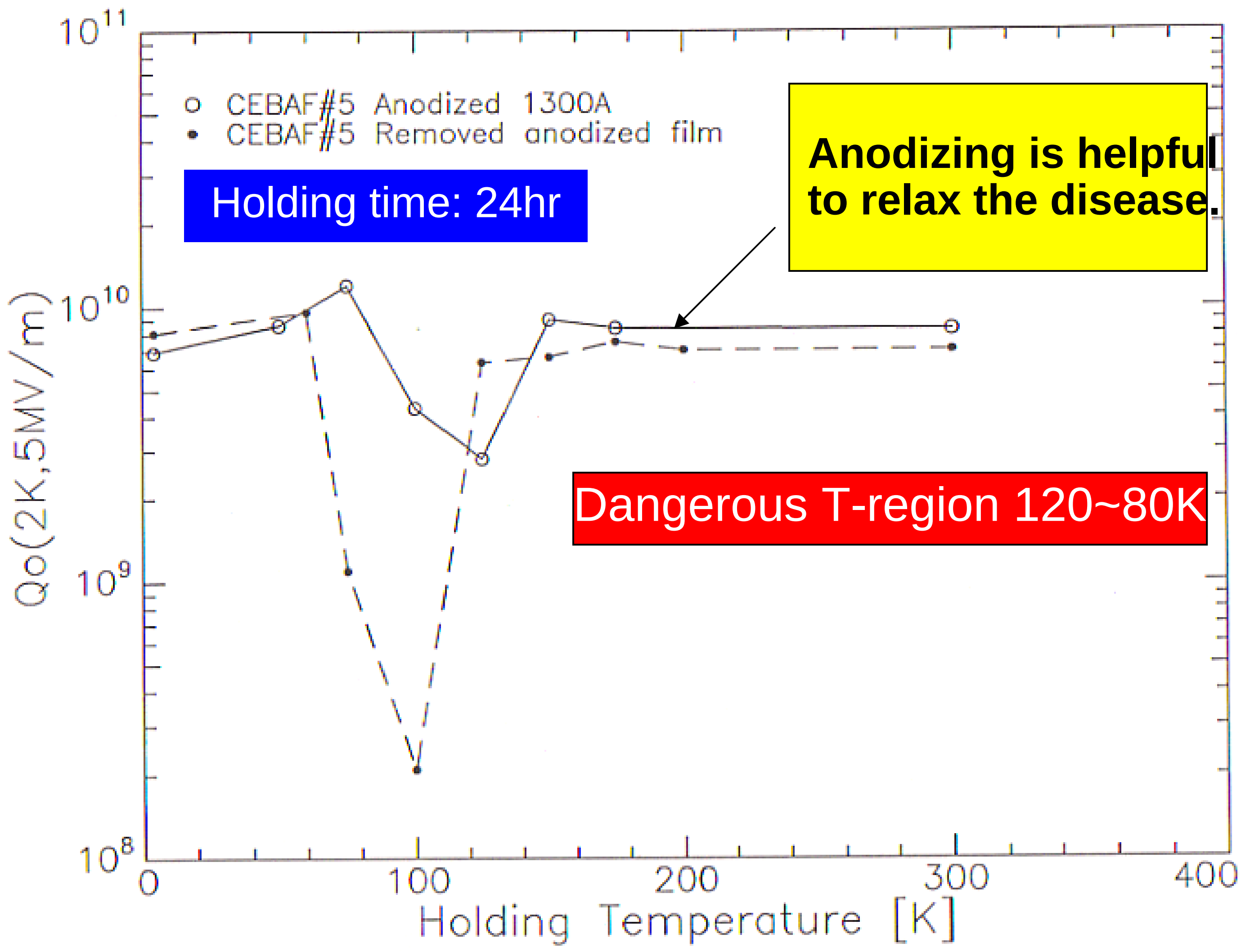




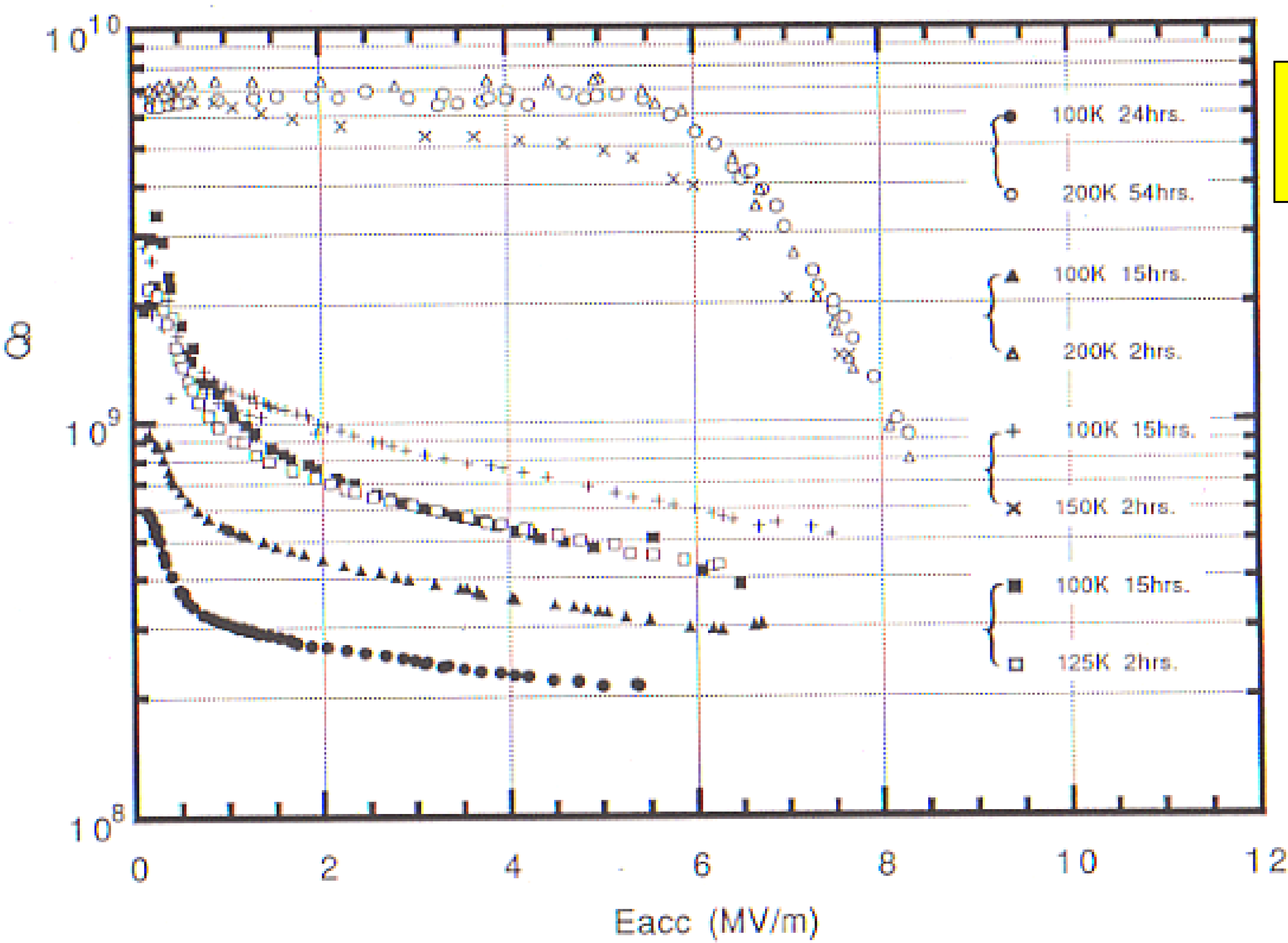
In 1990, Discovered
with chemically polished niobium cavity

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 disappe

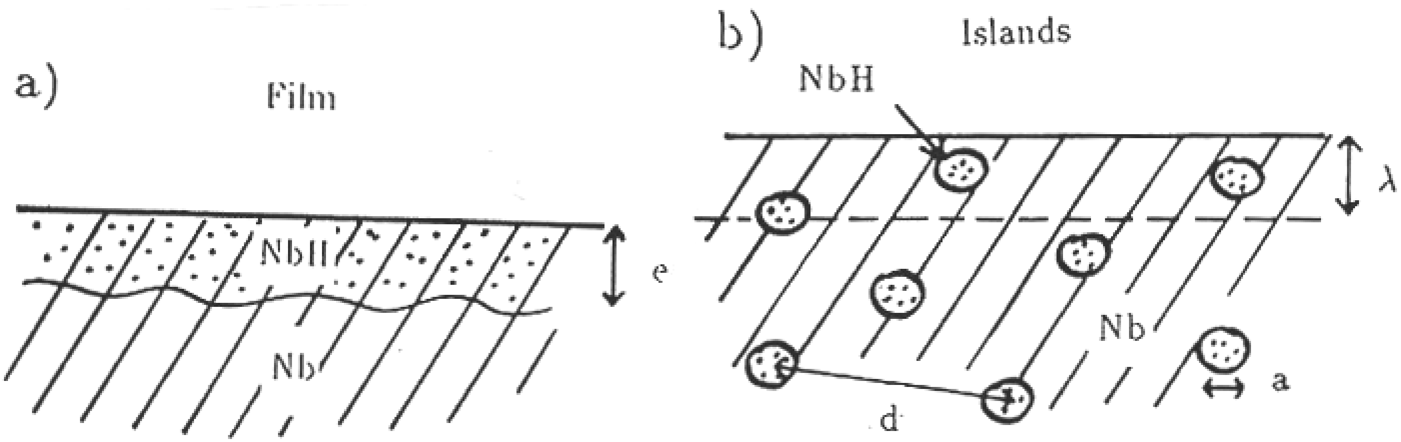
Mechanism of Hydrogen Q-disease

Mechanism
and Explanation of Symptons

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

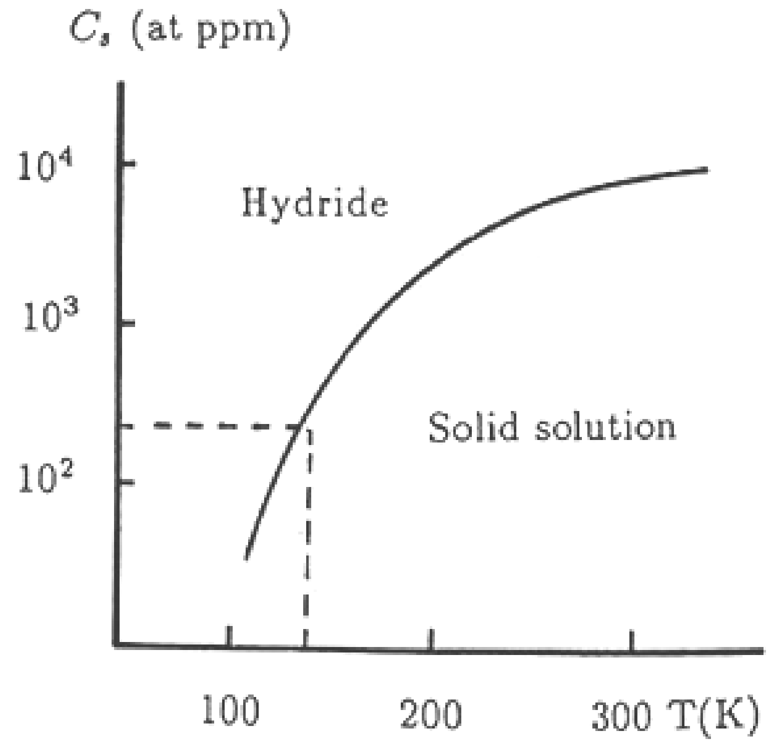
When a cavity is cooled the dissolved hydrogen precipitates as a hydride phase that has high rf loss
Tc of hydride = 2.8 K, Hc = 60 Oersted

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

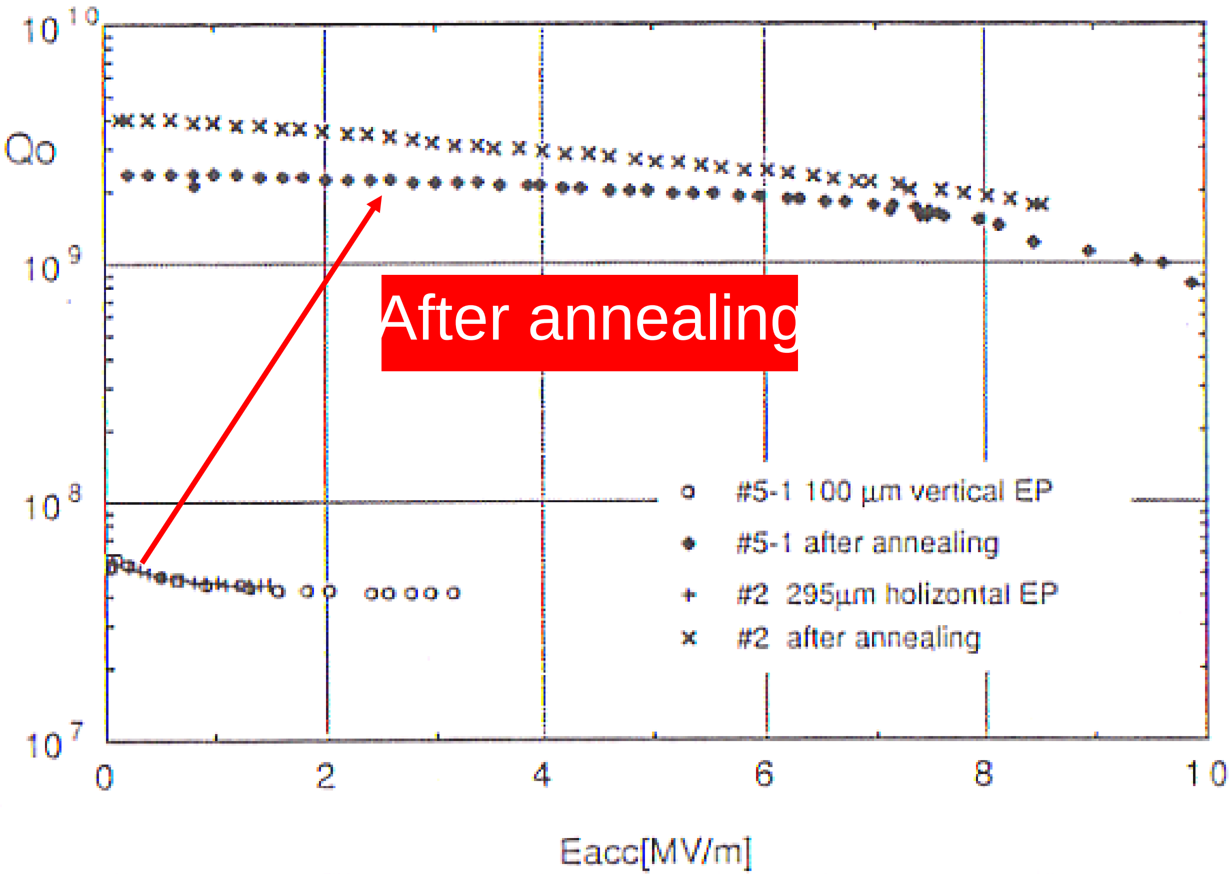


At room temperature the required conc. to form hydride phases is very high, e.g 4600, 7400 wt ppm

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

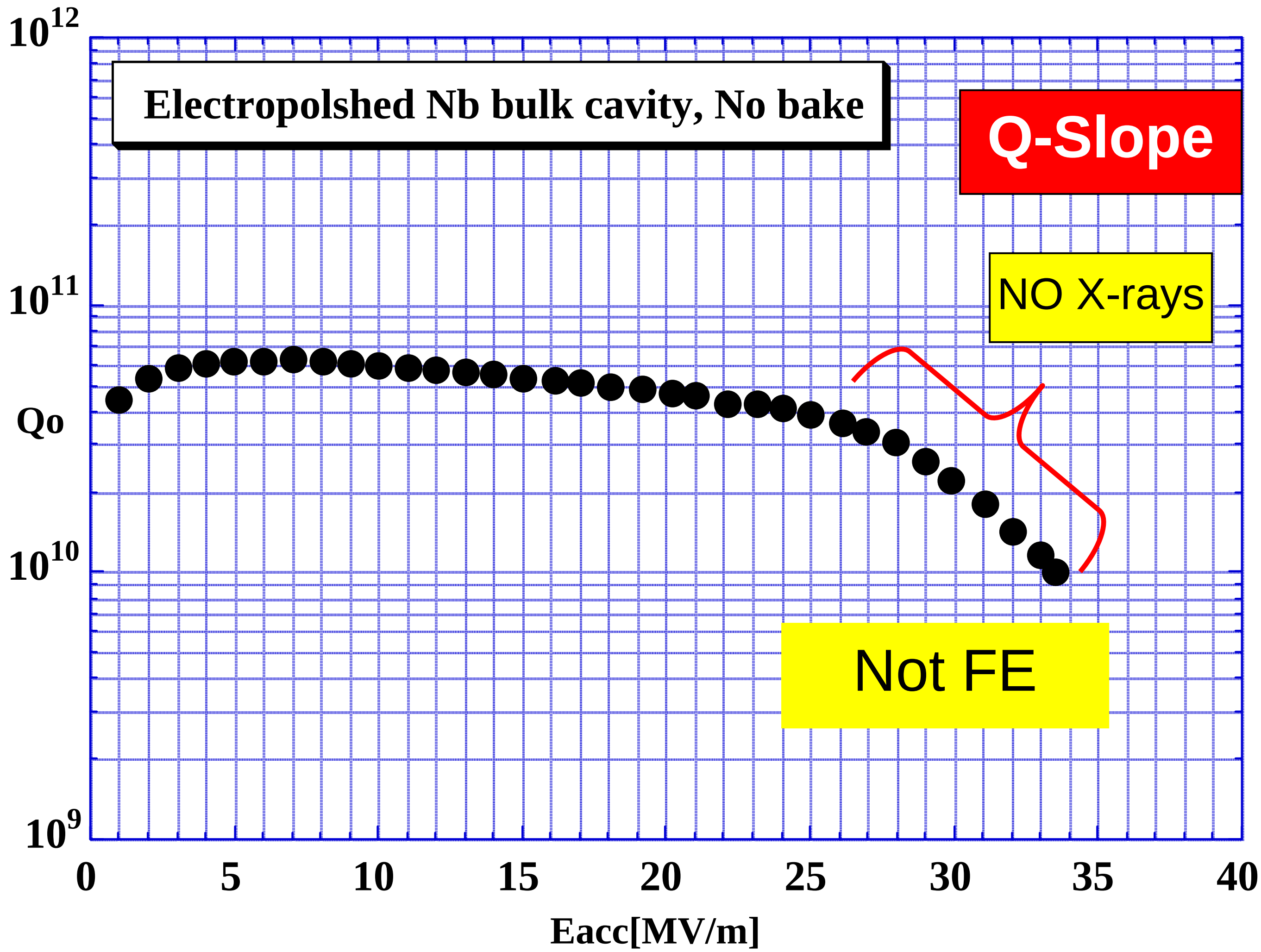


Hydrogen Q-disease in electropolished cavity



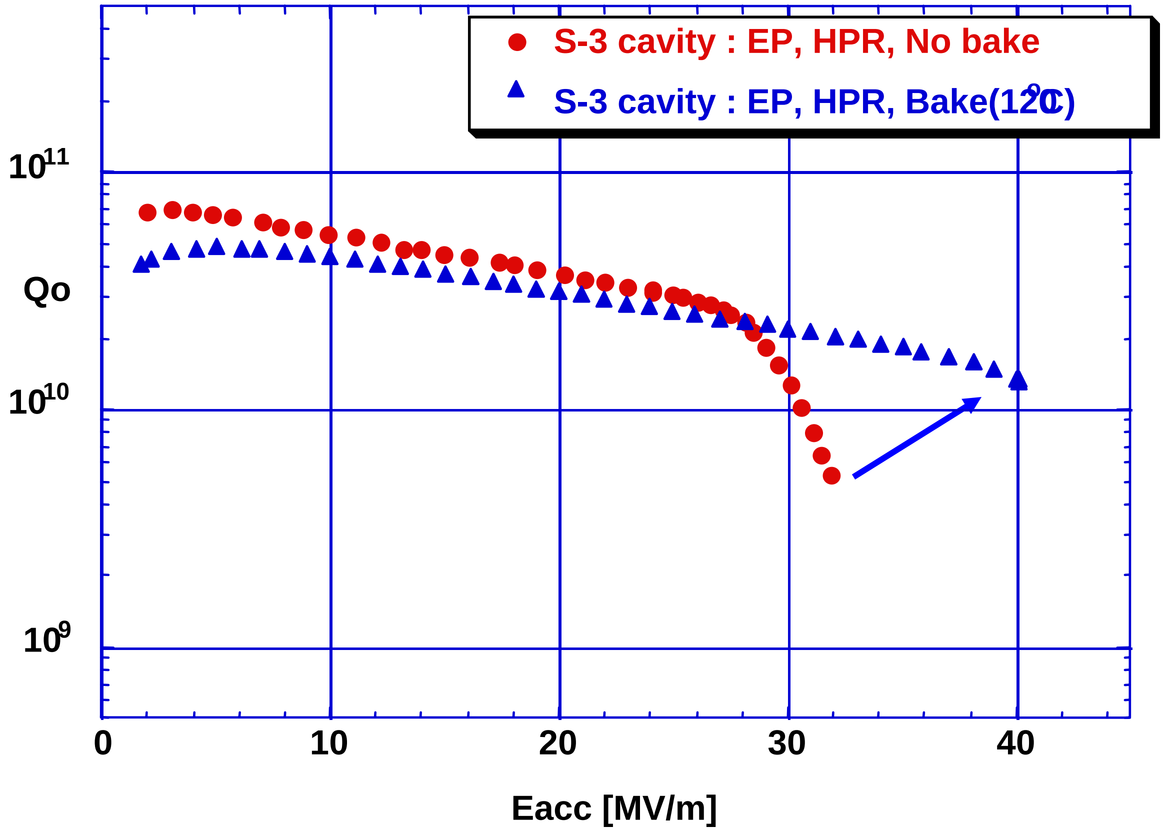
Hydrogen Q-disease is much serious on electropolished cavity
Hydrogen gas degassing annealing has been routinely used.
In those days, pre-cooling with liquid nitrogen had been used and none knew the disease depends on cooling down speed.

8.5 Q-Slope



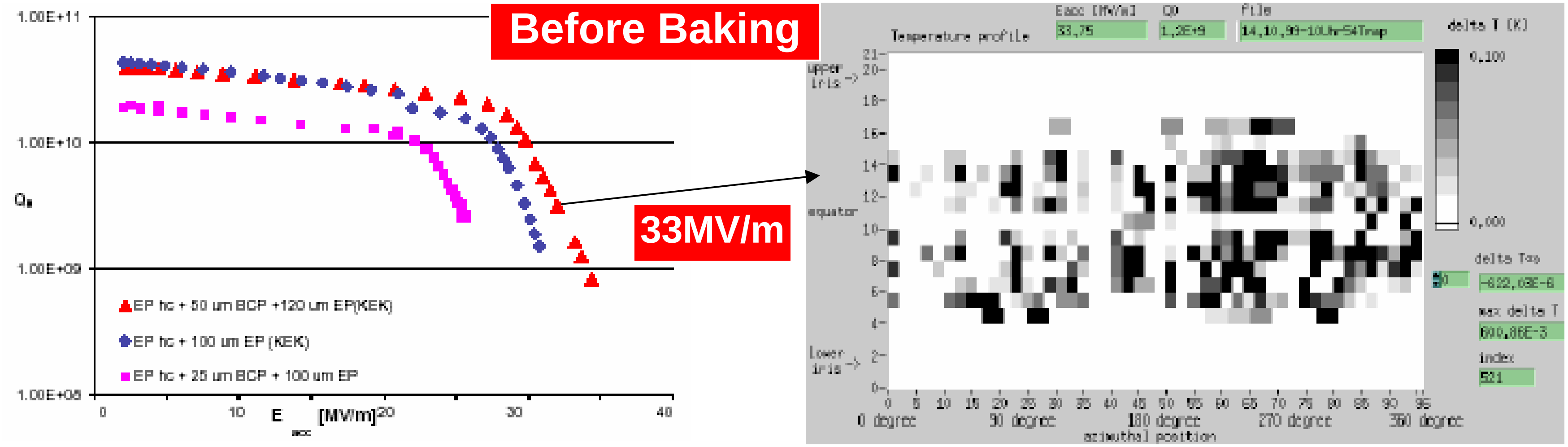
Discovered in 1998

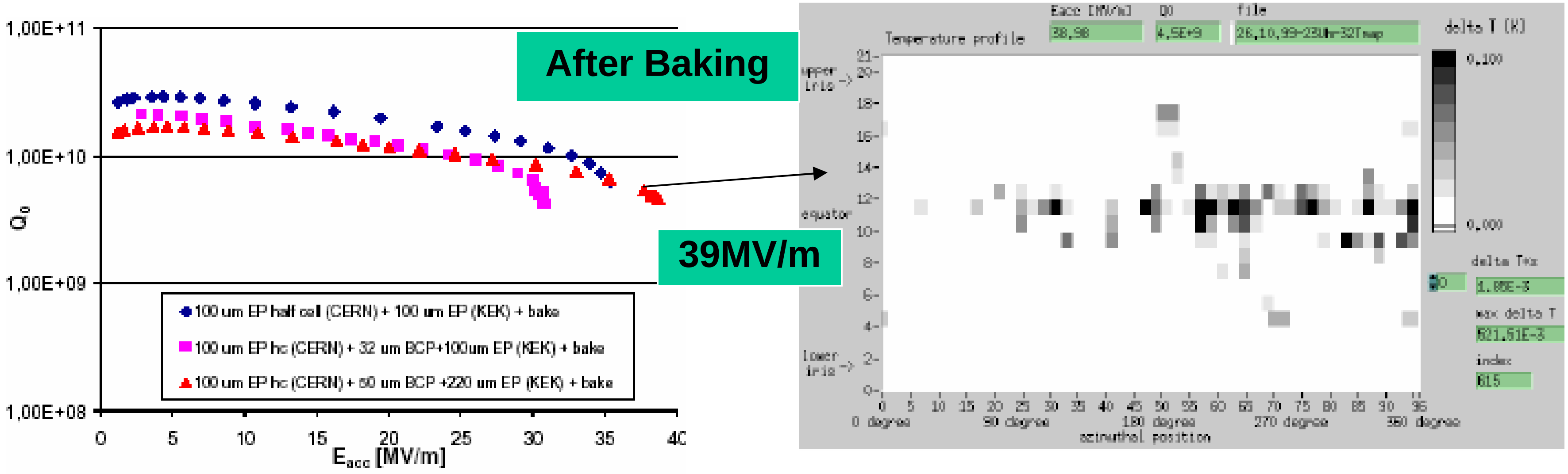
Crutial Baking Effect on EP Cavity



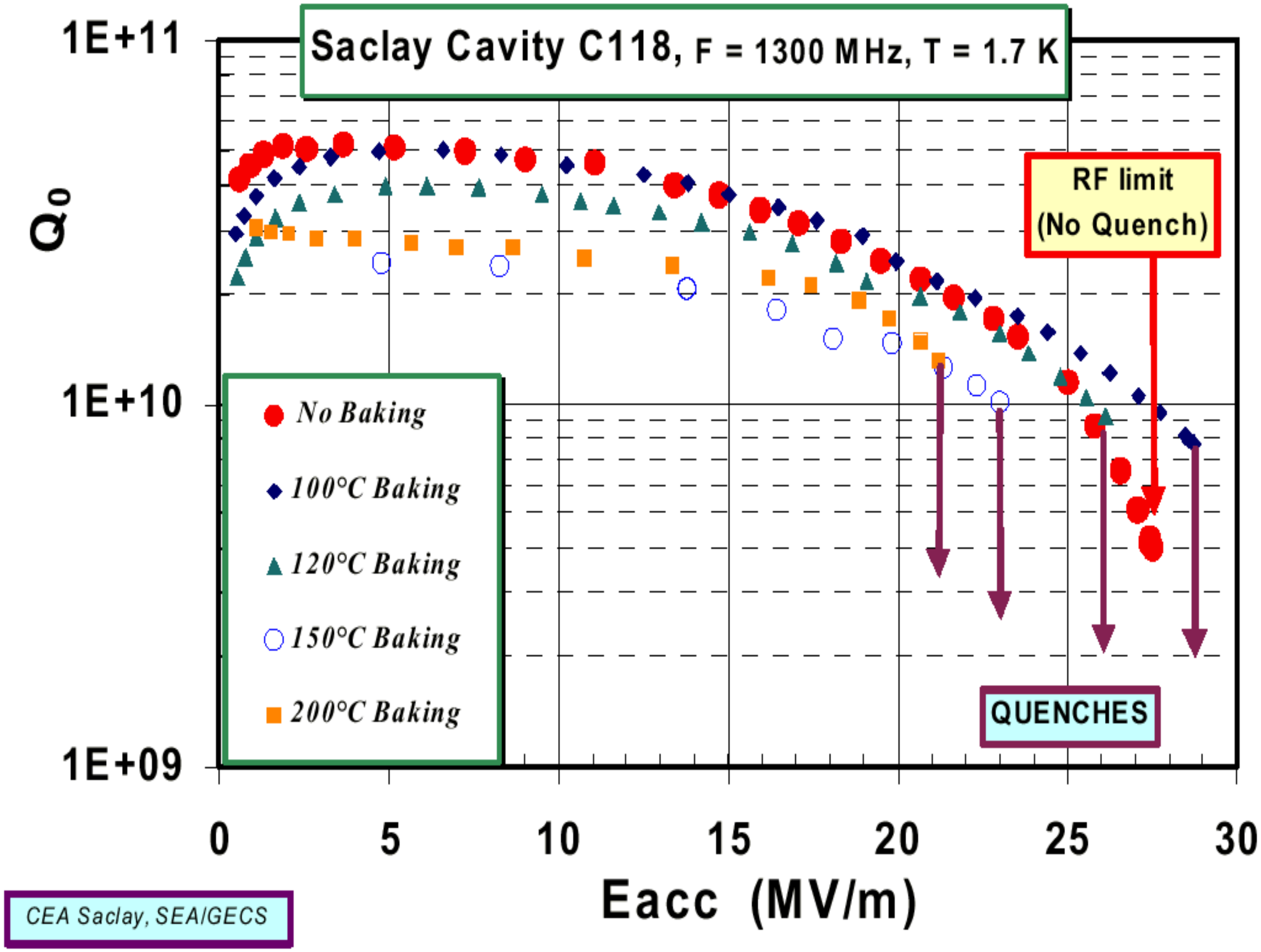
When took baking, Q-slope disappears in case of electropolished c
KEK has been used baking but it was for to get better vacuum.
They did not notice the baking effect.

Disappeared Heating Spots by Baking on EP Cavity



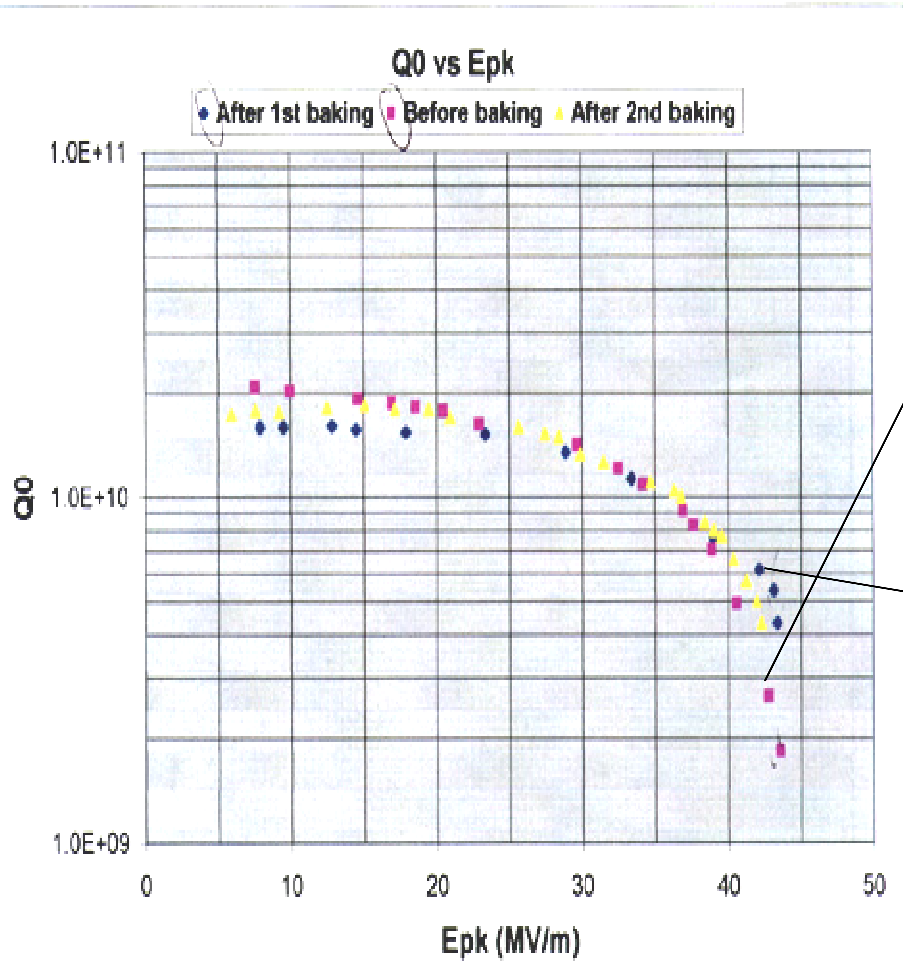


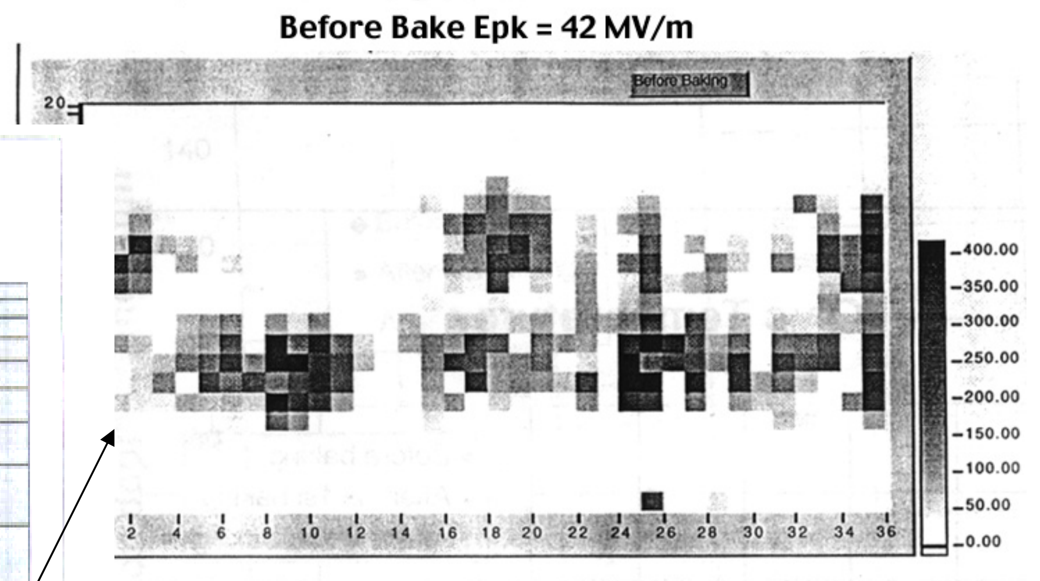
Small Baking Effect on CP Cavities



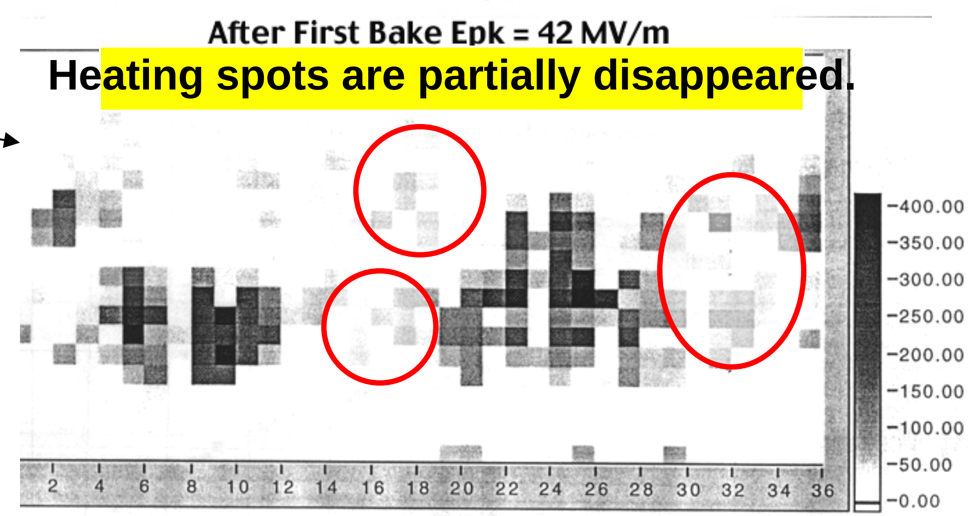
Baking effect on the Q-slope looks small on chemically polished polycrystalline cavity.

