Basic Principles of SRF

High Energy Accelerator Research Organization
KEK, Accelerator Lab

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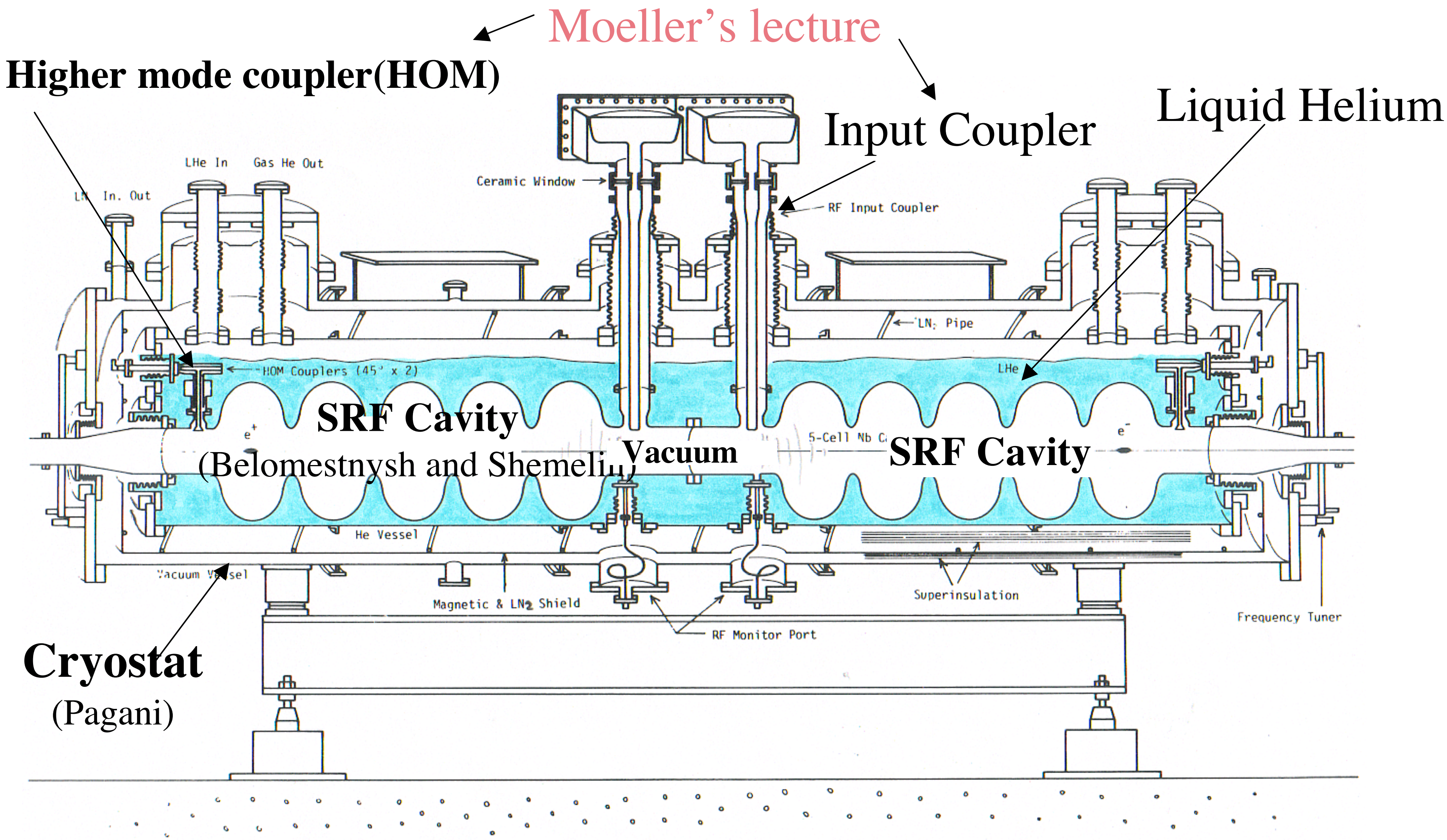
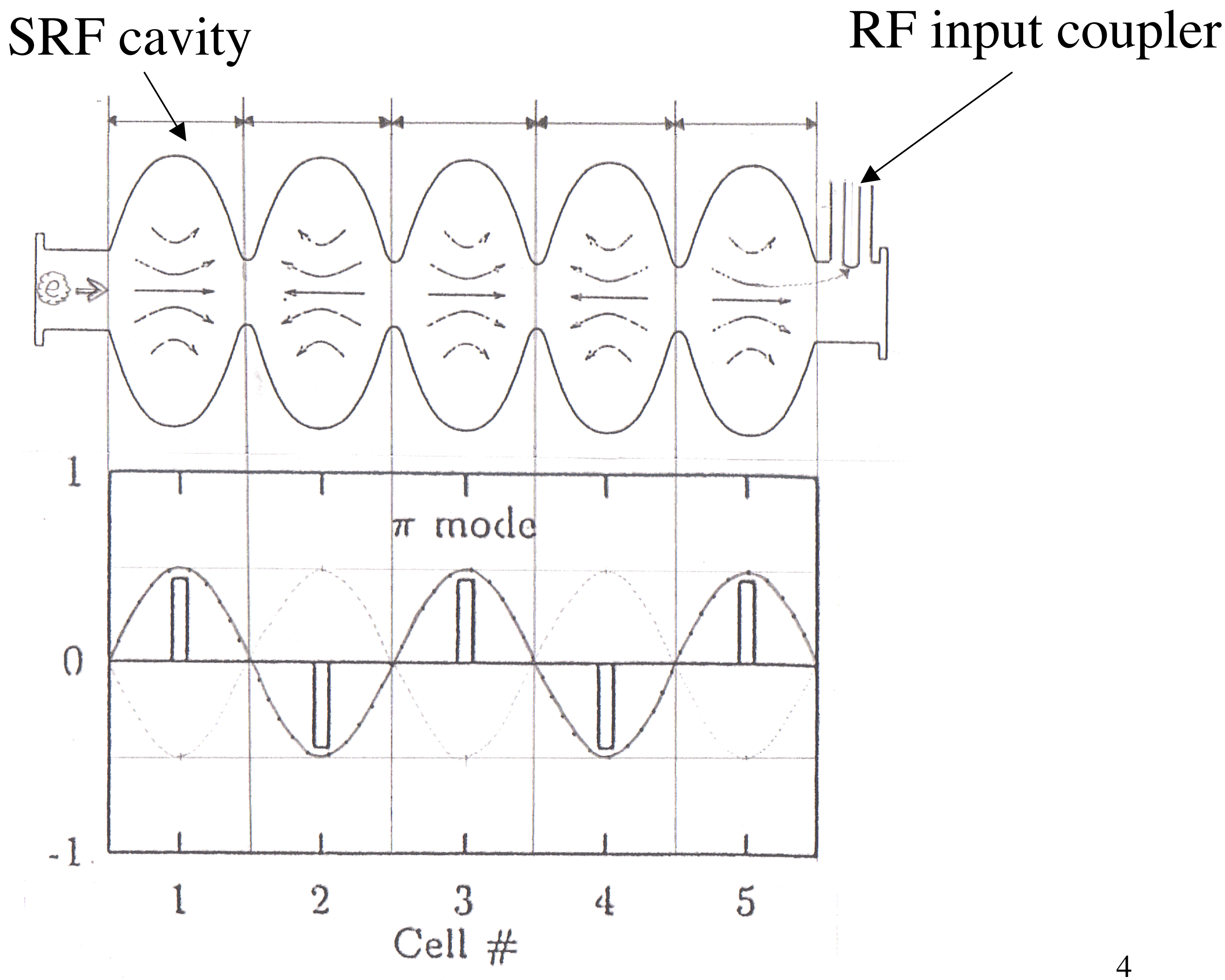
Introduction

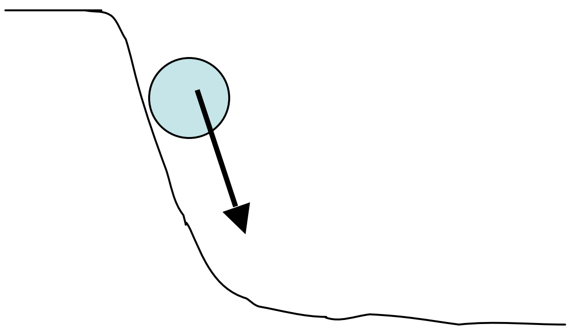
An example of real SRF Cryomodule (TRISTAN)

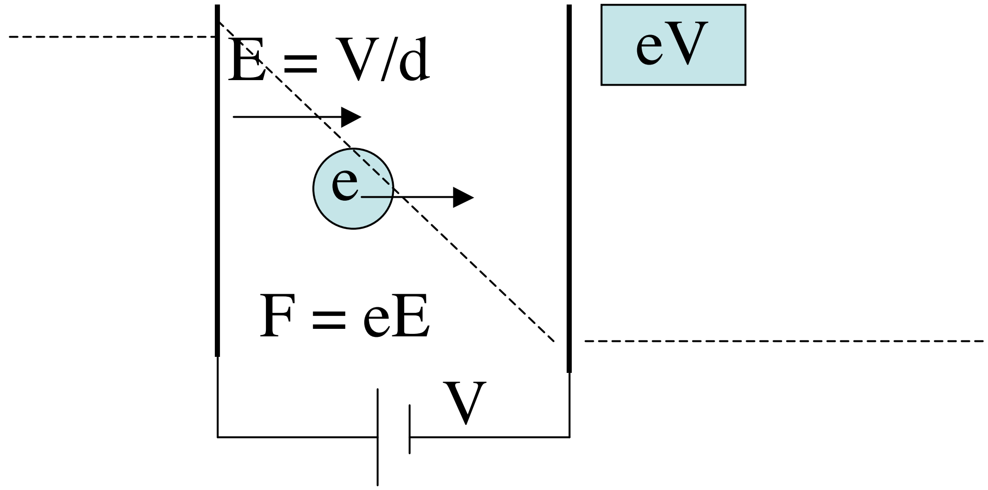


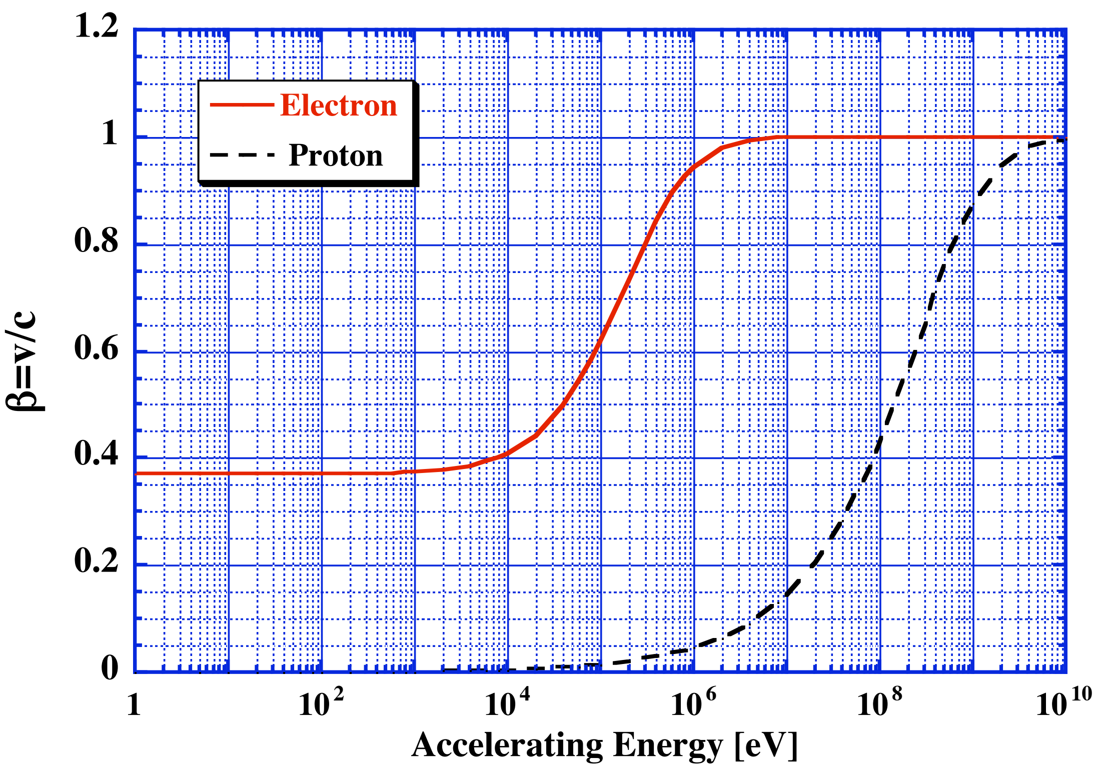
Principle of RF particle acceleration



Charged Particle Acceleration



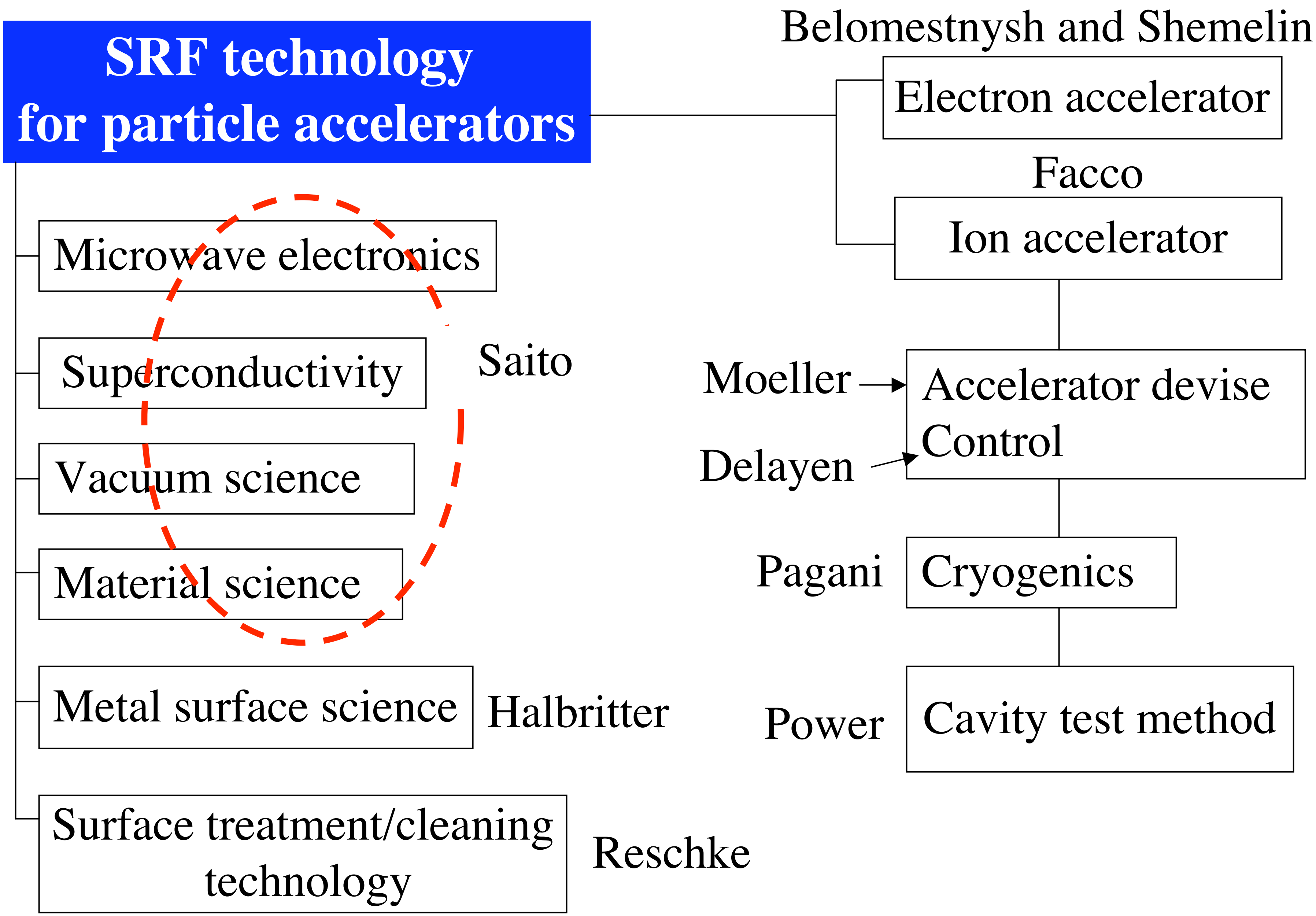




$$mc^2 = \frac{m_o c^2}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{m_o c^2}{\sqrt{1-\beta^2}} = m_o c^2 + W,$$

$$\beta = \sqrt{1-\left(\frac{m_o c^2}{m_o c^2 + W}\right)^2}, \quad m_e c^2 = 0.511 MeV,$$

$$m_p c^2 = 938.256 MeV$$


SRF technology
for particle accelerators
Belomestnysh and Shemelin
Electron accelerator
Facco
Ion accelerator
Microwave electronics
Superconductivity
Saito
Vacuum science
Material science
Moeller
Delayen
Accelerator devise Control
Pagani
Cryogenics
Metal surface science
Halbritter
Power
Cavity test method
Surface treatment/cleaning technology
Reschke

Q1: Why RF loss in SRF Cavities

Q2: What is the theoretical SRF field limitation

Q3: What kind of SC material is best for SRF application

Q4: Thermal Conductivity in Superconducting State and Residual Resistance Ratio (RRR)

Q5: Real SRF field limitation and Technologies to push gradient

Surface Impedance

For plane wave: $\vec{\mathbf{E}}_t = \vec{\mathbf{E}}_o \exp(i\vec{\mathbf{k}} \cdot \vec{\mathbf{x}} - i\omega t)$, $\quad \vec{\mathbf{H}}_t = \frac{1}{\mu\omega}\vec{\mathbf{k}} \times \vec{\mathbf{E}}_t$

here, k is orthogonal to E_t.

