Introduction to Superconducting RF and Cryogenics

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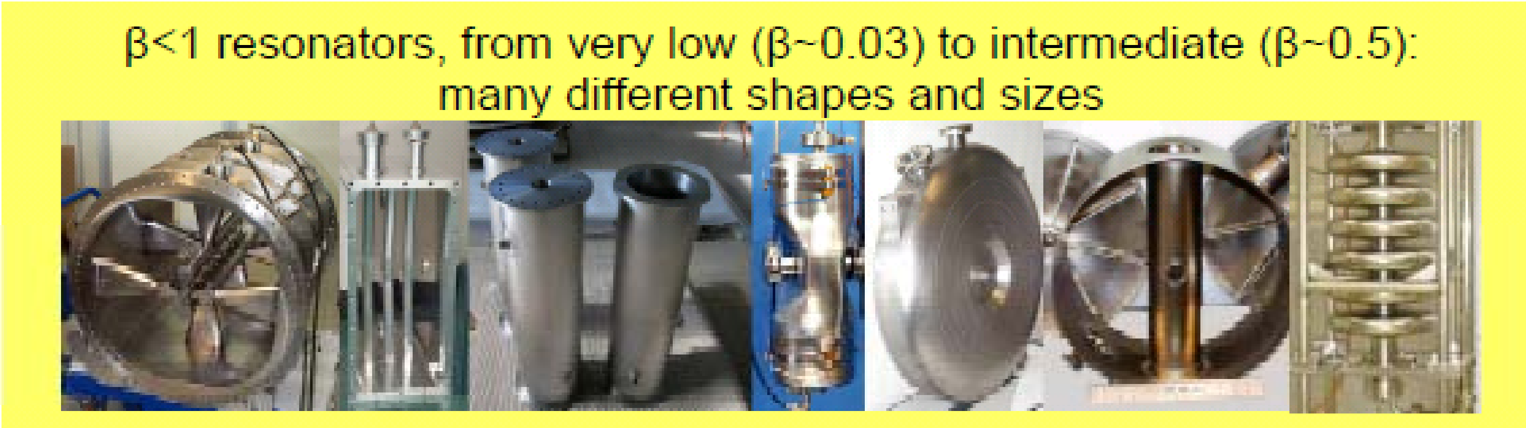
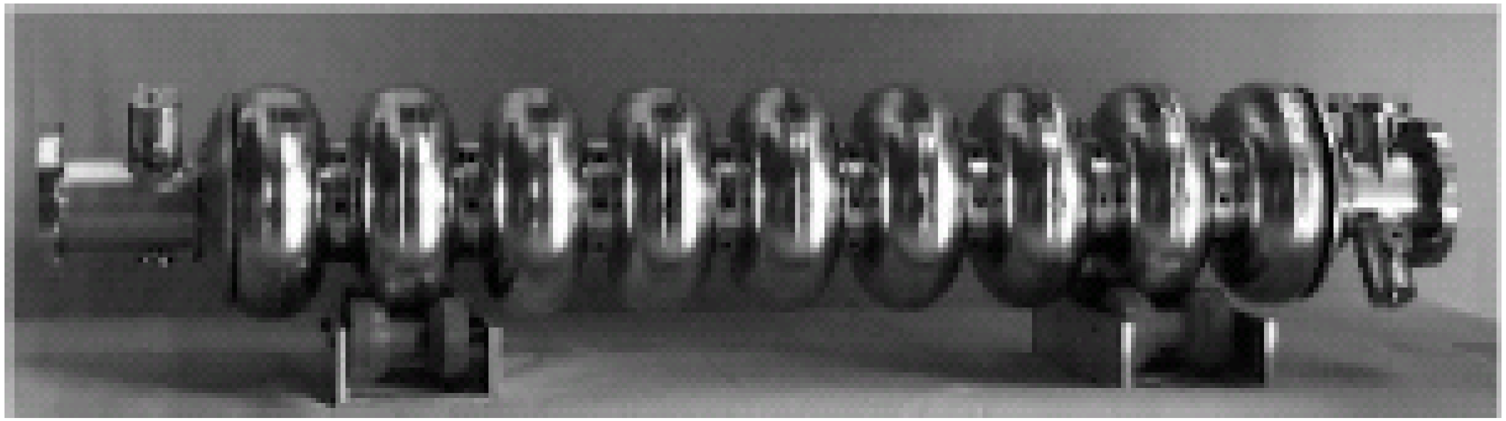
SRF Cavities: from low to high β

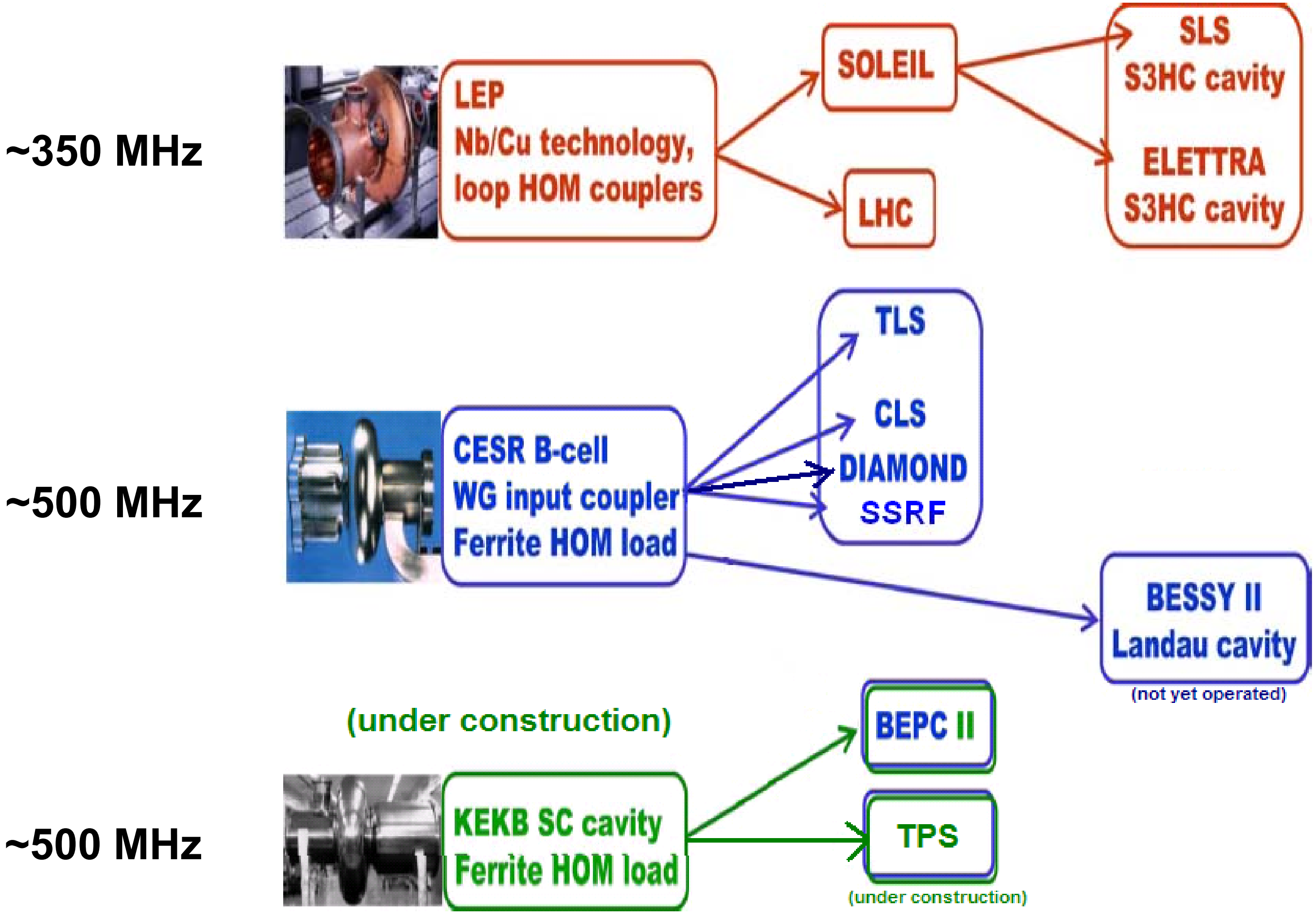


(Courtesy of A. Facco)

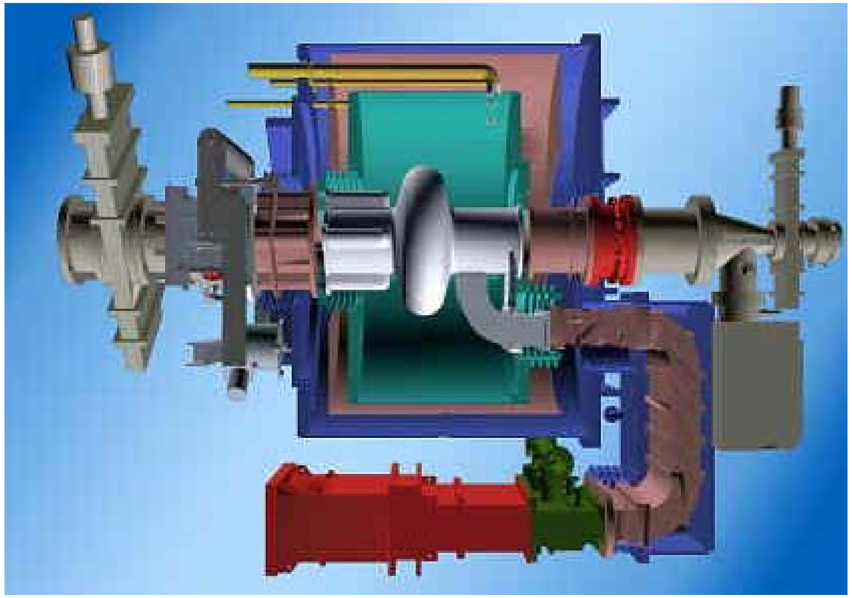
β=1 resonator (cavity)



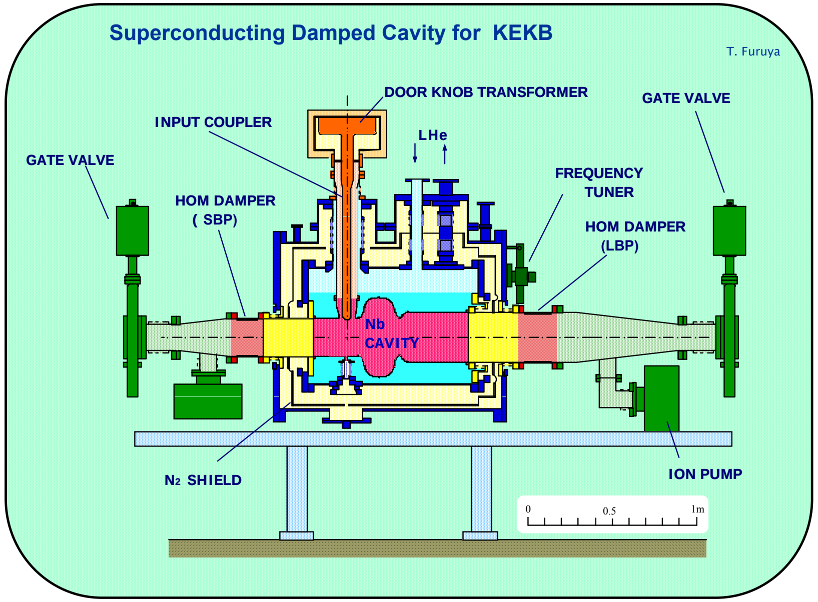
Historical Roadmap of SRF Modules for Light Sources



Options of 500-MHz SRF Modules

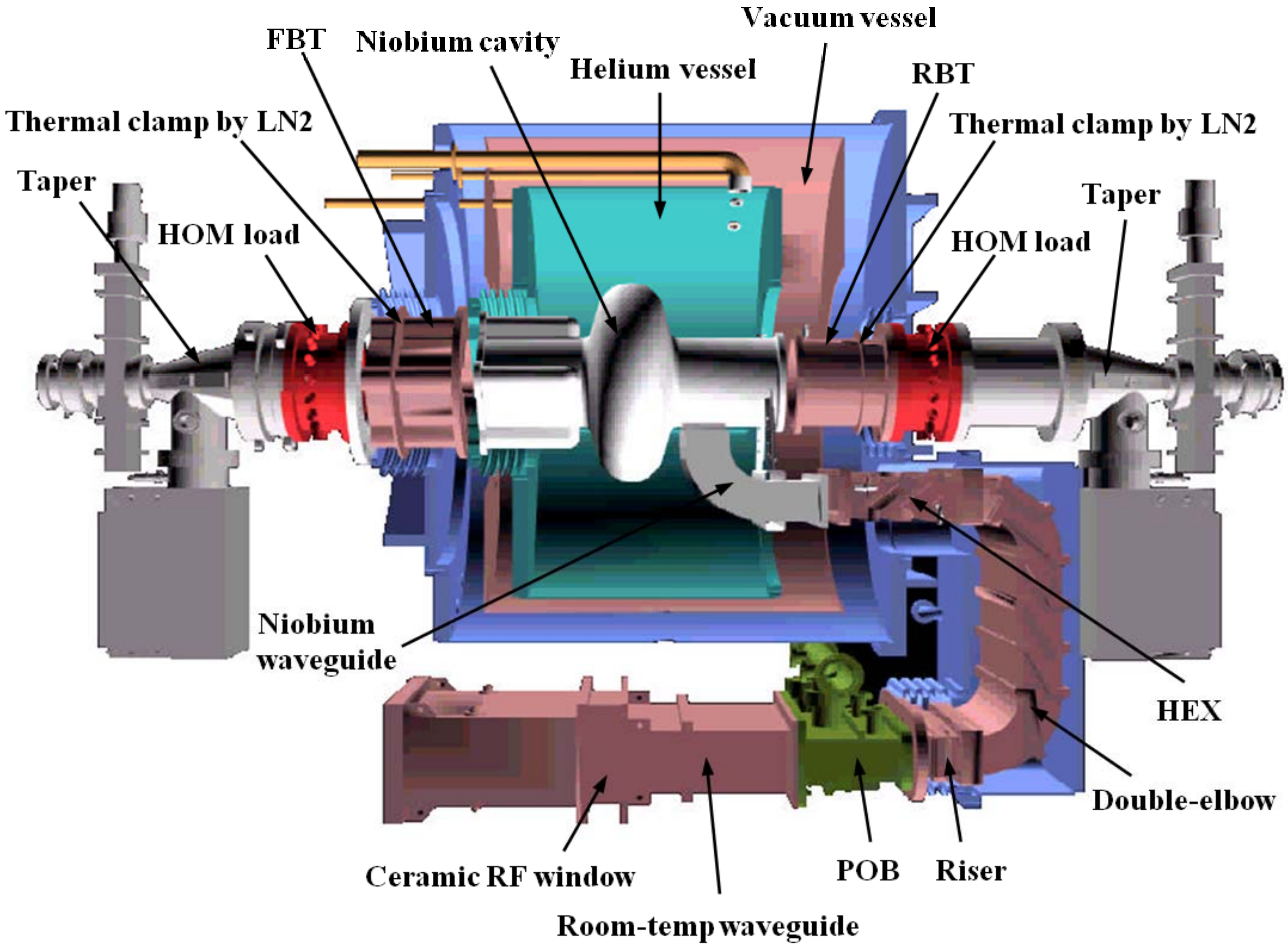


SRF module of Cornell design



SRF module of KEKB design

500-MHz SRF Module (β=1)



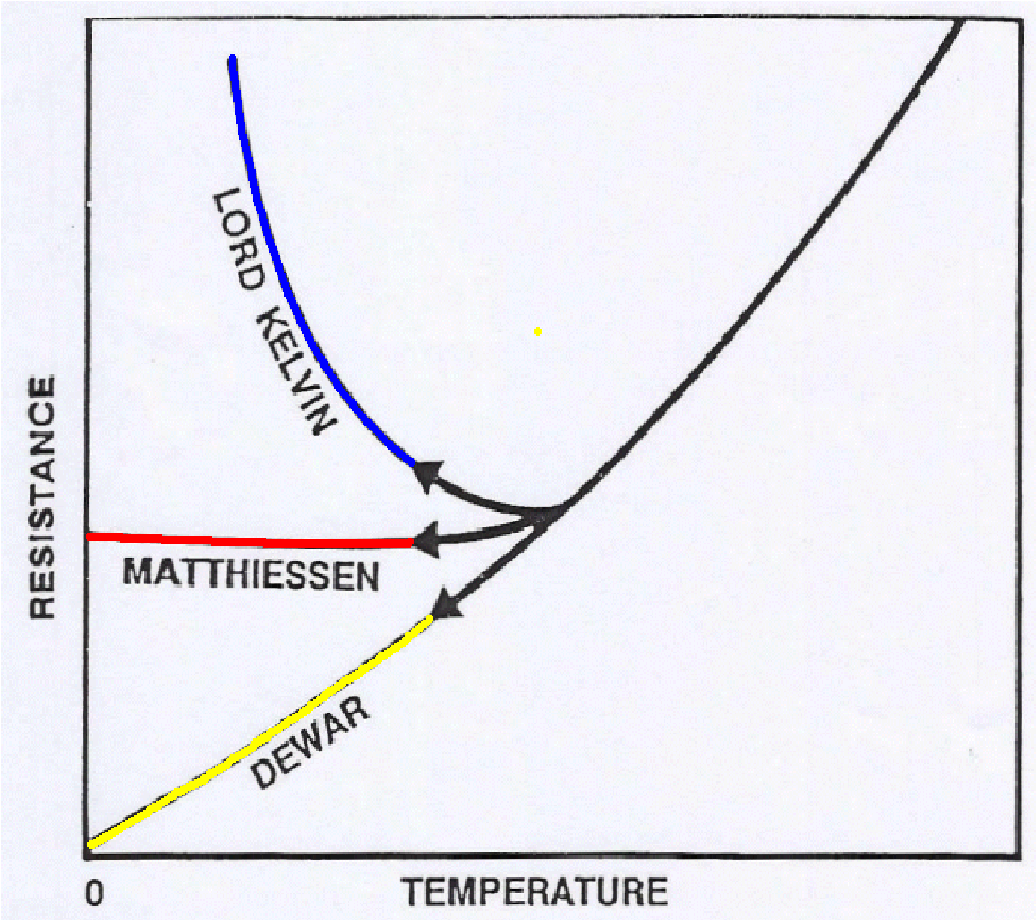
Outlines

- **Historical Remark**
- **Basic of Superconducting RF**
- **SRF Performance: Achievement and Challenge**
- **Cryogenic Plant for SRF Operation**

- **SRF Operation and Maintenance**

Motivation:

Behavior of Metallic Resistance near Absolute Zero



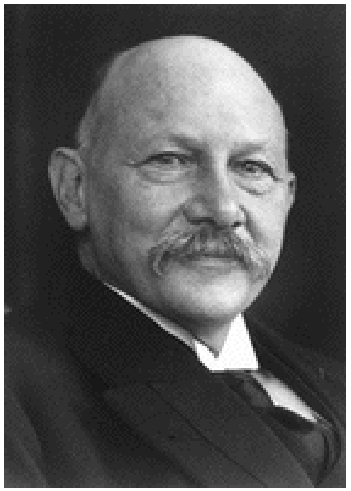
- C. Dorsman, G. J. Film, and G. Holst investigated metallic elements such as copper, gold and platinum, because of their excellent conducting properties at room temperature.
- They discovered that the resistivities of these materials leveled off at extremely low temperatures, this was attributed to impurities in the sample.
- What will happen if the metallic material can be arbitrary pure?
- The mercury (Hg) was a material well known for processing a very high degree of purity.

Historical Remark

Historical Remark

to Low Temperature Physics

- The study of the electronic behavior of materials at extremely low temperatures was **possible only after the successful liquefaction of helium**. The Dutch physicist Heike Kamerlingh Onnes made liquid helium (and in a large amount) possible in **1908** at the Cryogenic Laboratory of the University Leiden. **Onnes** discovered the superconductivity in 1911!

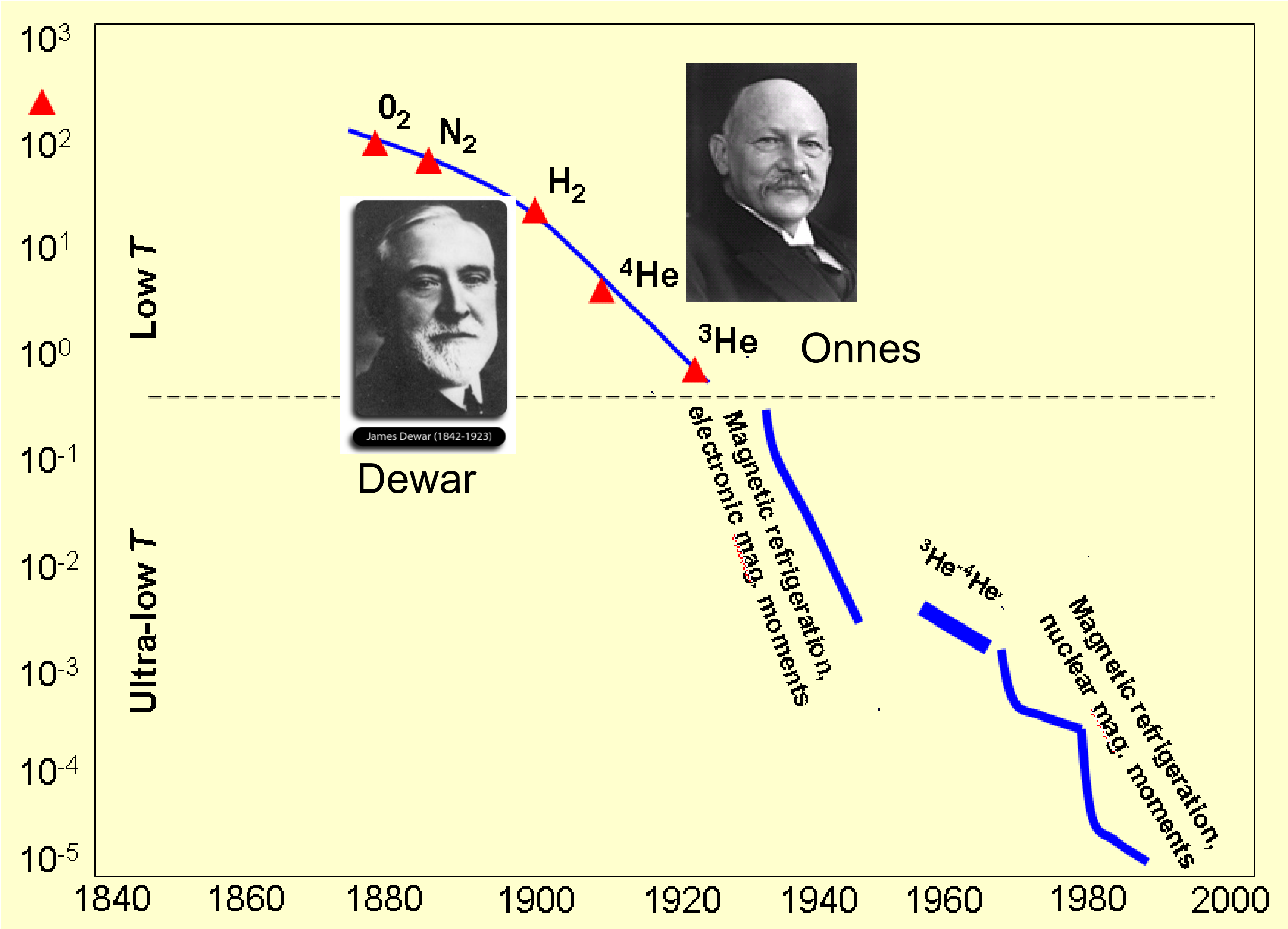


Onnes於1853年出生。
在1908年成功的發展出
大量製造液氦的技術。
那年Onnes的年紀已經54-55了。
從這裡也許可以看出發展技術與
理論創新的差異了。

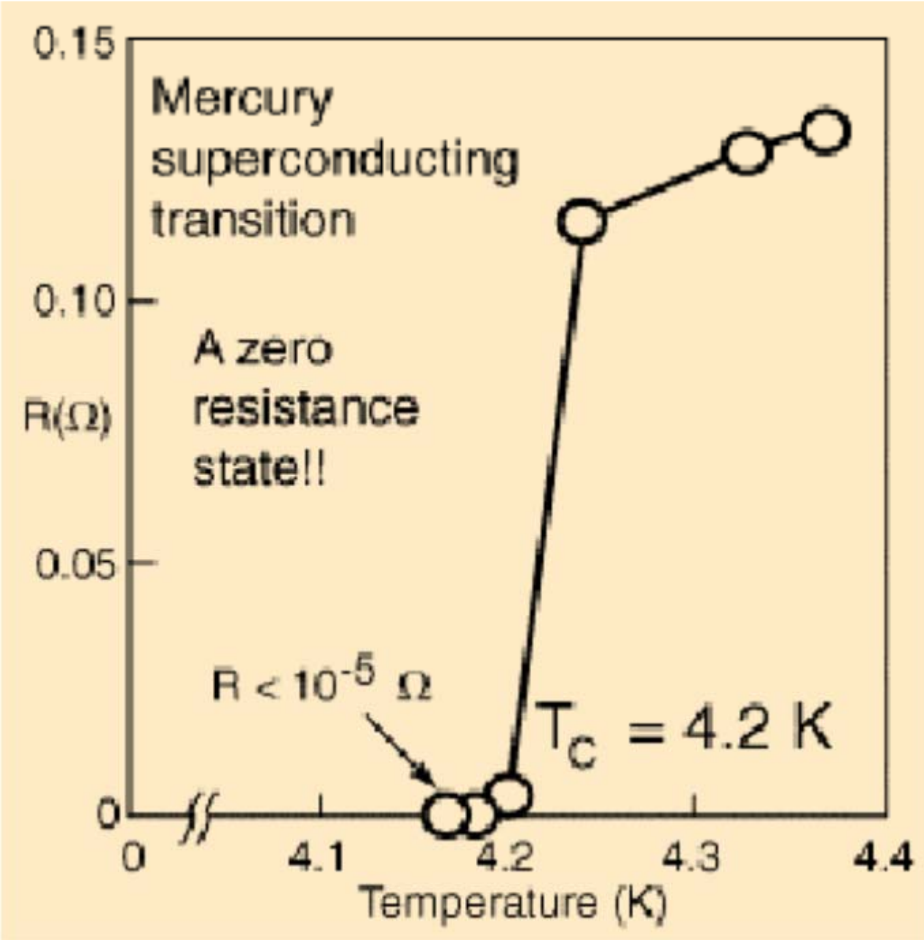
Onnes有了大量的液氦，3年後
(1911)發現了超導體。
雖然直到去世前(1926年)，
Onnes都不知道
超導體就是超導體，
一直以為超導體是完全導體。

Progress of experimental science is led by development of instrumentation.

100-Year Journey Toward Absolute Zero



Behavior of Metallic Resistance near Absolute Zero



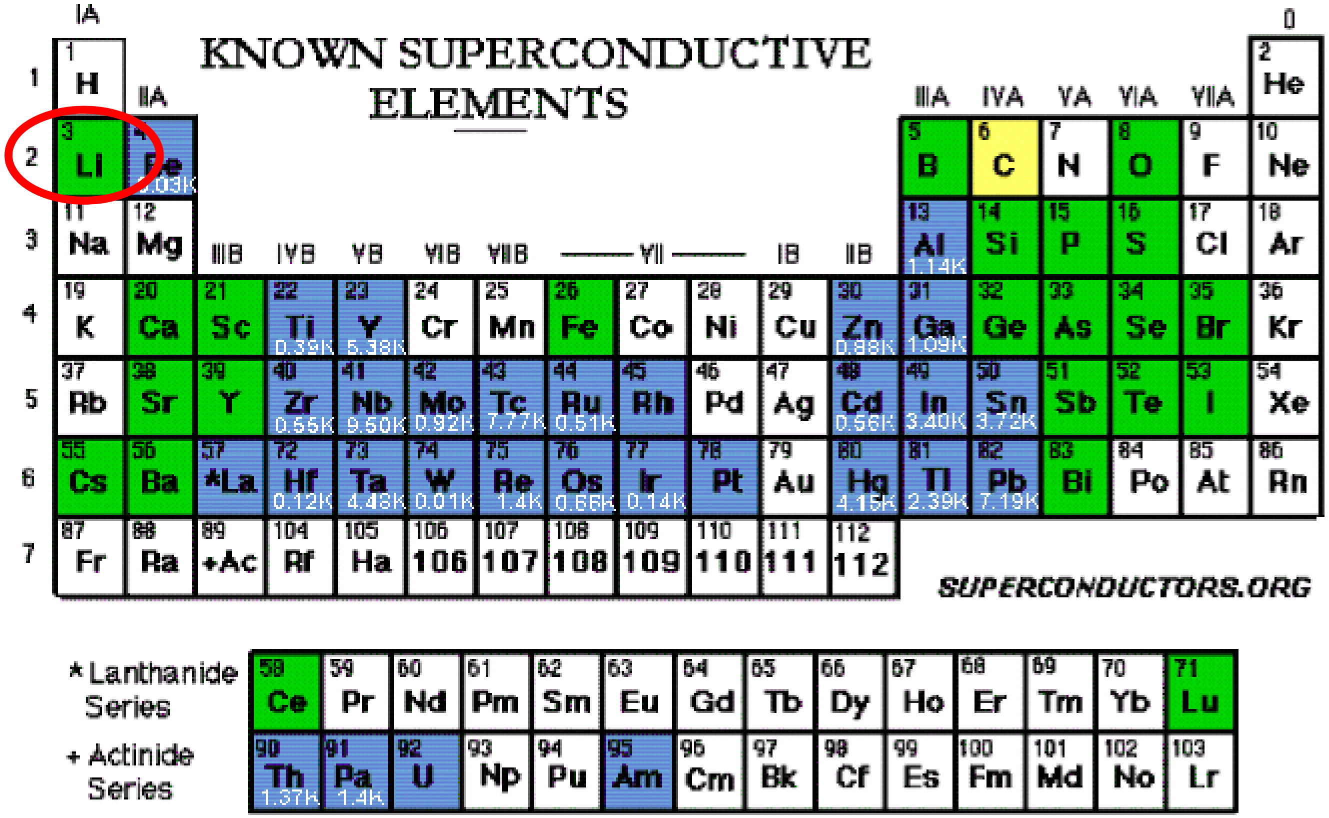
H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

- The mercury (Hg) was a material well known for **processing a very high degree of purity**.
- On cooling the mercury, Onnes found the resistance of the material dropped off abruptly at 4K. Onnes assigned a value of resistance to the mercury corresponding to the lowest level of sensitivity of his apparatus, as he simply could not believe that the resistance was zero.
- The DC resistance of a superconductor is lower than 10^{-20} Ω.

Historical Remark

Superconducting Elements

多數元素可以具有超導性



Ambient Pressure

High Pressure

Nb
(Niobium)
T_c=9K
H_c=0.2T

Superconductivity is not a rare phenomenon. About half of the metallic elements have been found to become superconductor at low temperatures.

New elements keep being added to the list. In 2002, Li was shown to superconducting under pressures of 23 to 36 GPa with critical temperature of 9 to 15 K. V.V. Struzhkin et al., Science 298, 1213 (2002).

Historical Remark

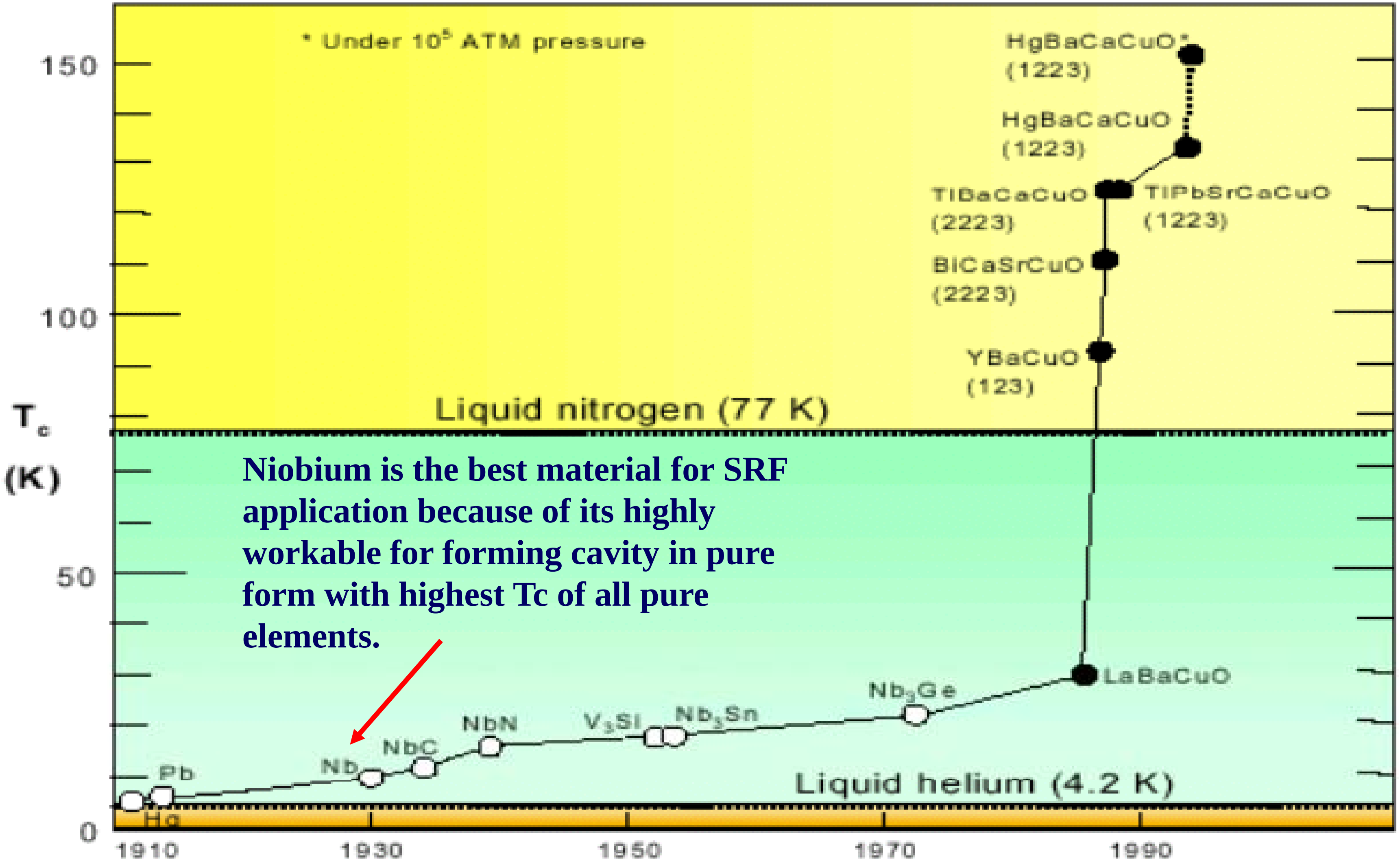
Superconducting Elements

超導體曾經讓人空歡喜一陣

- Transition temperatures (Tc) and critical magnetic fields (Hc) are general low;
- Metals with the highest conductivities are not superconductors;
- The magnetic 3d elements are not superconducting;

Milestones in Superconductivity

發明“實用”的高溫超導體是人類的科研的一個目標



Niobium is the best material for SRF application because of its highly workable for forming cavity in pure form with highest Tc of all pure elements.

(Courtesy of Brian Moeckly)

Historical Remark

How to Verify Zero Resistance?

Can we determine an upper limit for the resistivity of a superconductor?

This is done by injecting current into a loop of superconductor

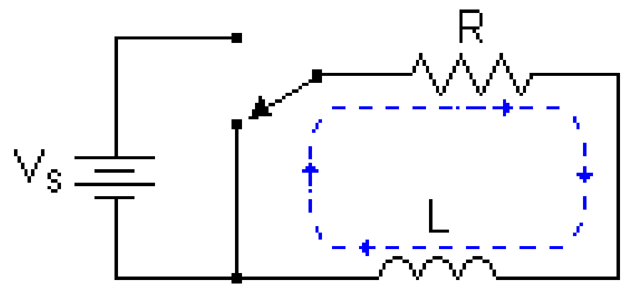
The current generates a magnetic field, and the magnitude of this field is measured as a function of time

This enables the decay constant of the effective R-L circuit to be measured:

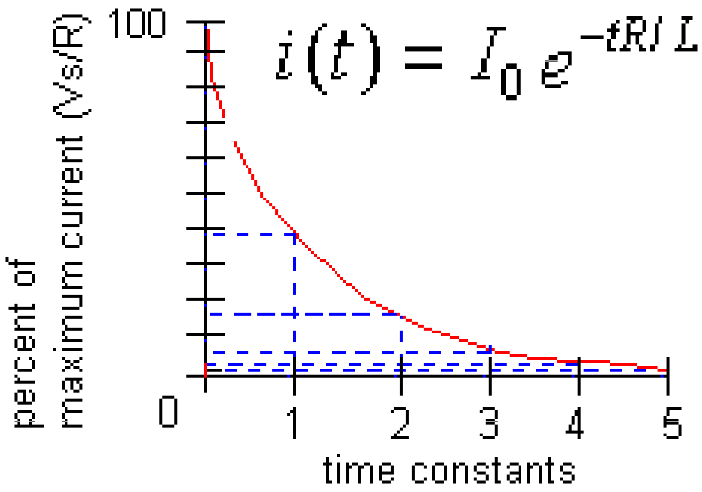
$$B(t) \propto i(t) = i(0)e^{-(R/L)t}$$

Using this technique, no discernable change in current was observed over two years:

$$\rho_{sc} \leq 10^{-24} \mu\Omega.\text{cm} \quad !!$$

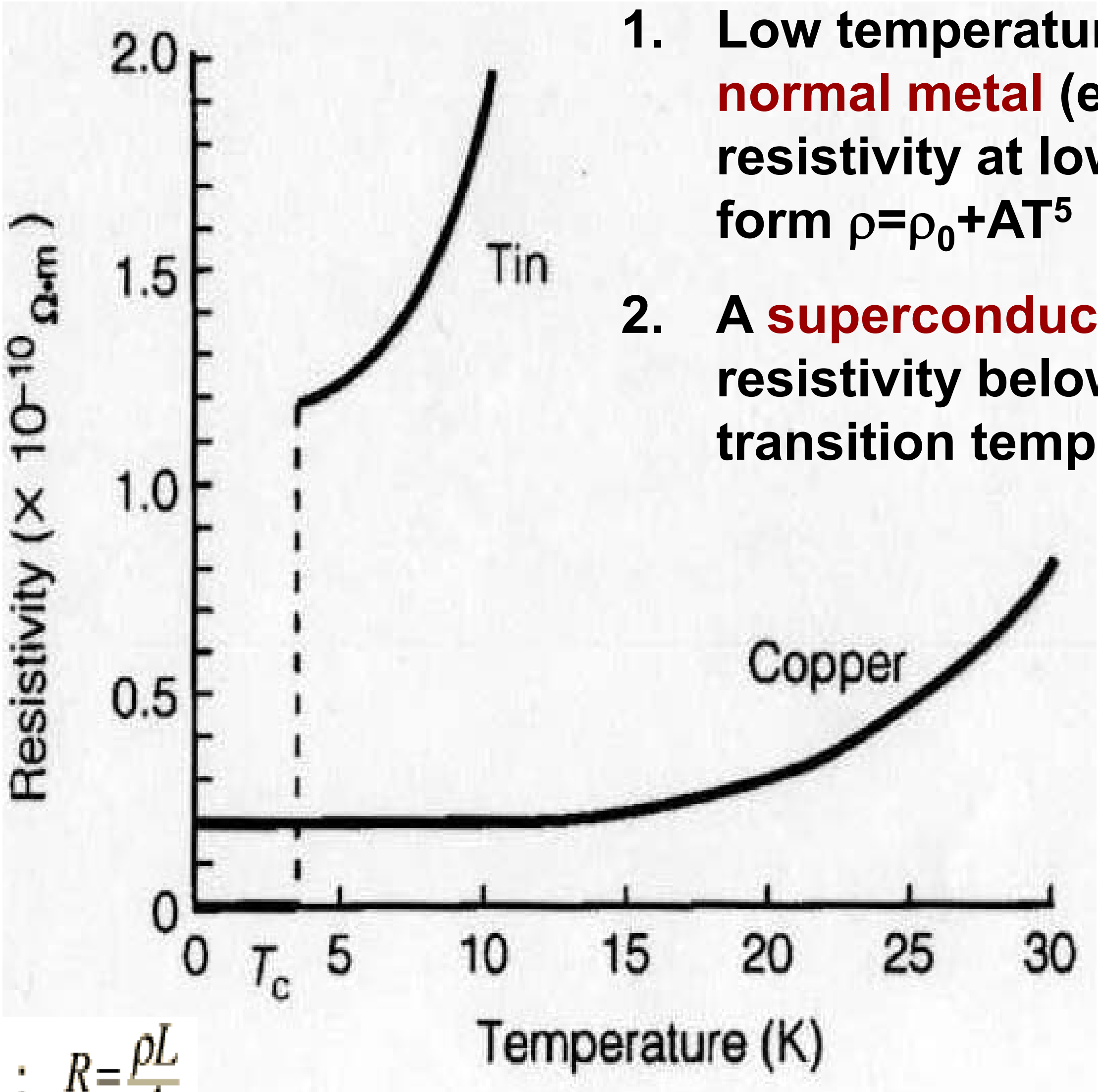


$$\tau_{RL} = \frac{L}{R}$$



Historical Remark

Superconductor vs. Normal Conductor



1. **Low temperature resistance of a typical normal metal (ex copper), showing a dc resistivity at low temperatures of the form $\rho=\rho_0+AT^5$**
2. **A superconductor showing zero resistivity below the superconducting transition temperature T_c.**
3. **Is a superconductor a perfect conductor or more than a perfect conductor? A perfect conductor is an electrical conductor without resistivity.**

$I=\frac{V}{R}$; $R=\frac{\rho L}{A}$

Historical Remark

Outlines

- Historical Remark
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- SRF Operation and Maintenance

本節重點提示

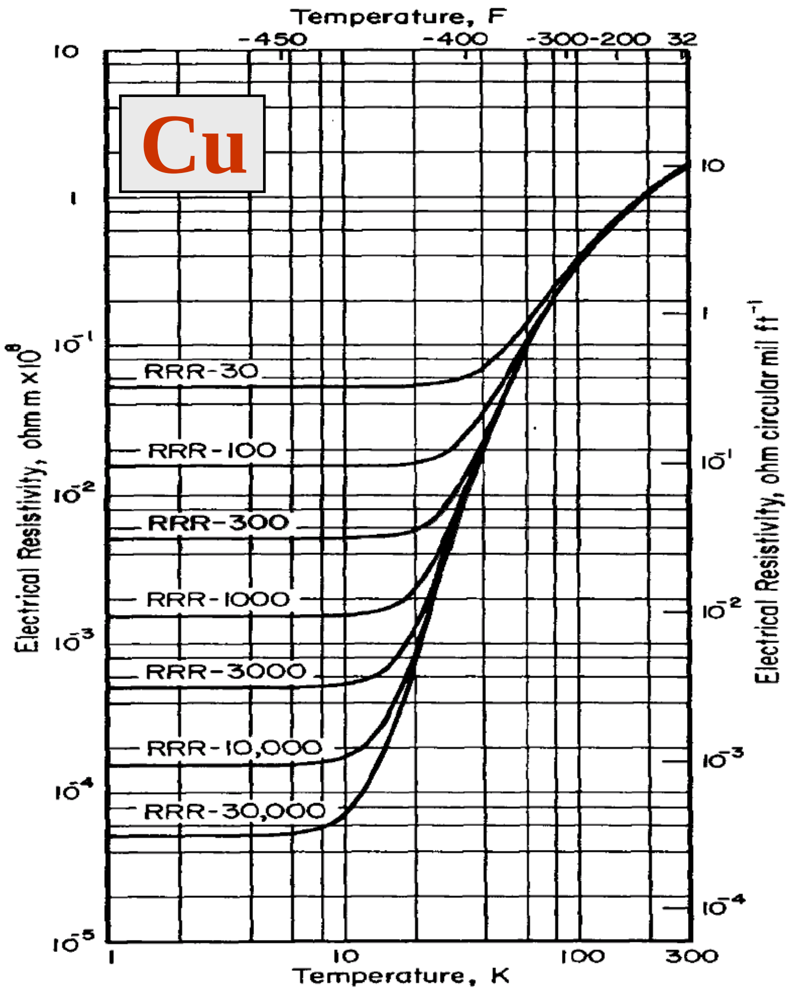
- RRR
  - DC resistance vs. AC/RF resistance
  - Resistance vs. thermal conductivity
- What is the superconductivity?
- Type I and type II superconductor?
- Futures of superconductor

What is the Residual Resistance Ratio (RRR)?

$$RRR = \frac{\text{Resistivity at 300K}}{\text{Residual resistivity at low temperature (normal state)}}$$

- High-purity metal has
  - high RRR values →**lower residual resistance**.
  - **higher thermal conductivity** at cold.