Partially Disappeared Heating Spots by Baking on CP Cavity



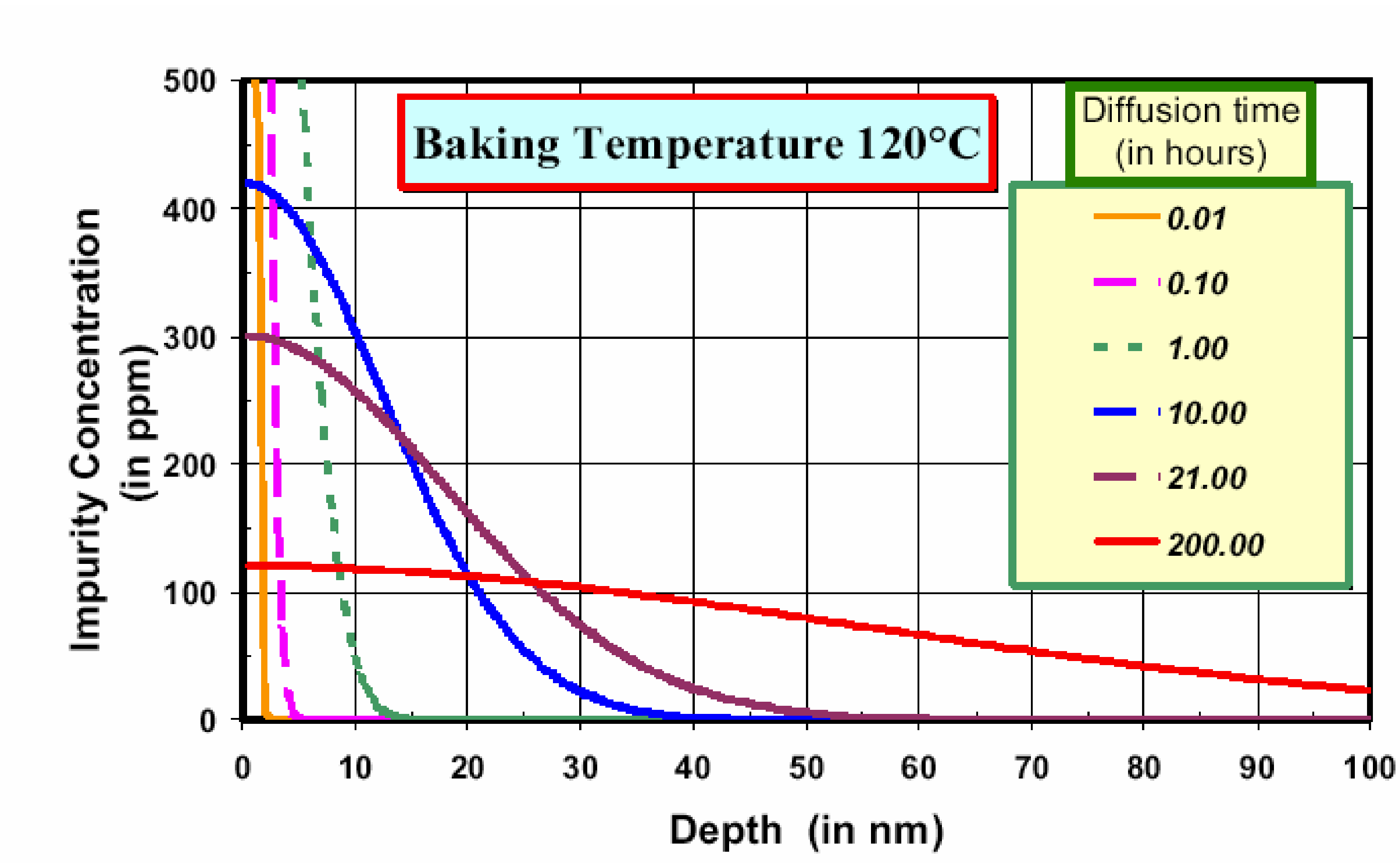


Heating spots are partially disappeared.



CORNELL
UNIVERSITY

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

nterface Tunnel Exchange(ITE Model
By J.Halbritter

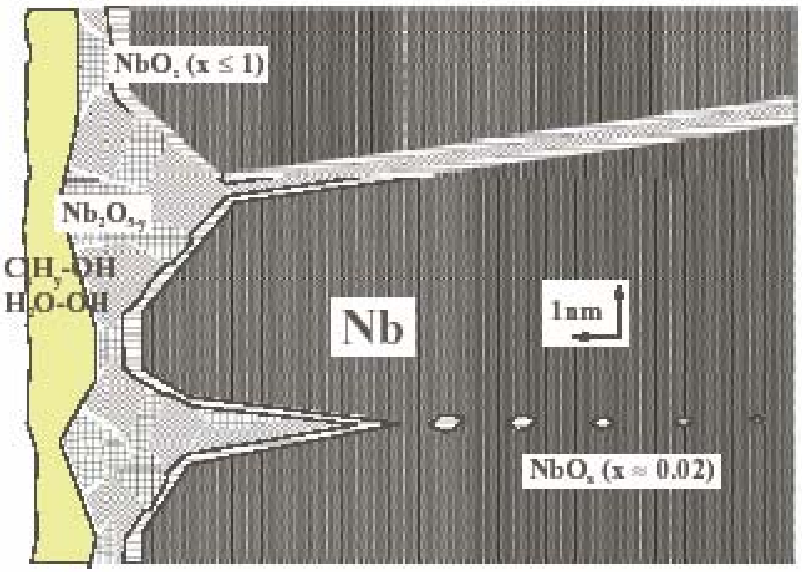


Fig. 1: Nb surface with crack corrosion by oxidation by Nb_2O_5 volume expansion (factor 3). Nb_2O_{5-y}-NbO_x weak links/segregates (y, x < 1) extend up to depths between 0.01 – 1/ 1-10 μm for good – bad Nb quality and weak - strong oxidation [8]. Embedded in the adsorbate layer of H_2O/C_xH_yOH (≥ 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.

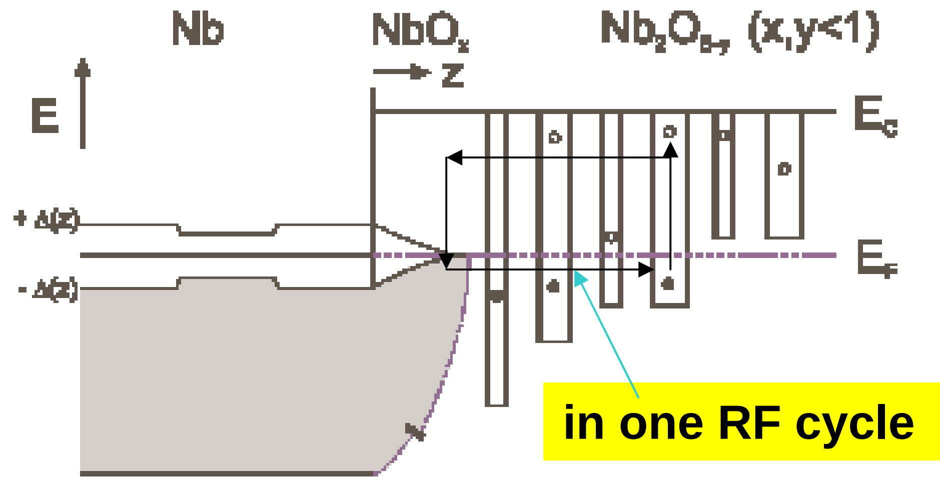
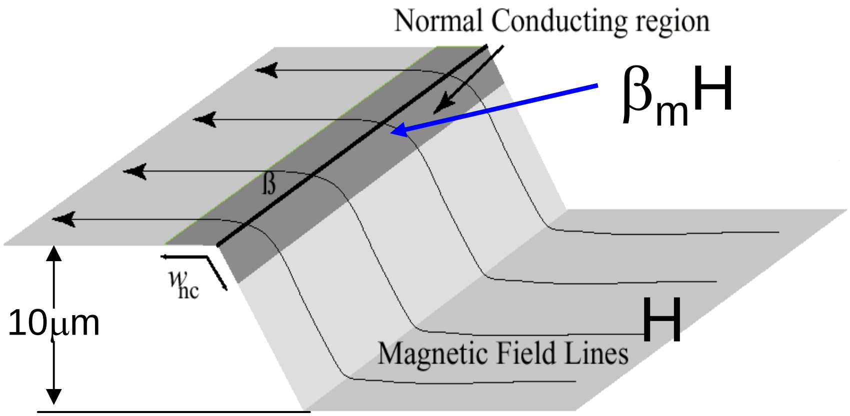
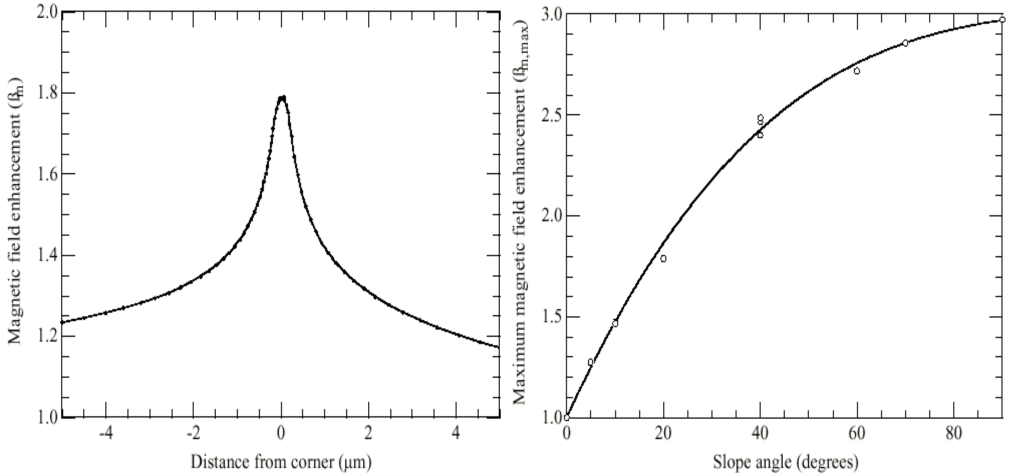


Fig. 3: Band structure at Nb-NbO_x-Nb_2O_{5-y} interfaces with E_c-E_F = φ ≈ 0.1 – 1 eV as barrier heights for tunneling along crystallographic shear planes (~ 0.1 eV) or of Nb_2O_{5-y} crystallites (~ 1 eV). Added is the superconducting energy gap $\Delta^*(z) < \Delta_o$ being reduced in NbO_x clusters 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.

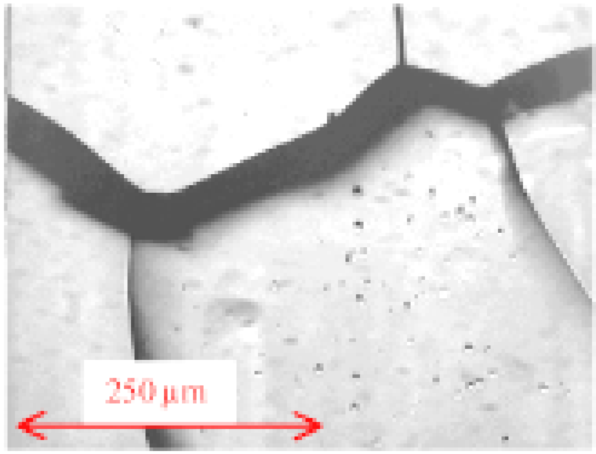
8.6 Magnetic Field Enhancement on Sharp Edges

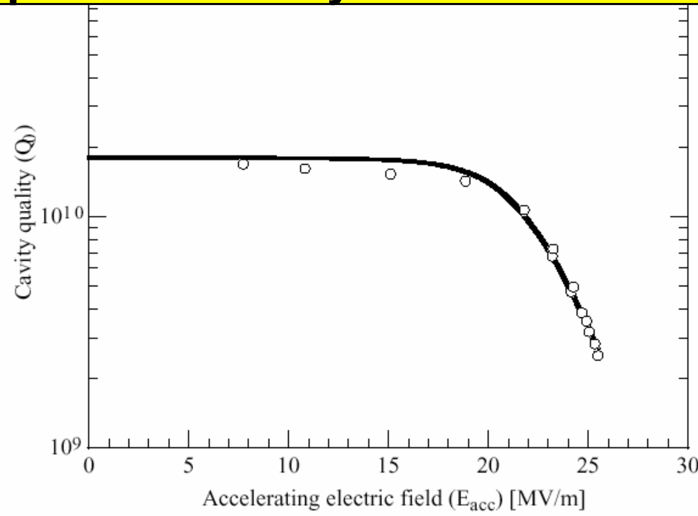




Why the gradient can not be improved after baking chemically polished cavity ?

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





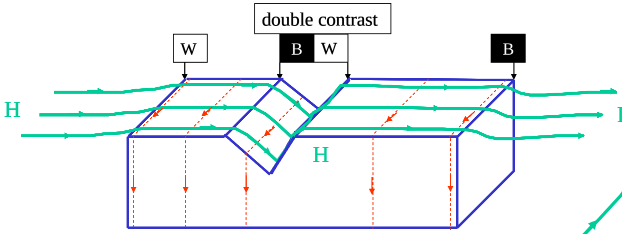
$$\beta_m \cdot H_{RF} \geq H_C = \frac{\sqrt{2} \cdot H_C(0)}{\kappa(0)} \cdot (1 - t^4)$$

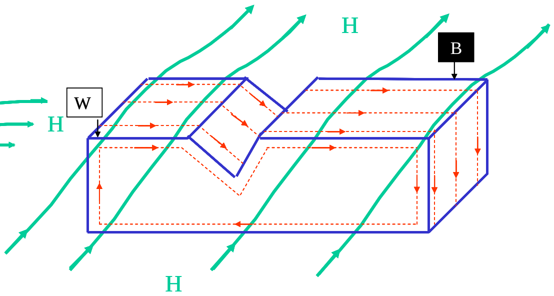
Figure 19: Comparison of the measured cavity quality (Test C) with that calculated by (25) using $H_{crit} = 1875$ Oe.

Monograph effect on Magnetic field

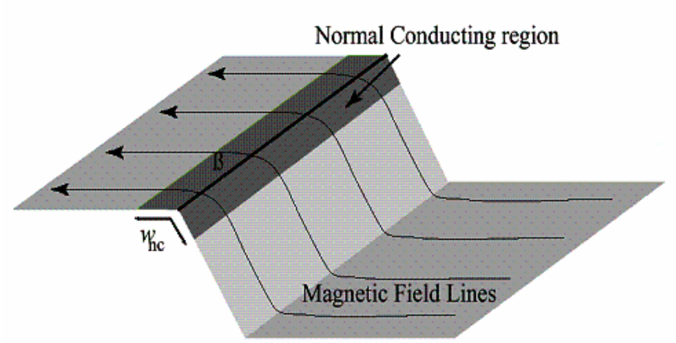
By C.Antone

CBP is right way to eliminate the monograph effect !!

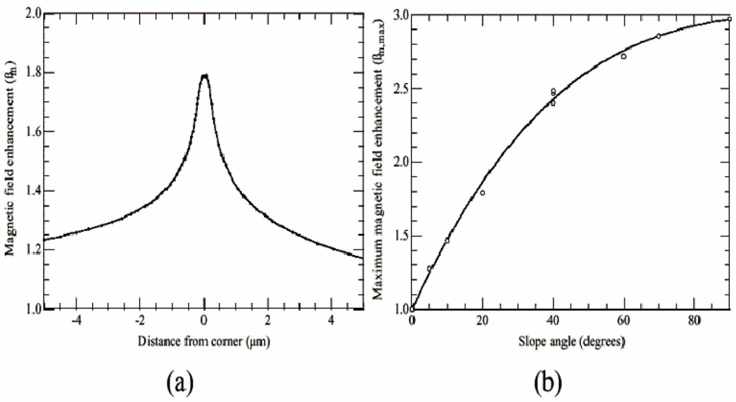




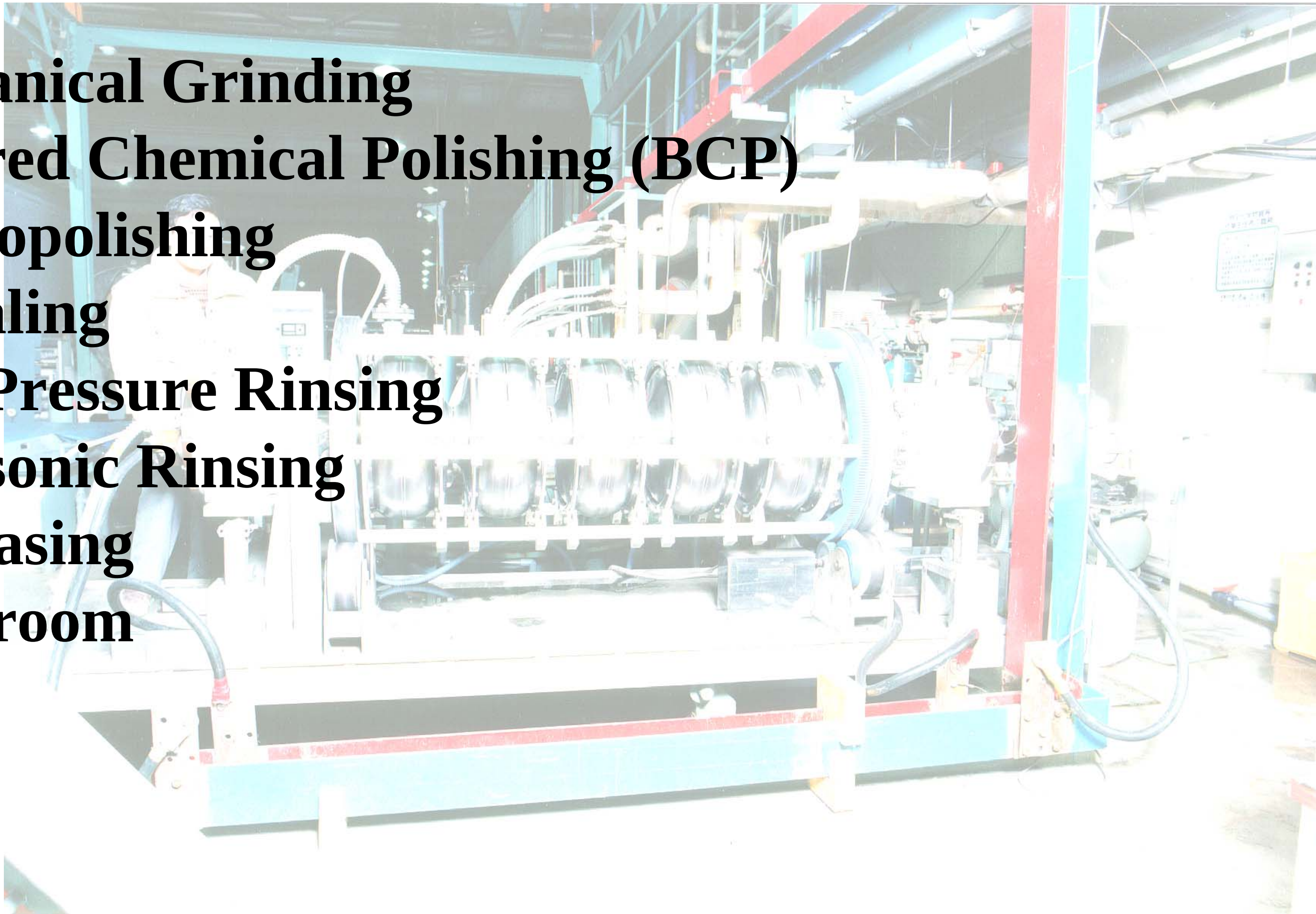
J.Knobloch



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

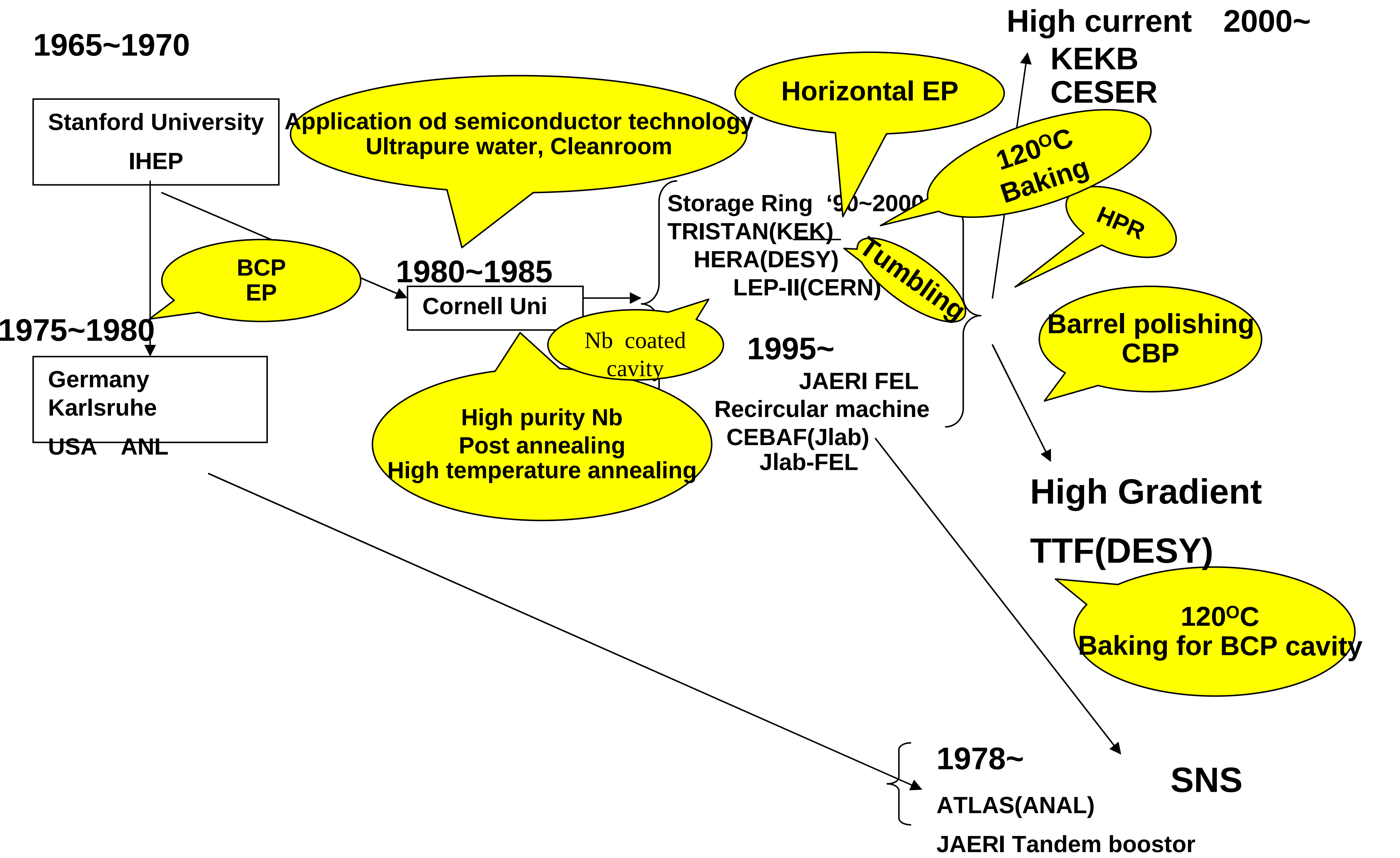


9. Surface Preparation Techniques

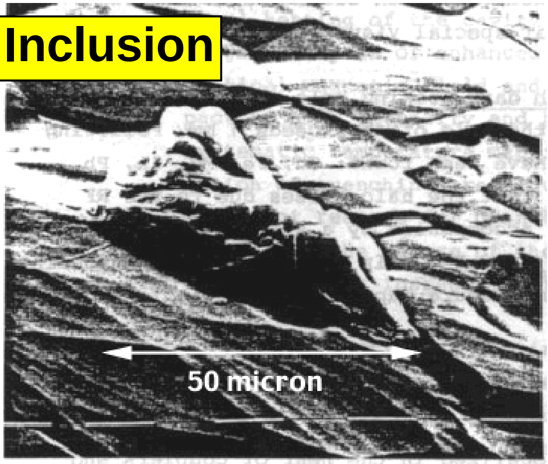


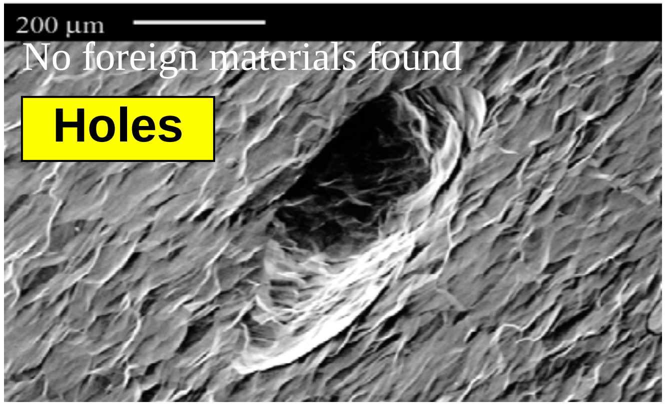
9.1 Mechanical Grinding
9.2 Buffered Chemical Polishing (BCP)
9.3 Electropolishing
9.4 Annealing
9.5 High Pressure Rinsing
9.6 Megasonic Rinsing
9.7 Degreasing
9.8 Cleanroom

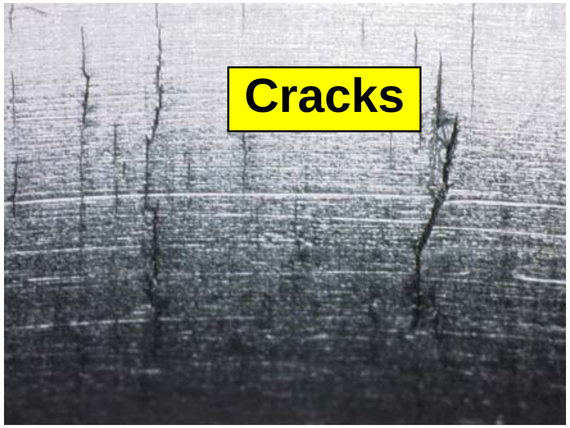
History of Preparation Technologies



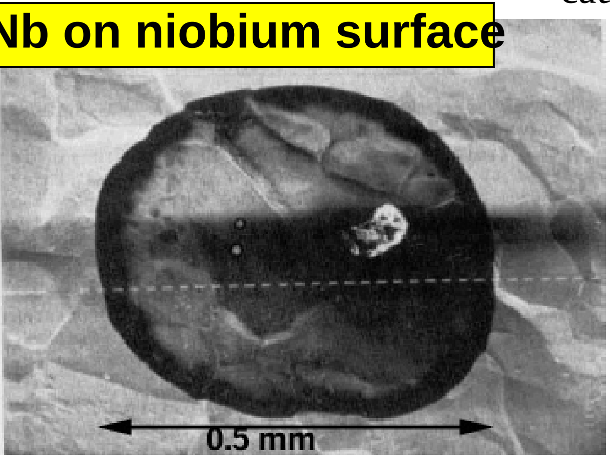
Various Surface Defects

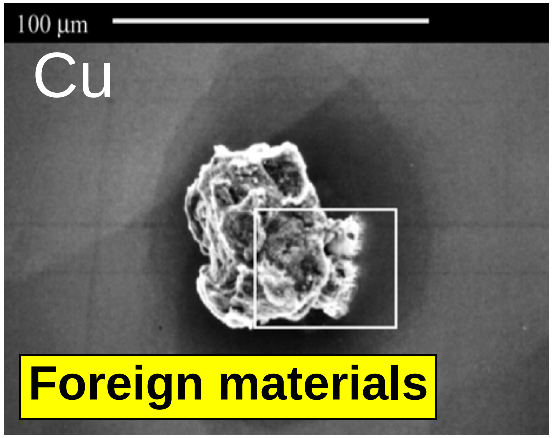


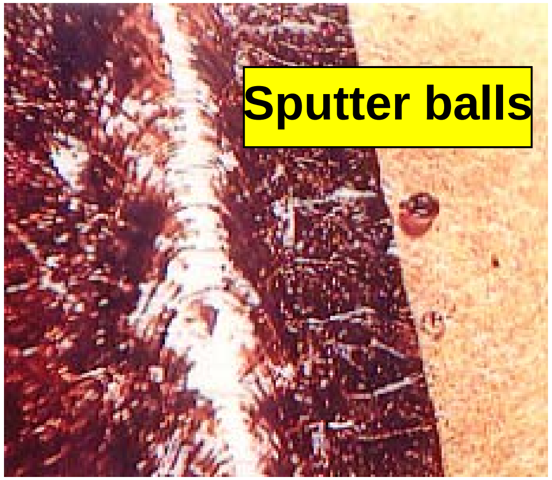




Surface defects, holes can also cause TB







Mechanical grinding is a powerful tool to remove large surface defects.

9.1 Mechanical Grinding

MG is very powerful to remove surface defects but remains Contamination on the ground surface.
It is usually used as pre-treatment before chemical preparation.

Buffin g

Buffing TRISTAN 320 half cups.