Surface impedance : $\quad Z \equiv R_s + iX_s \equiv \frac{E_t}{H_t} = \frac{\mu\omega}{k}$

For good conductor $\sigma >> 1$, $\quad k = (1+i)\sqrt{\frac{\mu\sigma\omega}{2}}$

$$Z = \mu\omega\sqrt{\frac{2}{\mu\sigma\omega}} \cdot \frac{1}{1+i} = \mu\omega\sqrt{\frac{2}{\mu\sigma\omega}} \cdot \frac{1-i}{2} = (1-i)\sqrt{\frac{\mu\omega}{2\sigma}}$$

$$\mathbf{R_s} = \sqrt{\frac{\mu\omega}{2\sigma}} = \frac{1}{\sigma}\sqrt{\frac{\mu\sigma\omega}{2}} = \frac{1}{\sigma\delta}$$

σ : electric conductivity

δ : skin depth

Why RF loss in SRF cavities

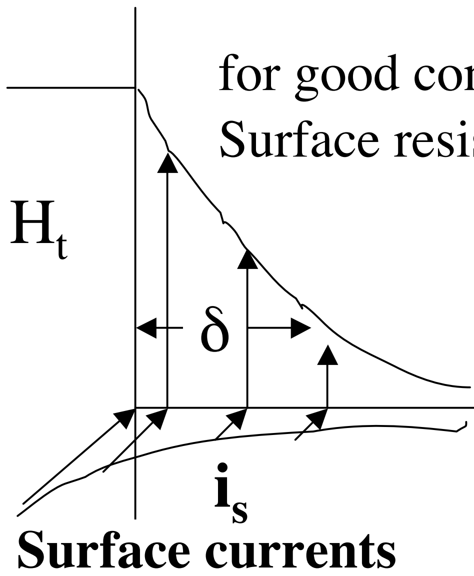
Normal conducting

δ : skin depth of microwave

for good conductor : $\frac{\sigma}{\omega\varepsilon} >> 1$

Surface resistance :

$$R_s = \sqrt{\frac{\mu\omega}{2\sigma}} = \frac{1}{\sigma\delta}$$



Metal

RF loss P

$$P = \frac{1}{2} R_s \int i_s^2 \, ds$$

$$= \frac{1}{2} R_s \int H_s^2 \, ds$$

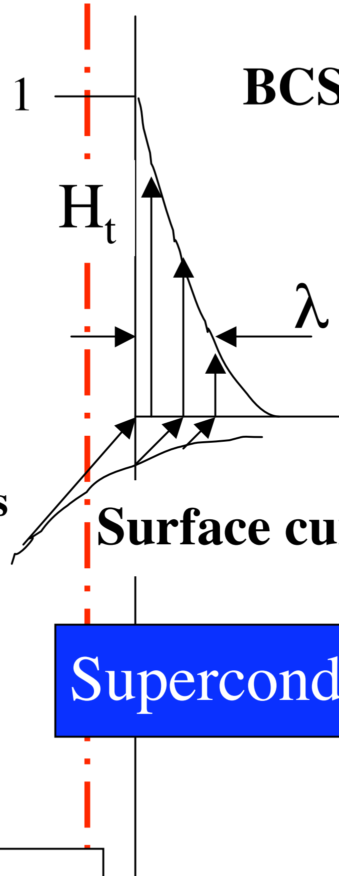
$Q_O = \omega U/Ploss = G/Rs$

Superconducting

λ : London penetration depth

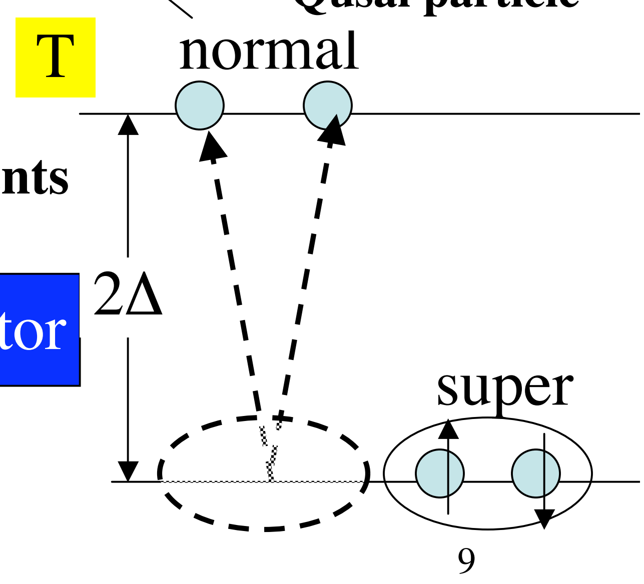
BCS theory

$$R_s \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$



Superconductor

$$e^{-\frac{\Delta}{k_B T}}$$



RF surface resistance in superconductor-Two Fluid model-

General equation: $m\frac{\partial \vec{v}}{\partial t} = q(\vec{E} + \vec{v} \times \vec{B}) - m\vec{v}\nu$

Two-fluid model

$$\vec{J} = \vec{J}_s + \vec{J}_n \;,\; \vec{J}_s = n_s q_s \vec{v}_s \;,\; \vec{J}_n = n_n q_n \vec{v}_n$$

Maxwell equation: niglecting the Lorentz term, $\vec{v} \times \vec{B} << 1$

$$m_s \frac{\partial \vec{v}_s}{\partial t} = q_s \vec{E},\; m_s = 2m_e,\; q_s = 2\cdot(-e)$$

$$m_e \frac{\partial \vec{v}_n}{\partial t} = q_n \vec{E} - m_e \nu \vec{v}_n \;,\; q_n = -e$$

$$\vec{E} = \vec{E}_o e^{i\omega t} \;\Rightarrow\; \vec{J}_s = \frac{n_s q_s^2}{i\omega m_s}\vec{E} \;,\quad \vec{J}_n = \frac{n_n e^2}{i(\omega - i\nu)}\vec{E}$$

$$\vec{J} = \left(\frac{n_s q_s^2}{i\omega m_s} + \frac{n_n e^2}{i(\omega - i\nu) m_e}\right)\vec{E}$$

$$\nu > \omega \;\Rightarrow\; \vec{J} = \left(\frac{n_n e^2}{\nu m_e} - i\frac{n_s q_s^2}{\omega m_s}\right)\vec{E} = (\sigma_n - i\sigma_s)\vec{E} = \sigma\vec{E}$$

$$\sigma = \sigma_n - i\sigma_s$$

$$Z = (1-i)\sqrt{\frac{\mu\omega}{2\sigma}} = (1-i)\sqrt{\frac{\mu\omega}{2(\sigma_n - i\sigma_s)}}$$

$$= (1-i)\sqrt{\frac{\mu\omega}{2}} \cdot \frac{1}{\sqrt{-i\sigma_s(1-\sigma_n / i\sigma_s)}}$$

$$\approx (1-i)\sqrt{\frac{\mu\omega}{2}} \cdot \frac{(1+\frac{\sigma_n}{i2\sigma_s})}{\sqrt{-i\sigma_s}}$$

$$= \sqrt{\mu\omega}\left(\frac{\sigma_n}{2\sigma_s^{3/2}} + i\frac{1}{\sigma_s^{1/2}}\right) \qquad \because \sqrt{-i} = \sqrt{e^{-\frac{\pi}{2}}} = \frac{(1-i)}{\sqrt{2}}$$

$$\boxed{Z = \frac{\mu\omega\lambda^3}{\delta^2} + i\mu\omega\lambda = \frac{\mu^2\omega^2\lambda^3\sigma_n}{2} + i\omega\mu\lambda}$$

Here, $\lambda = \sqrt{\frac{m_s}{n_s q_s^2 \mu}} = c\sqrt{\frac{2m}{4n_s\mu e^2}} = c\sqrt{\frac{m}{2n_s\mu e^2}}$ London penetration depth

Surface resistance in superconductor

$$\sigma_n = \frac{n_n \cdot e^2 \cdot l}{m \cdot v_F} = \frac{e^2 \cdot l}{m \cdot v_F} \cdot n_s(T=0) \cdot e^{-\frac{\Delta}{k_B \cdot T}}$$

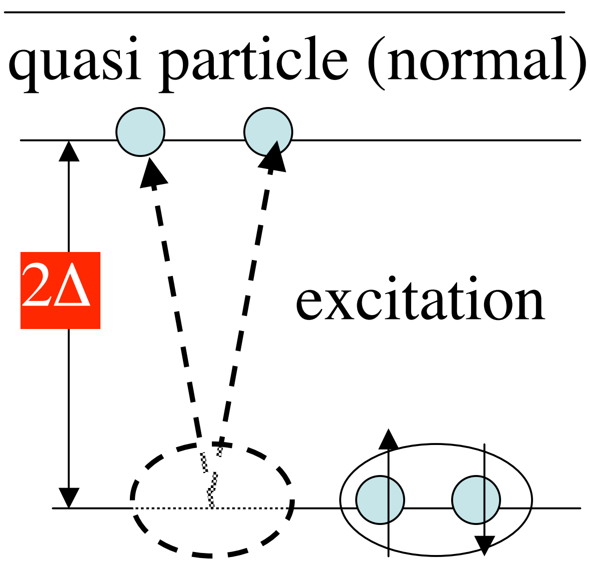
$$R_S = \frac{1}{2} \cdot (2\pi)^2 \cdot \mu^2 \cdot f^2 \cdot \lambda_L^3 \cdot l \cdot \frac{n_s(0)}{m v_F} \cdot e^{-\frac{\Delta}{k_B T}}$$

$$= A \cdot f^2 \cdot e^{-\frac{\Delta}{k_B T}}$$

BCS theory

$$R_{BCS}(T, f) = A(\lambda, \xi, l, Tc) \cdot \frac{f^2}{T} \cdot e^{-\frac{\Delta}{k_B T}}$$

At a finite temperature T



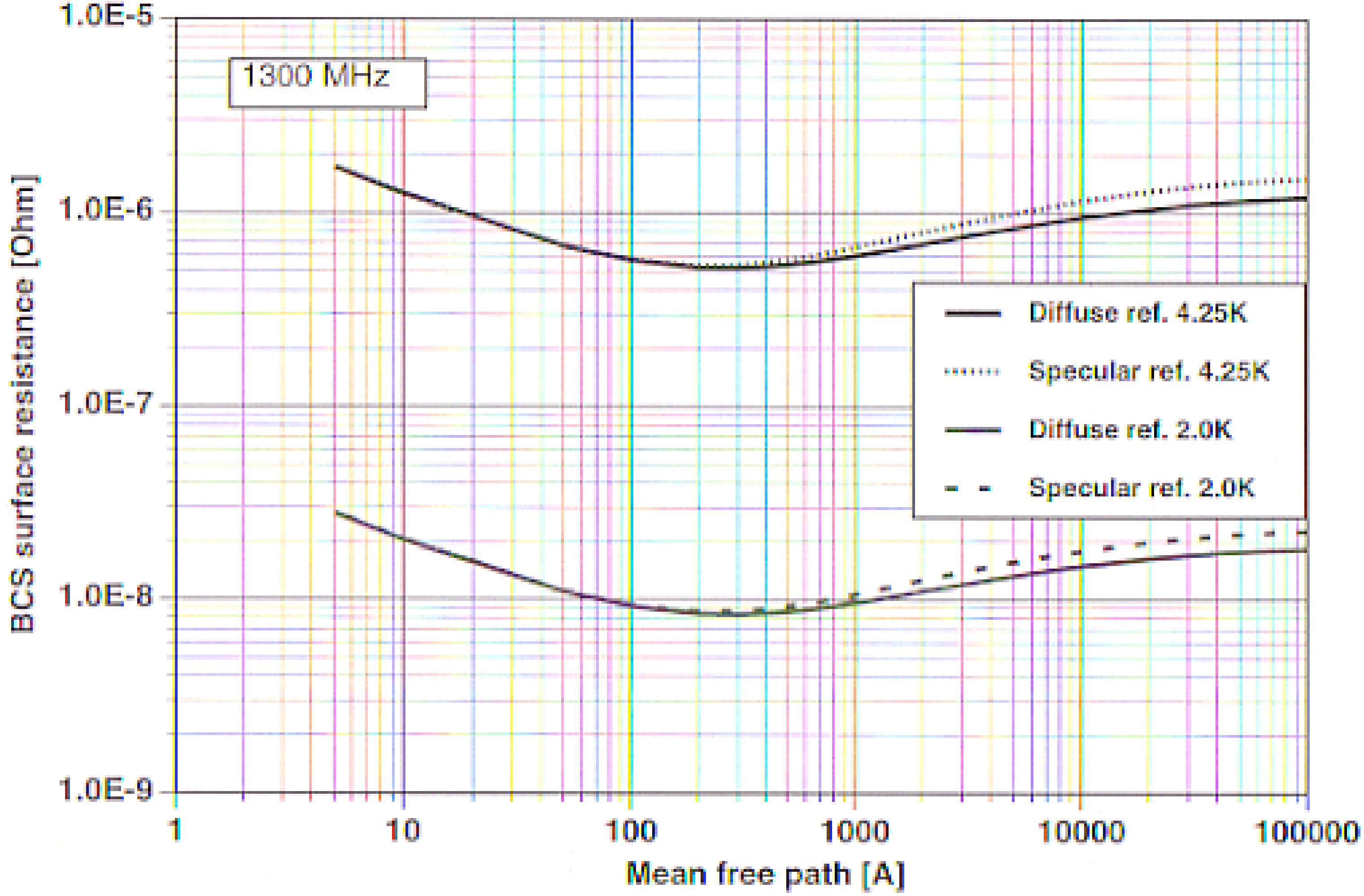
Superconducting state

$\Delta/k_B = 1.76 T_C$ by BCS theory

Higher T_c material produces lower R_{BCS}

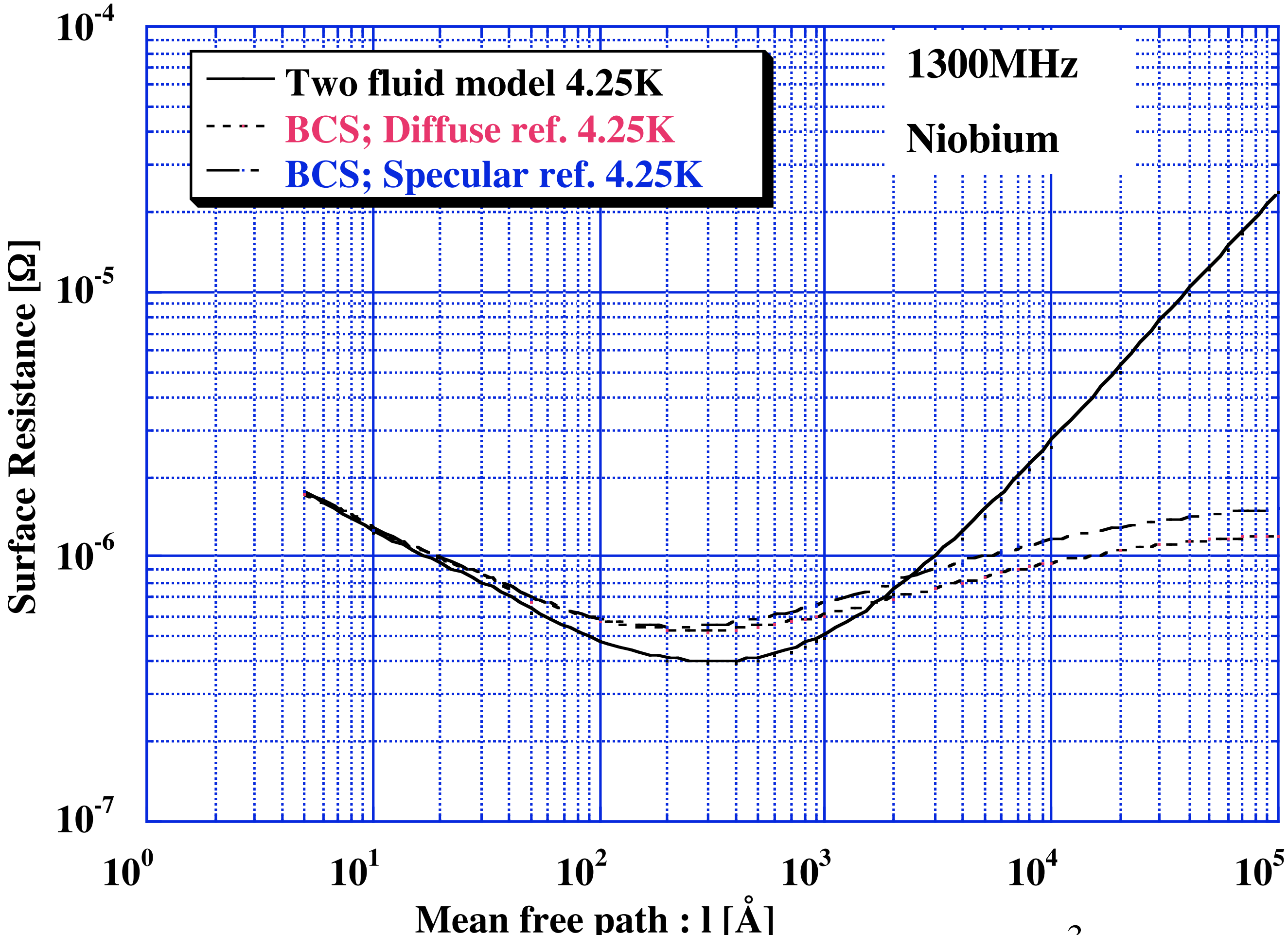
R_{BCS} at 2 and 4.25K

Used Harbritter's code



R_{BCS} ~ 8nΩ @ 2K, 1300MHz

Minimum of R_{BCS}



Strange behavior of R_{BCS} for mean free pass l

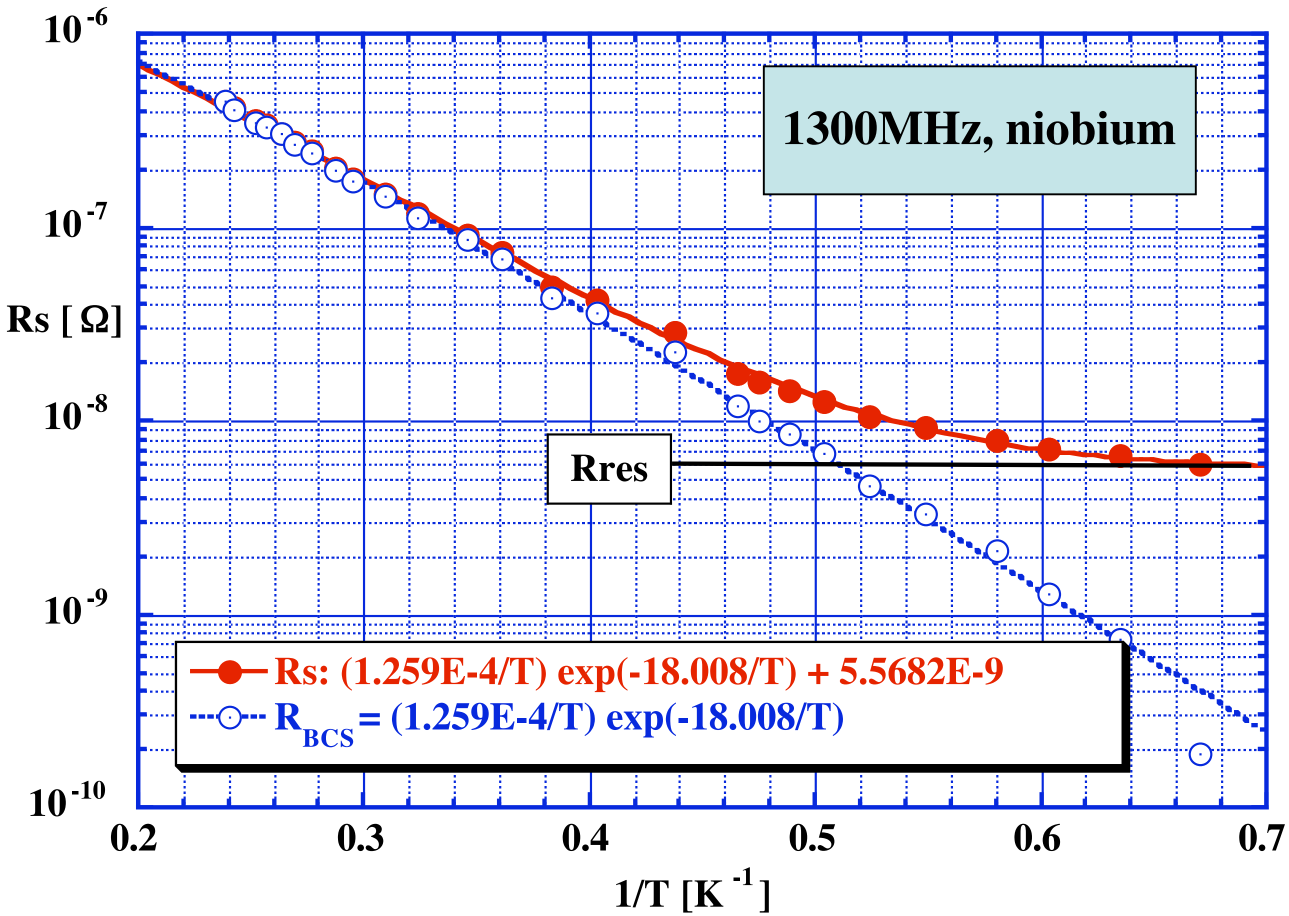
R_{BCS} minimum at

$l \approx$ **200 ~ 300** Å

$$l[A] = 20 \cdot \mathbf{RRR}$$

$$\lambda_L(l) = \lambda_L(l=\infty)\cdot\sqrt{1+\frac{\xi_o}{l}},\ R_S(TF\ model) \propto (1+\frac{\xi_o}{l})^{\frac{3}{2}}\cdot l,\quad l<<1, R_S \rightarrow \frac{\xi_o^{\frac{3}{2}}}{\sqrt{l}},\ l>>1, R_s \rightarrow l$$

Measurement of the Surface resistance



$$\frac{\Delta}{k_B} = 18.008 \Rightarrow \frac{2\Delta}{k_B T_c} = \frac{2 \cdot 18.008}{9.25} = 3.89$$

$$\frac{2\Delta}{k_B T_c} = 3.52 \text{ (BCS theory)}$$

Due to surface contamination、residual magnetic field in the cryostat.

$R_{BCS} \sim 8n\Omega$,
Quit fit to BCS theory.