- High-purity metal is softer
  - not good from mechanical rigidity point of view.

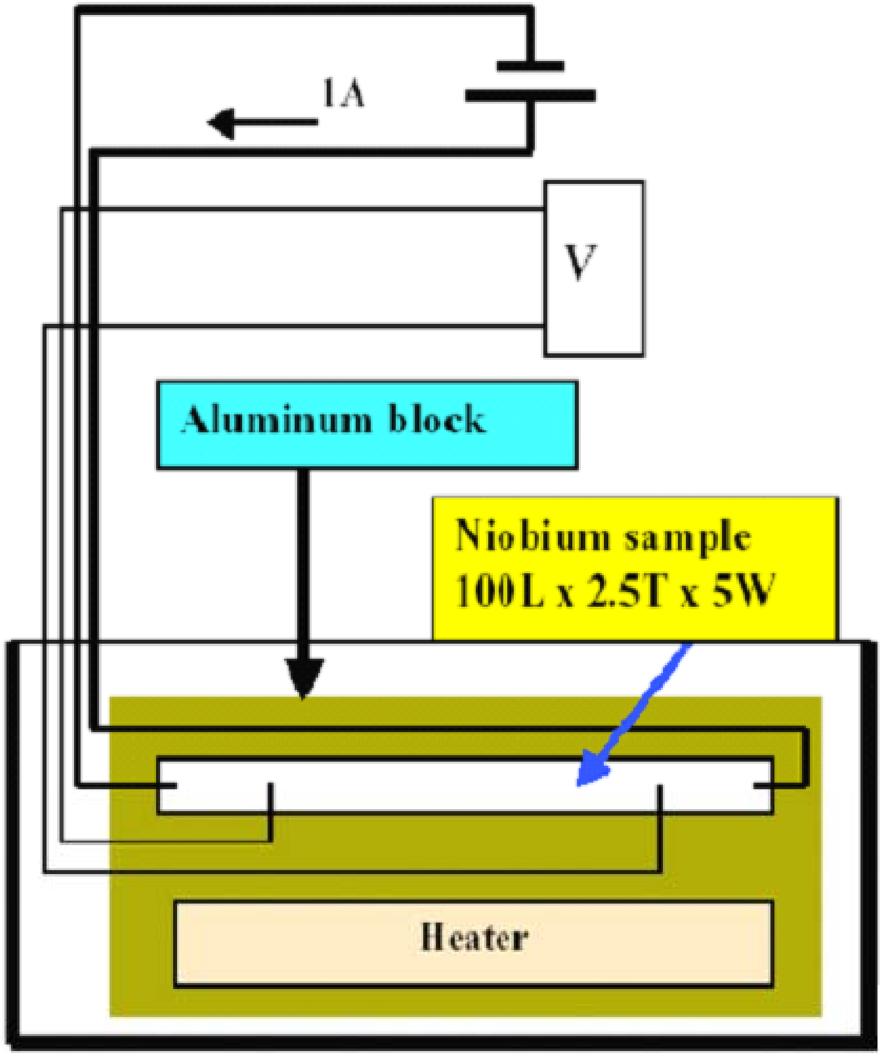


(Source: Handbook of Materials for Superconducting Machinery Battelle Columbus Laboratories, 1974)

Question: How to measure the RRR of a superconductor?

Measurements of RRR

How to Measure the RRR of a Superconductor?



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

Purification of Niobium Bulk

- Reactor grade niobium: RRR=40
- High purity niobium for SRF cavity: RRR=300~400

DC and AC/RF Resistivity

- The **dc resistivity** $\rho=1/\sigma$

$$I=\frac{V}{R} \quad ; \quad R=\frac{\rho L}{A}$$

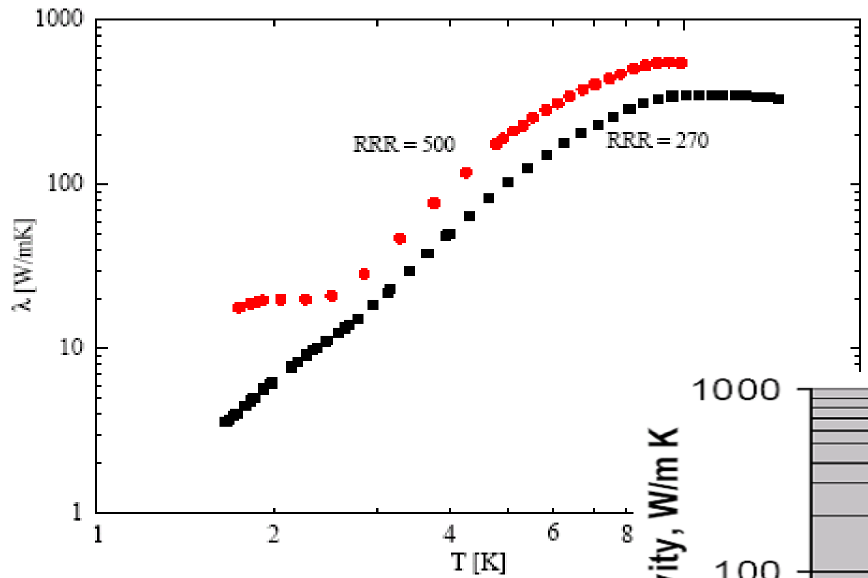
- The **AC/RF resistivity**: If skin depth > > mean free path, the **ac/rf surface resistance is given by**

$$R_S=\frac{1}{\sigma\delta}=\sqrt{\pi f\mu_o/\sigma}$$

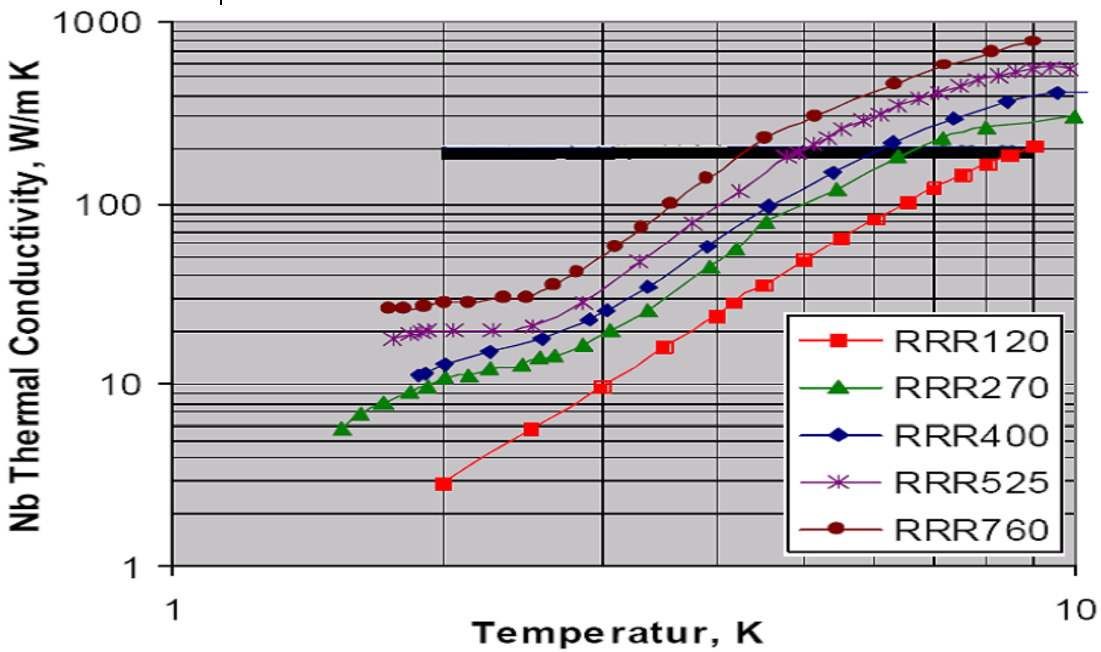
- But at very **low temp** and/or **high rf frequency**, **skin depth** may be shorter than the **mean free path**.
  - This makes the electron less effective to carry the rf current.
  - This make the **ac/rf surface resistance** larger….

For copper with RRR of 100, its dc conductivity increases by a factor of 100 at low temperature, but the ac/rf surface conductivity increases only by a factor of 6.

Thermal Conductivity of Niobium



1. The electrons bound in Cooper pairs (superelectrons) do not contribute to the heat conductivity, so the heat has to be transported by the (few remaining) normal conducting electrons and phonons;
2. The higher the RRR (the higher the electrical conductivity), the lower the degree of impurities and imperfections;
3. The increase of superconducting electrons may not be stepwise (Tc of Nb is 9.2K);



High RRR means high electrical and thermal conductivity at low temperature.

本節重點提示

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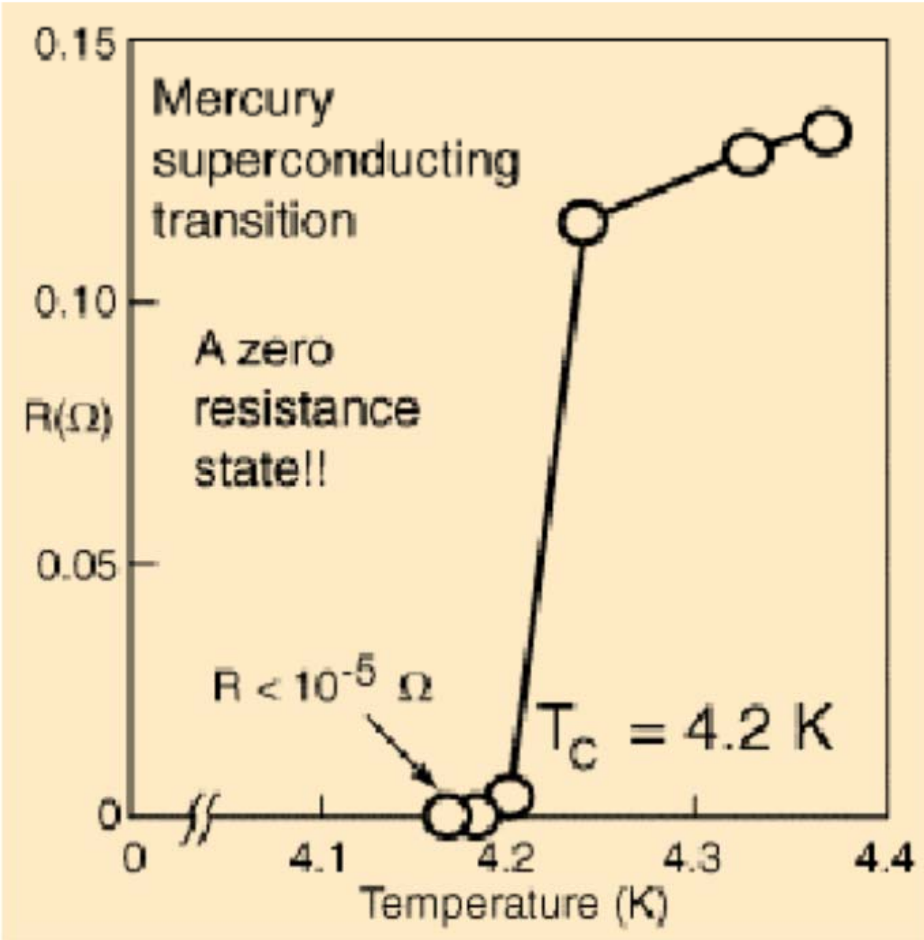
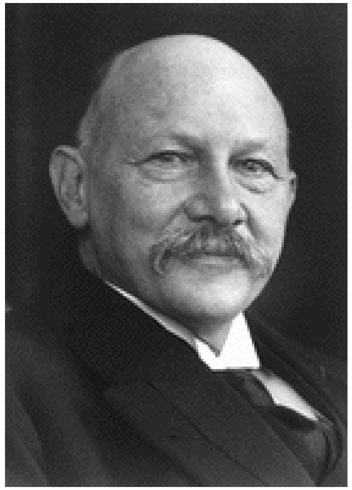
- **What is the superconductivity?**
- Type I and type II superconductor?
- Futures of superconductor

What is the Superconductivity?

A perfect conductor or more than a perfect conductor?



H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

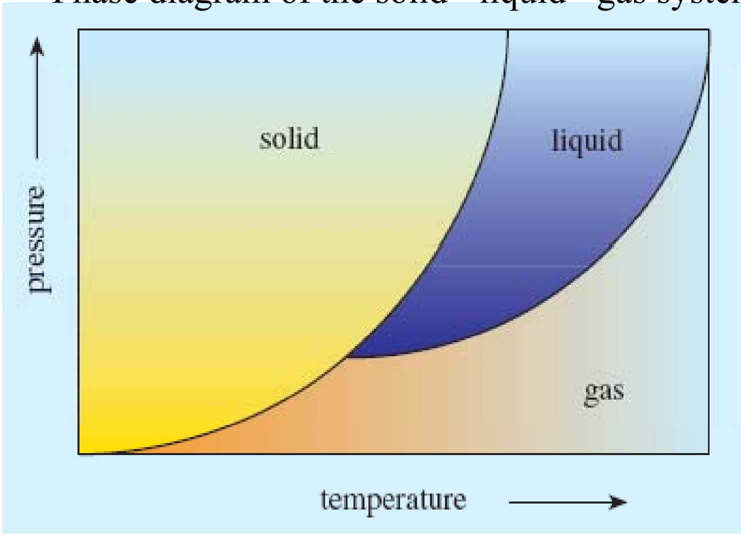


Onnes在1911年
發現超導體，
一直以爲超導體
就是perfect conductor。

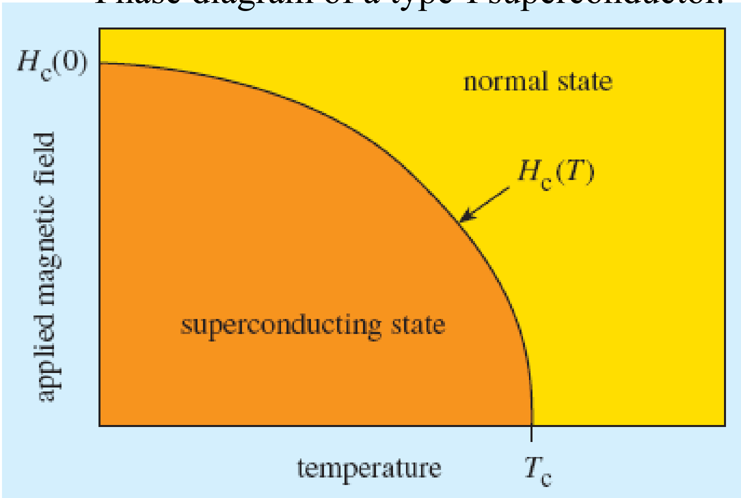
What is the Superconductivity?

- A **phase transition** from the normal conductivity state to superconducting state ….
  - A **phase transition** is the transformation of a **thermodynamic system** from one phase to another. At the phase transition, there is a change of the **degree of disorder**.
  - **Examples** of phase transition in daily life: from gas to liquid; from liquid to solid etc. The molecules in a gas state do not interact with each other, forming a disordered state. As the temperature decreases, the degree of disorder decreases. The liquid is more ordered than the gas state, and the solid state is so ordered that we can know where its molecules are situated.
  - **What is the change of the degree of order of the phase transition from normal conducting to superconducting?**
- This **transition** is **reversible (quench)**.
  - **Critical temperature**
  - **Critical magnetic field**
  - **Critical current**
- It happens within 10^{-4} K for pure elements.

Phase diagram of the solid - liquid - gas system.



Phase diagram of a type-I superconductor.

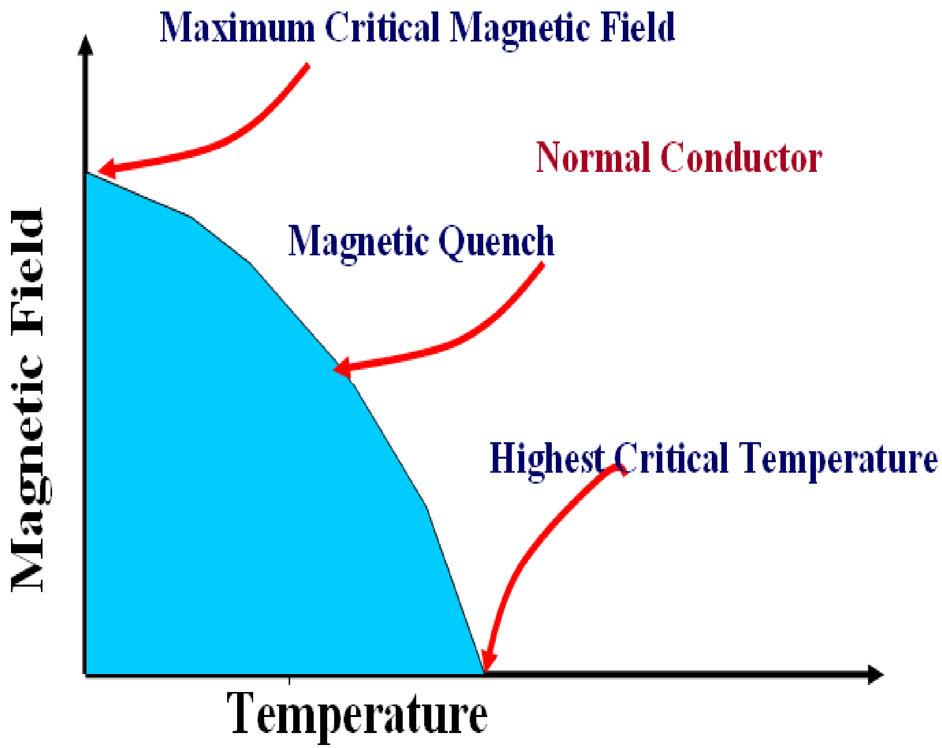


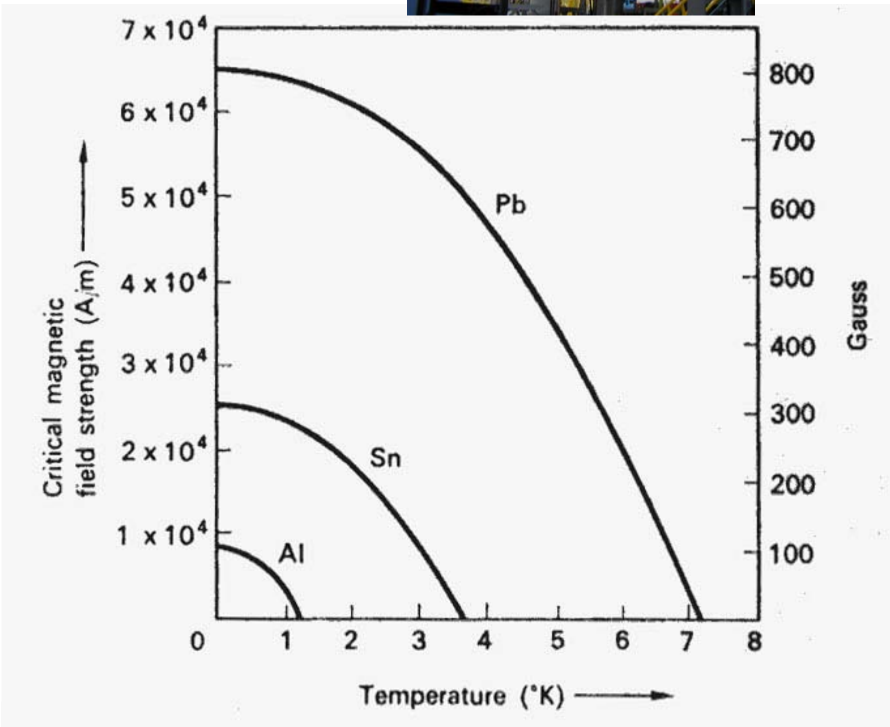
Quench of Superconductivity

- Critical Temperature, Critical Magnetic Field, and Critical Current Density

Experimentally it is found that

$$H_c(T) = H_o\left\{1-(T/T_c)^2\right\}$$



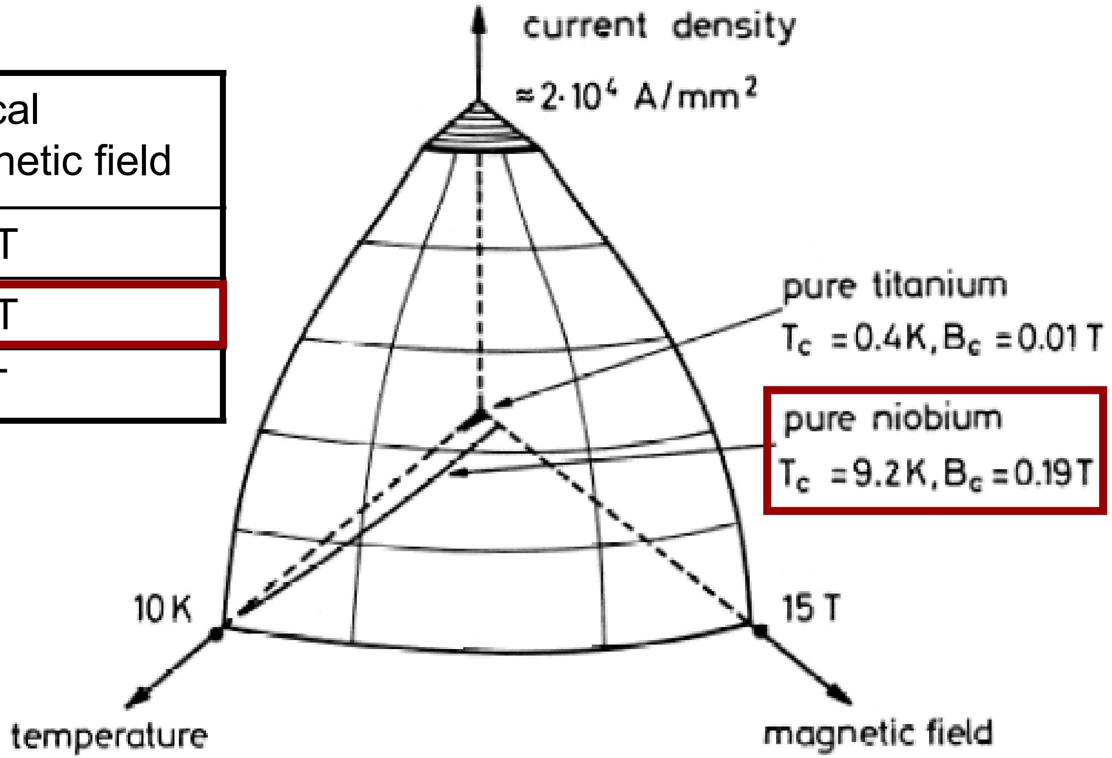


The lower the operating temp (always below critical temp), the higher the critical magnetic field.

Quench of Superconductivity

- Critical Temperature, Critical Magnetic Field, and Critical Current Density

	Critical temperature	Critical magnetic field
Titanium	0.4K	0.01T
Niobium	9.2K	0.19T
NbTi	~10K	~15T



Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

Superconductivity:

Critical Current - Silsbee Hypothesis

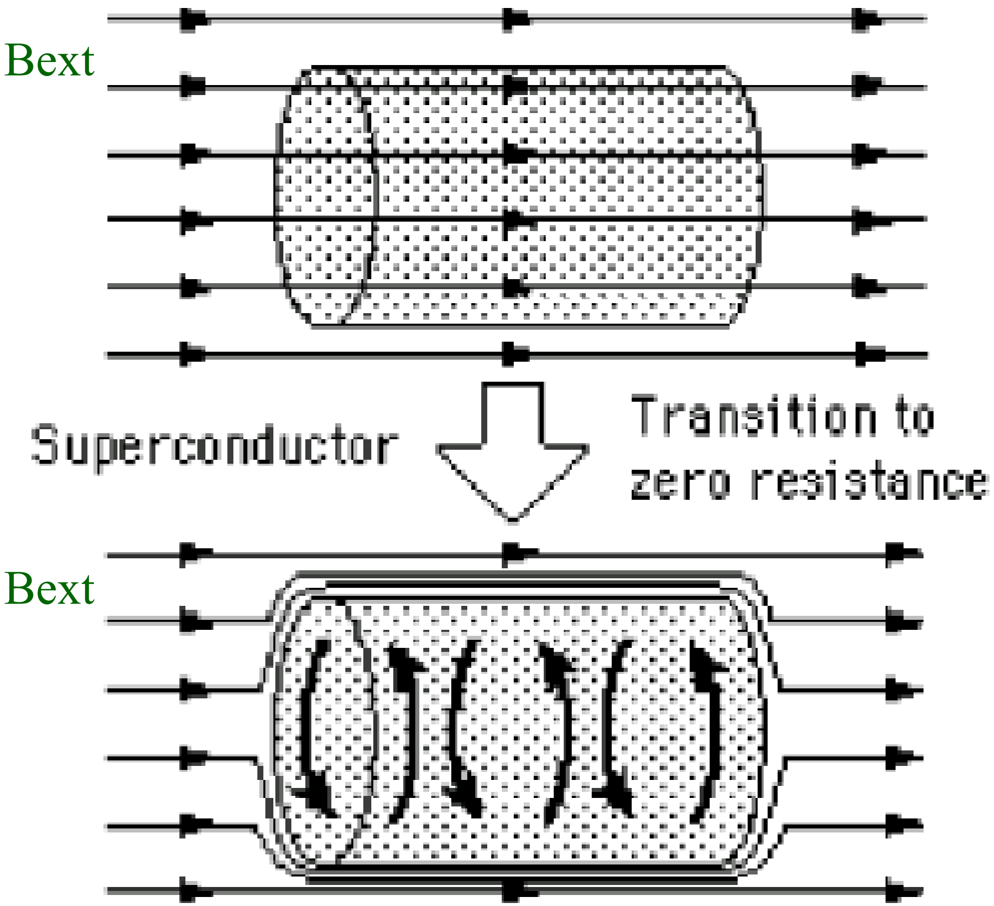
- When the electric current flowing in a type-I superconductor produces a magnetic field at the surface of the material which equals or exceeds the critical magnetic field, the normal state is restored.

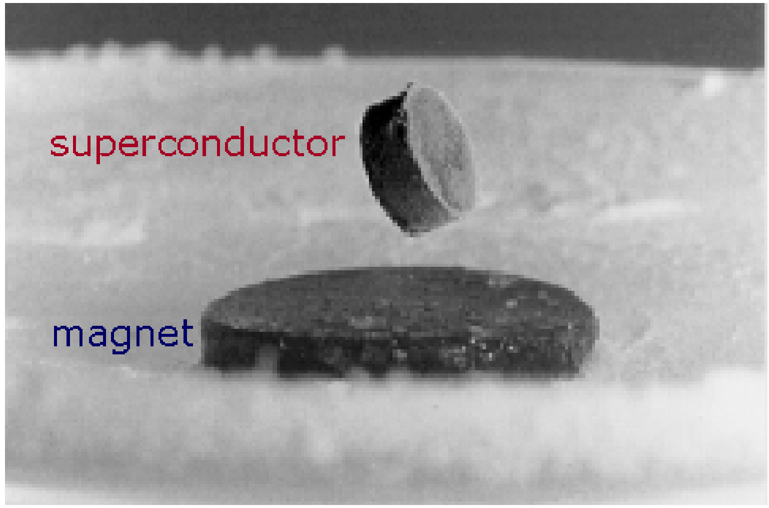
本節重點提示

- RRR
- What is the superconductivity?
- **Type I and type II superconductor?**
- Futures of superconductor

Meissner Effect (1933)

Superconductor is perfectly diamagnetic.

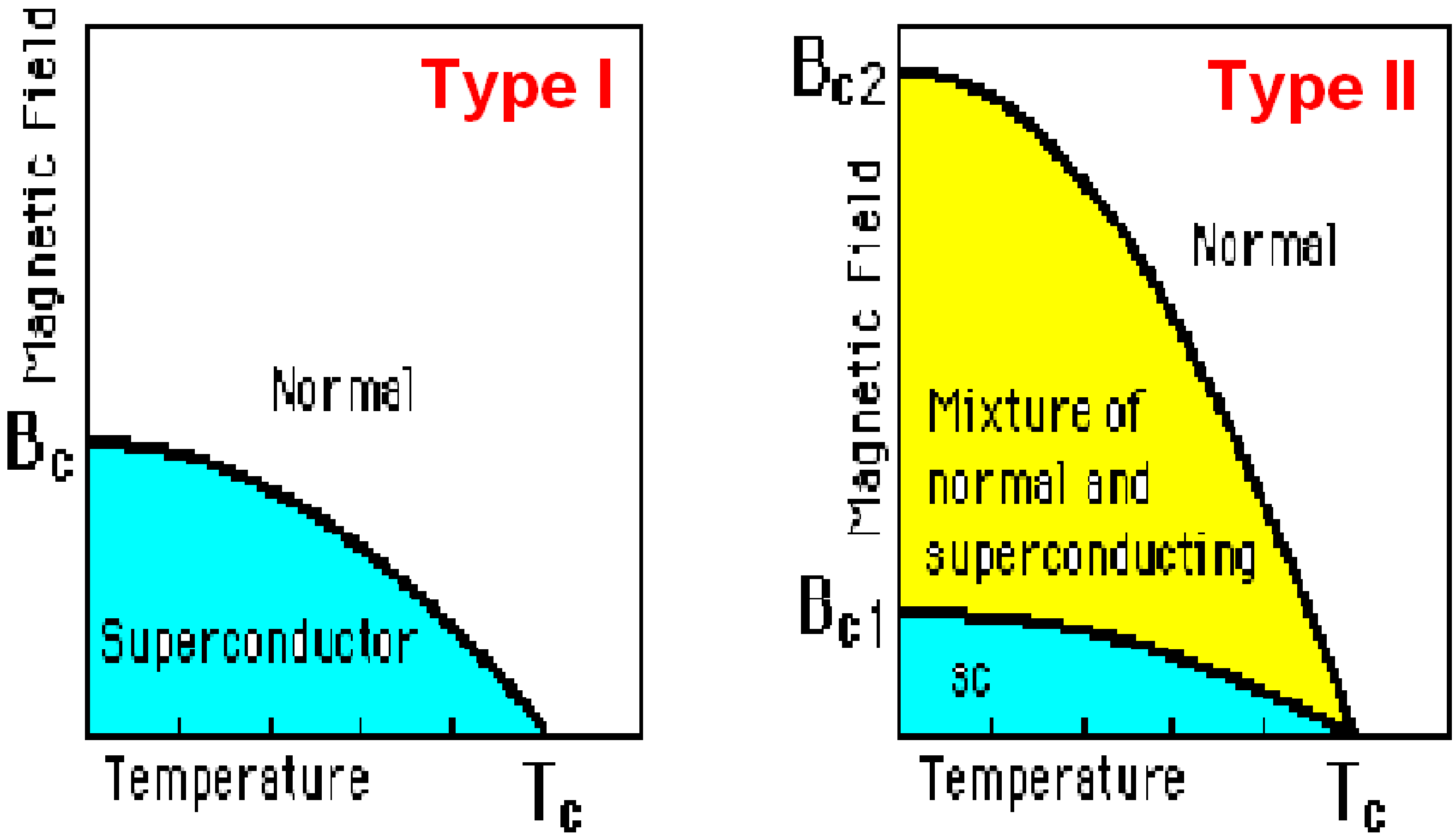




Onnes在1911年發現超導體，
但是1933年才知道Meissner效應.
也就是說在22年當中，
人們以爲超導體就是perfect
conductor.

Screen current will exclude Bext penetration.

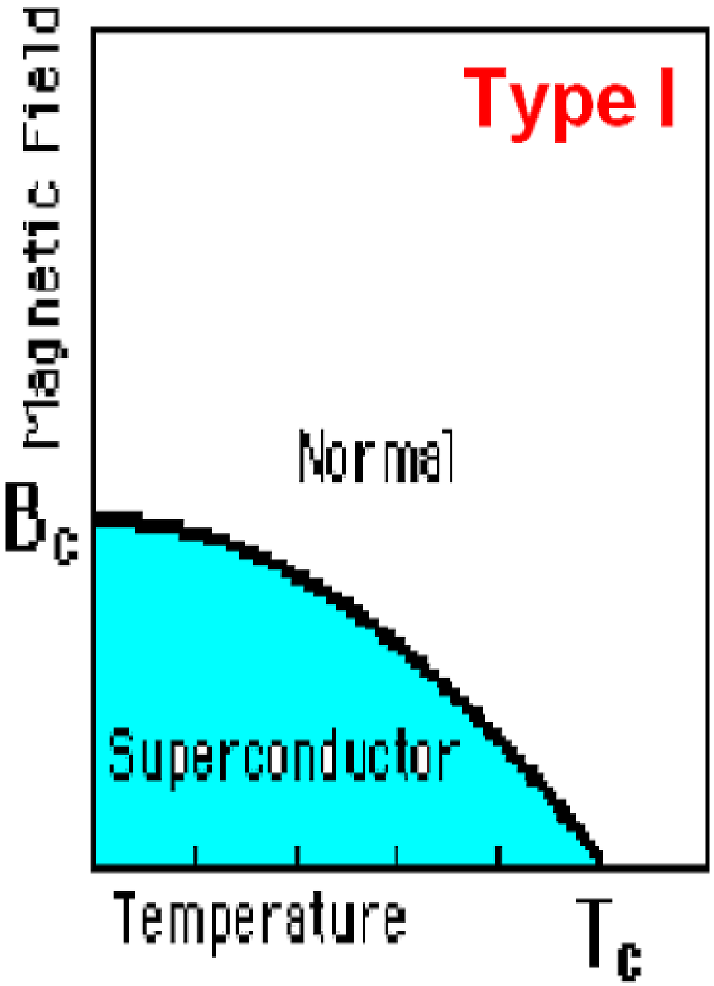
Type I & II Superconductor



Niobium is type II superconductor with T_c=9.2K under B_{ext}=0.

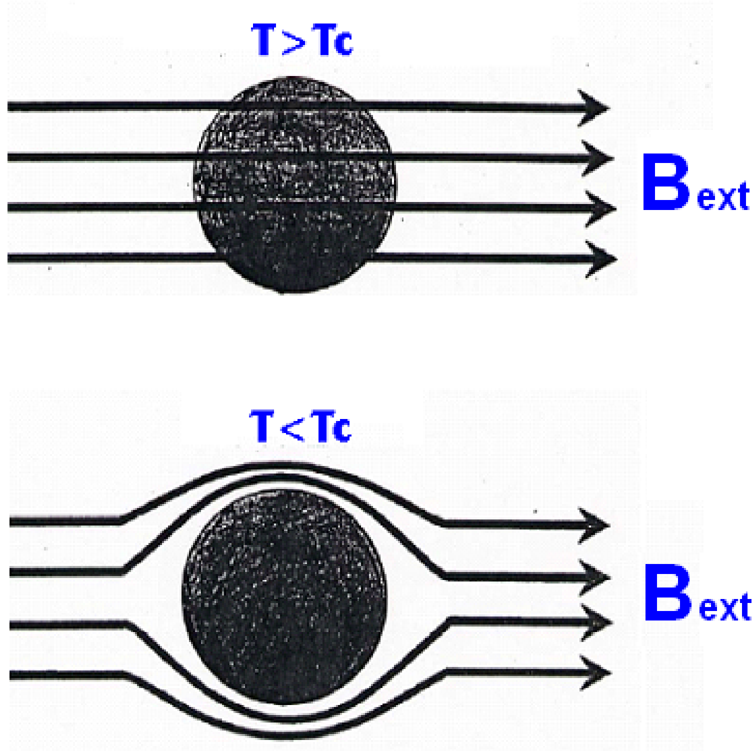
Type I Superconductor

- Complete Meissner Effect



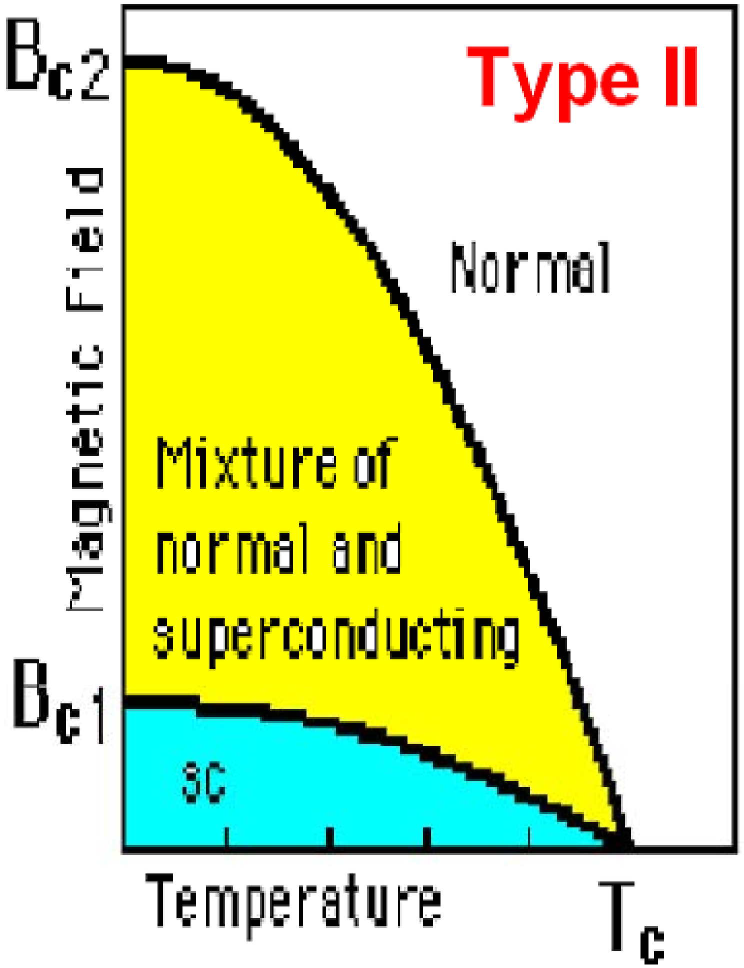
Type I

$$\mathcal{H}_c = \mathcal{H}_0[1 - (T/T_0)^2]$$



Type II Superconductor

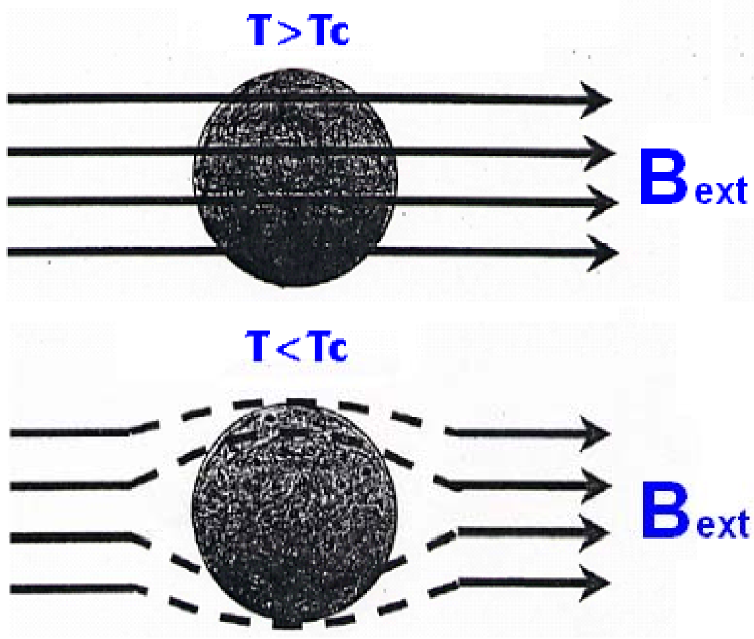
- Incomplete Meissner Effect



Type II

$$\mathcal{H}_{c_1} = \frac{\mathcal{H}_c(0.081 + \ln \kappa)}{\kappa\sqrt{2}}$$

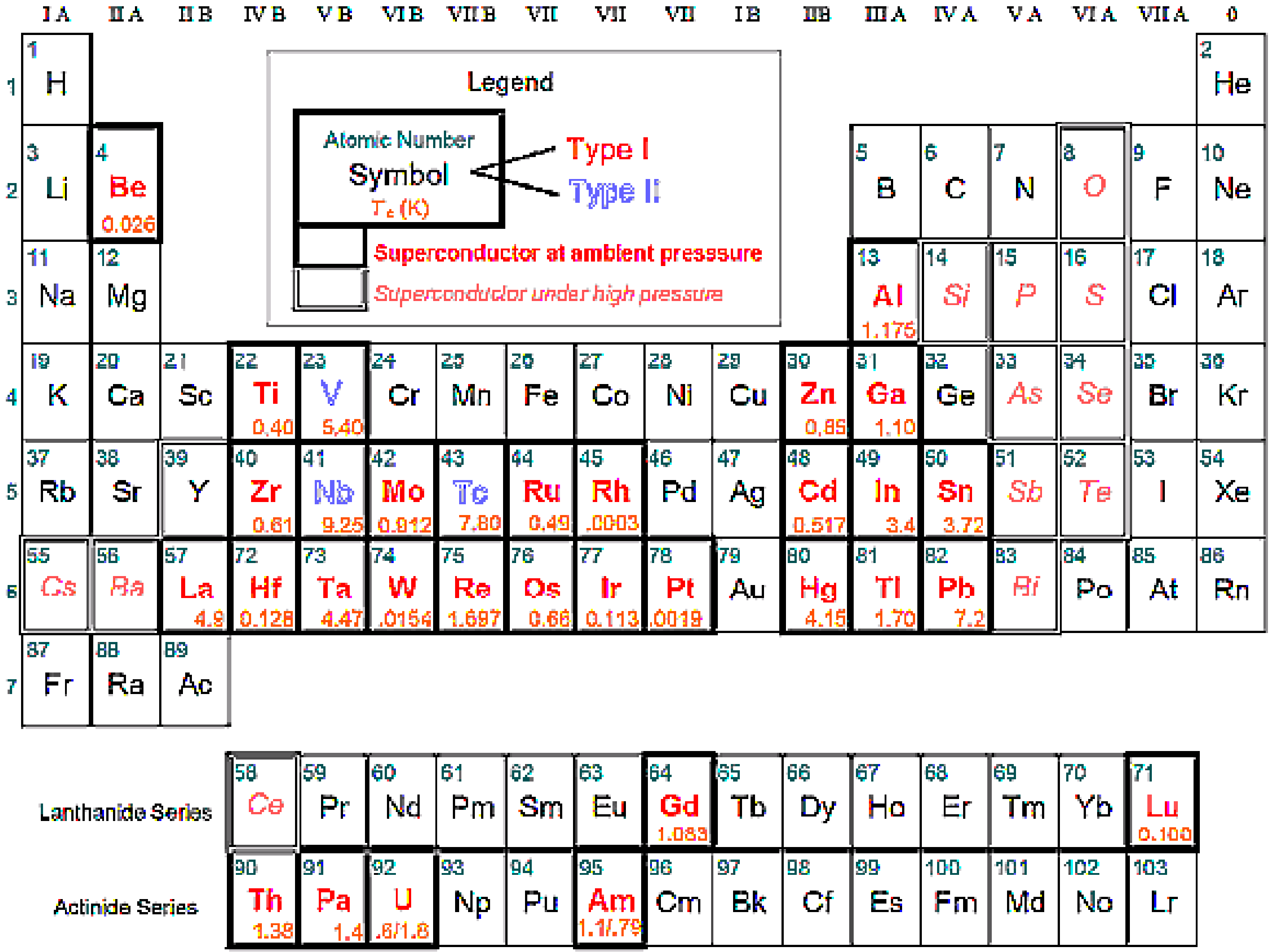
$$\mathcal{H}_{c_2} = \sqrt{2}\kappa\mathcal{H}_c$$



Type I & II Superconductor

- Niobium Belongs Type II.

