High Gradient Study in Superconducting RF Cavities

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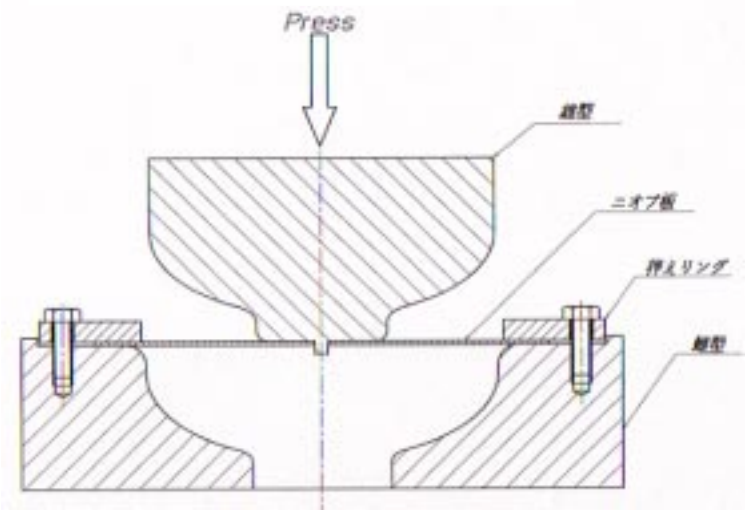
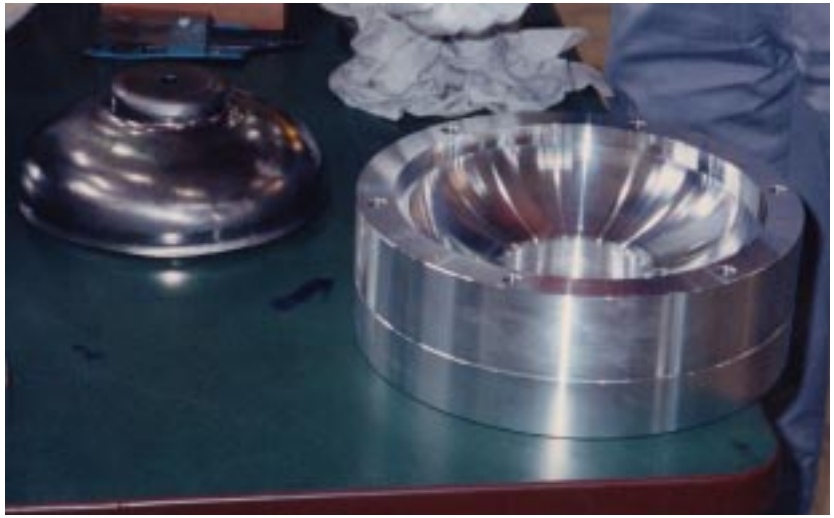
Outline

1. Fabrication and Surface Defects
2. Particle Contamination Control
3. Importance of Smooth Surface
4. Fundamental Field Limitation and A Way to TESLA 1000