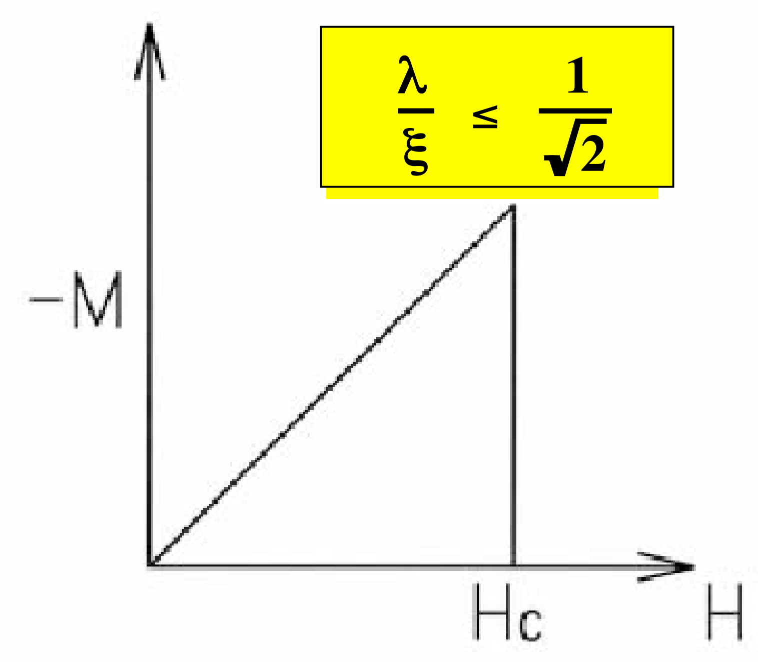
Real surface resistance : $R_S = R_{BCS}(T) + Rres$

Q2: Theoretical SRF field limitation
Q3: What kind of SC material is best for SRF application ?

Two types of superconductor

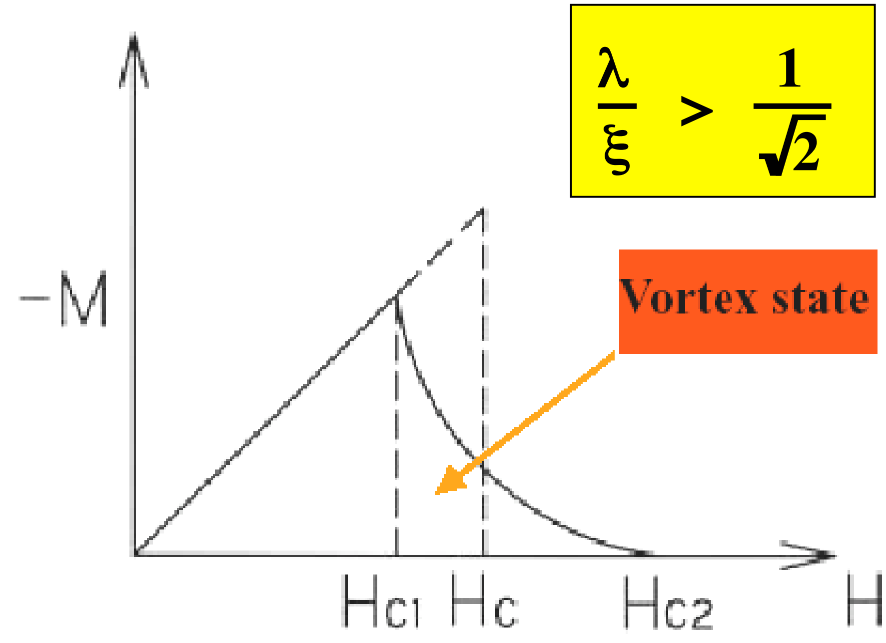
Type-I

$$\frac{\lambda}{\xi} \le \frac{1}{\sqrt{2}}$$



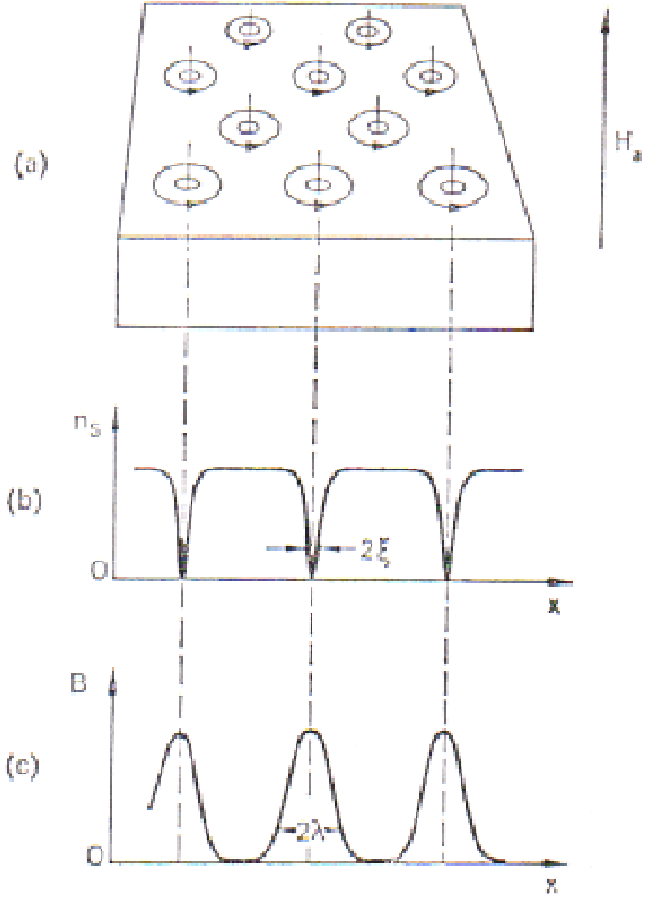
Type-II

$$\frac{\lambda}{\xi} > \frac{1}{\sqrt{2}}$$



$$\frac{\lambda}{\xi} \equiv \kappa : \textbf{Gintzburg - Landau Parameter}$$

Vortex state



Vortex state

ξ : Coherence length
size of Cooper pair

Observed vortex

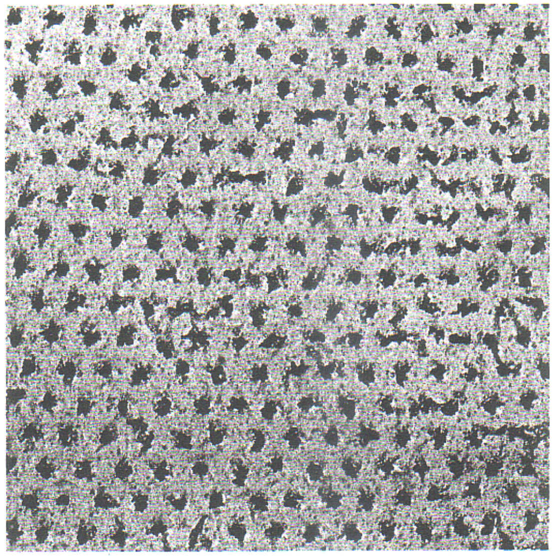


Figure 19 Triangular lattice of fluxoids through top surface of a superconducting cylinder. The points of exit of the flux lines are decorated with fine ferromagnetic particles. The electron microscope image is at a magnification of 8300, by U. Essmann and H. Träuble.

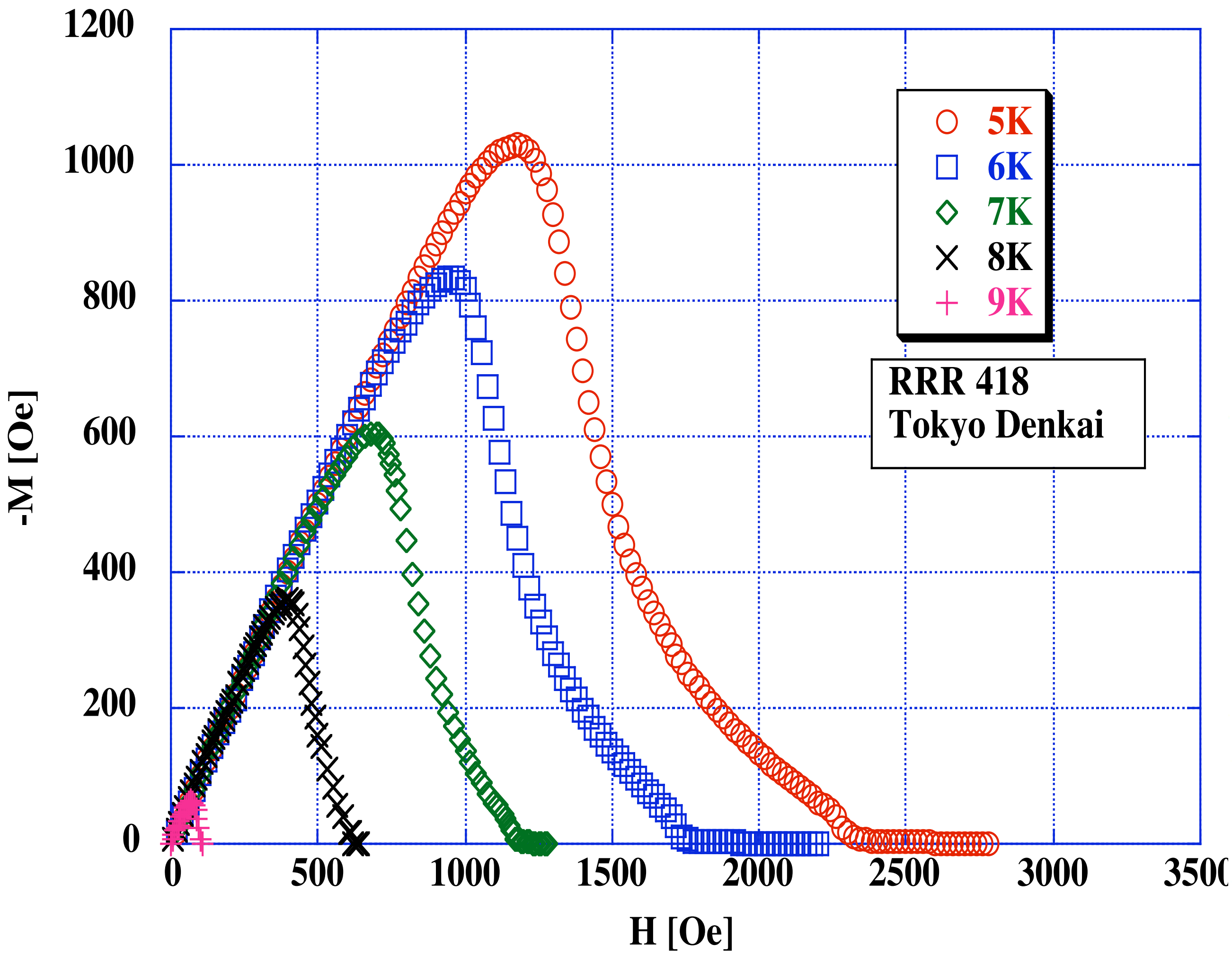
λ_L : London penetration depth

Depth of penetration of the magnetic field

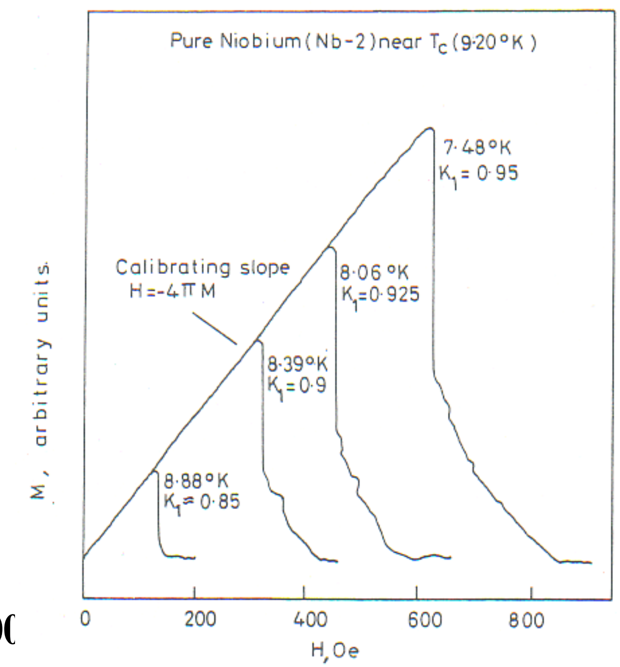
Hc measurement

Industrial material

Industrial Nb material is how different With magnetic property from lab material.



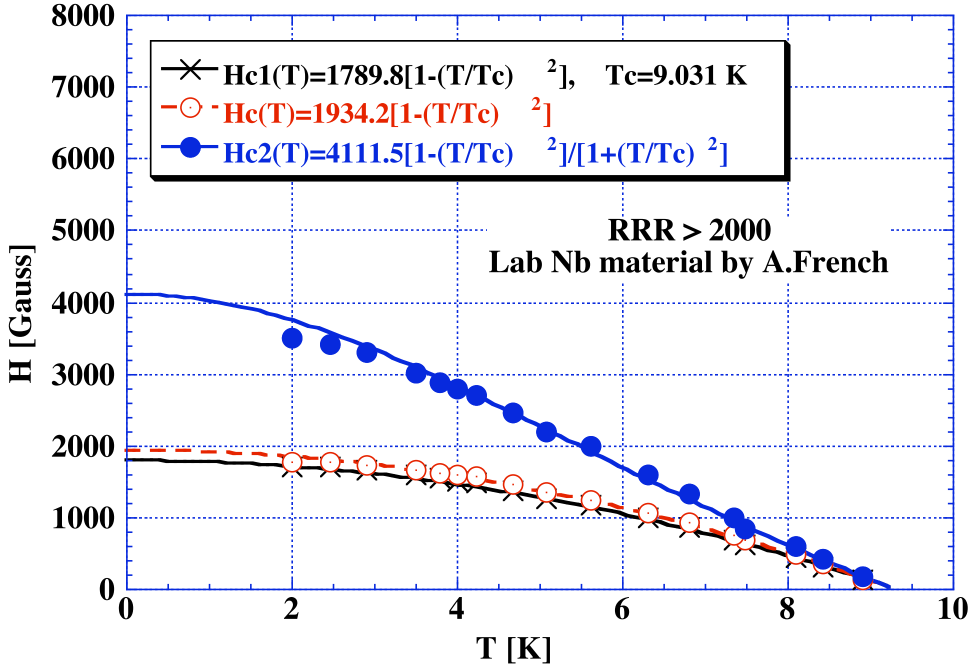
Lab material RRR~2000



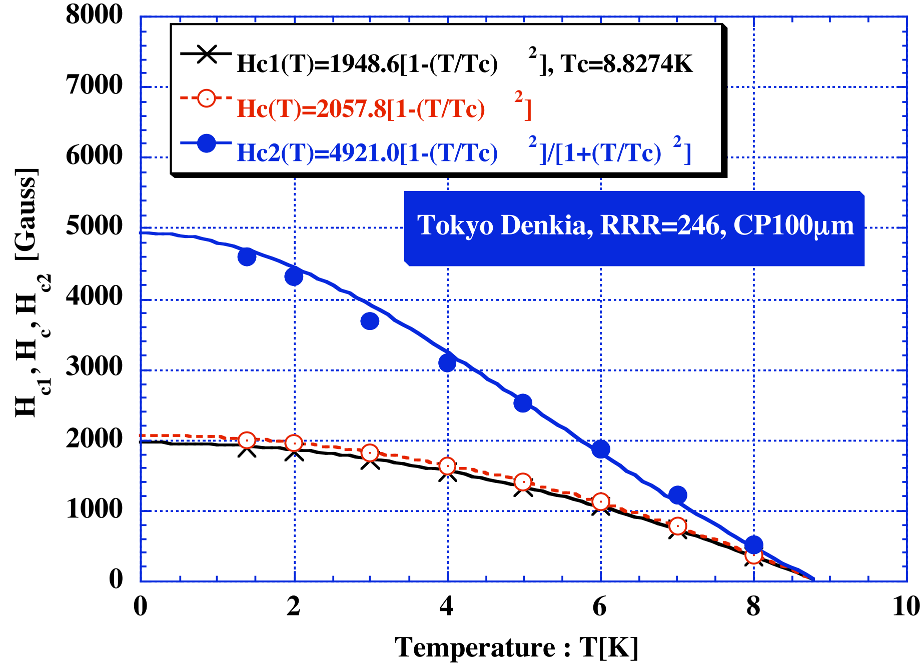
$$F_n - F_s = -\int_0^{H_{c2}} M dH = \frac{1}{2}\mu H_c^2$$

Measurement results with H_{C1}, H_C, H_{C2}

Lab Nb material



Industrial produced Nb material



$$H_c(T) = H_c(0)\cdot\left[1-\left(\frac{T}{T_c}\right)^2\right],\quad F_n - F_s = -\int_0^{H_{c2}} M\,dH = \frac{1}{2}\mu H_c^2$$

$$\mathrm{Hc2(T)} = \mathrm{Hc2(0)}\cdot\frac{[1-(T/Tc)^2]}{[1+(T/Tc)^2]}$$

Later you will derive this from Abrikosov theory.

Abrikosov Theory: Theory for Type-II SC

$$H_c = \frac{\kappa}{\lambda^2}\frac{\hbar c}{\sqrt{2}e^*} = \frac{\kappa}{\lambda^2}\frac{(hc/2e)}{2\pi\sqrt{2}} = \frac{\phi_0}{2\pi\sqrt{2}\lambda\xi}$$

$$H_{c2} = \sqrt{2}\frac{\lambda}{\xi}\frac{\phi_0}{2\pi\sqrt{2}\lambda\xi} = \frac{\phi_0}{2\pi\xi^2}$$

$$H_{c1} = \frac{\phi_o}{4\pi\lambda^2}\ln\left(\frac{\lambda}{\xi} + 0.08\right)$$

$$\phi_0 = hc/2e = 2.0678 \times 10^{-7}\, Gauss \cdot cm^2$$

$$= 2.0678 \times 10^{-15}\ T \cdot m^2$$

T-dependence of λ, ξ, κ

Abrikosov theory

$$\xi = \sqrt{\frac{\phi_o}{2\pi \cdot H_{c2}}}, \quad \lambda = \sqrt{\frac{\phi_o \cdot H_{c2}}{4\pi \cdot H_c^2}}$$

From both theory and experiment λ(T),Hc(T) are:

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}, \quad H_c(T) = H_c(0) \cdot \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