- **Very powerful**
- **High reliable**
- **Well controlled the surface roughness**

Used in the TRISTAN @ KEK

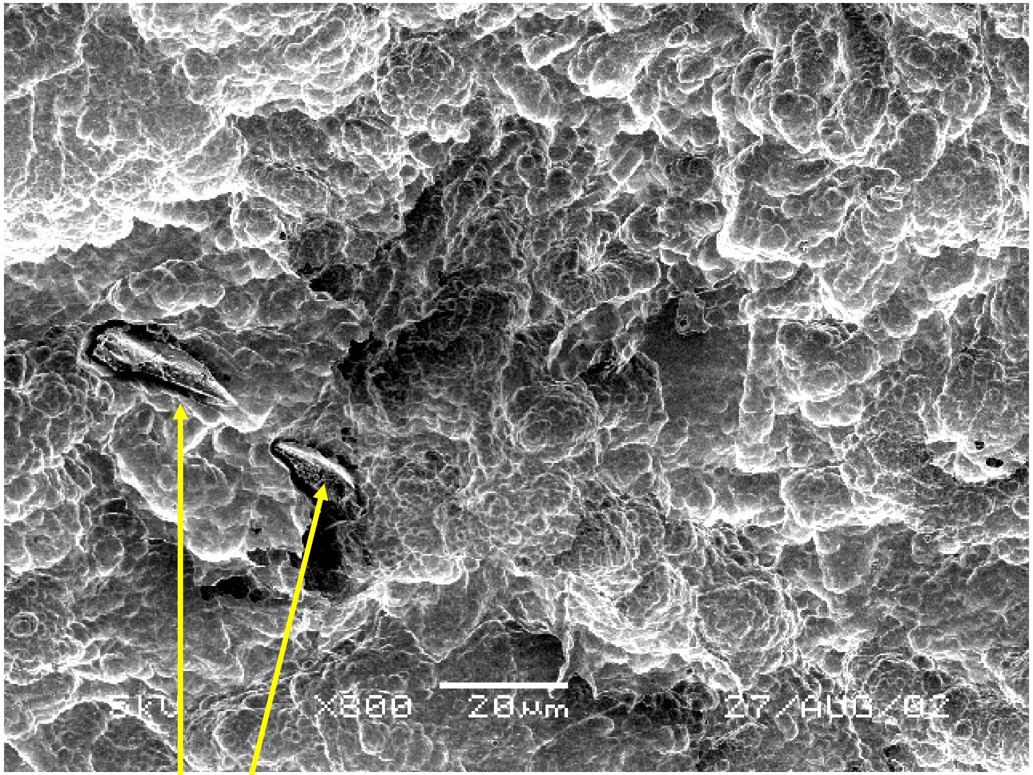
- **All half-cup were buffed.**
- **Other mechanical grinding for welding seams.**

Problem with buffing

1) High cost

2) Impossible to completed structure

Contamination by mechanical grinding

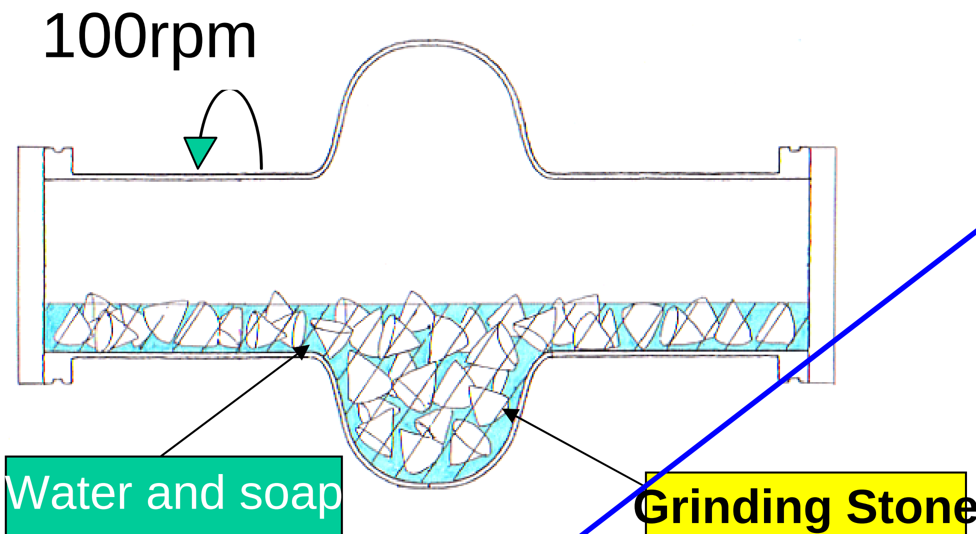


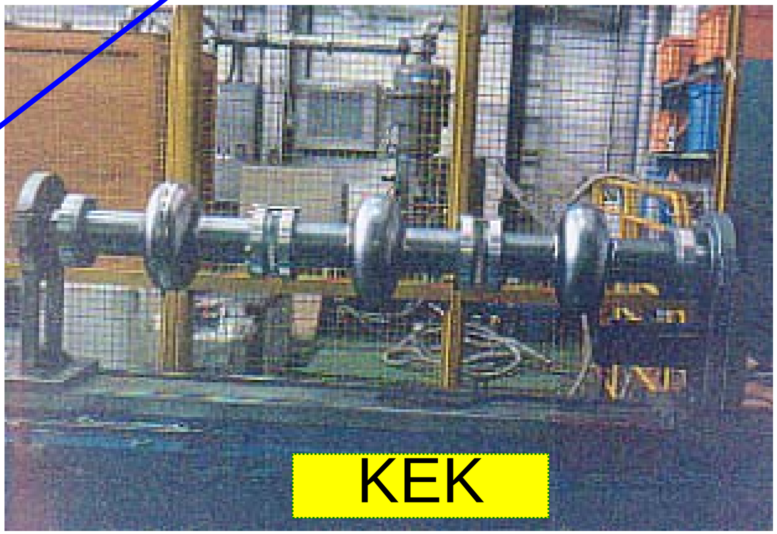
Need to make a chemical preparation in order to remove these contamination.

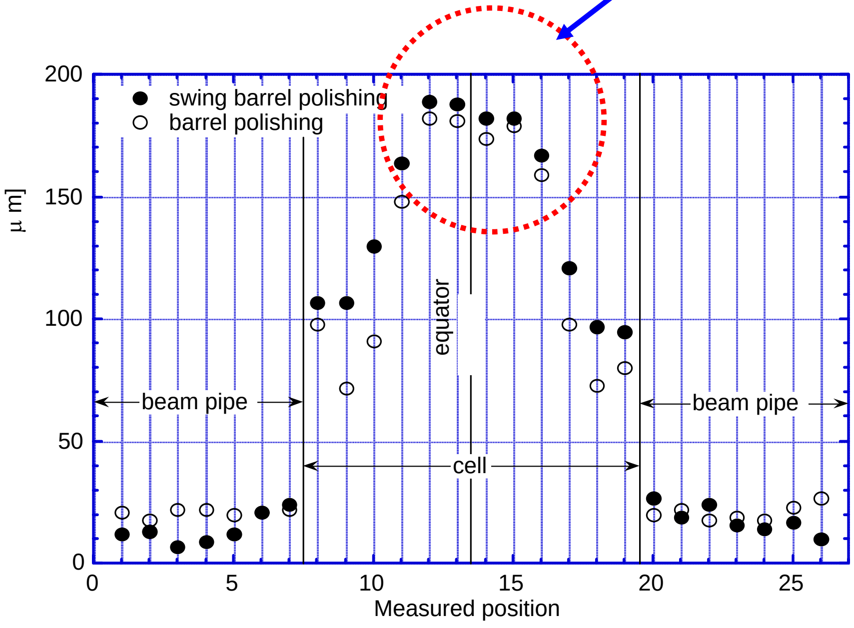
Remained grains of grinding material
（Barrel polishing）

Tumbling or Barrel Polishing(BP)

Easy for EBW seam at equator







- Simple
- Possible to a competed structure
- Low cost

Problem in BP

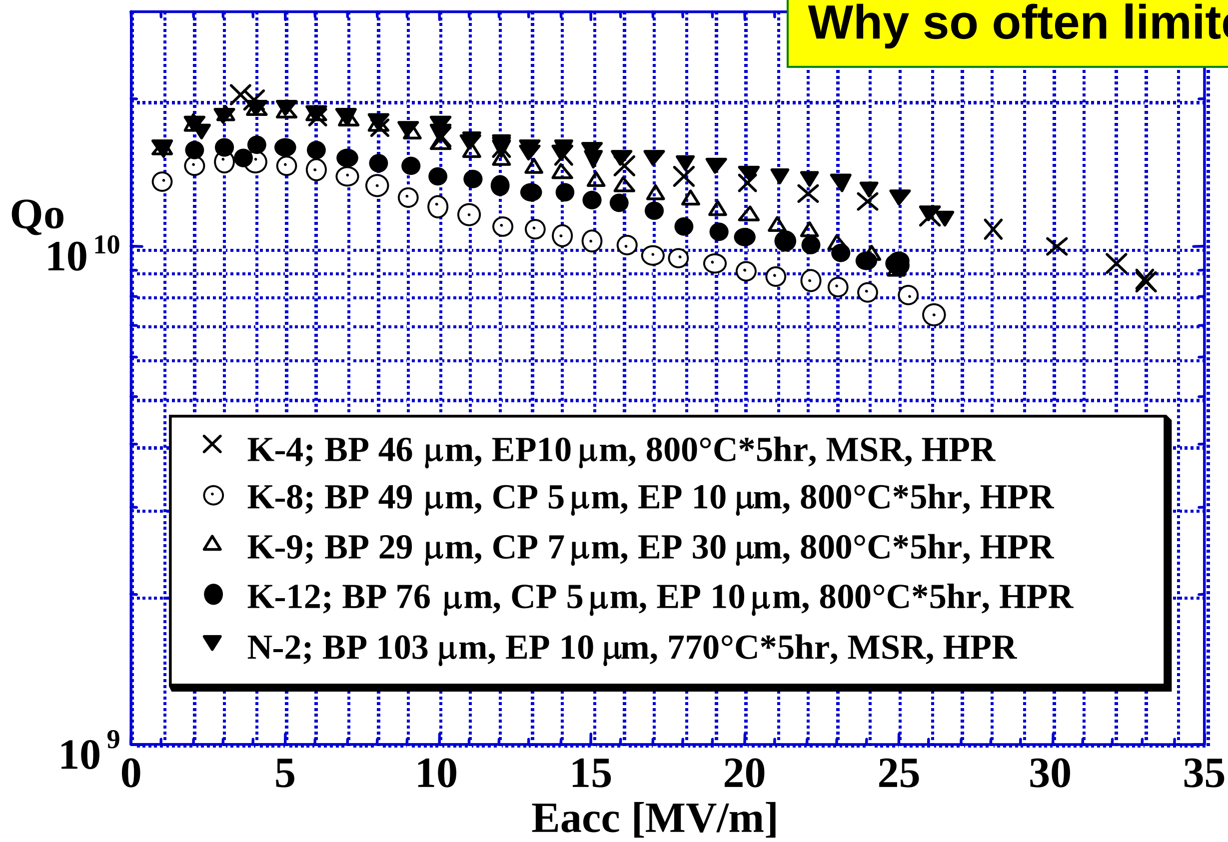
Slow material removal speed 3μm/day

Takes "one week" to remove 30μm.

Dopes hydrogen in the Nb material

Confirmation of the BP effectiveness as pre-treatment prior to EP

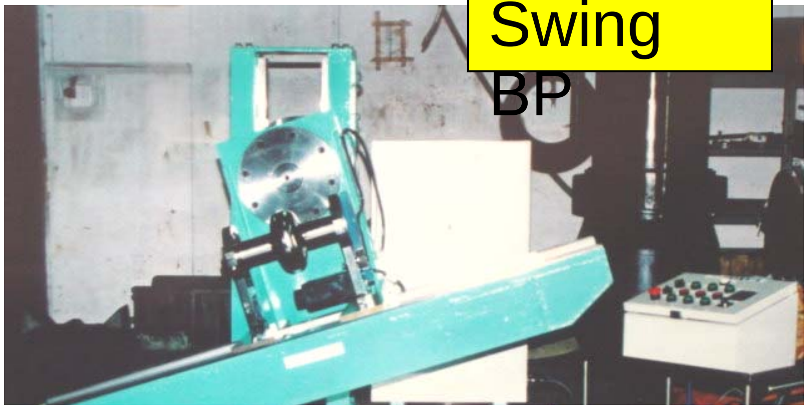
Cavity was annealed after BP.
Why so often limited at 25MV/m?



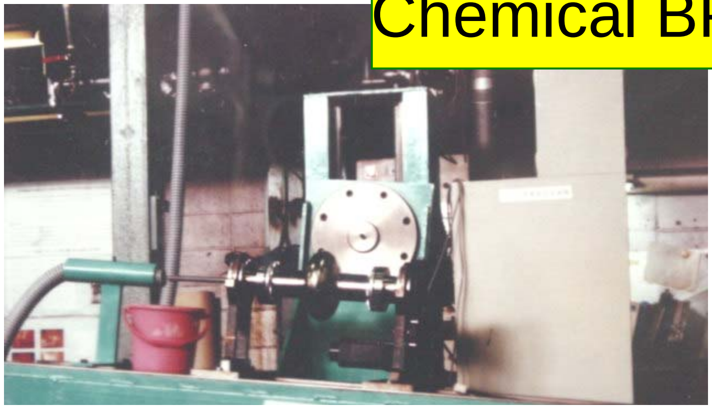
Confirmed 25MV/m by combination BP+Annealing + EP,
25MV/m was enough high gradient in those days (1995).

Some trials to improve the material removal speed of BP

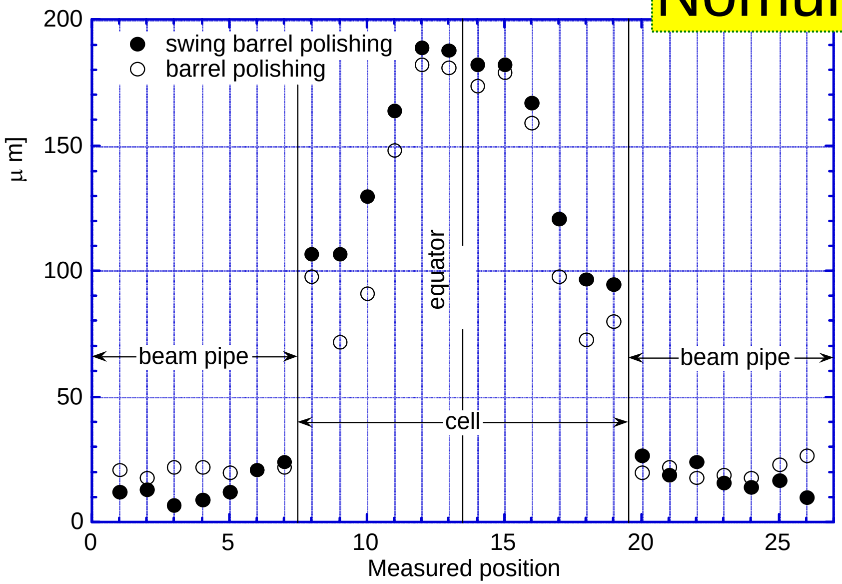
Swing BP

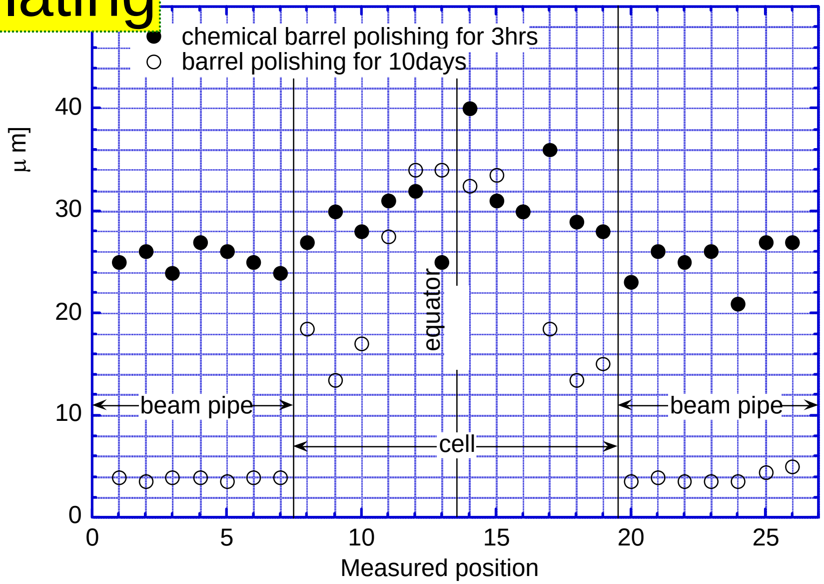


Chemical BP



Nomura Plating

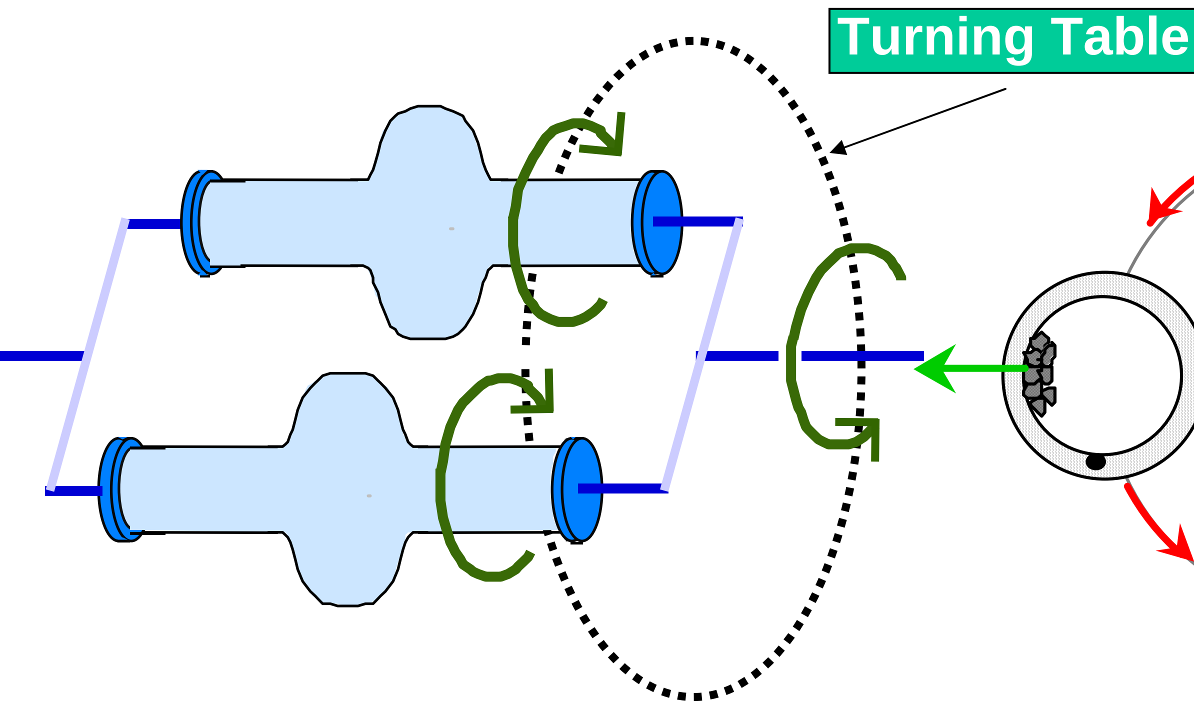


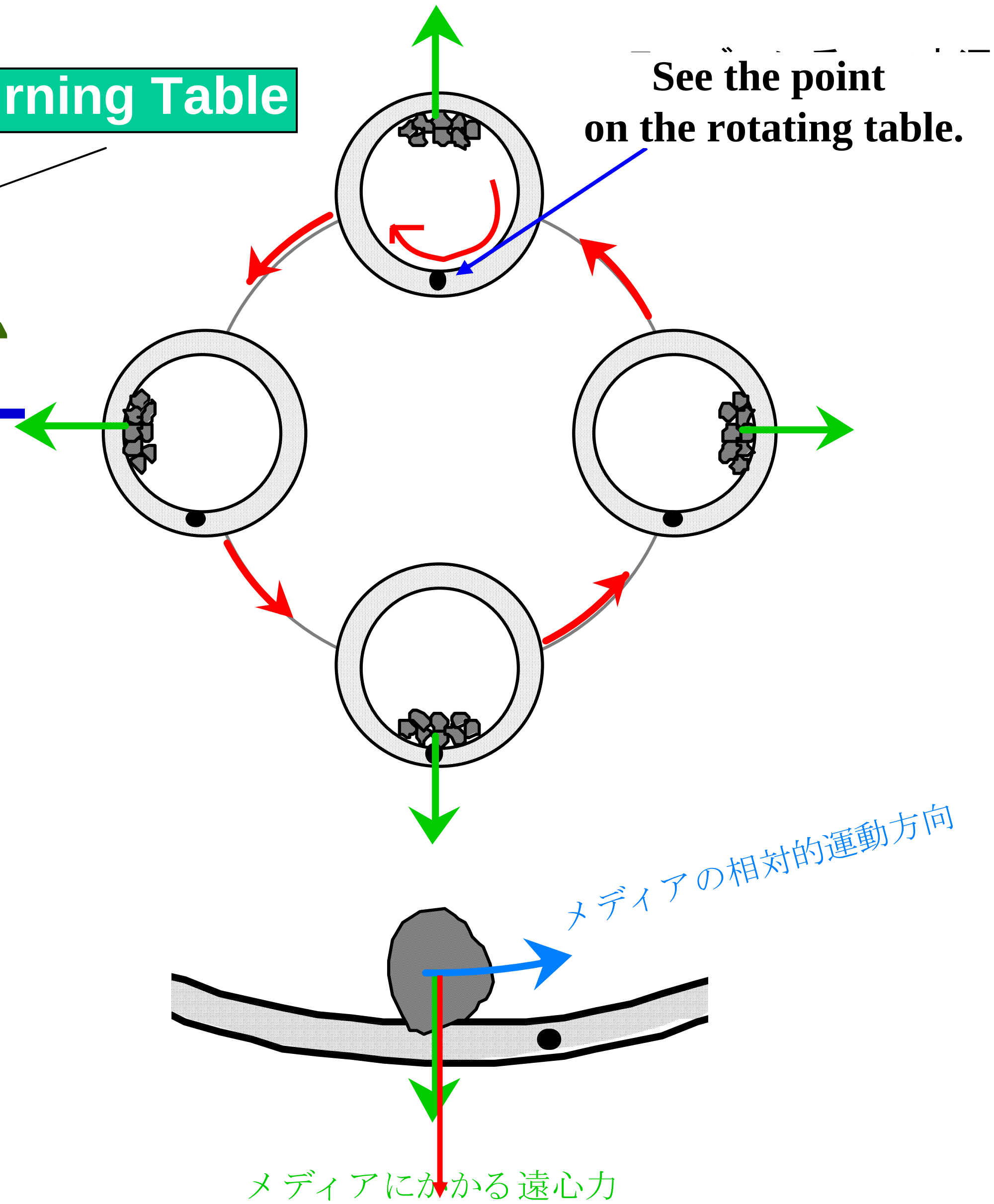


No improvement on the removal speed

Large removal speed but could not good cavity performance

Innovation Centrifugal BP (CBP)

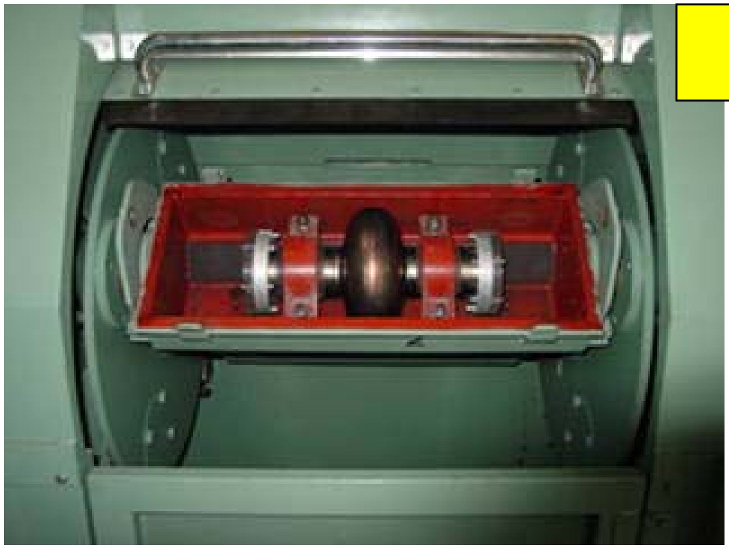




- Rotate cavity on a “rotating table”
- Rotation directions are opposite each other

Two centrifugal forces are added on the grinding

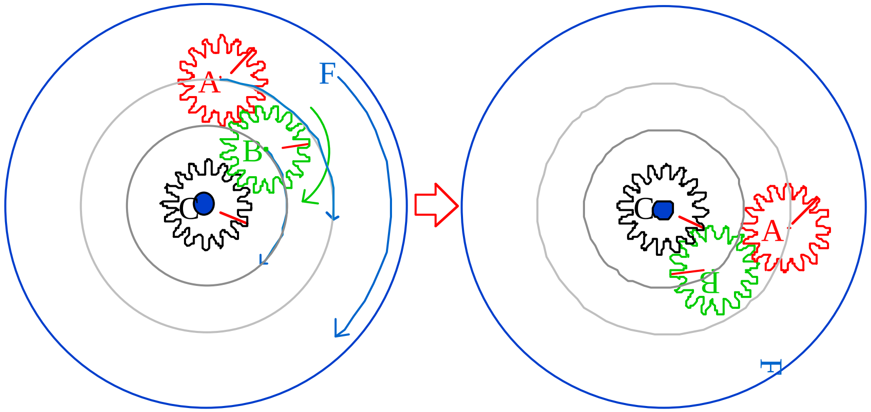
Developed CBP Machine

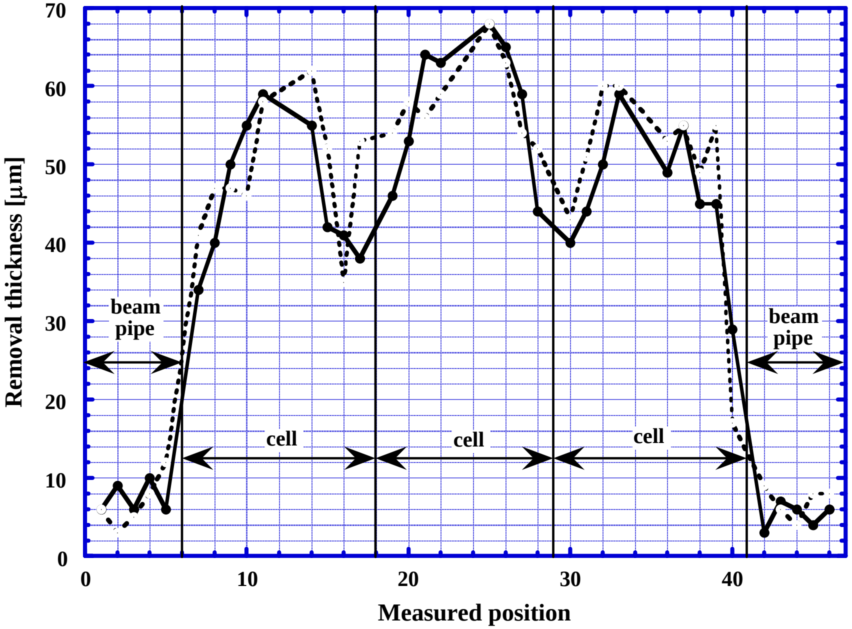


KEK

Front surface

Three cell CBP (1300MHz)





Rotation mechanism : Cavity rotating/table rotation

CBP Finishing Surface

Large Grain cavity case

Rough stone (rough) : 5 times (4 hour each)

Green stone (medium) : Once

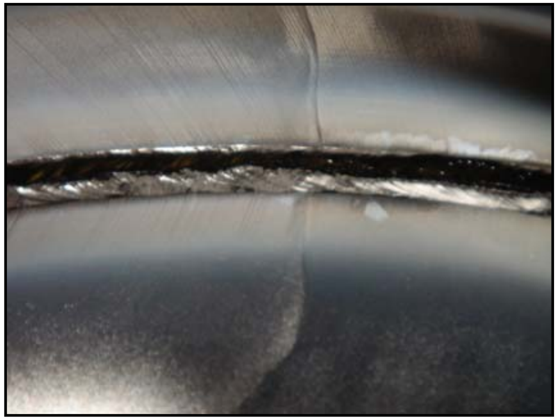
Brown stone (medium): Once

White stone (for final fine finish) : Once

Totally ~ 200 **μm removed @ equator**

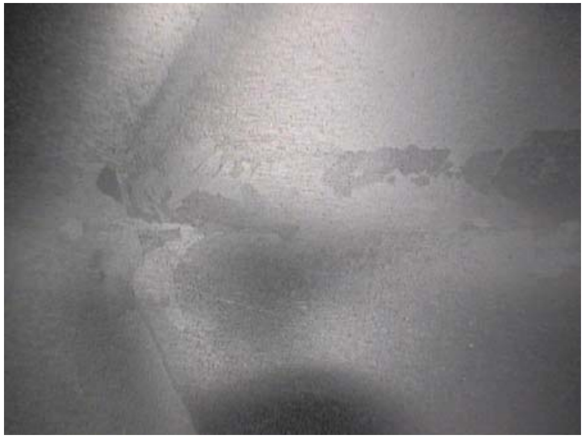
Very fast removal speed!

Material removal speed: "one week"(BP) → 4hr (CBP)



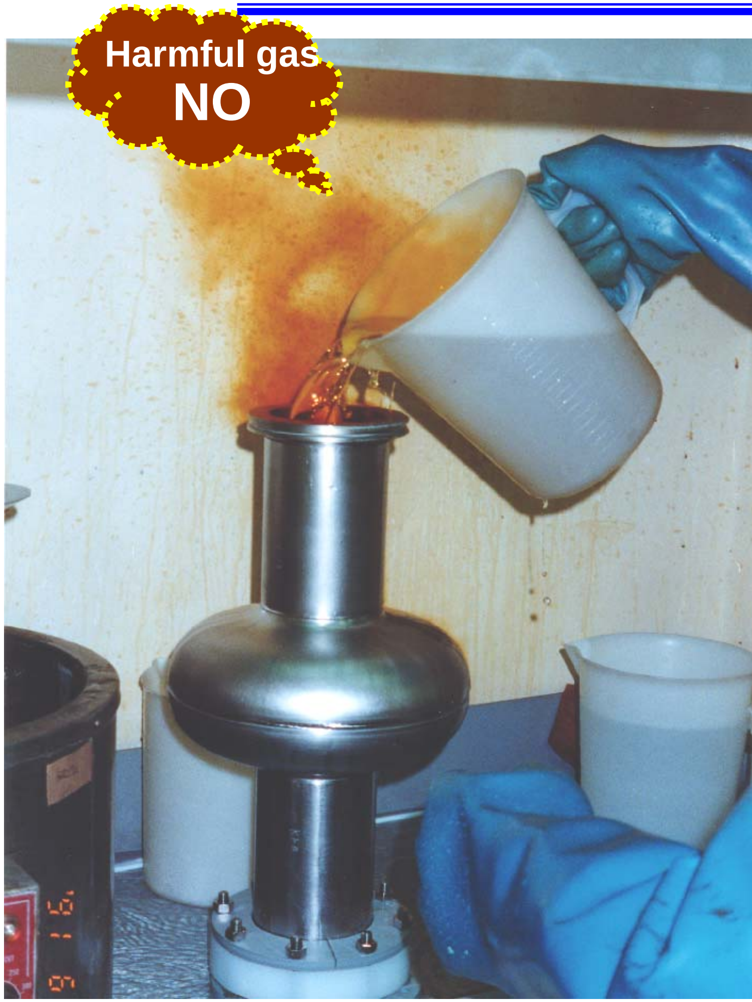
Before CBP (equator EBW seam)

After CBP



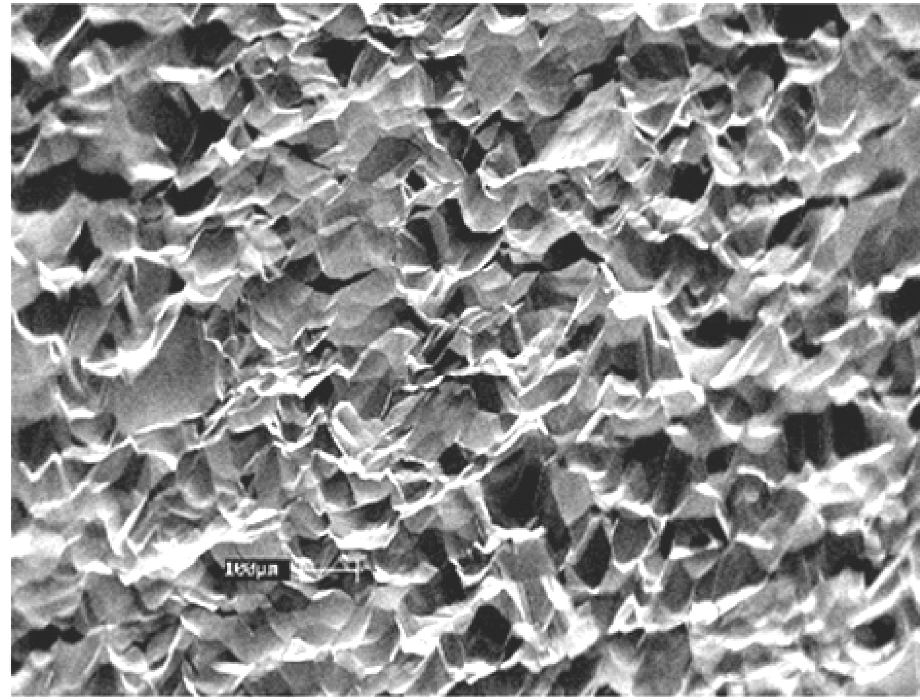
After light CP(10μm)

9.2 Buffered Chemical Polishing (BCP)



HF(46%) : HNO_3(60%) : H_3PO_4
1:1:1 (V/V)

No reaction with Nb, Mild the reaction, Increase viscosity of the acid.



- **Simple and A large material removal speed (10μm/min @ R.T.)**

Problem of BCP: Surface is not so smooth.