Cavity Fabrication

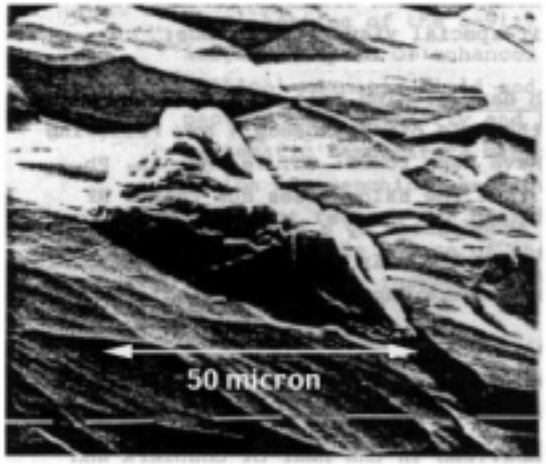
Deep Drawing of half cell



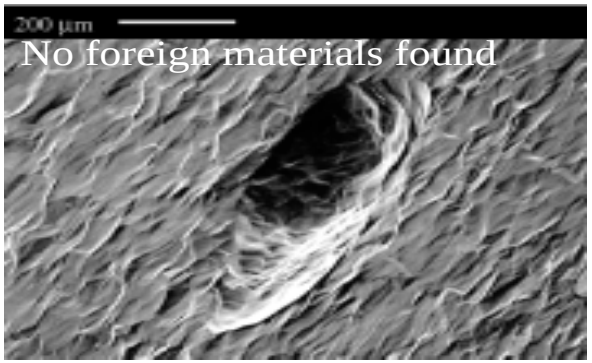


Electron Beam Welding

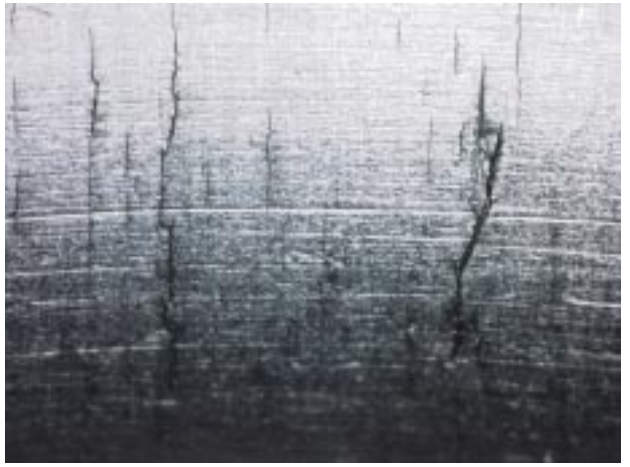
Surface Defects on Niobium SC Cavities



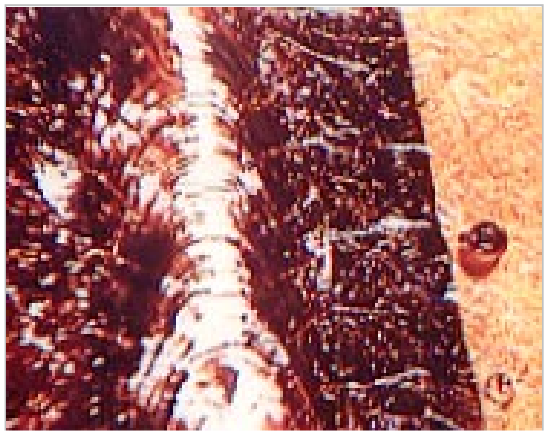
Inclusion



Surface defects, holes can also cause TB

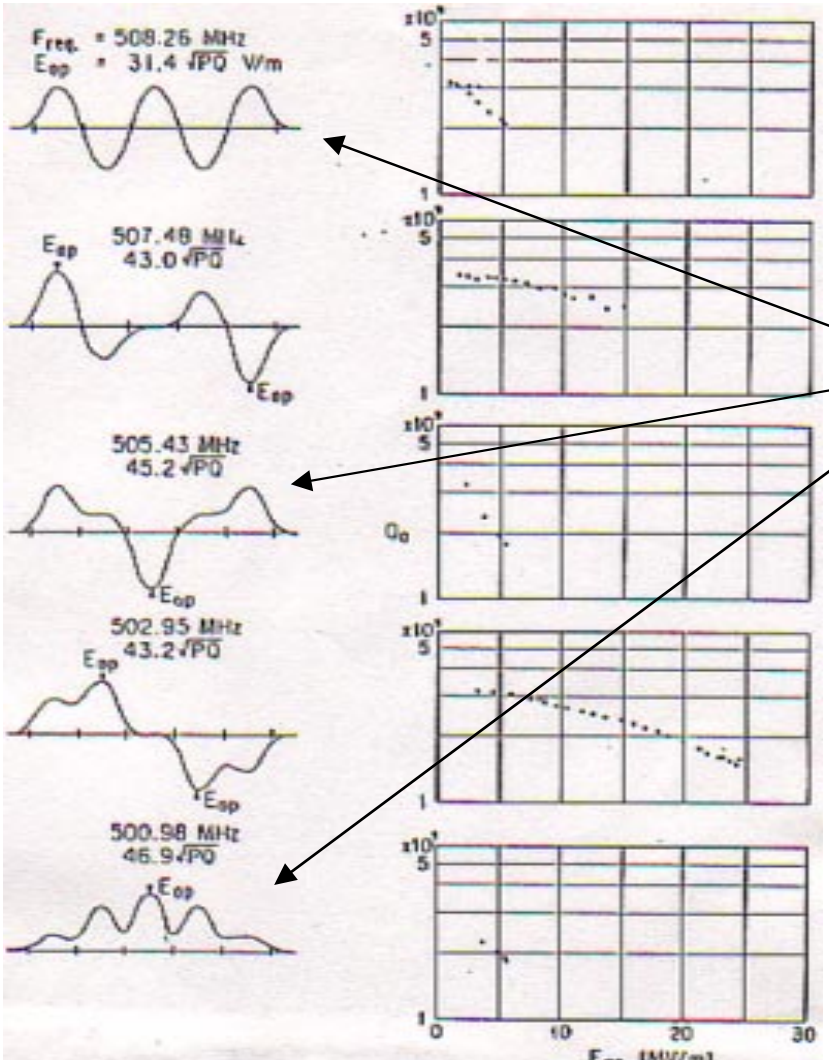


Cracks



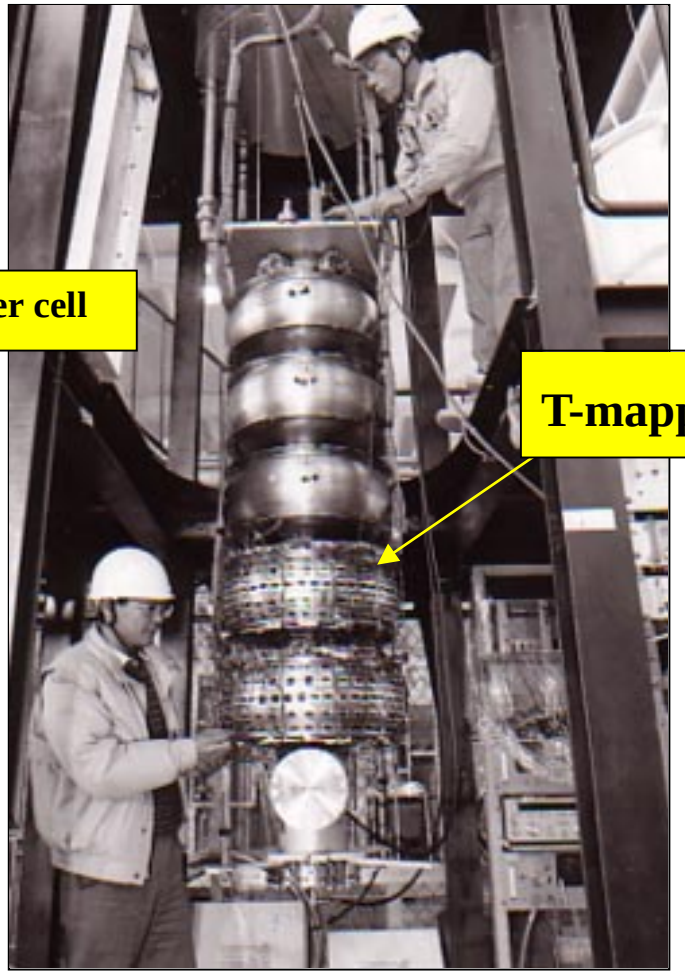
Sputter balls on EBW seam

Quench at Defects - Experience in the TRISTAN -



Field profile in pass bands

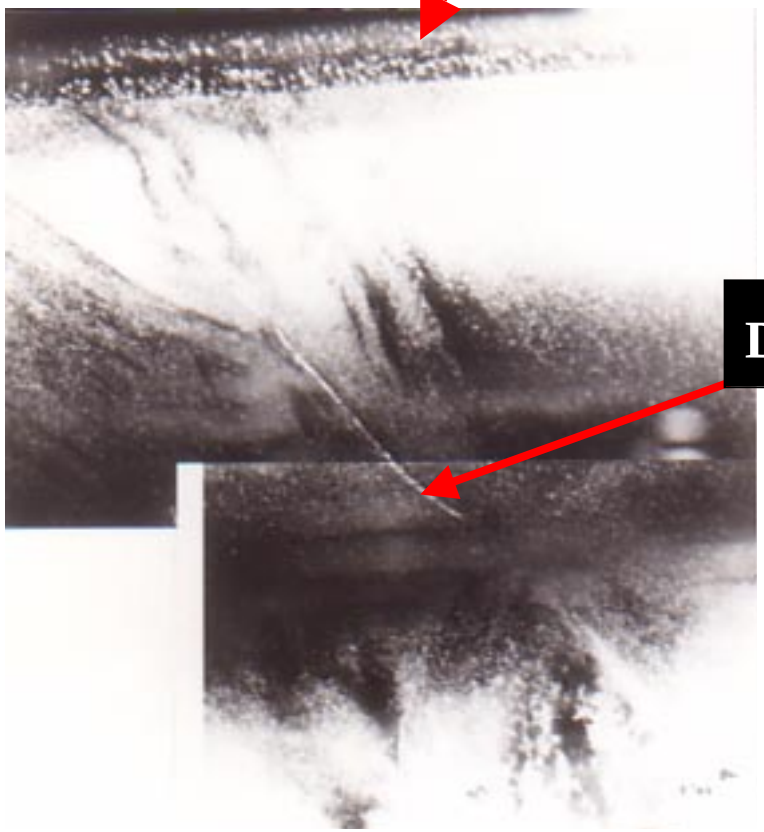
Eacc [MV/m]



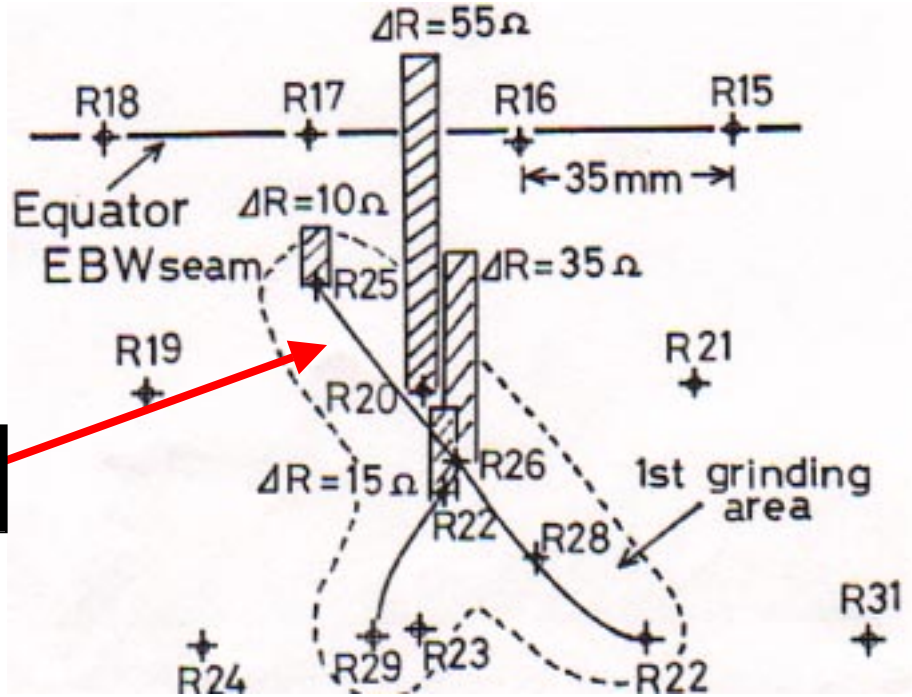
T-mapping to detect the heat location (TRISTAN)

Quench defects - Experience in the TRISTAN -

Electron beam weld seam



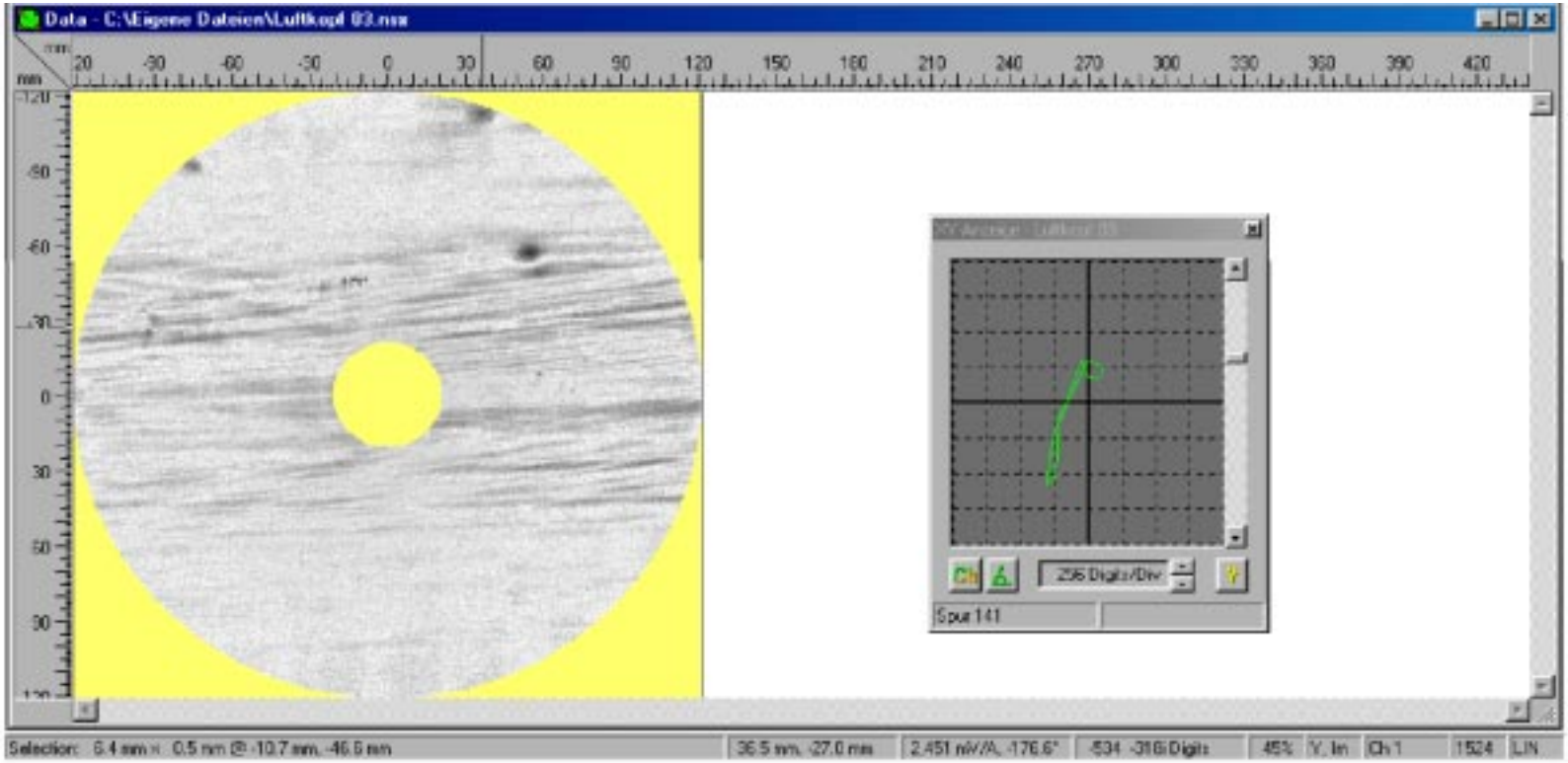
Defect



Tempeature mapping on the defects

Material Inspection

Eddy current scanning Nb discs, dia. 265 mm at DESY



Global view, rolling marks and defect areas can be seen

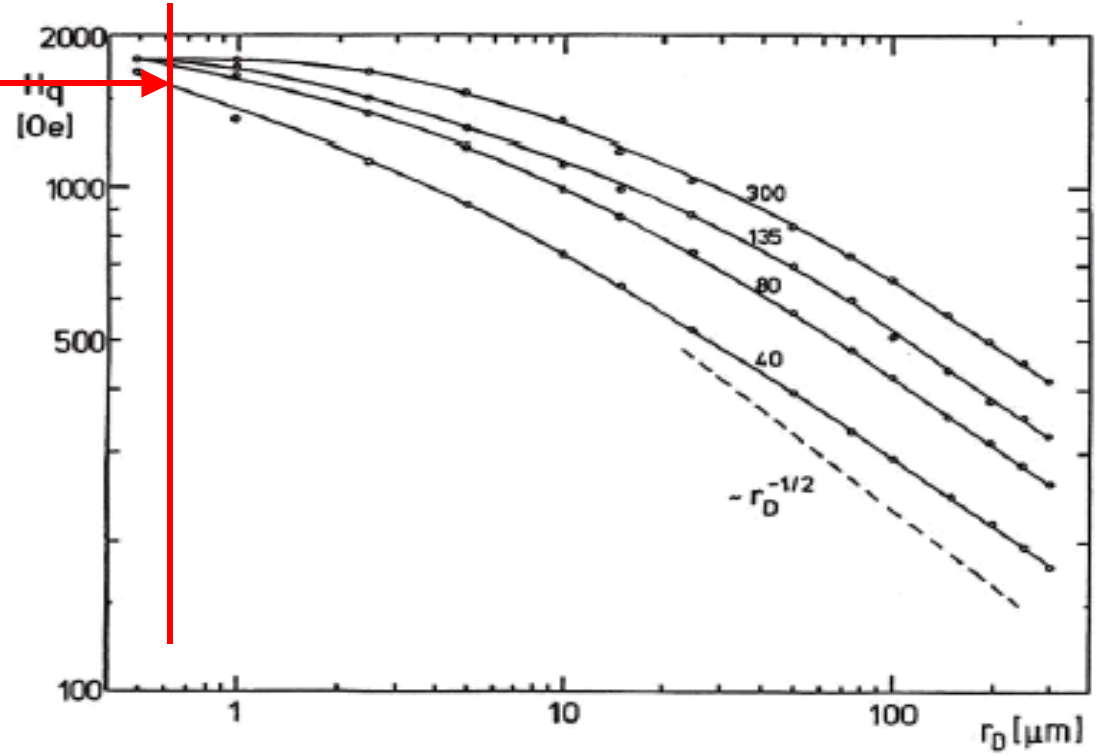
Real and imaginary part of conductivity at defect, typical Fe signal