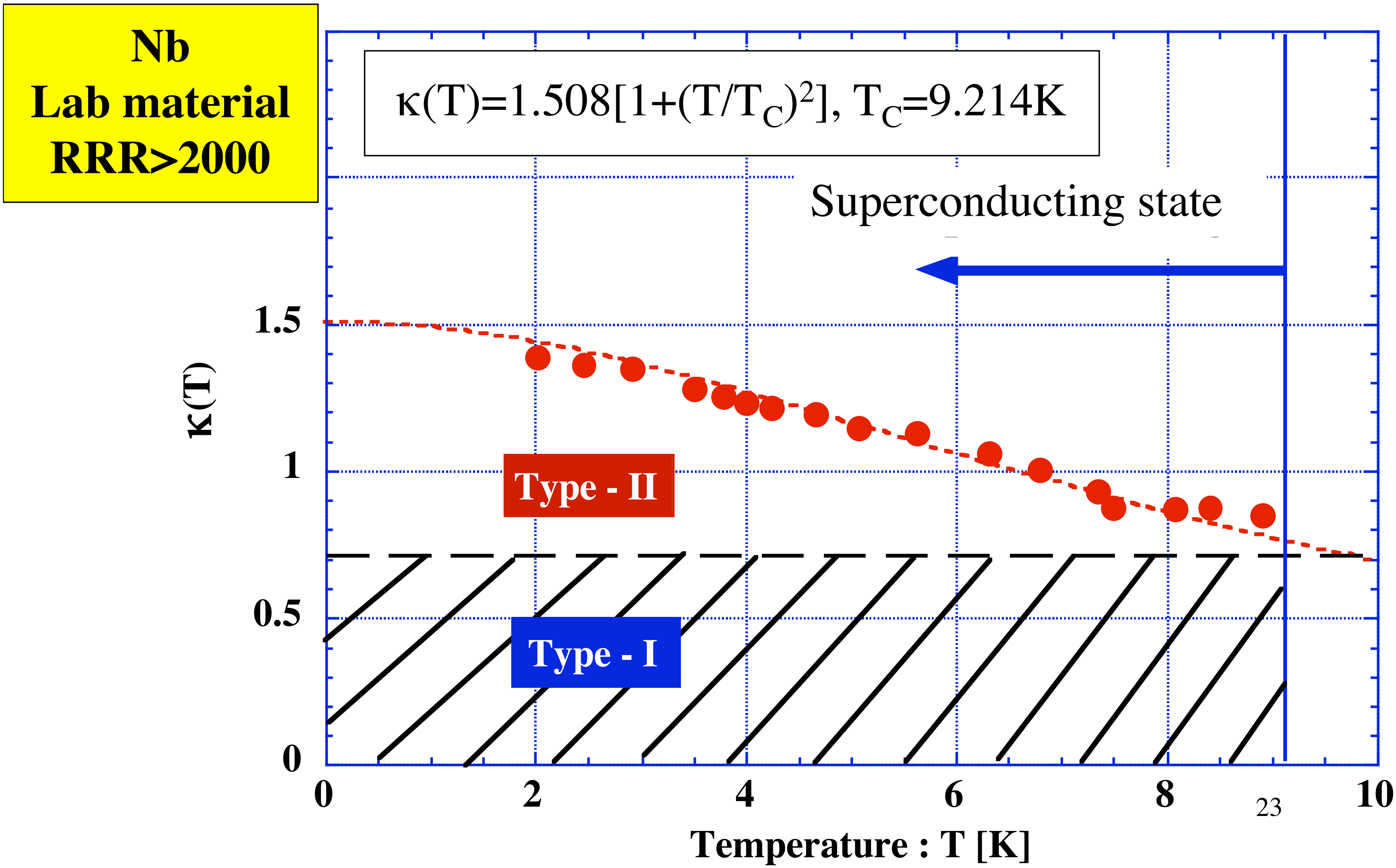
$$H_{c2}(T) = \frac{4\pi\lambda(T)^2}{\phi_o} \cdot H_c(T)^2 = \frac{4\pi\lambda(0)^2 \cdot H_c(0)^2}{\phi_o} \cdot \frac{\left[1-(T/T_c)^2\right]^2}{1-(T/T_c)^4}$$

$$= H_{c2}(0) \cdot \frac{1-(T/T_c)^2}{1+(T/T_c)^2}$$

$$\xi(T) = \sqrt{\frac{\phi_o}{2\pi \cdot H_{c2}(0)}} \cdot \sqrt{\frac{1+(T/T_c)^2}{1-(T/T_c)^2}} = \xi(0) \cdot \sqrt{\frac{1+(T/T_c)^2}{1-(T/T_c)^2}}$$

$$\frac{\lambda(T)}{\xi(T)} \equiv \kappa(T) = \frac{1}{\sqrt{2}} \cdot \frac{H_{c2}(T)}{H_c(T)} = \frac{H_{c2}(0)}{\sqrt{2} \cdot H_c(0)} \cdot \frac{1}{1+(T/T_c)^2} = \frac{\kappa(0)}{1+(T/T_c)^2}$$

T-dependence of κ with Lab material



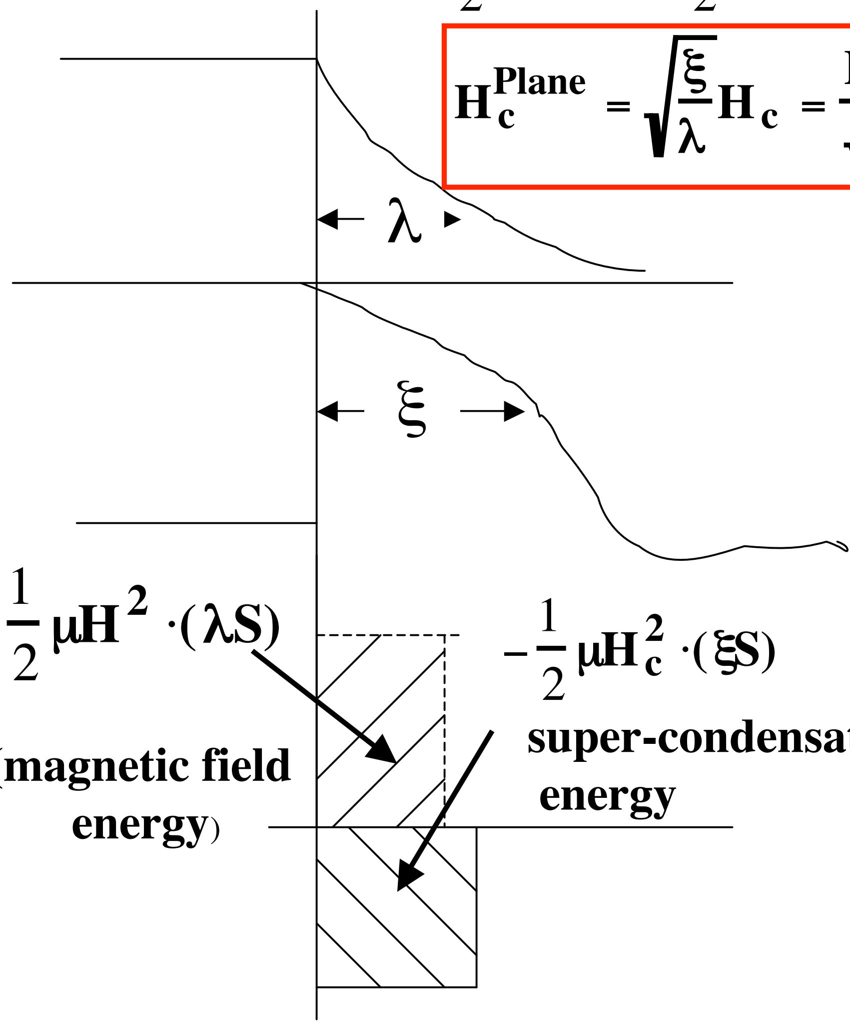
Critical field limitation in SRF application

Vortex plane nucleation Type-I

H:effective value

$$\frac{1}{2}\mu H^2 \cdot \lambda - \frac{1}{2}\mu H_c^2 \cdot \xi = 0$$

$$H_c^{Plane} = \sqrt{\frac{\xi}{\lambda}} H_c = \frac{H_c}{\sqrt{\kappa}}$$



$$\frac{1}{2}\mu H^2 \cdot (\lambda S)$$

(magnetic field energy)

$$-\frac{1}{2}\mu H_c^2 \cdot (\xi S)$$

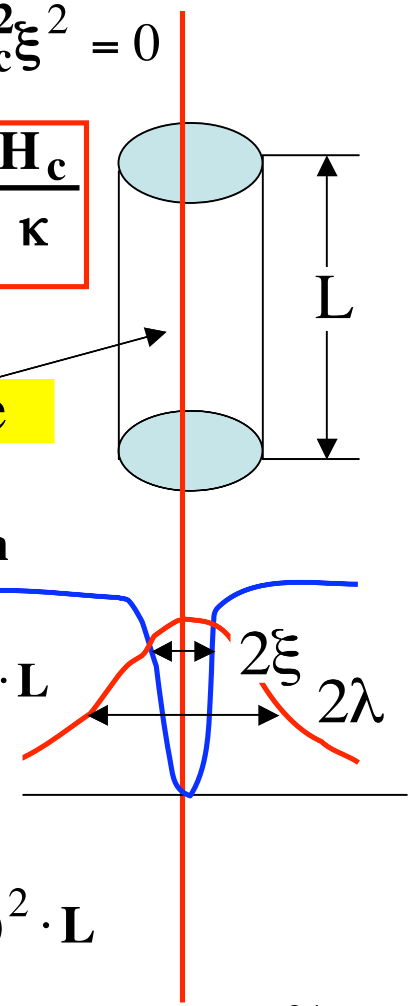
super-condensation energy

Vortex line nucleation Type-II

$$\frac{1}{2}\mu H^2 \lambda^2 - \frac{1}{2}\mu H_c^2 \xi^2 = 0$$

$$H_c^{Line} = \frac{\xi}{\lambda} H_c = \frac{H_c}{\kappa}$$

Vortex line



super-condensation energy

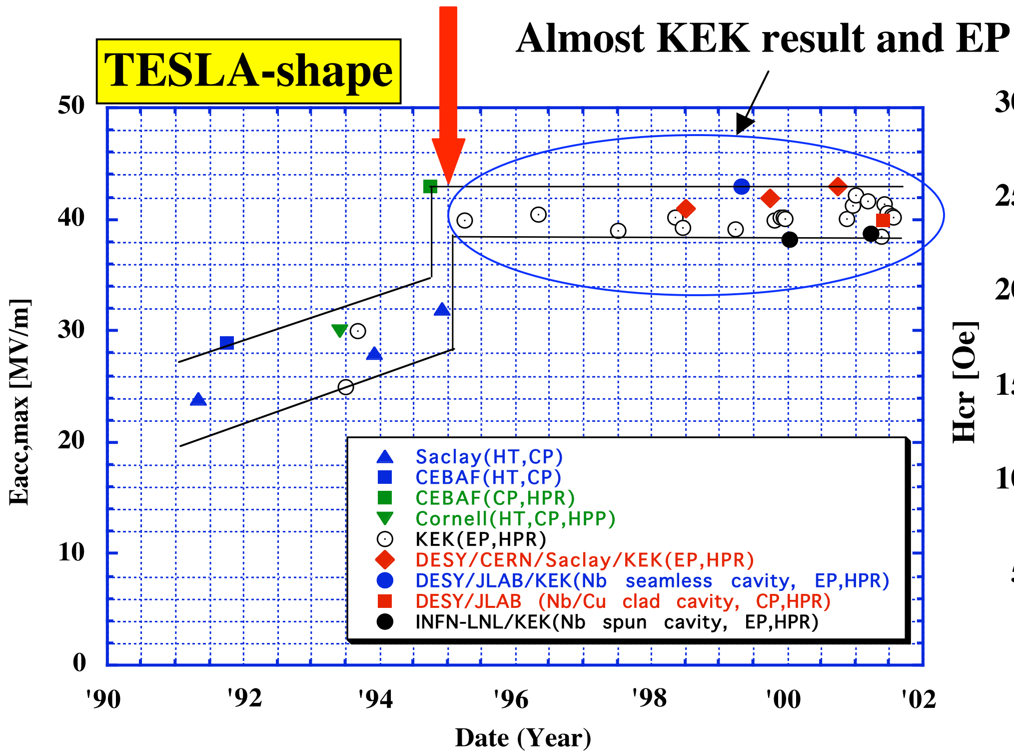
$$-\frac{1}{2}\mu H_c^2 (\pi \xi^2) \cdot L$$

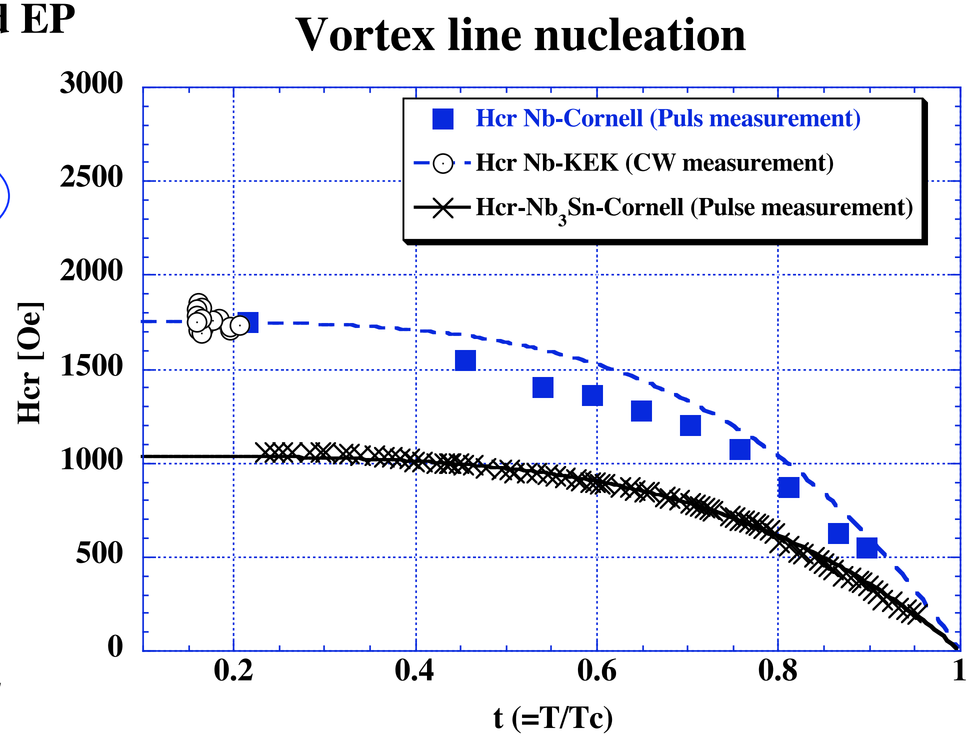
magnetic field energy

$$\frac{1}{2}\mu H^2 (\pi \lambda)^2 \cdot L$$

High Gradient Limitation of Type-II SRF cavities

Saito thesis : SRF Workshop 2001





$$H_{cr}(T) = \frac{\xi(T)}{\lambda(T)} \cdot \sqrt{2}H_c(T) = \frac{\sqrt{2}H_c(T)}{\kappa(T)} = \sqrt{2}\,\frac{H_c(0)}{\kappa(0)} \cdot \left[1 - \left(\frac{T}{T_c}\right)^4\right] \qquad H_{cr}^{Nb}(t) = 1750 \cdot [1 - t^4]$$

Eacc ~ 50 MV/m is still reachable if one changes cavity shape with a smaller Hp/Eacc (= 35 Oe / [MV/m]) ratio.

Which material is best ?

Material point of view:

- Smaller heat loading for refrigerator ➡ Higher T_C
- High gradient
  $H_{RF} > H_C^{RF}$, then normal conducting

$$H_c^{RF} = \sqrt{2} \cdot \frac{H_c}{\kappa}, \ \kappa : \text{G - L parameter}$$

The material with higher Hc and smaller κ-value

If Hc is high enough, Type-I material is better because of the smaller κ-value.

- Good formability

Materials	Tc [K]	Hc, Hc1 [Gauss]	κ	Type	Fabrication
Pb	7.2	803, -	0.65	I	Electroplating
Nb	9.25	1900, 1700	1.5	II	Deep drawing, film
Nb3Sn	18.2	5350, 300	7	II	Film
MgB2	39	4290, 300		II	Film

Niobium has higher Tc, Hc and enough formability.
Now, niobium is widely used for RF sc cavity production.

Q4: Thermal Conductivity in Superconducting State and Residual Resistance Ratio (RRR)

Thermal conductivity measurement

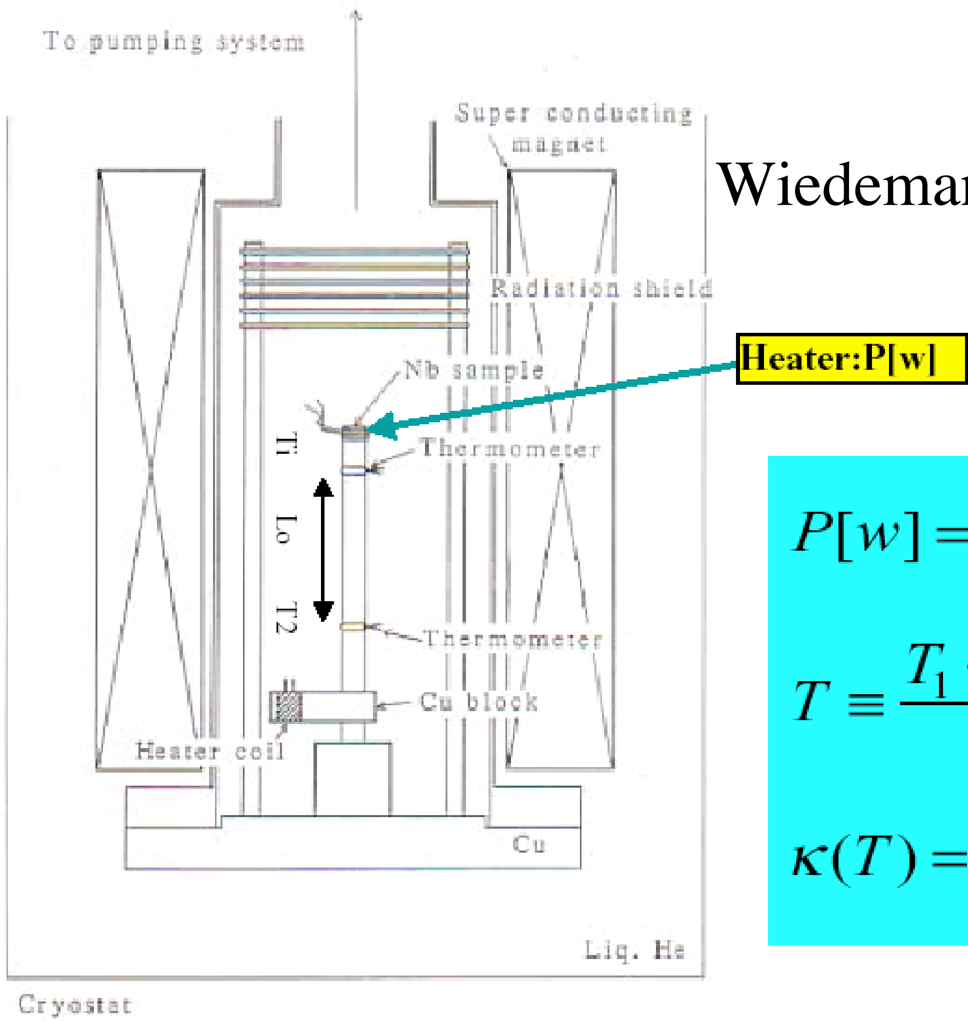
Normal conductor : $\kappa_{en} = \frac{1}{W_{en}} = \left[\frac{\rho}{L_O T} + aT^2 \right]^{-1}$

$\rho = \frac{\rho_{300K}}{RRR}$ e-impurities scatt.

e-lattices scatt.