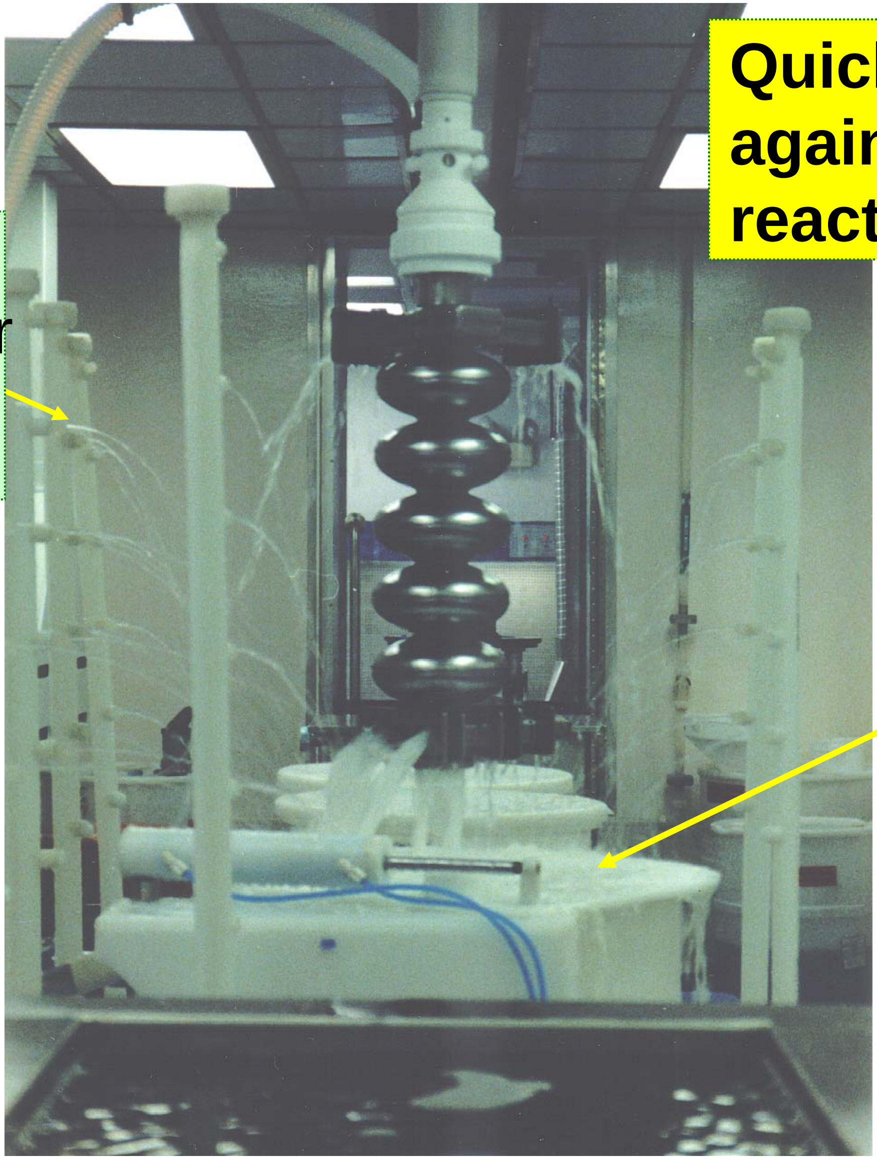
Chemical reaction:

$$6Nb + 10HNO_3 \rightarrow 3Nb_2O_5 + 10NO\uparrow + 5H_2O$$

$$Nb_2O_5 + 10HF \rightarrow 2NbF_5 + 5H_2O$$

$$6Nb + 10HNO_3 + 30HF \rightarrow 6NbF_5 + 10NO\uparrow + 20H_2O$$

CEBAF CP & Rinsing

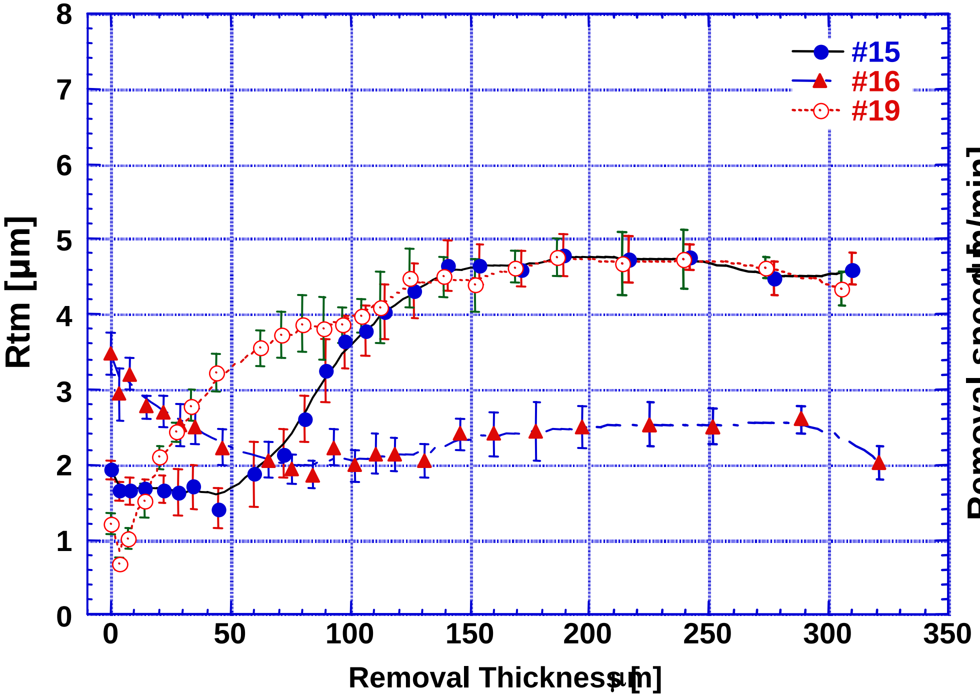


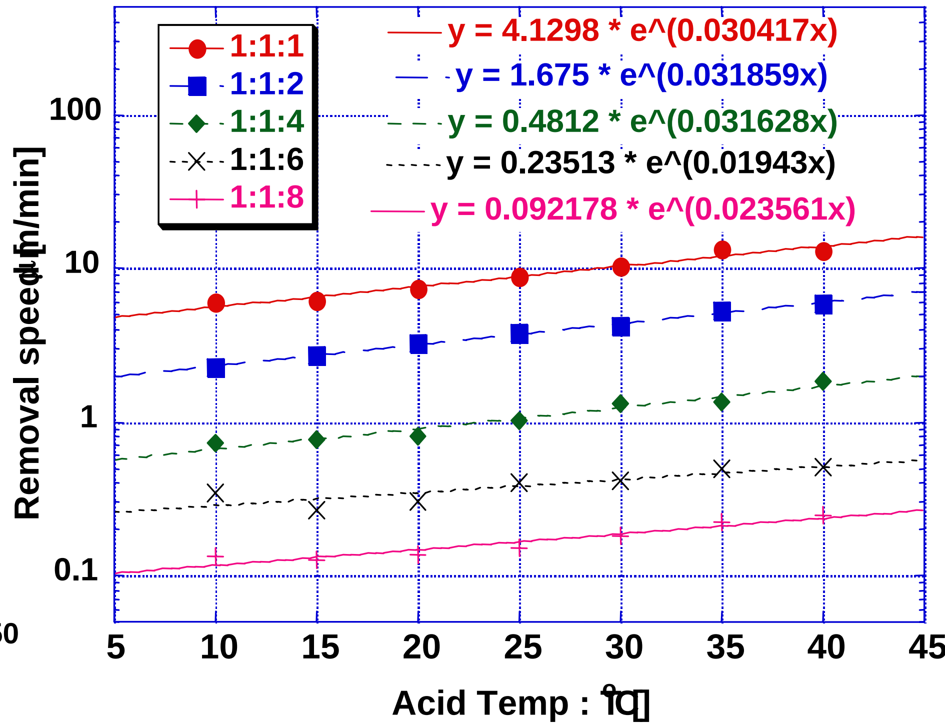
Shower for Rinsing the outer cavity surface

Quick rinsing against the runaway reaction

CP acid tank
Cavity is immersed in the BCP acid.

Characteristics of BCP



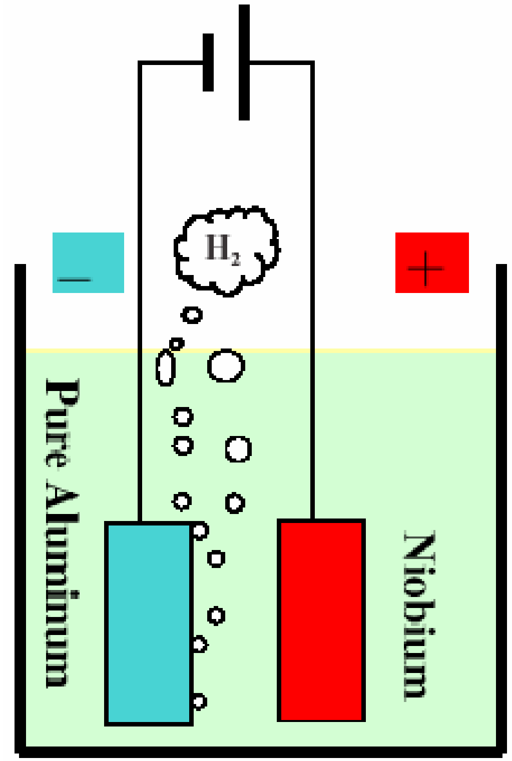


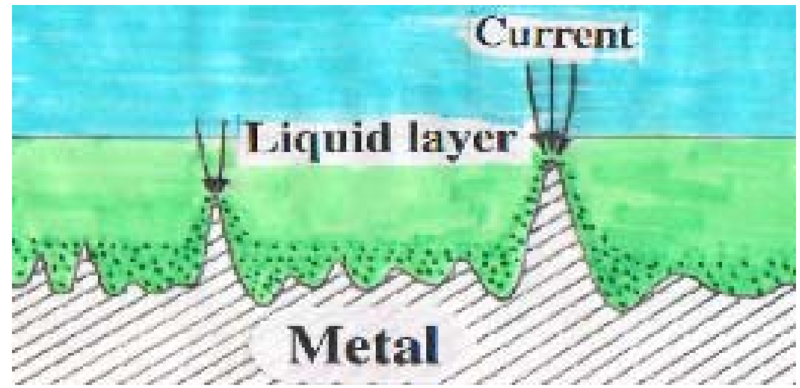
Typical surface roughness = 2 ~ 5 μm after 100μm CP,
Material removal speed ~ 10μm/min at the room temperature with CP acid 1:1:1

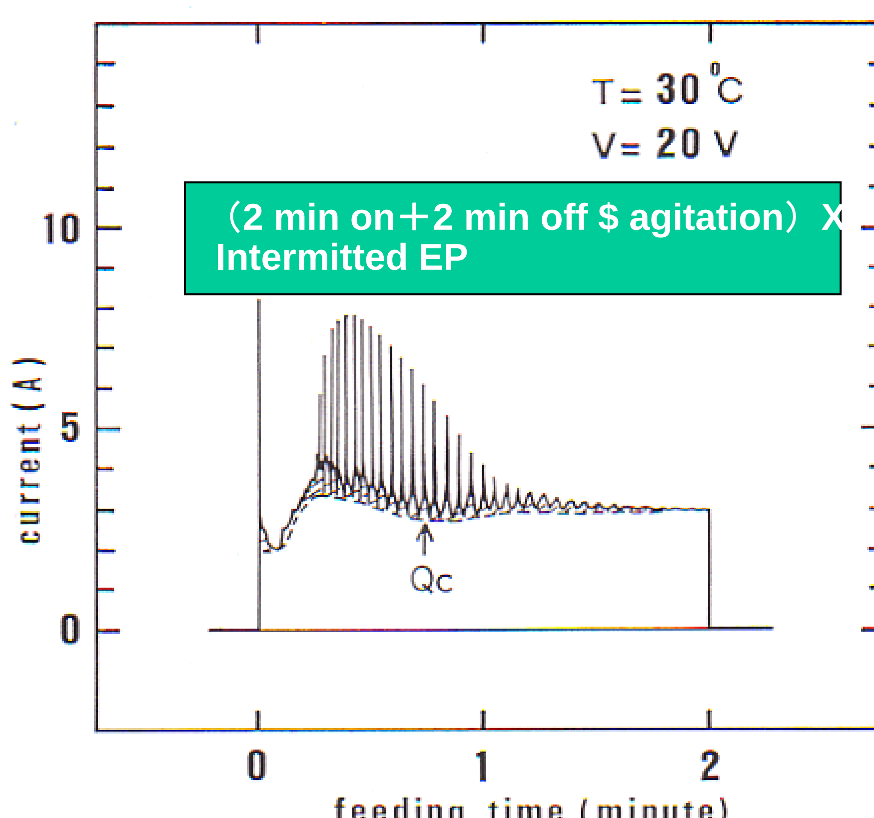
CP is faster in material removal speed than EP.

The finished surface roughness strongly depends on the grain size of the Nb ma

9.3 Electropolishing





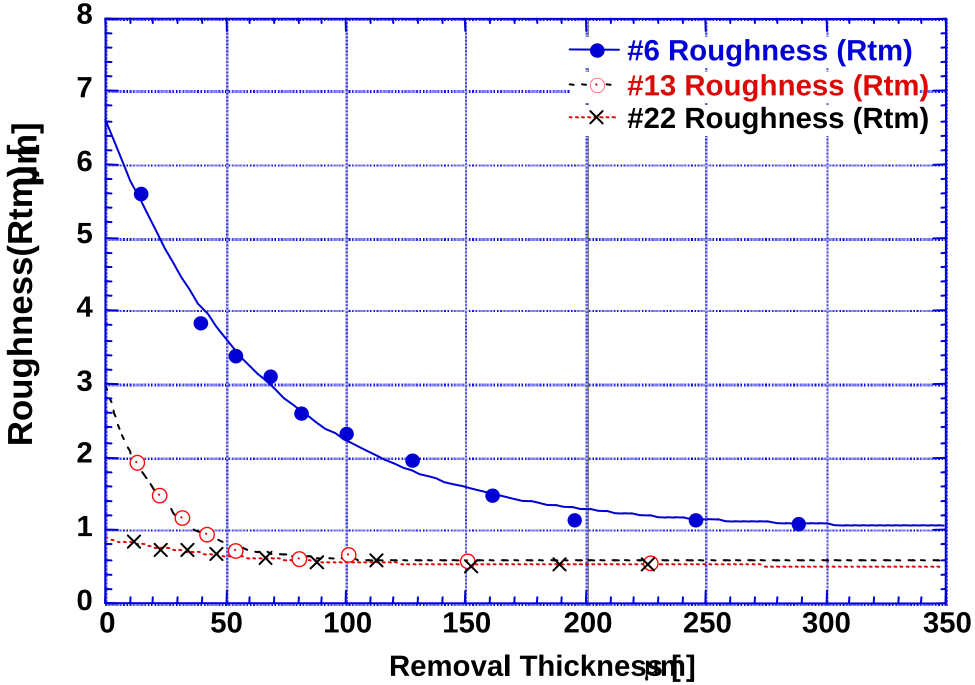


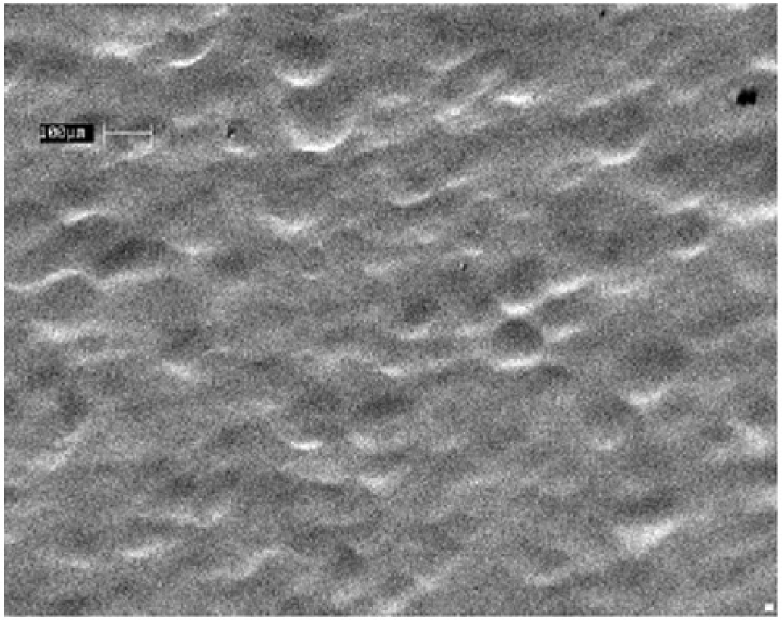
Acid:
H_2SO_4 (>93%): HF(46%)=10:1 V/V

Chemical reaction:
$2Nb + 10HF + 2H_2O \rightarrow 2H_2NbOF_5 + 5H_2\uparrow$

H_2SO_4 does not react with Nb, which make viscosity in the acid.

EP Finished Surface





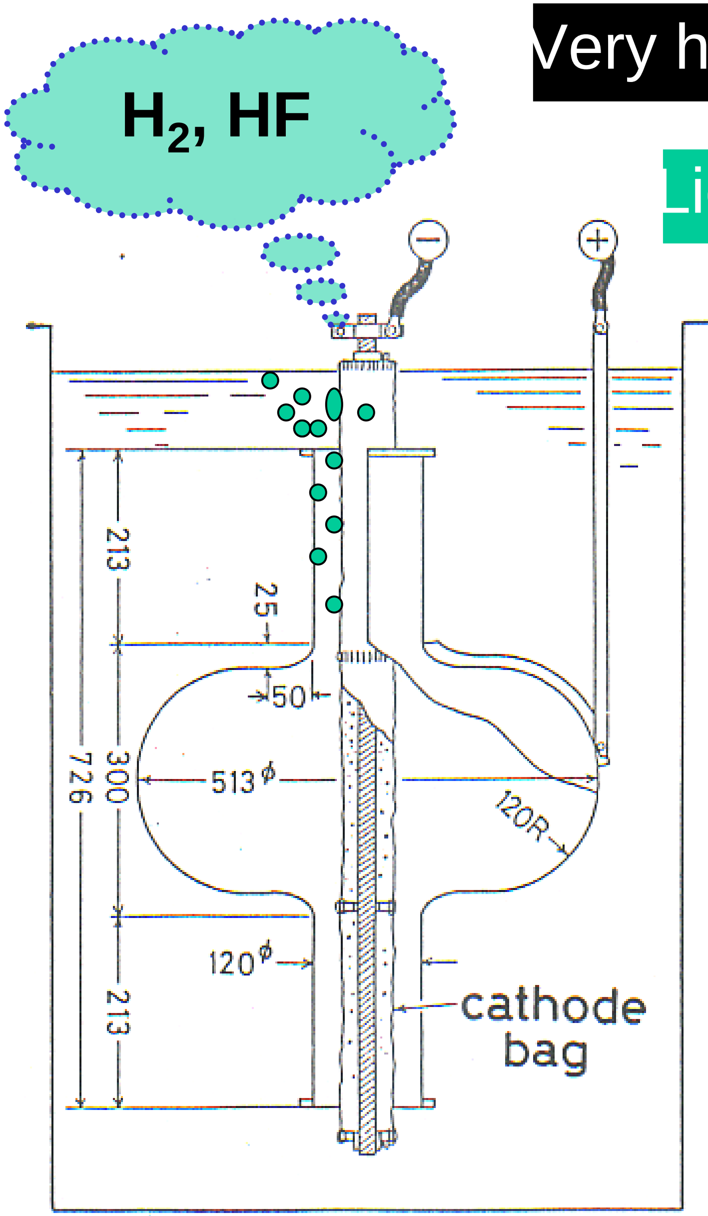
1) The finishing surface roughness depends on that of the initial surface.
2) The finishing roughness becomes smooth exotically with the material remova
3) Grain boundary is not sharp edge as that of BCP case.
4) Easy control of surface roughness.

KEK Early EP (Vertical EP)

Very hazardous working environment

Light hydrogen Q-disease

Hydrogen Q-disease



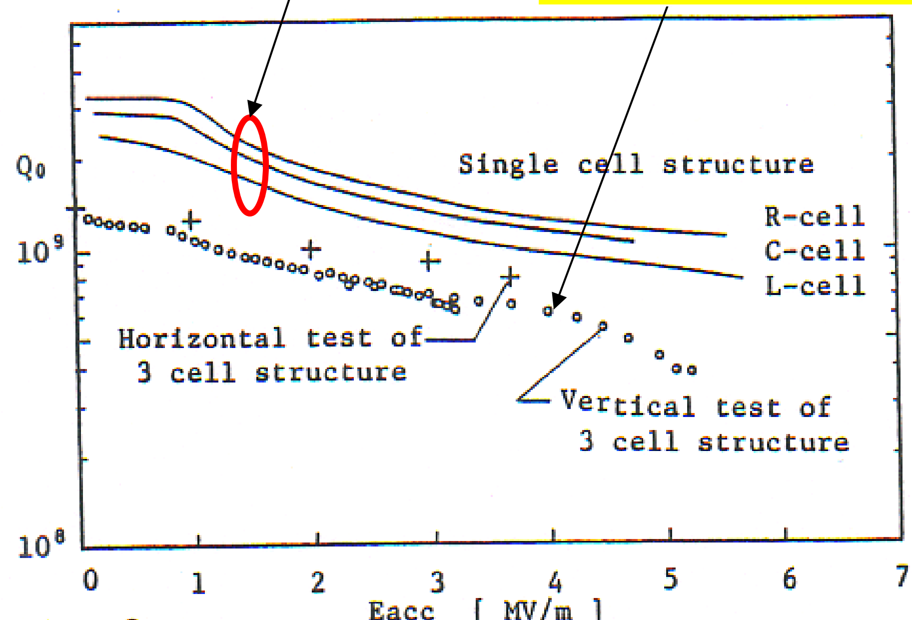
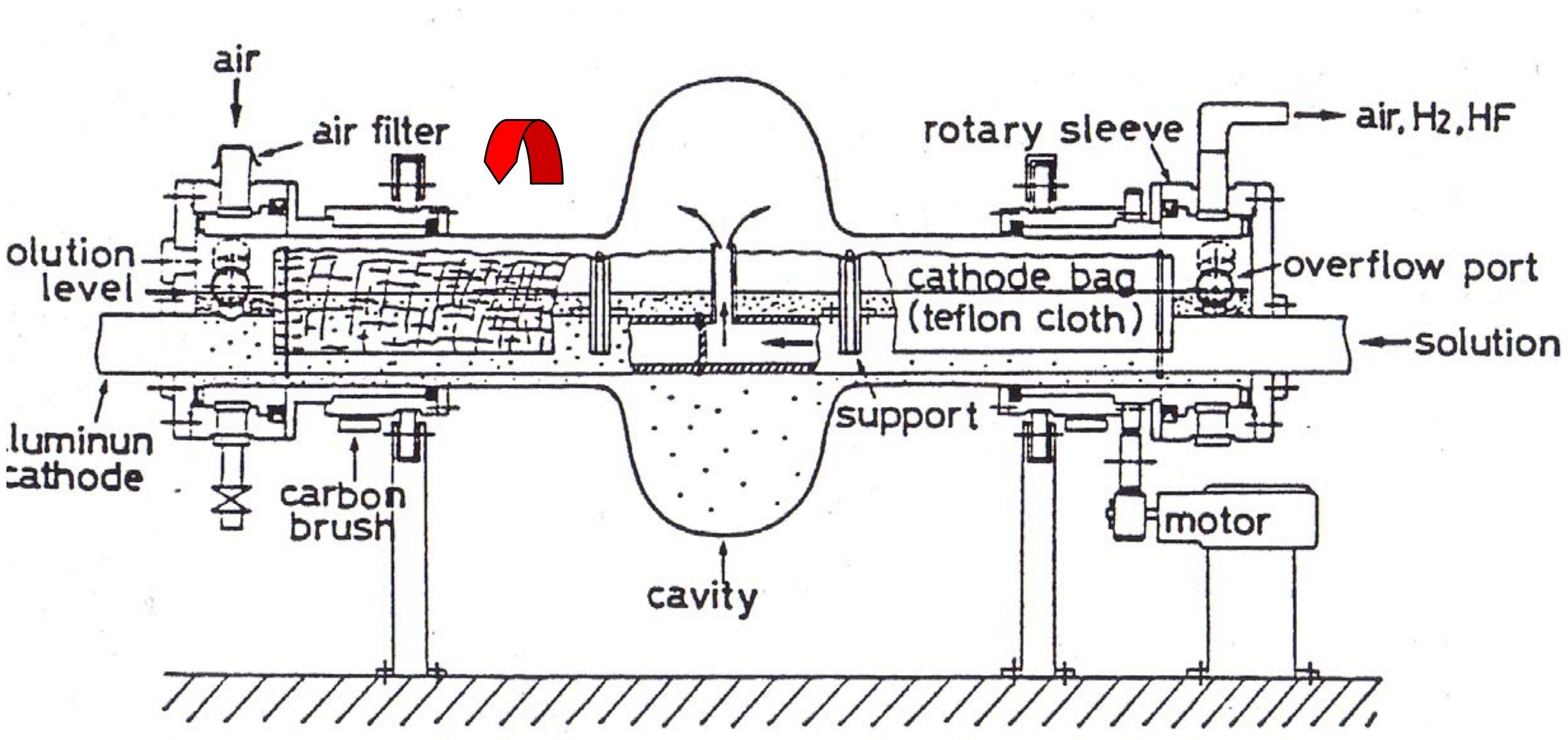


Fig.8
Qo-Eacc curves of a three-cell cavity electropolished using the vertical EP method. R,C,L-cell are single cell cavities before completing the three cell cavity.

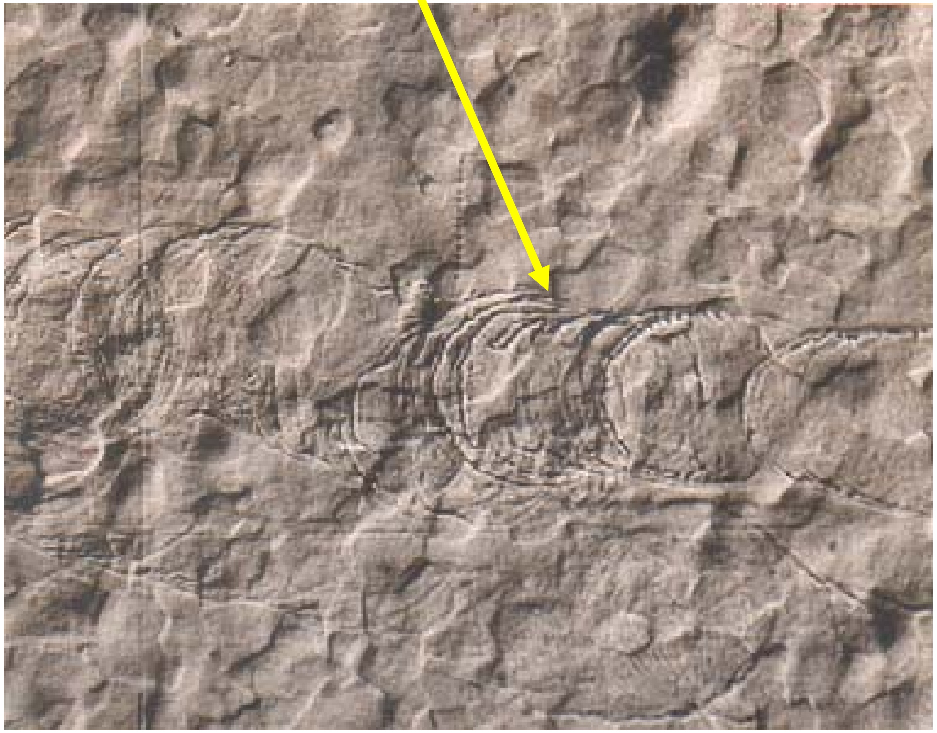
Innovation of a Horizontal EP



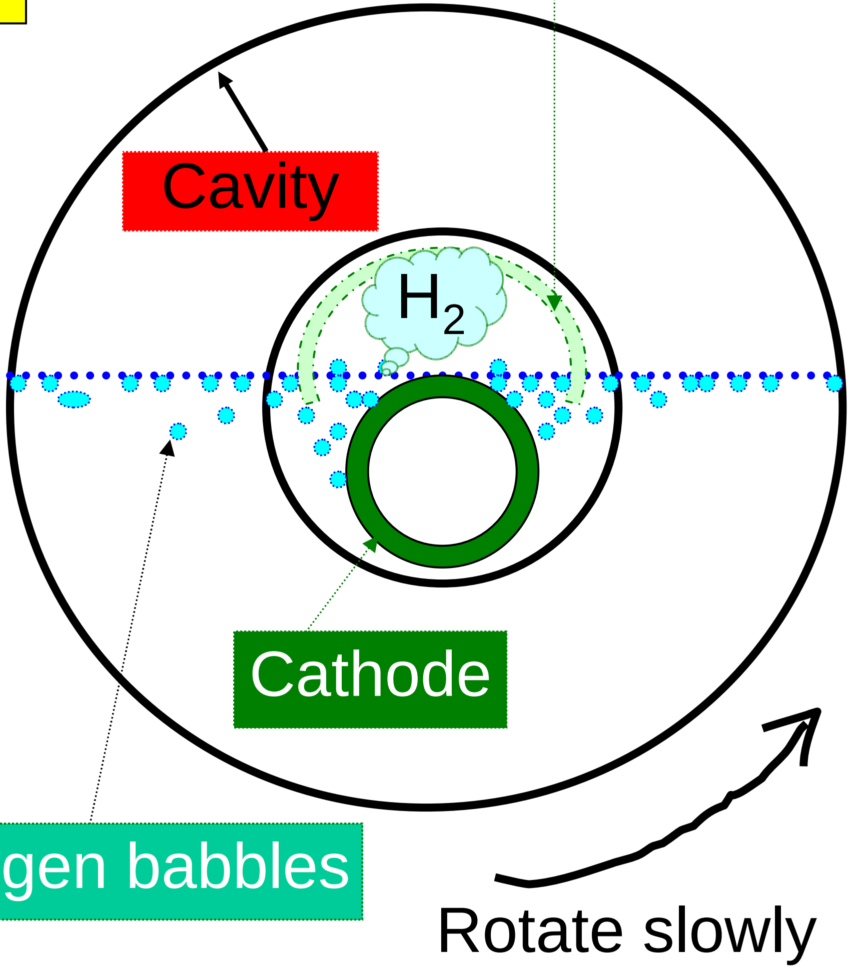
1) Close the EP acid in the EP system to improve the working environm
2) Easy H_2 gas evacuation even for multi-cell cavity.
3) Uniform material removal in each cell for multi-cell cavity.
4) Simple control.