Thermal instability(quench) - Cures –

Better quality ➡ **High RRR niobium material:** $Hq = \sqrt{\frac{4\kappa(Tc - Tb)}{r_D \cdot R_n}} \propto RRR^{\frac{3}{4}} \cdot \sqrt{\frac{(Tc - Tb)}{r_D \cdot R_n(300K)}}$

Hp/Eacc ~ 43
Hp = 43 x 40 ~ 1720 Oe

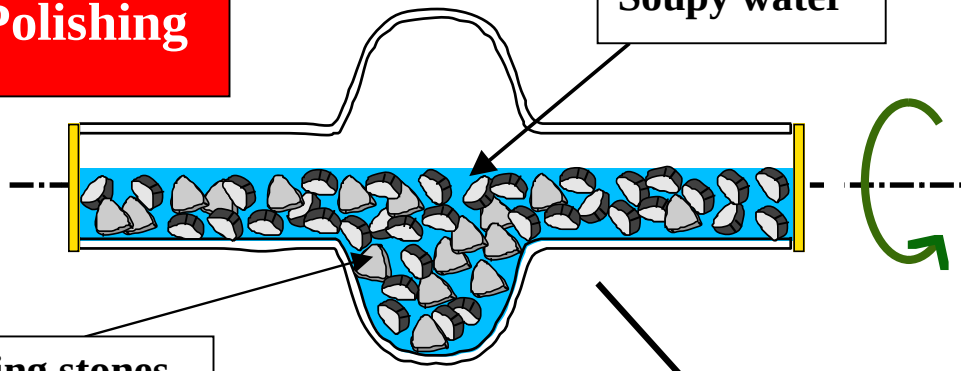
r_D ~ 2μm



For high gradient Eacc ~ 40 MV/m, RRR should be higher than several hundreds and defect size (radius :r_D) less than 1μm.