Wiedemann-Franz low:

$$\kappa_e = \frac{\pi^2 n k_B^2 \tau}{3m} \cdot T, \quad \frac{\kappa_e}{\sigma} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 \cdot T = L_O T$$



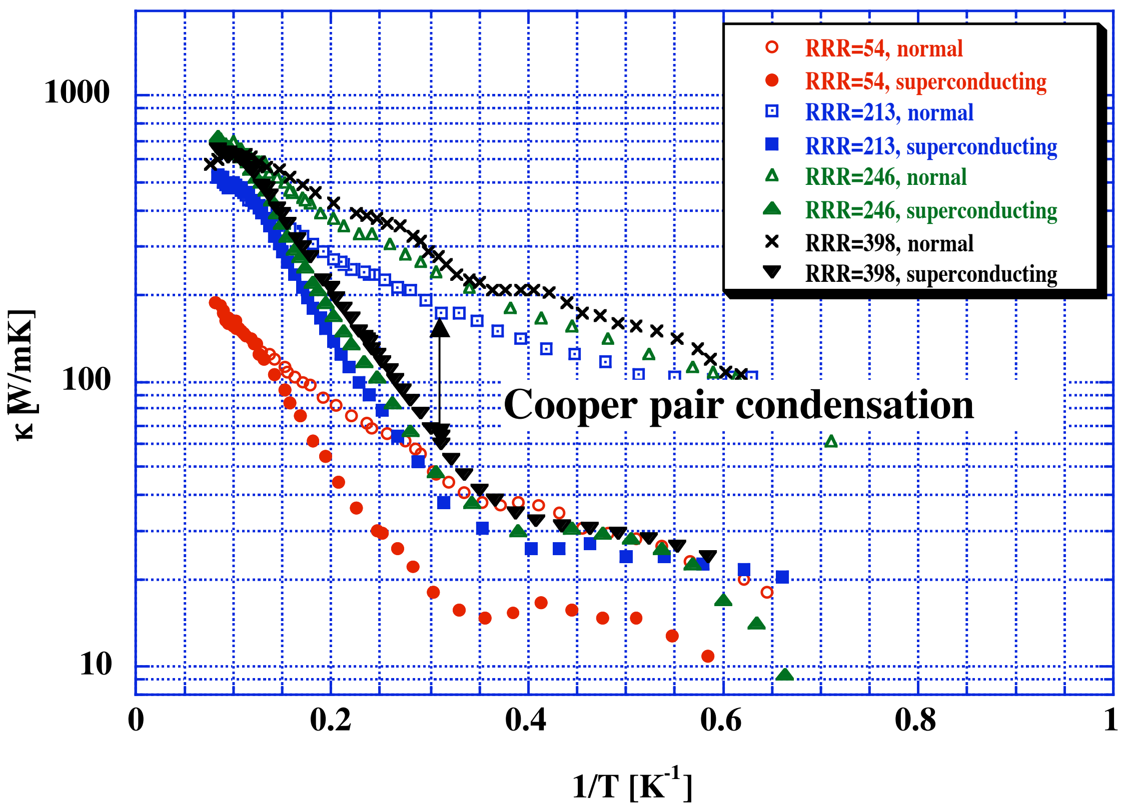
$$P[w] = S(m^2) \cdot \kappa(T) \cdot \frac{T_1(K) - T_2(K)}{L_O(m)}$$

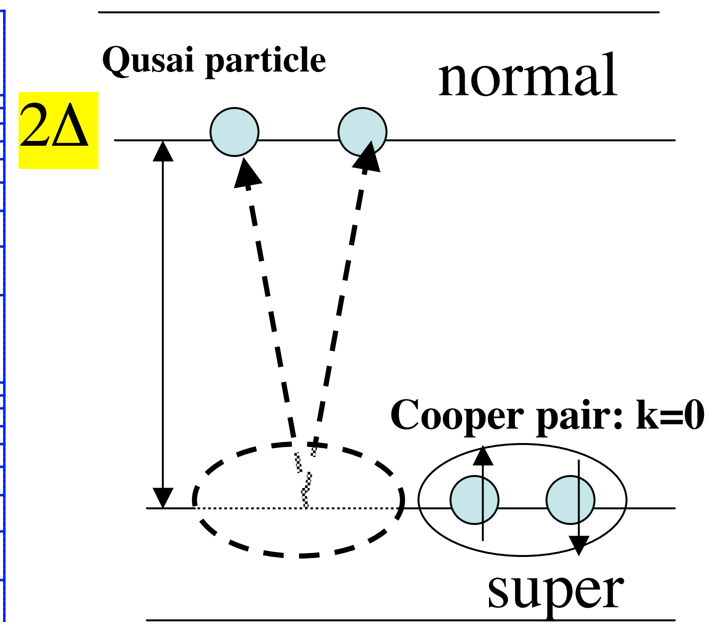
$$T \equiv \frac{T_1 + T_2}{2}, \; S\text{: area of cross-section}$$

$$\kappa(T) = \frac{P}{S} \cdot \frac{L_O}{T_1 - T_2} \qquad [\frac{w}{m \cdot K}]$$

Thermal conductivity of Nb material at low temperature

Boltzmann statistics : energy Δ, Temp.
Excitation probability @T and energy Δ → $\exp(-\frac{\Delta}{k_B \cdot T})$





Calculation of thermal conductivity based on Quantum mechanics

$$\kappa_s(T) = R(y)\cdot\left[\frac{\rho_{295K}}{L\cdot RRR\cdot T} + a\cdot T^2\right]^{-1} + \left[\frac{1}{D\cdot\exp(y)\cdot T^2} + \frac{1}{BlT^3}\right]^{-1}$$

e - impurities scatt. e - phonons scatt. lattice - phonnons scatt. lattice - grain boundaries scatt.

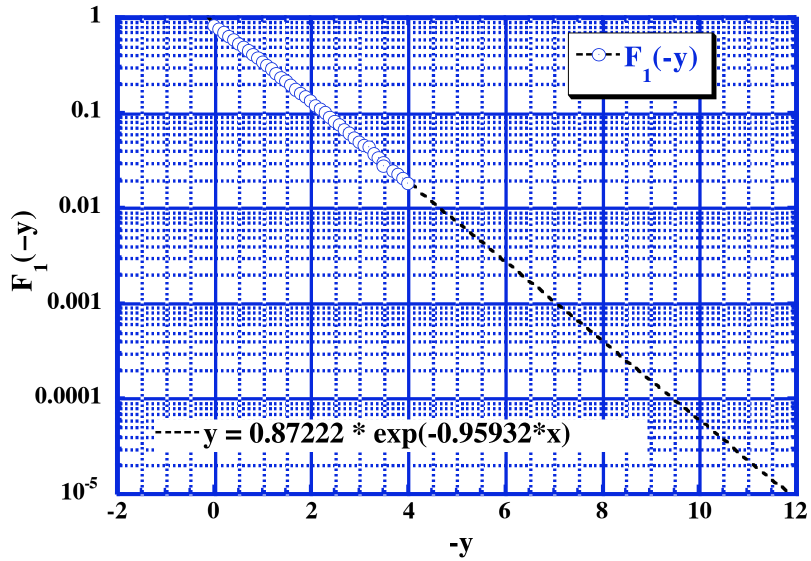
$L = 2.05E-8,\ RRR = 200,\ \rho_{295K} = 14.5E-8\ \Omega m,\ a = 7.52E-7$

$-y = \alpha\cdot\frac{T_c}{T},\ \alpha = 1.53,\ T_c = 9.25K,\ T \le 0.6\cdot T_c$

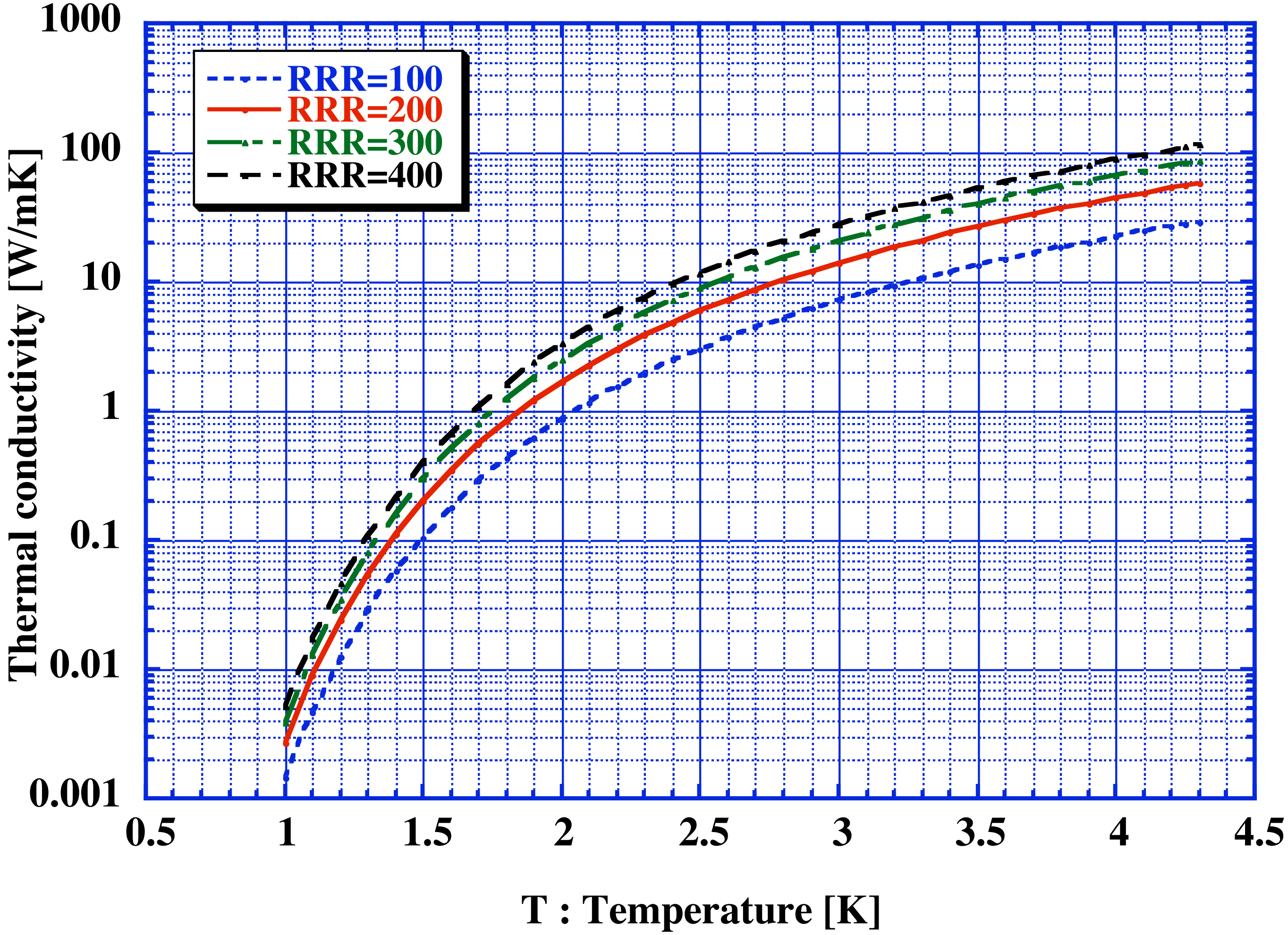
$D = 4.27E-3,\ B = 4.34E3,\ l = 50\mu m$

$$R(y) = \frac{\kappa_{es}}{\kappa_{en}} = \frac{2F_1(-y) + 2y\ln(1+e^{-y}) + \frac{y^2}{(1+e^{y})}}{2F_1(0)},$$

$$F_n(-y) = \int_0^{\infty}\frac{z^n}{1+e^{z+y}}dz$$



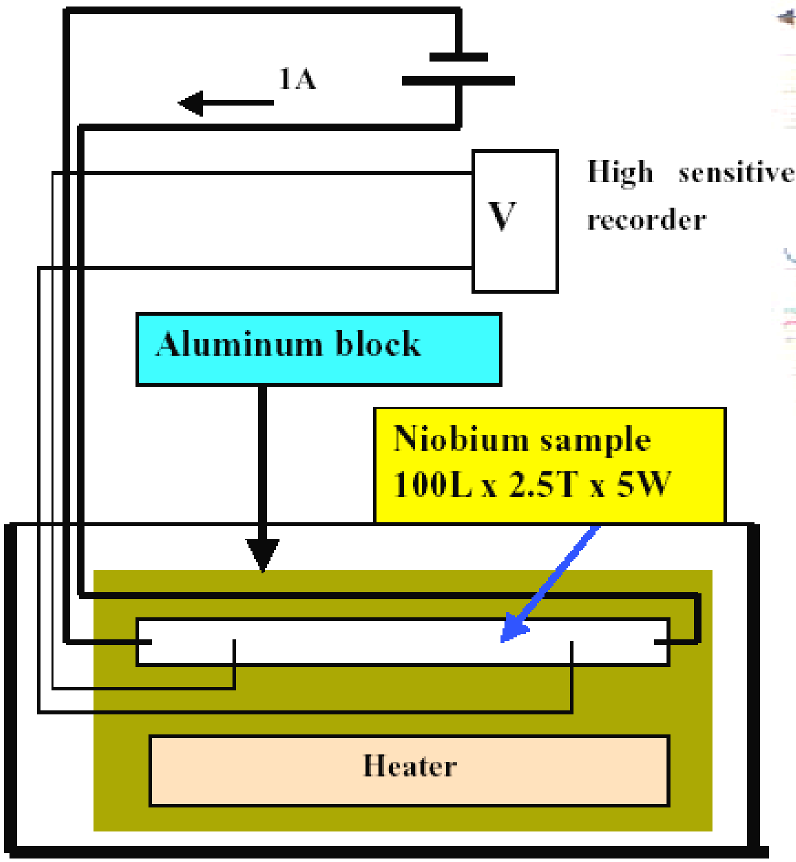
Calculated $\kappa_{sc}(T)$

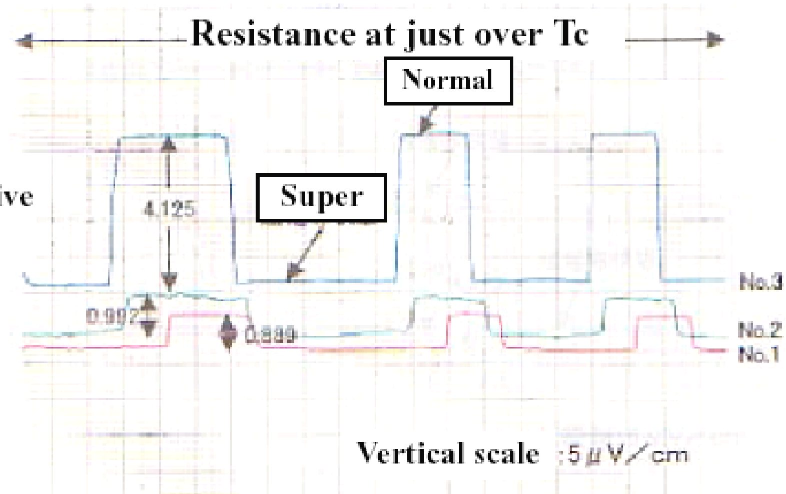


Thermal conductivity at 2K with Nb is ~1/15 of that of stainless at room. Temp.(15W/m*K)） or 1/6800 of that of copper at 4.2K (6800W/m*K).

RRR measurement

Very simple measurement !!





$$\kappa(T) \propto RRR$$

$$RRR \equiv \frac{R(300K)}{R(9.5K)}$$

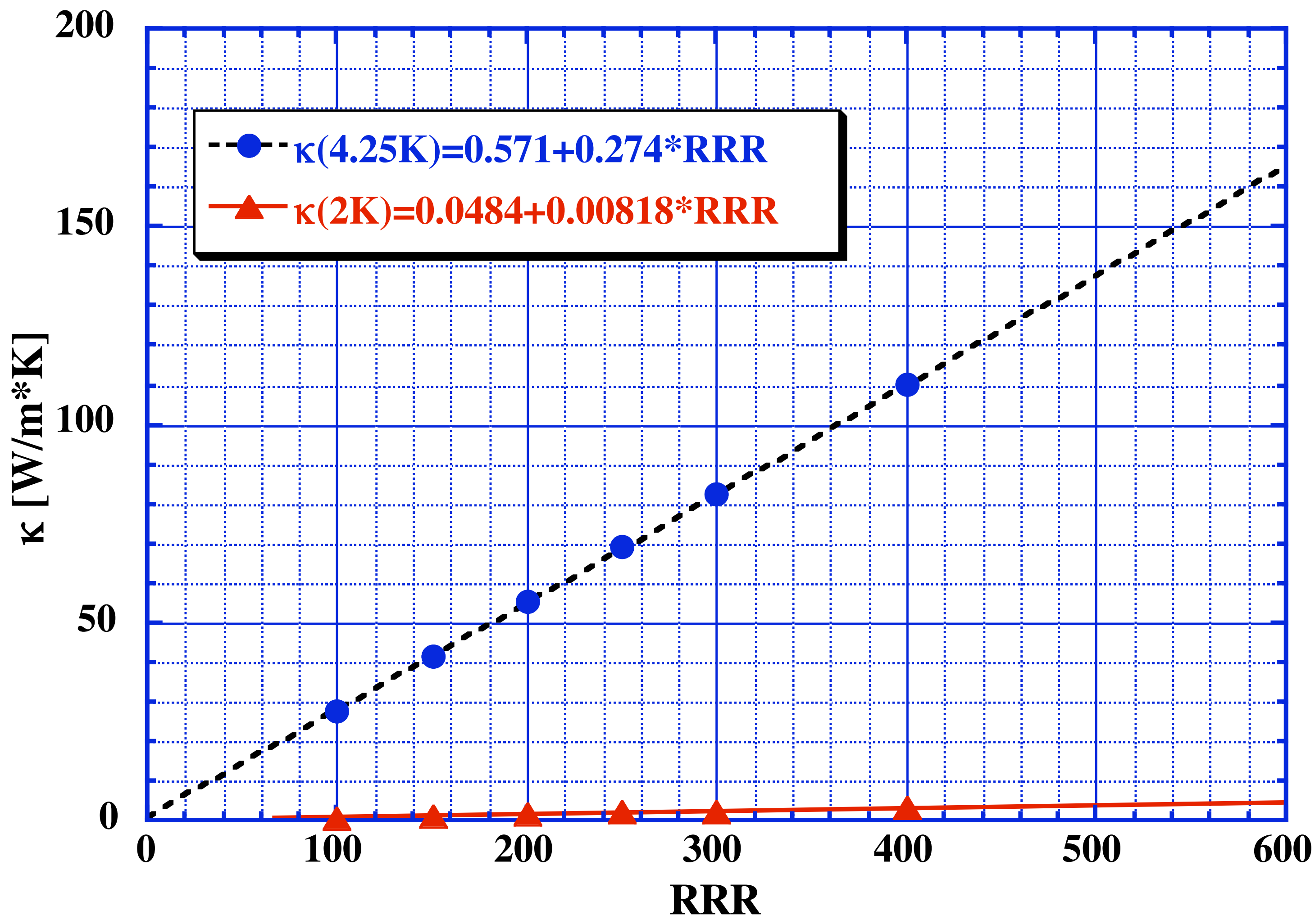
$$\frac{1}{RRR} = \sum_{\text{elements in Nb}} \frac{C(i)}{\rho(i)} = \frac{C_H}{1500} + \frac{C_C}{4100} + \frac{C_N}{3900} + \frac{C_O}{5000} + \cdots + \frac{C_{Ta}}{550000}$$

Example:

$$C_H = 1ppm, C_C = 5ppm, C_N = 5ppm, C_O = 7ppm, C_{Ta} = 400ppm \quad (99.9582\%)$$

$$RRR = 188.8$$

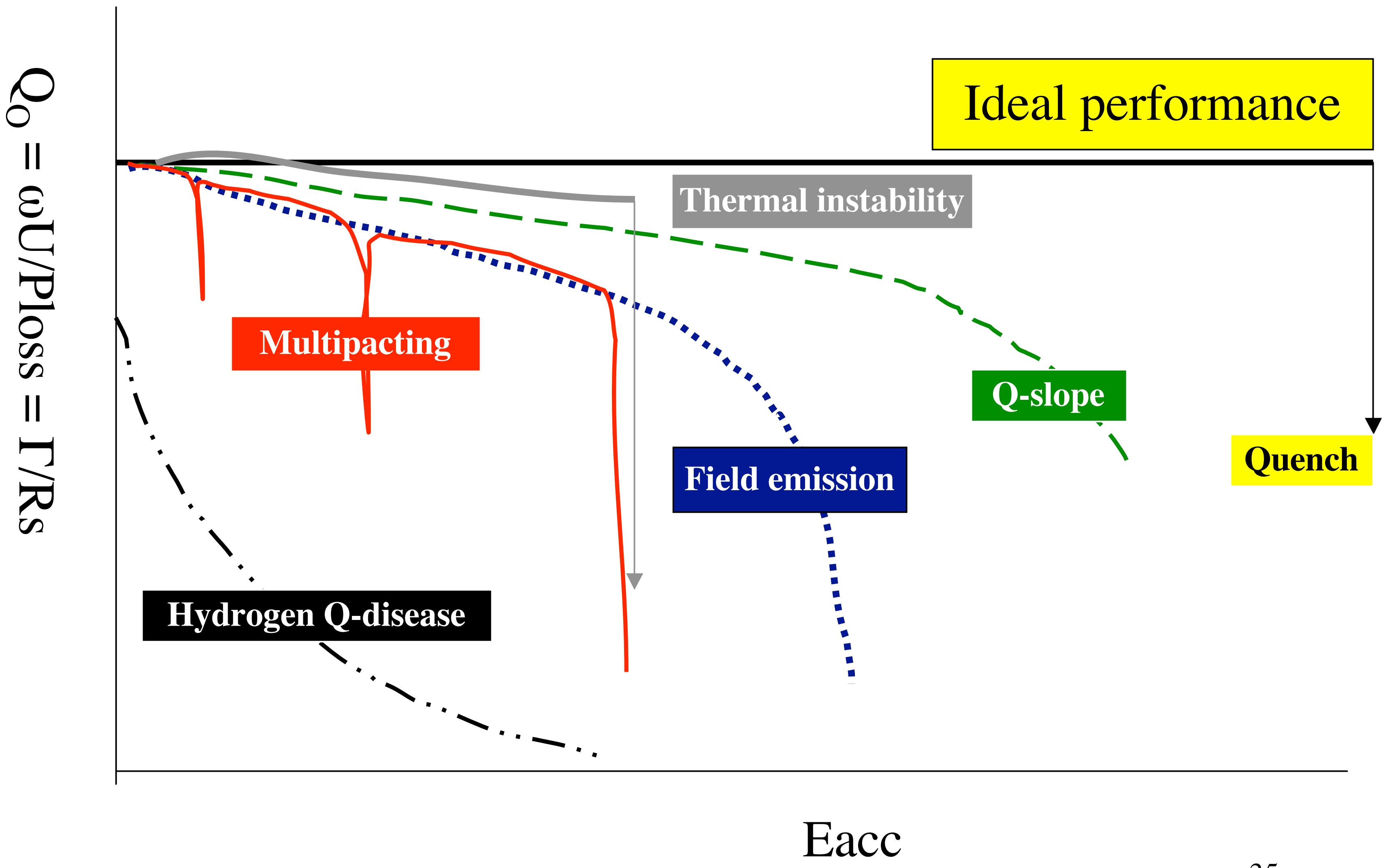
Linear relationship between κ_{SC} (2K, 4.25K) and RRR



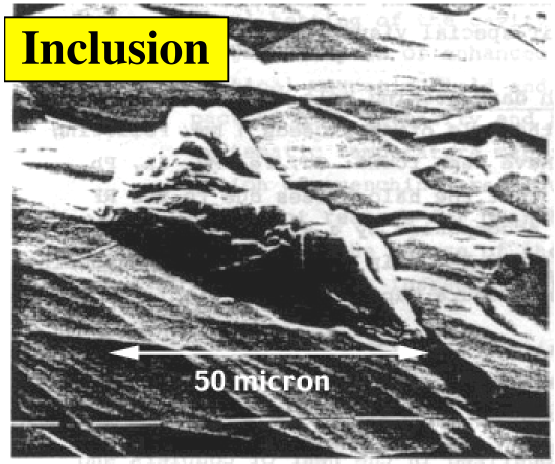
RRR is a good parameter to evaluate thermal conductivity of superconductor.