釩
鈮
鍀



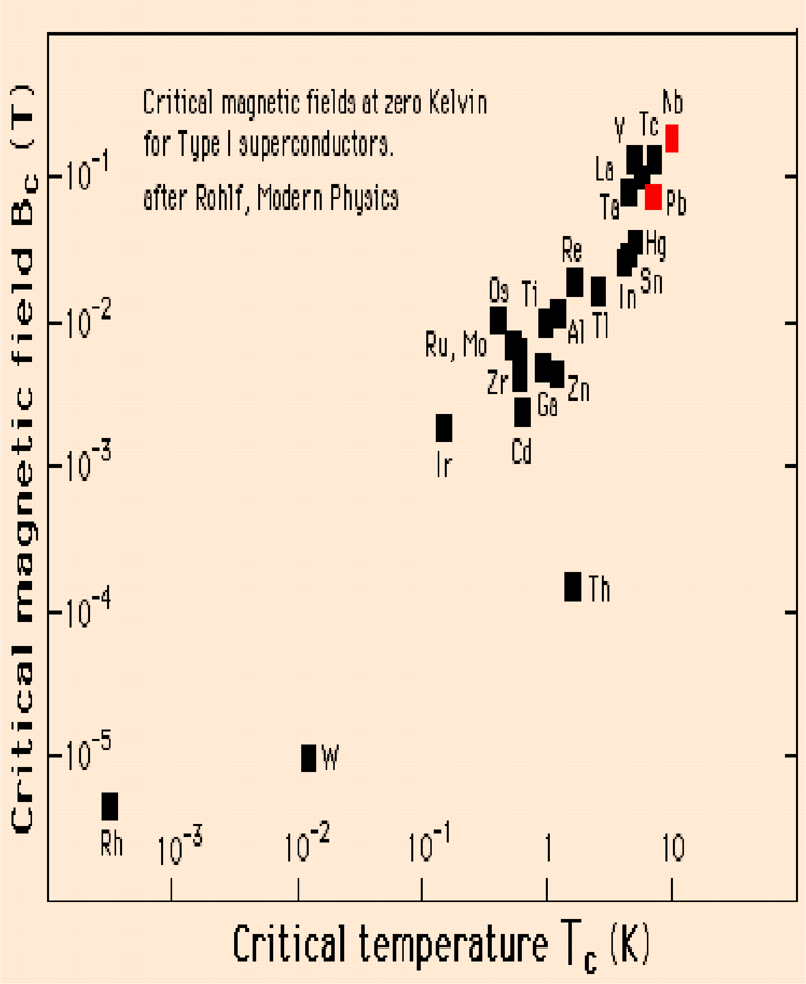
Type I & II Superconductor

-還好有Type II超導體

- Type I Superconductor
  - Lead (Pb),…
- Type II Superconductor
  - Niobium, Vanadium(釩) ,Technetium(鎝)
  - Alloys, transition metals, metallic glasses,
  - High Tc superconductor

Parameter	Pb	Nb	NbTi	Nb_3Sn
T_c (K)	7.9	9.2	9.4	18
B_c (T)	0.12	0.2	13	24
Application	RF	RF	DC	DC

Material	In	Pb	Sn	Nb
λ_0 (nm)	24	32	30	32
ξ_0 (nm)	360	510	170	39
κ	0.07	0.06	0.18	0.82
Type	I	I	I	II

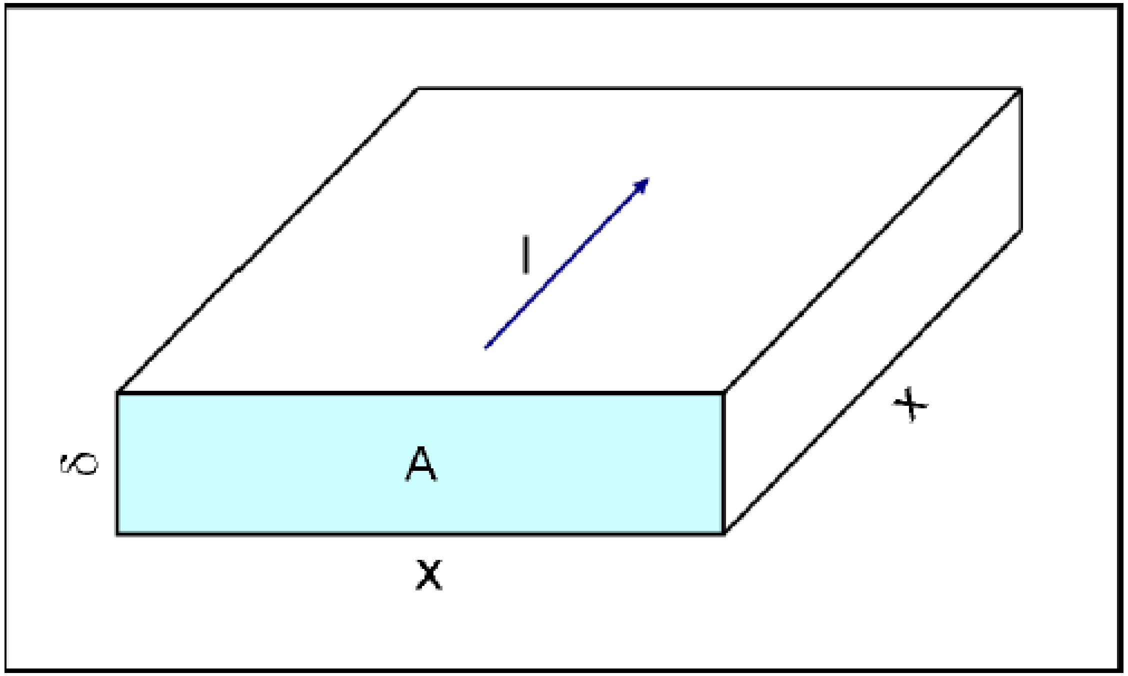


本節重點提示

- RRR
- What is the superconductivity?
- Type I and type II superconductor?
- **Futures of superconductor**
  - **Zero DC resistance (1911)** in Meissner state
  - **Small AC/RF resistance**
  - **Meissner effect (1933)**
    - exclusion of magnetic fields (perfect diamagnet)
  - **Quantum effects**
    - Magnetic flux quantization
    - Josephson junction (tunneling effect)
  - **Isotope effect (1950)**
  - **Phase transition**

RF Surface Resistance

Rs is Independent on the Surface Area



$$R_s = \frac{\rho l}{A} = \frac{x}{\sigma \delta x} = \frac{1}{\sigma \delta}$$

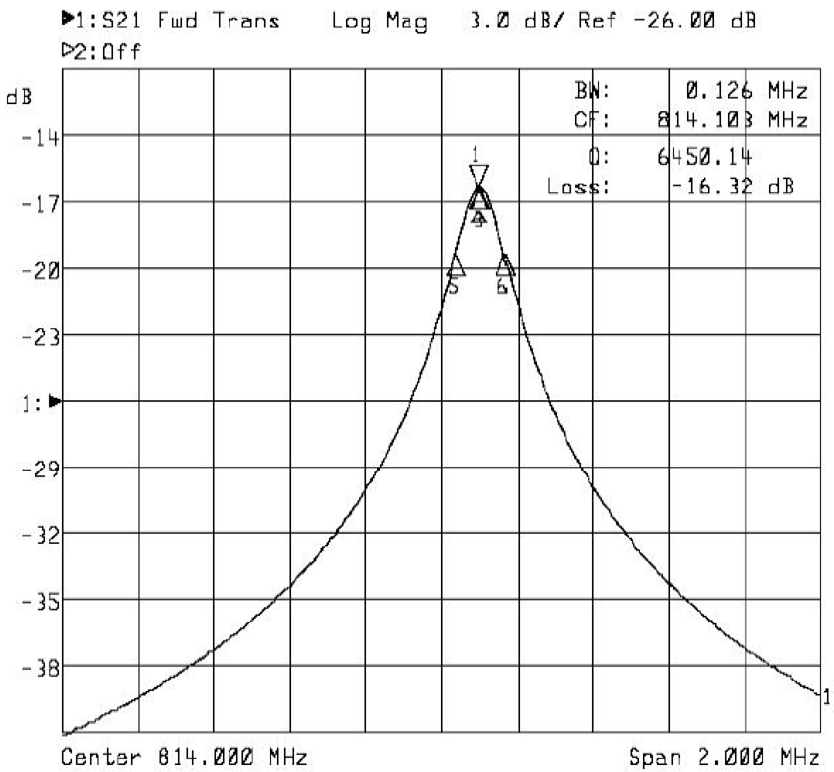
RF Surface Resistance

Connection to Performance of RF Cavity

$$Q_0 = \frac{\omega W}{P_c} = \frac{f}{f_2 - f_1} = \frac{f}{\Delta f}$$

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, dA$$

Power dissipation is reduced because of low BCS-value



- Normal conducting material (e.g. copper)

$$R_S = \frac{1}{\sigma\delta} = \sqrt{\pi f \mu_o / \sigma}$$

  - anomalous skin depth (at cold)
- Superconducting material (e.g. niobium)
  - BCS resistance (R_{BCS})
  - residual resistance (R_{res})
  - trapped magnetic flux (R_m)

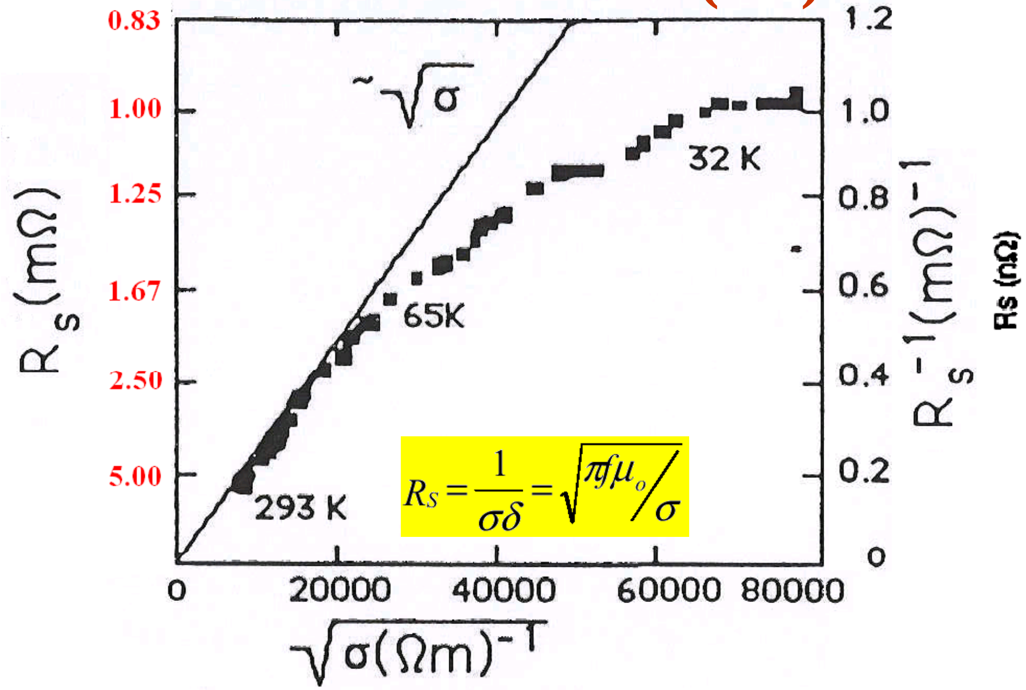
$$R_s = A \cdot \left(\frac{1}{T}\right) \cdot f^2 \cdot \exp\left(-\frac{\Delta(T)}{\kappa T}\right) + R_{res} + R_m \quad \text{for } T < Tc/2$$

$$R_m = 0.3^{[n\Omega]} \cdot H_{ext}^{[mOe]} \cdot \sqrt{f^{[GHz]}}$$

RF Surface Resistance

Normal Conductor vs. Superconductor

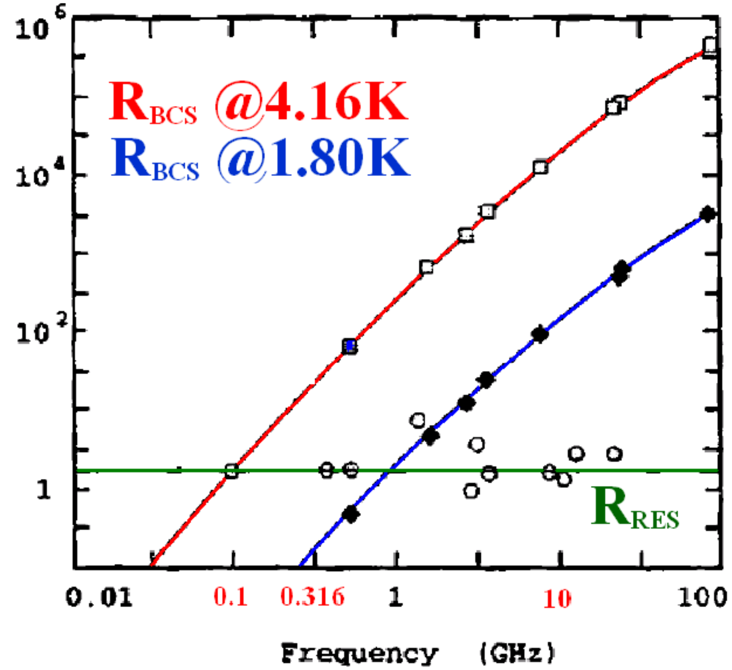
Normal conductor (Cu)



$$R_S = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu_o}{\sigma}}$$

Surface resistance of OFHC at 500MHz - comparing between anomalous and normal skin effect. (W. Weingarton)

Superconductor (Nb)



Surface resistance of Niobium cavity (in superconducting sate). (W. Weingarton, 1999)

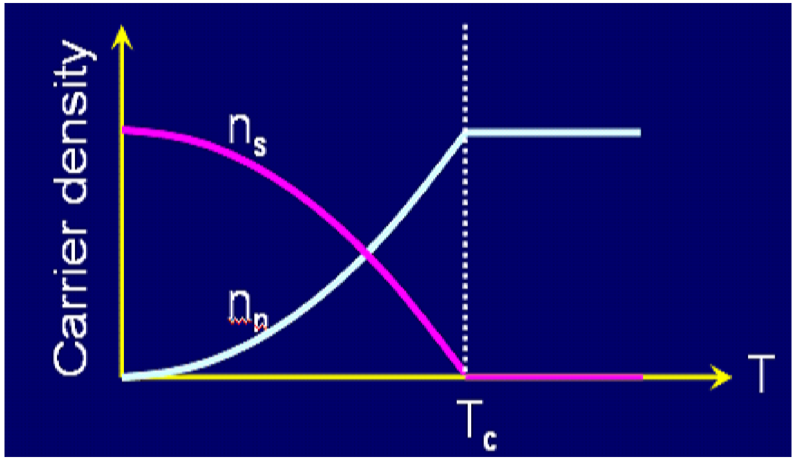
$$R_s = A \cdot \left(\frac{1}{T}\right) \cdot f^2 \cdot \exp\left(-\frac{\Delta(T)}{\kappa T}\right) + R_{res} + R_m \quad \text{for } T < Tc/2$$

Why Does a Superconductor Have a Small RF Resistance?

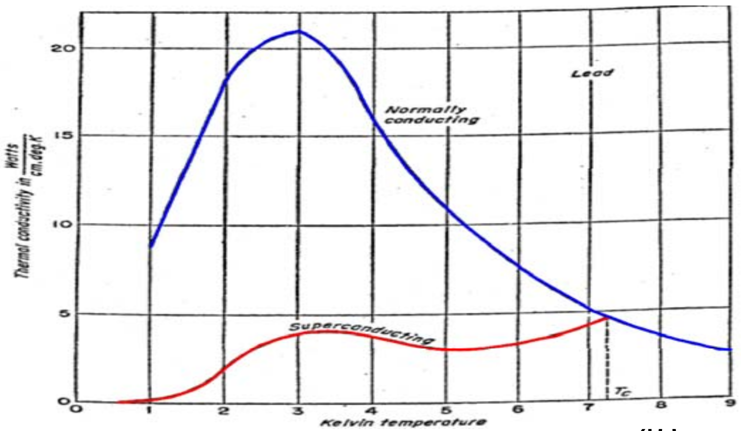
- The phenomenon of superconducting can be explained by **two-fluid model**:
  - $\mathbf{n} = \mathbf{n}_{\text{normal}} + \mathbf{n}_{\text{superconducting}}$
  - $\mathbf{N}_{\text{superconducting}} = 0$ at $T > Tc$
  - $\mathbf{n}_{\text{normal}} \neq 0$ at $T < Tc$
  - $\mathbf{n}_{\text{normal}} \rightarrow 0$ when $Tc \rightarrow 0$

  We will see the evidence from the change of **thermal conductivity** after phase transition from normal conducting to superconducting;

- The **cooper pairs** are superconducting electrons.



Here we are talking about the volume density of electrons.



Why Does a Superconductor Have a Small RF Resistance?
- RF Surface Resistance of a Superconductor

Cooper pairs have inertia → can't follow immediately RF fields

→ Unpaired electrons feel electric field → RF losses proportional to n_n

$$n_n \propto \exp\left(-\frac{\Delta}{k_b T}\right) \Rightarrow R_{s,BCS} \propto \exp\left(-\frac{\Delta}{k_b T}\right)$$

$$R_{s,BCS} = 2 \cdot 10^{-4} \frac{1}{T} \left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

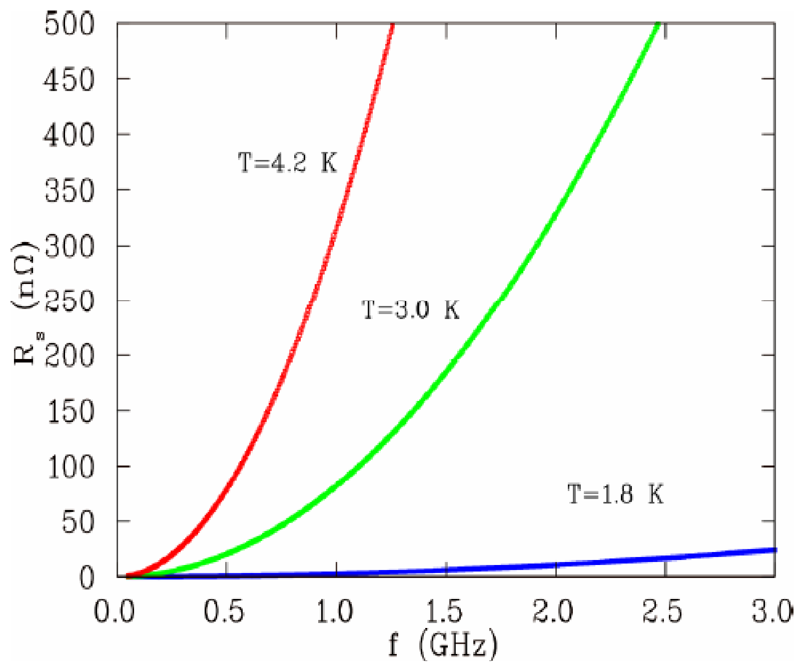
$$R_s = R_{BCS} + R_{magnet} + R_0$$

$R_s \approx n\Omega$

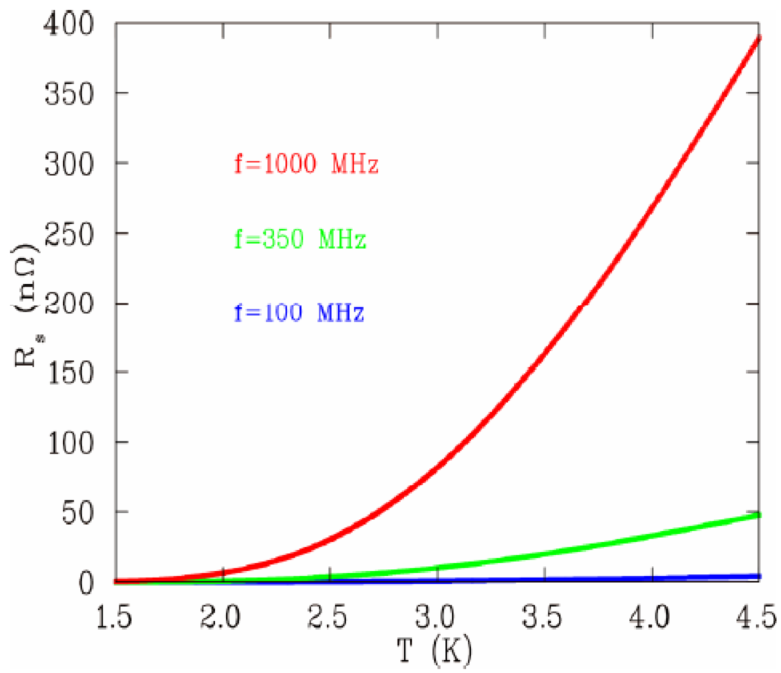
BCS RF Resistance

- The Higher the RF Frequency, the Larger the BCS RF Resistance.

as function of frequency



as function of temperature



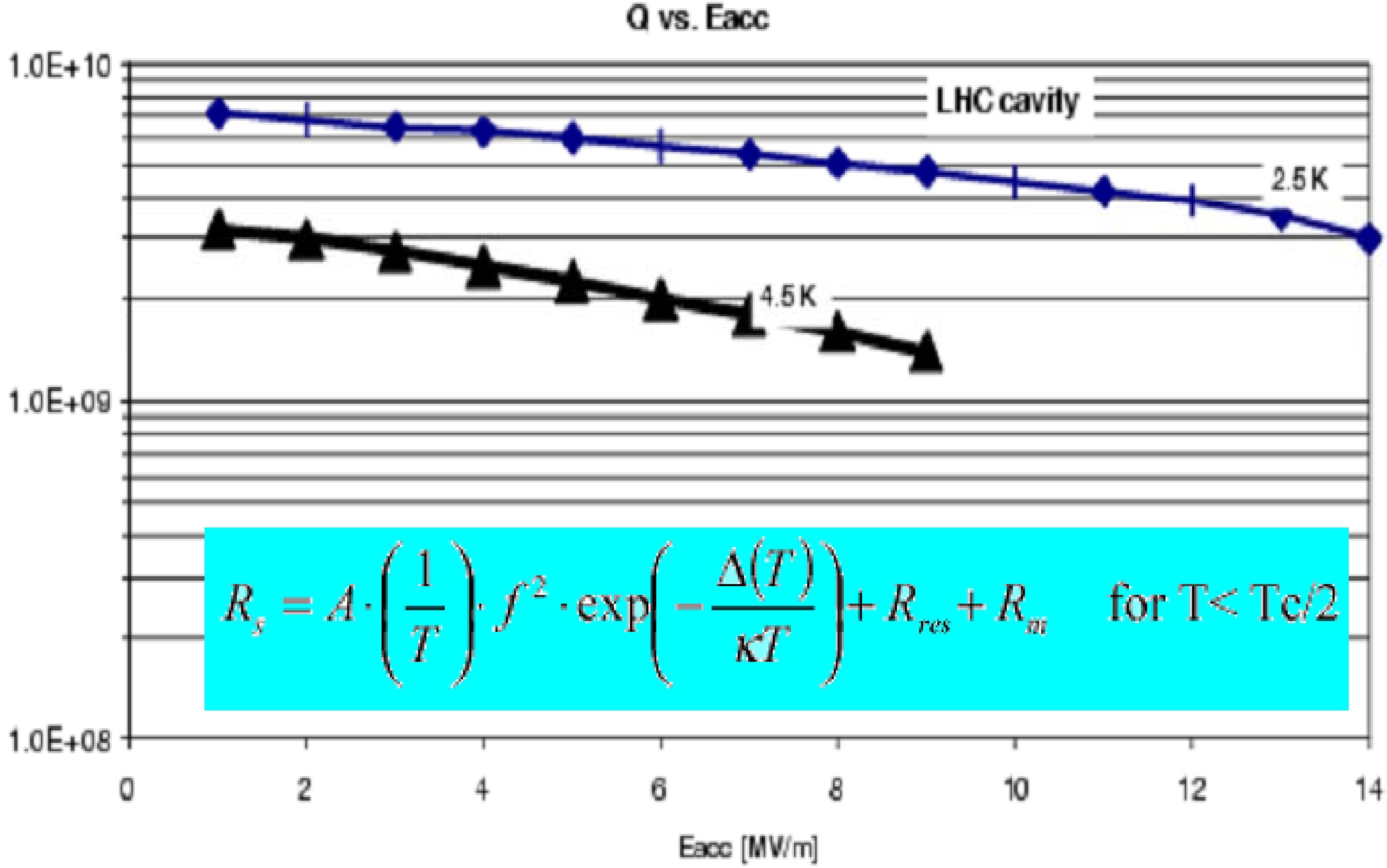
Low frequency → 4K

high frequency → 2K

$$R_s = A \cdot \left(\frac{1}{T}\right) \cdot f^2 \cdot \exp\left(-\frac{\Delta(T)}{\kappa T}\right) + R_{res} + R_m \quad \text{for } T < Tc/2$$

BCS RF Resistance

- The lower the temperature, the smaller the BCS RF Resistance and the higher the quality factor (Q_0) of the cavity.



$$R_s = A \cdot \left(\frac{1}{T}\right) \cdot f^2 \cdot \exp\left(-\frac{\Delta(T)}{\kappa T}\right) + R_{res} + R_m \quad \text{for } T < Tc/2$$

BCS RF Resistance

- The lower the temperature, the smaller the BCS RF Resistance.

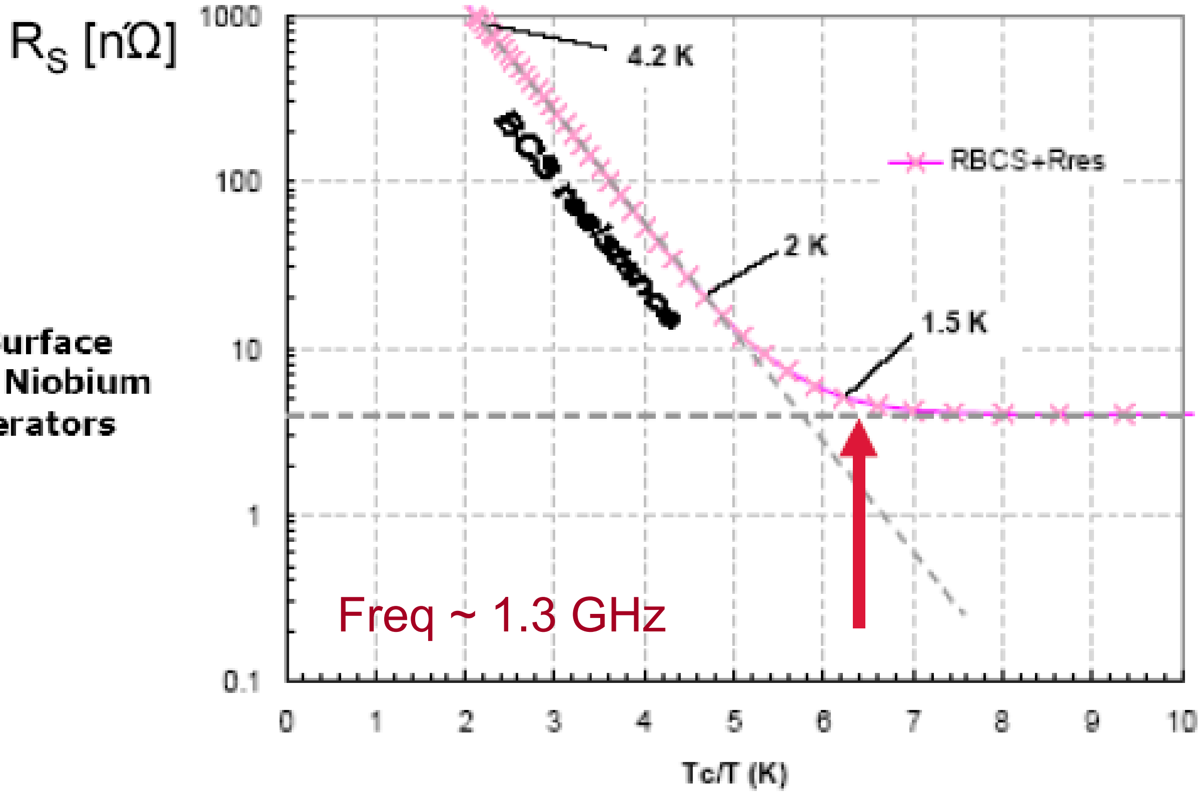


Diagramm taken from:

Review of Models of RF Surface Resistance in High Gradient Niobium Cavities for Particle Accelerators

P. Bauer

Fermilab, Technical Division

TD-04-014, June 2004

$$R_s = A \cdot \left(\frac{1}{T}\right) \cdot f^2 \cdot \exp\left(-\frac{\Delta(T)}{\kappa T}\right) + R_{res} + R_m \quad \text{for } T < Tc/2$$

BCS RF Resistance

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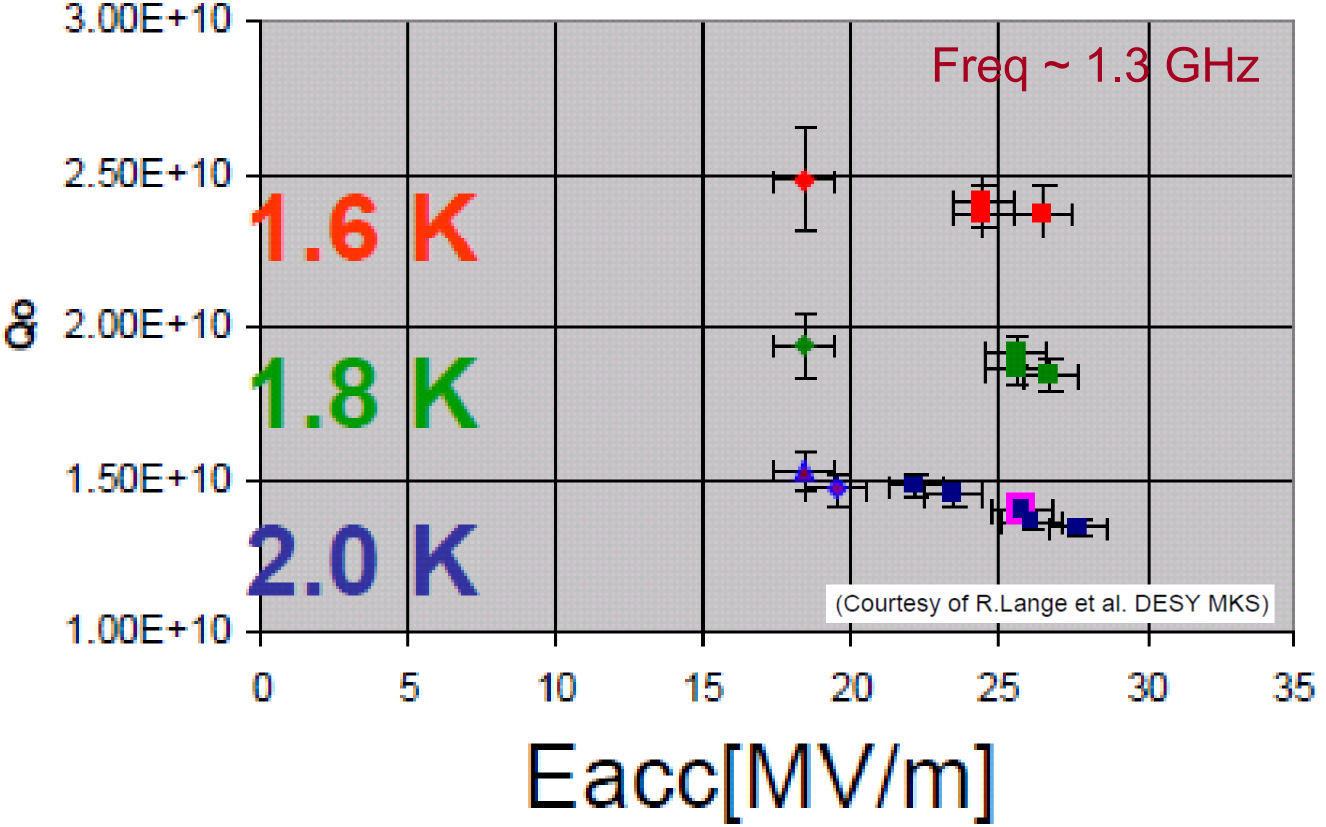


$$R_s = A \cdot \left(\frac{1}{T}\right) \cdot f^2 \cdot \exp\left(-\frac{\Delta(T)}{\kappa T}\right) + R_{res} + R_m \quad \text{for } T < Tc/2$$

Efficiency of Large Cryogenic Plant

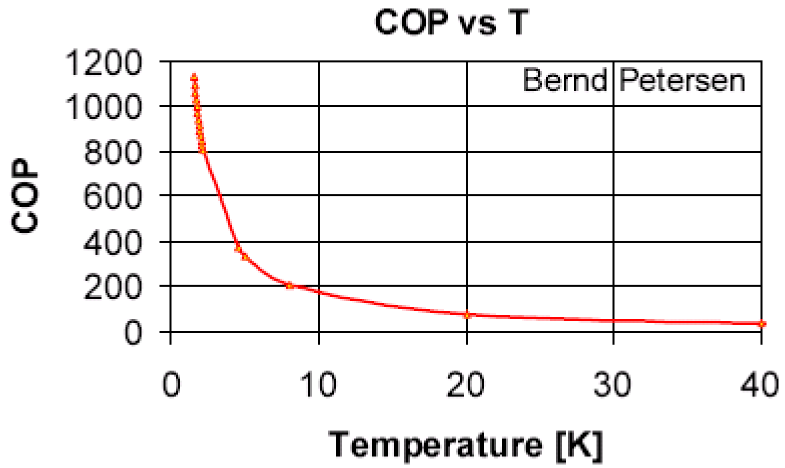
Some Refrigerator COPs

Refrigeration Temperature	Carnot 1/η IDEAL WORLD	XFEL-Spec REAL WORLD	% Carnot
2 K	149	870 w/w	17
5 K	79	220 w/w	36

1 W useful refrigeration at 2 K = 870 W Primary Power !!!

COP= Primary Power/ Power at LT

COP=1/(K * η CARNOT)
η CARNOT = T/(300 -T)



Efficiency cannot be better than Carnot limit.
The large the capacity of the cryo-plant,
the higher the efficiency (Coefficient of Performance, COP).

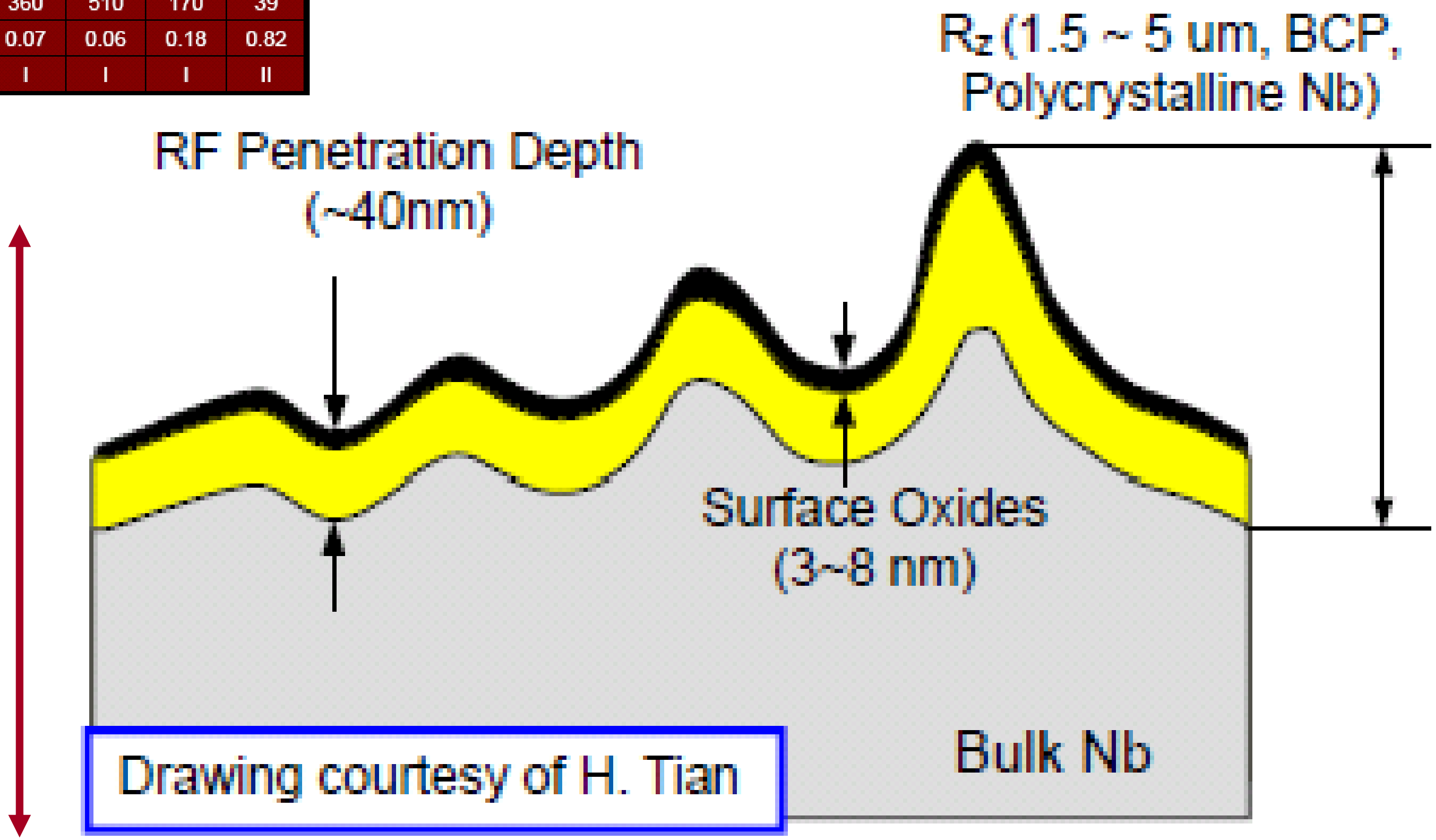
Efficiency of Small Cryogenic Plant

Operation mode (4.5 K)	TPS cryogenic system (700 W) [% of Carnot Cycle]	TLS cryogenic system (460 W) [% of Carnot Cycle]
Liquefaction without LN2	N/A	9.29%
Liquefaction with LN2	15.9%	12.9%
Refrigeration without LN2	15.1%	12.2%
Refrigeration with LN2	16.9%	13.8%

(Courtesy of Huang-Hsiu Tsai)

RF Surface Resistance of a Superconductor

Material	In	Pb	Sn	Nb
λ_0 (nm)	24	32	30	32
ξ_0 (nm)	360	510	170	39
κ	0.07	0.06	0.18	0.82
Type	I	I	I	II



2~3 mm

Outlines

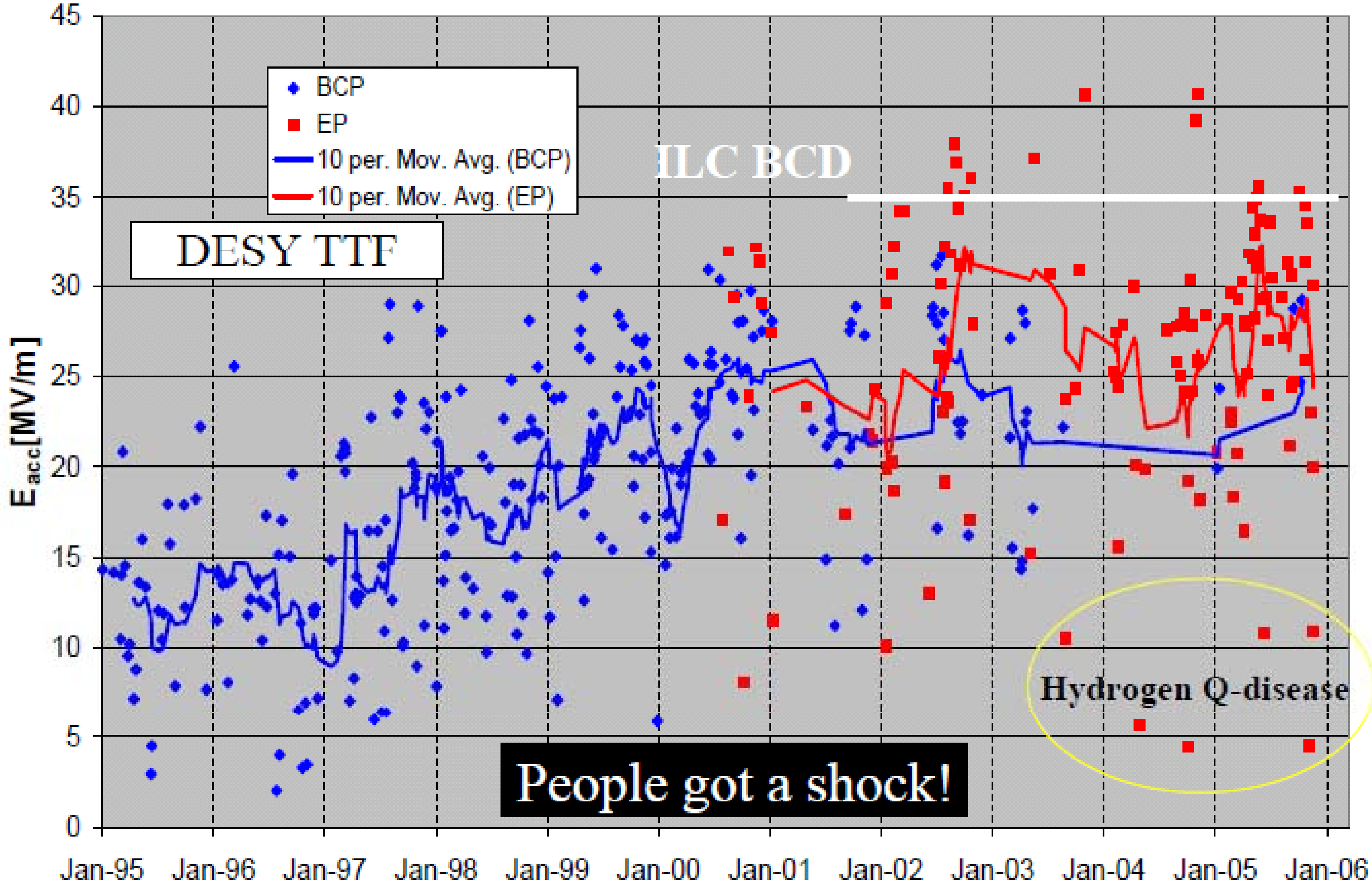
- Historical Remark
- Basic of Superconducting RF
- SRF Performance: Achievement and Challenge
- Cryogenic Plant for SRF Operation

- SRF Operation and Maintenance

Theoretical Performance Limitations

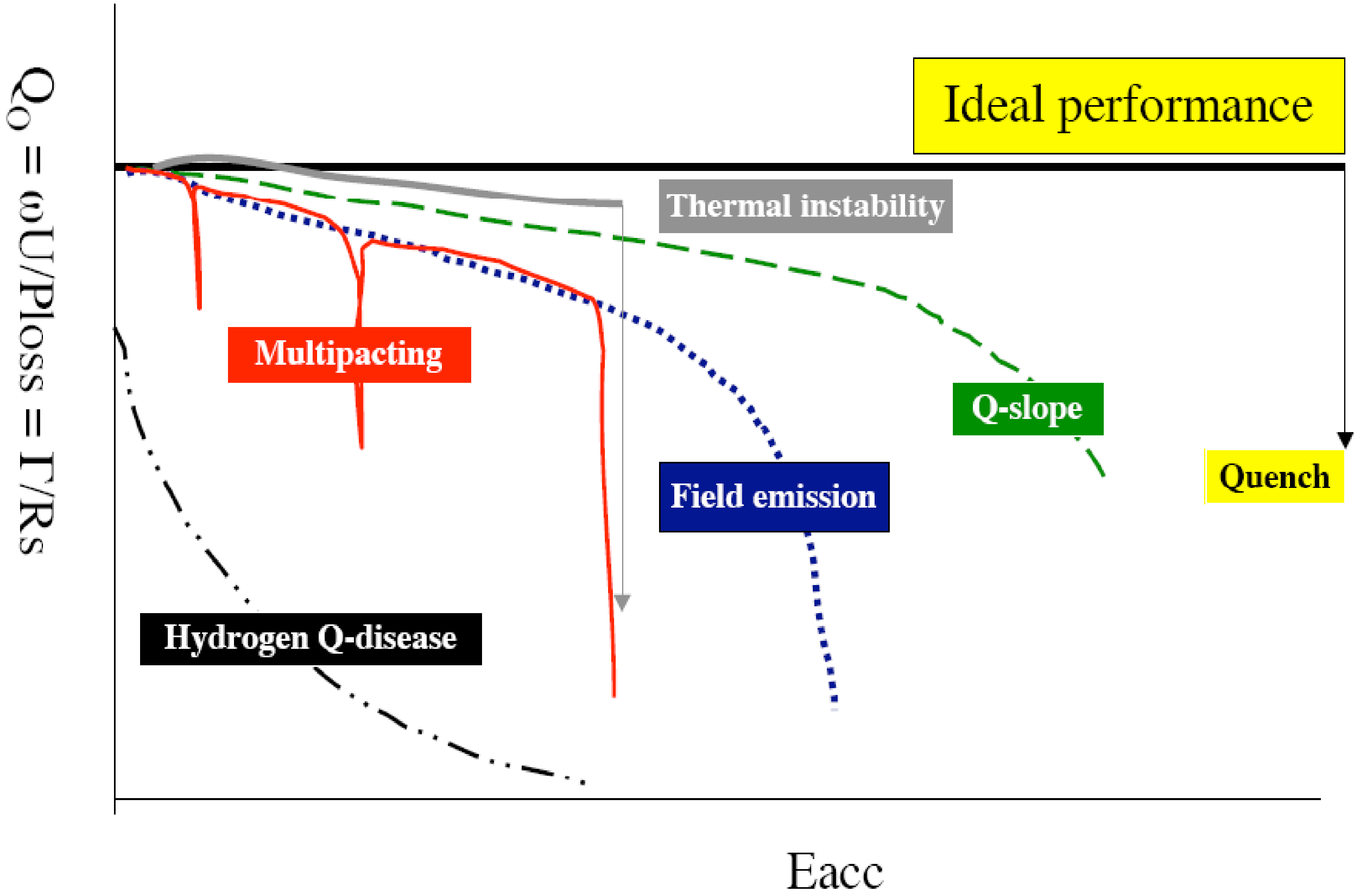
- Surface magnetic field limitation
  - lower than rf critical magnetic field H_{sh};
  - for niobium at 0K, $H_{peak} < H_{sh}(0) = 2300$ Oe; or $E_{acc} <$ 49 MV/m for typical SRF elliptical cavity.
- Surface electric field limitation
  - larger than 120 MV/m demonstrated
- TESLA cavity
  - larger than 30 (20) MV/m for 1.3GHz single cell cavity (multicell structure) demonstrated.