Cathode Bag

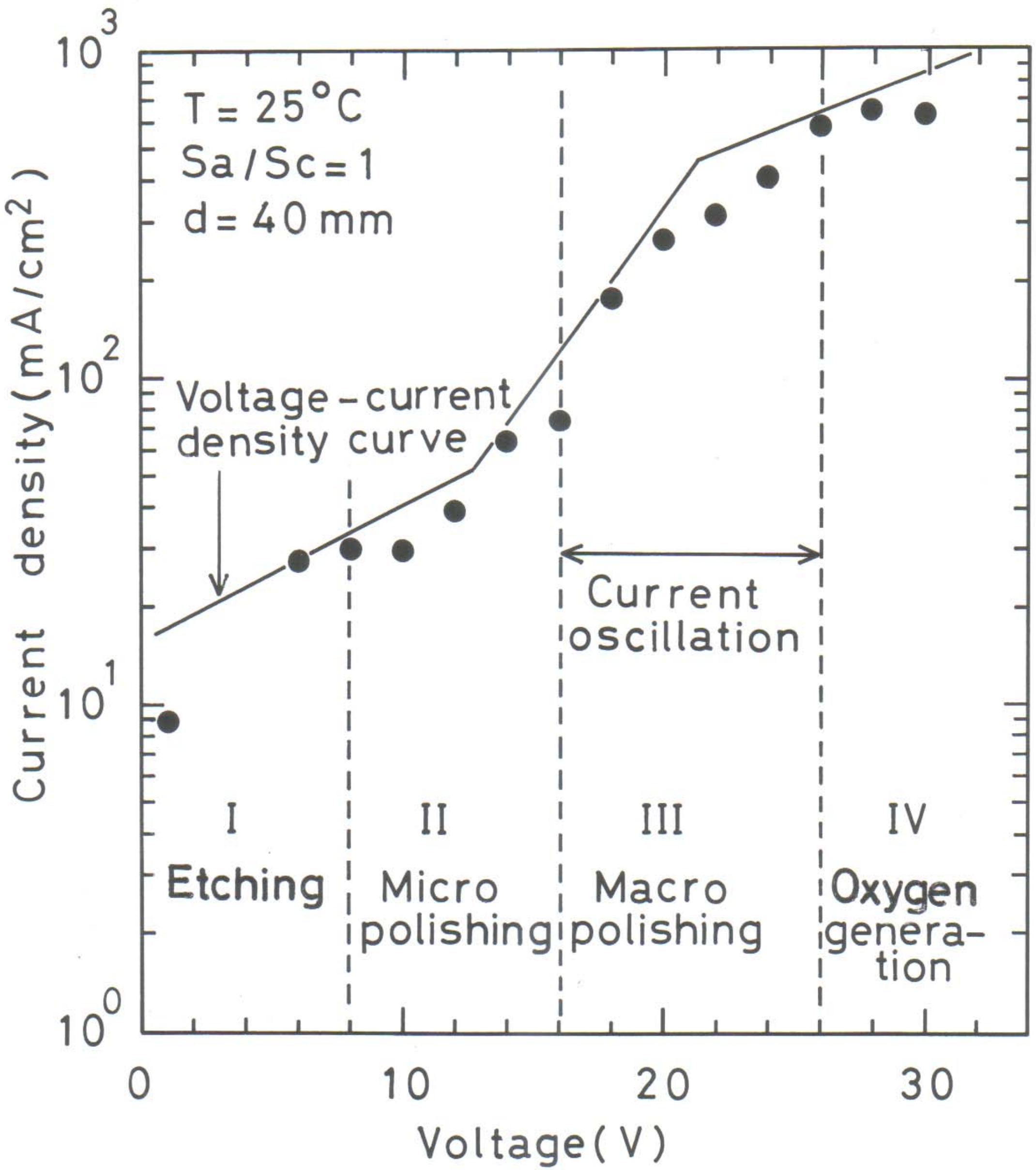
Hydrogen babble trace on Nb surface

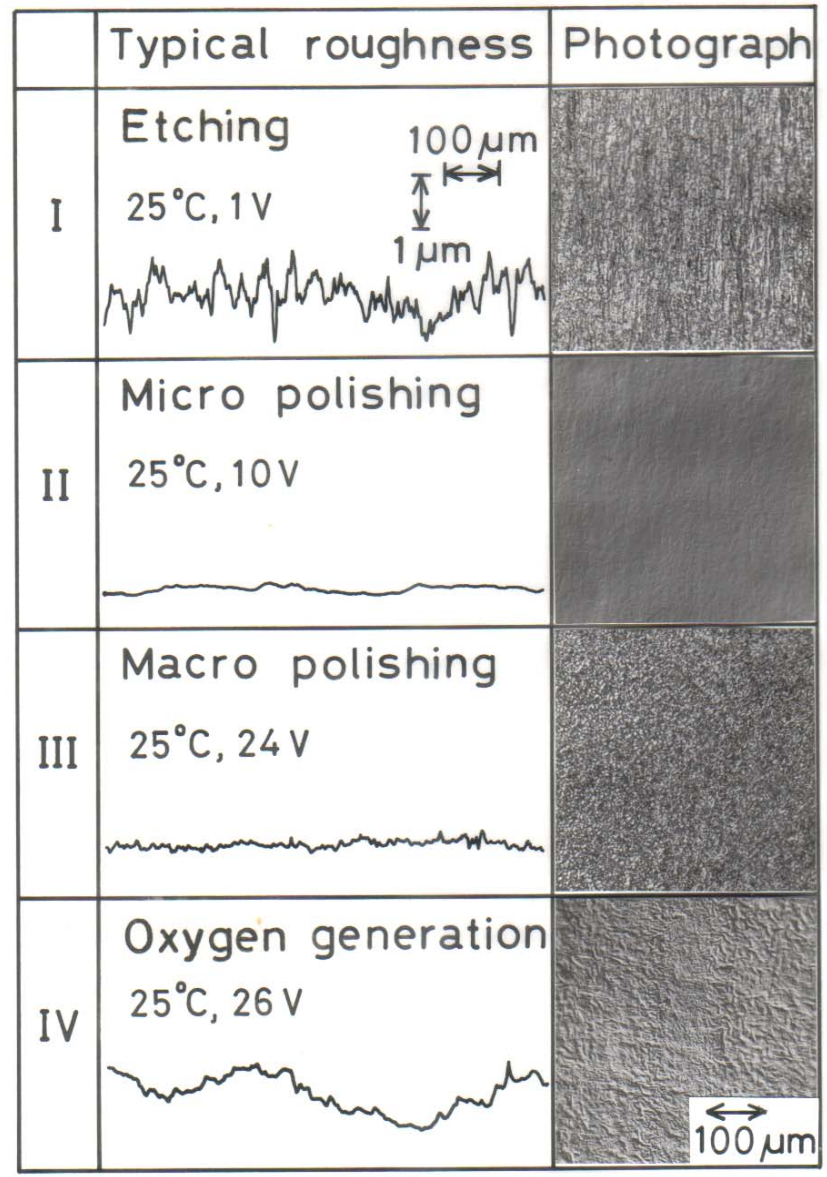


If no cathode bag



Electrolishing Characteristics with Nb



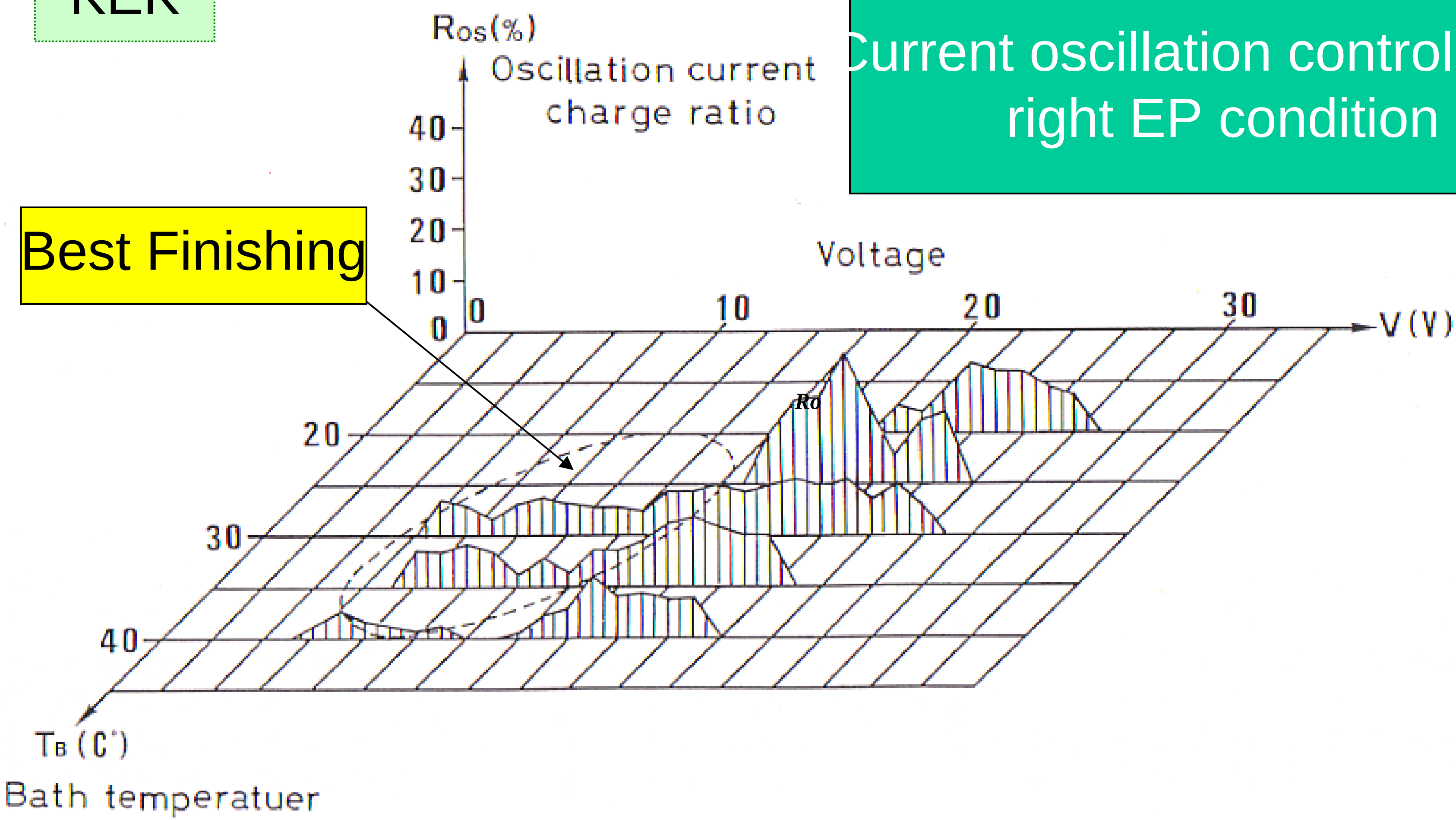


Reconsideration of the Current Oscillation

KEK

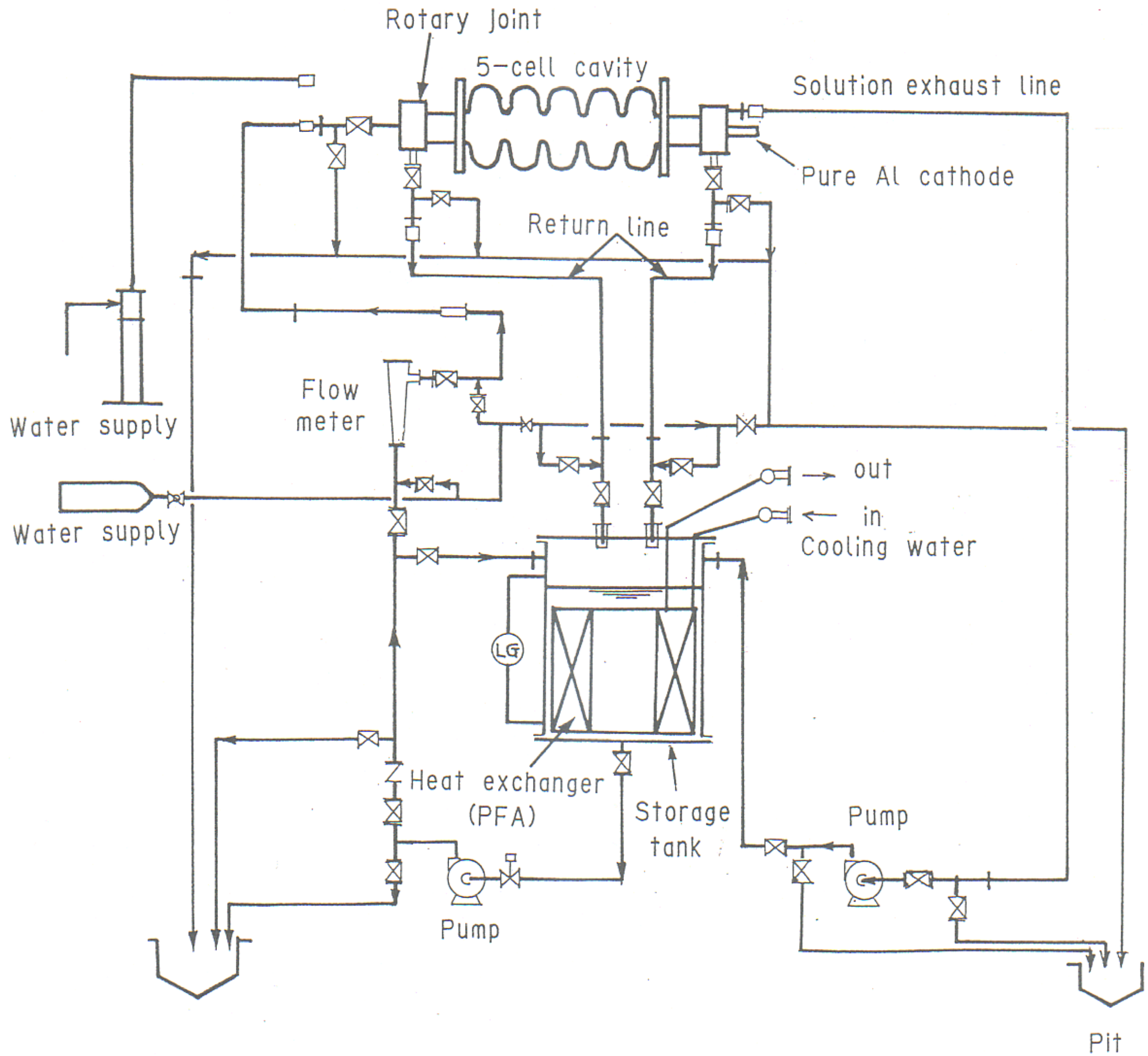
Current oscillation control is not right EP condition

Best Finishing



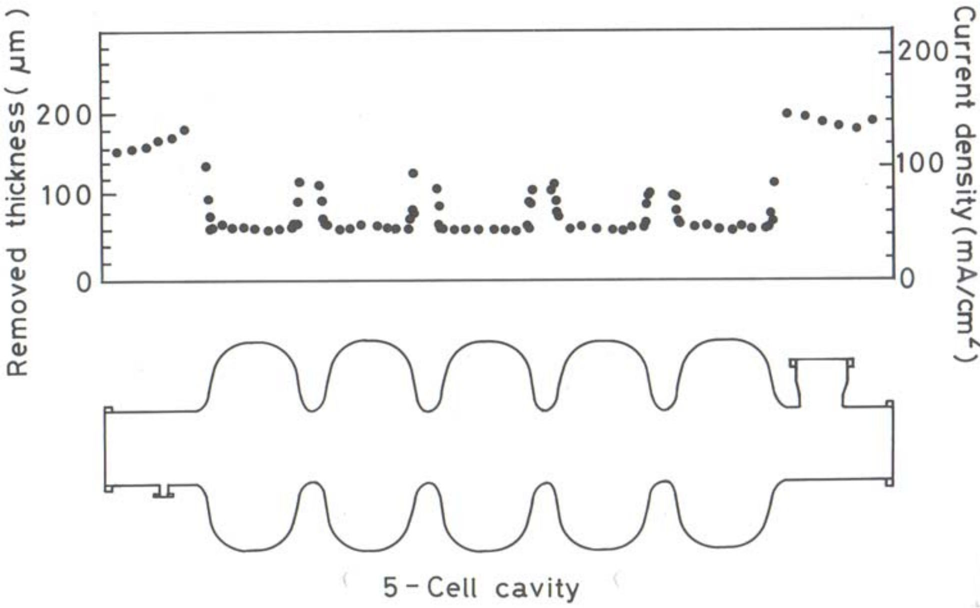
Successfully developed Horizontal EP system

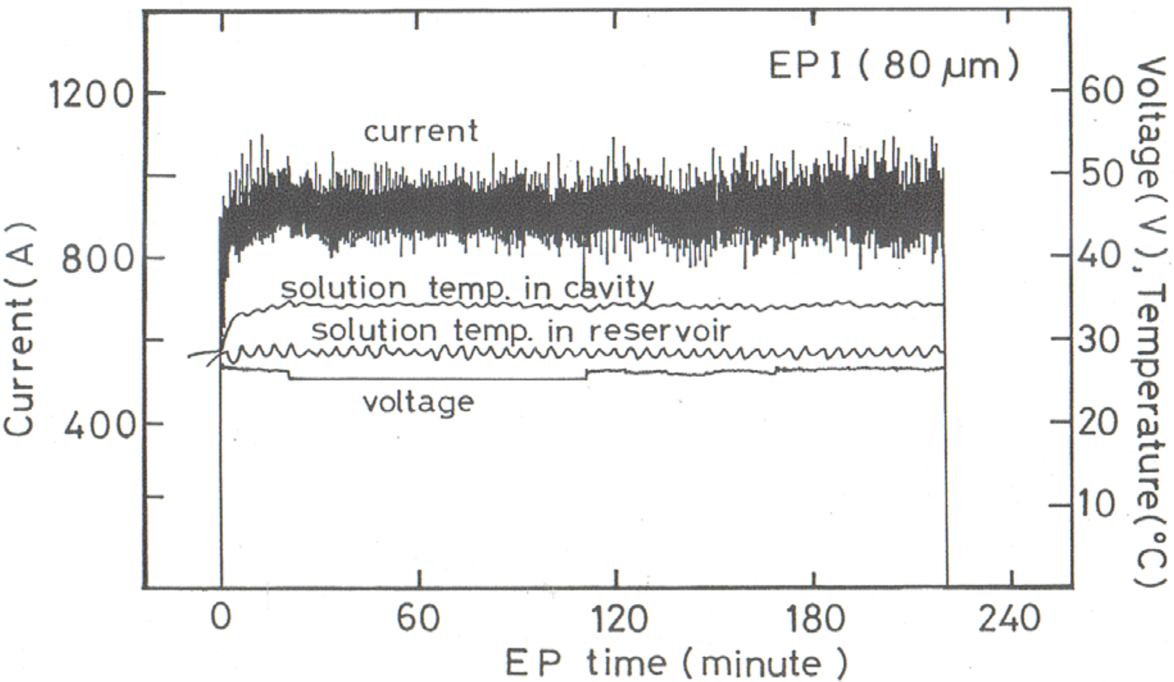
EP System Flow



EP Control

TRISTAN 508MHz 5-cell cavity, Continuously EP





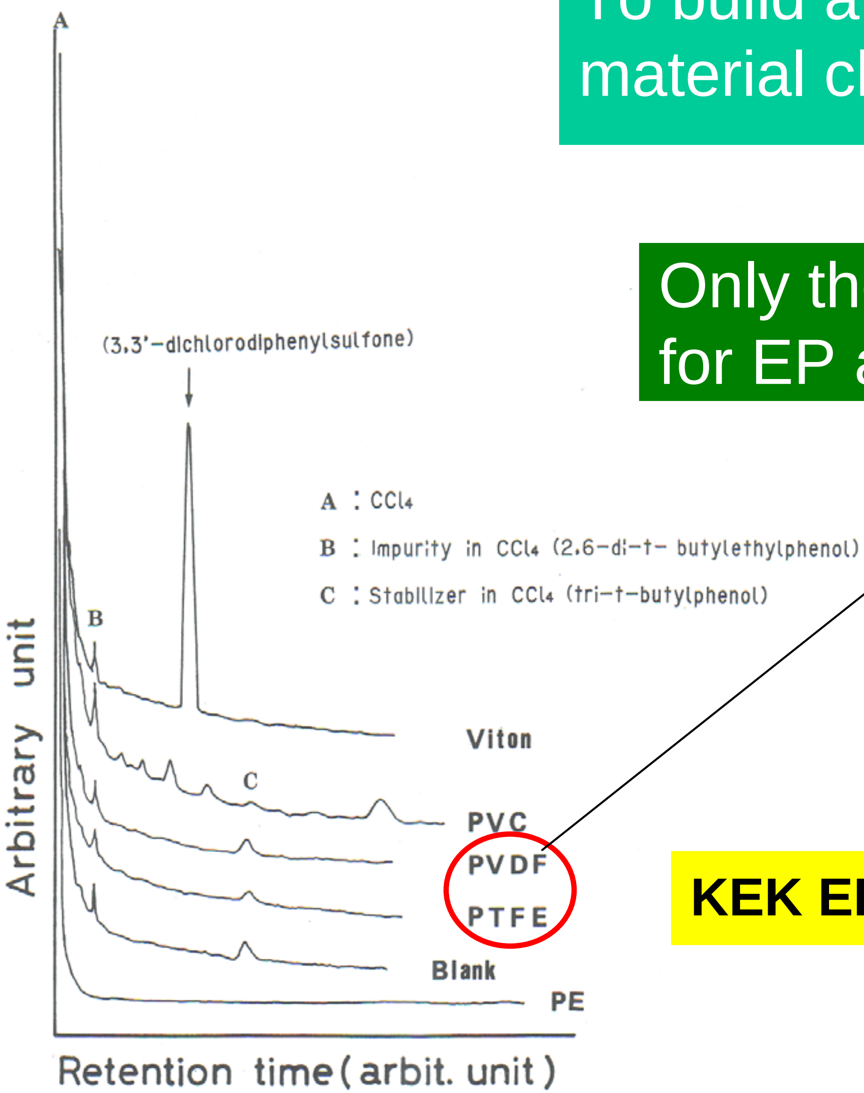
Uniform removal in each cell

Cathode extraction after EP : TRISTAN

Nomura Plating

Material Choice for the Reliable EP System

To build a reliable EP,
material chose in the EP acid line is curta

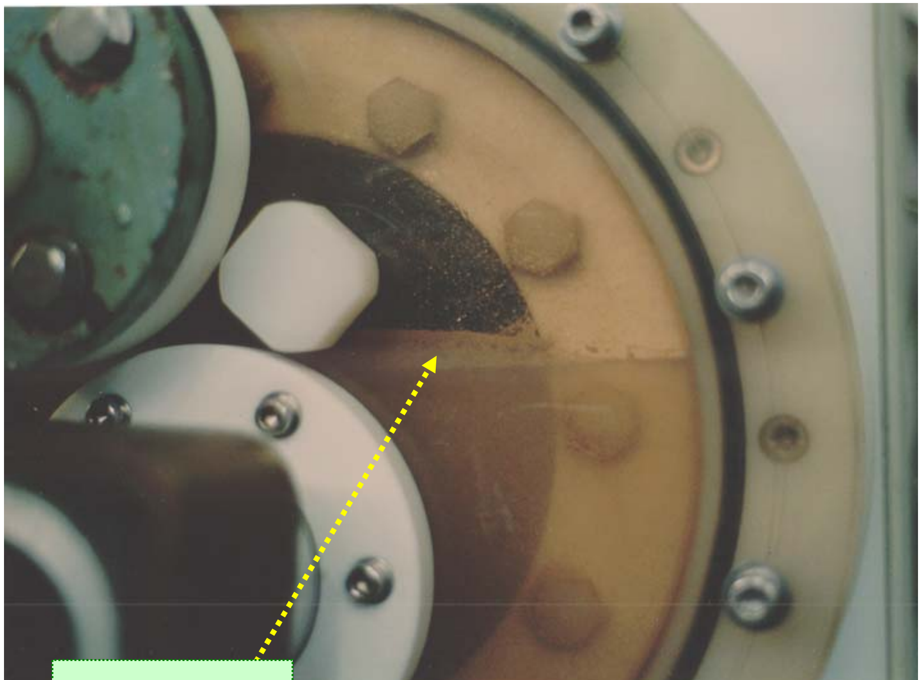


issolved chemicals into EP acid from Plastic Material

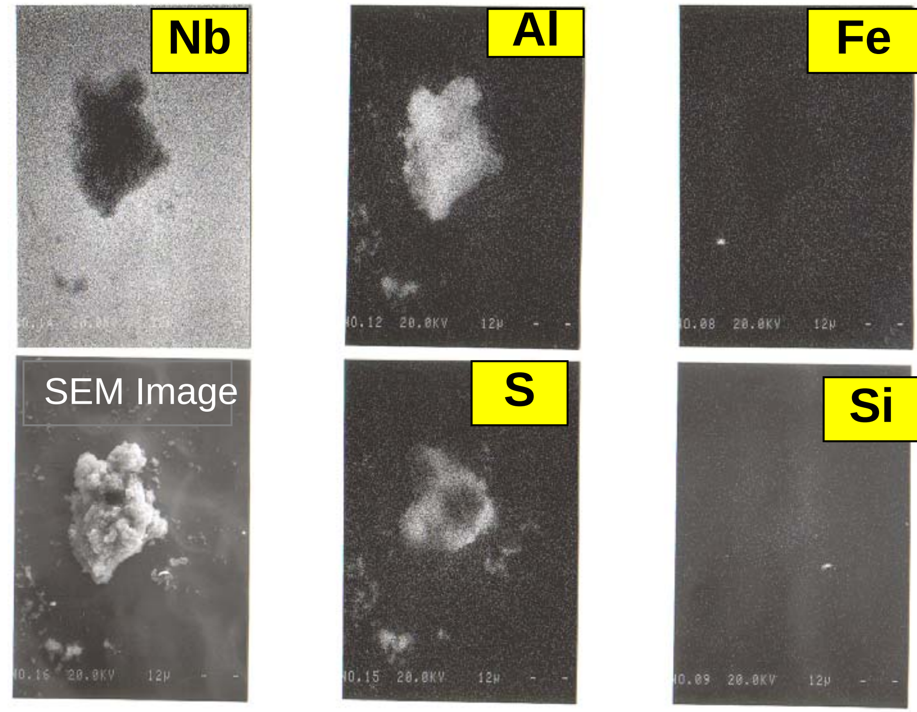
Only the Teflon is the reliable material for EP acid line.

KEK EP system is still working for 20 years.

Contamination Problem from Buffing



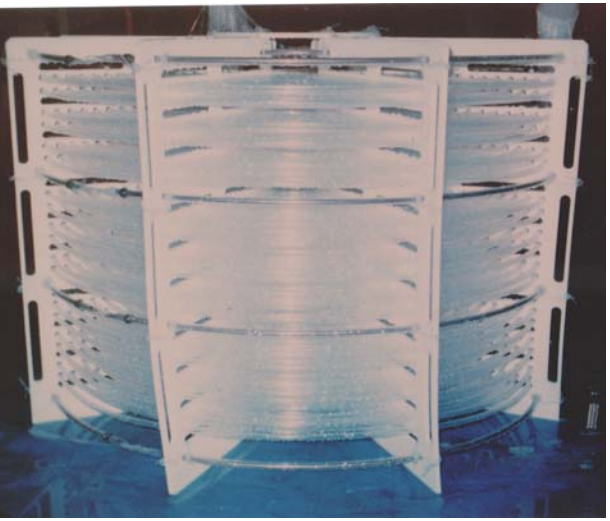
Sulfur



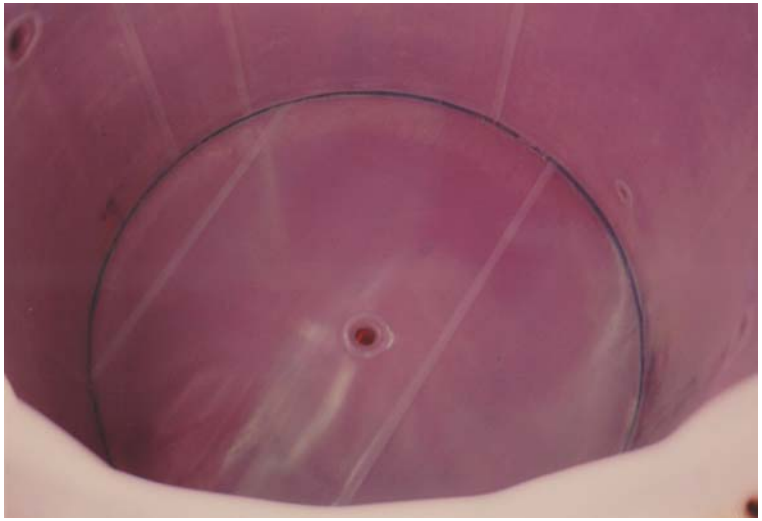
Al, Si, Fe are originated from buffing (TRISTAN)
S is due to decomposition of H_2SO_4 during EP proc

In the early stage of the TRISTAN mass production, these contami
brought heavy field emission on cavity performance.
The EP system was overhauled once. See next slide.

Sulfur Contamination in EP System



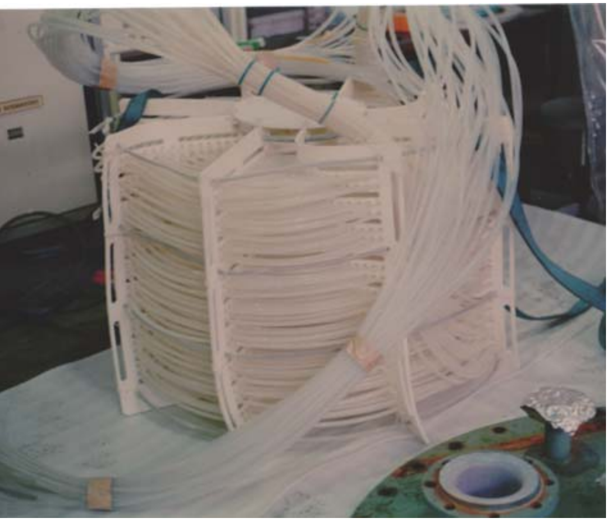
Teflon heat exchanger tube （Brand-new）



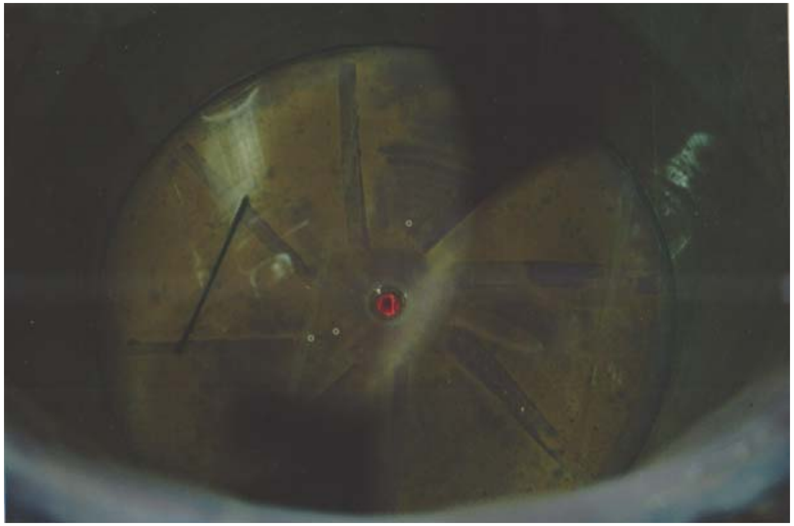
Teflon lining EP acid tank（brand-new）

Reduced H_2SO_4

S precipitated on the contaminants



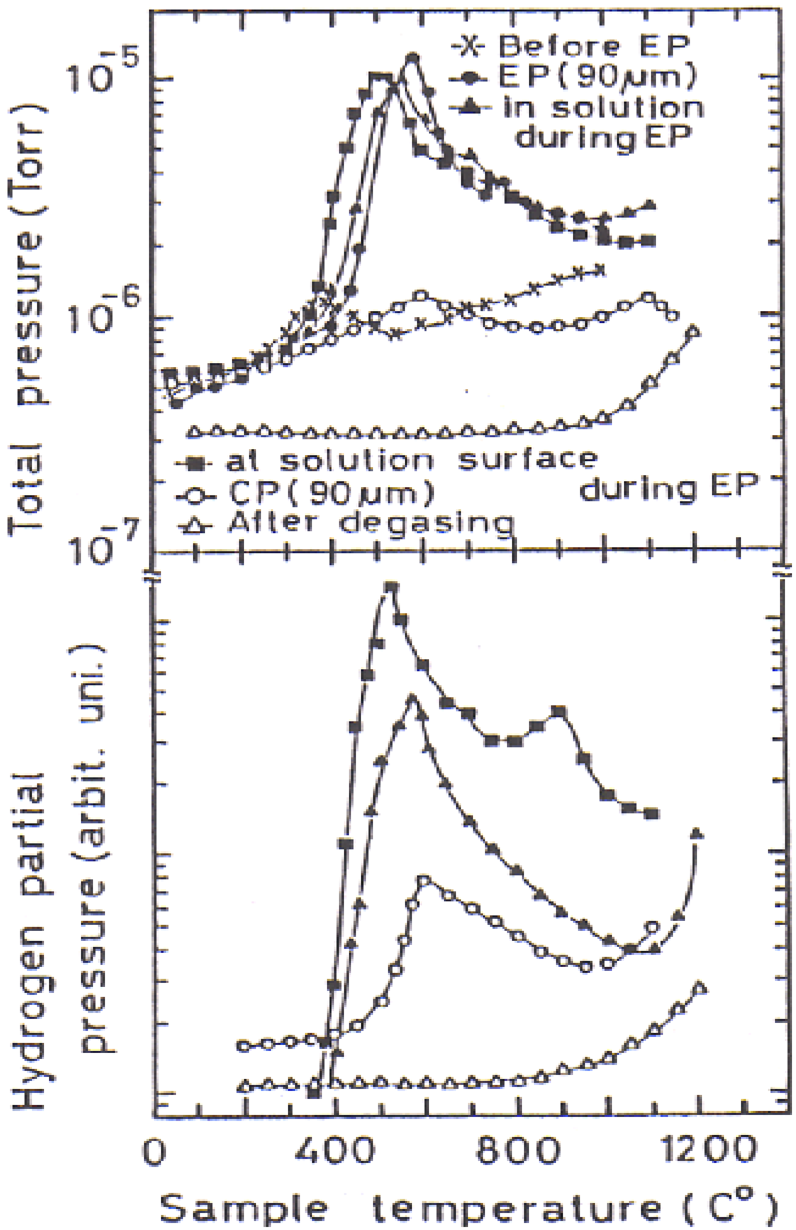
The contaminated heat

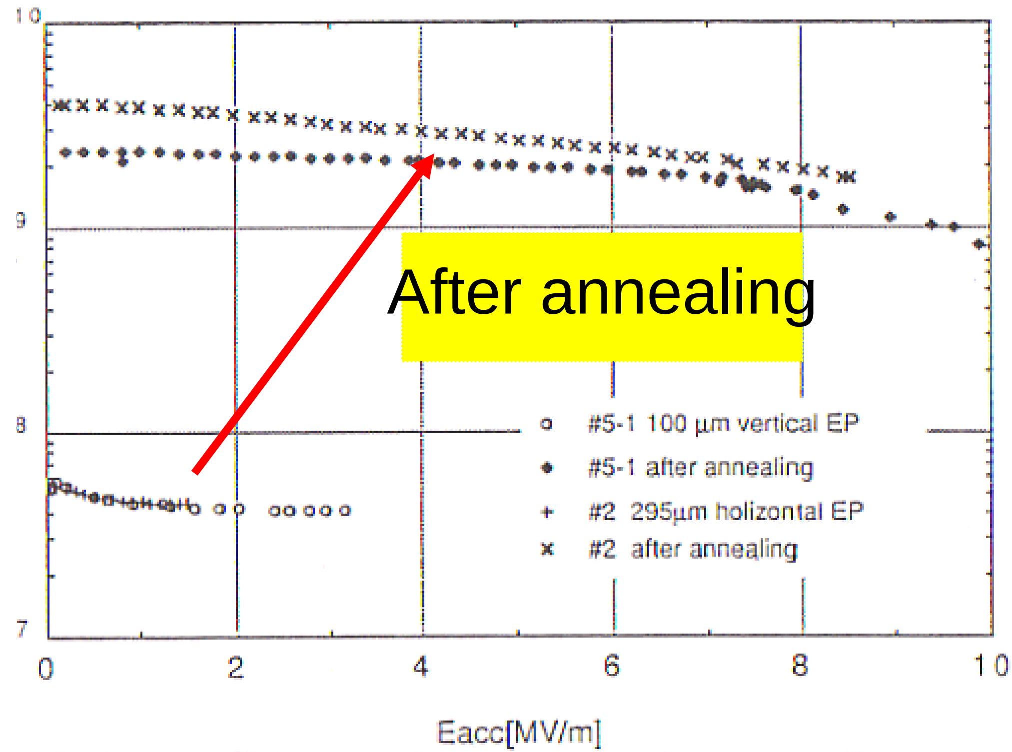


The contaminated EP acid tank

EP system was cleaned up

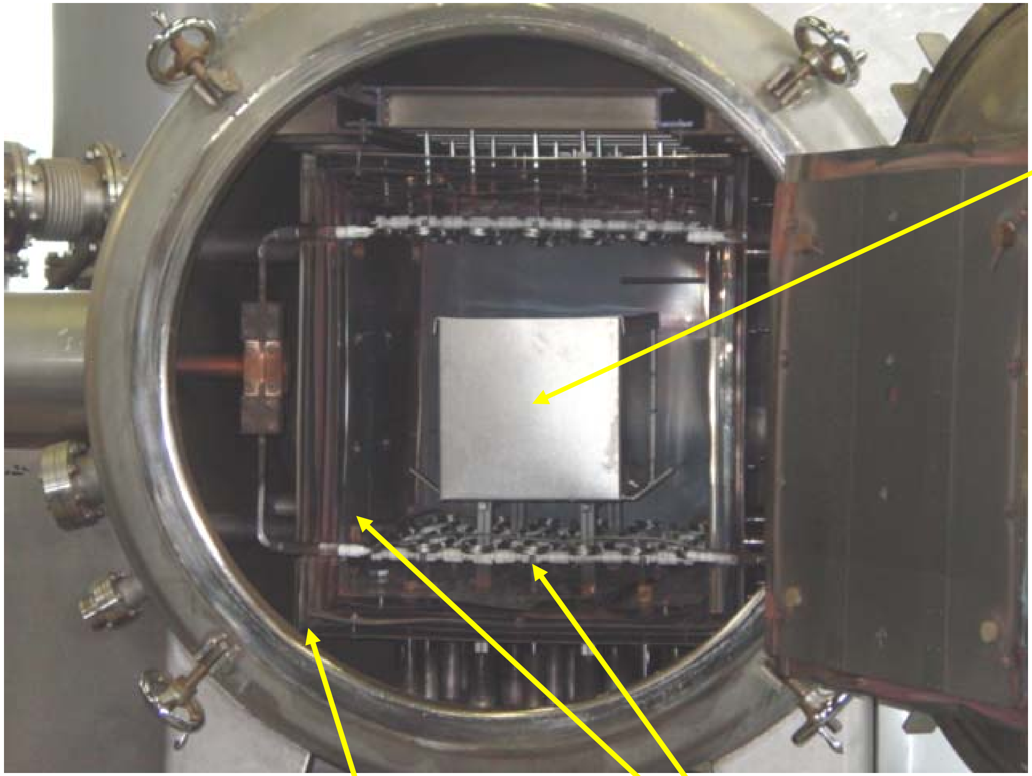
9.4 Annealing





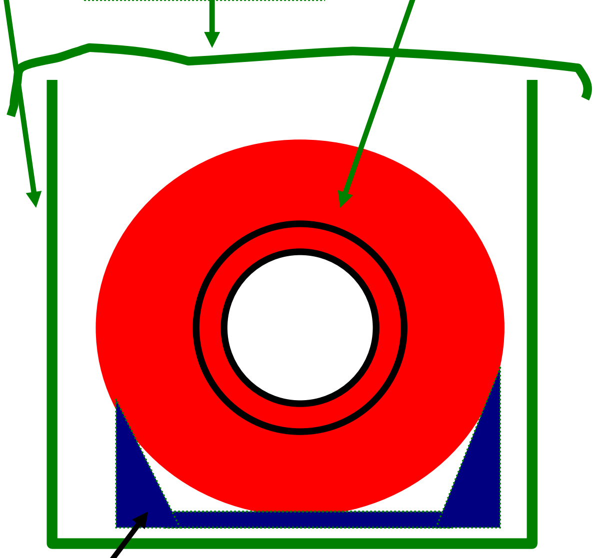
Hydrogen doped in niobium material is easily degassed at 700~800^{O}C.
This temperature dose not soft the niobium material.