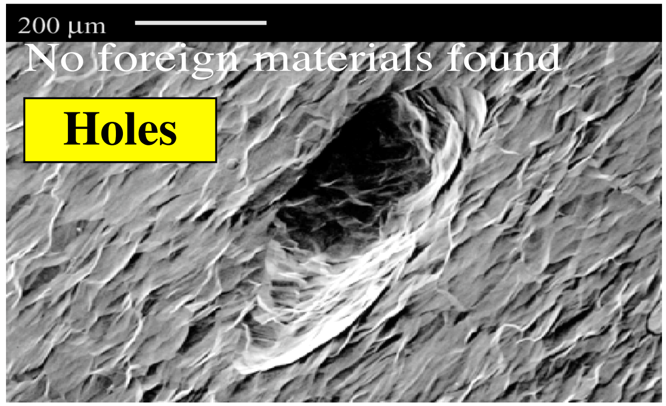
Q5: Real SRF field limitation and Technologies to push gradient

Real SRF Cavity Performance

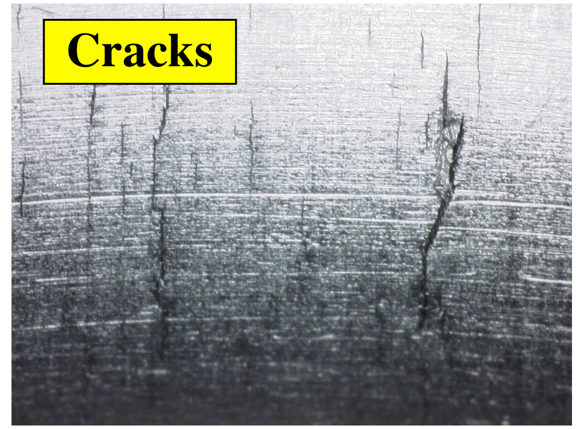


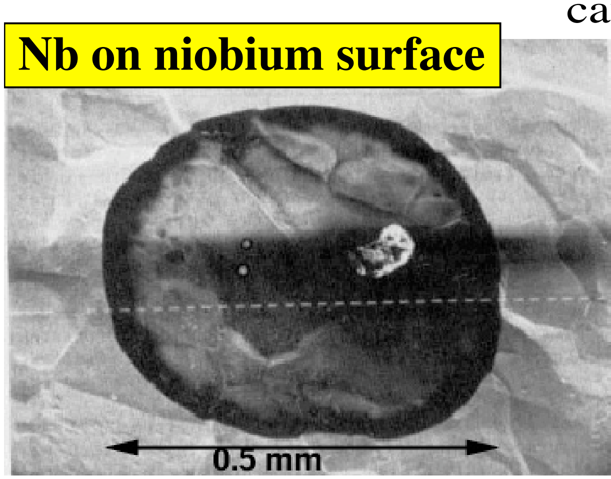
Various Surface Defects

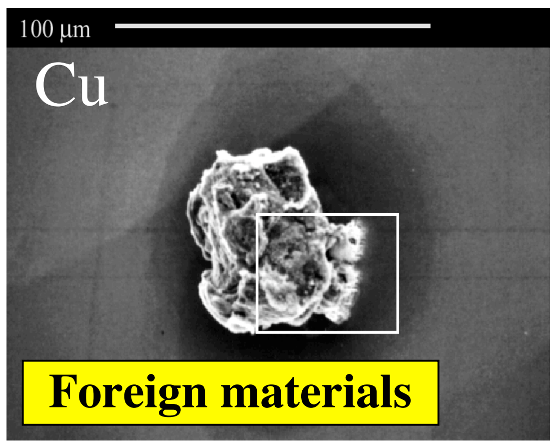


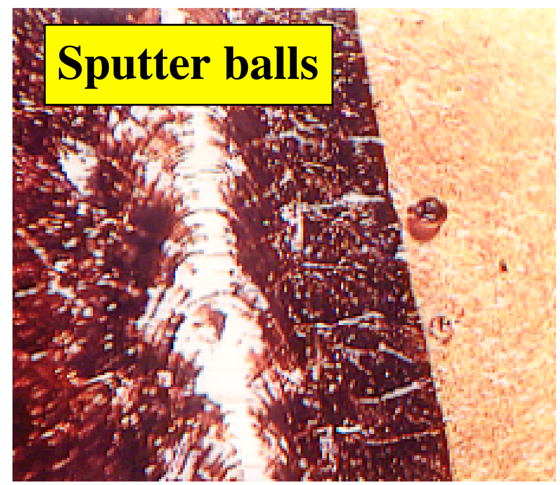


Surface defects, holes can also cause TB

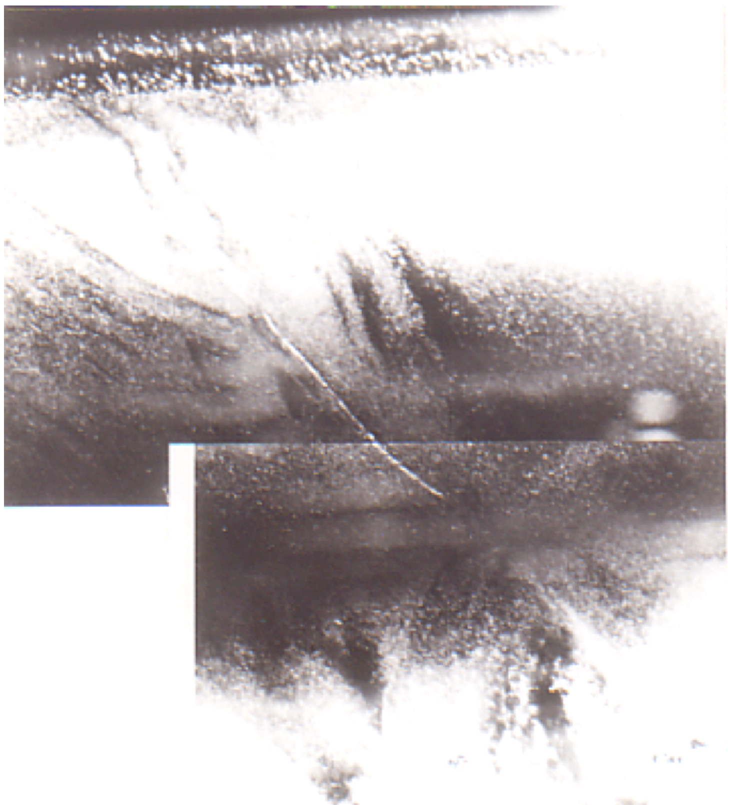




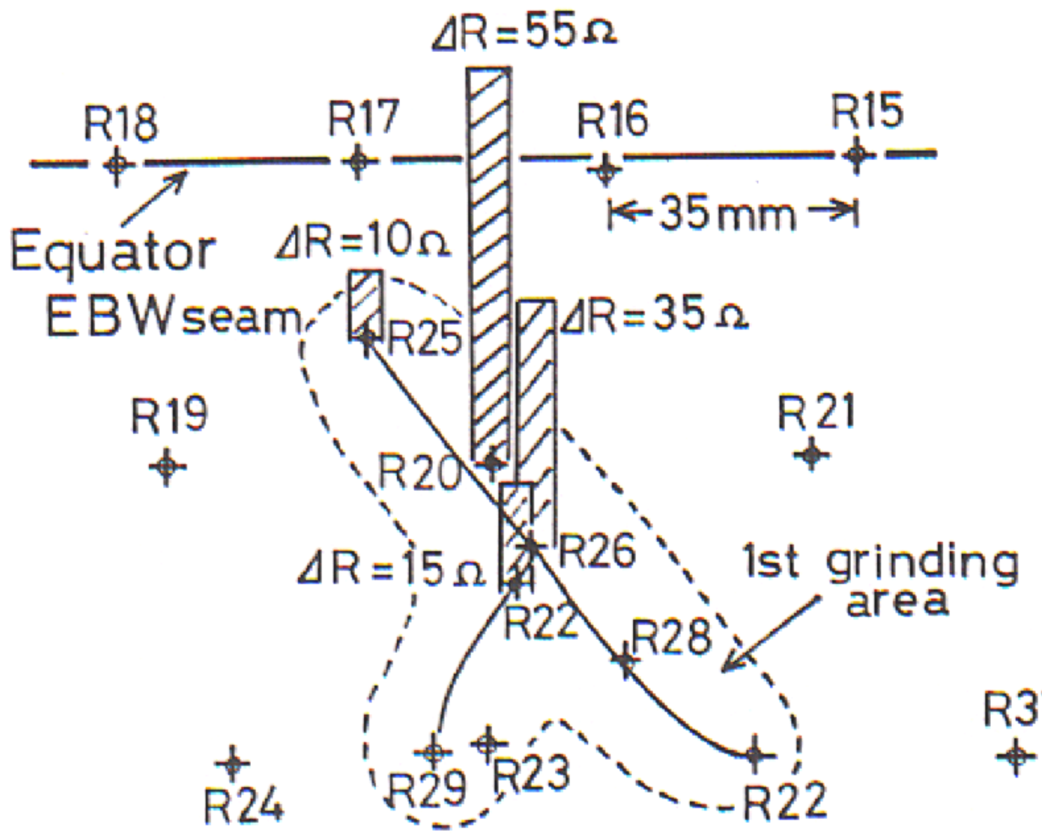




Surface Defect

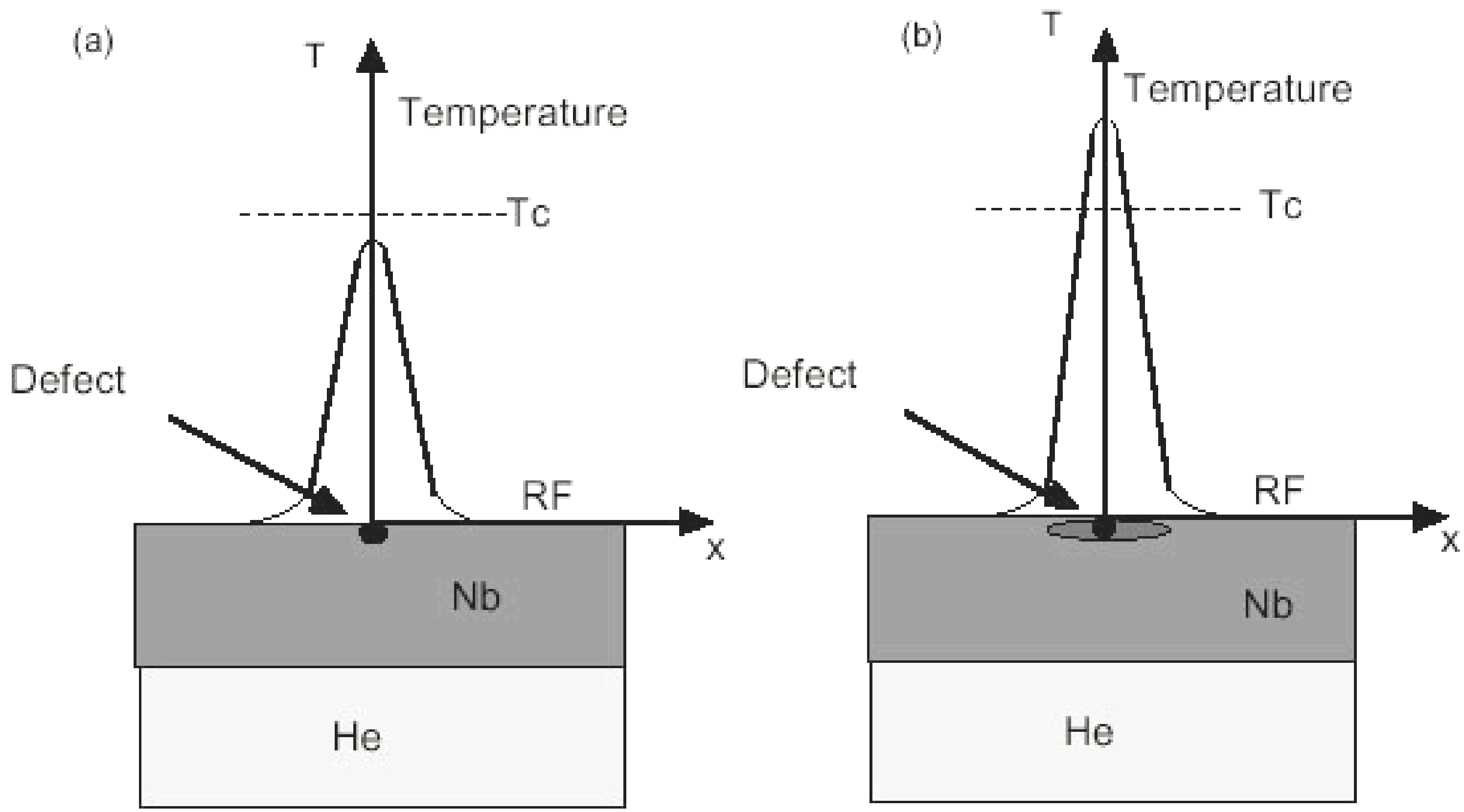


Picture of the defect area



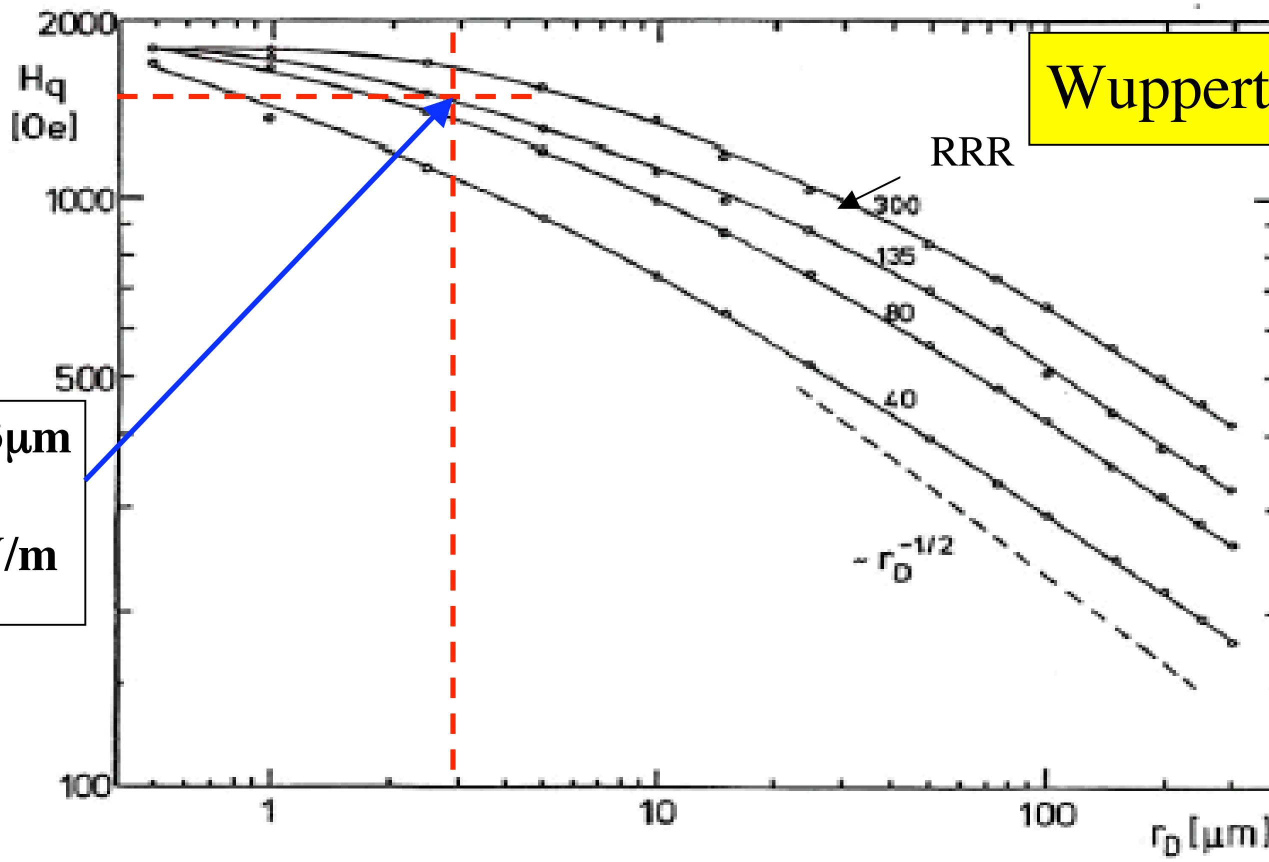
T-mapping on the defect

Mechanism of Thermal Instability



RRR Dependence of Quench Field

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



Wuppertal Uni.

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

Defect radius

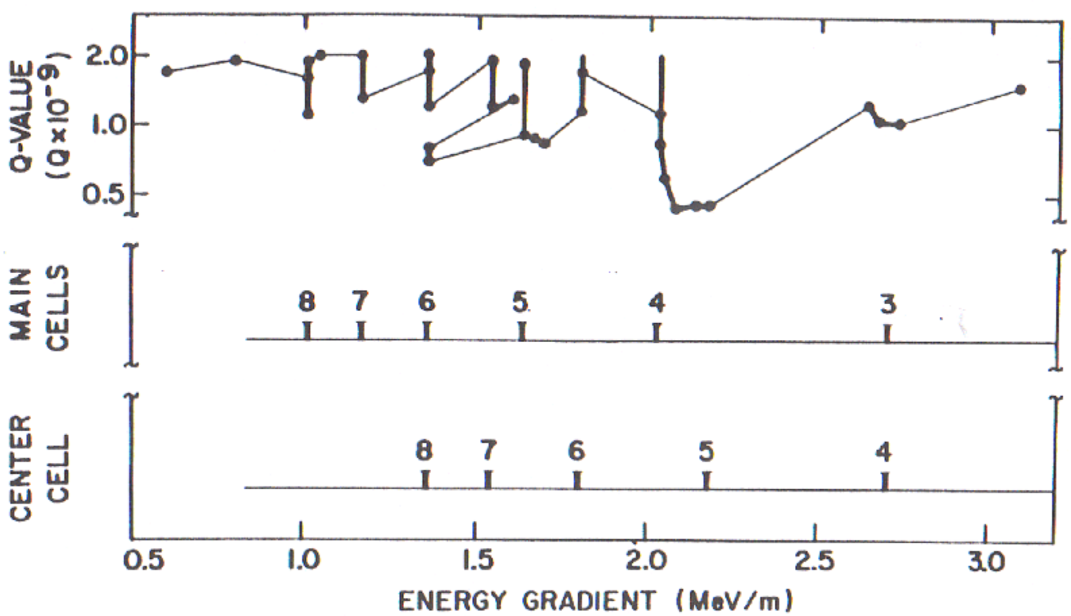
Needs control the defects with 1mm size, Use high pure niobium material with RRR>200

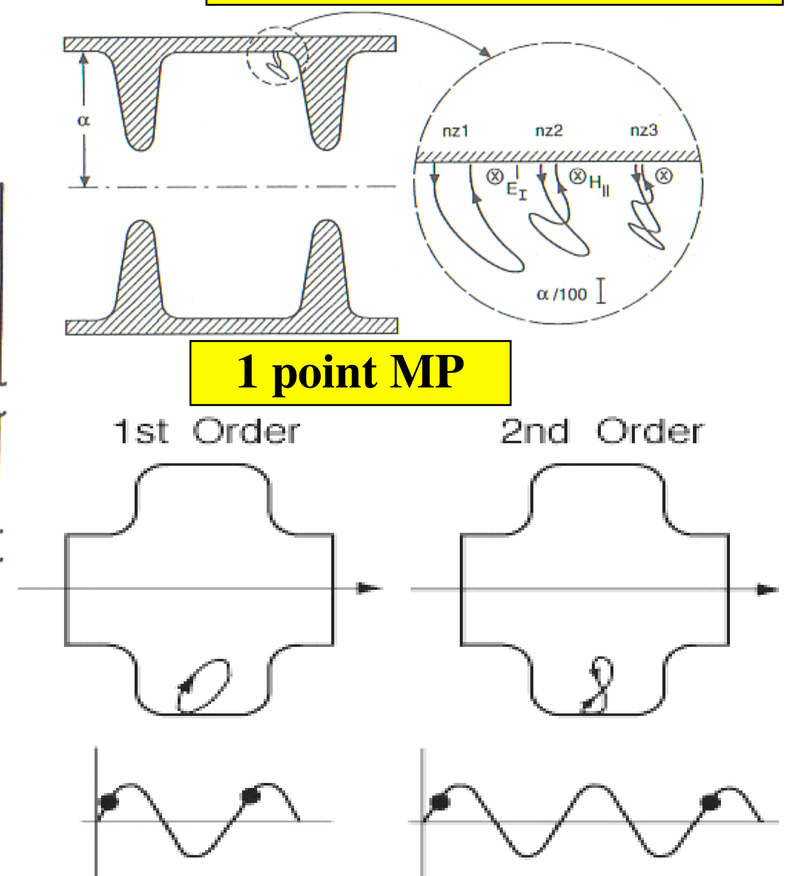
Multipacting

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

Limited the performance by 1PM or 2PM.