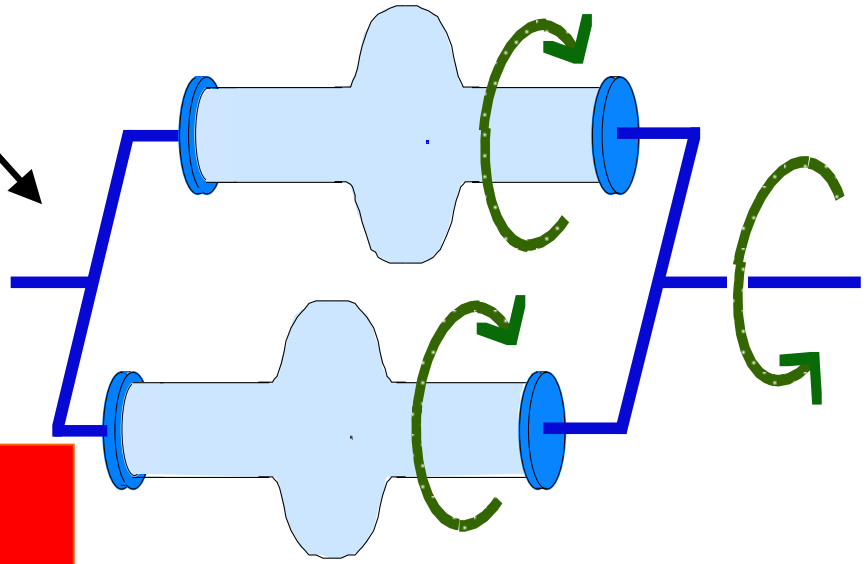
Simple Mechanical Grinding

Barrel Polishing



Simple but
slow material removal

Centrifugal barrel polishing

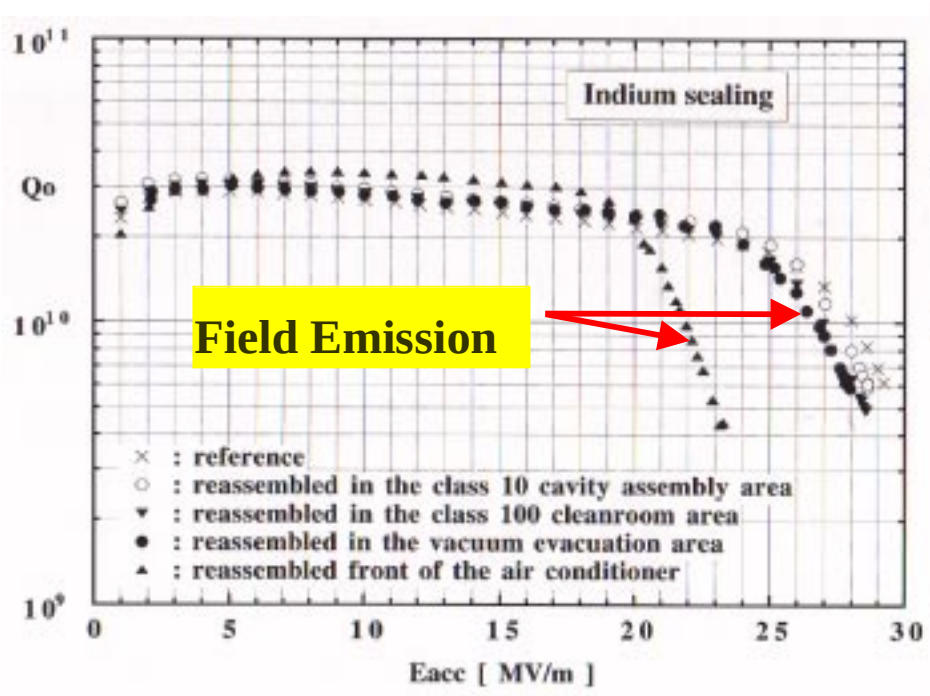


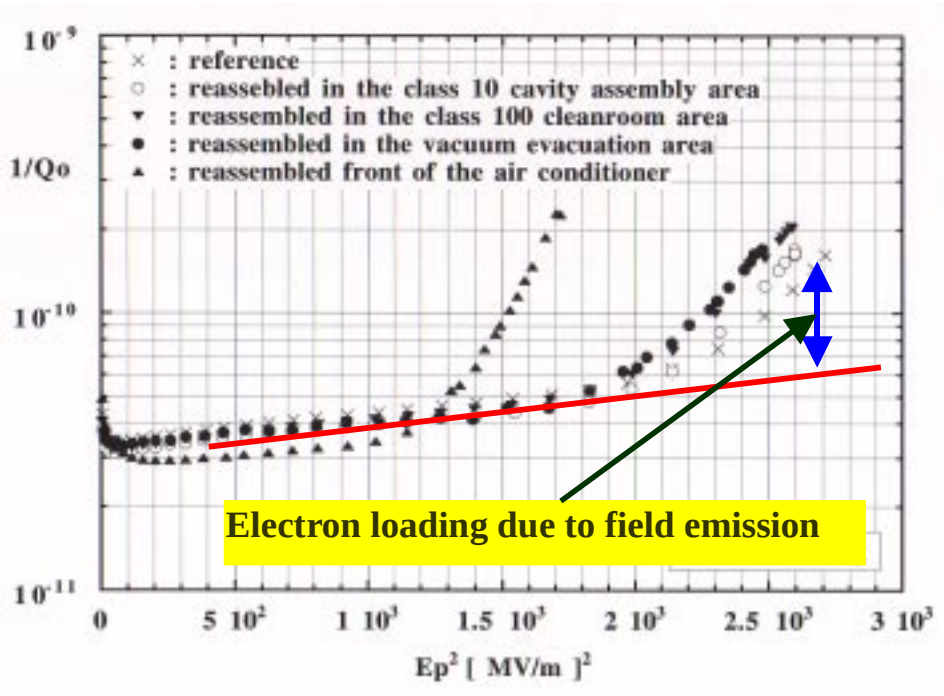
High material removal speed

Succesufully developed CBP

One week **4 hours**

Field Emission



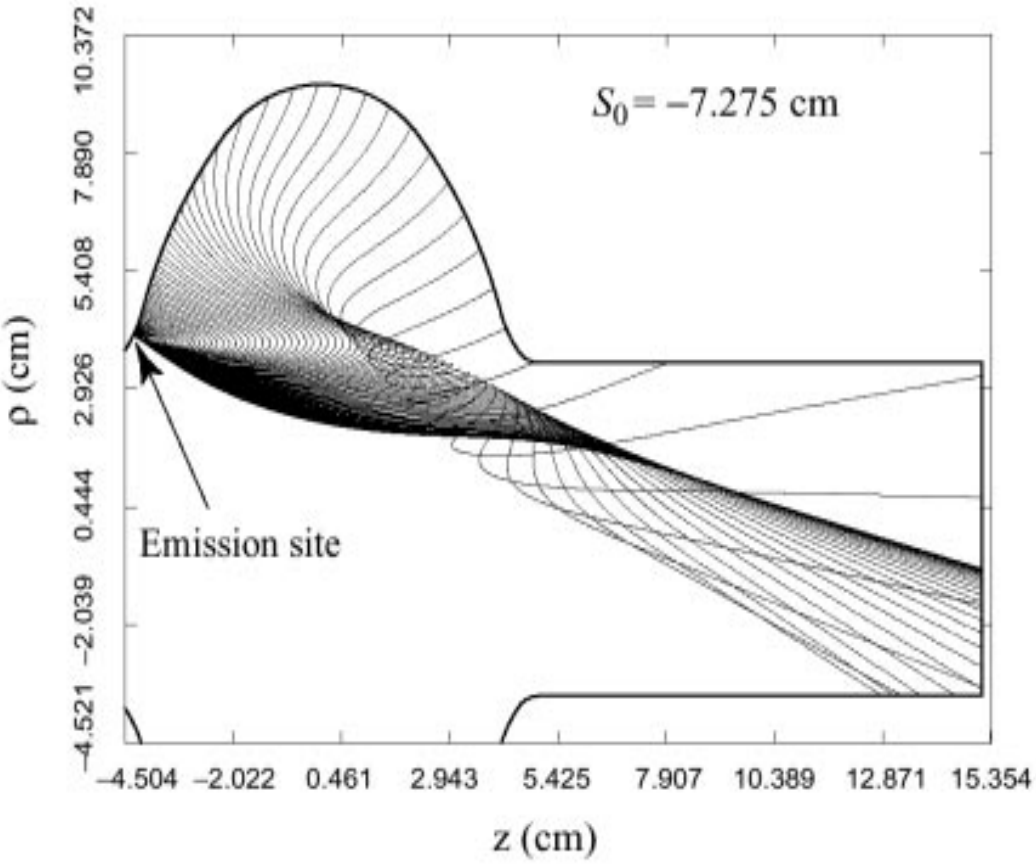


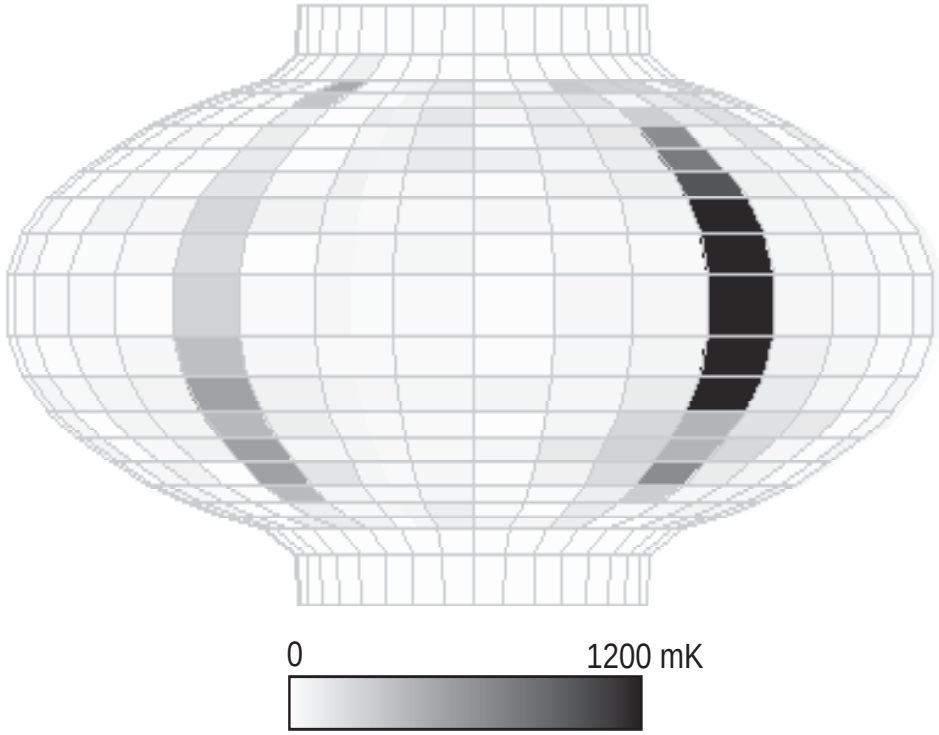
$$\frac{1}{Q_o} = A + B \cdot E_p[MV/m]^2,\ \Delta\left(\frac{1}{Q_o}\right) = \frac{1}{Q_o(E_p^2)} - (A + B \cdot E_p[MV/m]^2)$$

Flower-Nord Hiem Plot: = $$\Delta\left(\frac{1}{Q_O}\right) = S \cdot E_p^{1.5} \cdot \exp\left(-\frac{\phi}{\beta \cdot E_P}\right) = S \cdot E_p[MV/m]^{1.5} \cdot \exp\left(-\frac{5.46E4}{\beta \cdot E_P[MV/m]}\right)$$

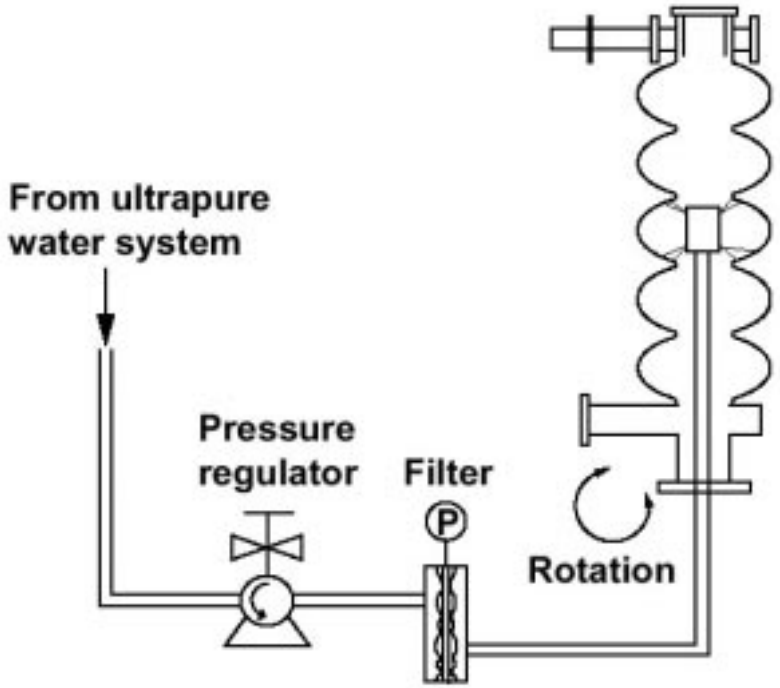
Electron Trajectory in Field Emission

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

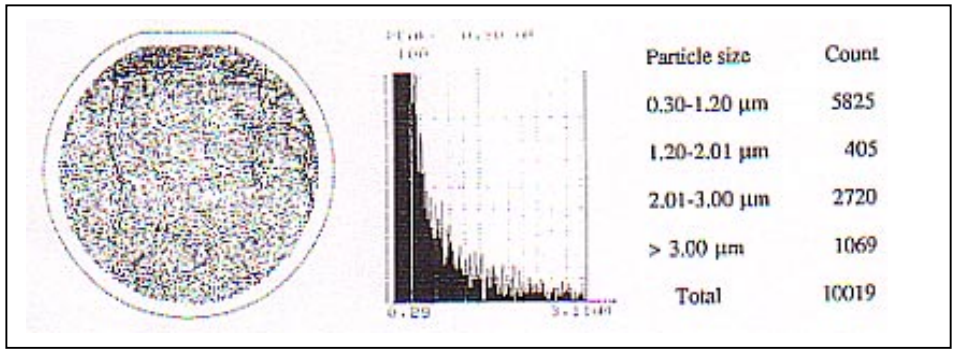




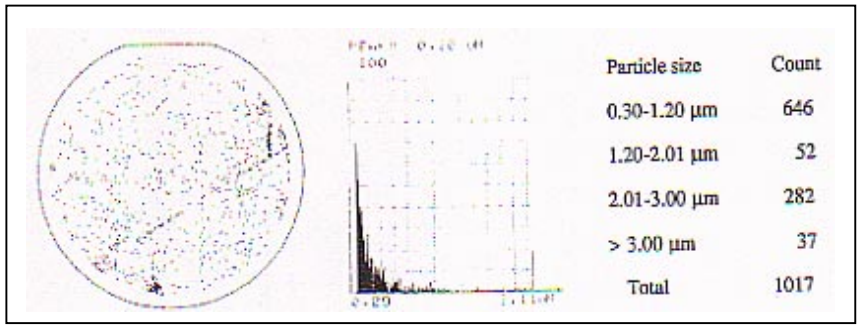
High Pressure Water Rinsing (HPR)



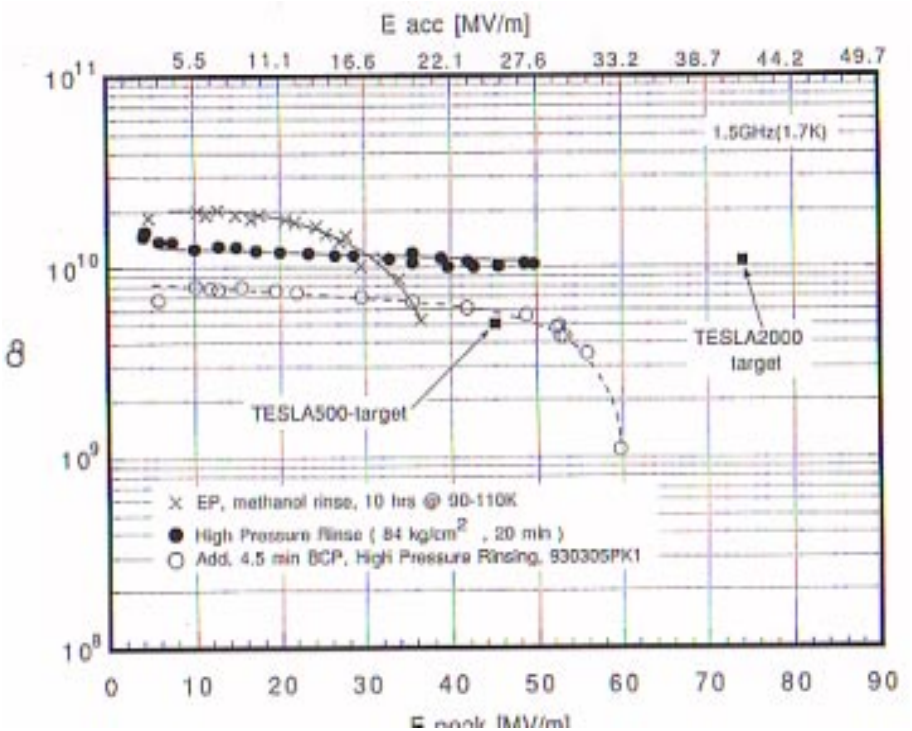
Effect of High Pressure Water Rinsing (HPR)