Annealing Furnace in KEK Machining Center



KEK Machining Center

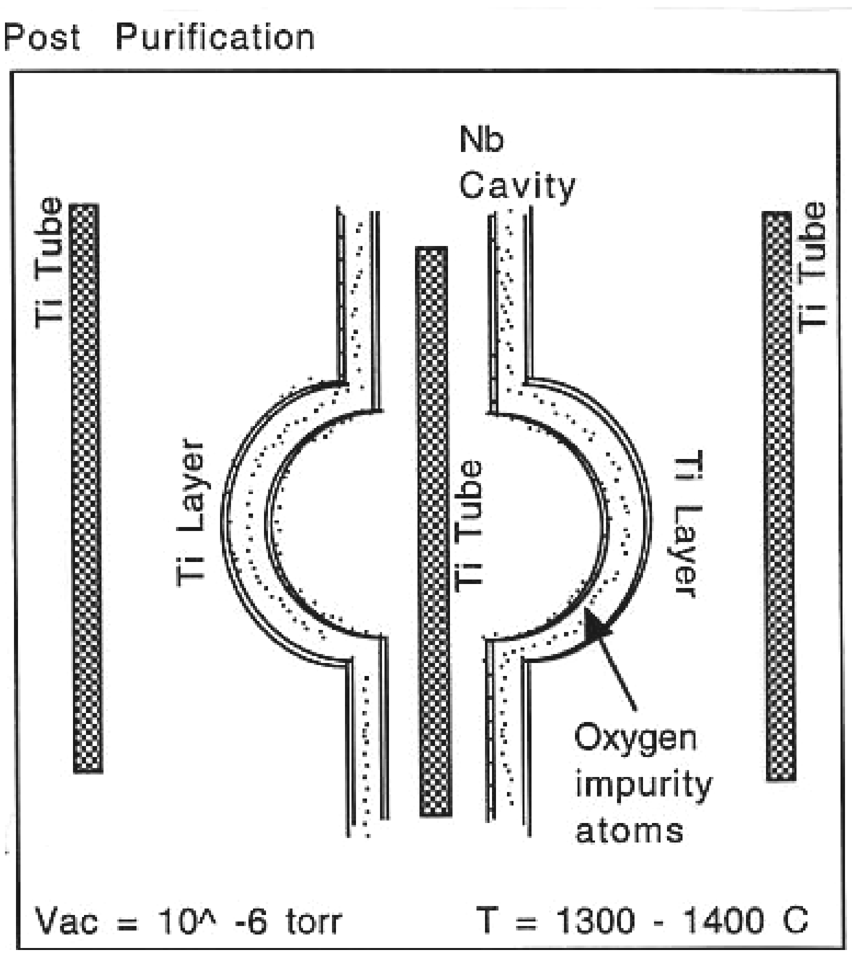
1300^{O}C max, 1X10^{-6} Torr



Large Vacuum furnace for ILC cavity （KEK Machining Center）

Specification：800^{O}C, ~E-6 Torr,
Working zone 500ϕx 3000L

Post Purification (Titanization)



$1400^{O}C$ annealing with Ti @ DESY TTF cavity

Using Titanium getter effect, Oxygen in Nb material can be reduced.

RRR cab be increased by this process.

Problem: Softening of the material

Diffusion Coefficients

$$O: 0.20\exp\left(-\frac{1.354 \cdot 10^4}{T}\right) \ cm^2/sec$$

$$C: 0.043\exp\left(-\frac{1.670 \cdot 10^4}{T}\right) \ cm^2/sec$$

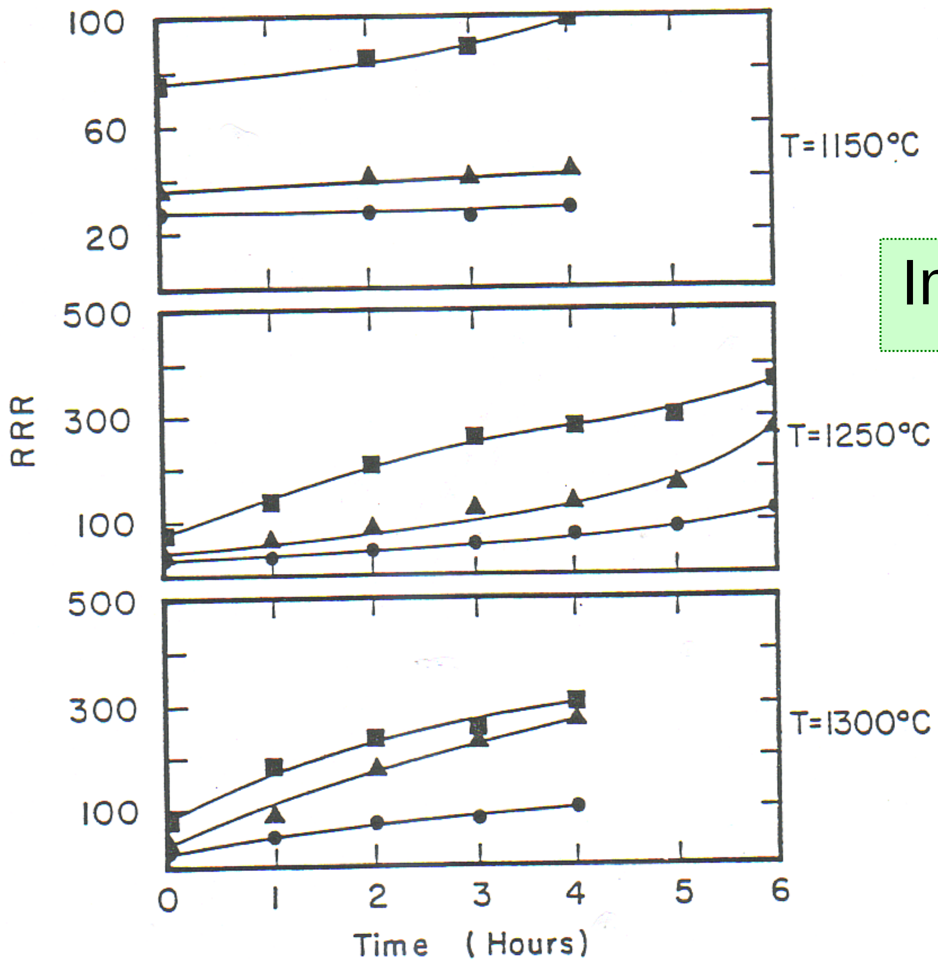
$$N: 0.0085\exp\left(-\frac{1.758 \cdot 10^4}{T}\right) \ cm^2/sec$$

T (^{o}C)	O (mm / hr)	N (mm / hr)	C (mm / hr)
900	0.4	0.005	0.005
1000	0.6	0.008	0.008
1100	0.9	0.13	0.13
1200	1.2	0.19	0.19
1400	2.0	0.38	0.38

RRR Improvement by Post Purification

P.Kneisel

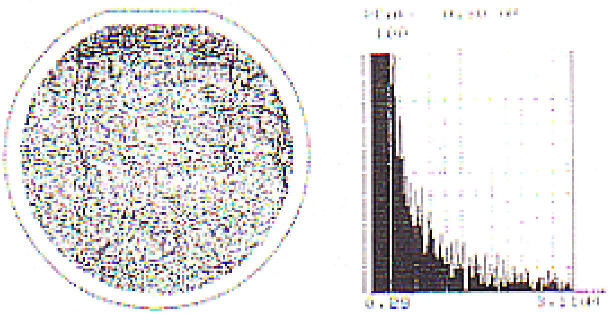
Improved by a factor 3



Dependence of the RRR-value on reaction temperature and reaction time for niobium samples of different purity exposed to titanium vapor (● 1/8" thick, RRR=27; ▲ 1/8" thick, RRR=37; ■ 1/16" thick, RRR=77)

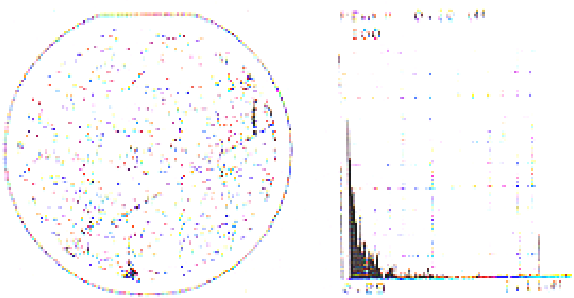
9.5 High Pressure Water Rinsing (HPR)

TRISTAN rinsing method

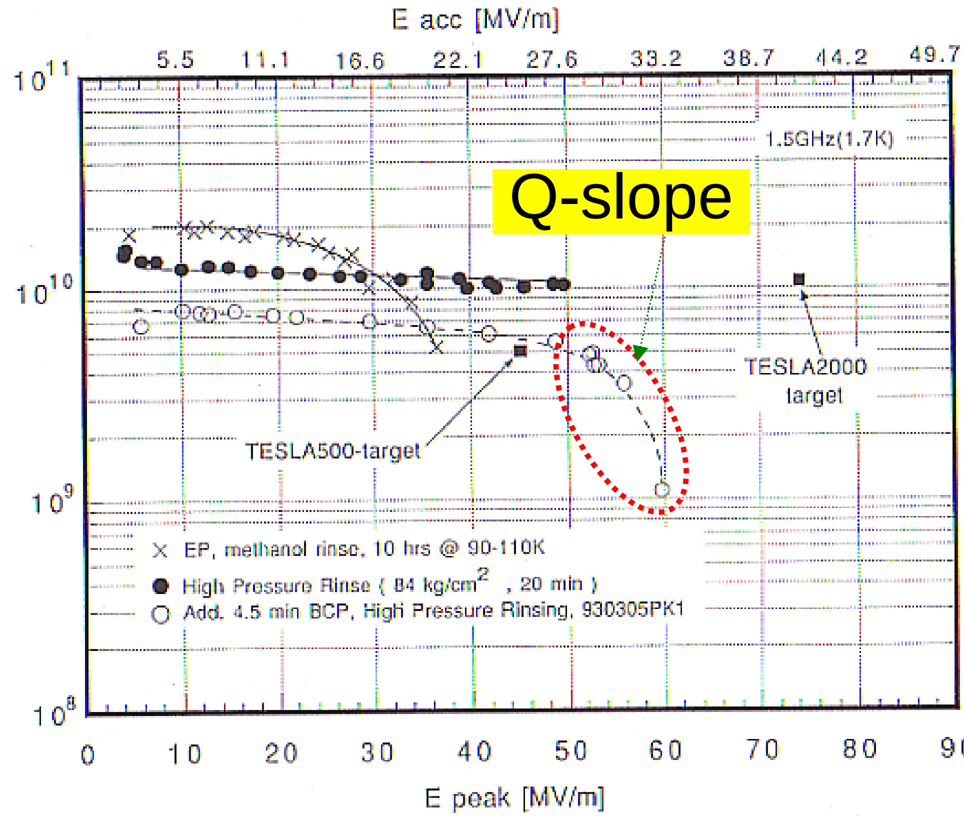


Particle size	Count
0.30-1.20 μm	5825
1.20-2.01 μm	405
2.01-3.00 μm	2720
> 3.00 μm	1069
Total	10019

HPR rinsing

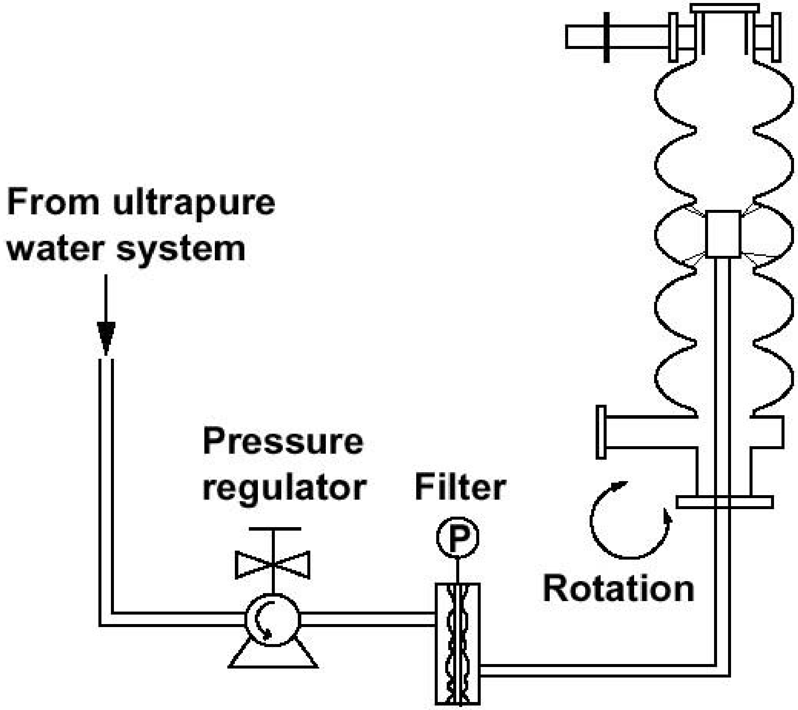


Particle size	Count
0.30-1.20 μm	646
1.20-2.01 μm	52
2.01-3.00 μm	282
> 3.00 μm	37
Total	1017



HPR is a very powerful tool to remove the particle contamination on niobium cavities.

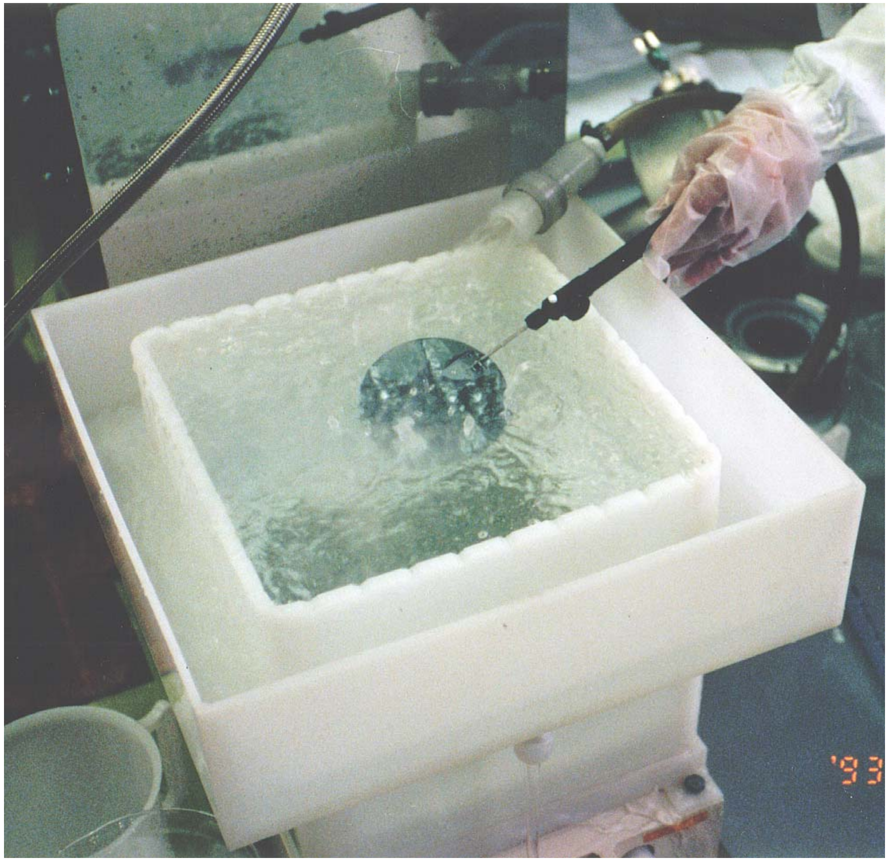
HPR System at KEK/Nomura Plating



Nomura Plating

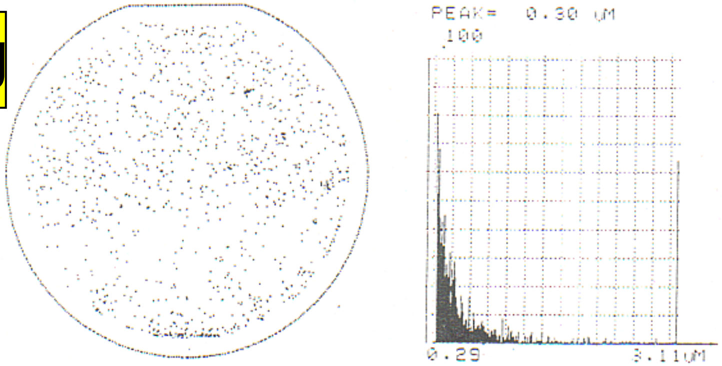
9.6 Megasonic Rinsing

An atractve rinsing method if compact oscillator can be product.



Megasonic Rinsing Effect

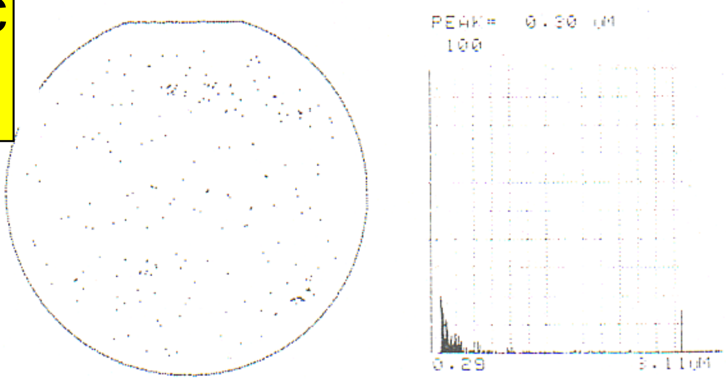
HPR rinsing



Particle size	Count
0.30-1.20 µm	673
1.20-2.01 µm	50
2.01-3.00 µm	305
> 3.00 µm	90
Total	1118

Fig. 11 Residual particles on a wafer surface after HPR; rinsing condition 19 in Table 1

Mega-sonic rinsing



Particle size	Count
0.30-1.20 µm	158
1.20-2.01 µm	5
2.01-3.00 µm	43
> 3.00 µm	18
Total	224

Fig. 12 Residual particles on a wafer surface after megasonic rinsing; rinsing condition 16 in Table 1.

Amount of particle Contamination is reduced to 1/5 of HP

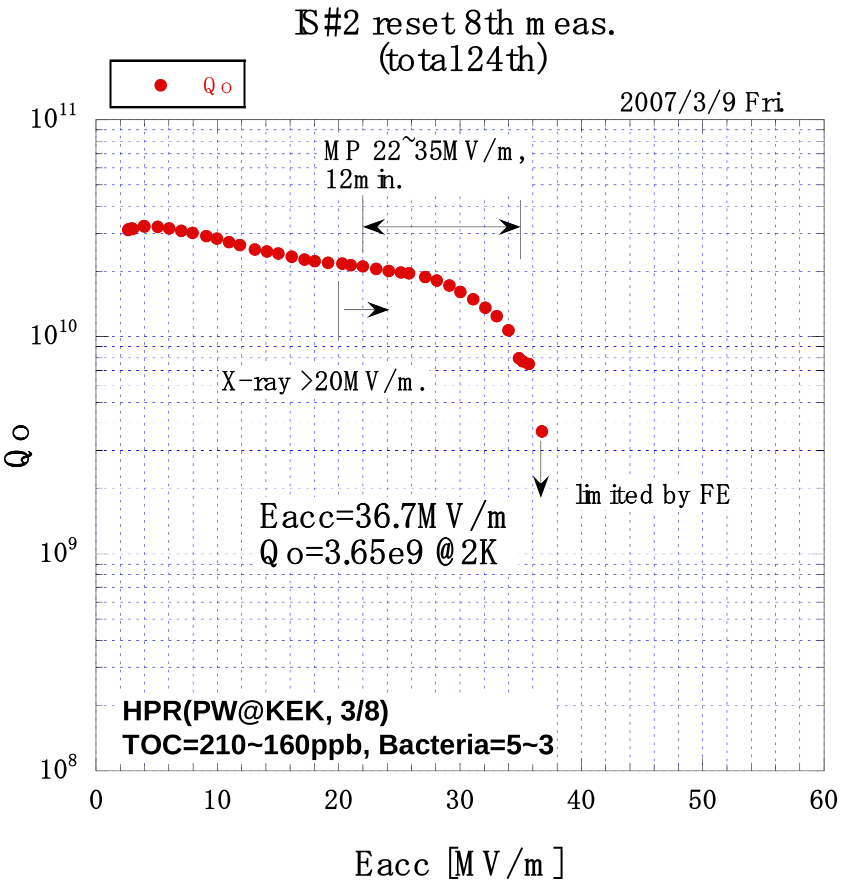
Megasonic rinsing can be an alternative of HPR ?

KEK will start investigation of Megasonic.

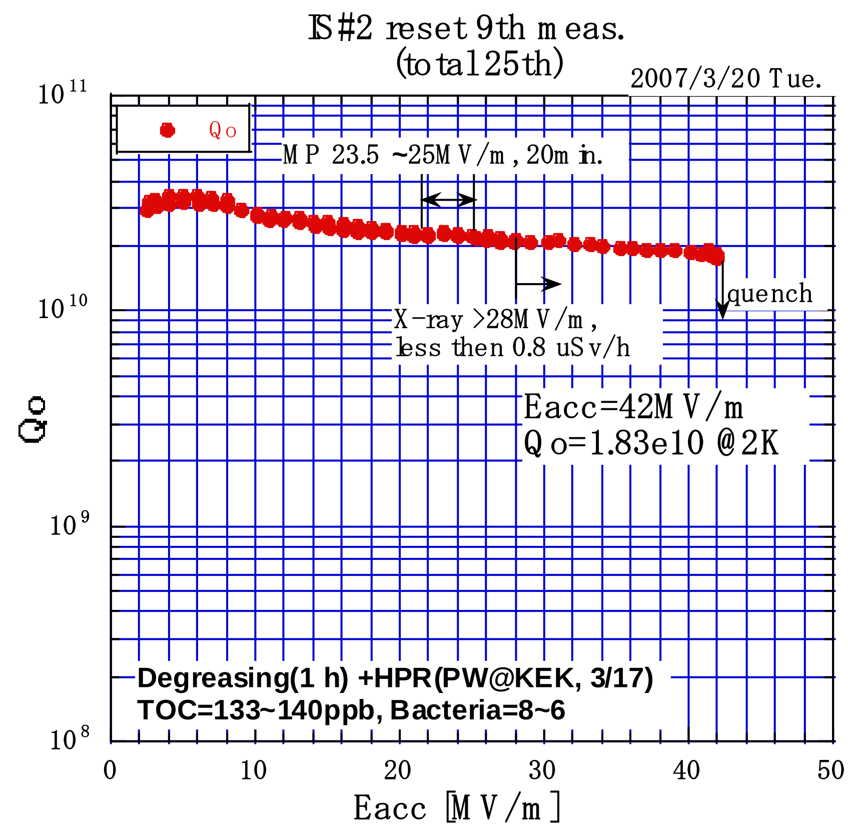
9.7 Degreasing after EP

Developed @ JLAB, J.Mammosser

Additional HPR @KEK



Additional Degreasing + HPR@KEK

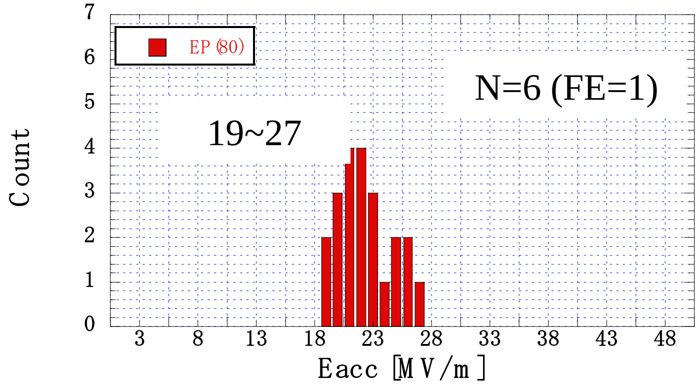


(Use Japanese degreaser)

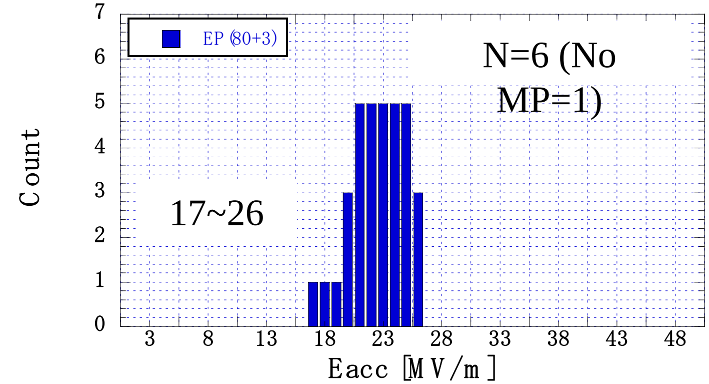
Degreasing is very much effective to eliminate contamination !

Multipacting

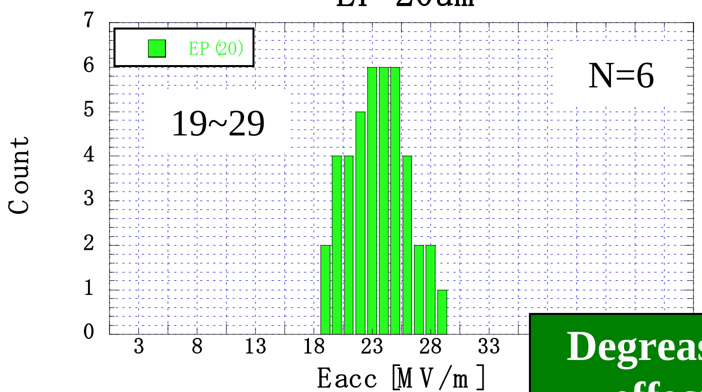
EP 80um



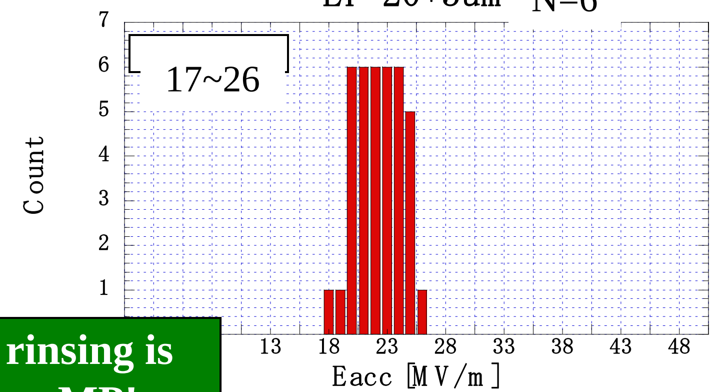
EP 80+3um



EP 20um

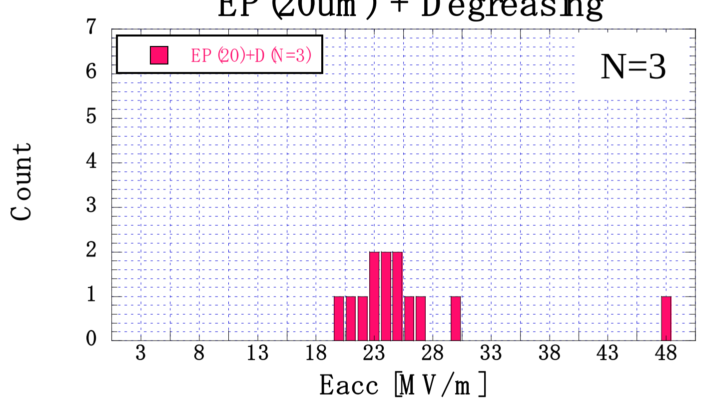


EP 20+3um N=6

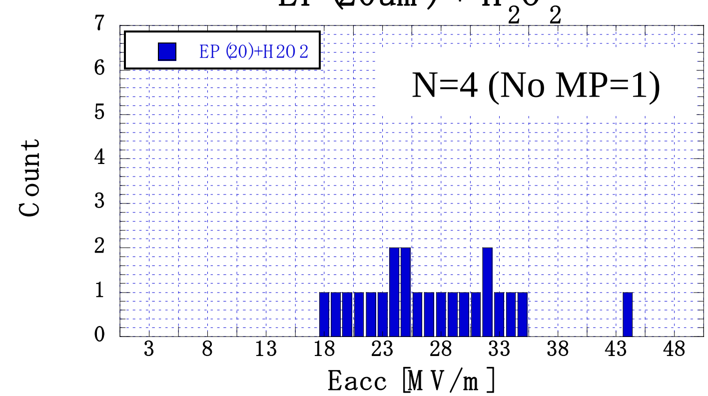


Degreasing or H_2O_2 rinsing is effective to suppress MP!