<u>One point multipacting</u>





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

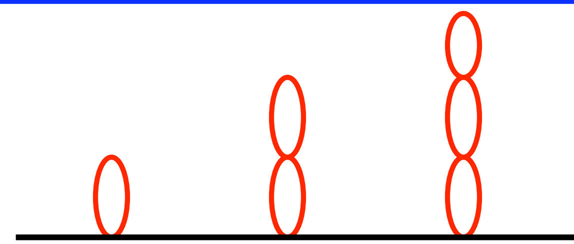
Onset Field of One-point MP

Scale law on RF frequency with the maltipacting levels

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

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

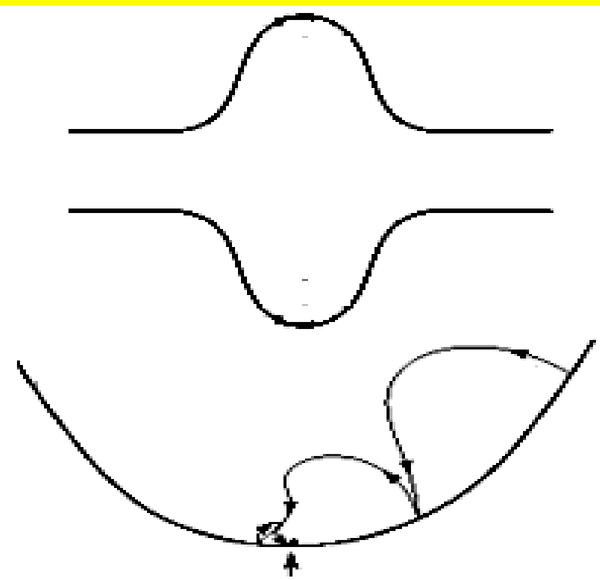
$$T(1P-nth) = \frac{1}{f(1P-nth)} = \frac{2\pi \cdot c \cdot m}{e \cdot H(1P-nth)} = n \cdot T_{RF} = \frac{n}{f_{RF}}$$



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

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

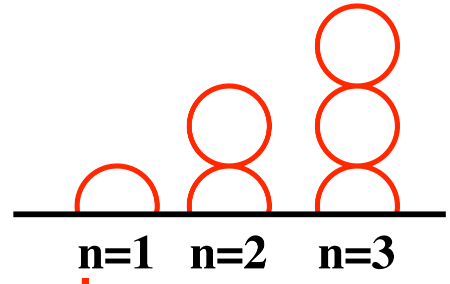
Eacc(1P-1st) = 390/43.8=8.9 MV/m

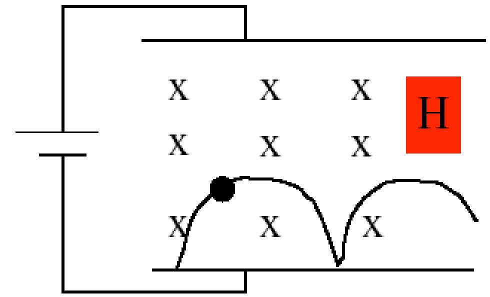
1P-2nd order ・・・ Eacc(1P-2nd) = 4.5 MV/m

Two-point MP

Two-point multipacting

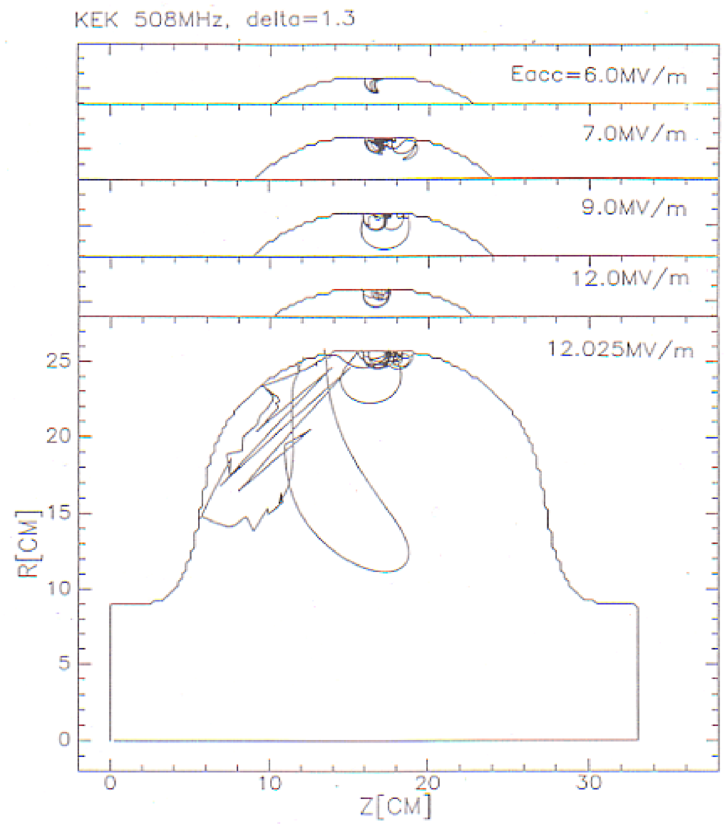
$$T(2P-nth)=(2n-1)T_{RF}$$





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

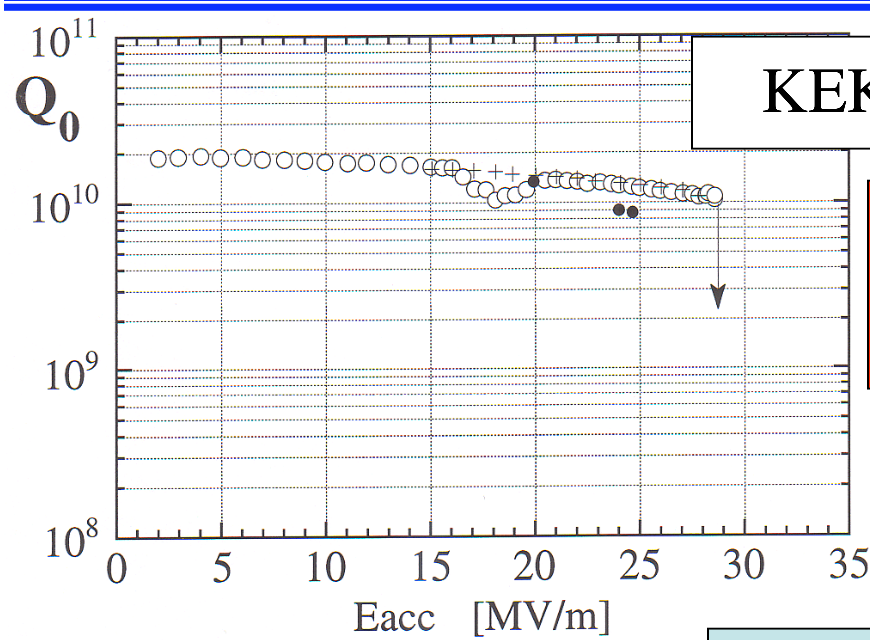
1300MHz, Hp/Eacc=43.8 [Oe/(MV/m)]

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

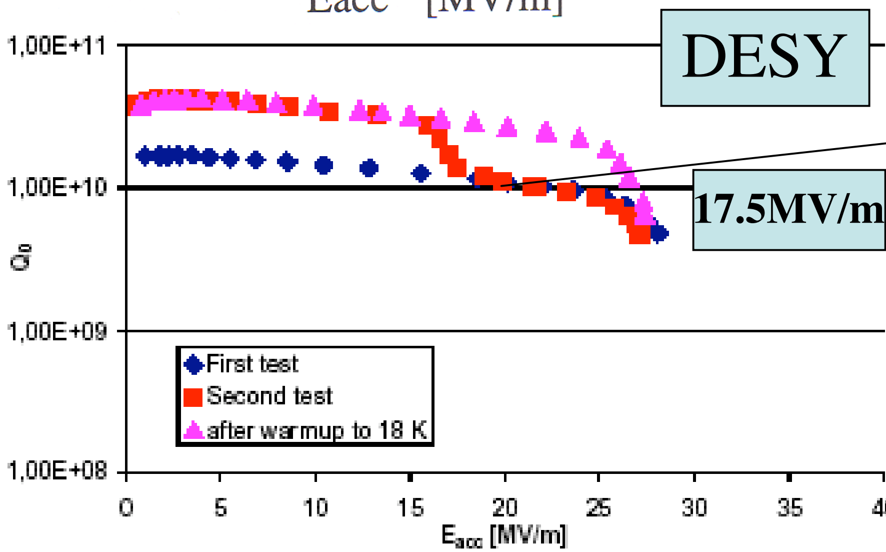
T-mapping of Tow-point MP



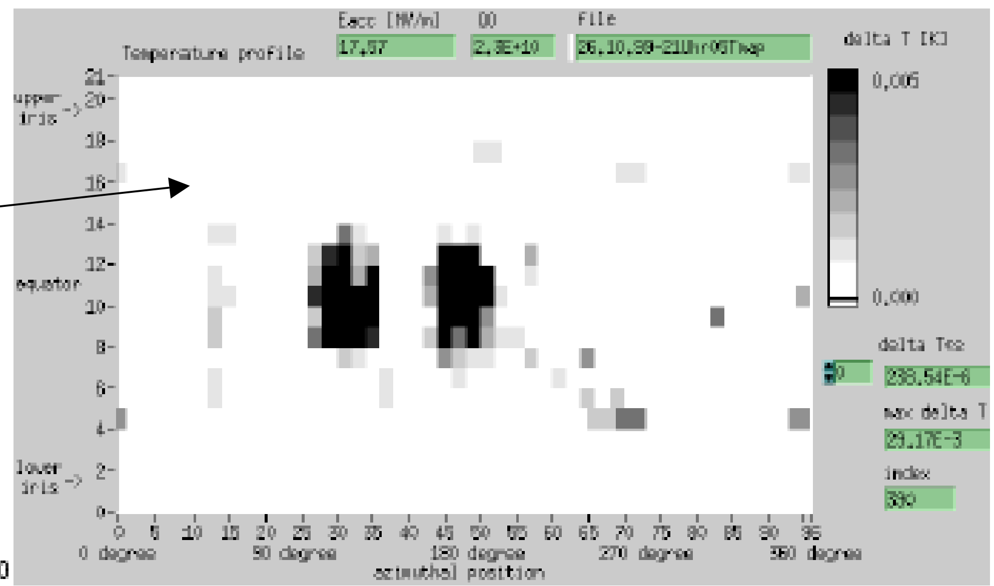
MP → Frozen flux trapping → Warm-up T>Tc

↓

Disappear of the heating spots



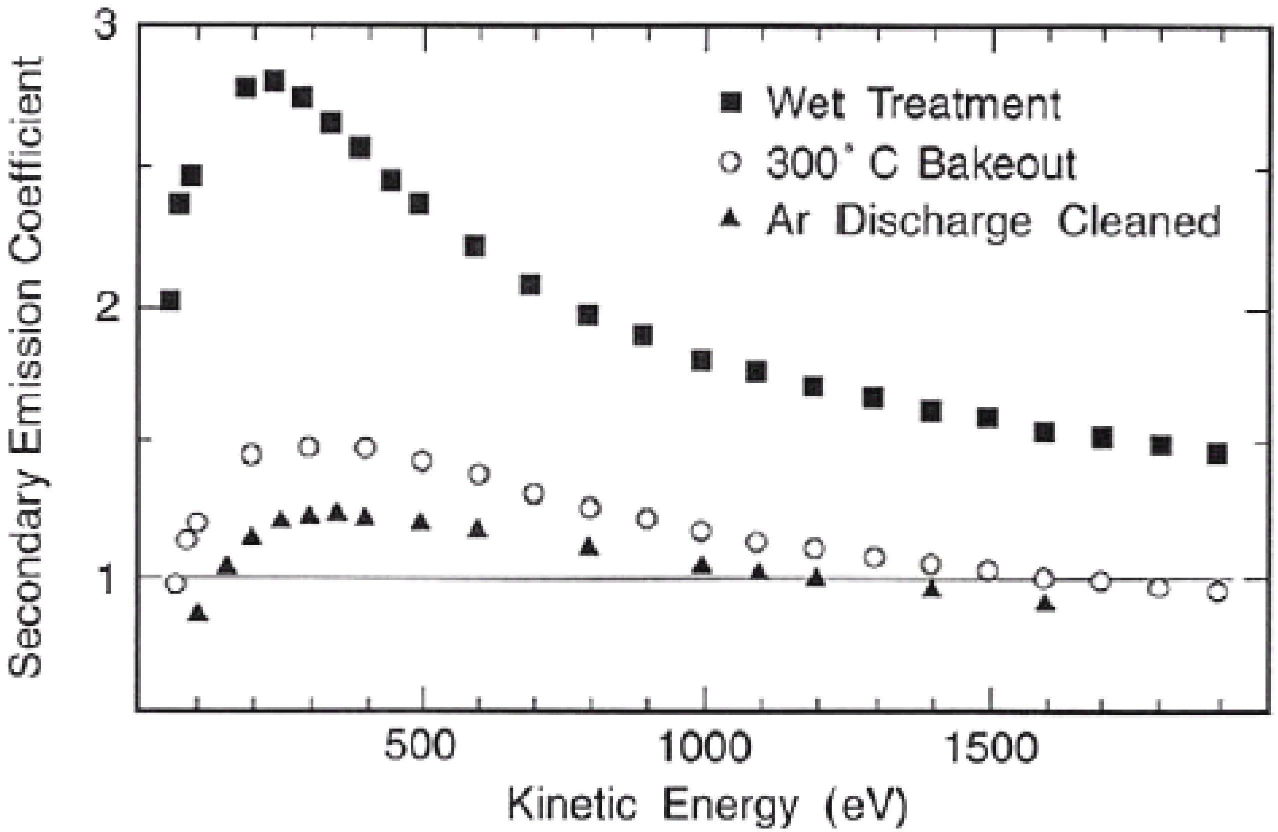
T-mapping at 17.5MV/m



Cures against MP

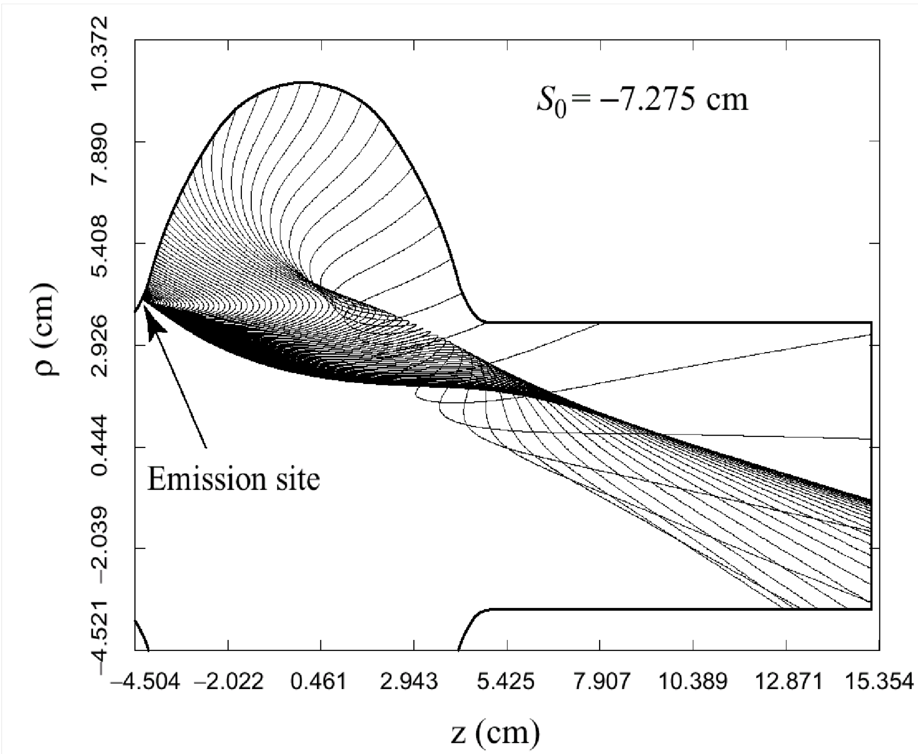
1) Cavity shape ⟶ Spherical or Elliptical shape
(effective for one point multipacting)

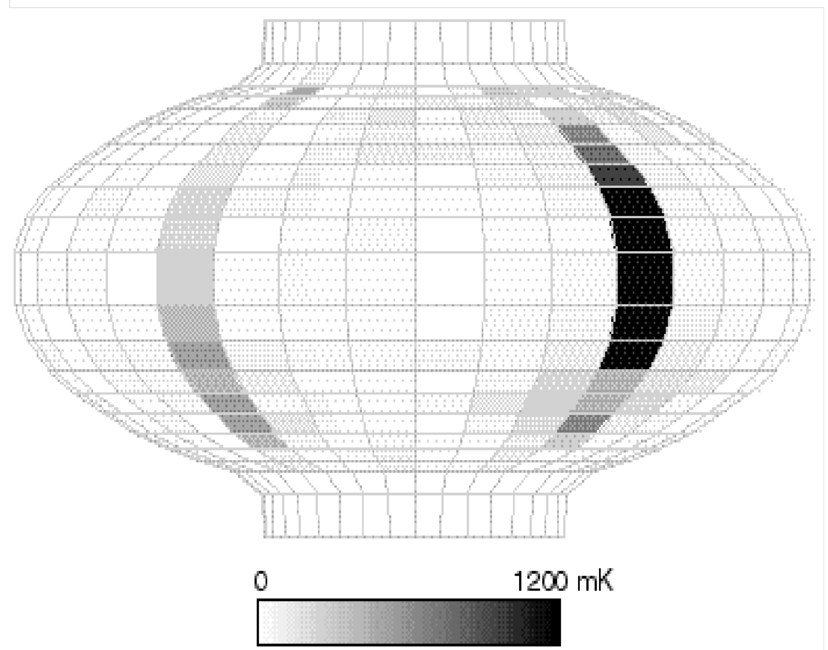
2) $\delta < 1$: Clean surface ⟶ Surface preparation
High pressure water rinsing
Argon gas or Helium gas discharge cleaning