SRF Performance:
Achievement and Challenge



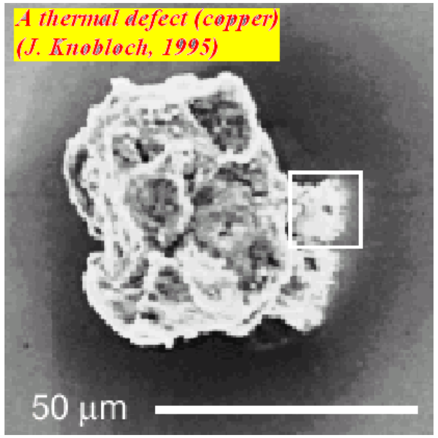
(K. Saito)

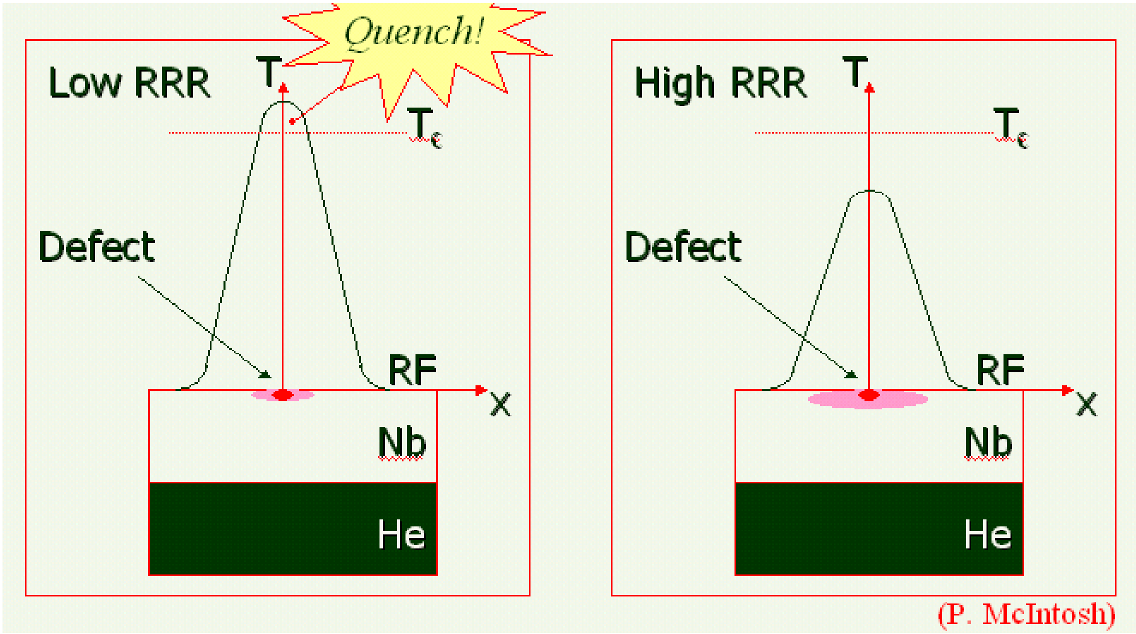
Limitations of the SRF Cavity Performance



Thermal Defect or Thermal Instability

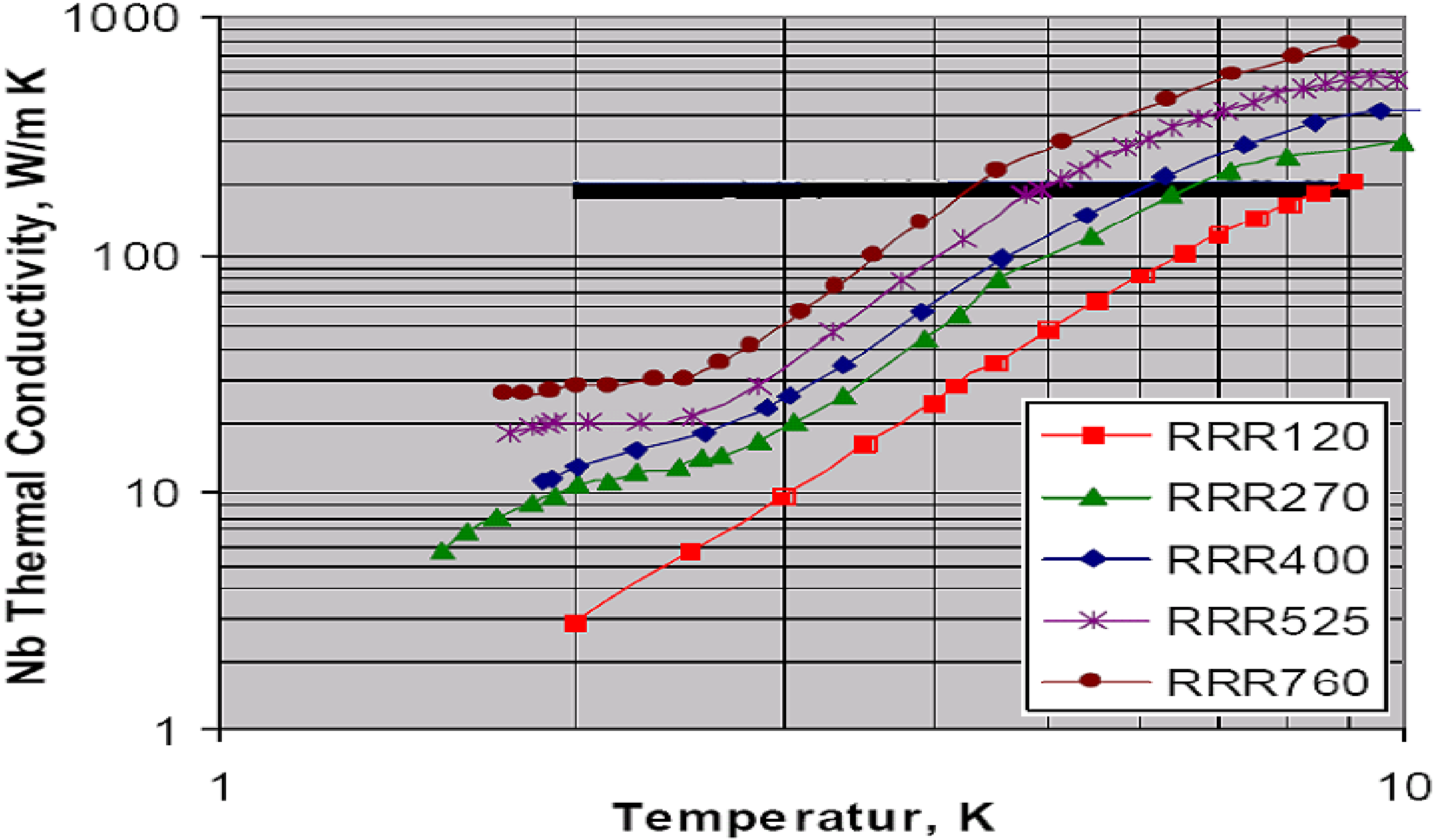
- Existence of normal conducting area in a size of sub-millimeter.





- Surface power dissipation on the defect increases with the E_{acc} and results in quench after reaching threshold of thermal instability.
- Temperature instability can be suppressed by using superconducting material with higher thermal conductivity (larger RRR!)

Measured Thermal Conductivity in Niobium Samples

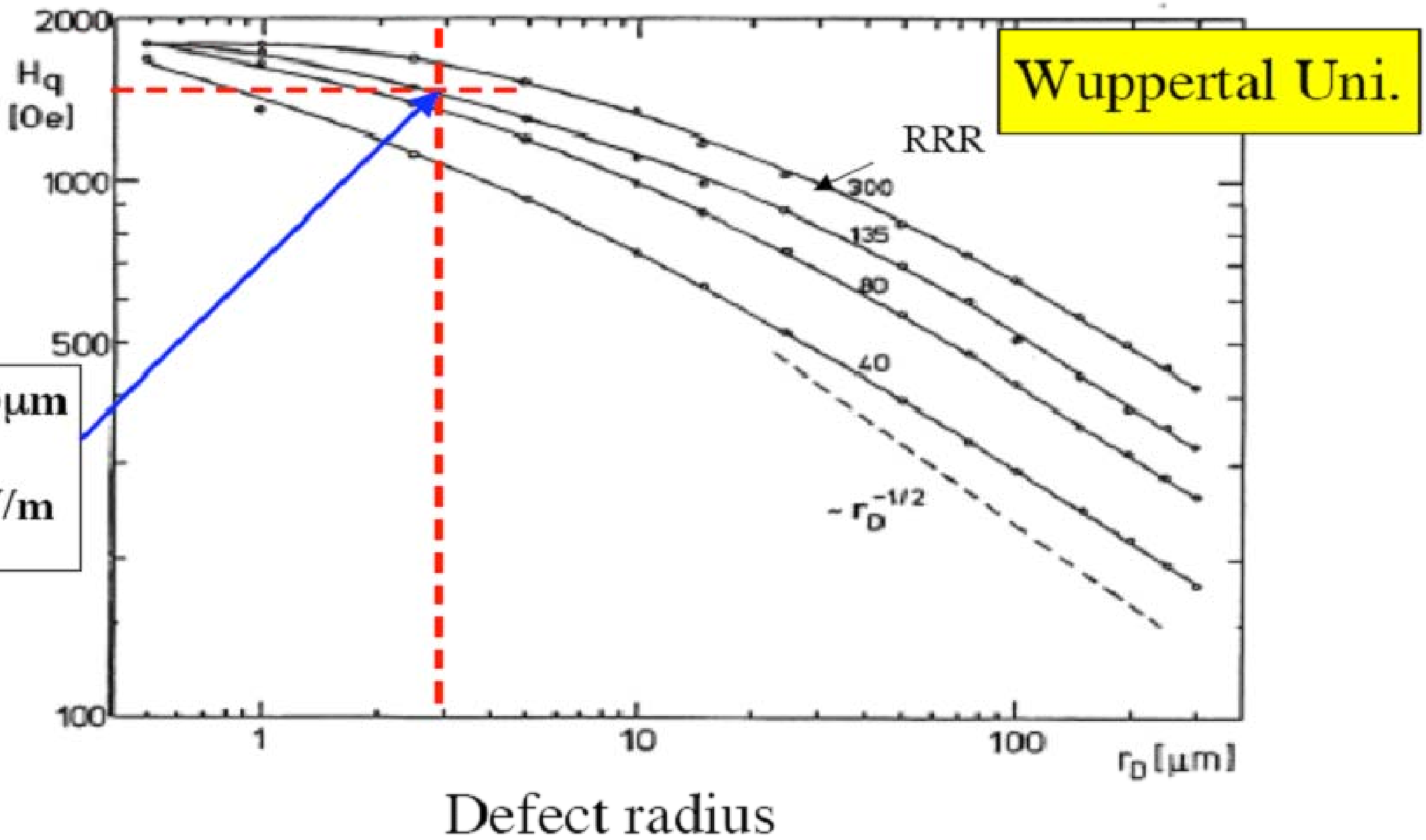


Low RRR means

low thermal conductivity at low temperature.

RRR and Quench Field

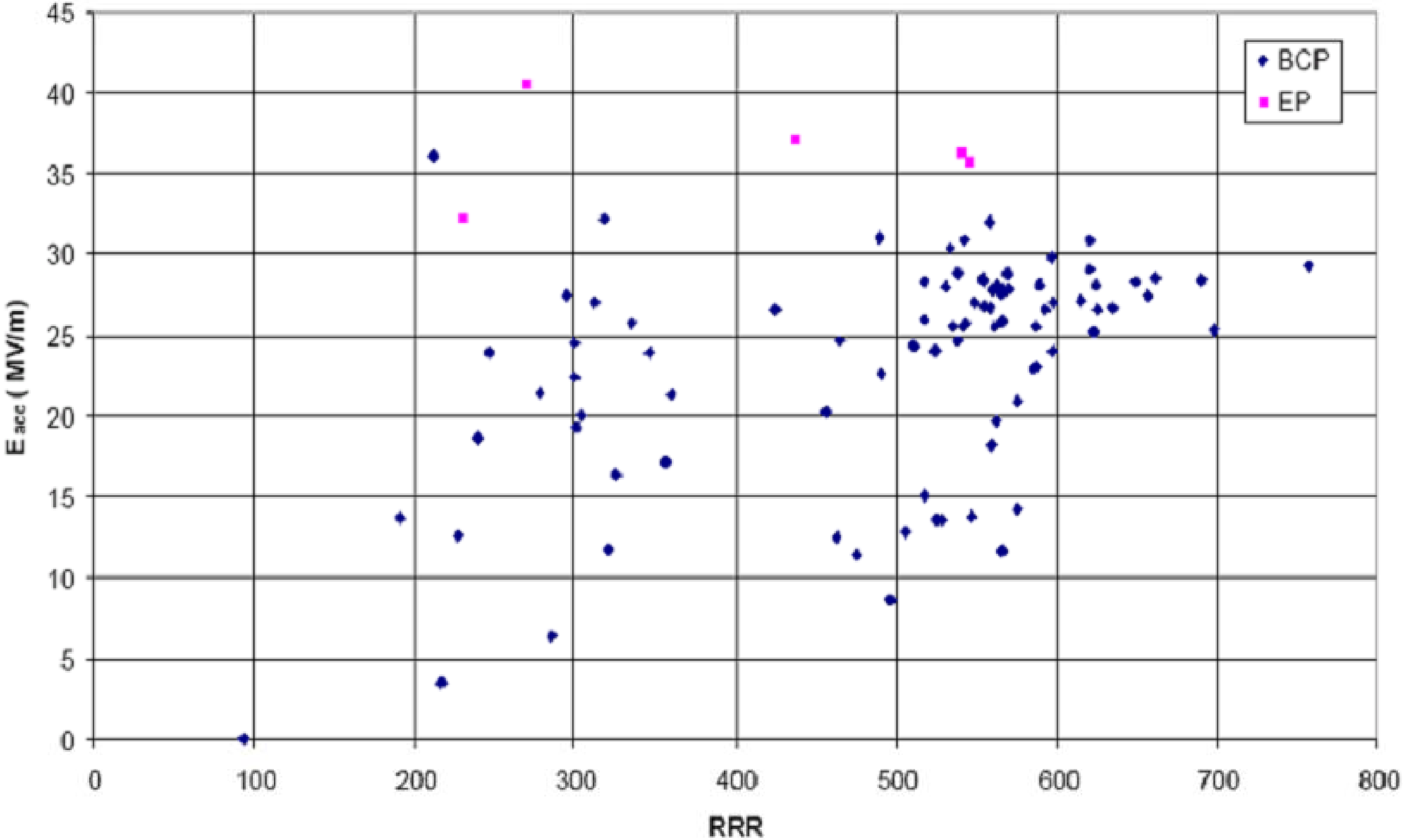
$$\text{Quench Field : } Hq=\sqrt{\frac{4\kappa(Tc-Tb)}{r_D\cdot R_s(Tb)}}\propto RRR^{\frac{3}{4}}\cdot\sqrt{\frac{(Tc-Tb)}{r_D\cdot Rs(300K)}}$$



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

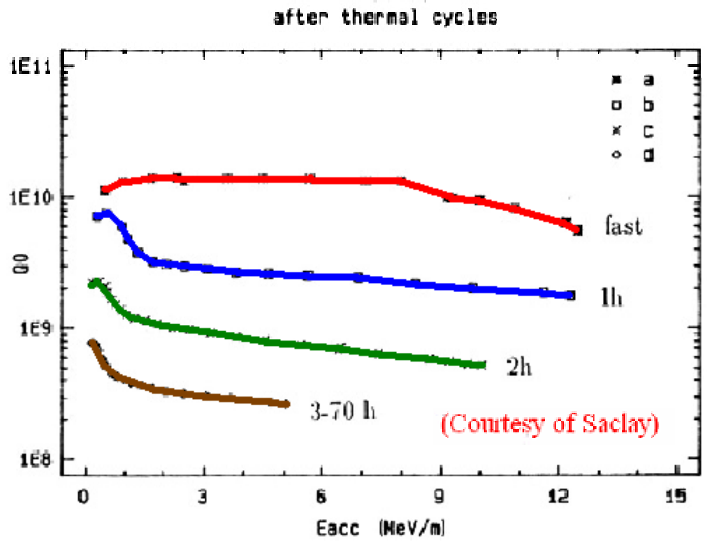
Performance Limitations vs. RRR

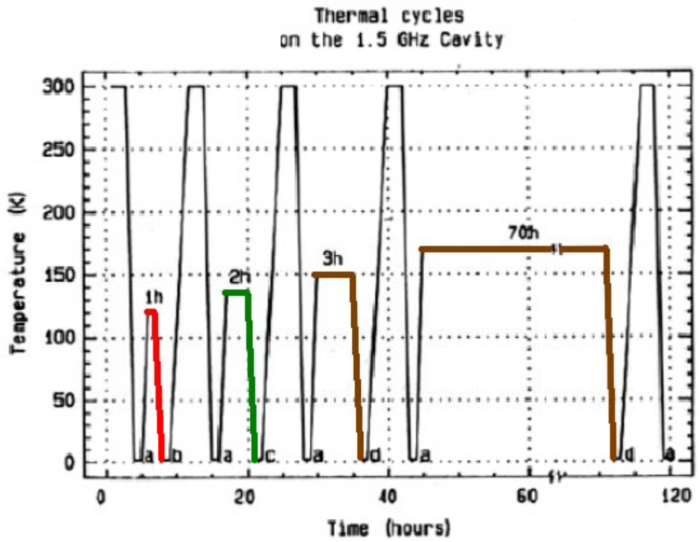
- Eacc vs. RRR of TTF Cavities



Hydrogen Q-Virus (Q-Disease)
- Residual Resistance due to Excess H in the Nb Bulk

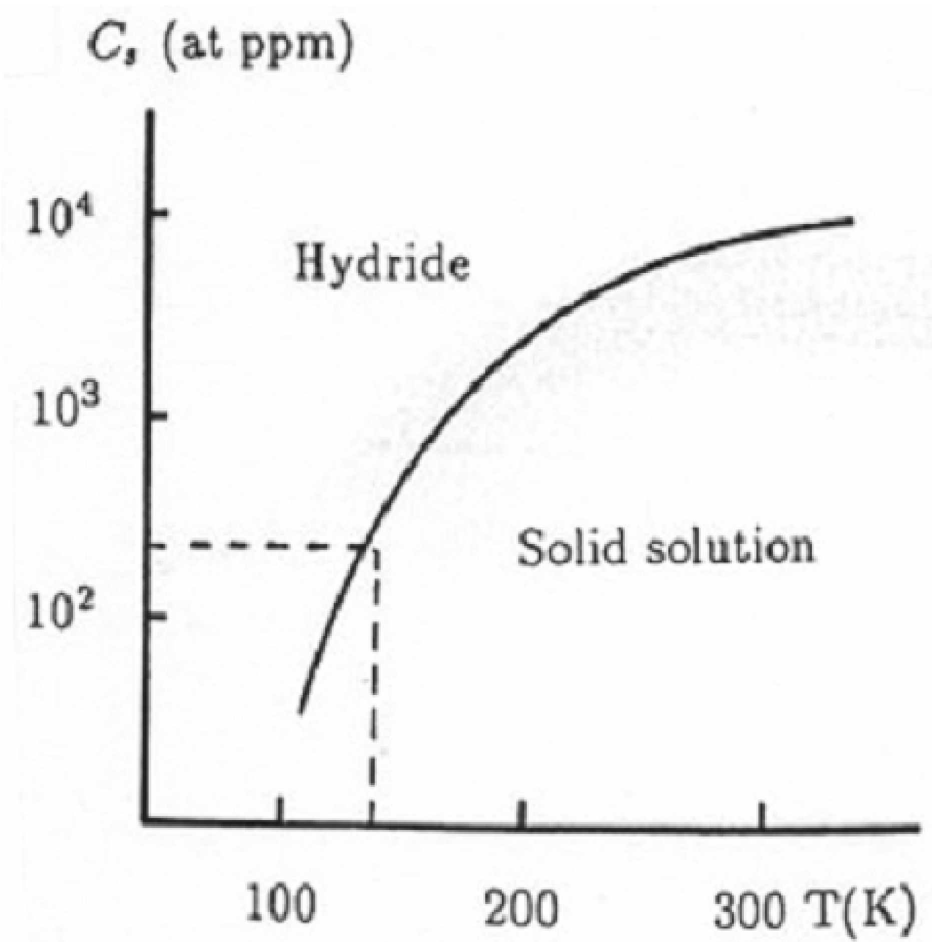
- Excessive hydrogen can be condensed into the RF surface of the cavity made by high purity niobium.
- Q-virus results in Q_0 drop at low field but without field emission.
- The hydrogen contamination may be avoided by controlling the temperature of acid etch (lower than 15°C) and other factors which is used to prepare a sufficiently clean surface.
- Solutions:
  – Baking of niobium cavity in a vacuum oven to 700-900°C is sufficient to remove the hydrogen from the niobium.
  – Quick cool down between 150K to 60K can minimize the extend of hydride formation and the accompanying residual losses (problem with thermal stress owing to fast cool-down needs be considered).



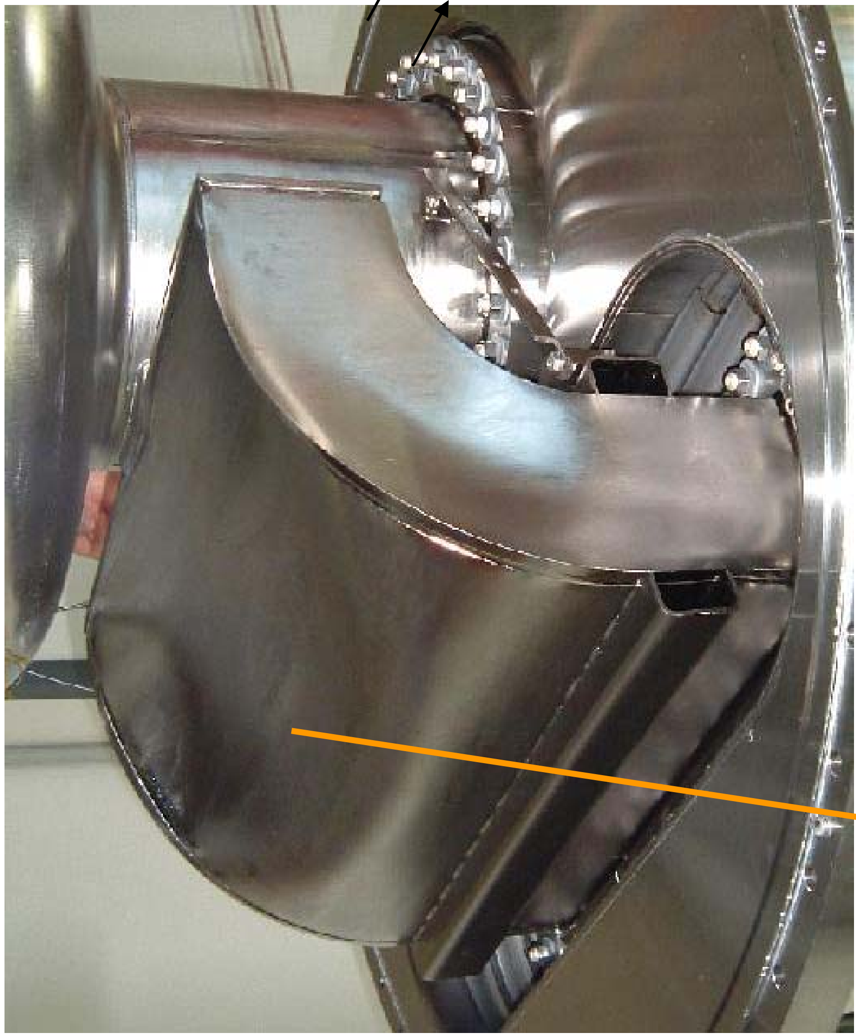


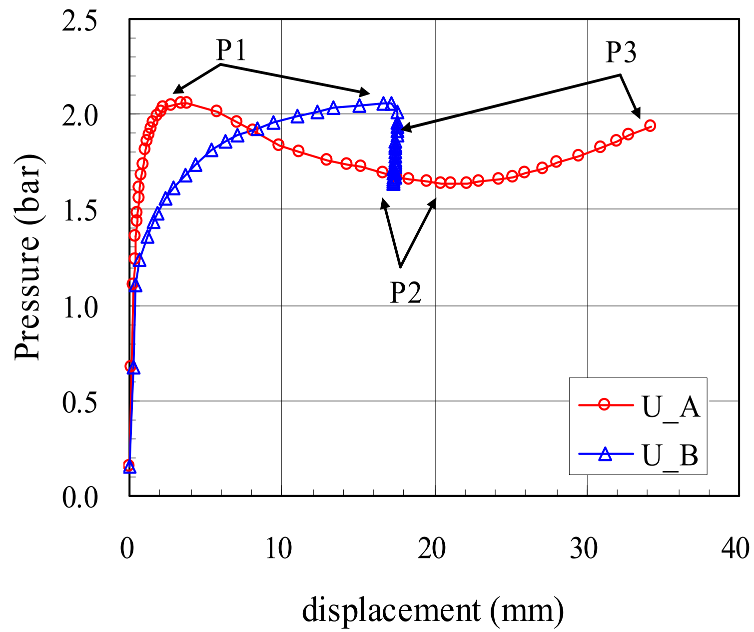
Hydrogen Q-Virus (Q-Disease)
- Mechanism and Symptom Explanation

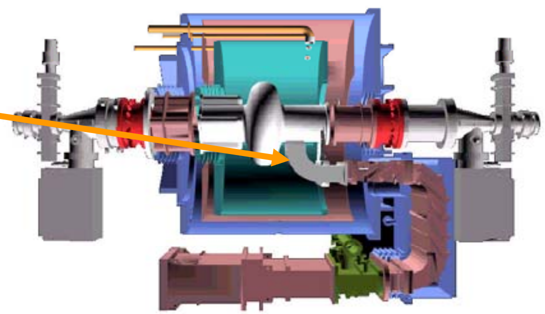
- At room temperature hydrogen (H) moves freely inside the niobium bulk.
- When a cavity is cooled, the dissolved hydrogen precipitates as a hydride phase.
- At room temperature, the required concentration of hydrogen to form hydride phases is very high, e.g. 4600 wt ppm, but the required concentration drops to < 10 wt ppm below 150 K.
- The hydride phase has high rf loss. This explains the Q-drop of a Q-disease (Q-virus) cavity.



Buckling of Nb Waveguide of SRF Module after High-Pressure Test



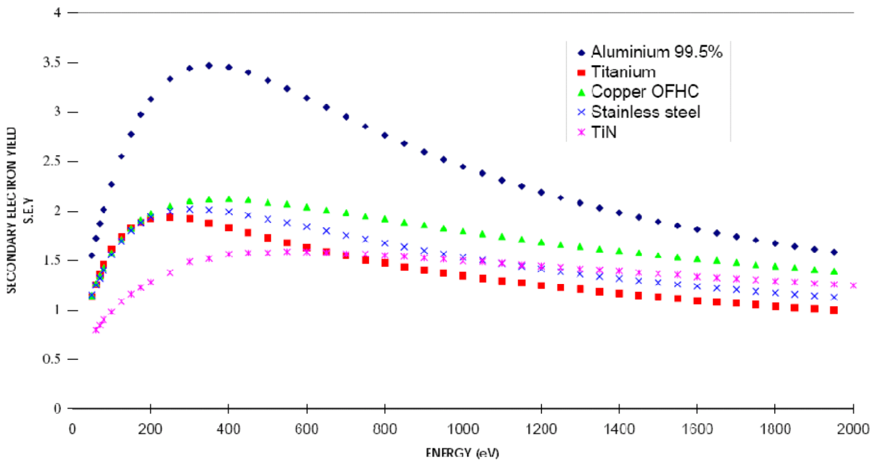




RF Multipacting

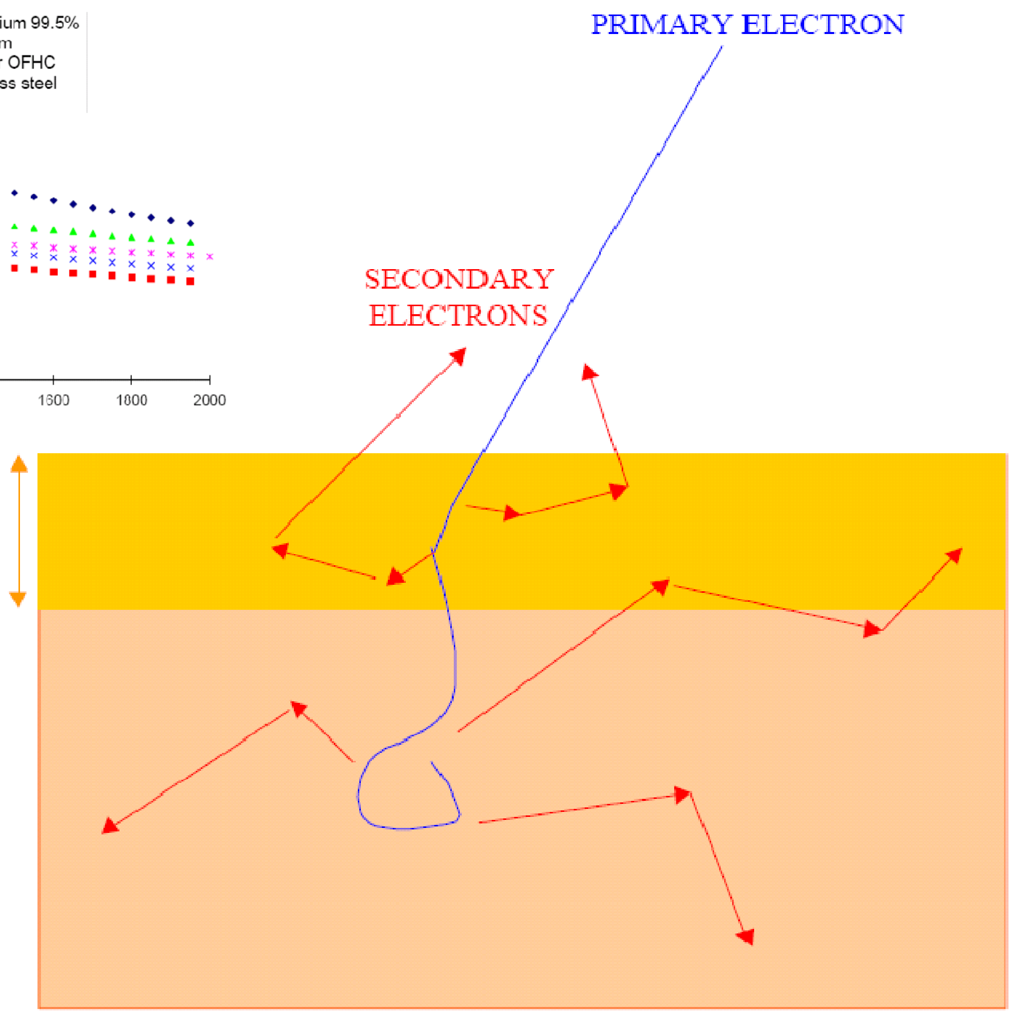
- Multipacting is
  - an avalanche effect under high vacuum rf/e$^-$-beam environment;
  - a resonance process between secondary emission electrons and RF field oscillations (dependent on RF frequency and ratio of forward to reverse power level, etc.);
  - Number of secondary emission electrons per impact is very sensitive to the surface conditions (pre-treatment, baking, post rf processing, and post gas condensation);
  - not always processable (soft barrier and hard barrier);

Secondary Emission Coefficient (SEC)

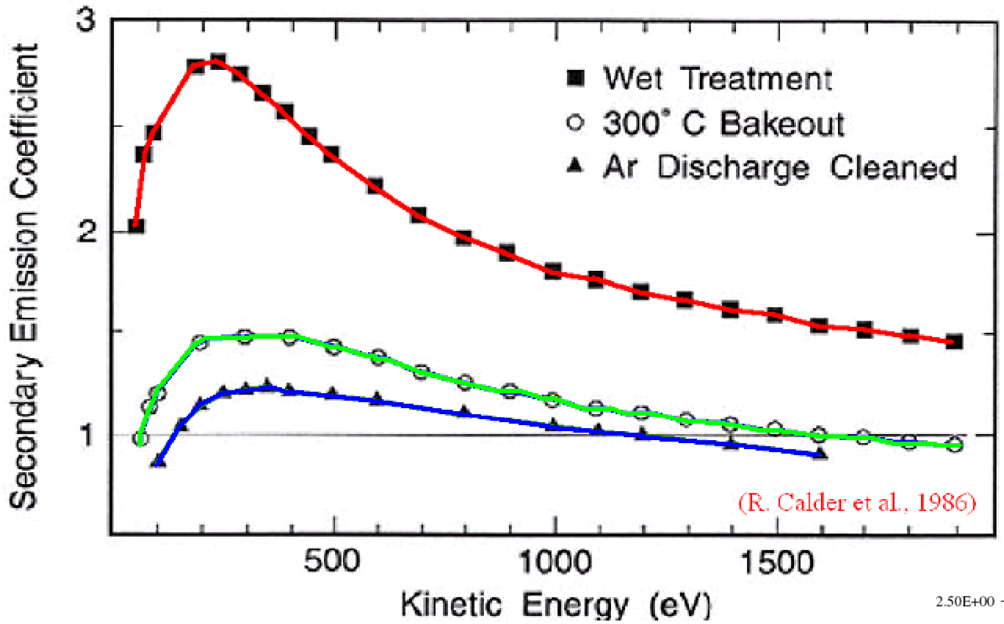


SECONDARY ESCAPE DEPTH

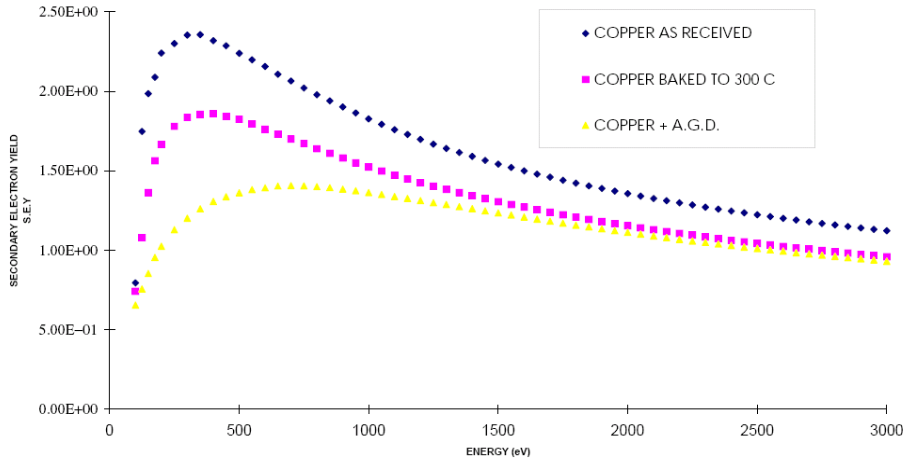
Metals <> insulators



SEC of Niobium vs. Surface Treatment

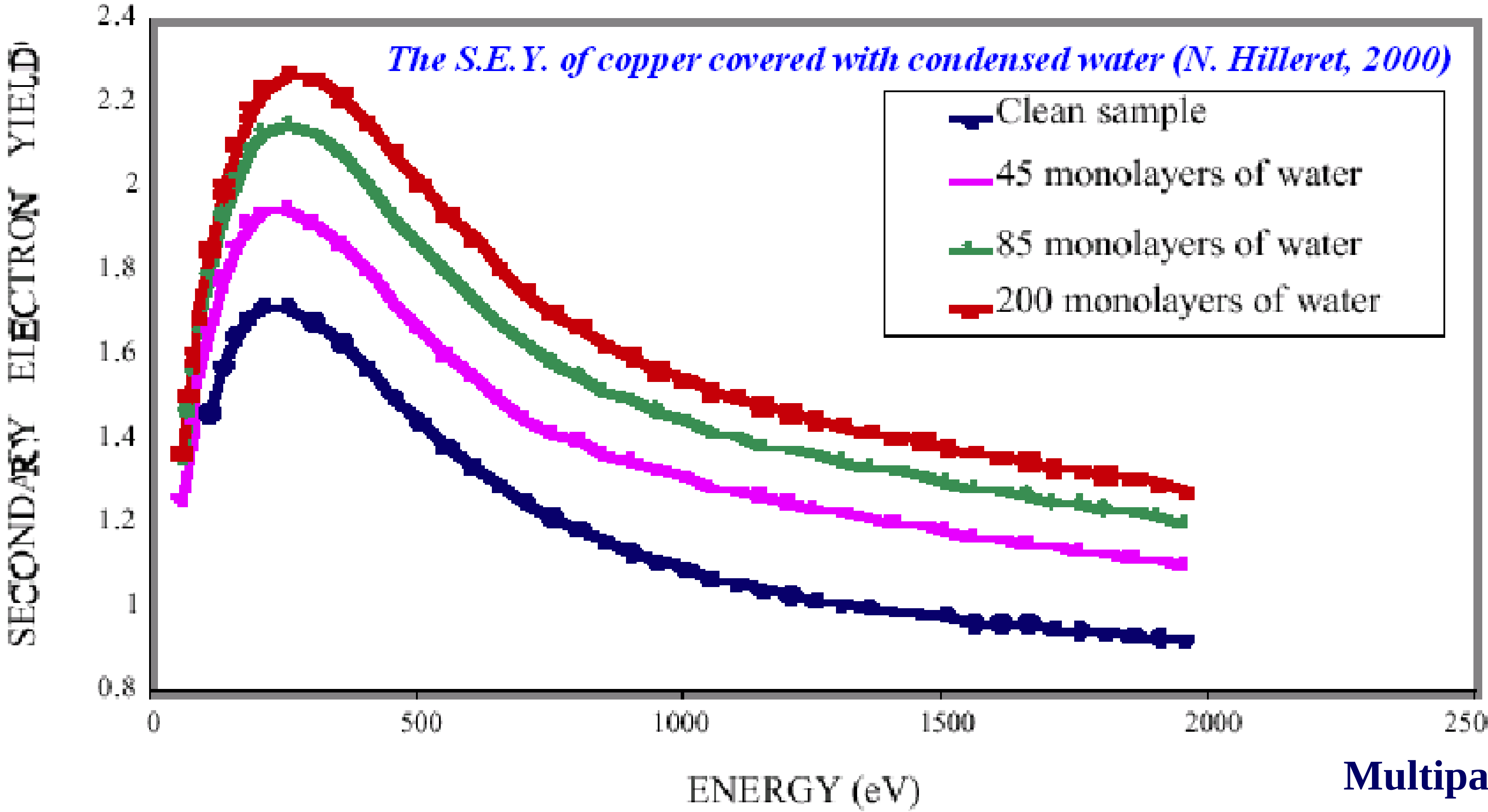


由於SRF module要使用indium來封真空，而indium的熔點只有156°左右，SRF module無法像一般的真空元件那樣的baking。Niobium cavity的baking，與真空元件的標準baking步驟無關。另外， LHe vessel的外面有superinsulation，也無法baking。



SEC of Copper at Cold

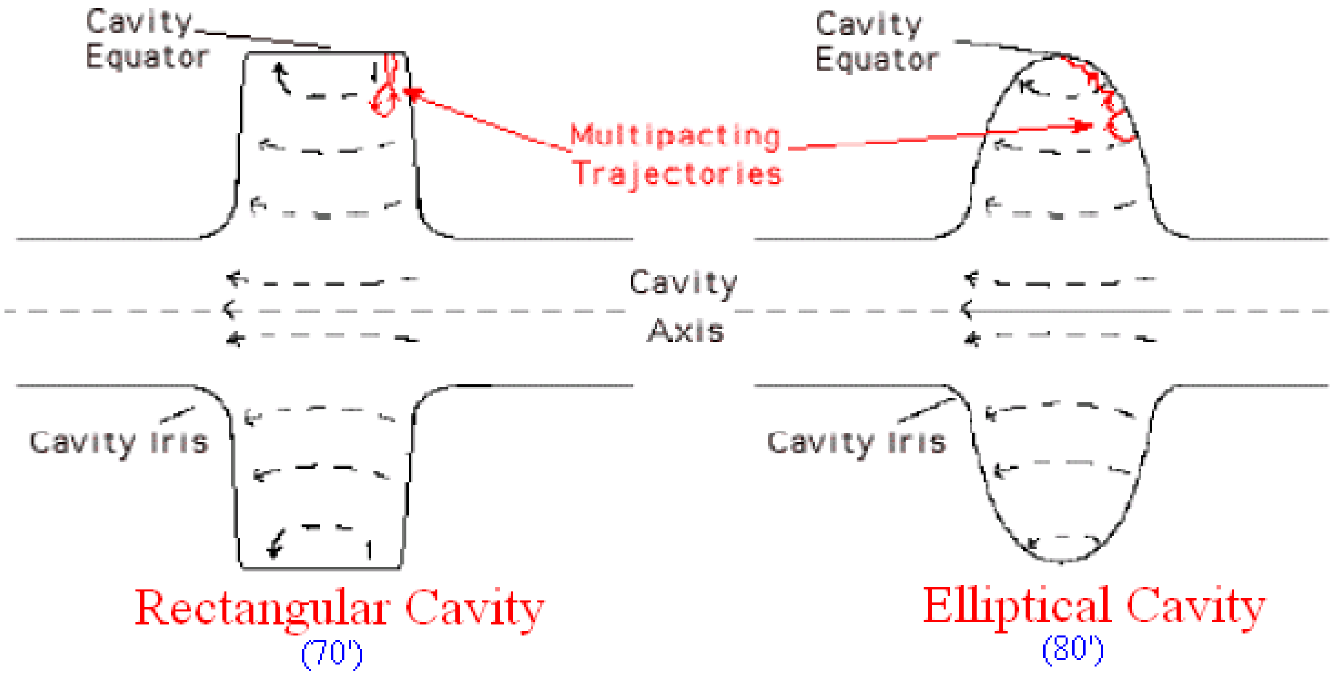
- **Multipacting may be enhanced after cryogenic condensation/adsorption of water/gas on the cold metal surface.**