TRINSTAN rinsing method without HPR



TRISTAN rinsing method + HPR

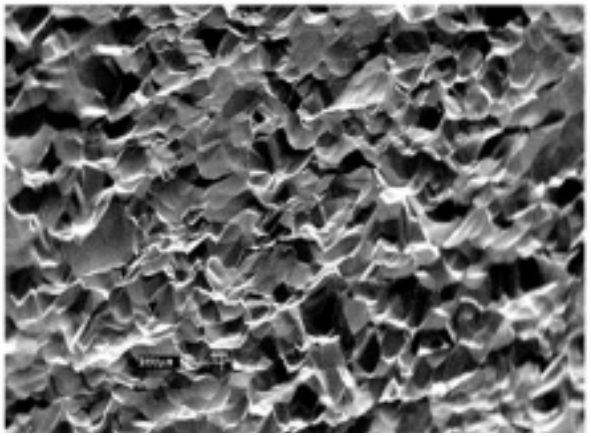


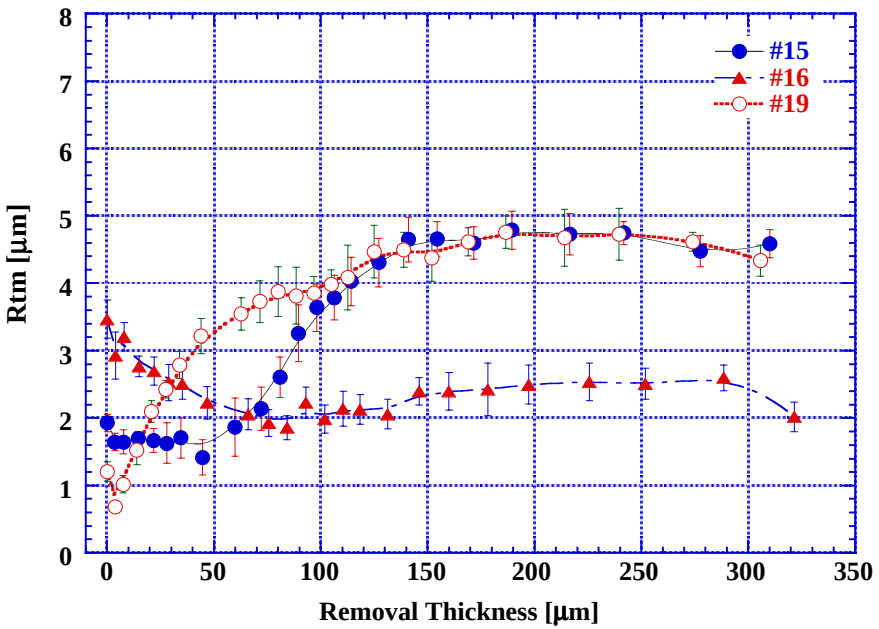
The first confirmation of HPR by P.Kneisel

HPR is a very powerful tool to eliminate particle contamination on cavity surface!