Field Emission

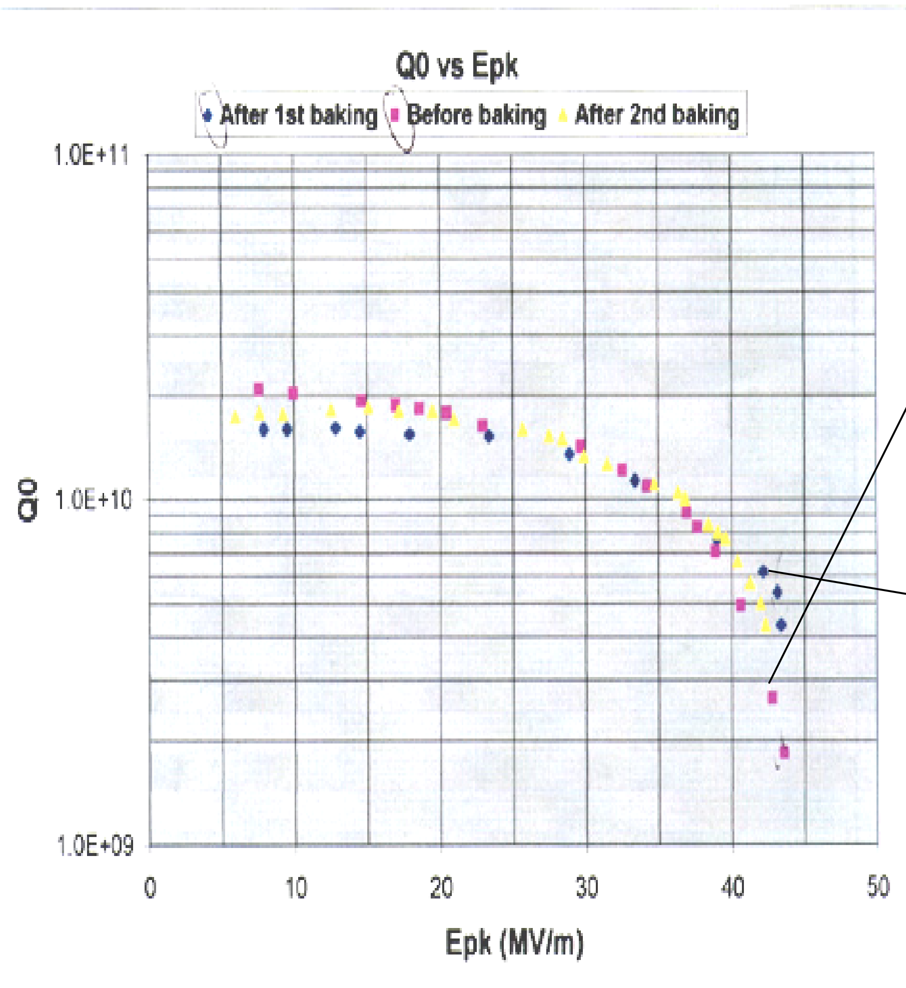
Non-resonant electron loading due to field emitted electrons by tunneling effect



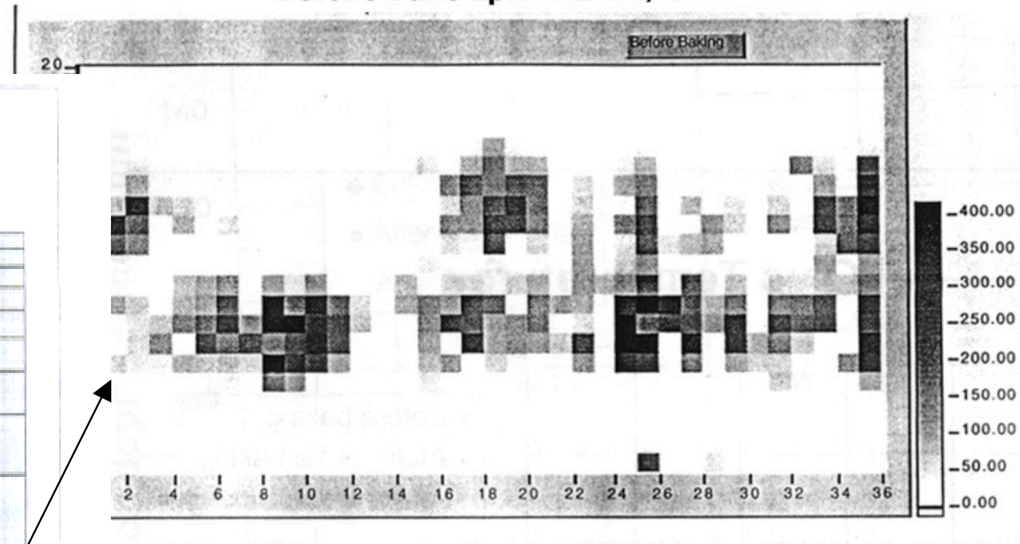


Heating on meridian

Q-slope: Partially Disappeared Heating Spots by Baking on CP Cavity

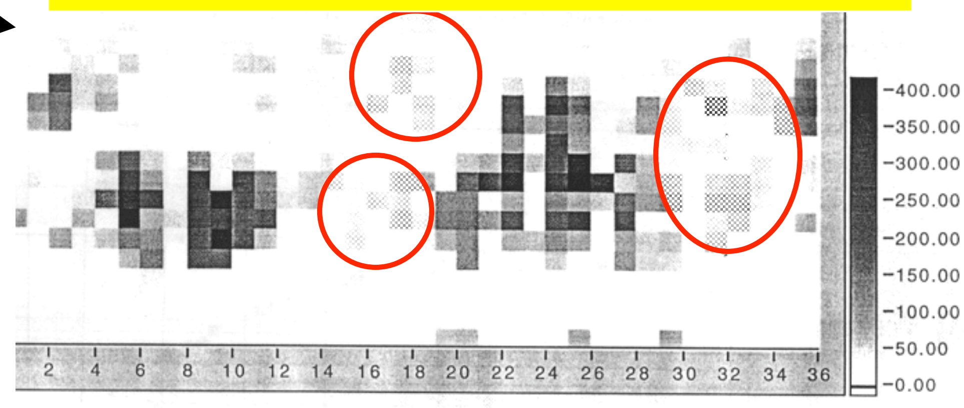


Before Bake Epk = 42 MV/m



After First Bake Epk = 42 MV/m

Heating spots partially disapper after baking.



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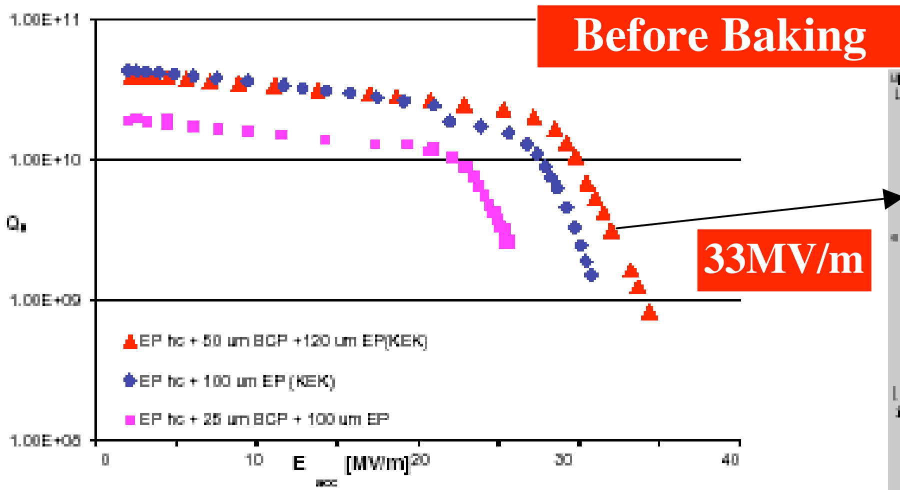
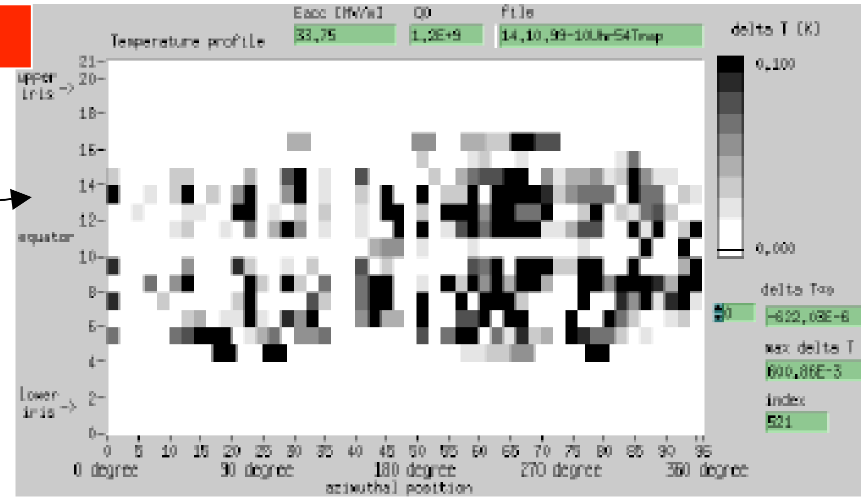
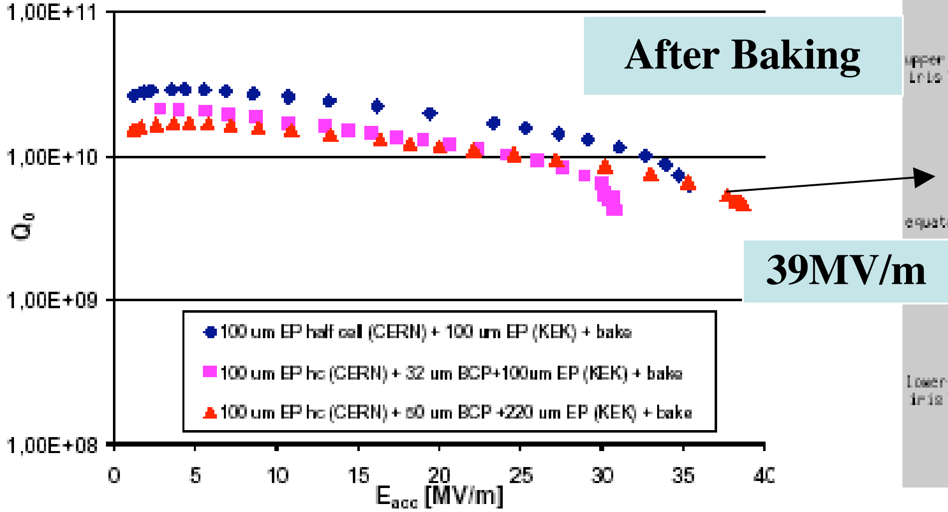
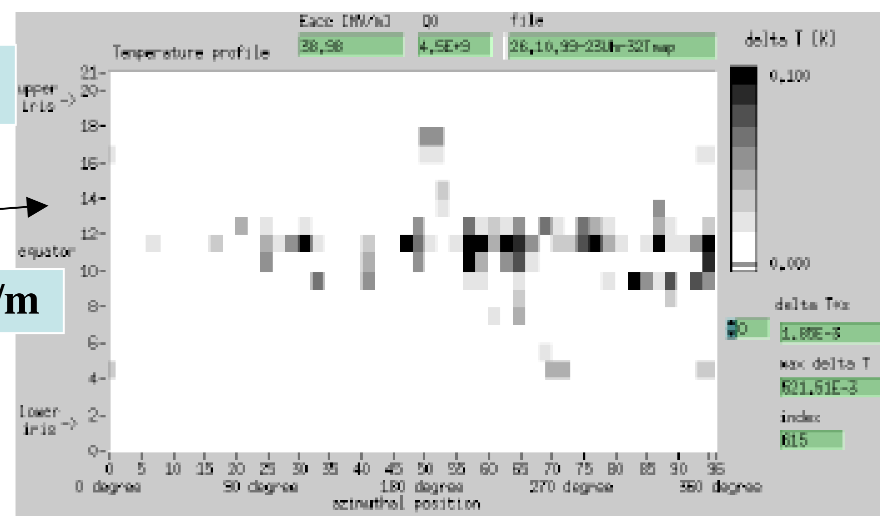
Q-slope: Disappeared Heating Spots by Baking on EP Cavity

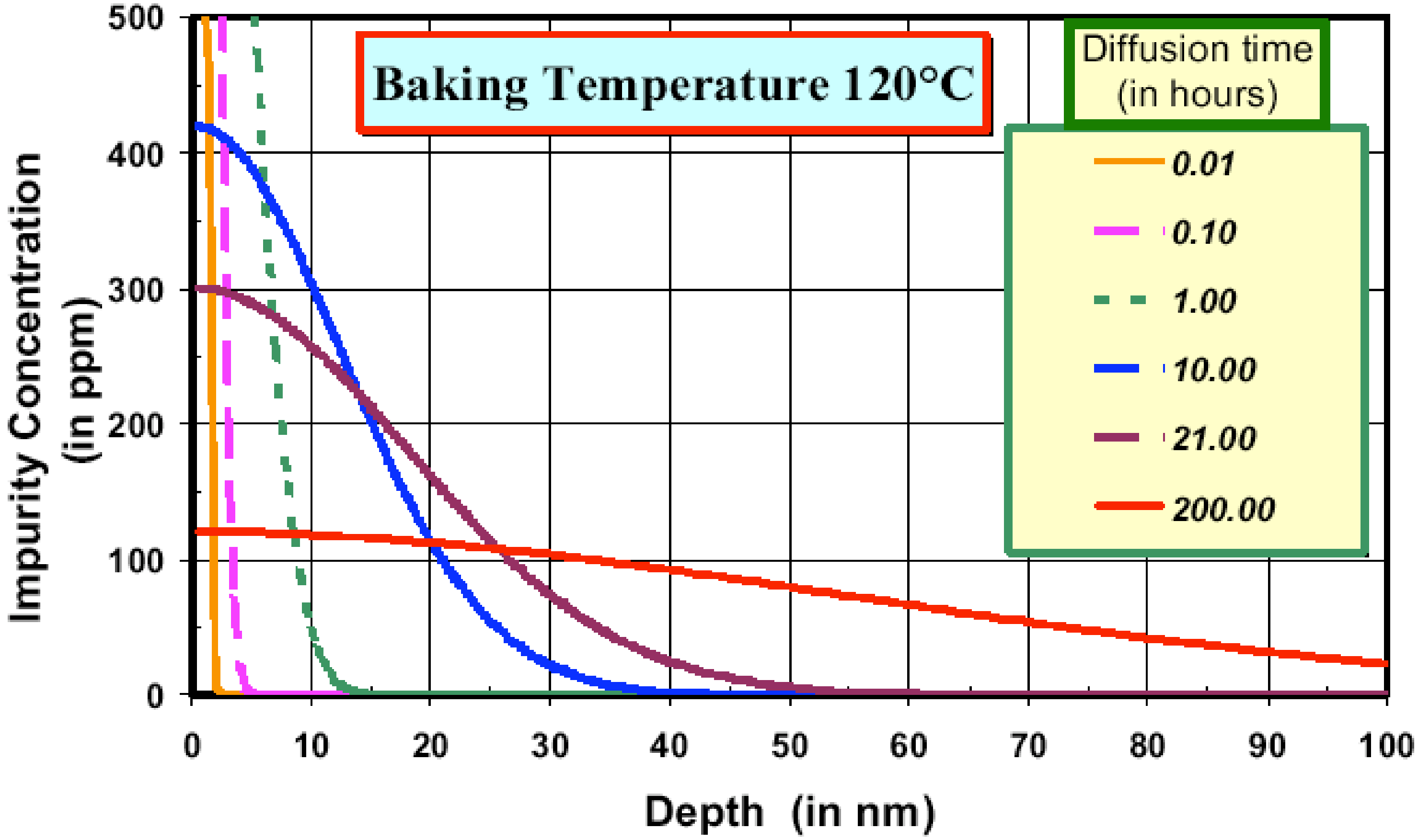








Oxygen Diffusion



Oxygen on top diffuse into bulk by baking ($120^{O}C$ for 48 hr).

Loss Mechanism

Interface Tunnel Exchange(ITE Model)
By J.Halbritter

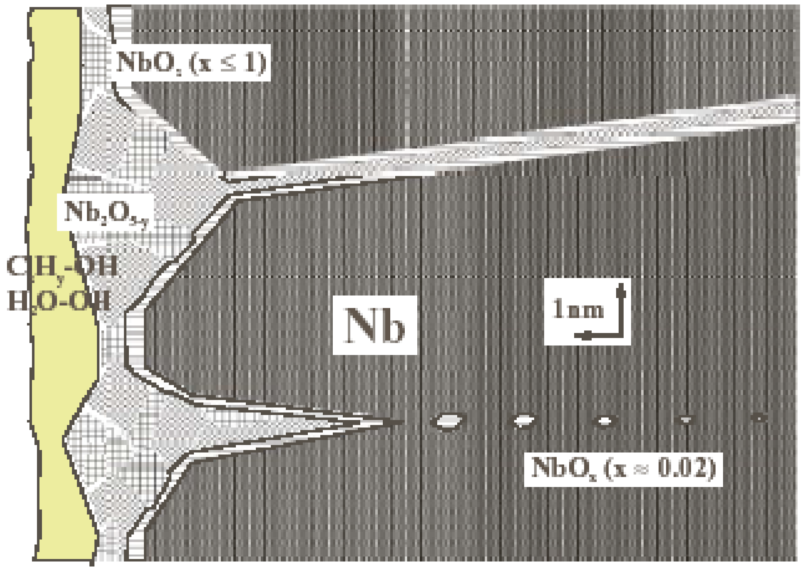


Fig. 1: Nb surface with crack corrosion by oxidation by Nb_2O_5 volume expansion (factor 3). Nb_2O_{5-y}-NbO_x weak links/segregates (y, x < 1) extend up to depths between 0.01 – 1/ 1-10 μm for good – bad Nb quality and weak - strong oxidation [8]. Embedded in the adsorbate layer of H_2O/C_xH_yOH (≥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

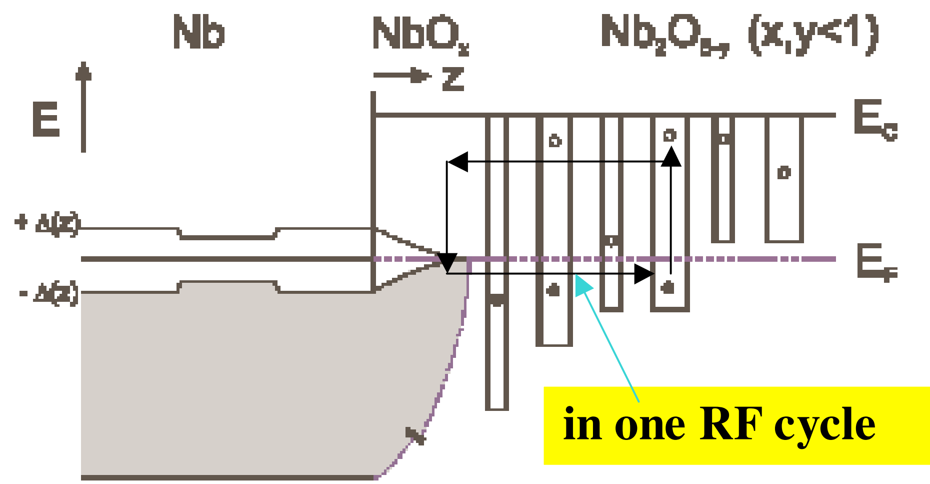


Fig. 3: Band structure at Nb-NbO_x-Nb_2O_{5-y} interfaces with E_c-E_F = φ ≈ 0.1 – 1 eV as barrier heights for tunneling along crystallographic shear planes (~ 0.1 eV) or of Nb_2O_{5-y} crystallites (~ 1 eV). Added is the superconducting energy gap $\Delta^*(z) < \Delta_o$ being reduced in NbO_x clusters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

Disease	Phenomena	Cures
Thermal instability	Quench at bad spot	Mechanical grinding, Use high pure niobium material Sever material control
Multipacting	Q-drop at discrete field levels (Electron resonant loading), Heating around equator section X-ray	Make clean surface Use spherical shape
Field emission	Exponential Q-drop with gradient (Electron non resonant loading) Heating on meridian X-ray	Make clean and smooth surface Use ultrapure water Use clean room assembly High pressure water rinsing
Hydrogen Q-disease	Low Q from low field, Depends on cooling speed	Annealing
Q-slope	Exponential Q-degradation without / with x-ray	Baking