RF Multipacting

- Multipacting was a problem of the SC cavity

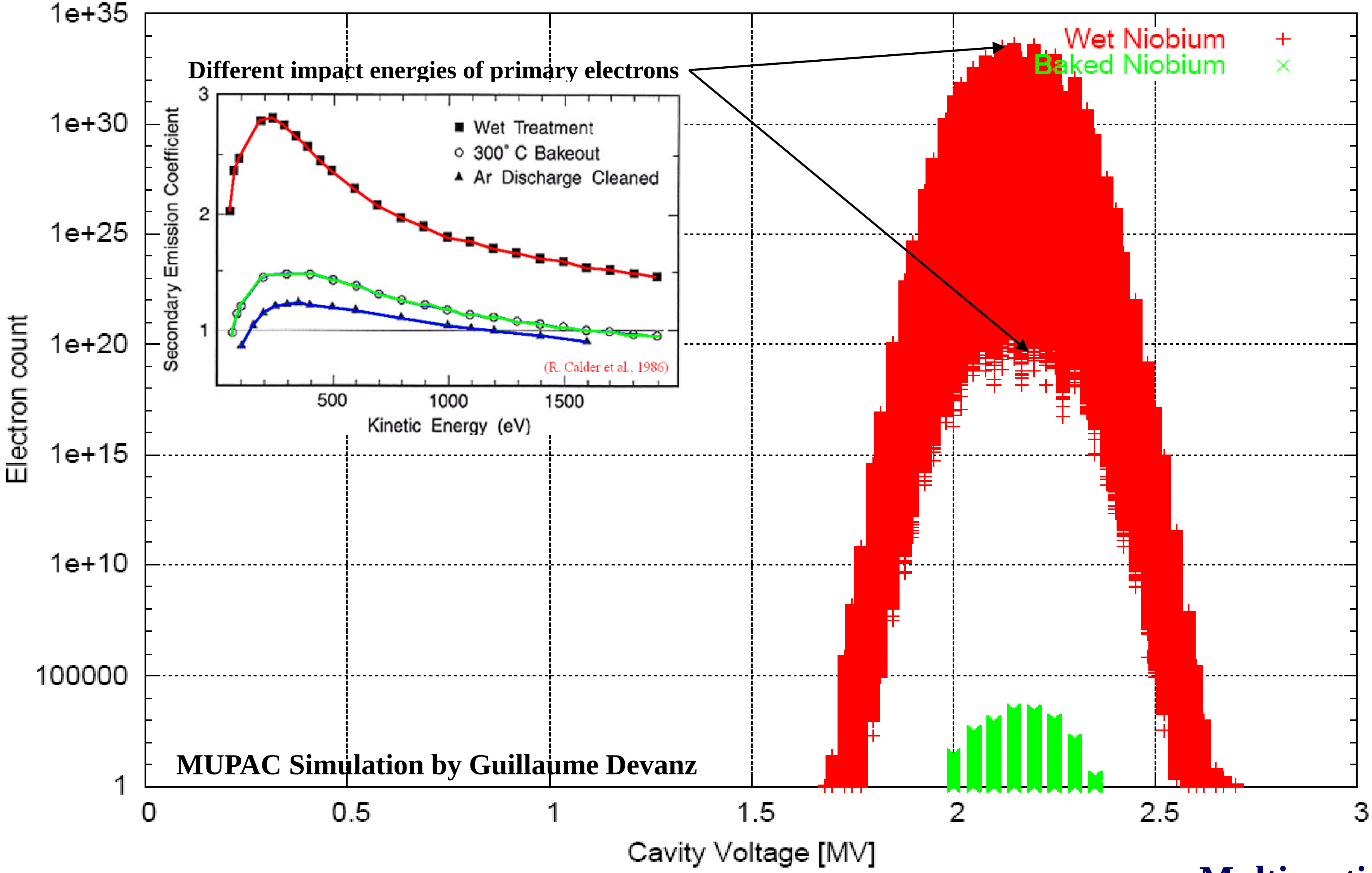
Multipacting in SRF Cavity



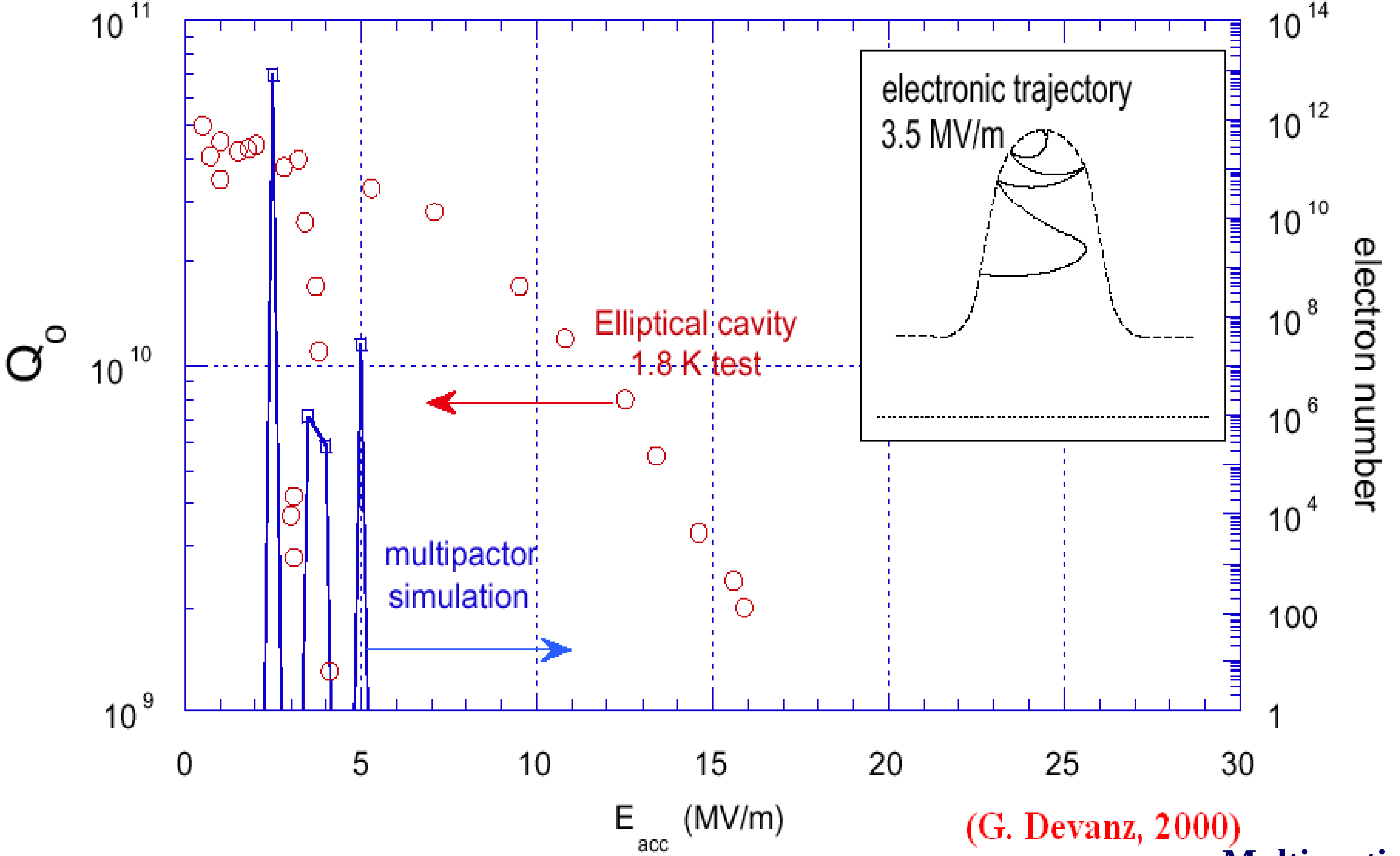
Comparison of multipacting trajectories in rectangular and elliptically shaped RF cavities. In the rectangular cavity, the electrons return to essentially the same point from which they were emitted, where they can cause secondary emission, eventually cascading such that all available RF energy is absorbed. In the elliptical cavity, the emitted electrons drift towards the cavity equator, where the electric field is not strong enough for secondary emission to recur.

(Courtesy of Cornell)

Multipacting Simulation for Cornell's 500 MHz SC Cavity



Multipacting in SRF Cavity

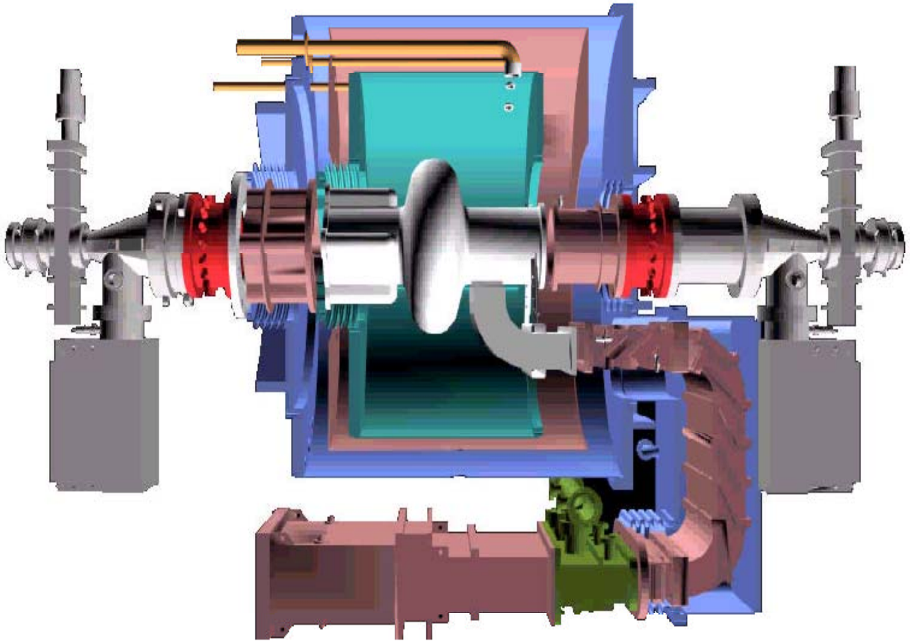


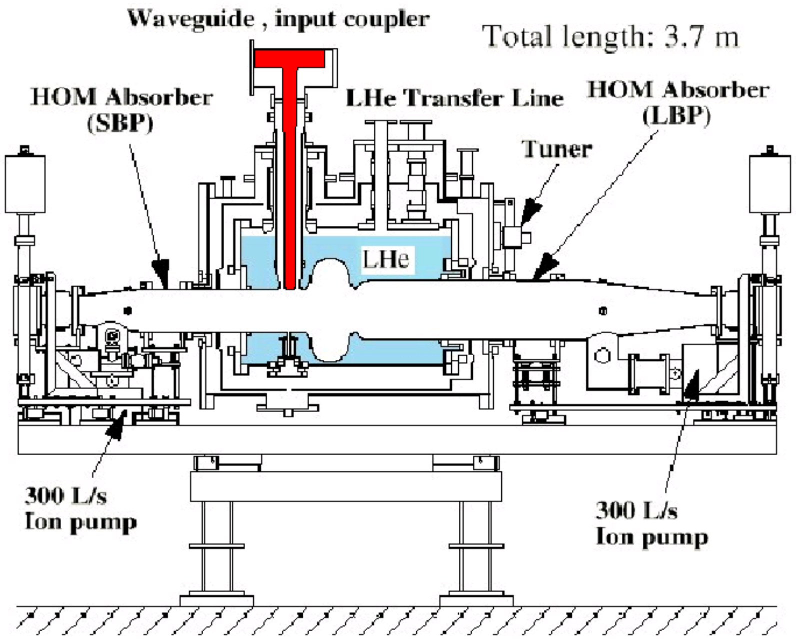
(G. Devanz, 2000)

RF Multipacting

- Multipacting is now more a headache problem of the in-vacuum RF main power coupler (for both coaxial and waveguide types) owing to the requirements of high power transmitting.

RF Input Power Coupler





KEK-B Cavity in Cryostat

RF Input Power Coupler

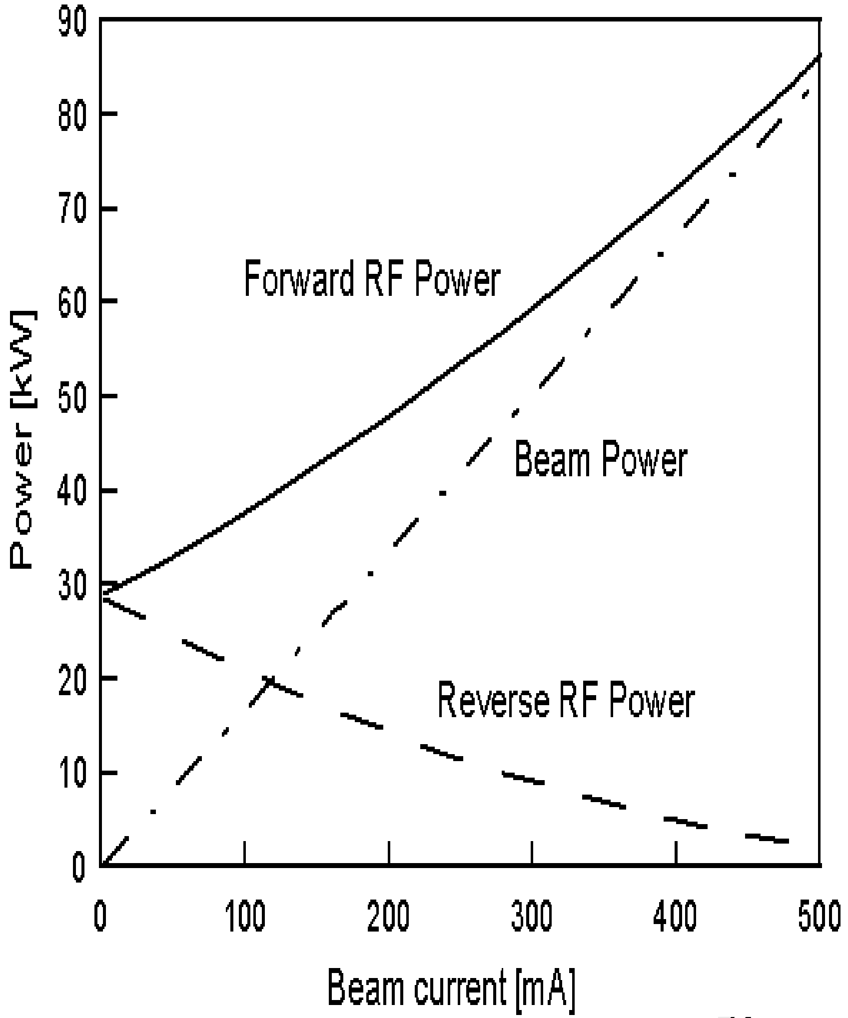
Parameter		LEP	LHC	SOLEIL	CESR	KEK-B (HER)
I beam tot	[mA]	6	560 (per ring)	500	750	1100
ΔU	[MeV/turn]	3000		0.7	1.3	3.5
P beam	[MW]	18.2		0.4	0.98	4
f rf	[MHz]	352	400.8	352	500	508.9
V rf tot	[MV]	3500	32	3.8	7.4	17.9
E acc (design)	[MV/m]	7.5 (9)	5.3	5	6 (10)	5
N cell/cav		4	1	1	1	1
Cavity length	[m]	1.702	0.375	0.425	0.3	0.295
N cav		288	16 (8+8)	2	4	8
N cav/cryomodule		4	4	2	1	1
Modular length	[m]	2.553		3.2	2.86	3.7
L active	[m]	490	6	0.9	1.2	2.36
N kly		36		1	4	8
SC material		Nb/Cu	Nb/Cu	Nb/Cu	Nb	Nb
R/Q	[Ohm]	465	89	90	89	93
G - geometry factor	[Ohm]				265.7	252.5
Qo	[10^9]	>3.2 (6 MV/m)	>2 (5 MV/m)	3 (6 MV/m)	1 (6 MV/m)	1
Epk/Eacc		2.3		2	2.5	1.68
Qext		2×10^6	var.	2×10^5	2×10^5	7×10^4
Input coupler		Coax	Coax	Coax	WG	Coax
Prf at window	[kW]	80 (500)	176 (500)	200	280 (500)	380 (800)
Static heat leak per cryomodule	[W]	<90	25*	20	30	30
P refr @ 4.5K	[kW]	4x16		0.15	2x0.6	
HOM couplers		Coax	Coax	Coax	Beam-line	Beam-line
k - cryomodule loss factor (σ, mm)	[V/pC]	1.76 (13) / 5 (10)		3 (5)	0.48 (13) / 0.6 (10)	1.8 (4)
k tr.	[V/pC/m]	8 (10)				

*without couplers & second beam tube, 2 cavities

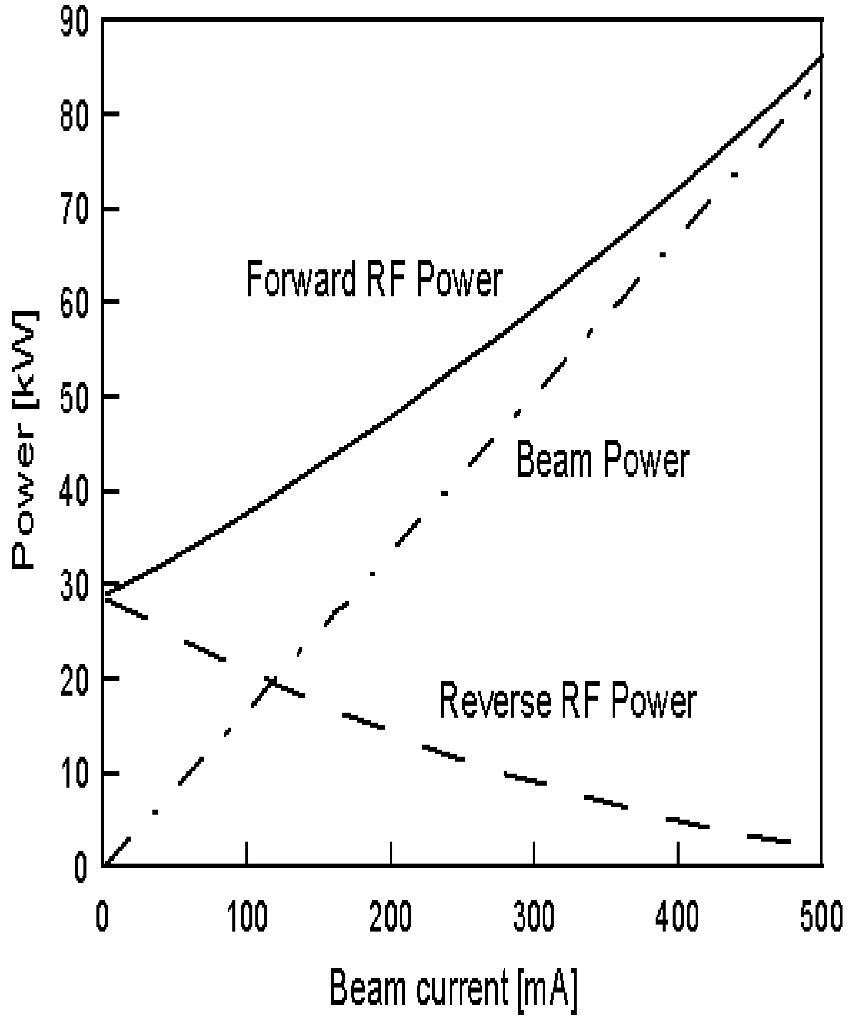
Multipacting on RF Power Coupler

- **Multipacting needs be processed away off-line (w/o beam) for reliable operation.**
  - How long will the surface remain in multipacting-free for a specific MP barrier after processing?

- **Without beam, the RF feed-line is always operated in the standing wave condition.**
  - How to process the multipacting barrier in the mixed wave condition (partially reflected)? Beam processing -> low efficiency.
    - DC bias (only available for coaxial coupler);
    - magnetic coil;
    - high pulsed power processing;
    - helium processing;



Multipacting on RF Power Coupler



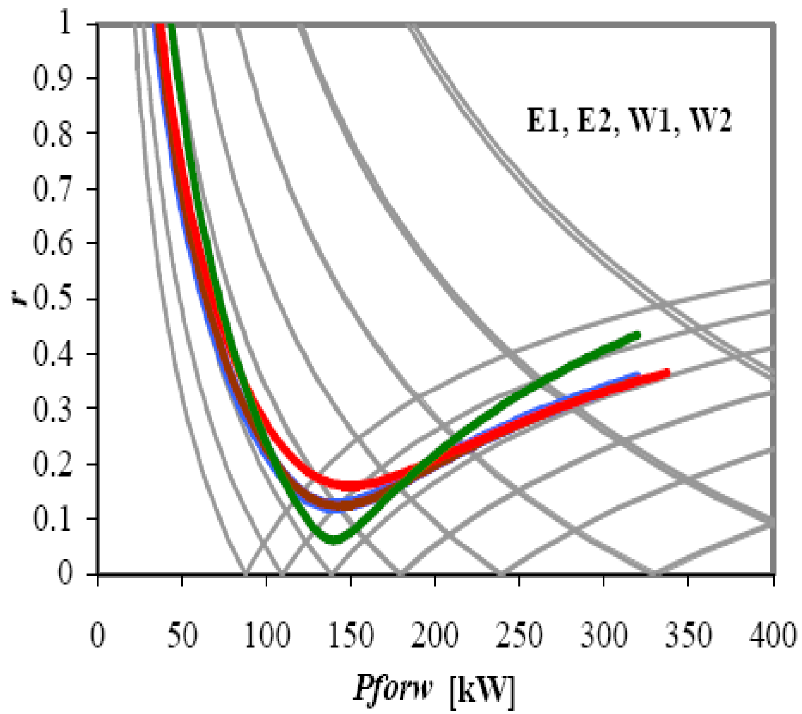
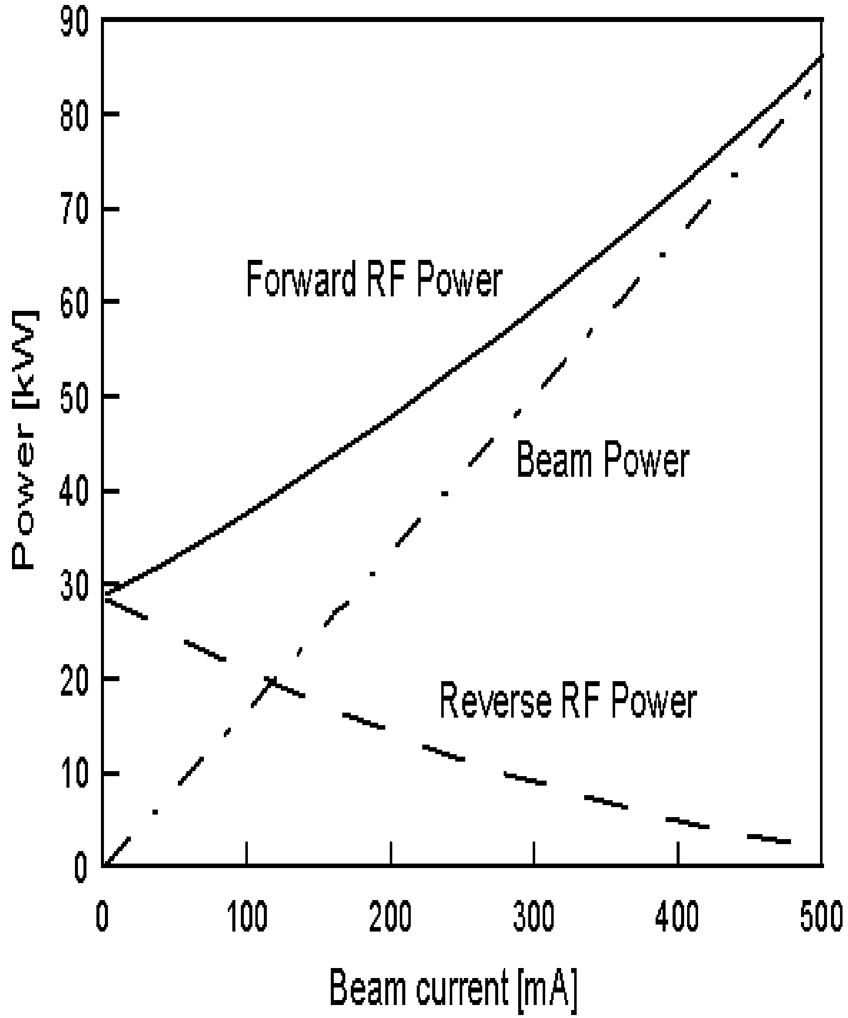


Figure2: Multipacting zones for the B-cell reduced height rectangular waveguide superimposed with loading curves of the CESR SRF cavities for the total beam current from 0 to 800 mA.

Multipacting on RF Power Coupler



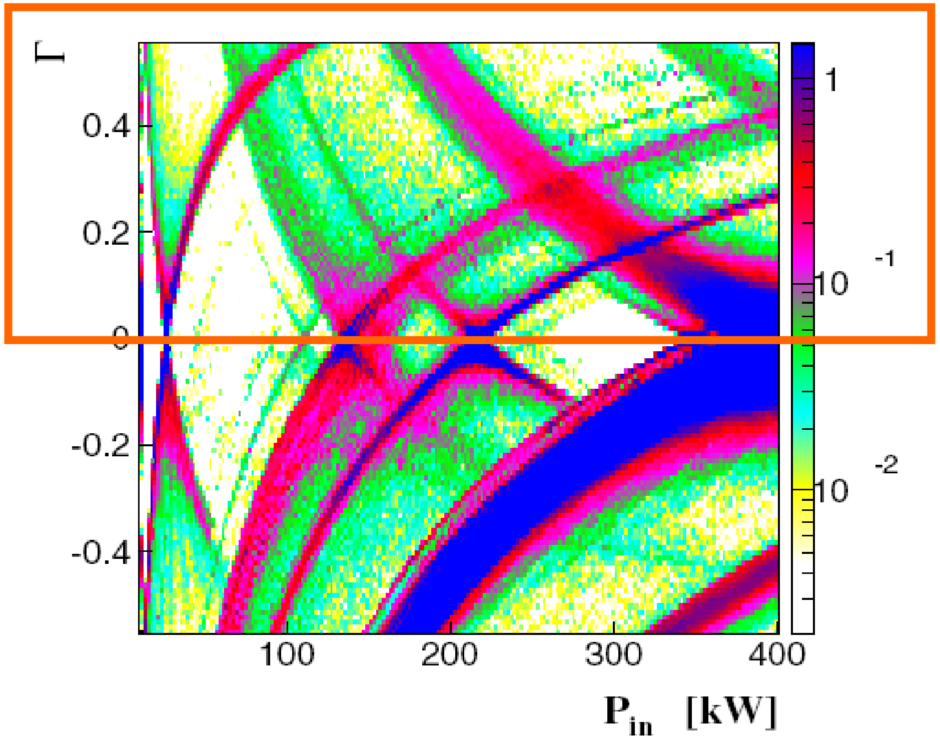


FIG. 3. (Color) Multipactoring zone map for the coaxial line of the ARES input coupler, showing the quantity $\mathcal{M}$ defined in Eq. (5). The horizontal axis indicates the time average of the input rf power, and the vertical one for the reflection coefficient.

Multipactoring zone map of an rf input coupler and its application to high beam current storage rings

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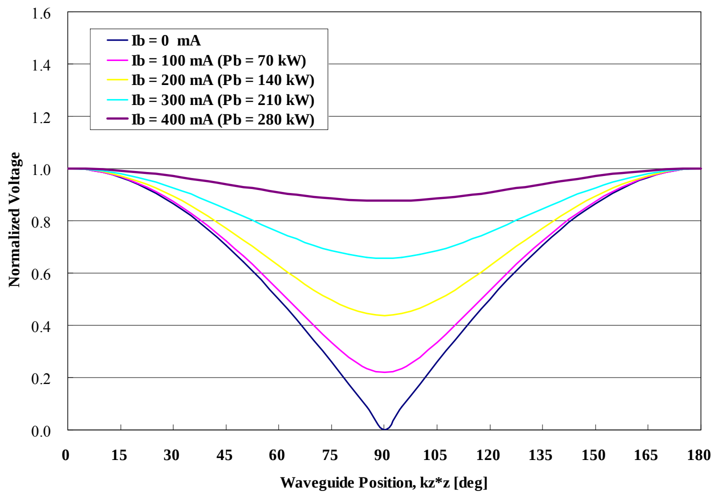
(Received 16 November 2005; published 20 June 2006)

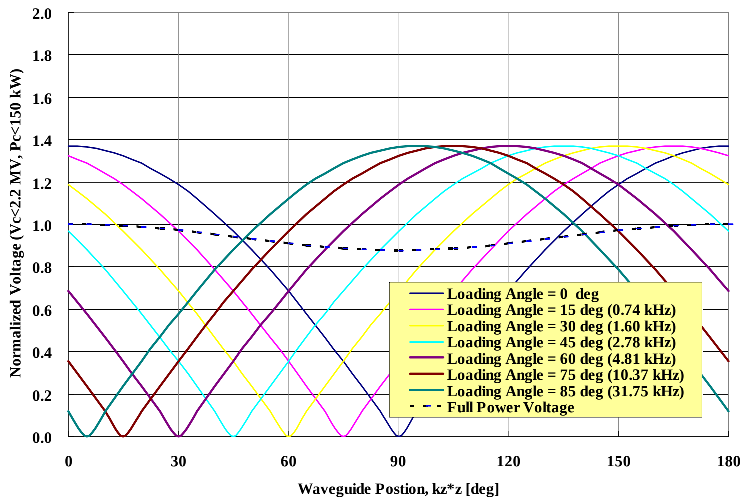
RF Processing (beam-off)

Operational conditions: Vc = 1.6 MV,
Q0= 1.0e9, Qext=9e4,
Pb @400 mA = 280 kW/cavity,
Two cavities in operation.

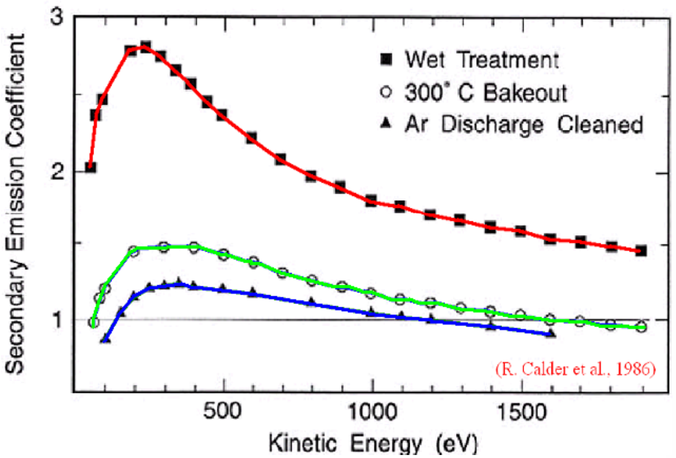
The voltage along the waveguide power coupler is normalized to the voltage at detuned short position under operational conditions, which is equal to the voltage in the traveling wave with an RF power of 319.58 kW

RF Conditioning: Up to
1) Vc = 2.2 MV, or
2) Pf = 150 kW
By detuning from -85^o to 85^o.





Hard Multipacting…



Review of Secondary Emission Coefficient

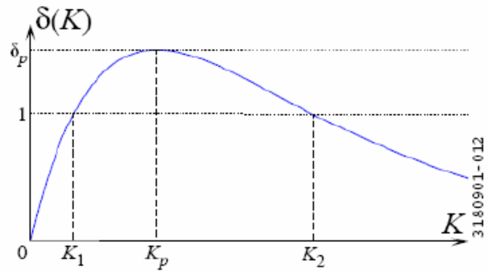


Figure 2. Generic dependence of SEY on kinetic energy.

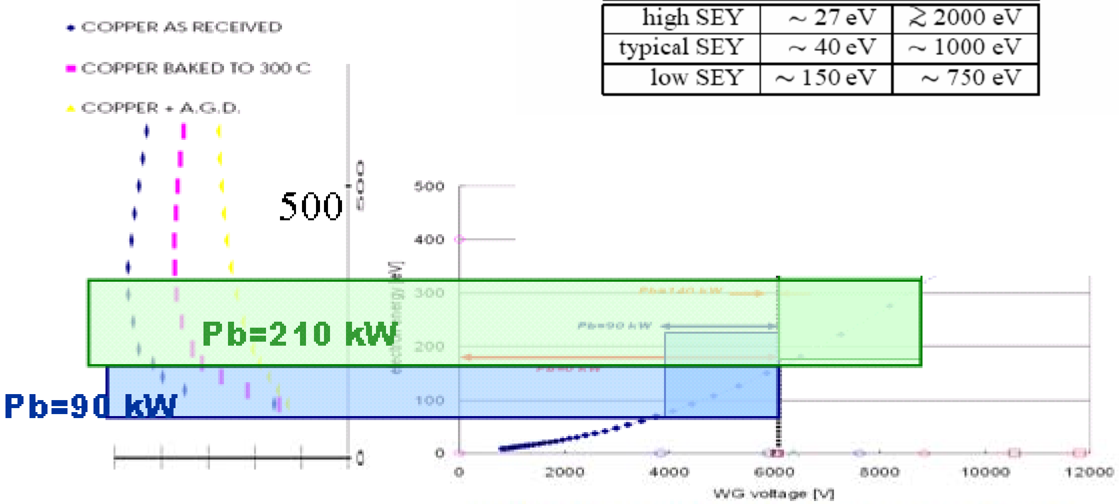
Table 1. Approximate parameters for SEY curve of Nb.

Condition	K_1	K_2
high SEY	~ 27 eV	≳ 2000 eV
typical SEY	~ 40 eV	~ 1000 eV
low SEY	~ 150 eV	~ 750 eV

- If an electron impacts the cavity surface with a Kinetic Energy between 150eV and 750eV, then more than one secondary electron will be emitted, on average, and multipacting will be sustained. This is a "hard multipacting barrier".
- The more contaminated the surface, the lower K1 becomes and the higher K2 becomes, thus broadening the range that multipacting can occur.
- If an electron hits the cavity surface with a Kinetic Energy less than 150eV or higher than 750eV, this is considered a "soft multipacting barrier". With sufficient processing, the localized area where multipacting occurs can be rid of contaminants, thus raising K1 (or lowering K2) such that the multipacting trajectory at that Epeak can no longer be sustained.

MICHIGAN STATE UNIVERSITY

The NSCL is funded in part by the National Science Foundation and Michigan State University.



Secondary electron yield

WG voltage is function of beam power.

RF Processing (w/ e-beam)

Various methods of conditioning were developed including operation with a voltage ripple on top of the main voltage, sweeping to move the phase of the standing wave, but ultimately the most successful conditioning was by slow increments in current often as low as 0.2 mA. The current is injected at a voltage above the multipactor region and subsequently the voltage is slowly reduced though the multipactor band. This process was slow but once the window and waveguide had been thoroughly conditioned, the modules maintain their condition even after a complete warm-up.

Molten Jensen (DLS)

The tuner-loop needs be very good!

Multipacting Suppression and Excitation by DC Biased Voltage

KEKB SRF Module (Qext high)

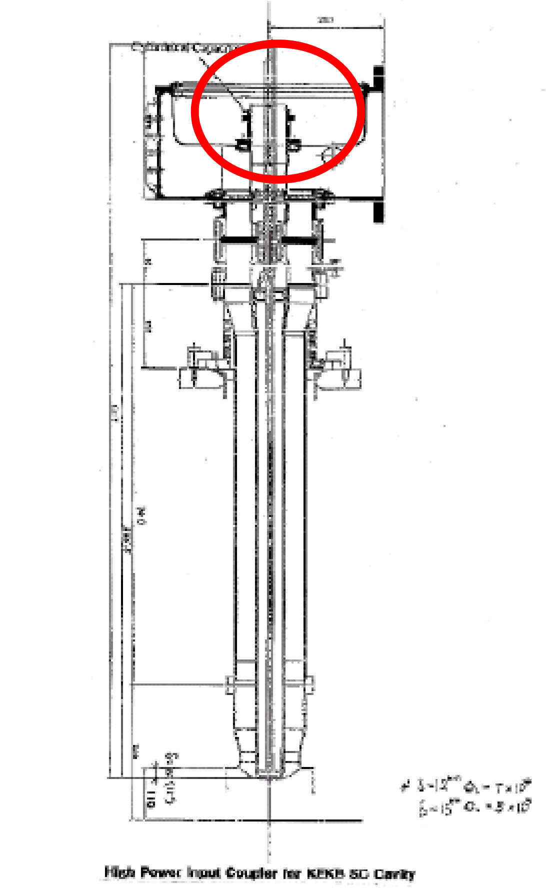
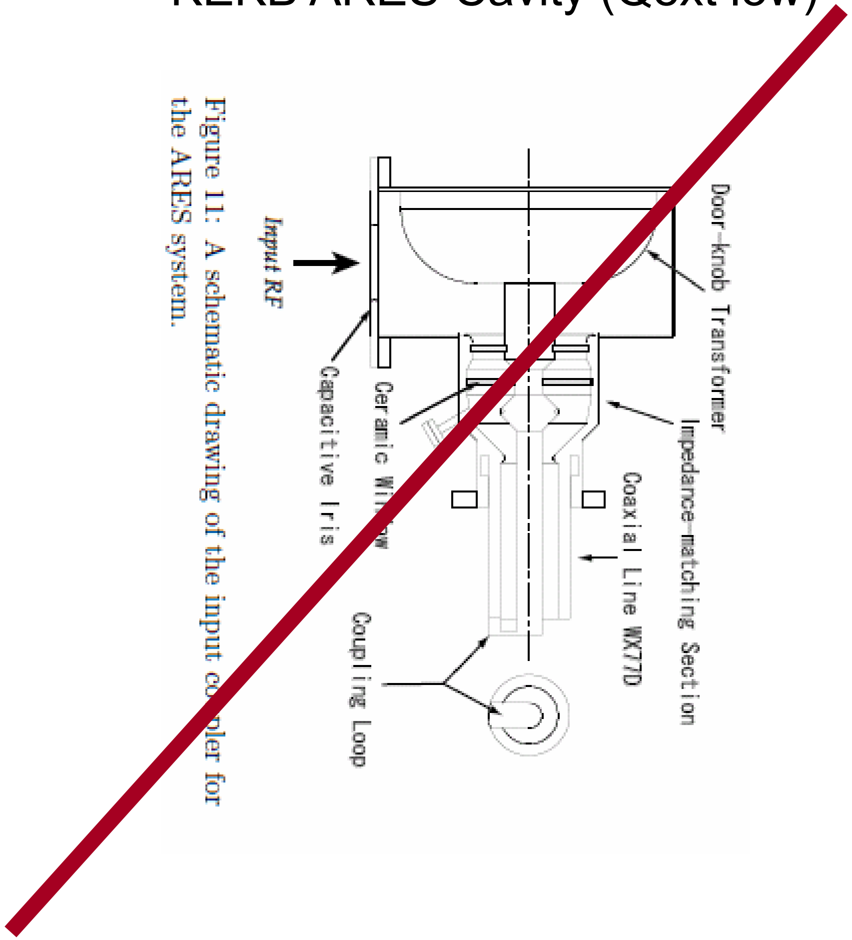
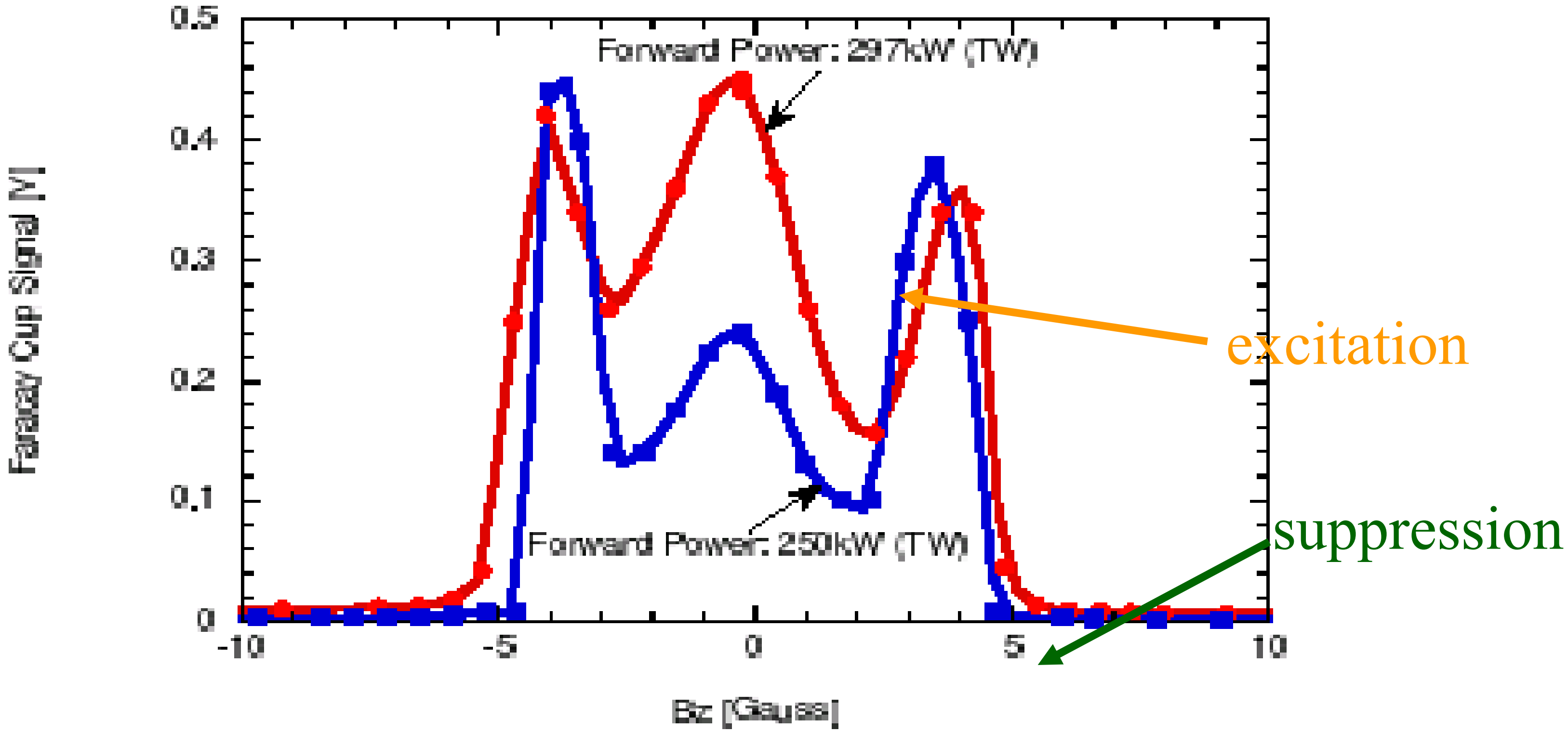


Figure 1. Input coupler for the KEKB

KEKB ARES Cavity (Qext low)



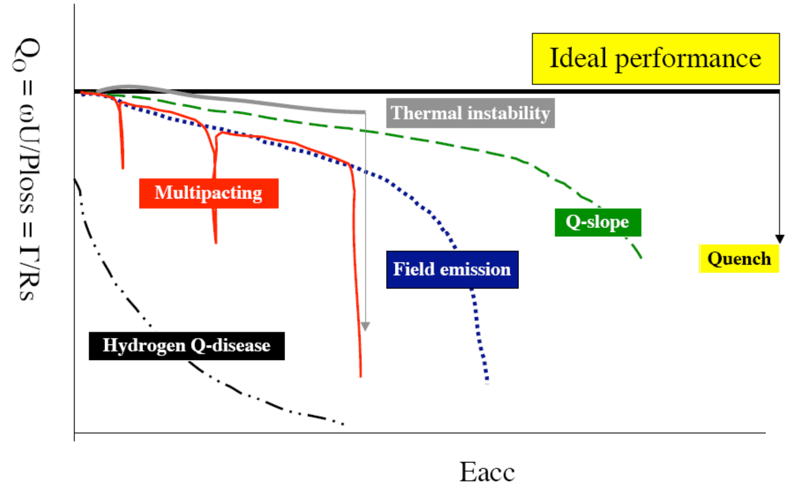
Multipacting Suppression and Excitation by Magnetic Field



The effect of a magnetic bias field on multipacting current. Complete suppression is realized above a critical field value. (R.L. Geng, 2002)

Multipacting

- **Characteristic: Q-drop at some *discrete* field levels, X-ray at the levels.**



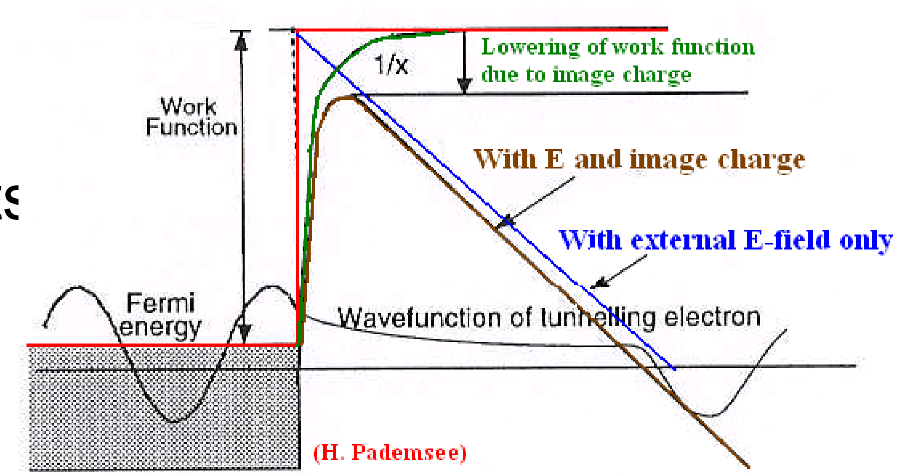
- **Diagnostics: Temperature mapping & X-ray mapping**

"Conventional" Field Emission

- Thermal emission:
  - Electrons pass over the barrier (work function).
  - Possible to explain by classical mechanism.