EP (20um) + Degreasing



EP (20um) + H_2O_2

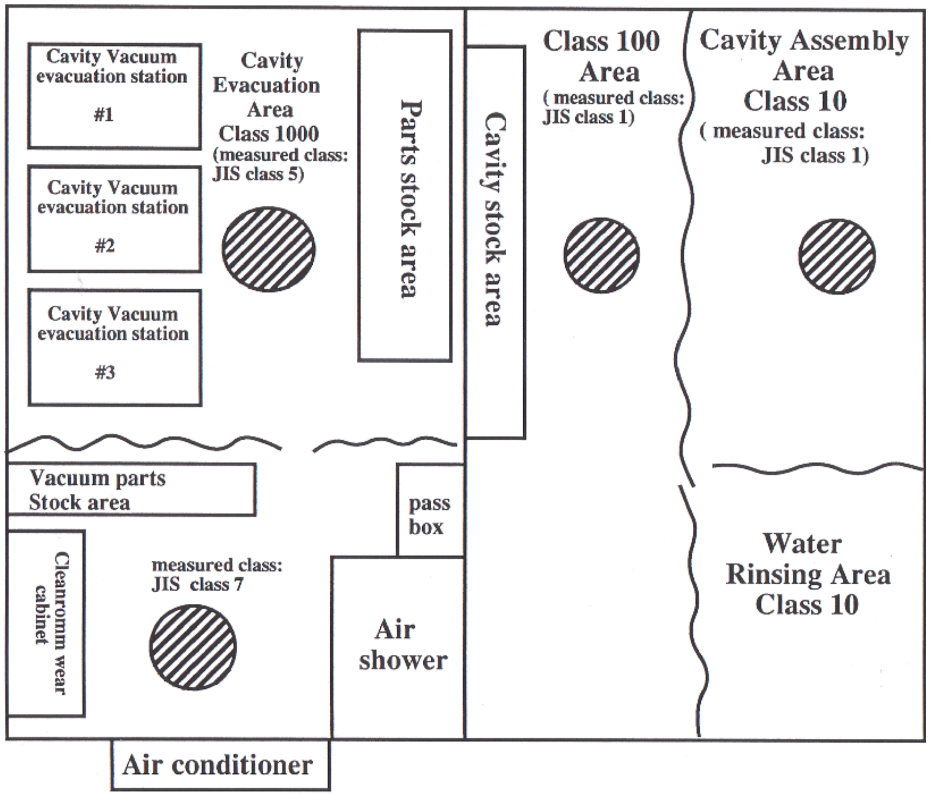


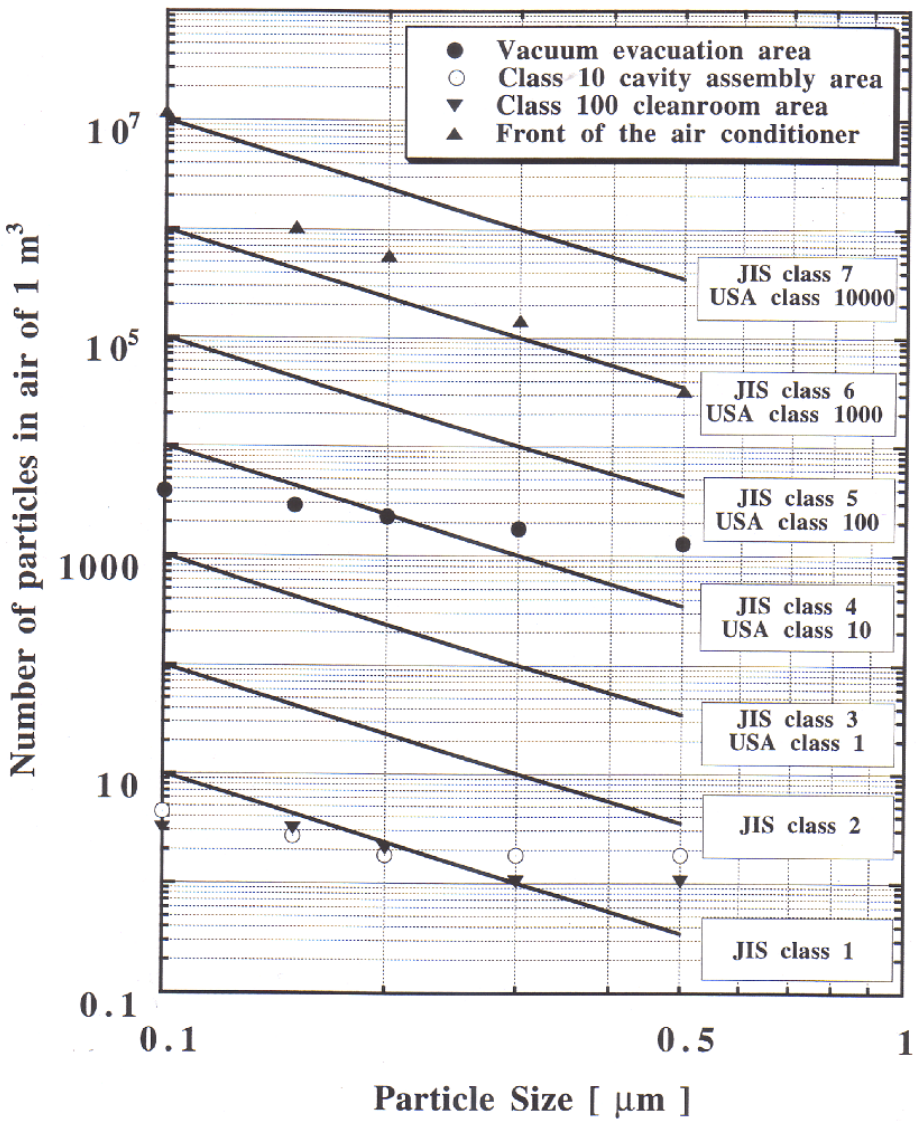
9.8 Cleanroom Technology

HEPA filter (class 100)

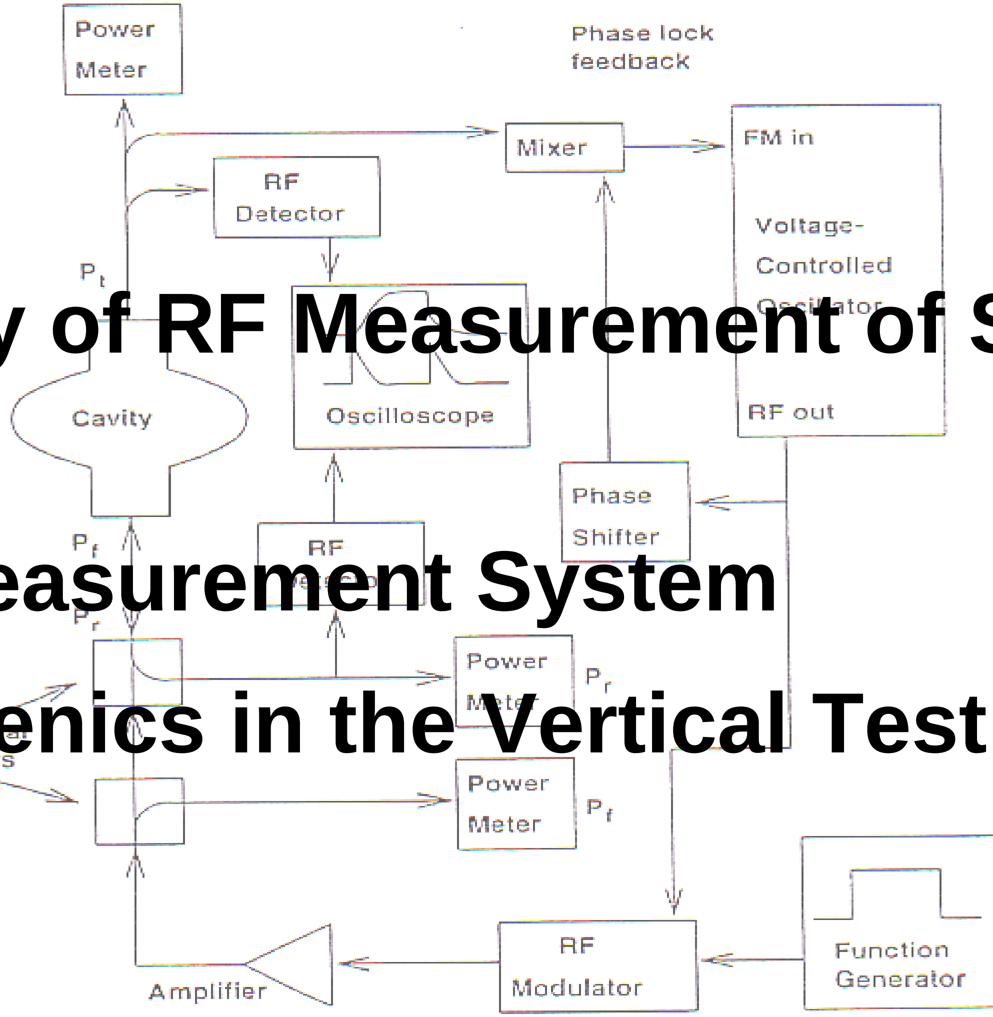
ULPA filter (class 10)

Cleanliness





10. Performance Evaluation

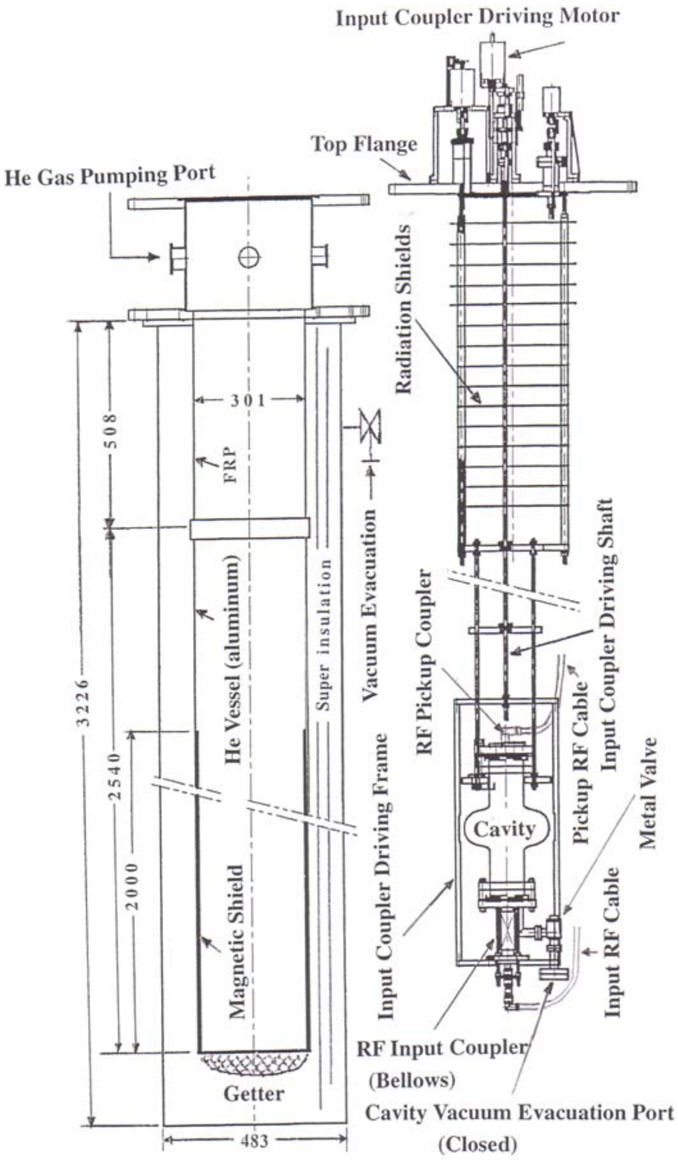


10.1 Theory of RF Measurement of SRF Cavities

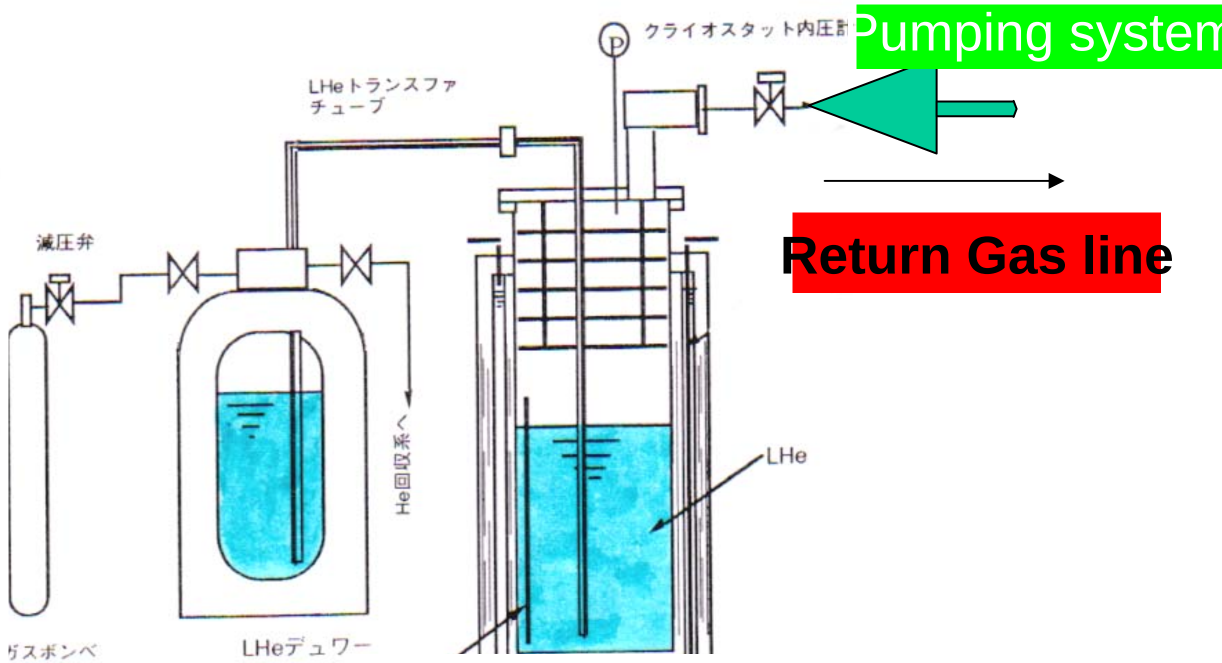
10.2 RF Measurement System

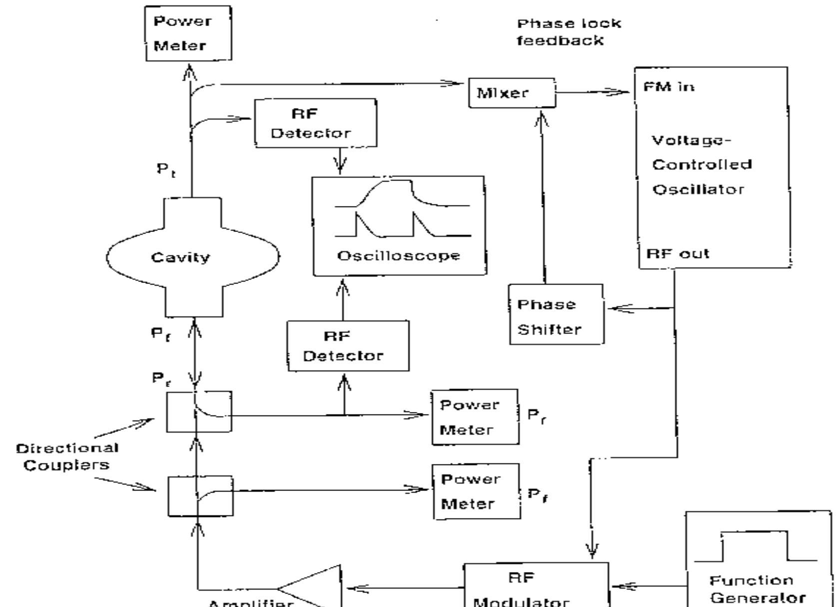
10.3 Cryogenics in the Vertical Test

SRF Cavity Measurement System

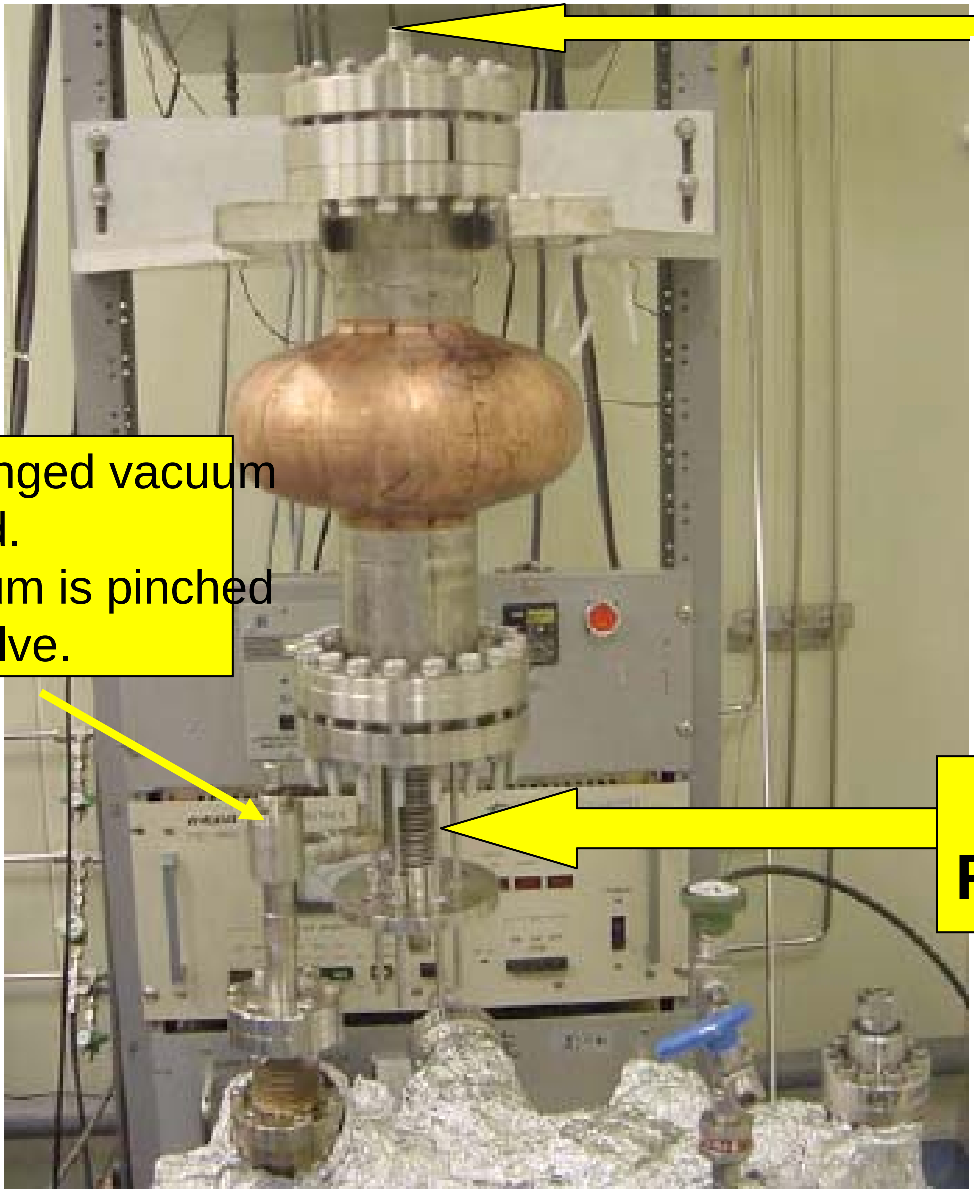


Vertical Cryostat Vertical Test Stand





SRF Cavity (Nb/Cu clad cavity)

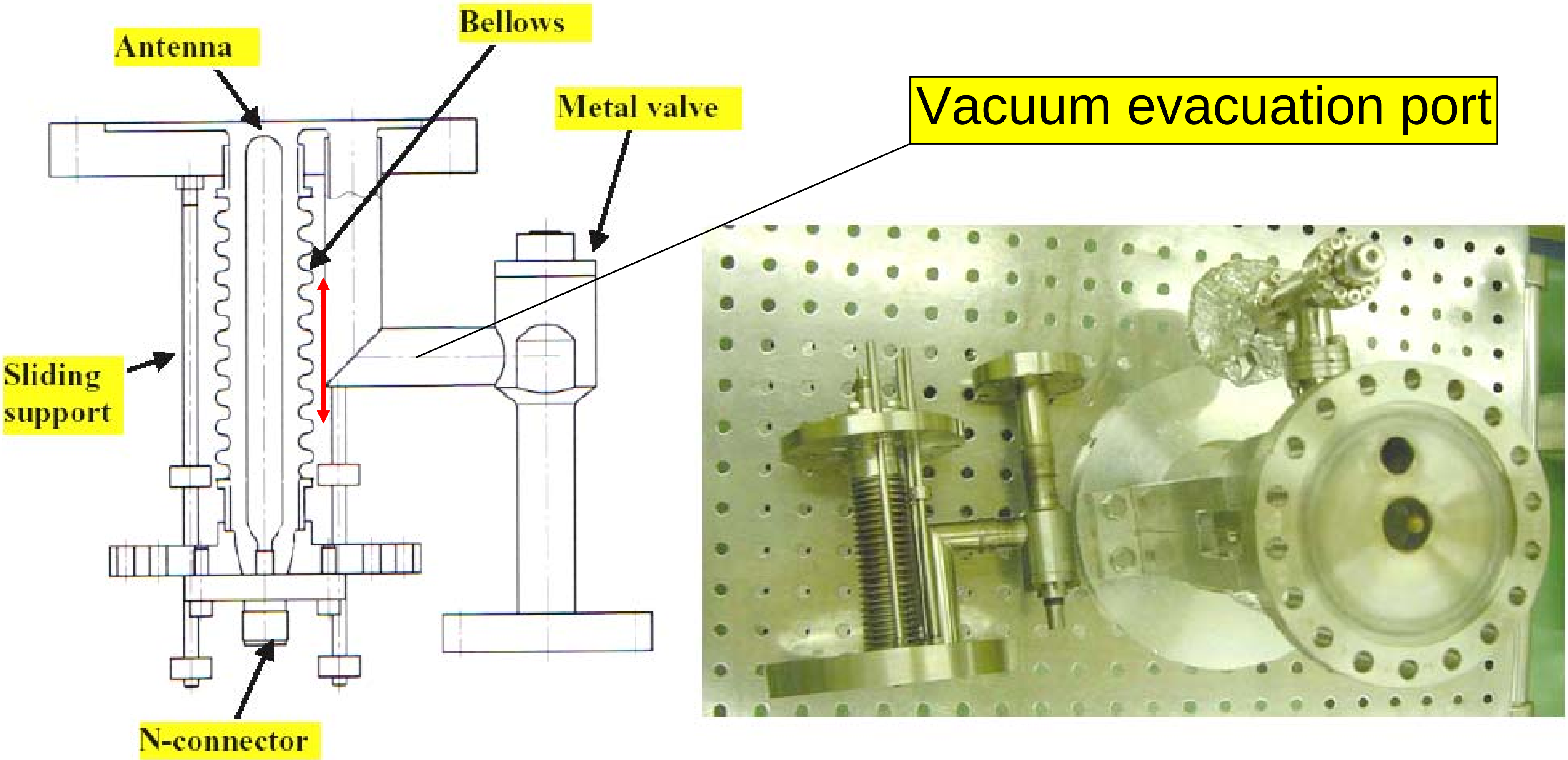


Pickup coupler

A SRF cavity hanged vacuum evacuation stand.
The cavity vacuum is pinched off by a metal valve.

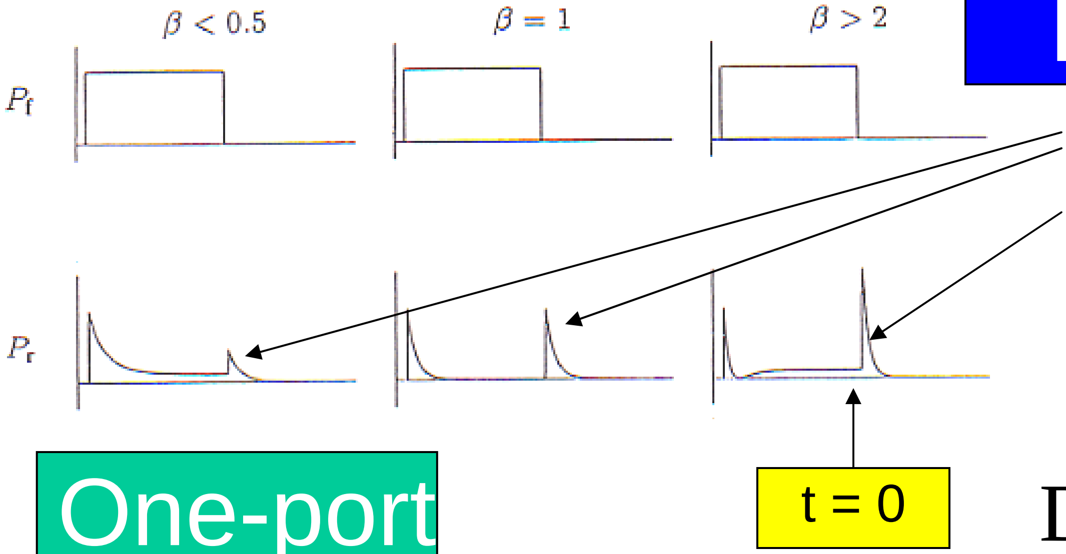
Variable RF Input coupler

Structure of the Variable RF Input Coupler



Variable input coupler for the vertical test in KEK

Theory of Measurement

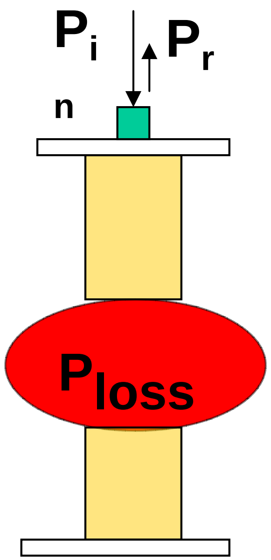


Pulse method

$$P_t(t) = P_o \exp(-\frac{\omega}{Q_L} t)$$

$\omega = 2\pi f$, Q_L : Loaded Q

One-port



Decatime : $\tau_{1/2}$

$$P_t(\tau_{1/2}) = \frac{1}{2} P_o = P_o \exp(-\frac{\omega}{Q_L} \cdot \tau_{1/2})$$

$$\ln(2) = \frac{2\pi f}{Q_L} \tau_{1/2}$$

$$Q_L = 2\pi f \cdot \frac{\tau_{1/2}}{\ln(2)}$$

One-Port Cavity

$$Q_O \equiv \frac{\omega U}{P_{loss}},$$

$$Q_L \equiv \frac{\omega U}{P_{loss} + P_e} = \frac{\omega U}{P_{loss}\left(1 + \frac{P_e}{P_{loss}}\right)}$$ (for one port)

$$= \frac{Q_O}{(1+\beta_{in})}$$

$$Q_O = (1+\beta_{in}) \cdot Q_L$$

$\tau_{1/2}$, P_{in}, P_r } Measurement

Calculation Q_L, β_{in}

Equivalent Circuit model

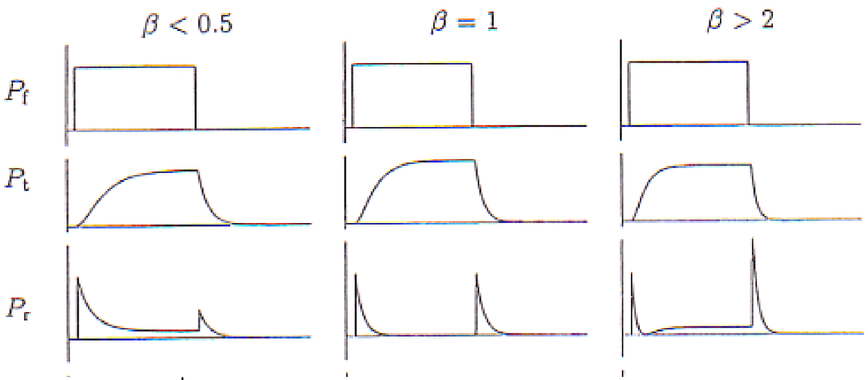
Judgment from Pr

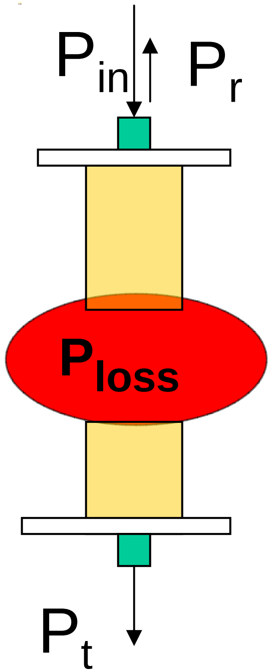
$$\beta_{in} \equiv \frac{P_e}{P_{loss}} = \frac{1 \pm \sqrt{P_r / P_{in}}}{1 \mp \sqrt{P_r / P_{in}}}$$ (over > 1/ under < 1)

Calculation Qo

$$R_s = \frac{\Gamma}{Q_o}$$

Two-Port Cavity





$$P^*_{loss} = P_{loss} + P_t$$

$$Q^*_o = \frac{\omega U}{P^*_{loss}} = \frac{\omega U}{P_{loss} + P_t}$$

$$= \frac{\omega U}{P_{loss}\left(1 + \frac{P_t}{P_{loss}}\right)}$$

measurement

$$= \frac{Q_o}{(1+\beta_t)} \quad \because \beta_t \equiv \frac{P_t}{P_{loss}}$$

$$= (1+\beta^*_{in})Q_L$$

measurement

$$\beta^*_{in} = \frac{1 \pm \sqrt{P_r / P_{in}}}{1 \mp \sqrt{P_r / P_{in}}} \quad \text{(over > 1/ under < 1)}$$

$$Q_o^* = \frac{Q_o}{(1+\beta_t)} = (1+\beta_{in}^*)\cdot Q_L$$

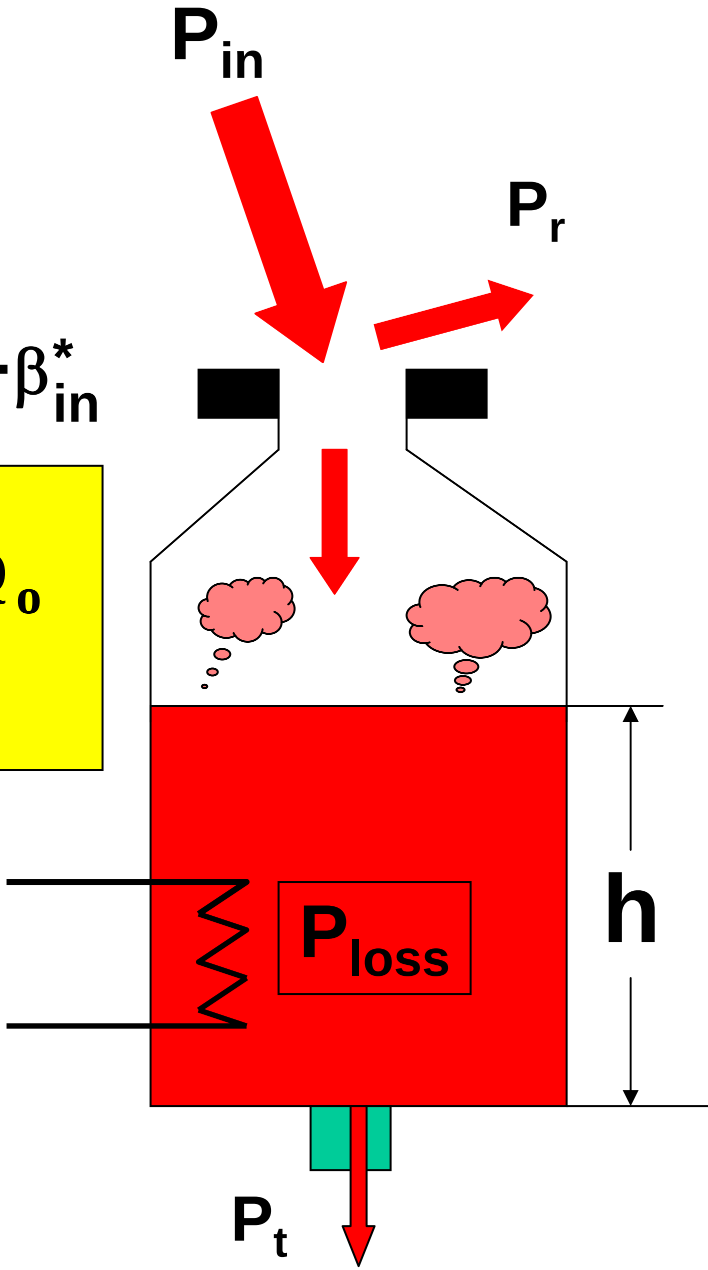
$$Q_o = (1+\beta_{in}^*)\cdot(1+\beta_t)\cdot Q_L$$
$$= \left[1+(1+\beta_t)\cdot\beta_{in}^* + \beta_t\right]\cdot Q_L$$
$$= (1+\beta_{in}+\beta_t)\cdot Q_L \quad \because\ \beta_{in} \equiv (1+\beta_t)\cdot\beta_{in}^*$$

$$Q_o \equiv \frac{\omega U}{P_{loss}},\ Q_t \equiv \frac{\omega U}{P_t} = \frac{\omega U / P_{loss}}{P_t / P_{loss}} = \beta_t \cdot Q_o$$

$$\omega U = Q_o \cdot P_{loss} = Q_t \cdot P_t$$

$$P_{loss} = P_{in} - P_r - P_t$$

Stationary state : h = constU const



Calculation of Gradient

$$R_{sh} = \frac{V^2}{P_{loss}} \quad \because \; V = E_{acc} \cdot d_{eff}$$

$$= \frac{(Eacc \cdot d_{eff})^2}{P_{loss}}$$

$$Eacc = \frac{1}{d_{eff}} \cdot \sqrt{R_{sh} \cdot P_{loss}} = \frac{\sqrt{R_{sh} / Q_O}}{d_{eff}} \cdot \sqrt{Q_O \cdot P_{loss}} = Z \cdot \sqrt{Q_O \cdot P_{loss}}$$

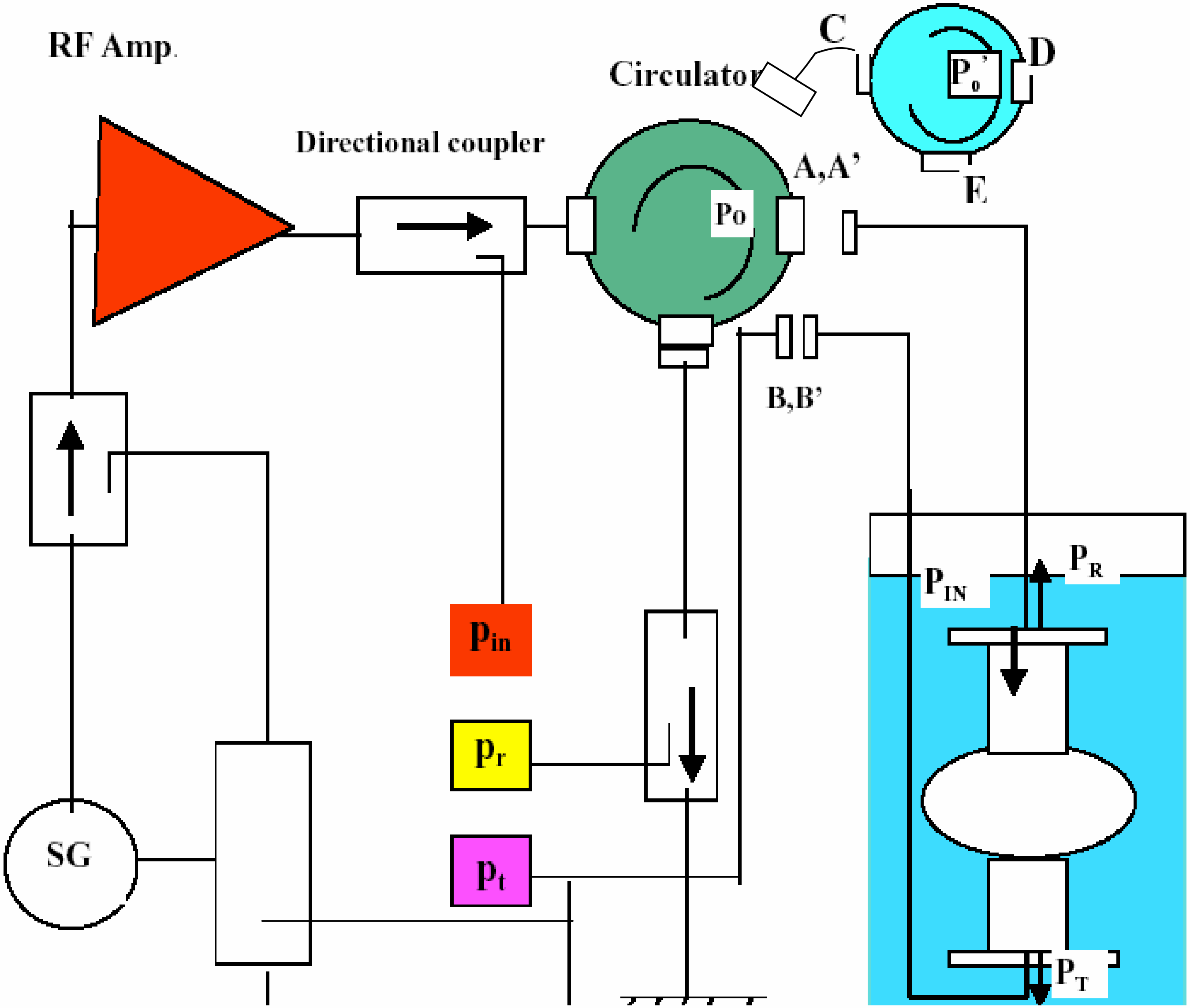
$$= Z \cdot \sqrt{Q_t \cdot P_t}$$

$$\because \; Q_O \cdot P_{loss} = Q_t \cdot P_t$$

Cable Correction

p_{in}, p_r, p_t : measured in the measurement room

P_{IN}, P_R, P_T : Power at the cavity (cooled), $P_{IN} = c_{in} \cdot p_{in}$, $P_R = c_r \cdot p_r$, $P_T = c_t \cdot p_t$



p_{in}, P_O at A,

p_r: short A

p_t : connect B to A

P_O/p_{in}, P_O/p_r, P_O/p_t

P_O' at E : connect A and C , and short D

p_{in}' at E : connect D to A'

p_t' at E : connect D to B'