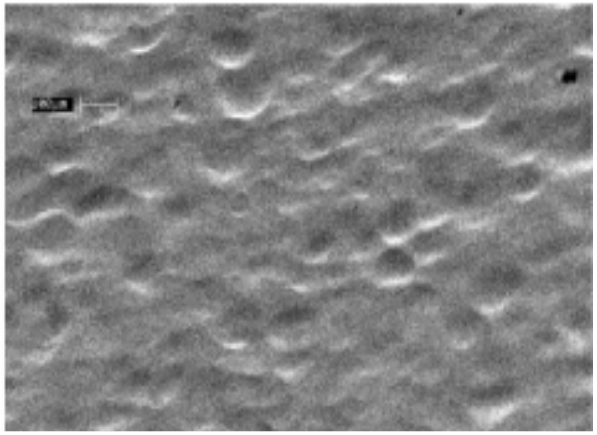
Importance of Smooth Surface

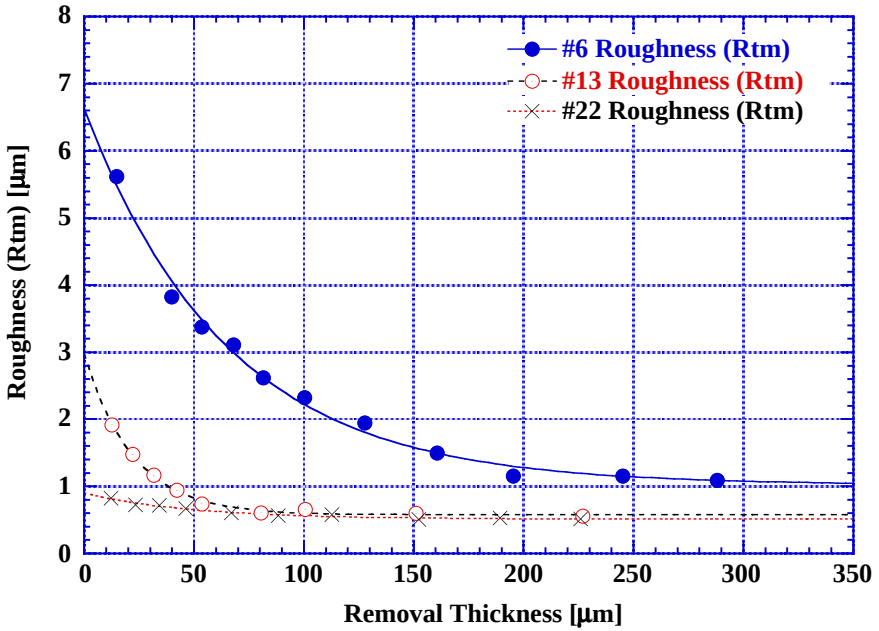
Chemical Polishing



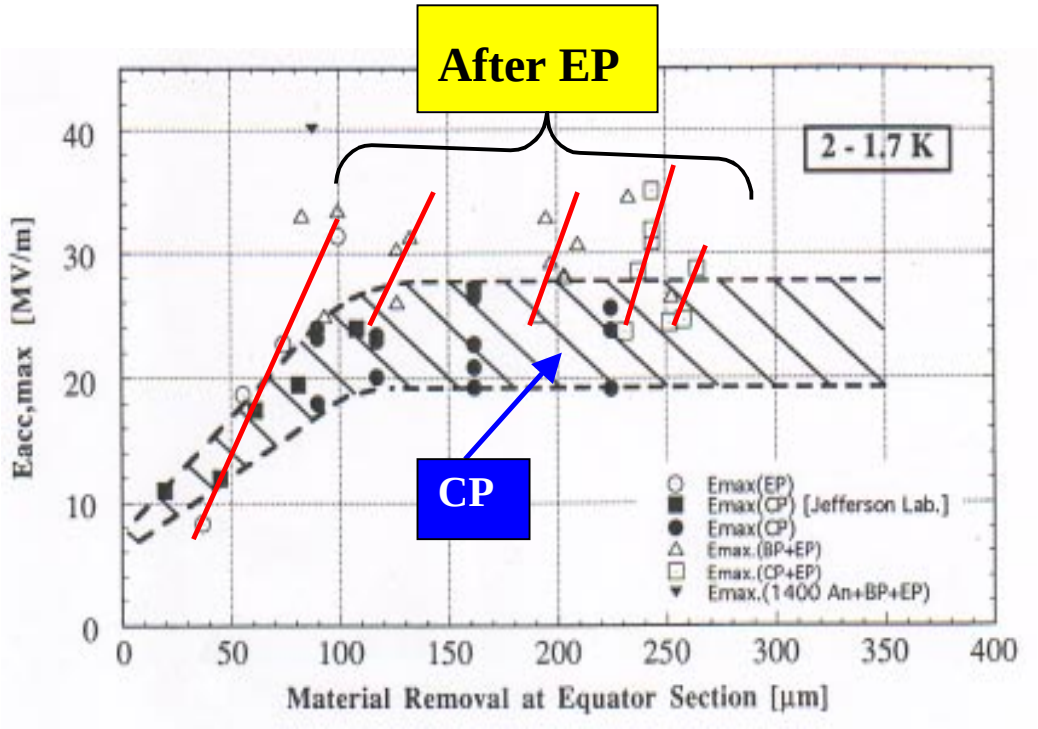


Electropolishing

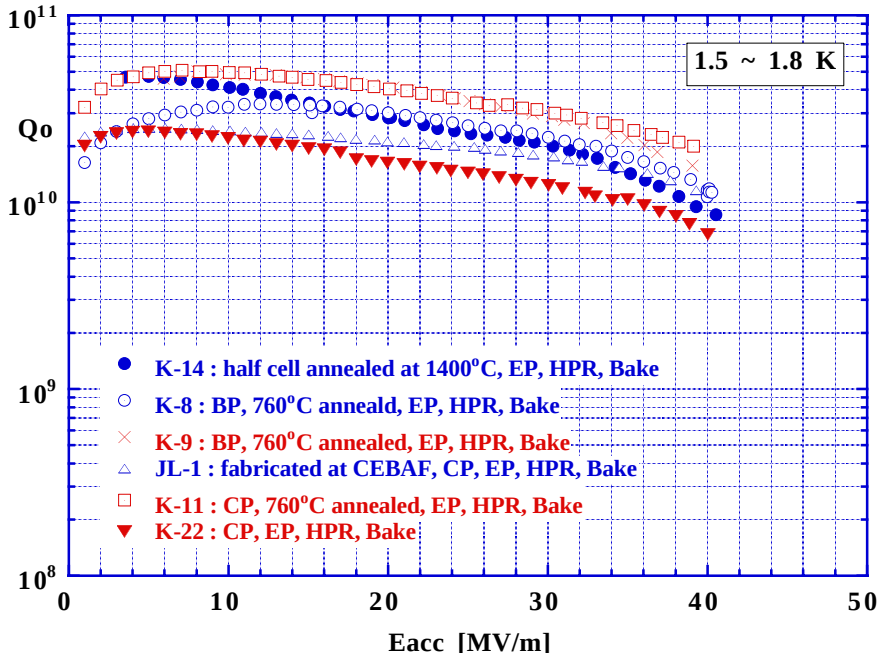




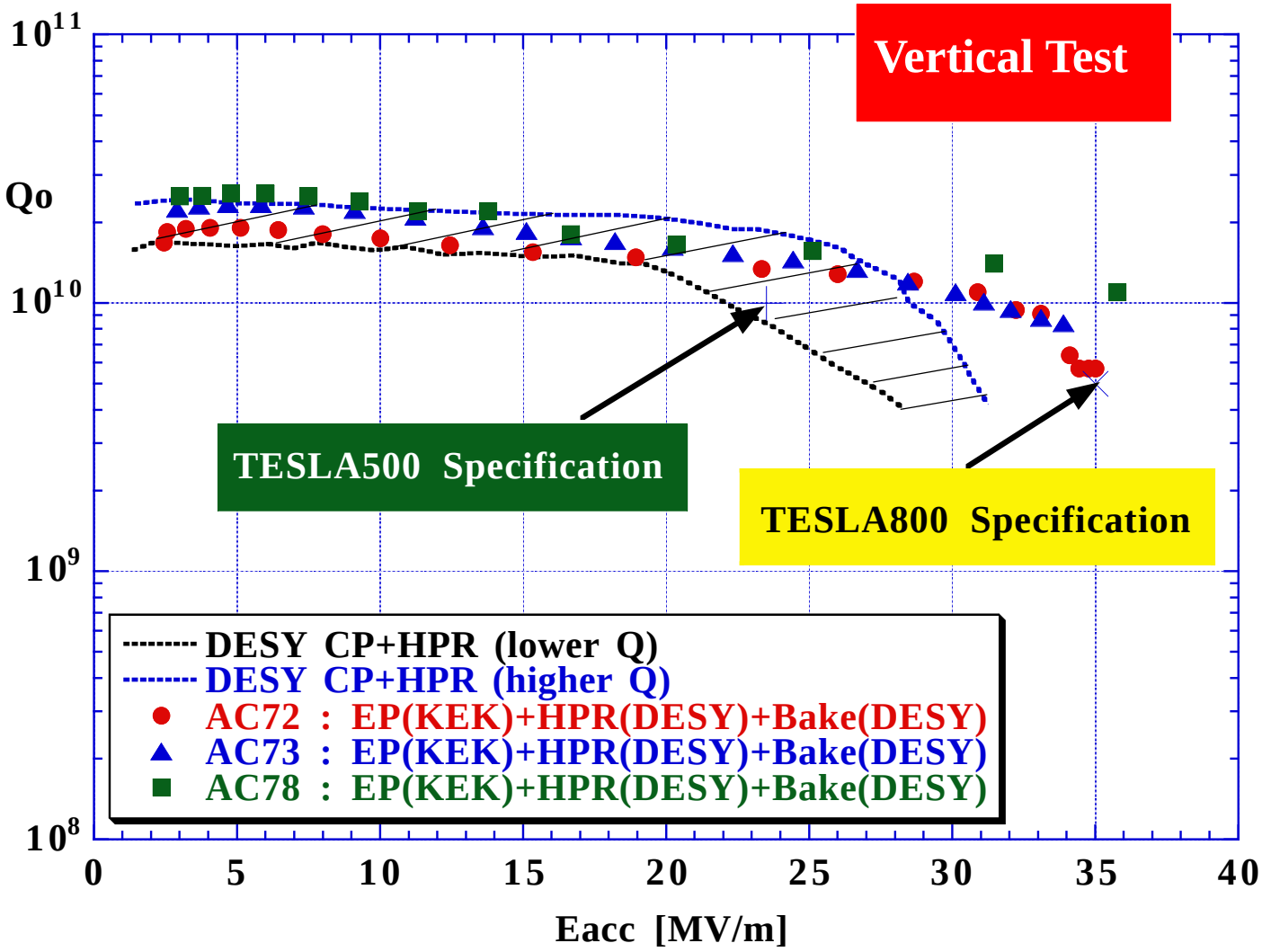
High Gradient Performance with EP



Electropolished Cavities in KEK (1300MHz single cells)

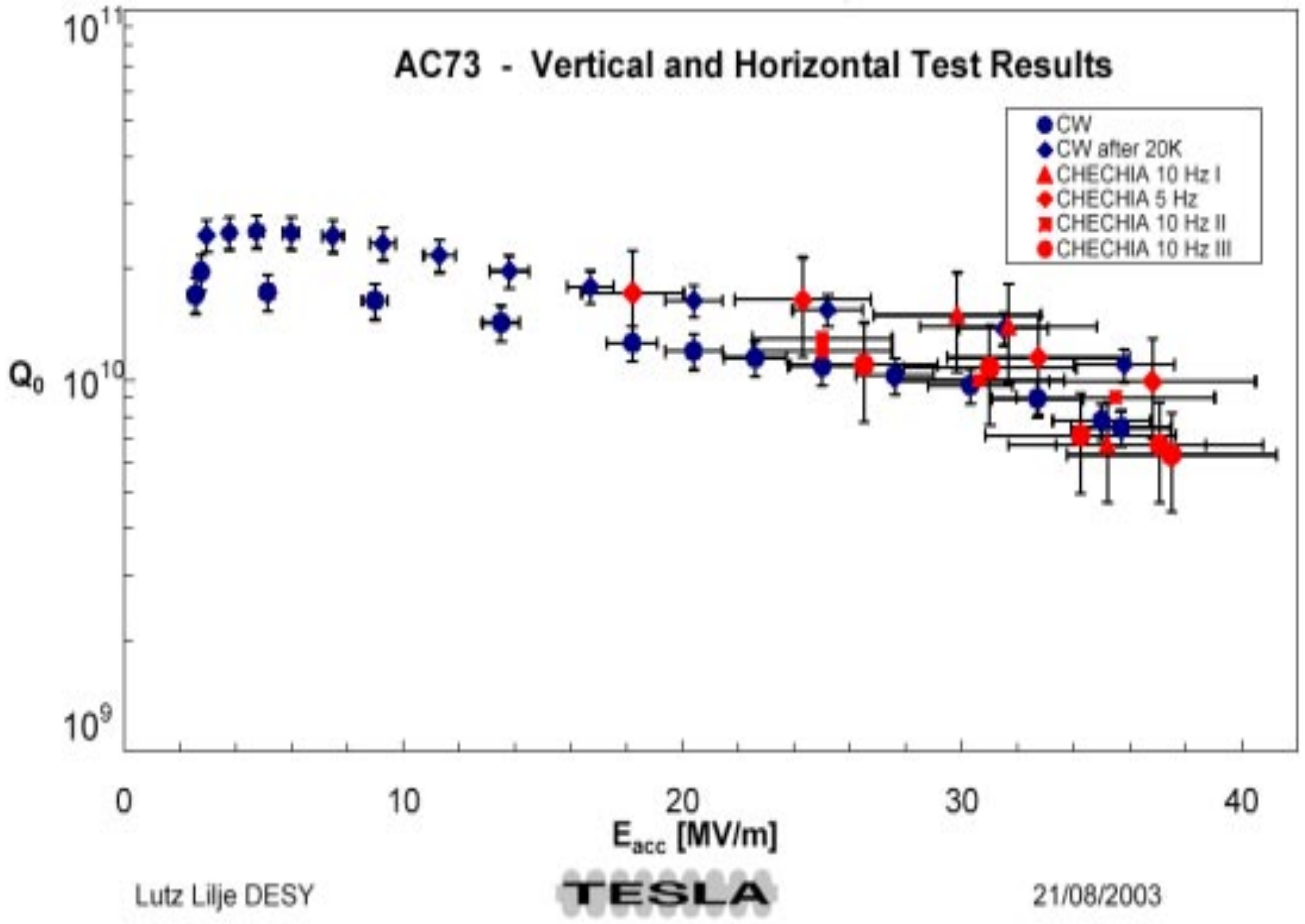


High Gradient TTF Cavities by EP



35 MV/m has been achieved in 4 cavities of 8 electropolished TTF ones in the vertical test.

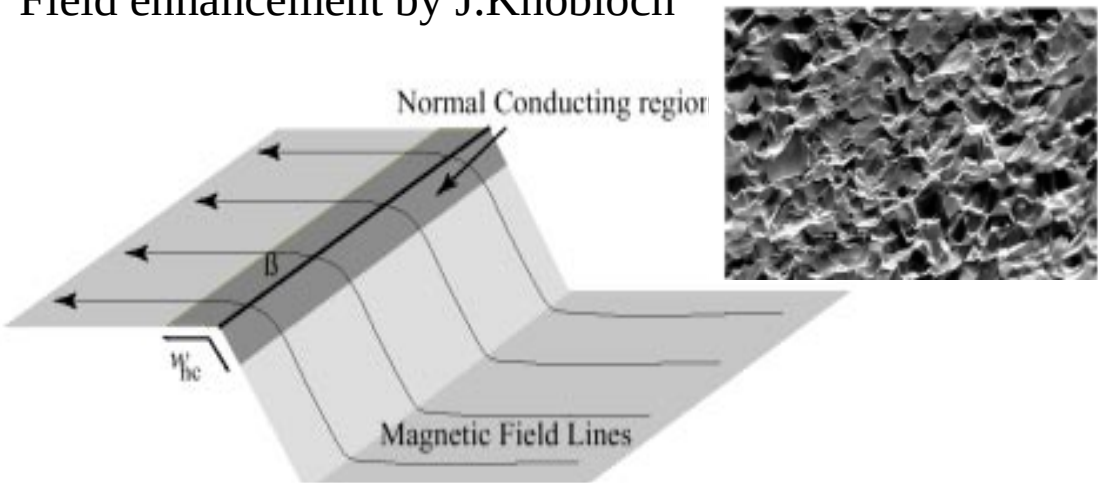
High Power Test Result of an Electropolished TTF Cavity