- Field emission:
  - Electrons pass through the barrier because of its wavelike properties (tunneling effect).
  - A pure QM mechanism.

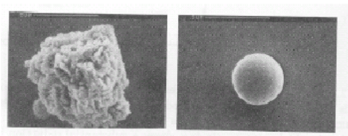
$$I \propto E^{2.5} \exp\left(-\ C\ \frac{\phi^{3/2}}{E}\right)$$



“Conventional” Field Emission

- Theoretically, electric fields of 3-5 GV/m are needed for field emission, according to Fowler and Nordheim (FN) theory.

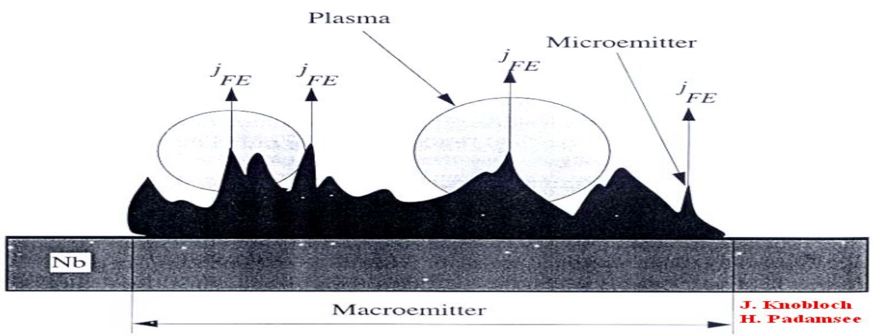
- But, field emission is an empirically-observed field. How can it be?



  - Microscopic imperfections (bumps and scratches) can raise the field on the surface of the structure by a factor of 100.

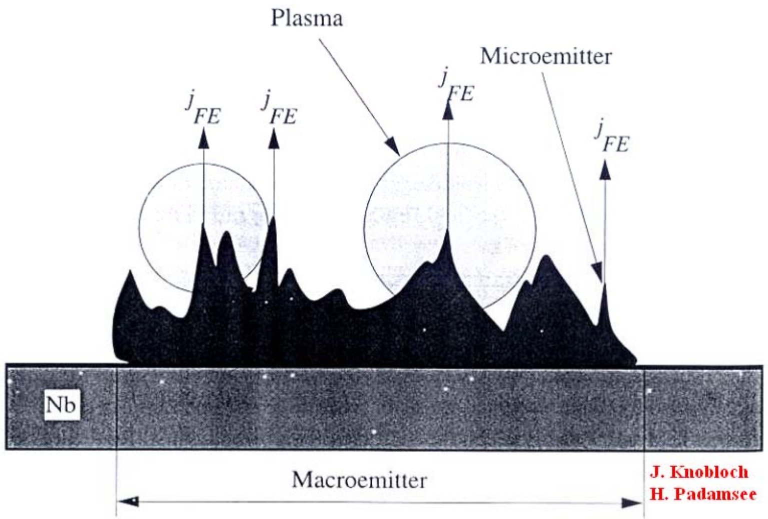
$$I \propto E^{2.5} \exp\left(- \ C \ \frac{\phi^{3/2}}{E} \right)$$

$$I \propto (\beta_{FN} E)^{2.5} \exp\left(- \frac{C \ \phi^{3/2}}{\beta_{FN} E} \right)$$



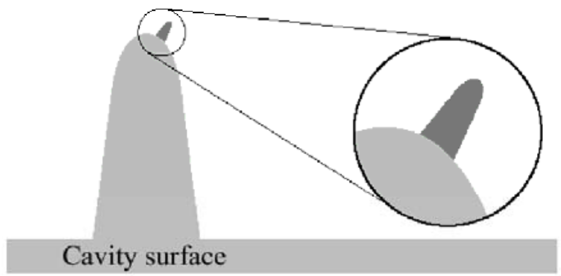
SRF Field Emission: Cornell Model I
- Tip-on-tip Model

- Theoretically, electric fields of 3-5GV/m are needed for field emission, according to Fowler and Nordheim (FN) theory.
- Observation of field emission in SRF cavity started at E_{pk} of 10-20MV/m (factor of few hundred!)
- Modifying the FN equation with an artificial field enhancement factor β (between 50 and 500) for experimental fitting => Tip-on-tip model



$$I(E) = \frac{A_{FN} A_e (\beta_{FN} E)^2}{\phi} \exp\left(-\frac{B_{FN}\phi^{3/2}}{\beta_{FN} E}\right)$$

where A_e is the effective emitting area and β_{FN} is the field enhancement factor.

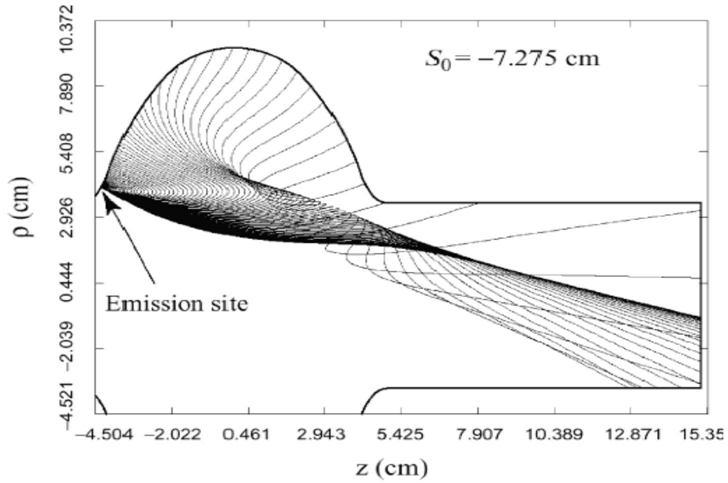


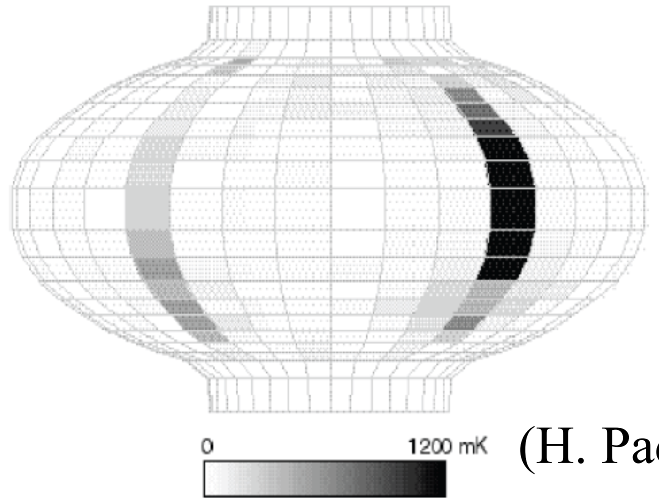
SRF Field Emission

- SRF field emission is normally caused by **foreign particle contamination**
  - Emitted electron current grows exponentially with field
  - Reaching the surface accelerated electrons produce cryo-losses and quenches
  - Part of the electrons reaches high energies: Dark Current

- Observation of field emission in SRF cavity started at E_{pk} of 10-20MV/m (factor of few hundred!)

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

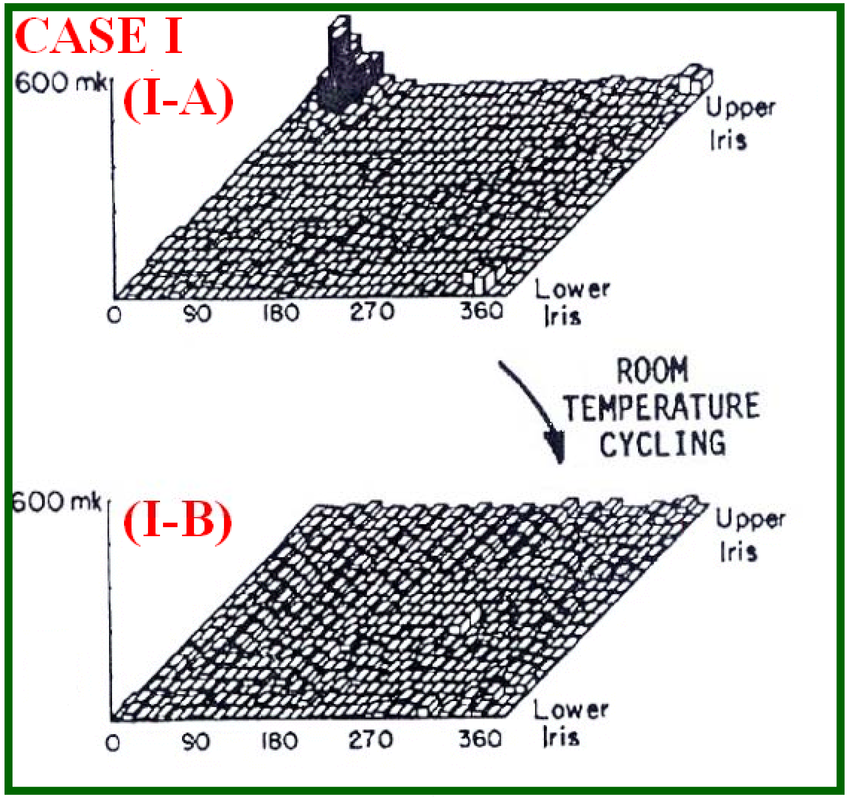


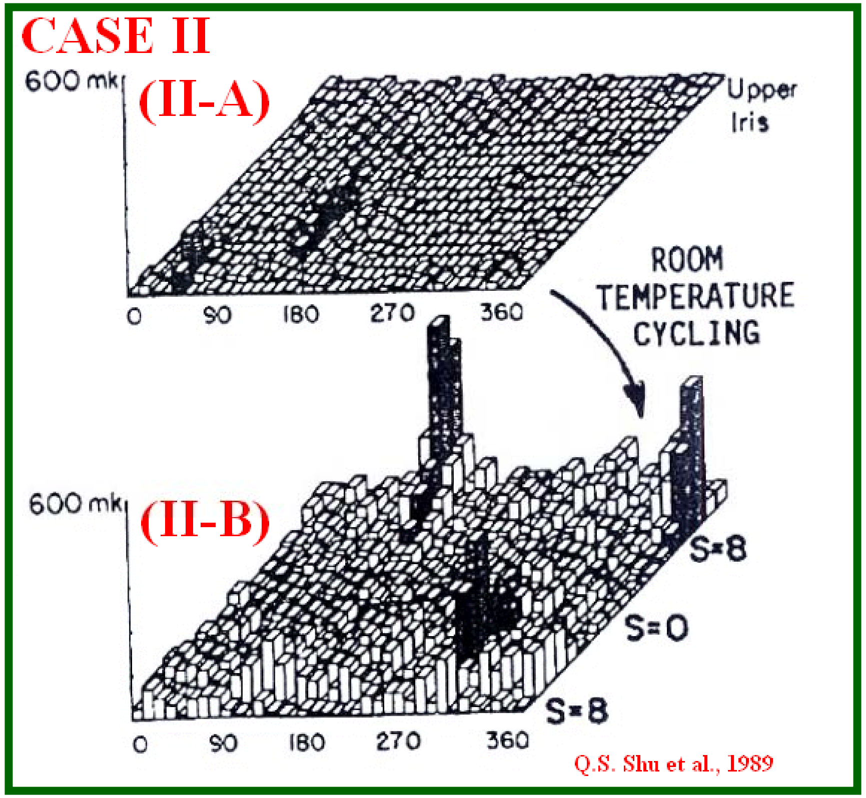


(H. Padamsee)

SRF Field Emission w/ a Puzzle Nature

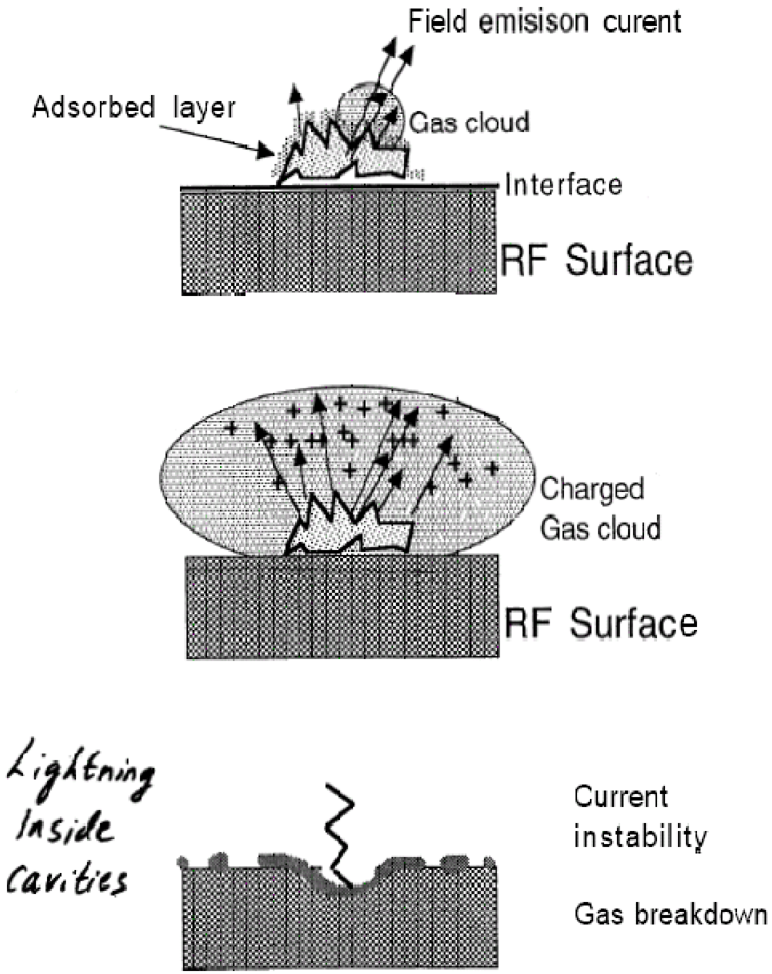
- Metallic particles of irregular shape; typical size: 0.5-20μm
- Only 5-10% of the total number of foreign particles actually present on the surface were found to emit (H. Pademsee), or condensed residual gas can…
- The activated/deactivated emitters can become deactivated/activated after warm-up and cool-down thermal cycle (Q. S. Shu et al.), or condensed residual gas can…





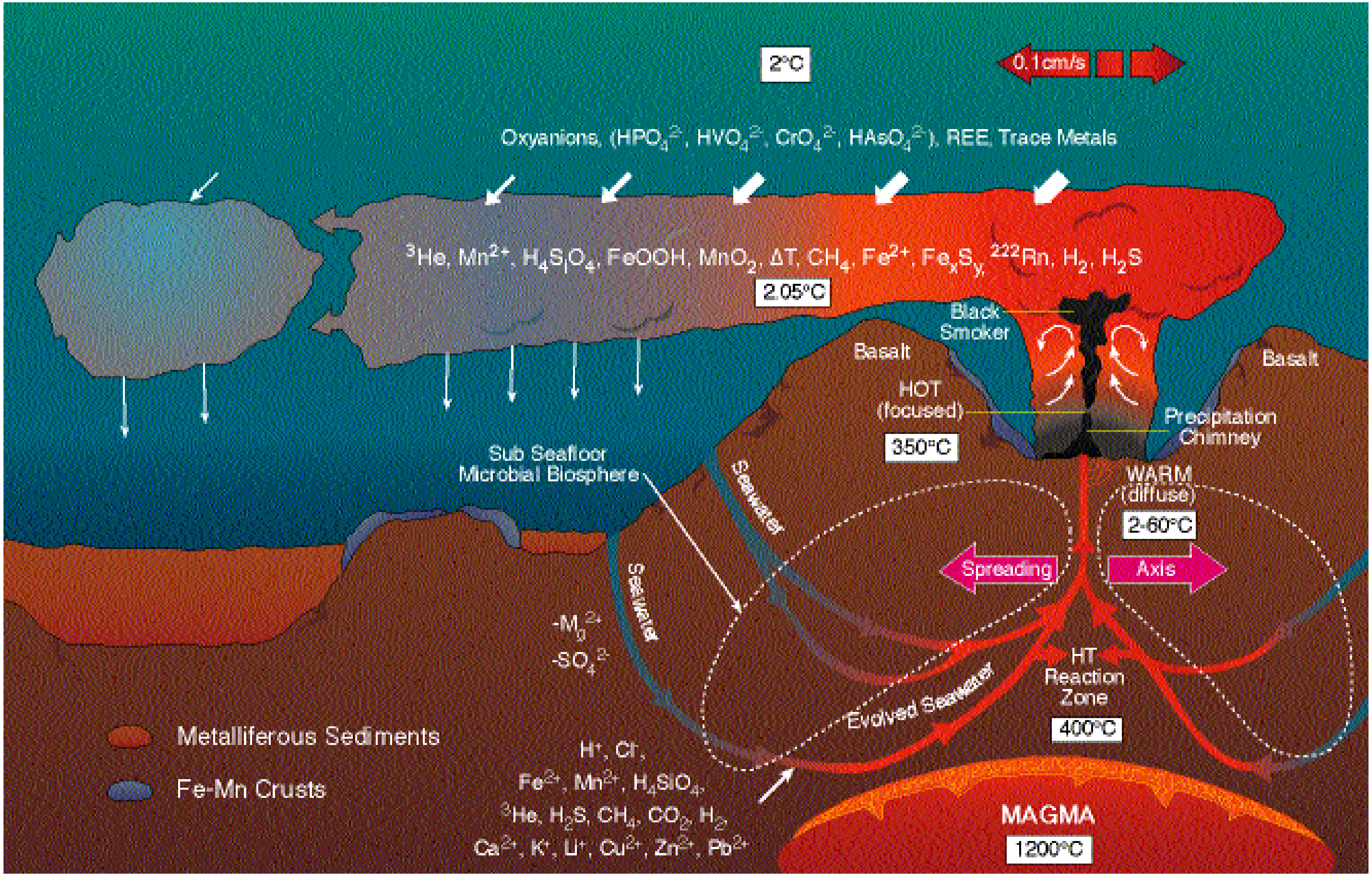
SRF Field Emission: Cornell Model II
- A "Concluding Picture"?

- local heating
- liberation of gas from surroundings - up to 1 bar!
- generation of plasma in stationary ion cloud
- 'uni-polar' arc
- local melting
- characteristic times are very short compared to (our) pulse lengths (SRF tests at ~CW)



Ref: Marc Ross

Volcanoes of the Deep Sea



Solutions to SRF Field Emission

- *Chemical surface treatment: EP vs. BCP*

- *Minimize foreign particle contamination*
  - *apply high pressure rinsing (HPR);*
  - *cavity assembly in a class 10-100 clean room;*

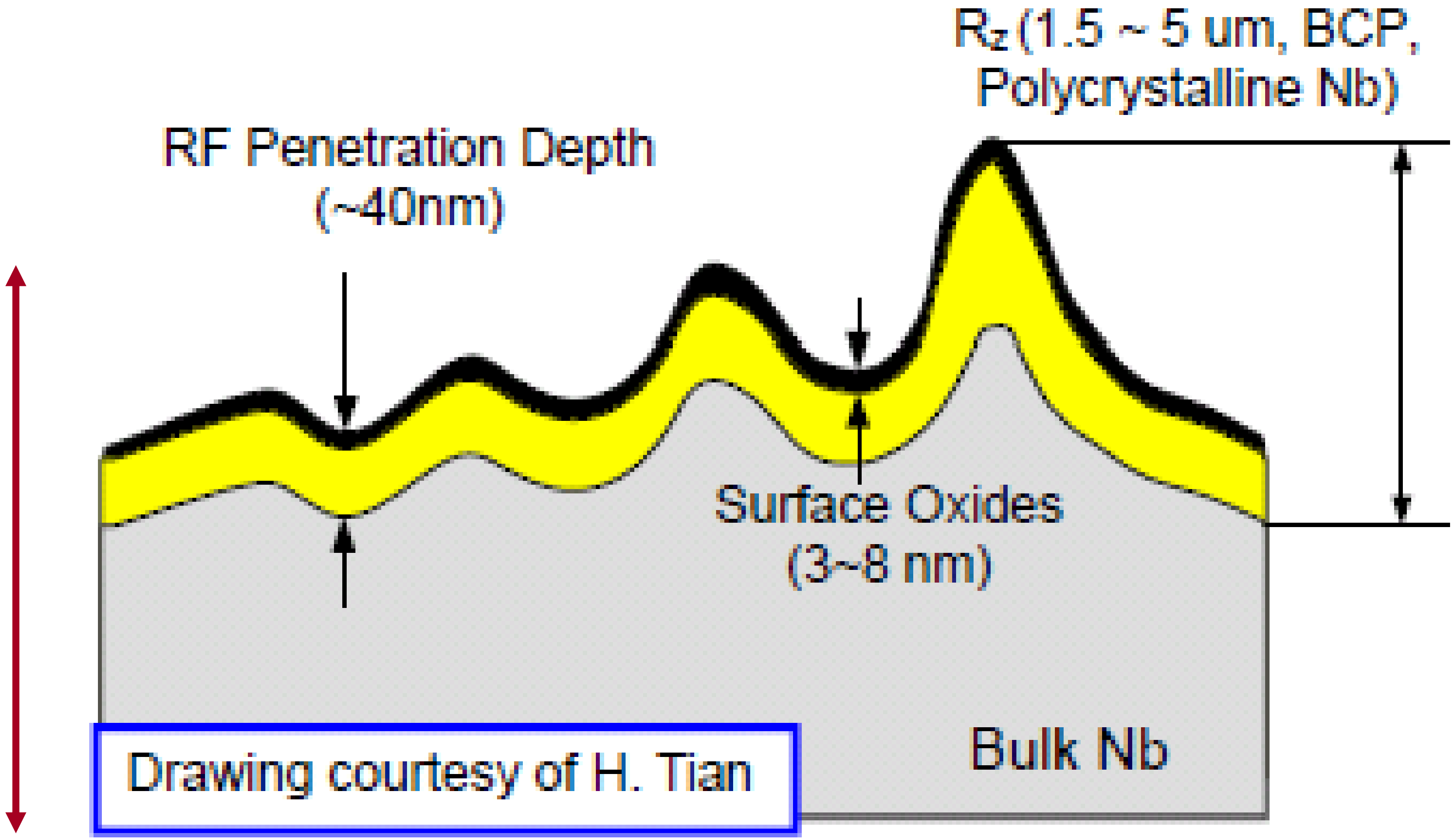
- *Apply high pulsed power processing (HPP);*
  - *damage activated emitters;*

- *Apply helium processing (HP);*

- *Apply cavity baking (avoid global field emission);*

Surface Treatments for SRF Cavity

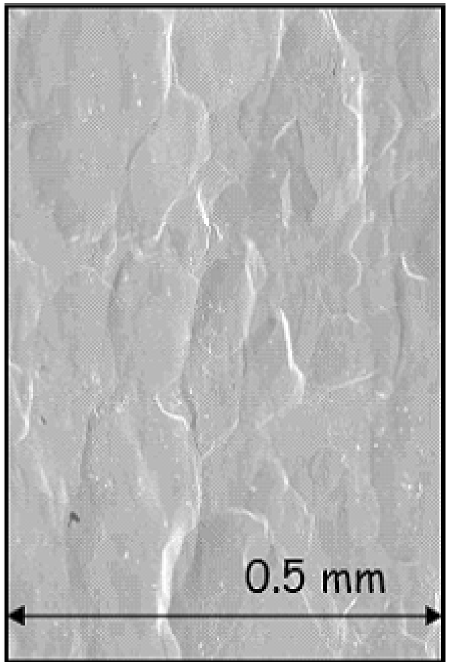
< 300 um



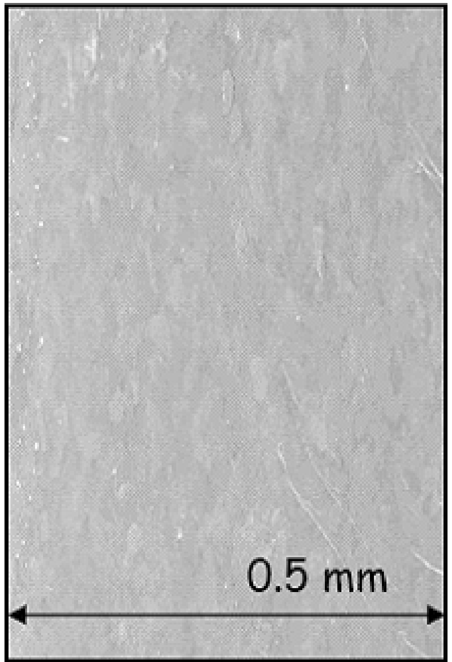
2~3 mm

Chemical Surface Treatments

- **BCP (Buffered Chemical Polishing)**
  - HF (48%) : HNO_3(69%) : H_3PO_4 (84%) with volume ratio 1:1:2 or 1:1:1
- **EP (Electropolishing)**
  - HF : H_2SO_4 with volume ratio 1:9
  - EP makes an improvement on the onset level of field emission
    - Much smooth surface → Less local field enhancement;
    - Better cleaning with high pressure water rinsing;



BCP Surface
(1μm roughness)



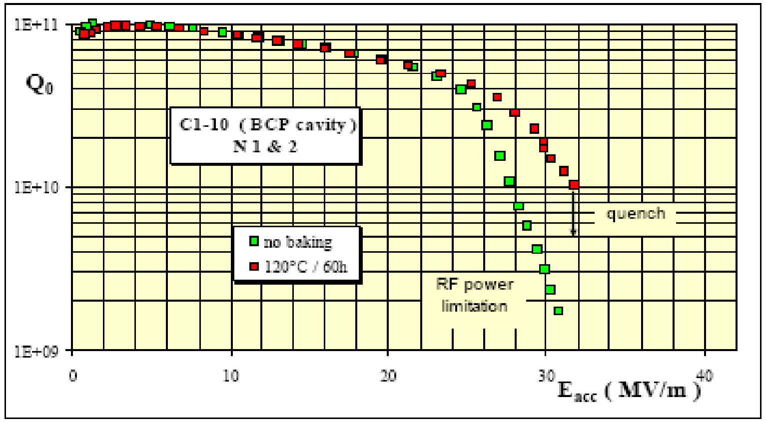
EP Surface
(0.1μm roughness)

(Carlo Pagani, 2005)

Chemical Surface Treatments

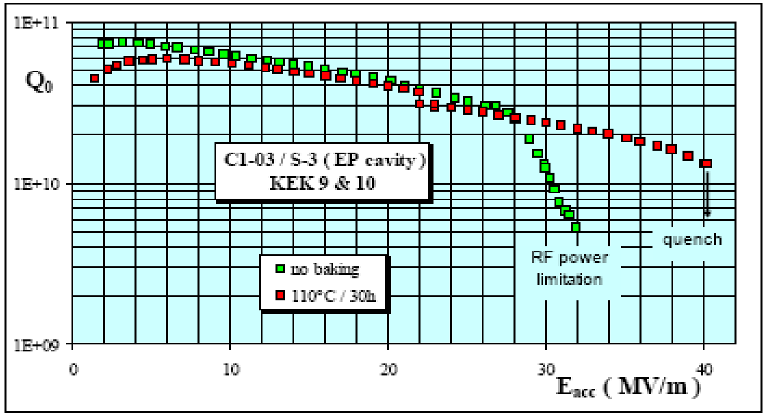
- Increase of the Quench Field Level if EP Adopted Instead of BCP.

- higher efficiency of baking on EP cavities (from 85°C)
- residual slope on BCP cavities even with baking (120°C)

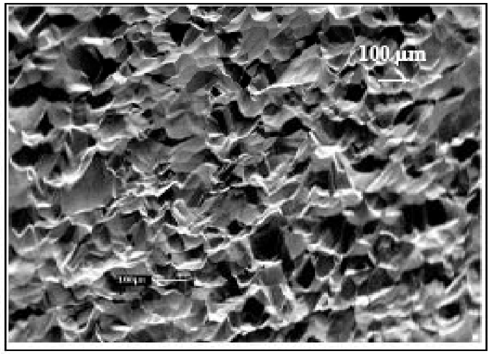


⇦ BCP

EP ⇨



- higher quench field for EP cavities (40 MV/m)

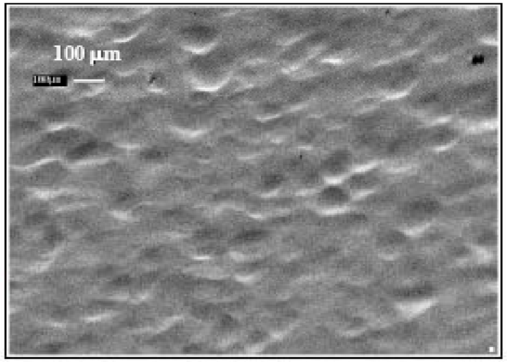


- surface roughness

(R.L. Geng *et al.* - SRF '99 – Santa Fe)

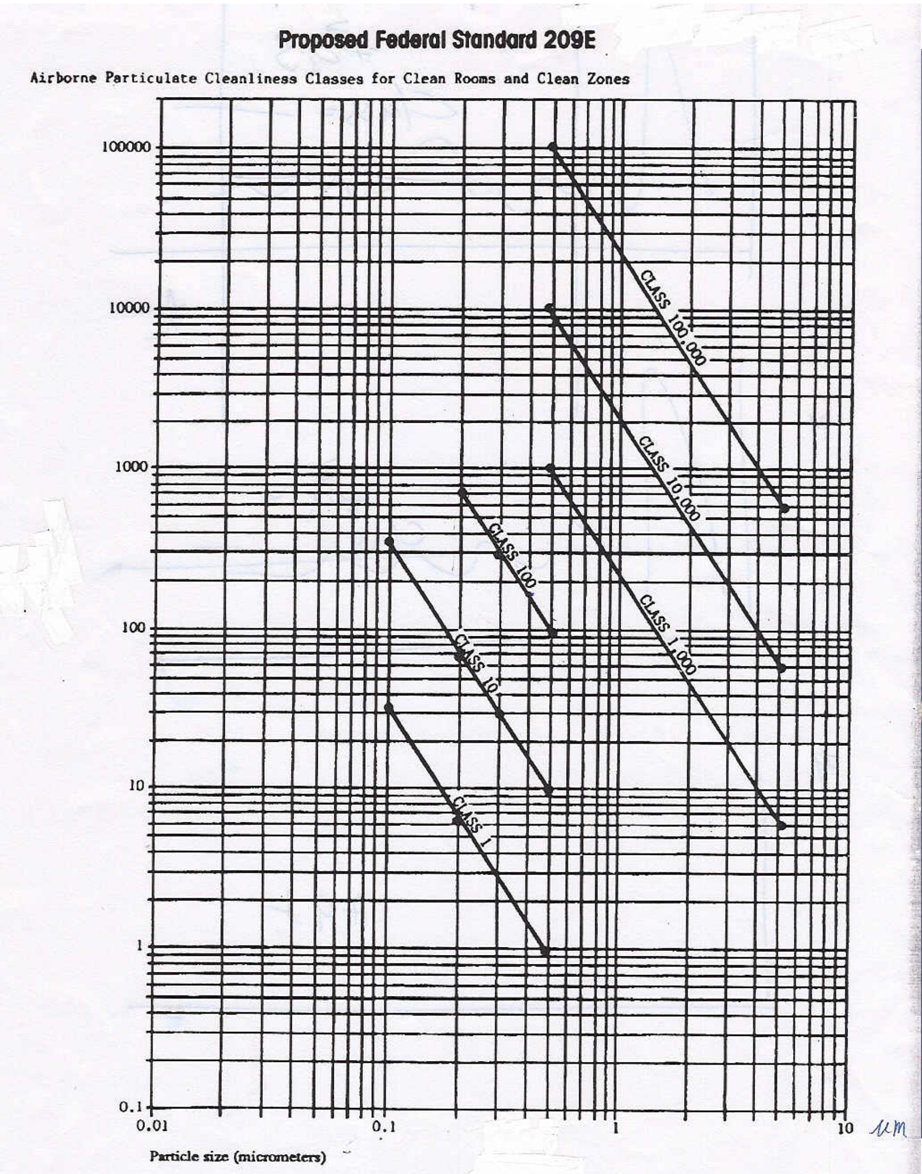
⇦ **BCP** (117 µm) **EP** (90 µm) ⇨

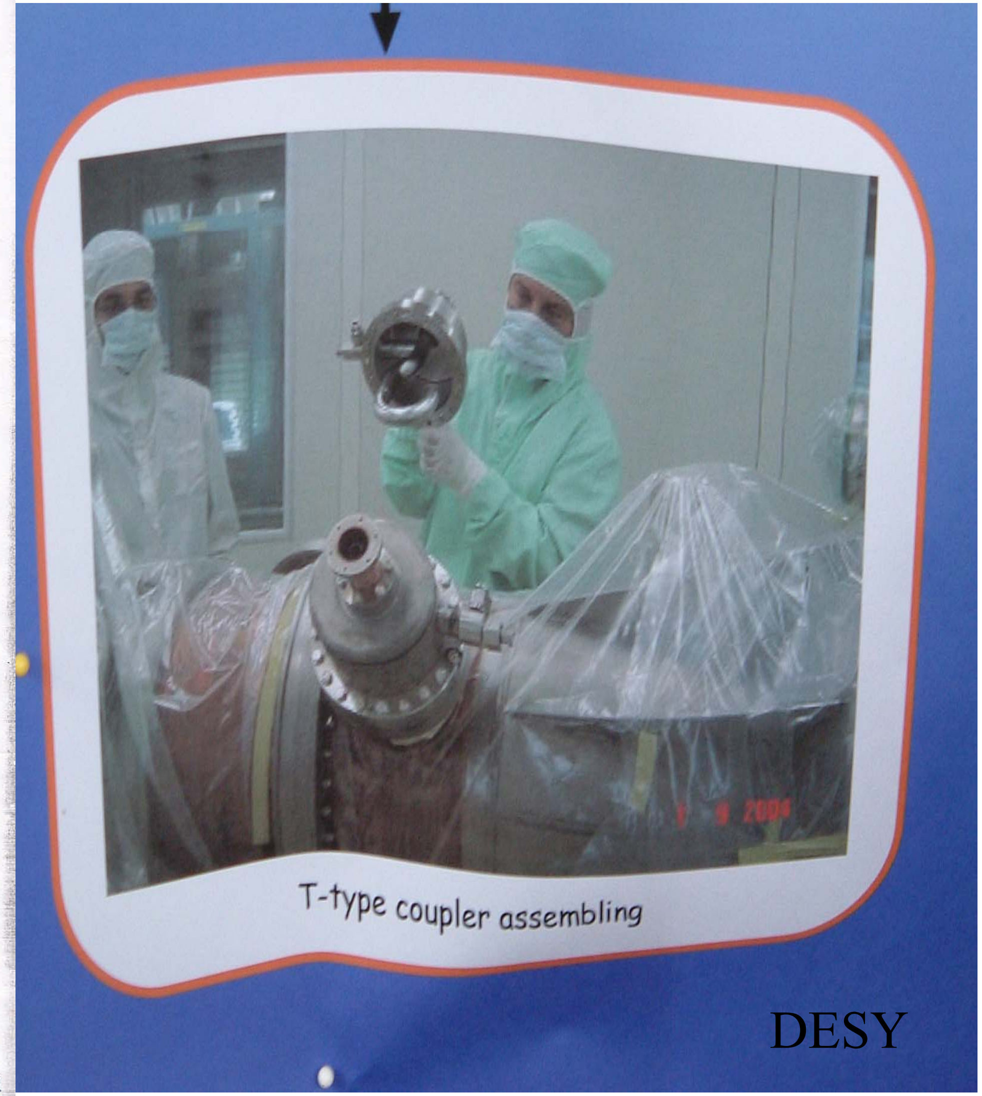
5-9 µm (statistic on step height) 2-5 µm



Solution for High Field Gradient

- SRF Assembly in Class-10 or Class 100 clean room





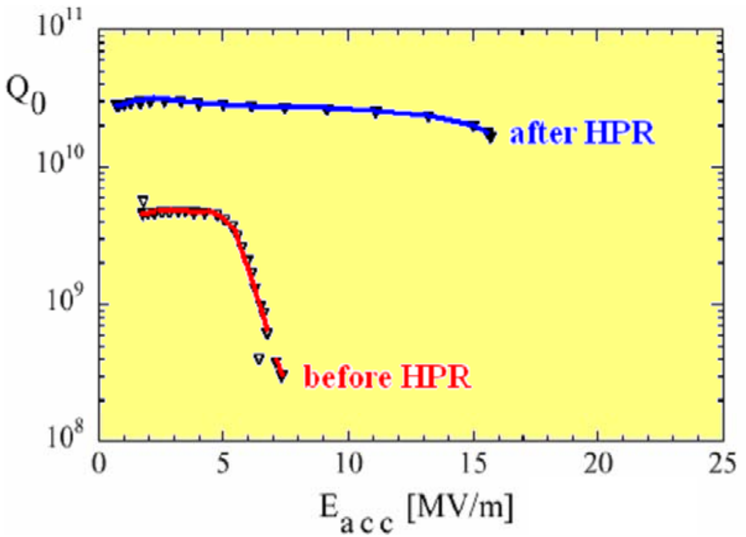
Solution for High Field Gradient

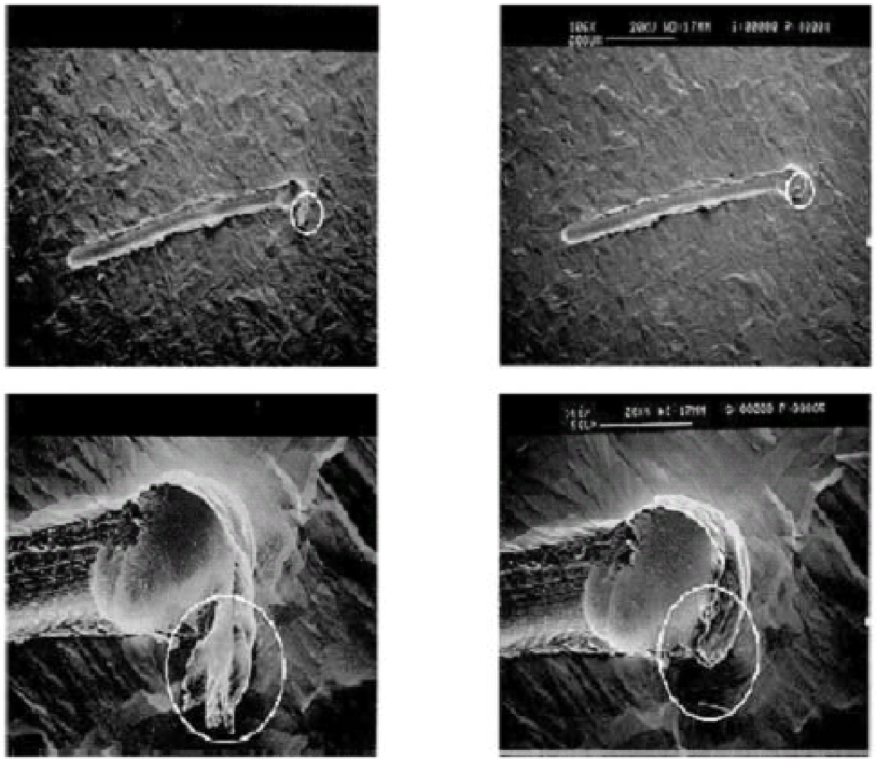
- High-pressure water rinsing in Clean Room

Ultra-pure water (18 MΩ-cm, particle filter<0.4 micron) is sprayed with a pressure of 100 bar on the niobium surface. This removes particles very efficiently.

Solution for High Field Gradient

- High-pressure water rinsing in Clean Room





- Cavities can improve by new rinses
- Particle removal
- Samples show modification of surfaces due to the water jet forces

Before HPWR

After HPWR

Lutz Lilje

2005/11/30

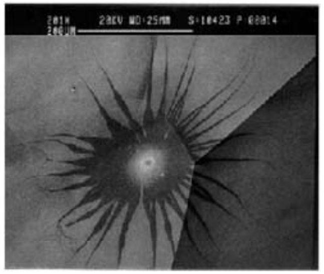
High Pulsed Power Processing

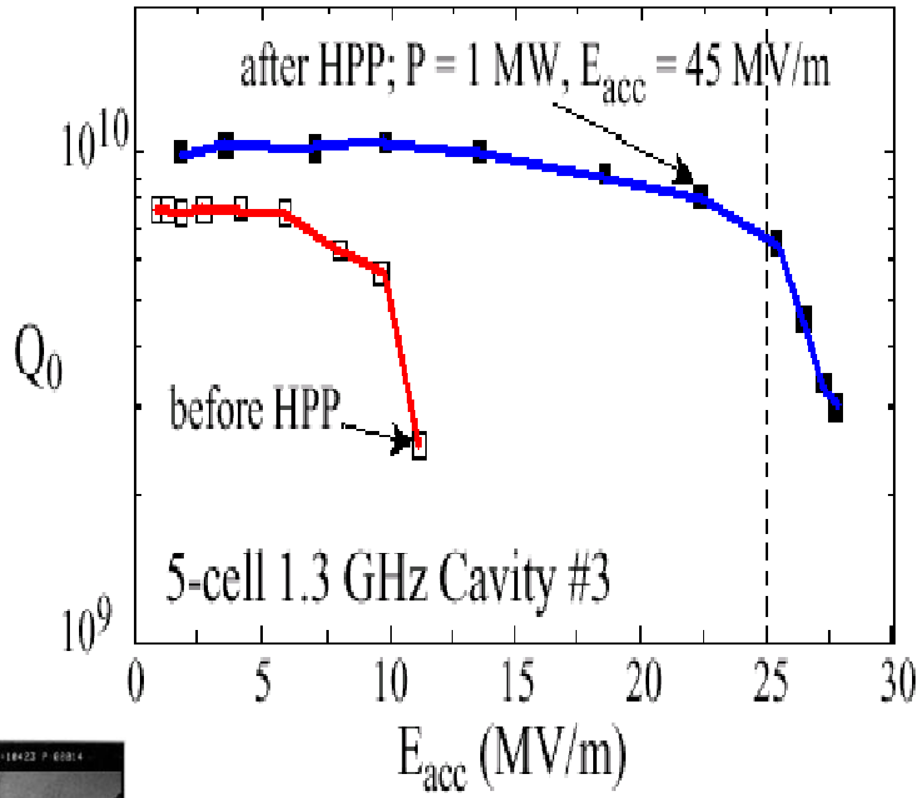
- with pulse length up to 2 msec, and repetition rate of about 1 Hz

- A newly-fabricated RF structure will breakdown frequently at low gradient. As the structure is operated, the breakdown rate at a given gradient (or RF pulse length) decreases gradually, and the gradient and pulse length can be increased (thus increasing the breakdown rate again).