$C_{in}=(P_O/p_{in})\cdot(p_{in}'/P_O')^{1/2}$

$C_r=(P_O/p_r)\cdot(P_O'/p_{in}')^{1/2}$

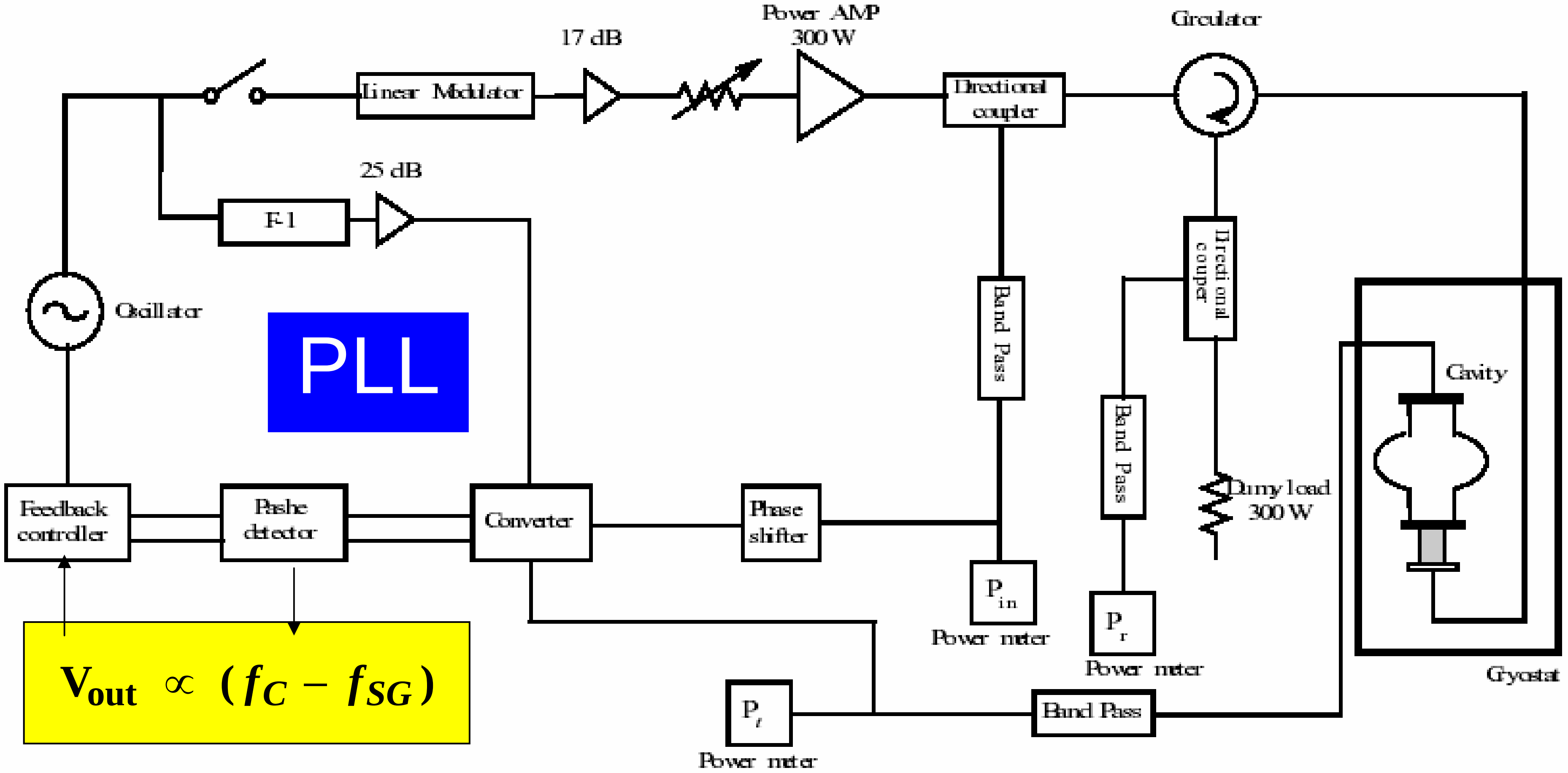
$C_t=(P_O/p_t)\cdot(P_O'/p_t')^{1/2}$

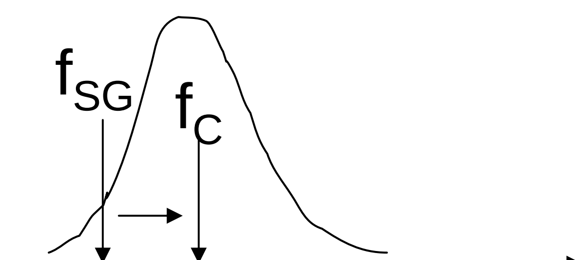
$P_{IN} = c_{in} \cdot p_{in}$

$P_R = c_r \cdot p_r$

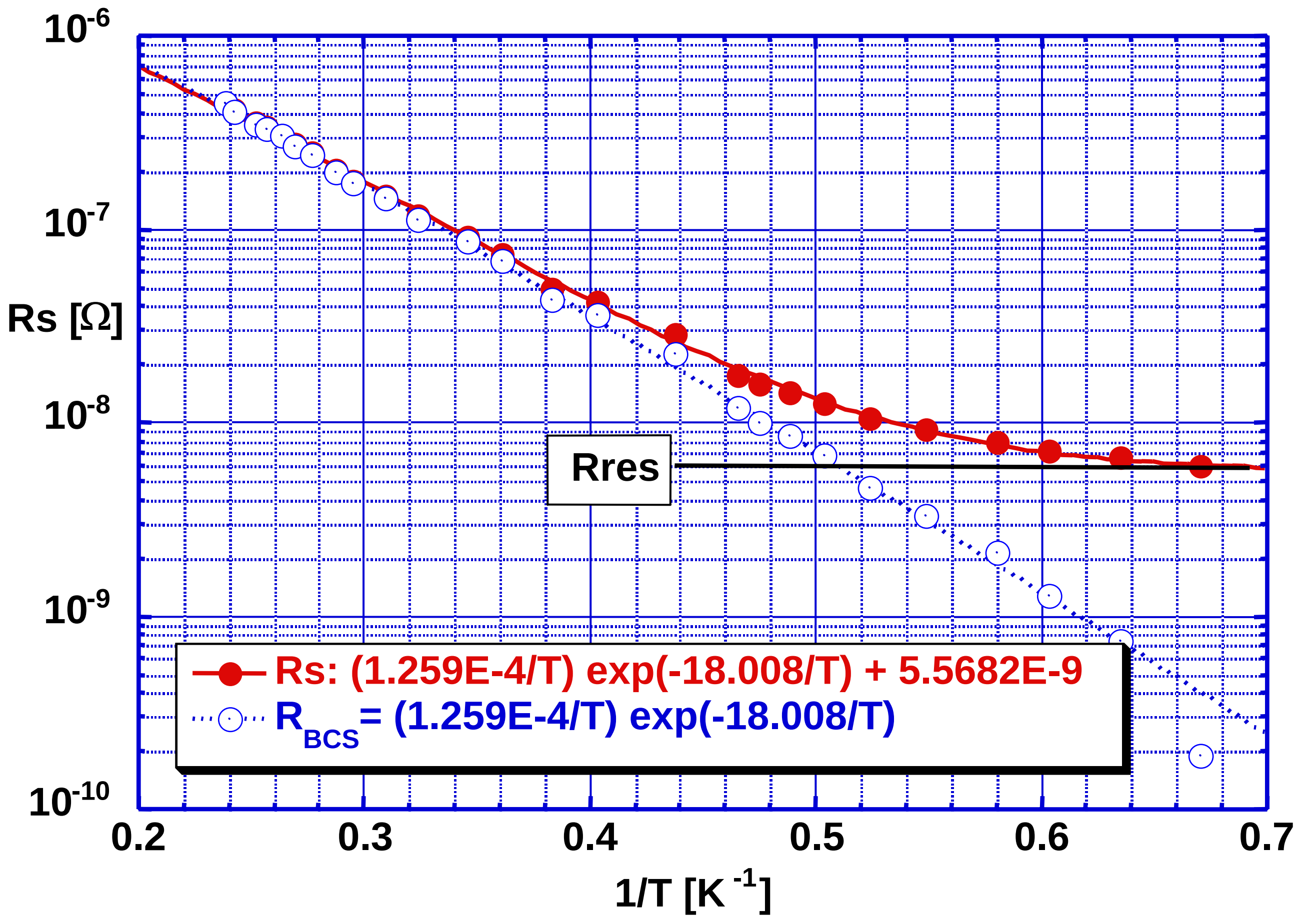
$P_T = c_t \cdot p_t$

Feed Back System





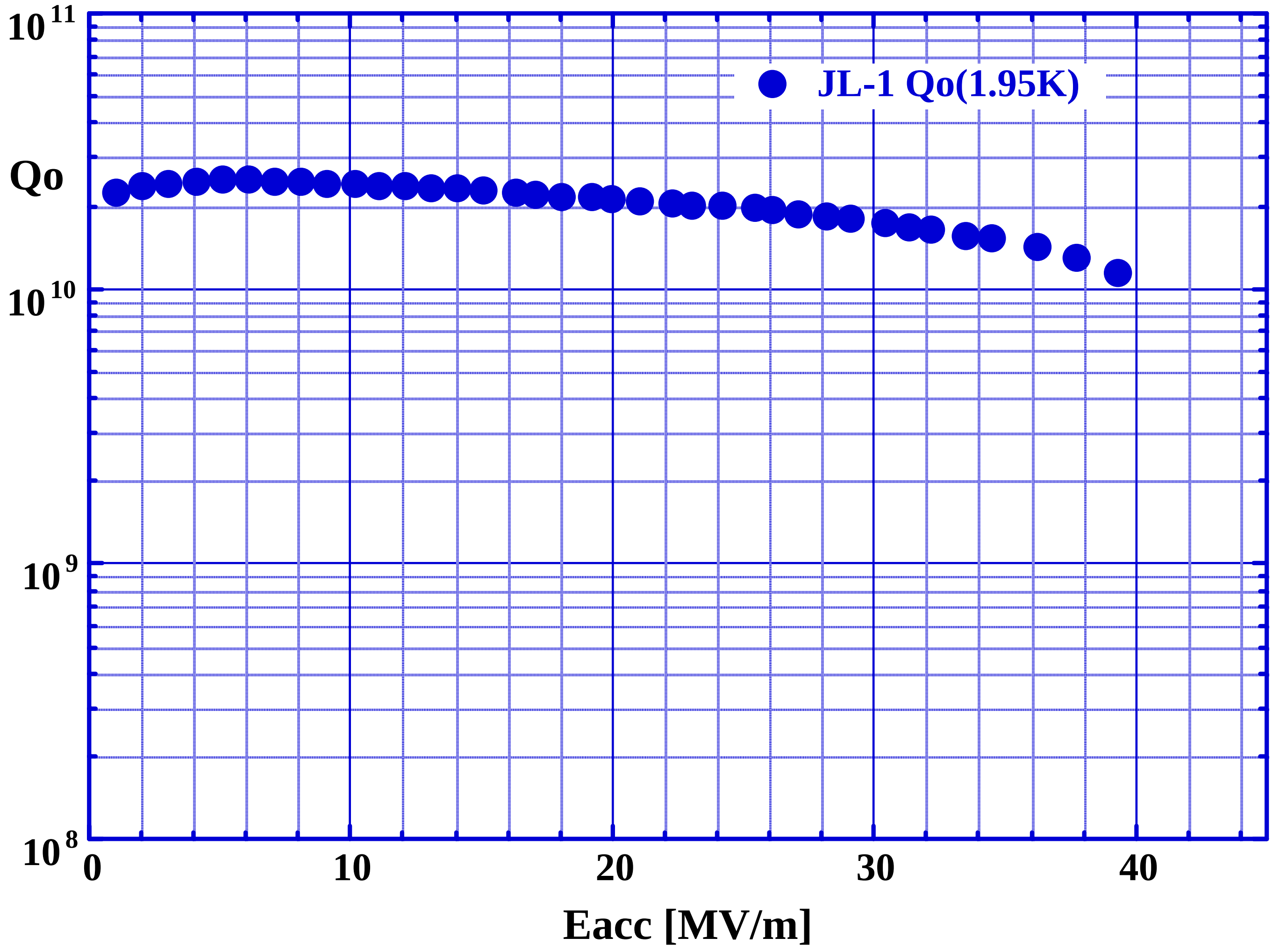
Measurement of Surface Resistance



$$R_S - \text{fit}: R_S(T) = \frac{A}{T} \cdot \exp\left(-\frac{B}{T}\right) + R_{res}$$

$$B = \frac{\Delta}{k_B}$$

High Gradient Measurement: Qo-Eacc curve



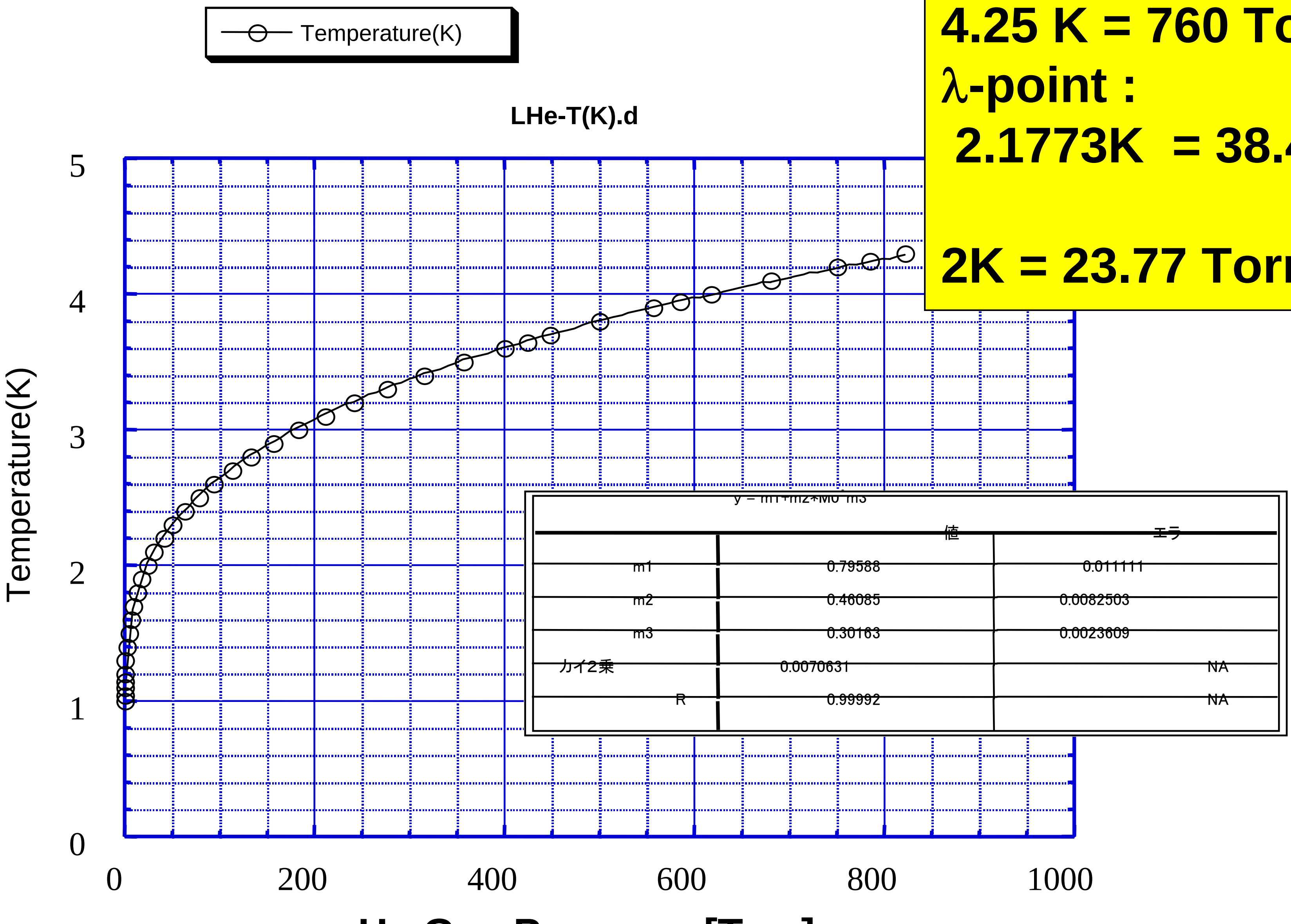
Lhe temperature: P vs. T

4.25 K = 760 Torr

λ-point :

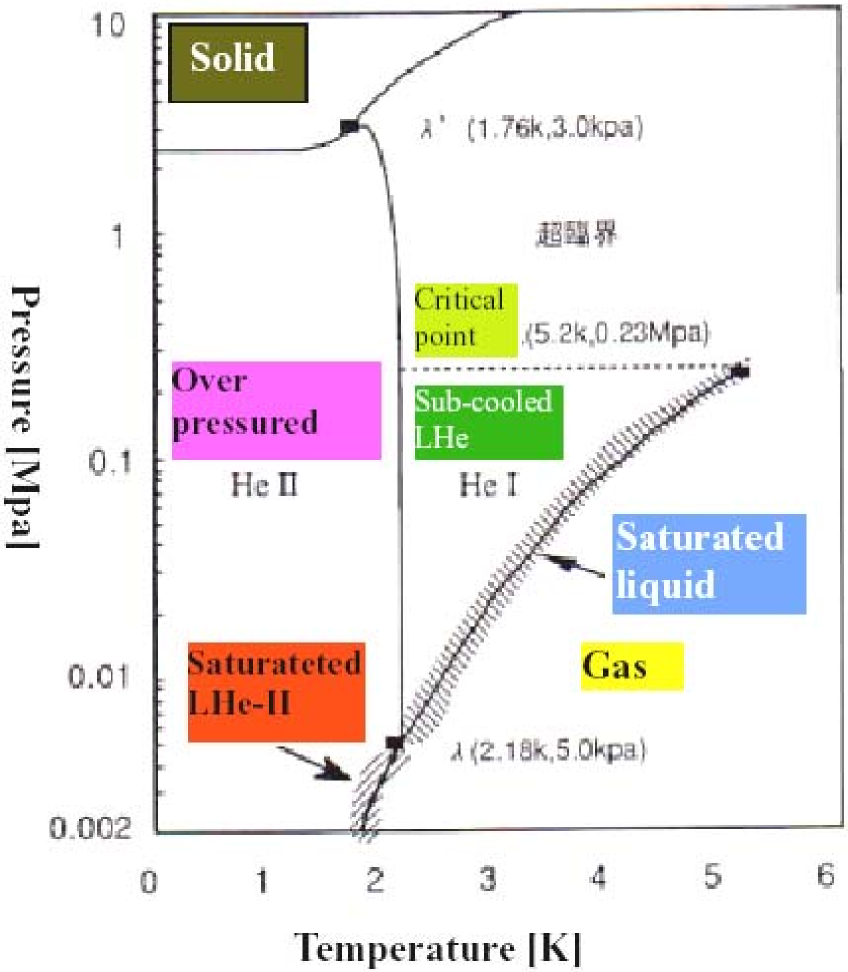
2.1773K = 38.41 Tor

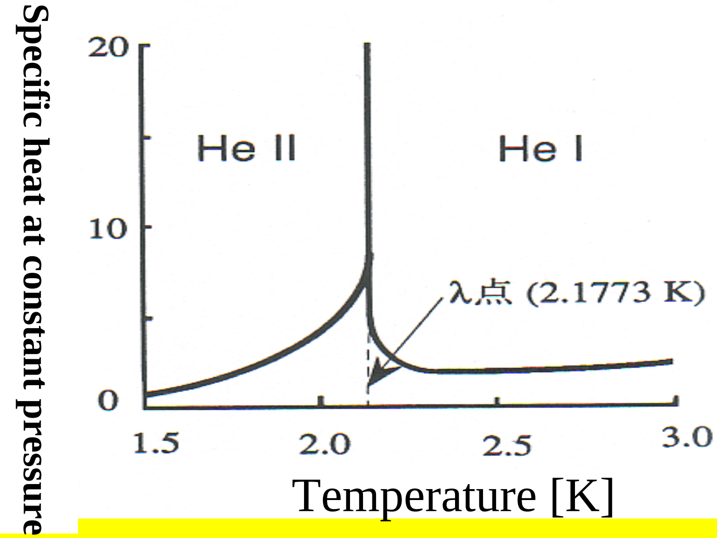
2K = 23.77 Torr



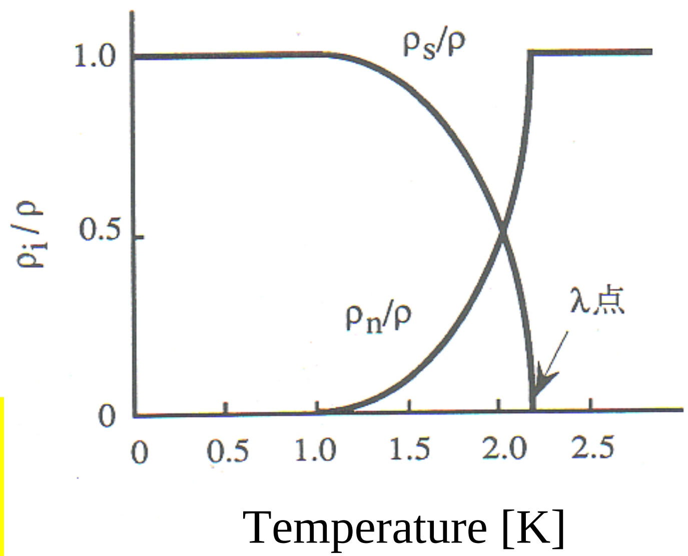
	値	エラー
m1	0.79588	0.011111
m2	0.46085	0.0082503
m3	0.30163	0.0023609
カイ2乗	0.0070631	NA
R	0.99992	NA

Characteristics of He-II





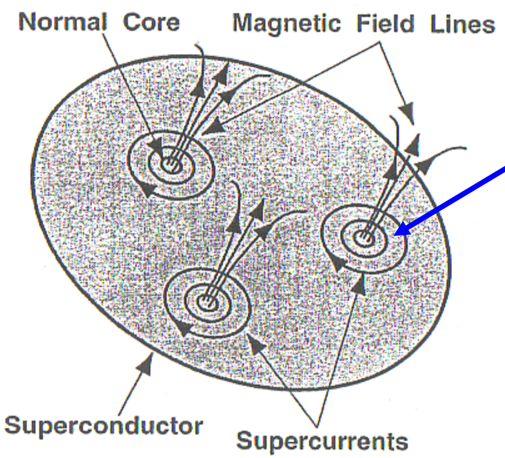
T-dependence of specific heat

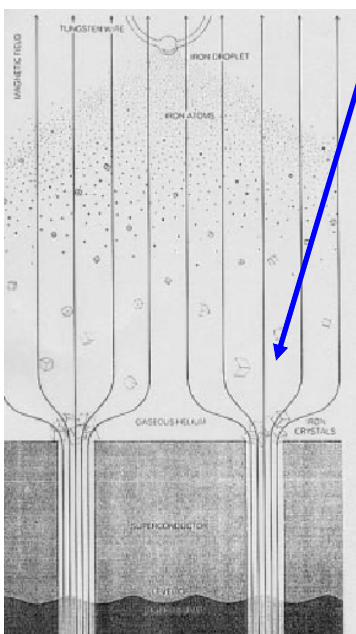


T-dependence of the ratio of ρ_n(normal)/ρ_s(super)

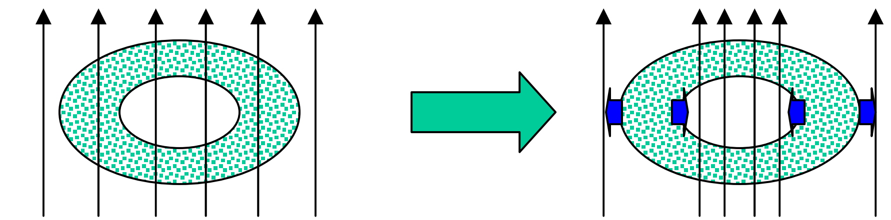
- LHe makes transition to superfluid state (He-II) below λ-point.
- LHe has almost no viscosity in the He-II.
- He-II has very large thermal conductivity, higher 100 than that of cooper at cryogenic temperat

Influence of residual magnetic field on Surface resistance





If magnetic field penetrated the Nb cavity in the cryogeni temperature, it is trapped in the niobium and makes norn conducting area.



$T > T_C,\ H < H_C$ $\qquad$ $T < T_C,\ H < H_C$

$$R_s(H_{ext}) = R_n(T =\sim K)\cdot\frac{H_{ext}}{H_{c2}(T)}$$

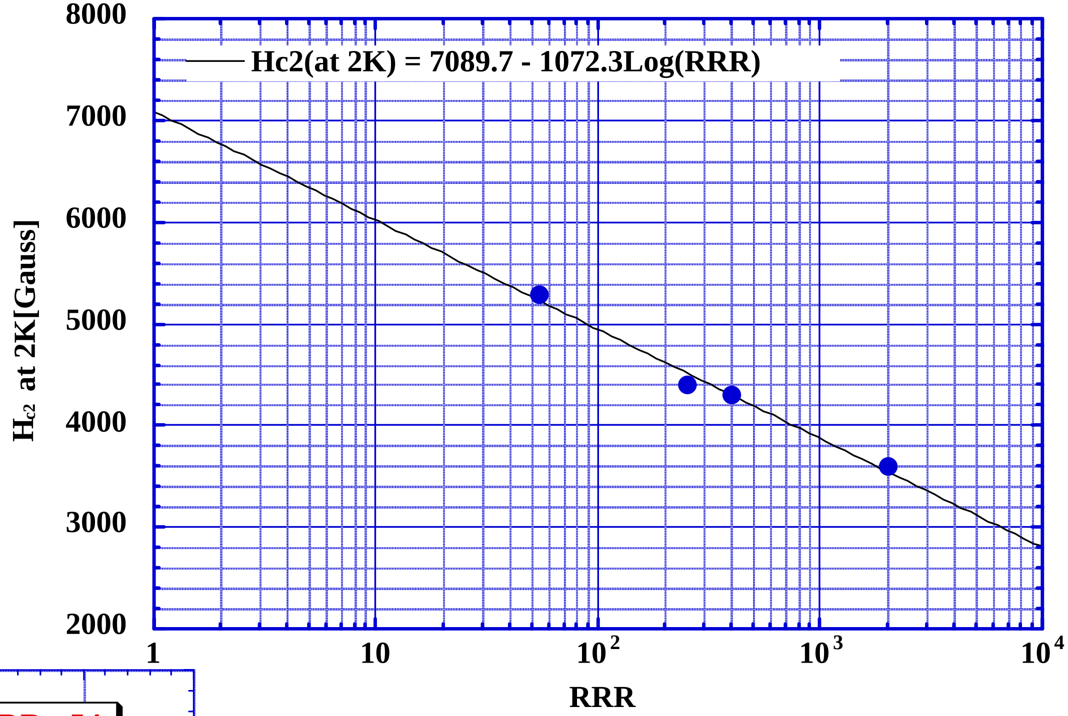
$$R_n(300K) = \sqrt{\frac{\mu\omega}{2\sigma(300K)}}$$

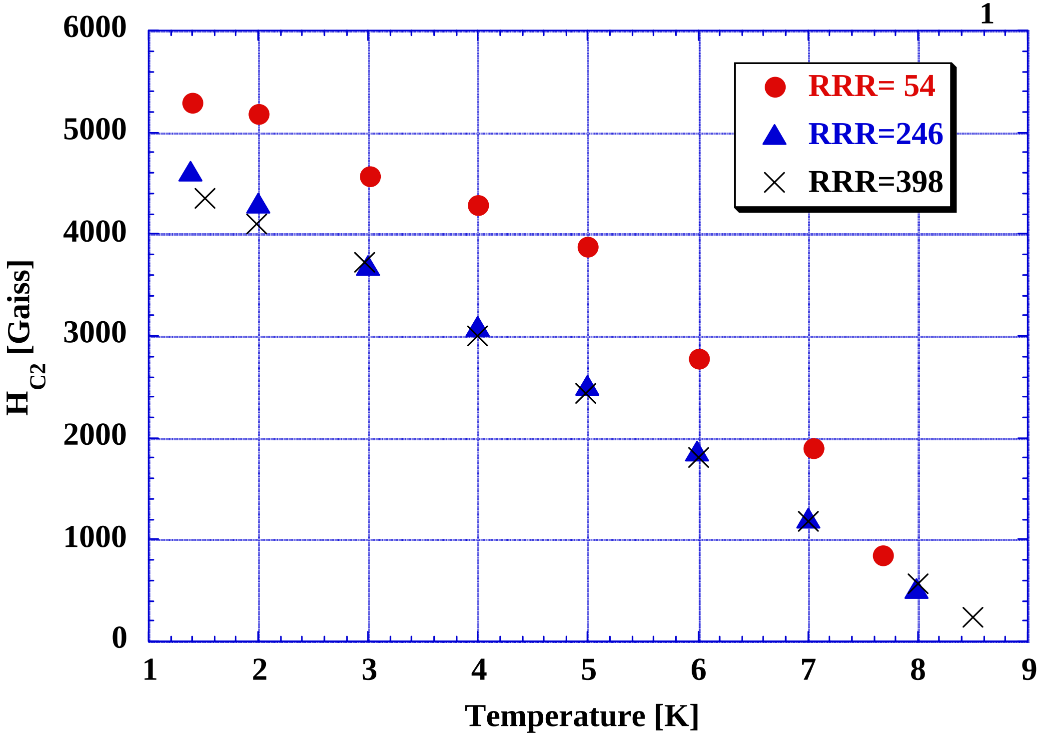
$$\boldsymbol{R_s(H_{ext}) = \sqrt{\frac{\mu\omega}{RRR\cdot\sigma(300K)}}\cdot\frac{H_{ext}}{H_{c2}}}$$

$$\boldsymbol{= R_n(300K)\cdot\frac{H_{ext}}{\sqrt{RRR}\cdot H_{c2}(T,RRR)}}$$

$$\boldsymbol{= R_o(T,RRR)\cdot H_{ext}}$$

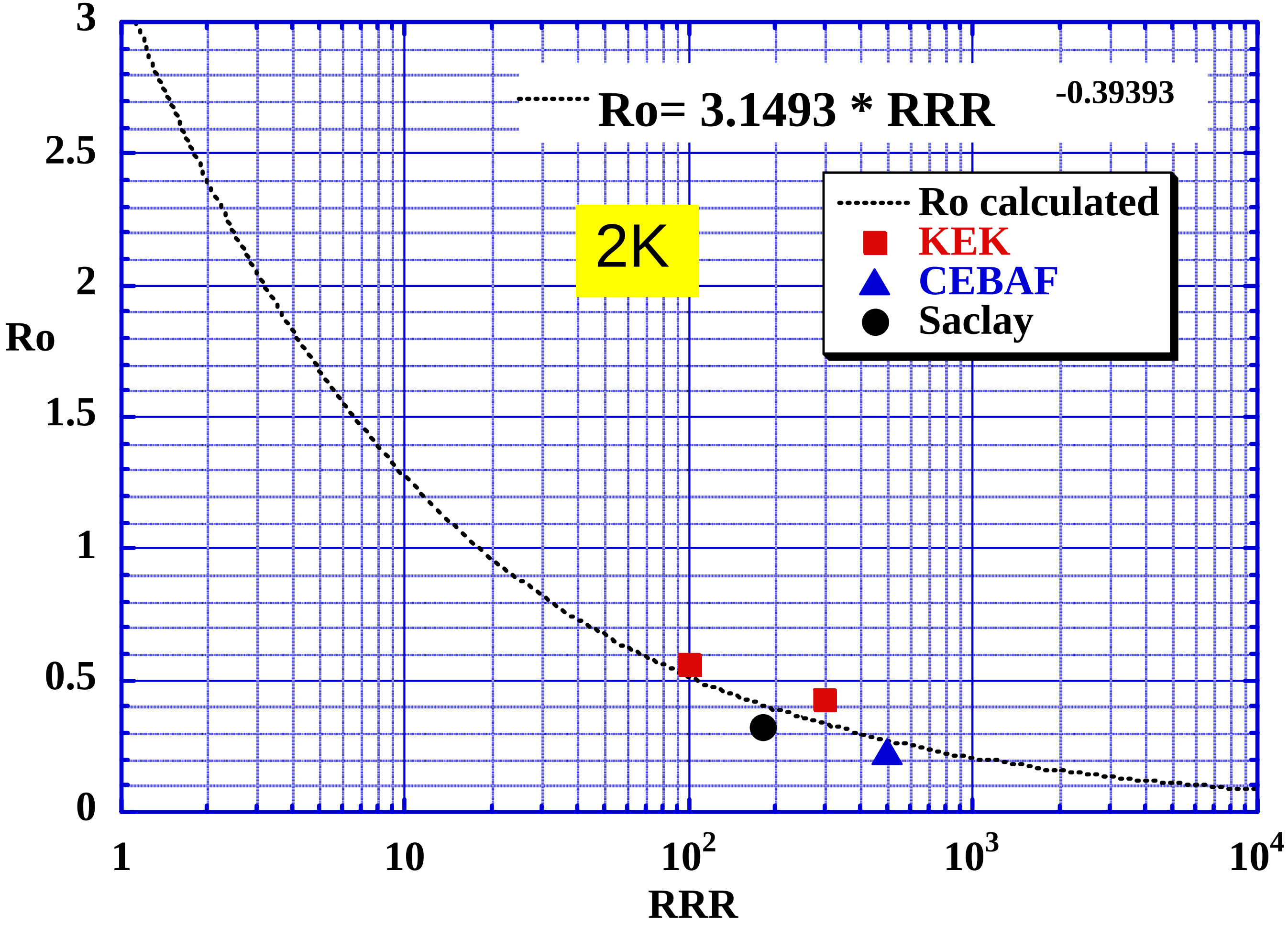
H_{C2} vs. RRR


Hc2(at 2K) = 7089.7 - 1072.3Log(RRR)
H_{c2} at 2K[Gauss]
8000
7000
6000
5000
4000
3000
2000
1
10
10^2
10^3
10^4
RRR


RRR= 54
RRR=246
RRR=398
H_{C2} [Gaiss]
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
Temperature [K]

RRR vs. Residual resistance due to magnetic field

$$R_{res}(H_{ext}) = R_0 \cdot H_{ext}$$



High RRR Nb material is good against the Frozen flux trapping. Residual surface resistance of RRR=500 is a half of RRR=100.