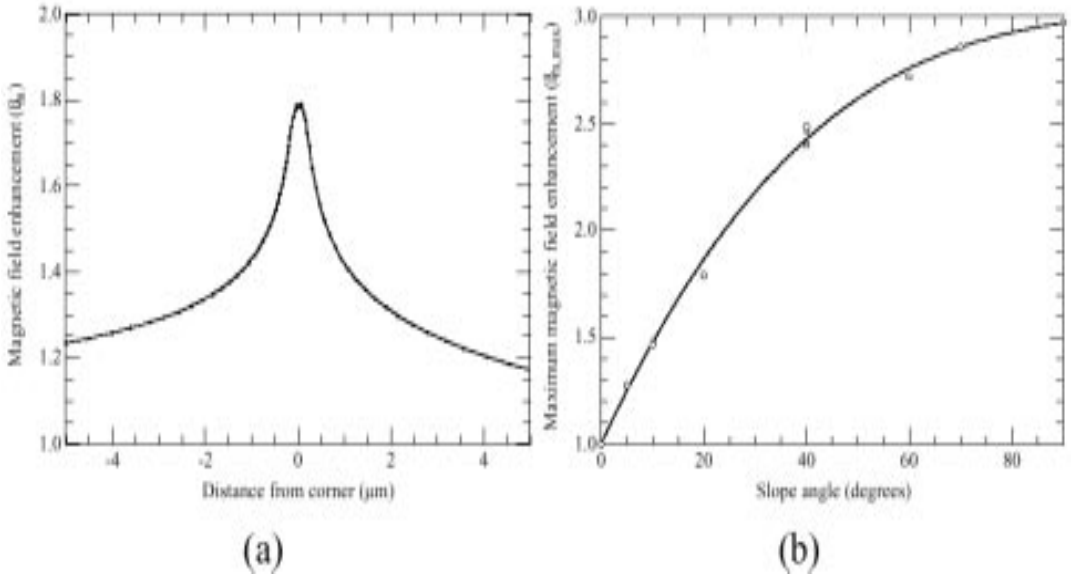


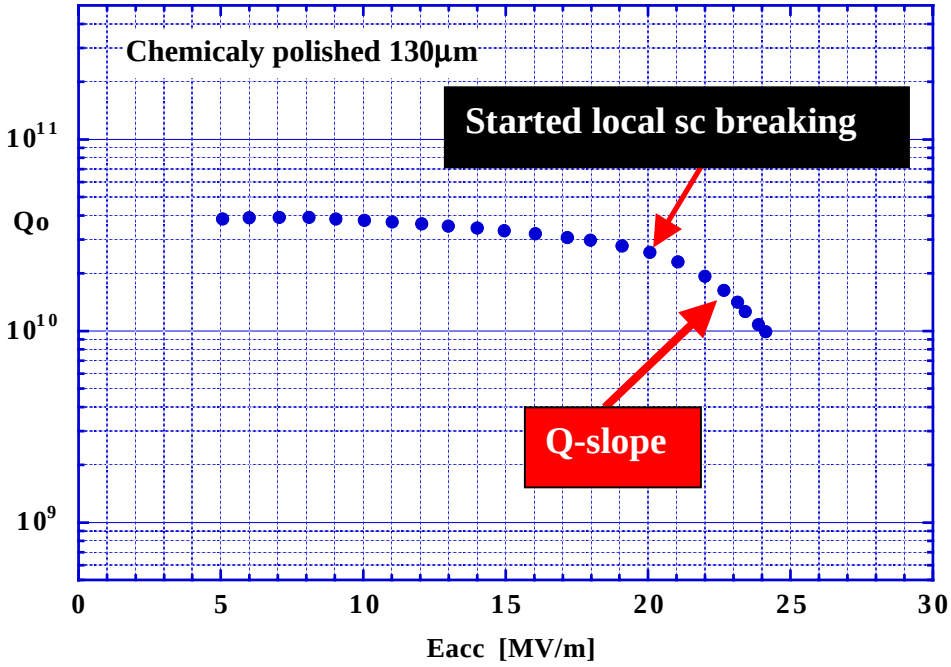
Successful stable operation at 35 MV/m for more than 1000 hours.
No degradation was seen in such a high gradient performance.

What happens in CP cavities at the high gradient?

Field enhancement by J.Knobloch

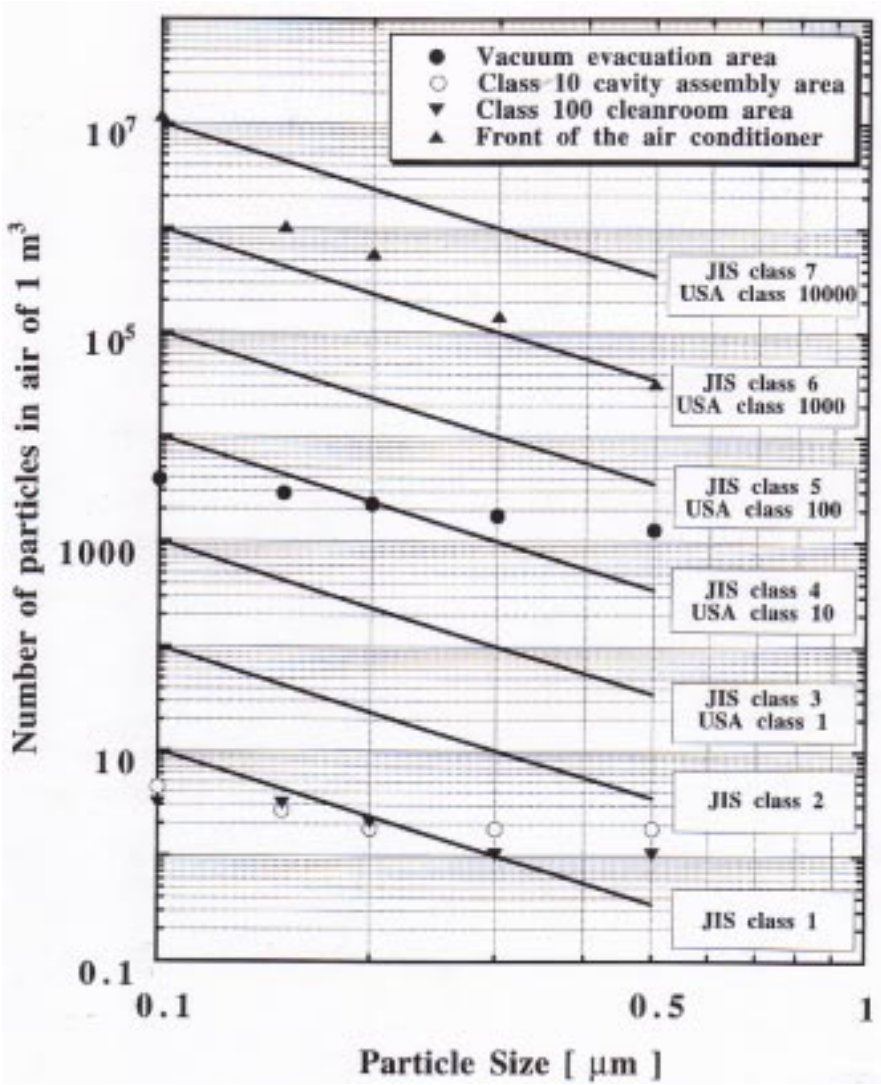




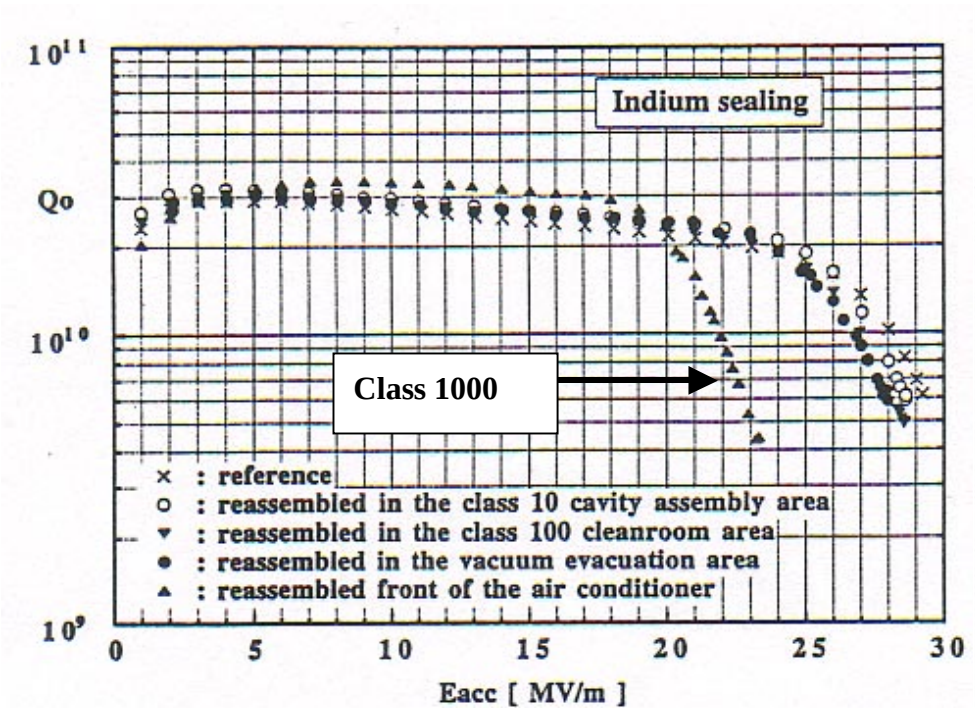


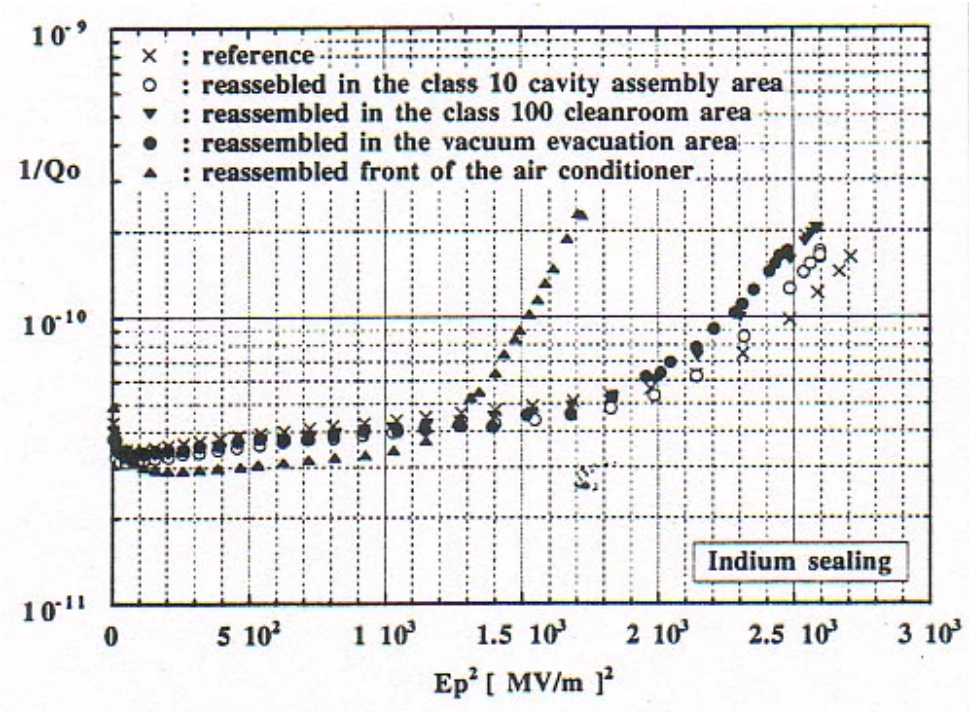
Eacc,max = 40 MV/m
Field enhancement ~ 2 40/2 = 20 MV/m
Local sc braking starts around 20MV/m
heating → Q-slope