- This cycle, called "RF processing" is repeated until at some point no further progress can (or need to) be made - no amount of running will reduce the breakdown rate at a given gradient and pulse length within a reasonable time period.

- The reason appears to be that processing "polishes away" (vaporized) small surface features; in the process, some molten metal splashes from the vaporization point to nearby ones, forming new features.



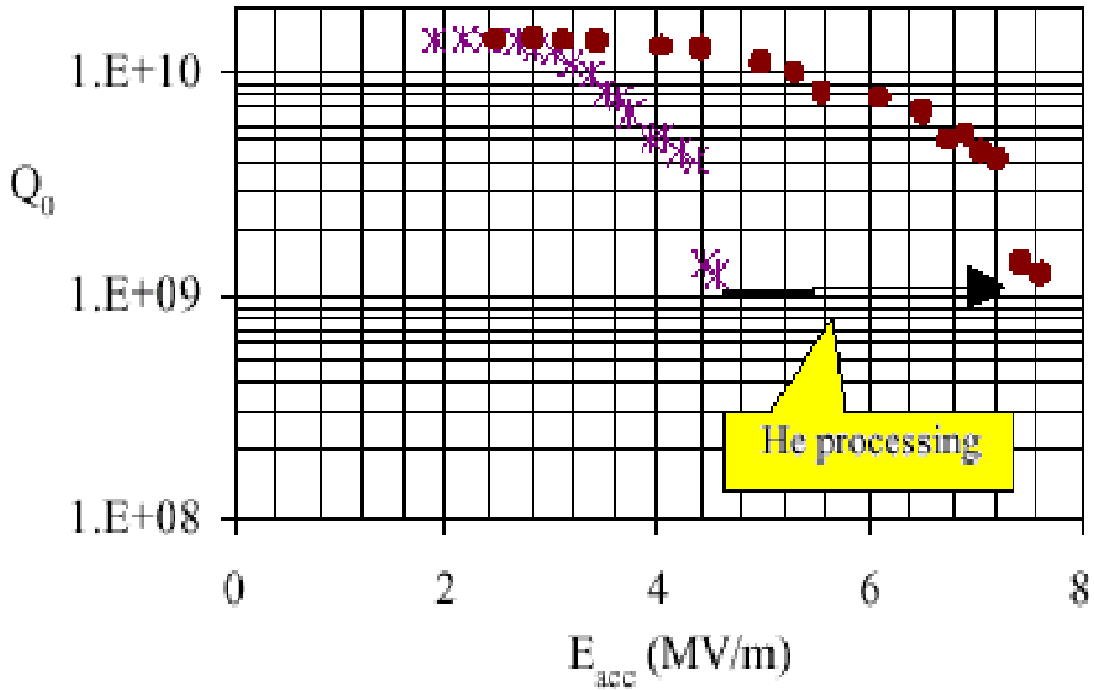


Q_0 vs. E_{acc} plots showing high power processing (HPP) results on a 5-cell 1.3 GHz cavity at Cornell.

Helium Processing

- a) Modification of the Adsorbed Gases; b) Explosive Destruction

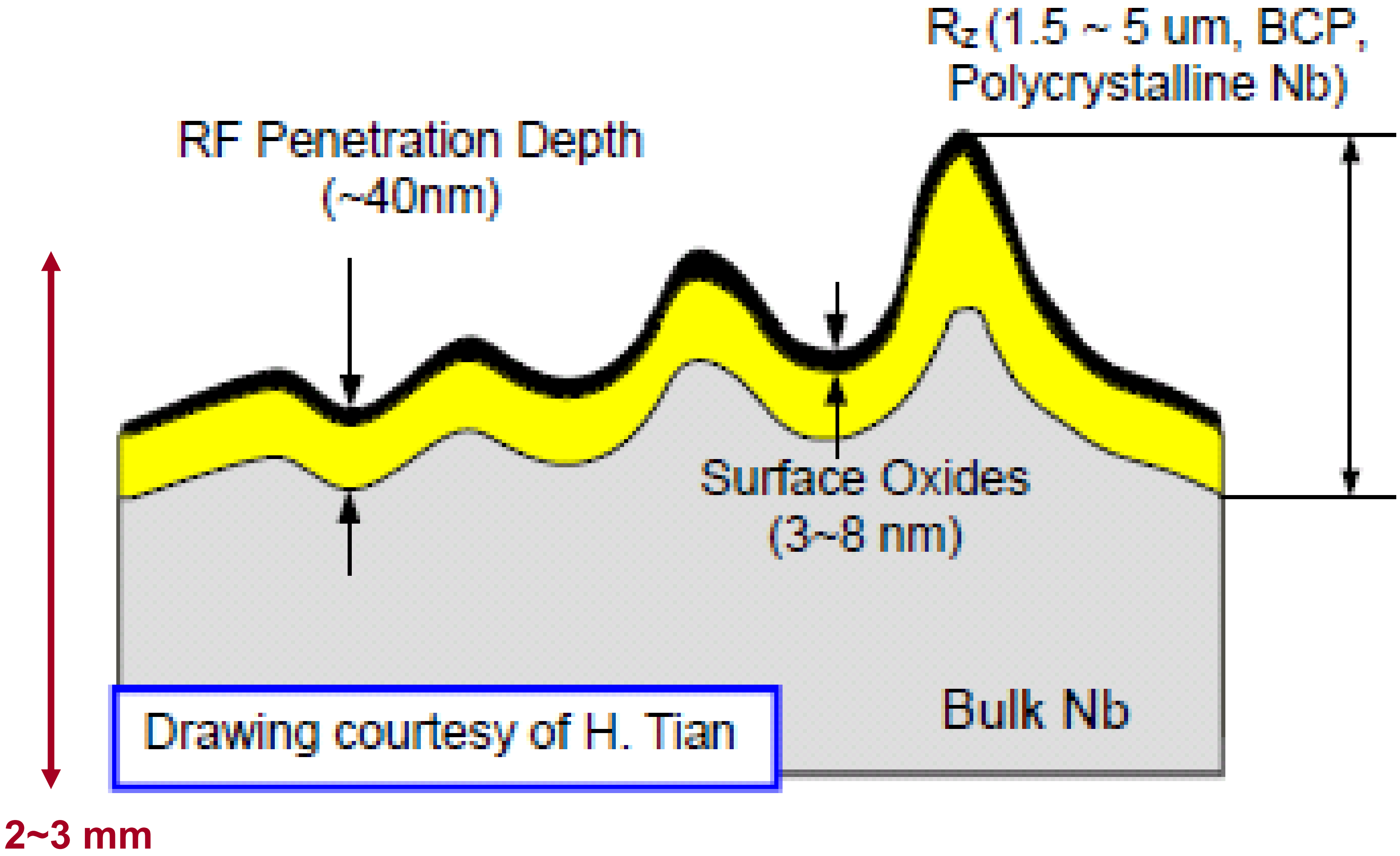
- Fill helium gas into the SRF cavity up to 10^{-6} Torr and then RF processing.
- Risk of vacuum accident.
- Many possible mechanisms had been proposed.
- Sometimes helpful for Multipacting (MP) and field emission (FE) suppressed, but not always!



Effect of a mixture of helium processing and further BCP. Also shown is the data after welding of inner helium vessel. This data is of Sylvia cavity.

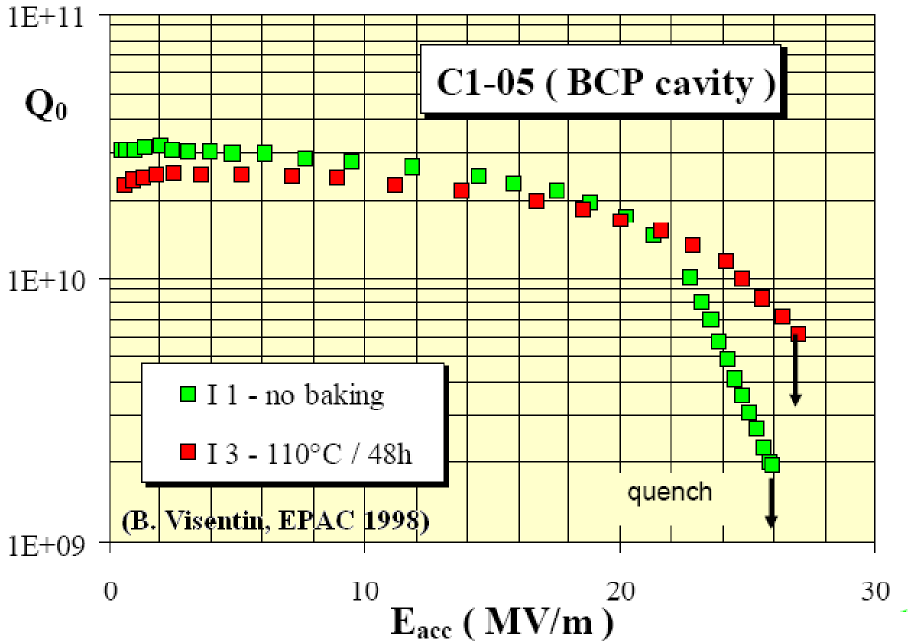
(T. Tajima et al., 2001)

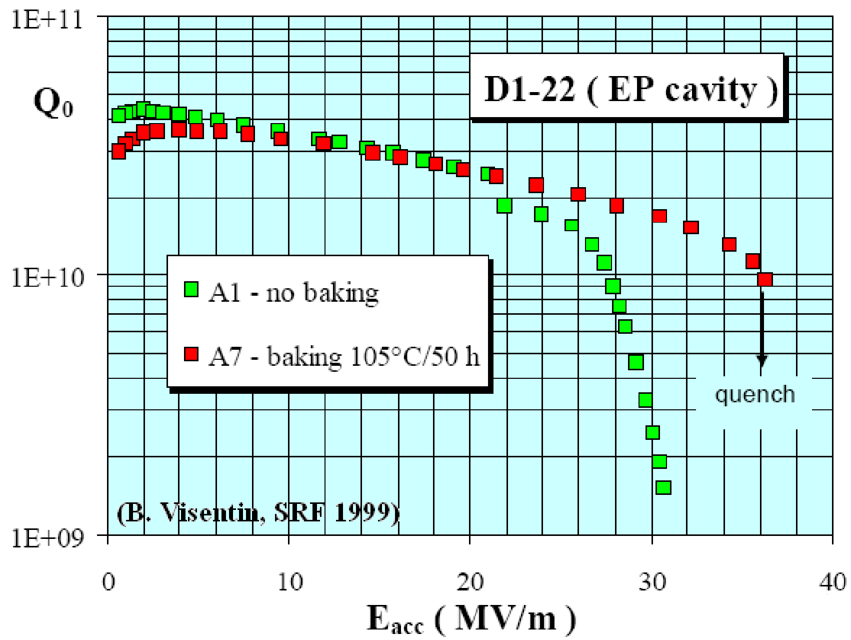
Baking ~ Surface Treatments



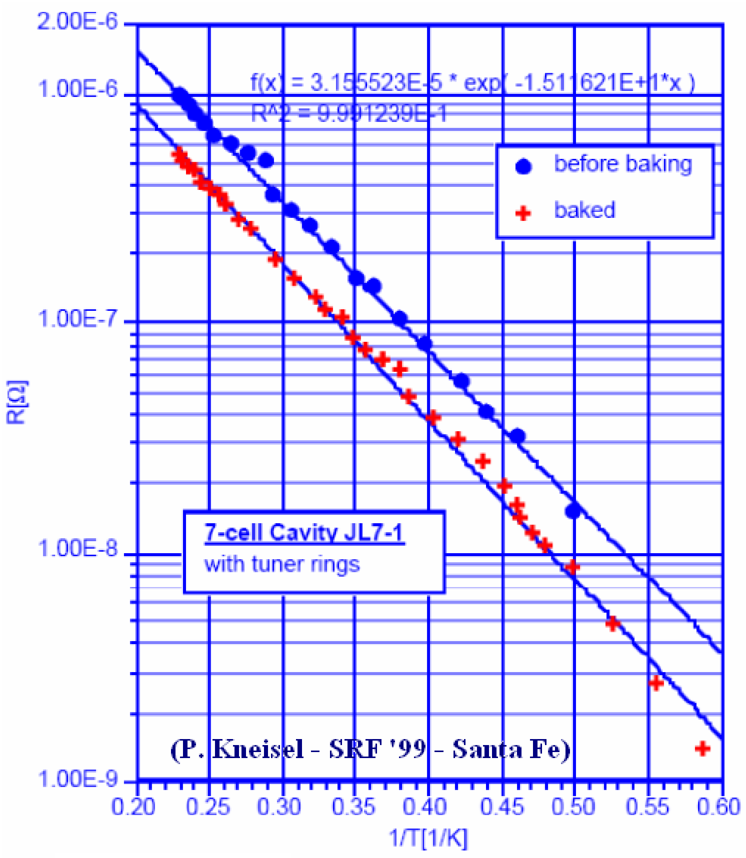
Effects of Cavity Baking on Q-Slopes
-developed by CEA-Saclay

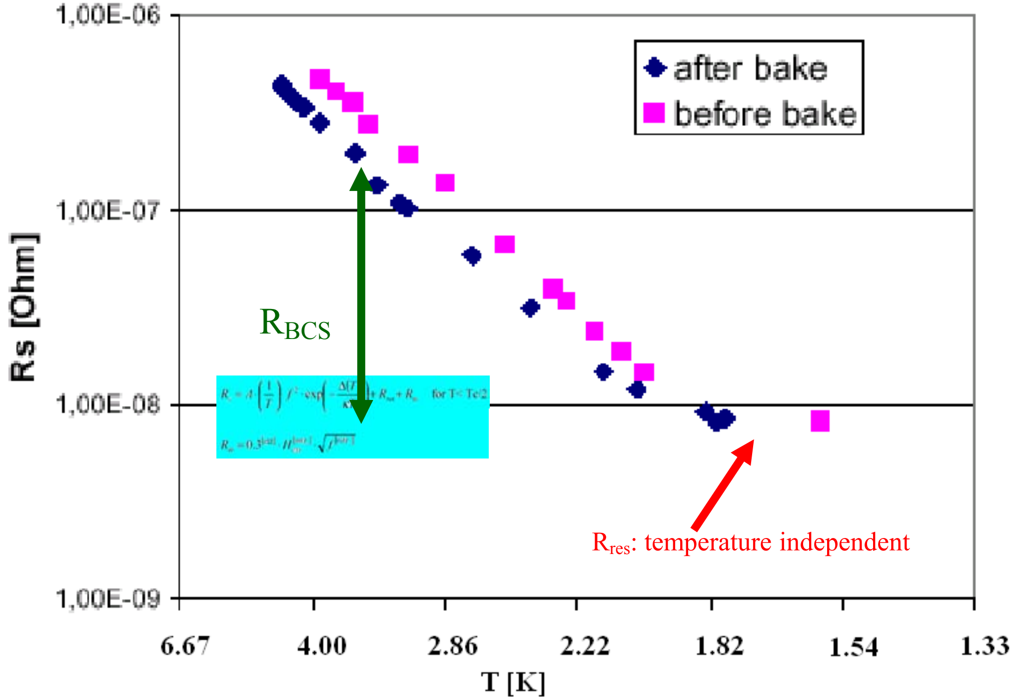
- Enhancement of Q-slope at low field level;
- Minor flattening of the Q-slope at medium field;
- Strong improvement of Q-slope at high field;





Differences Made by Cavity Baking





Reduction of R_{BCS} by bakeout. The residual resistance R_{res} is nearly unchanged. (L. Lilje)

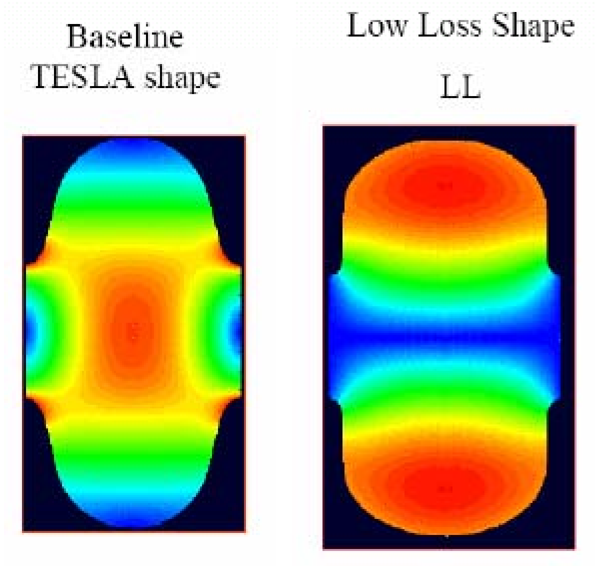
- Baking causes a reduce of BCS resistance in a factor of about 2.

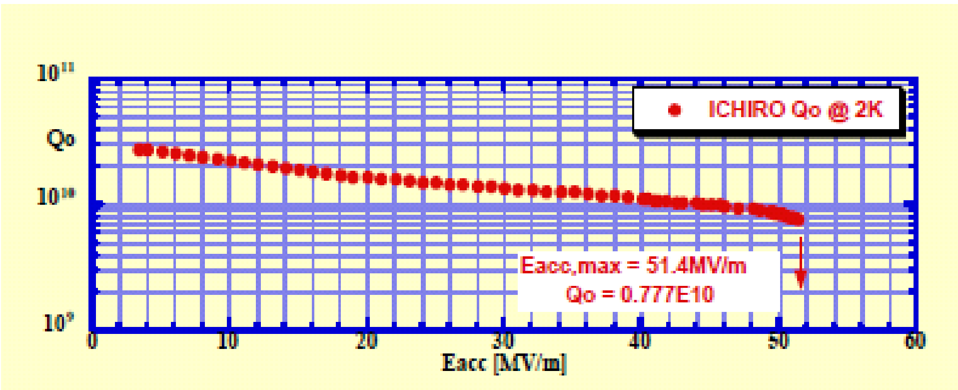
- Baking does not change or increase slightly the residual resistance.

Disease	Phenomena	Cures
Thermal instability	Quench at bad spot	Mechanical grinding, Use high pure niobium material Sever material control
Hydrogen Q-disease	Low Q from low field, Depends on cooling speed	Annealing
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
Q-slope	Exponential Q-degradation without / with x-ray	Baking

More Gradient…New Cavity Shape

- Surface magnetic field limitation
  - lower than rf critical magnetic field H_{sh};
  - for niobium at 0K, $H_{peak} < H_{sh}(0) = 2300$ Oe; or $E_{acc} < 49$ MV/m for typical SRF elliptical cavity.
    - Ratio of Hpeak/Eacc ≒ 47 Oe/(MV/m).
- New design of cavity shape – reentrant, low loss profile, Ichiro Single.
  - First done by R.L Geng (Cornell);
  - Ratio of Hpeak/Eacc ≒ 36 Oe/(MV/m).

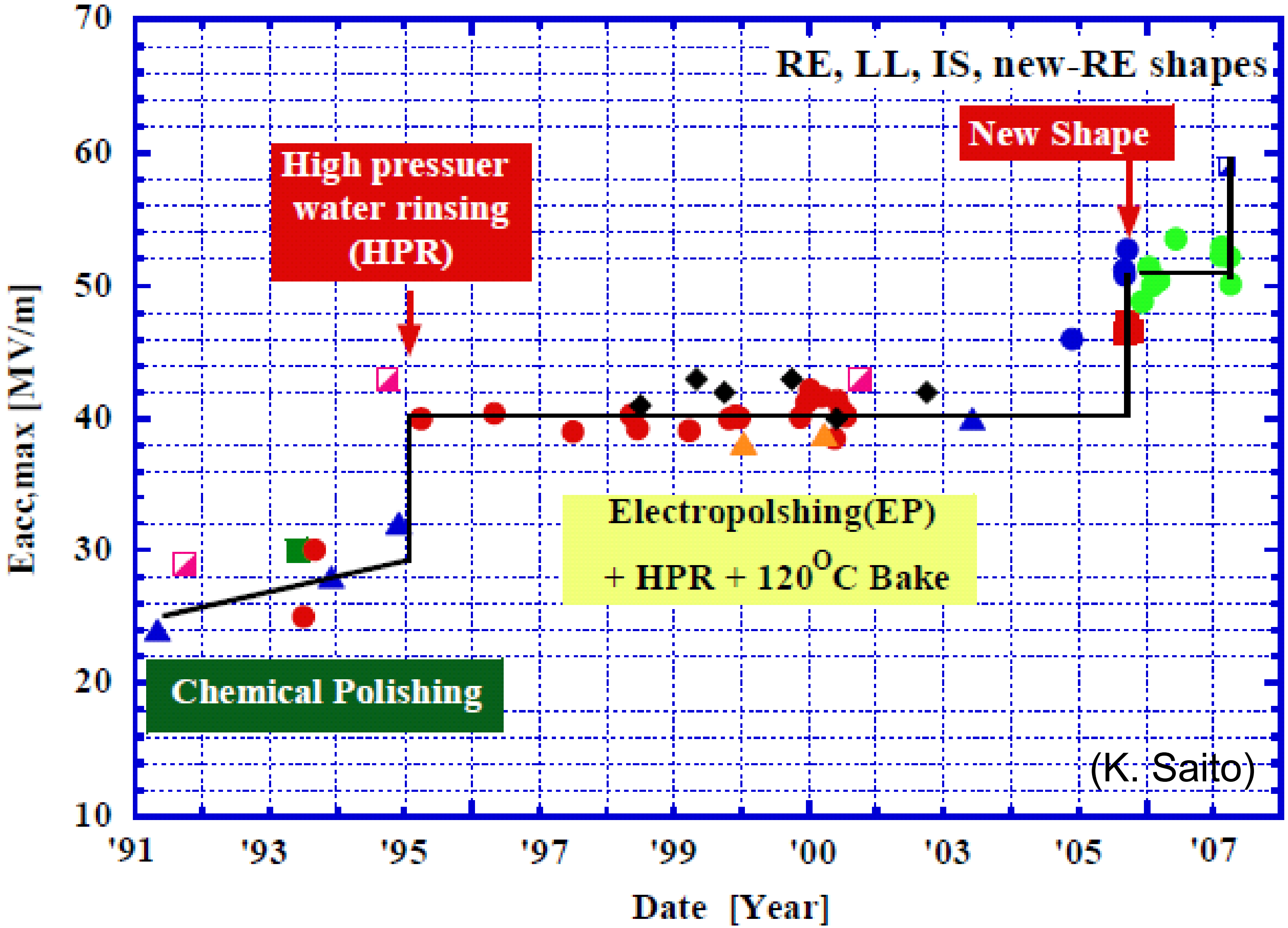




Diameter [mm]	61
Ep/Eacc	2.02
Hp/Eacc [Oe/MV/m]	35.6
R/Q [W]	138
G[W]	285
Eacc max	49.2

(K. Saito)

Results of Last 15 Years!



Collider vs. Light Source

- Collider (ILC) needs high gradient (RF gap voltage) to reduce the total number of operating sc cavities;
- Light sources need high beam current (RF power) but low gradient.

Outlines

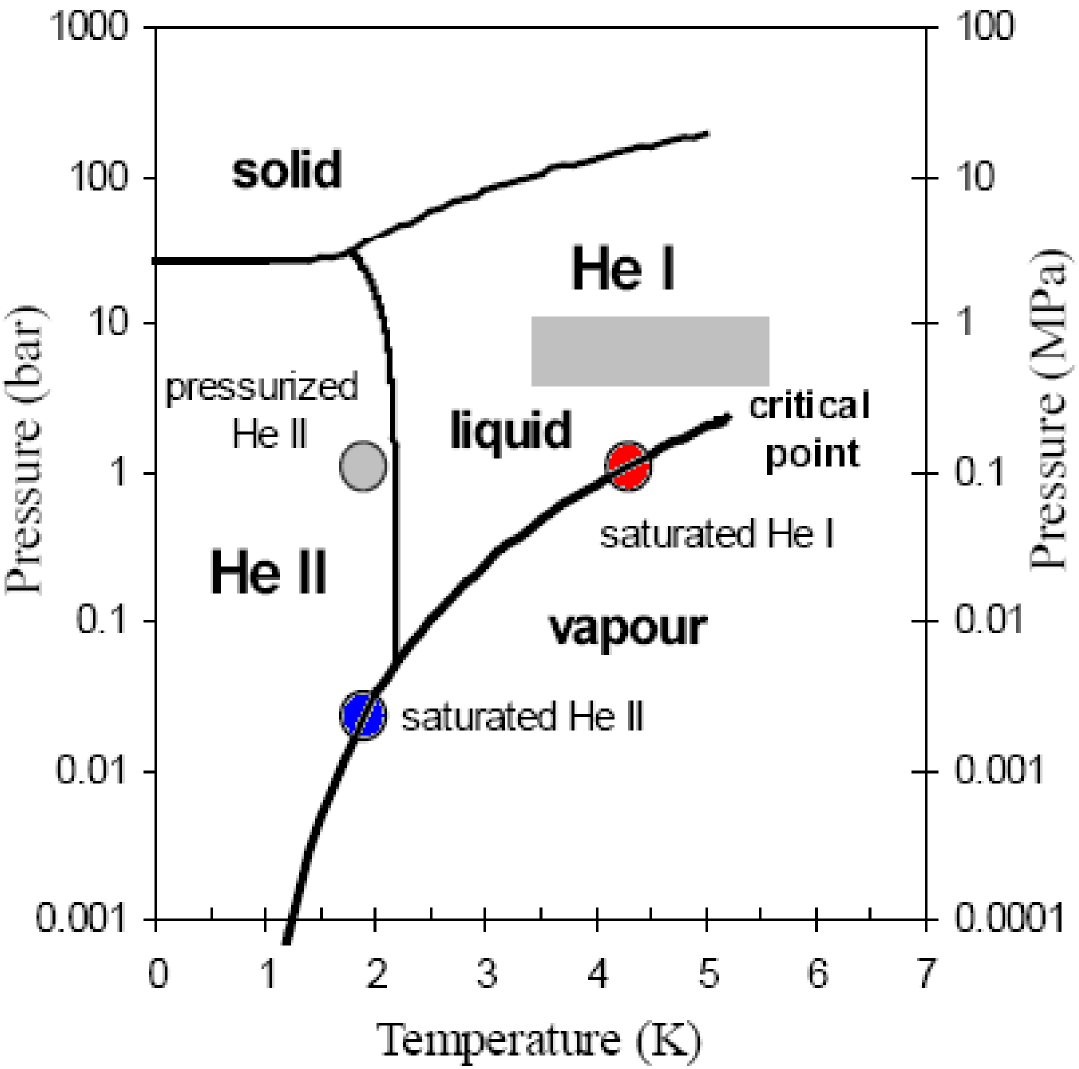
- Historical Remark
- Basic of Superconducting RF
- SRF Performance: Achievement and Challenge
- Cryogenic Plant for SRF Operation

- SRF Operation and Maintenance

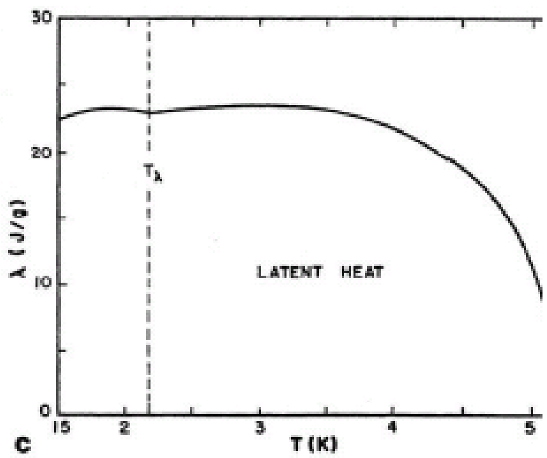
4.5K LHe Cryogenic Plant for SRF Operation

- ***Requirements:***
  - long term continuous operation
  - vibration free
  - fast cool down capacity
  - high redundancy
  - energy saving and load matching
  - easy operation
  - SRF operating LHe pressure as low as possible
- ***Solution:***
  - turbine machine
  - large helium inventory (2000 liter main dewar)
  - capacity safety factor of 1.5
  - frequency driver
  - fully automatic control
  - Cold-box's HEXs with low-pressure drops (~150 mbar)

Working Point of Cryogenic Plant

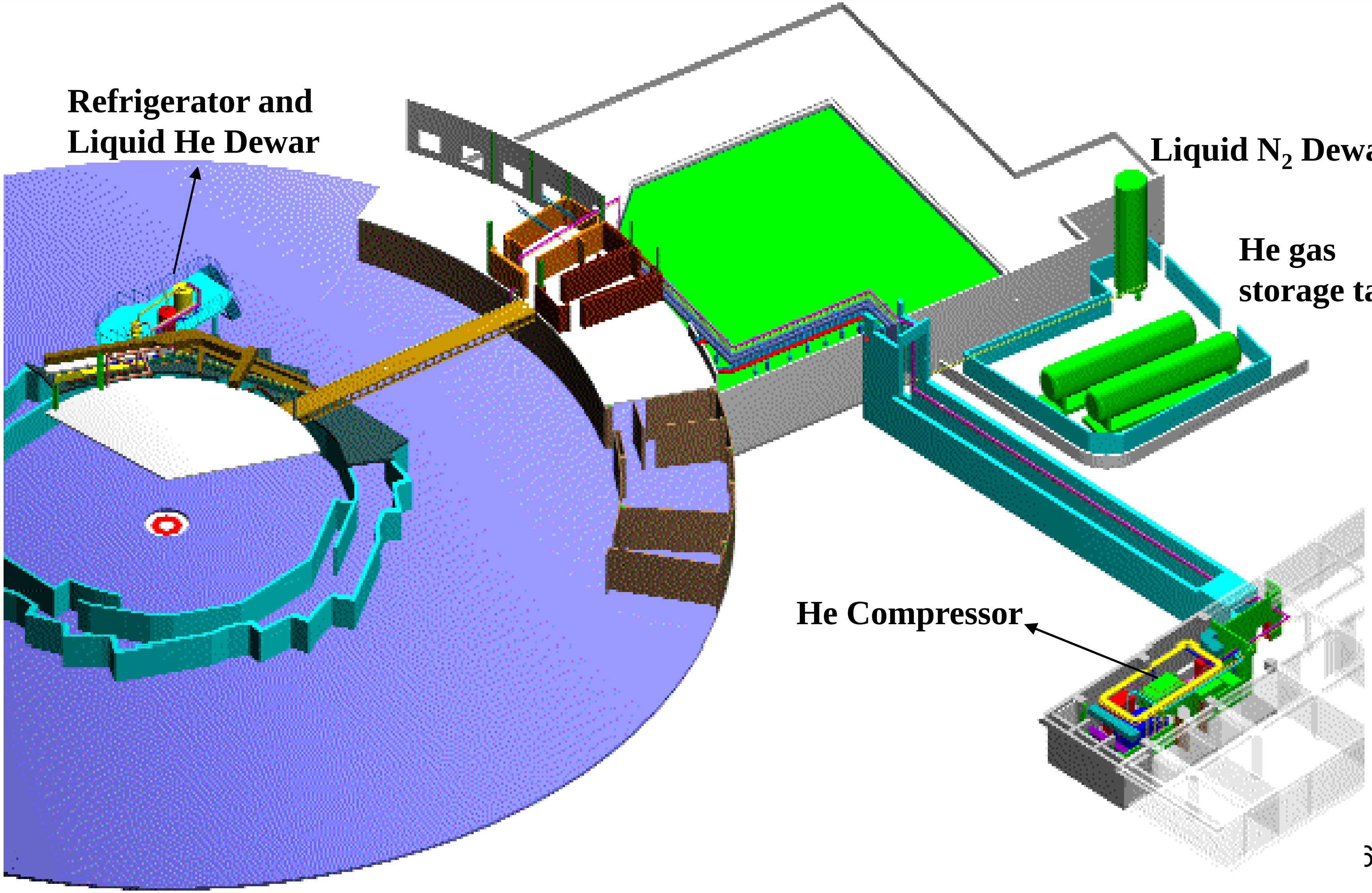


Latent heat of
water: 2260 J/g (100^{o}C)
LN2: 200 J/g (77.15K)
LHe: 21 J/g (4.22K)



Latent heat of vaporization of liquid helium.

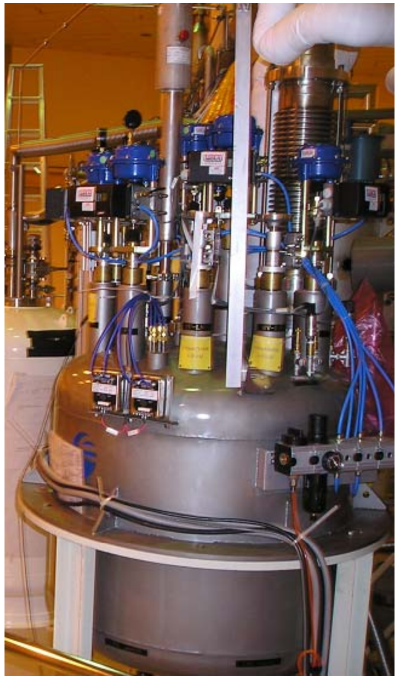
4.5K LHe Cryogenic Plant for SRF Operation at TLS

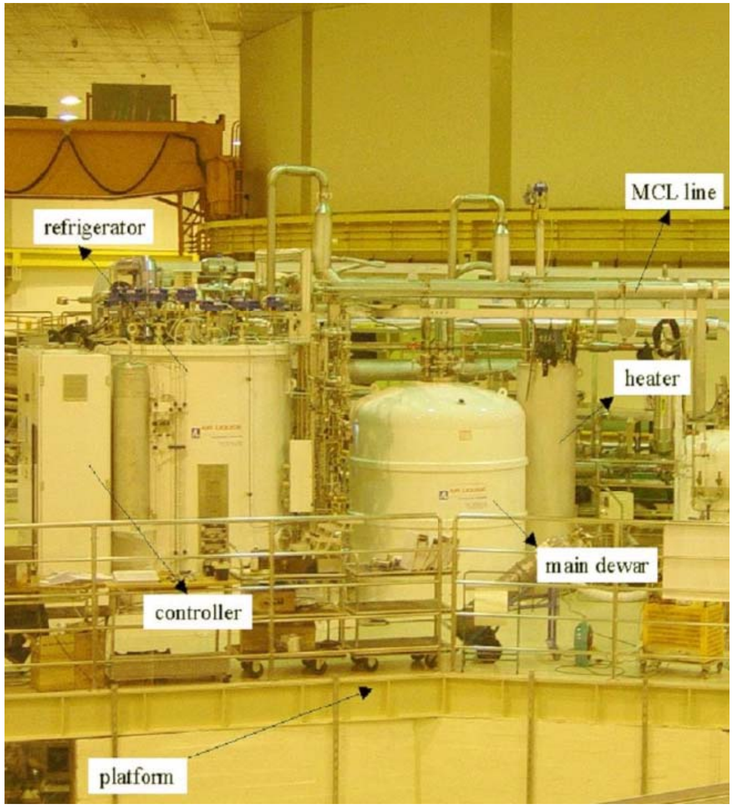


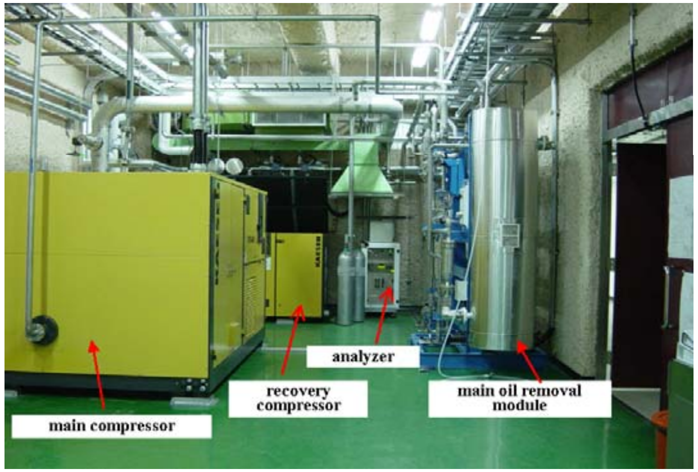
4.5K LHe Cryogenic Plants at TLS

- One for SRF (2003) and the Other One for SMAG (2005)

4.5K LHe Cryogenic Plant

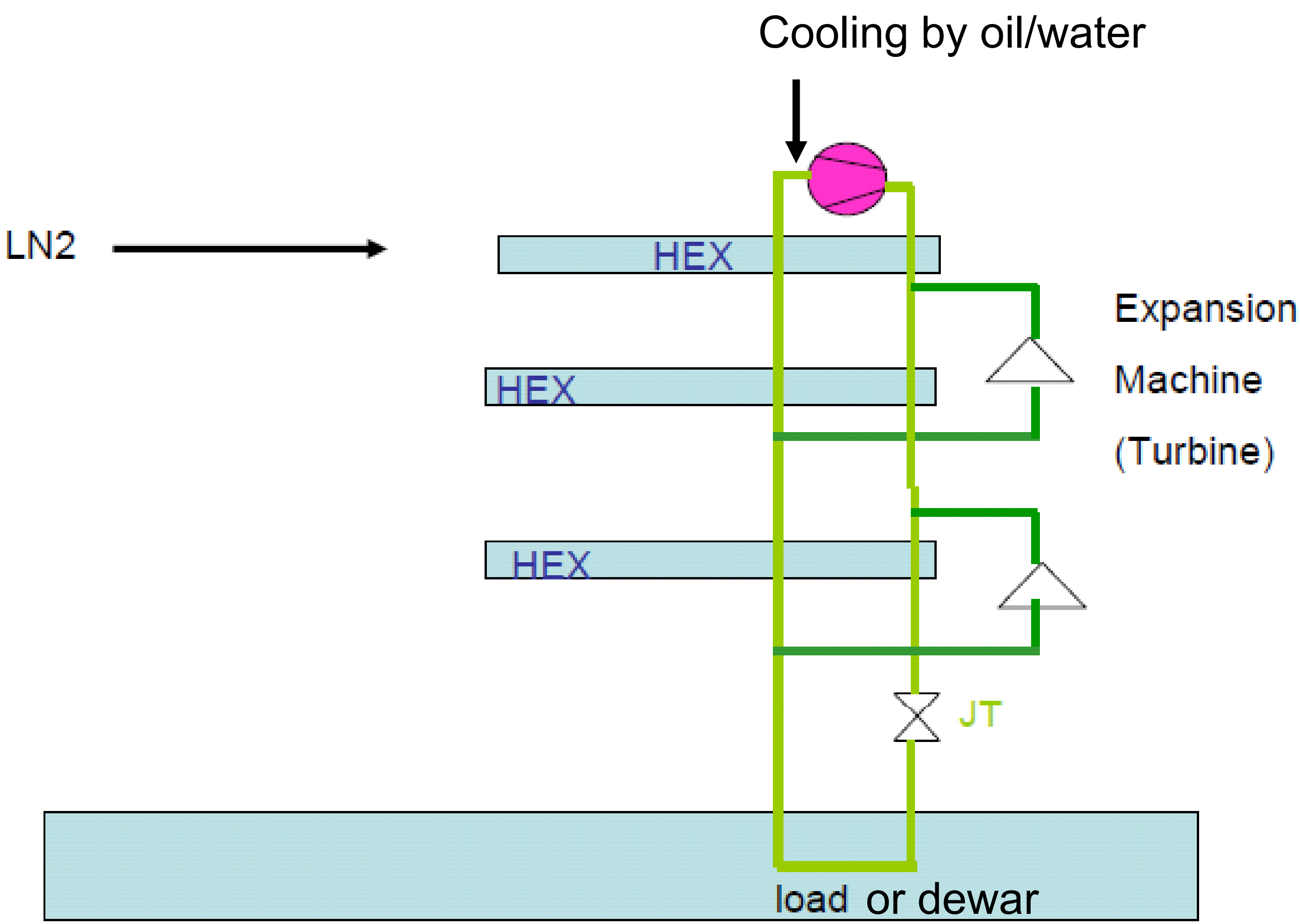




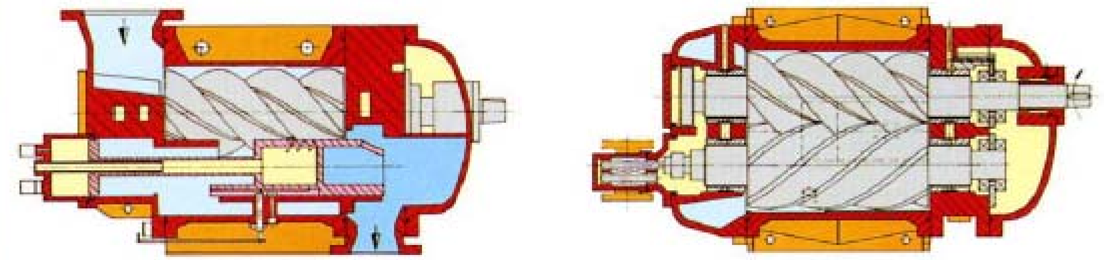


Some Helium Refrigerator Cycles

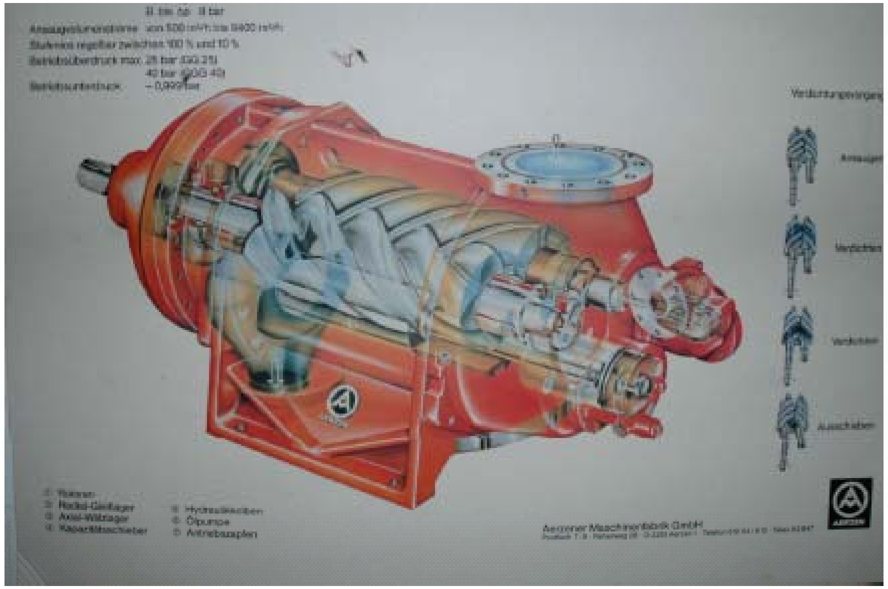
-Simple Collins Cycle



Screw Compressor



Längsschnitt: Ansicht von der Seite. Abb. AERZENER Maschinenfabrik, Aerzen Längsschnitt: Ansicht von oben.