Clean Assembly



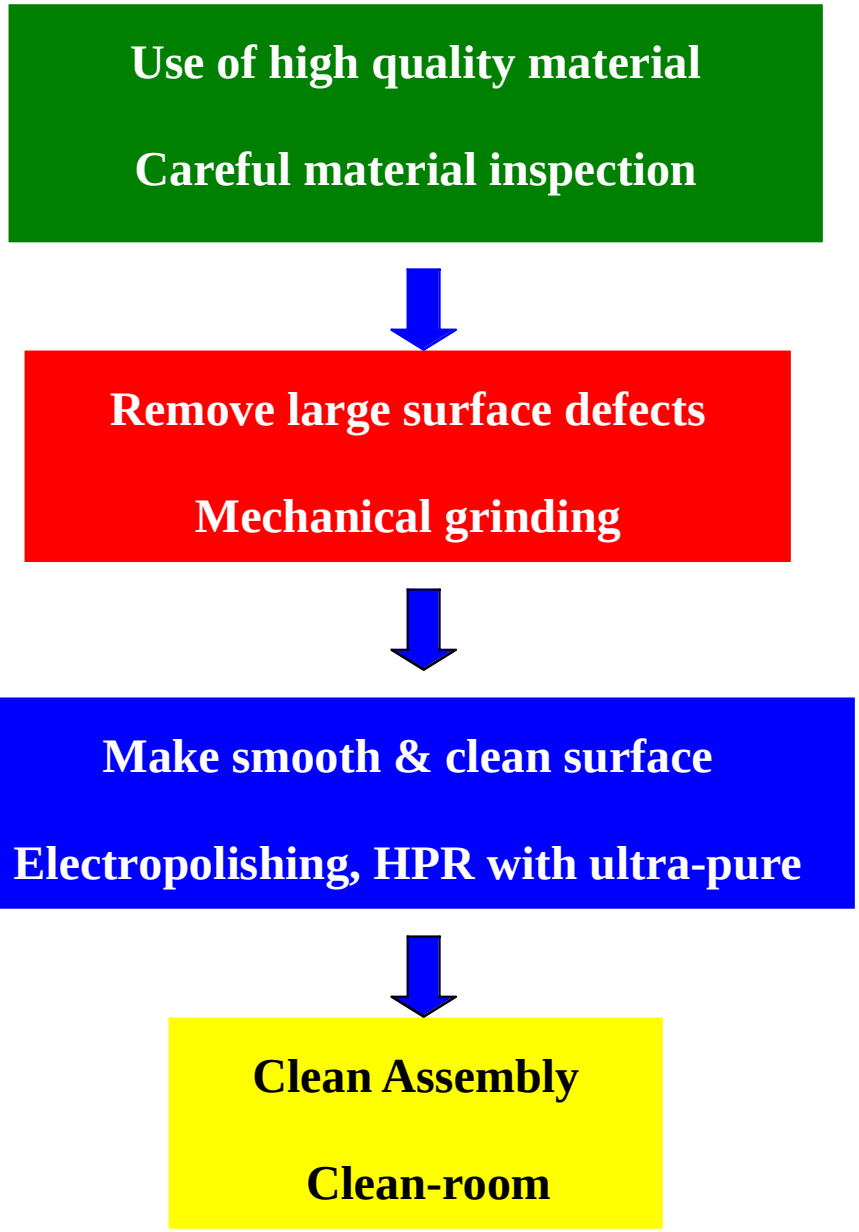
Cleanness and Field Emission





Cleanness must be better class 100 against field emission.

Procedure for High Gradient SC Cavity Fabrication



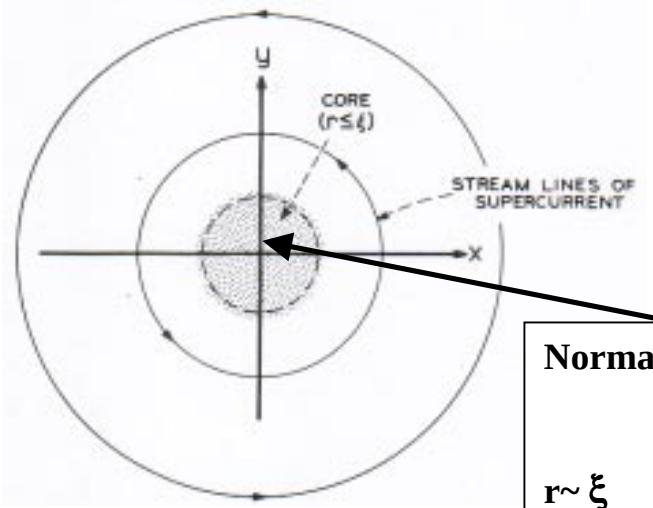
Fundamental Field Limitation

Vortex line nucleation model (VLNM)

$$(\lambda H_a)^2 = (\xi H_c)^2$$

$$\Rightarrow \quad H_{sh} = \frac{\xi}{\lambda}\cdot H_c = \frac{H_c}{\kappa}\ , \quad \kappa \equiv \frac{\lambda}{\xi} \quad \textbf{(GL - parameter)}$$

$$H_{sh}(T) = \frac{H_c(T)}{\kappa(T)}, \qquad \textbf{for AC application } H_{sh}(T) = \frac{\sqrt{2}H_c(T)}{\kappa(T)}$$

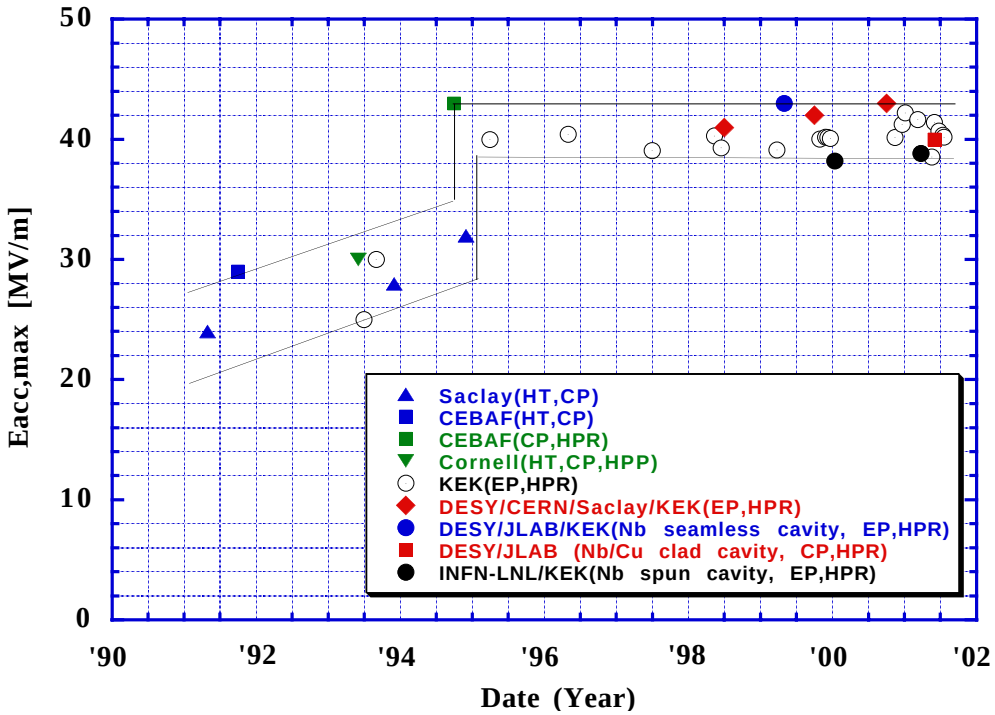


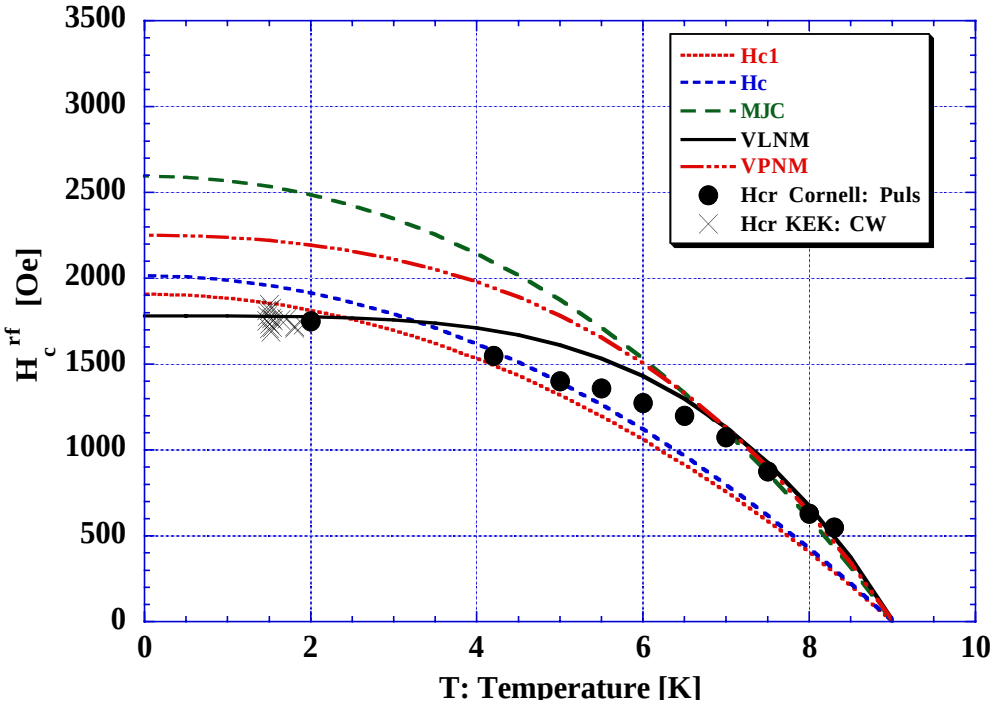
Flux line nucleation $\quad f = f_{core} + f_{mag} = -\pi\xi^2\frac{H_c^2}{8\pi} + \pi\lambda^2\frac{H_c^2}{8\pi} \le 0$

Normal core : condensation energy $\qquad$ **magnetic energy**

r~ ξ $\qquad f_{core} = -\pi\xi^2\frac{H_c^2}{8\pi} \qquad f_{mag} = \pi\lambda^2\frac{H_c^2}{8\pi}$

A way to TESLA 1000





The RF critical field of niobium might be limited around 1800 Oe by vortex line nucleation.

Resent cavity shape: Hp/Eacc = 42 ~ 44 ⇨ Eacc =1800/(42 ~ 44) = 43 ~ 41 MV/m

For beyond 40 MV/m, one should go to the cavity design with smaller Hp/Eacc ratio.

50 MV/m Hp/Eacc=36 ; TESLA 800 (35MV/m) ➡ TESLA 1000 (45MV/m)

Summary

1) **Today, the high gradient of niobium superconducting RF cavity has been achieved 40 MV/m with single cell cavities.**

2) **This achievement also has been done in TESLA cavities.**

3) **Current my understanding for high gradient cavity production is :**

   ■**Use high pure Nb material (RRR=200~300) with careful material inspection,**

   ■**Remove surface defects by mechanical grinding prior to chemical process,**

   ■**Make smooth surface using electropolishing,**

   ■**Finish clean surface by high pressure water rinsing.**

   ■**Assembly cavities in a clean-room better than class 100.**

4) **For the TEALA1000, the gradient must be upgraded to 45MV/m.**

Cavity shape with a smaller Hp/Eacc rato ~36 has to be redesigned for such a high gradient.