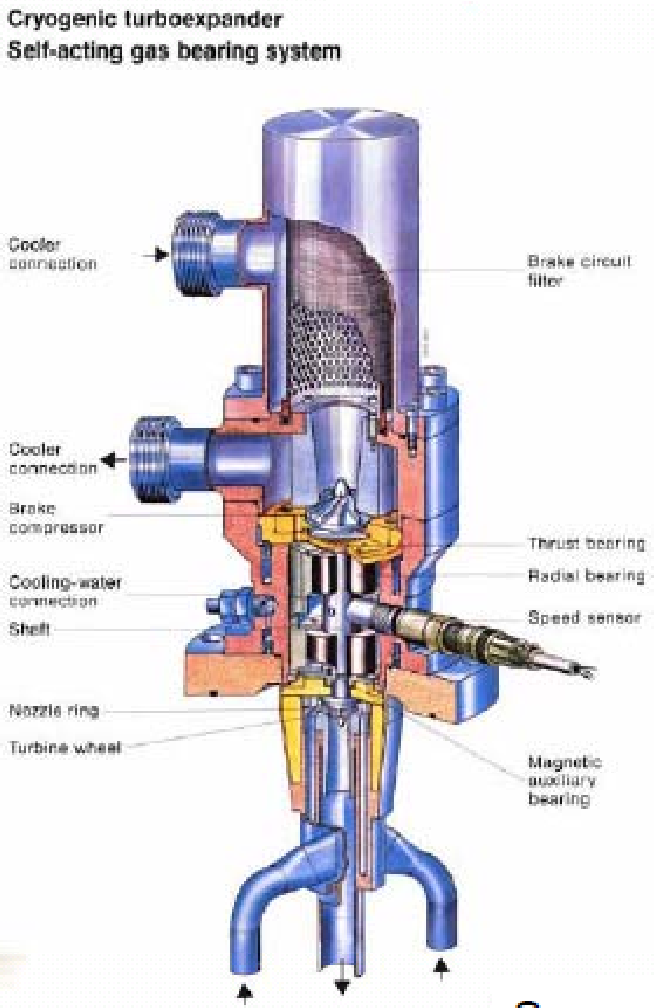


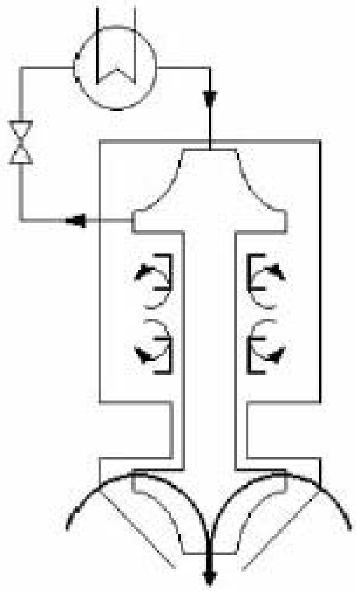
Source:

AERZEN

Heat Exchangers (HEX) inside a Cold Box

Cryogenic Turboexpander inside a Cold Box

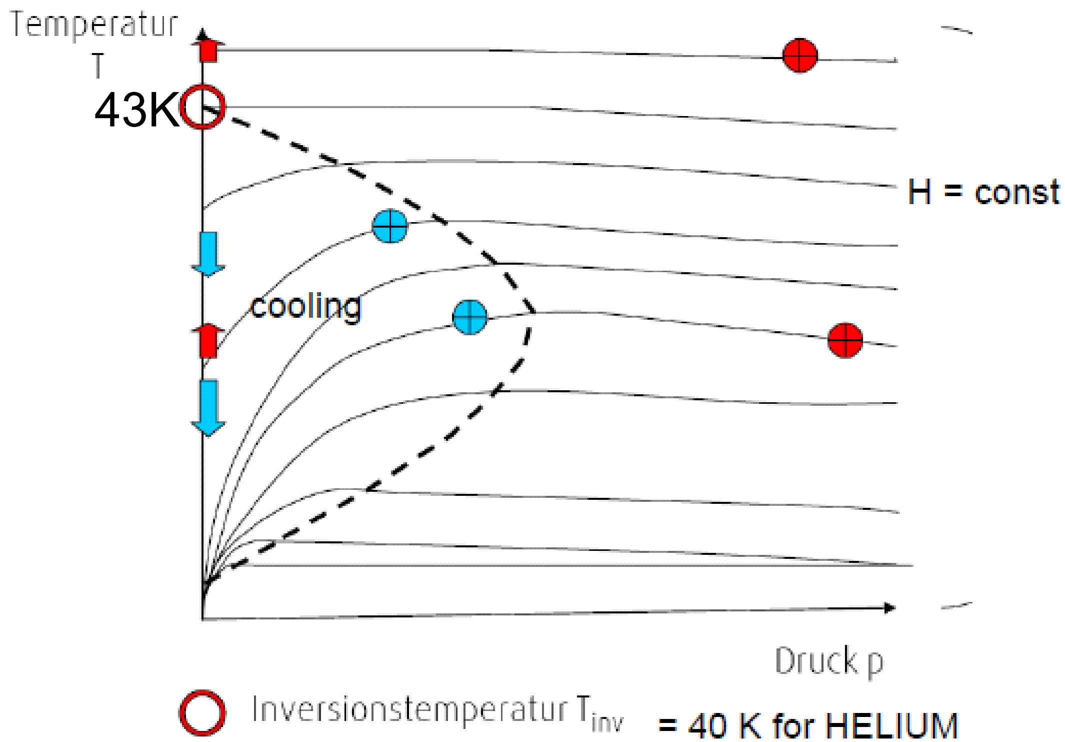




Source: LINDEKRYOTECHNIK AG

J/T (Joule-Thomson) Valve

-Cooling by Rapid Expansion



1. The helium gas first must be cooled below its inversion temperature of 43K. Otherwise, its temperature cannot be reduced by passing through J/T valve.

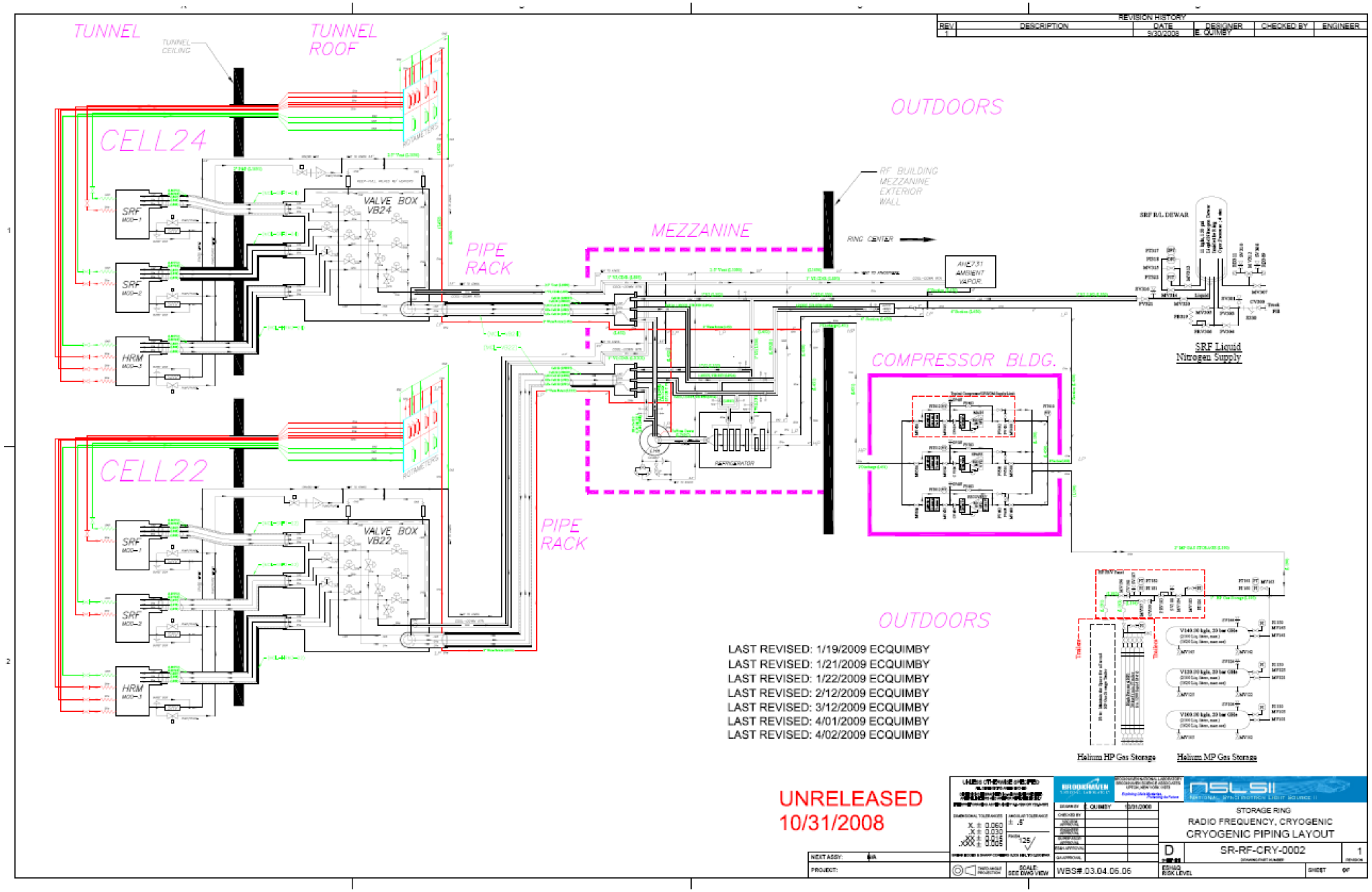
2. The helium gas must be cooled even further (<15K) in order to produce liquid helium at 4.2K.

3. Similarly, <5K for 2K LHe.

如果回來的冷氦氣太熱，以至於最後一級的熱交換器(heat exchanger)無法將進入J/T valve前的高壓氦氣溫度降到適當的低溫，cold box是無法產生液氦的。

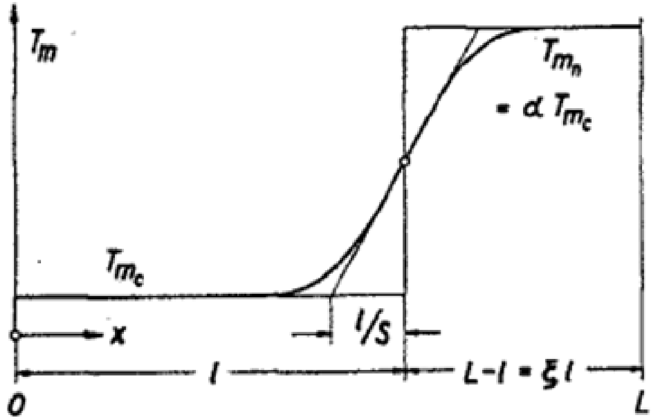
進入J/T valve前的高壓氦氣的溫度越低，出J/T valve 的飽和氦的乾度越低。

Typical Piping Layout

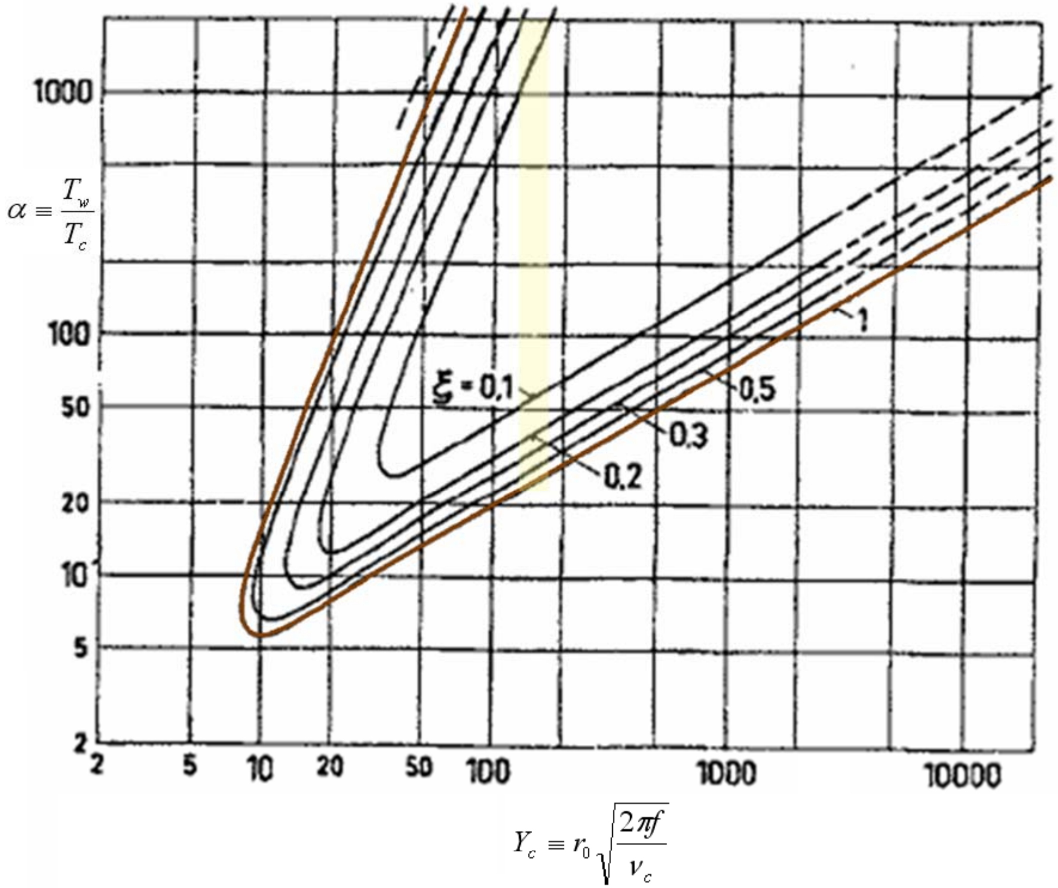


Typical Piping Layout:

Avoid Thermal Acoustic Oscillation

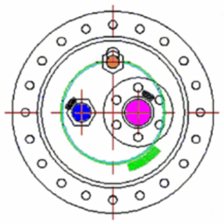
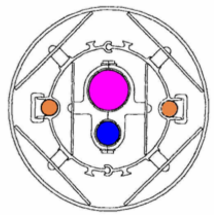
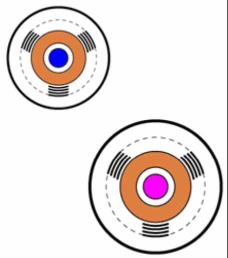


Rott's Diagram



$\nu_c = \frac{\mu_c}{\rho_{m,c}}$ the kinematic viscosity of helium gas at cold $\qquad r_0$ = tube radius

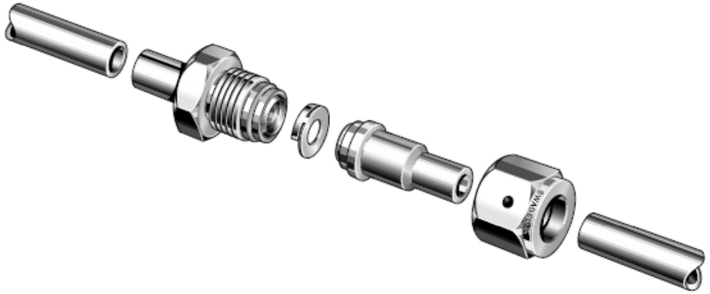
Cryogenic Piping

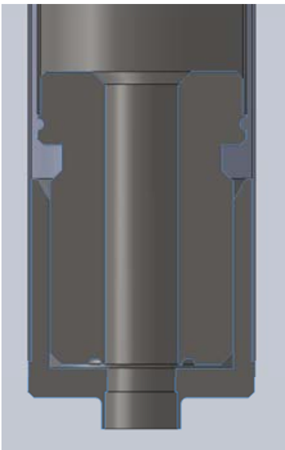
	NSRRC (DeMaCo)	KEK (KEK)	CERN & BESSY (Nexan)
			
diameter: LHe pipe	17.27 mm	17.3 mm	21/25 mm
diameter: GHe pipe	29.97 mm	34.0 mm	39/44 mm
Heat loss	0.3 W/m (69W for 230m)	0.05 W/m (11.5W for 230m)	0.06 W/m (13.8W for 230m)
Cost	6500 EUR/m	cheap	1900 EUR/m

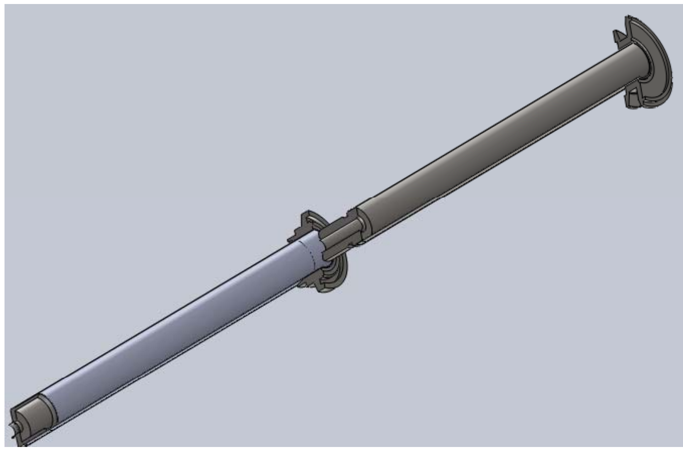
Flexible transfer lines delivered to NSRRC and the supporting frame to unroll these lines.

Cryogenic Pipe Connection

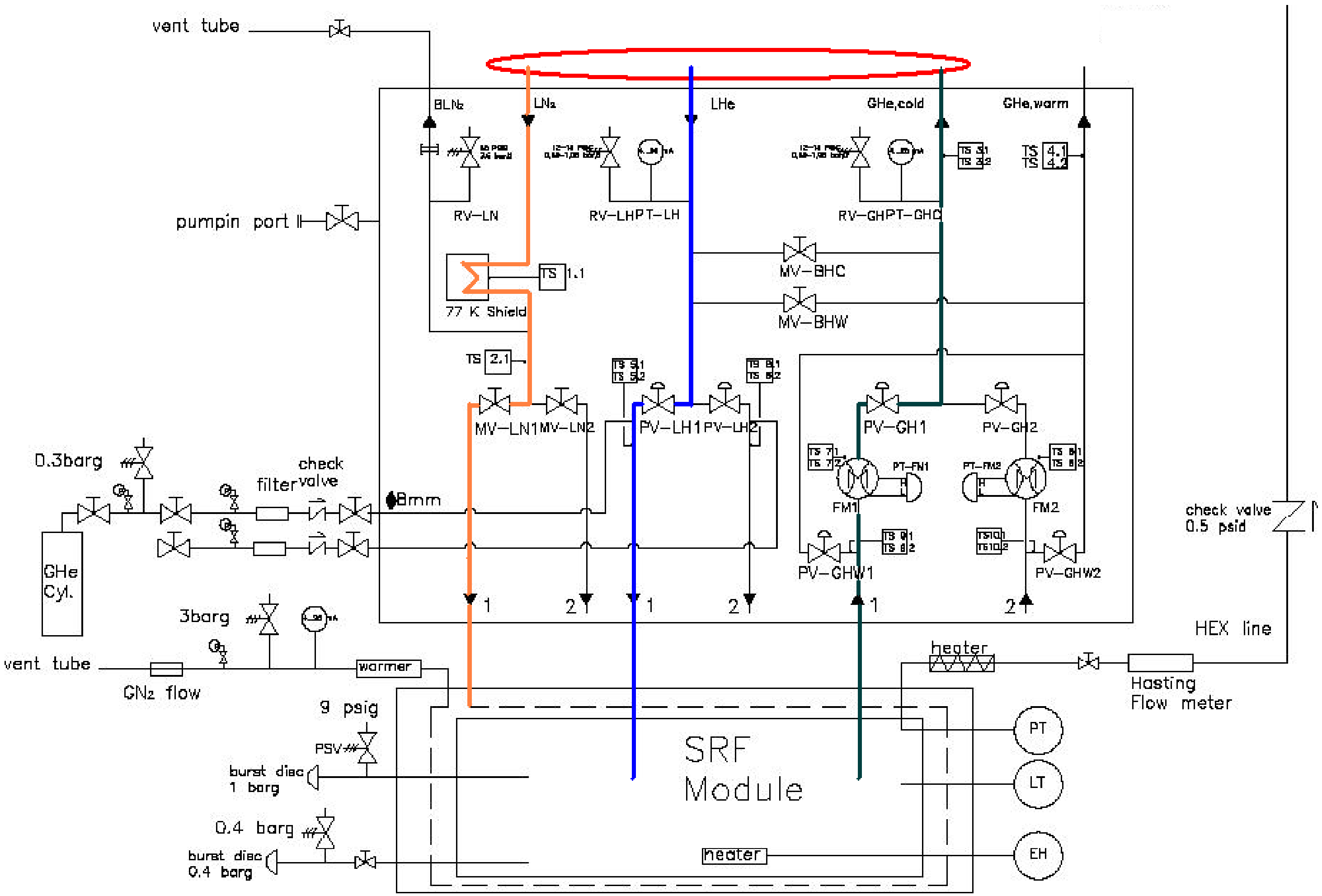
- Swagelok VCR connection
- CF flange gasket
- Bayonet connection





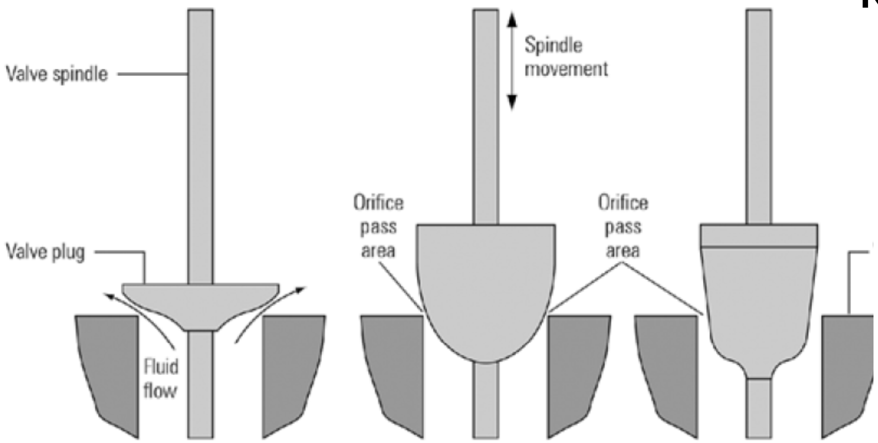


Cryogenic Valve Box



Cryogenic Valve

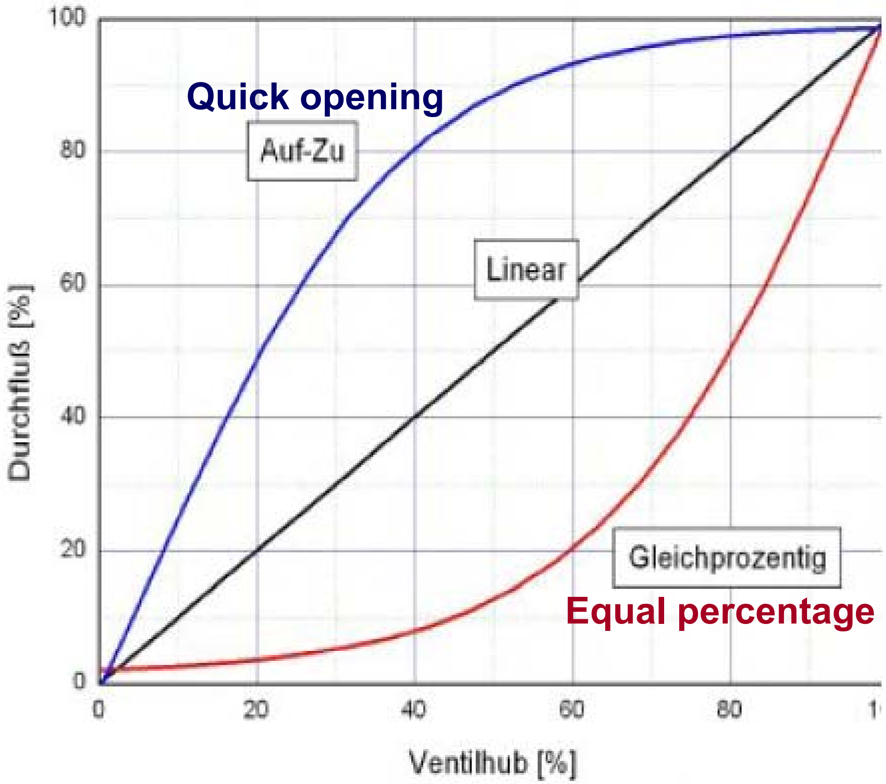
Shape of the Trim Determines the Valve Characteristic



Quick opening | Linear | Equal percent

Linear	$C_v / C_{v,max} = \ell$
Quick opening:	$C_v / C_{v,max} = \ell^{1/\alpha}$, $\alpha >$
Equal percentage:	$C_v / C_{v,max} = R^{\ell-1}$

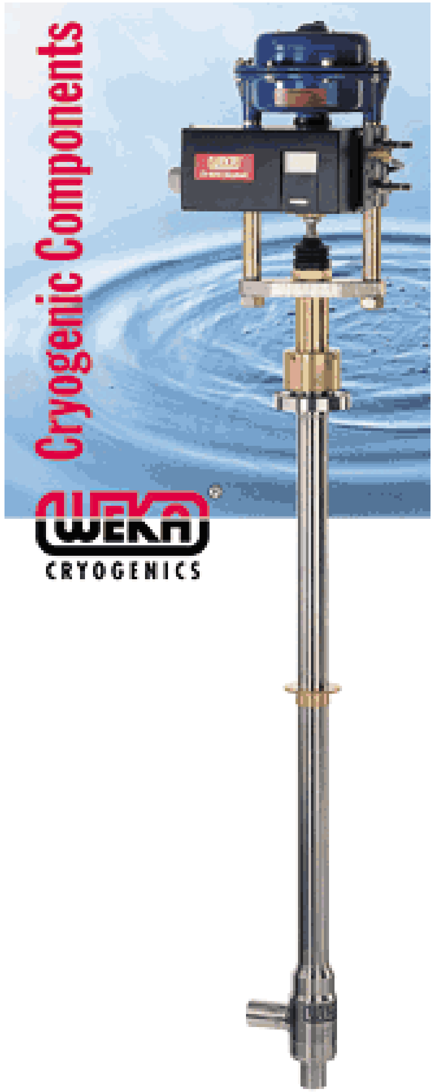
Relative valve flow coefficient [%]



Relative valve travel [%]

Equal-Percentage Cryogenic Valve

Valve Coefficient Kv and Rangeability R Determines the Valve Characteristic.



a) Liquid Service:

aa) with Q in m^3 / h

$$Kv = Q * \sqrt{\frac{\rho}{1000 * \Delta p}}$$

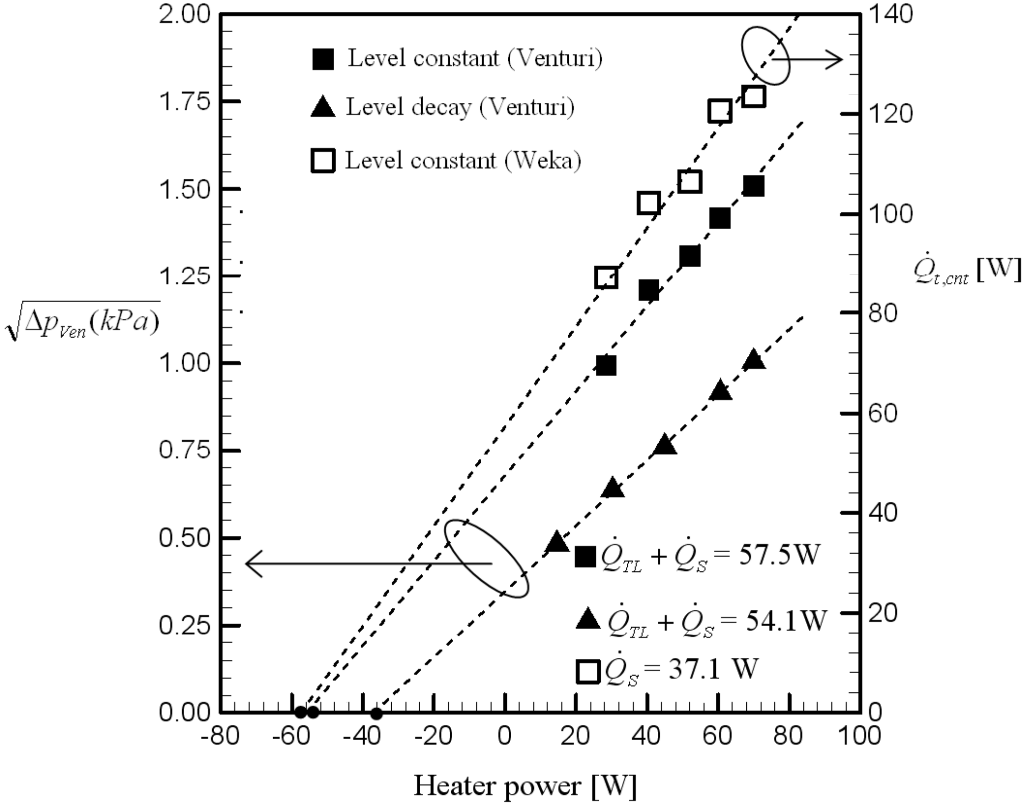
$$\dot{V}_t = 519 K_{v,\max} R^{(l-1)} \sqrt{\frac{\Delta p_{val} \cdot P_2}{\rho_g \cdot T_1}}$$

b) Gas Service:

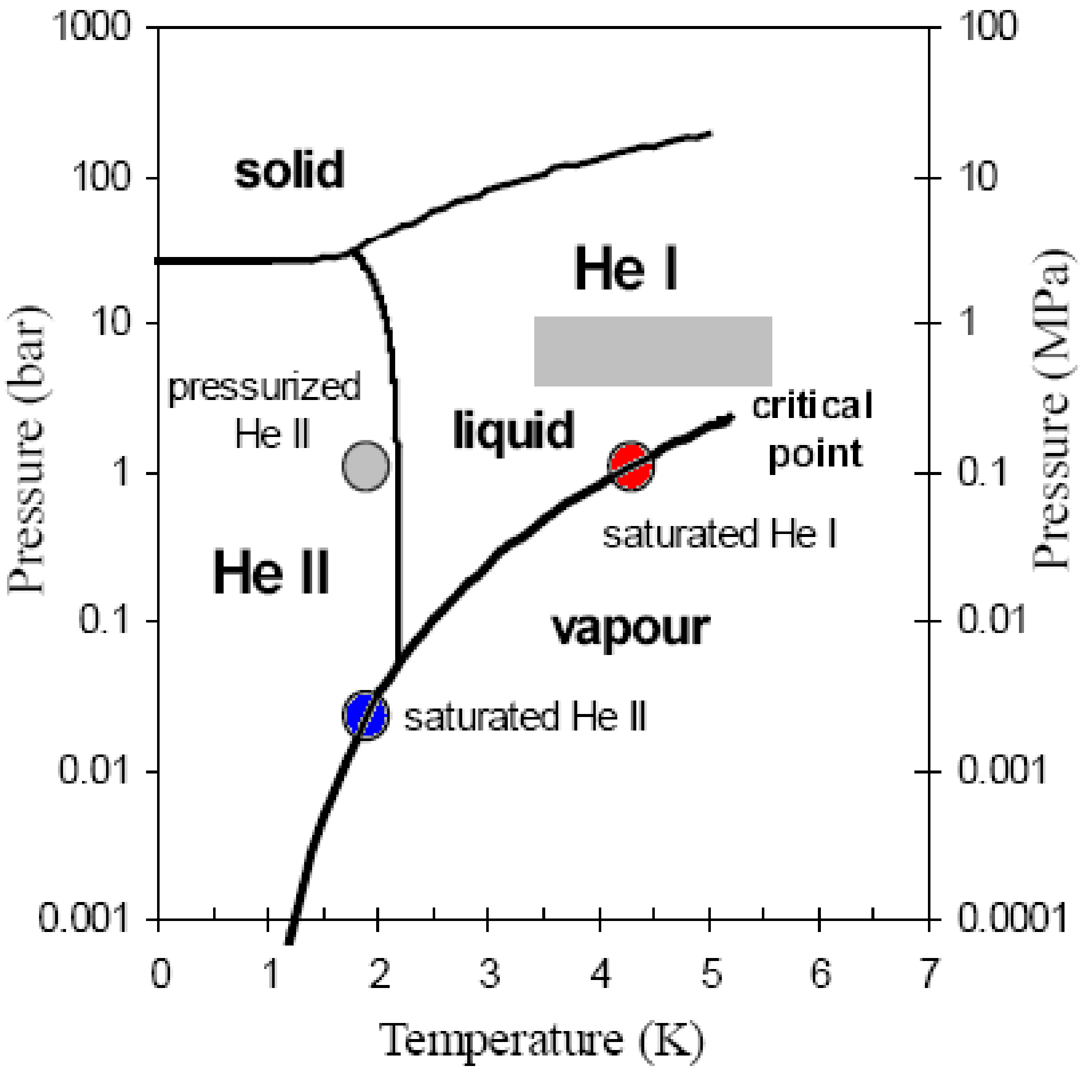
ba) sub-critical flow i.e. $p_2 > p_1/2$ and $\Delta p < p_1/2$

baa) with Q in m^3 / h

$$Kv = \frac{Q_G}{519} * \sqrt{\frac{\rho_G \cdot T_1}{\Delta p * p_2}}$$



Working Point of Cryogenic Plant

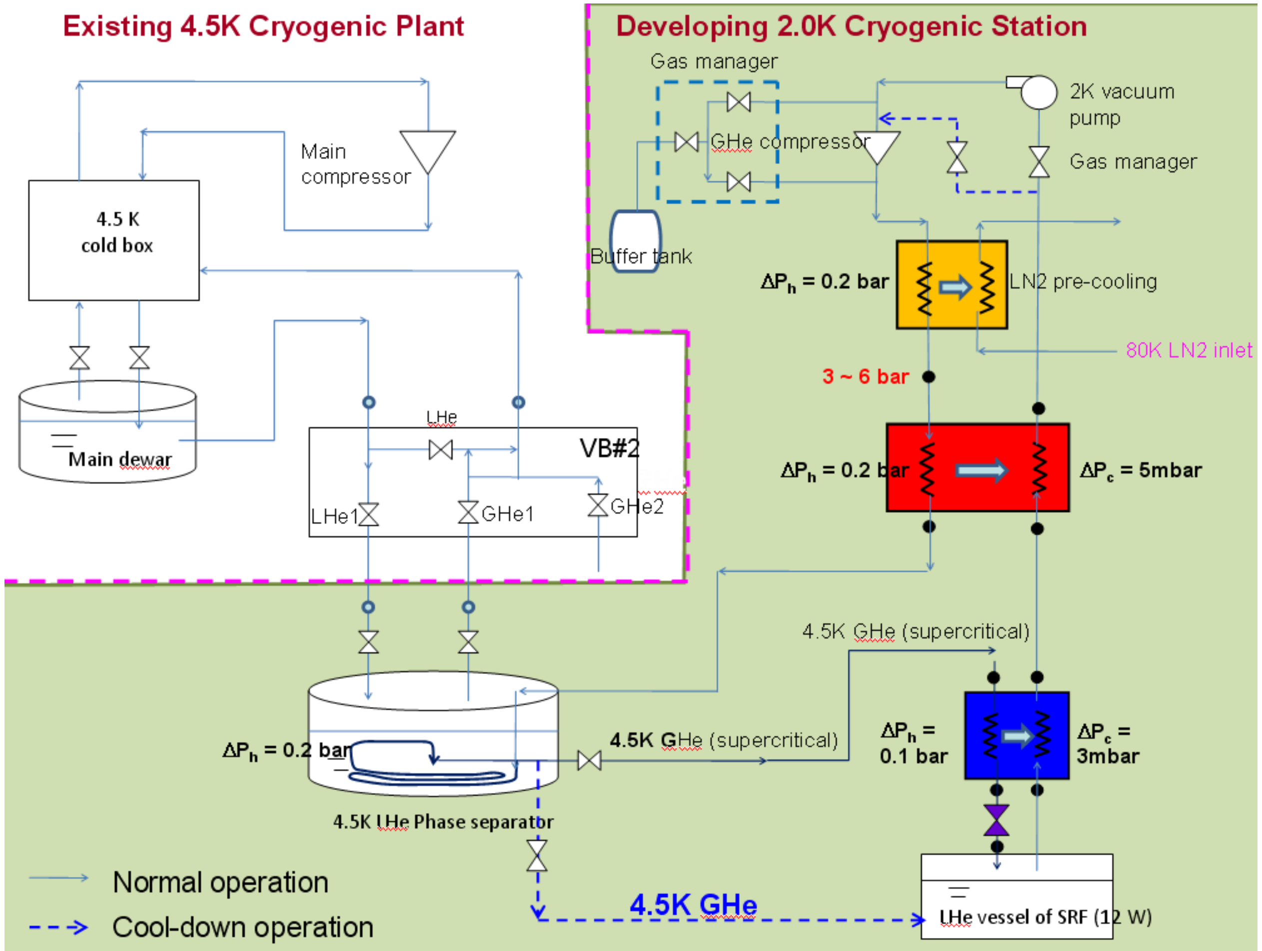


當飽合態的氦的溫度由4.2K下降到2.17K的溫度時，液氦表現出超流體的特性有，很好的導熱性。
這時液氦不再沸騰，
液面變的非常平靜。

Onnes應該在他的實驗當中多次看到了超流體的特性但是Onnes沒有認出超流體來，否則**Onnes**可能又會得到另一個諾貝爾獎。

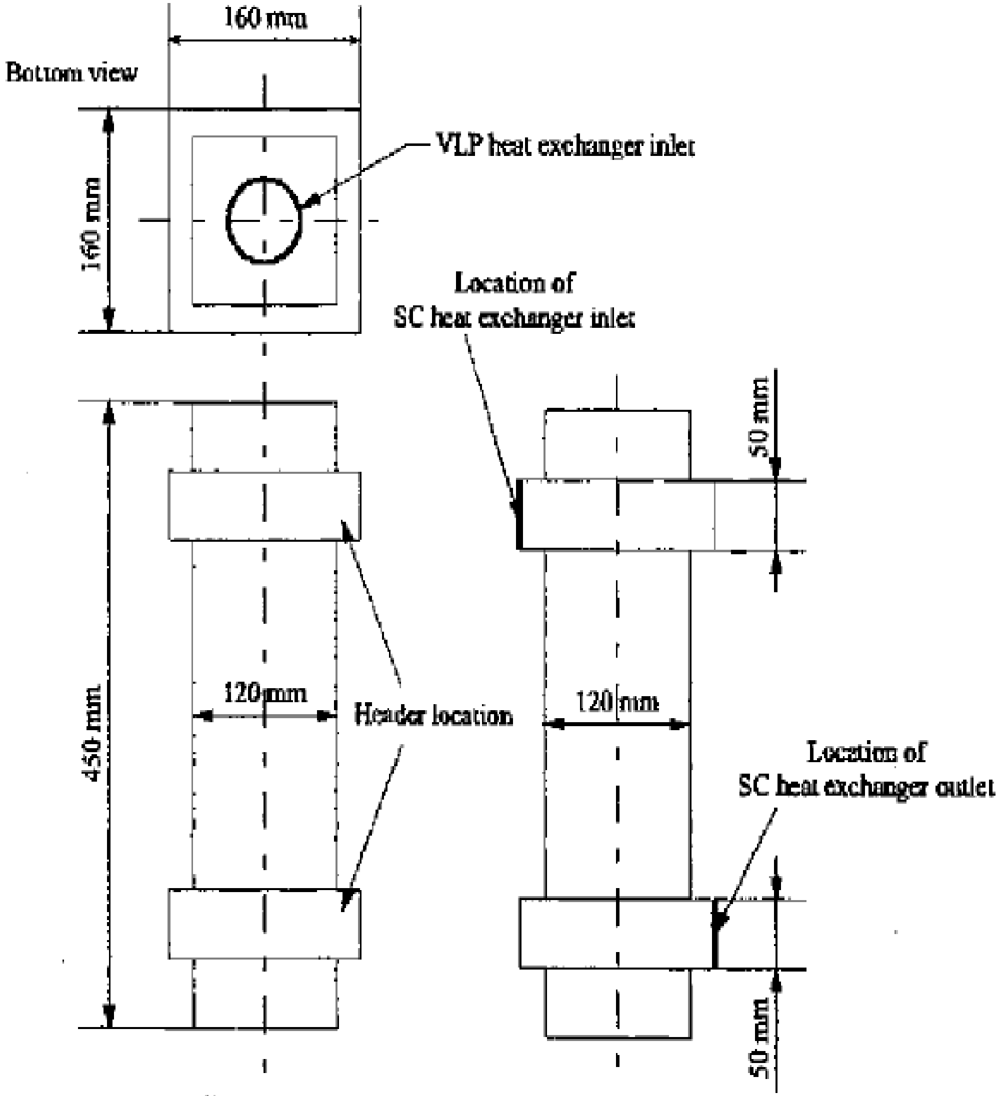
Kapitsa等人在1937年
發現液氦可以變成超流體。

Possible 2K Scheme

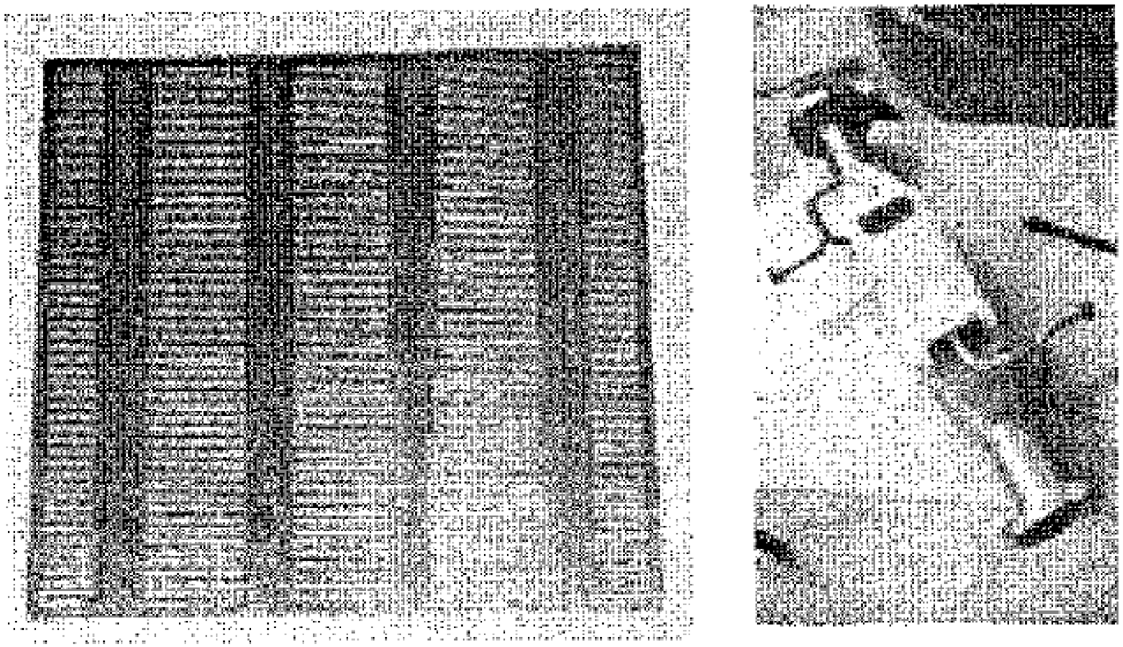


- Use the available cryogenic capacity of the existing cryo-plant.
- Use vacuum pump instead of cold compressor because of small mass flow rate (~1 g/sec).
- Avoid the impurity contamination from the low-pressure helium vacuum pumping system.
- Reduce the equivalent cryogenic loss at 4.5K significantly by recovering the cold capacity from the low pressure stream using warm heat exchanger.

2 K Heat Exchanger for LHC/CERN: Coiled Tube Design (ROMABAU)



2 K Heat Exchanger for LHC/CERN: Perforated Design (SNLS)



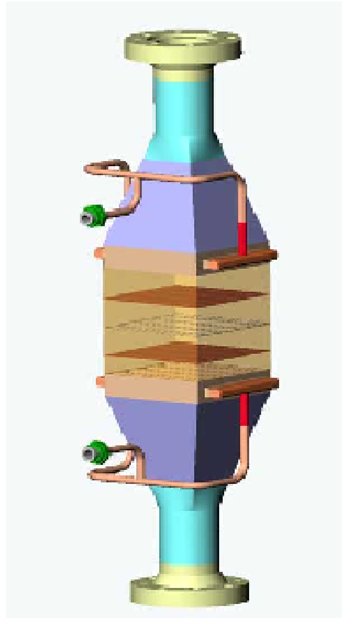


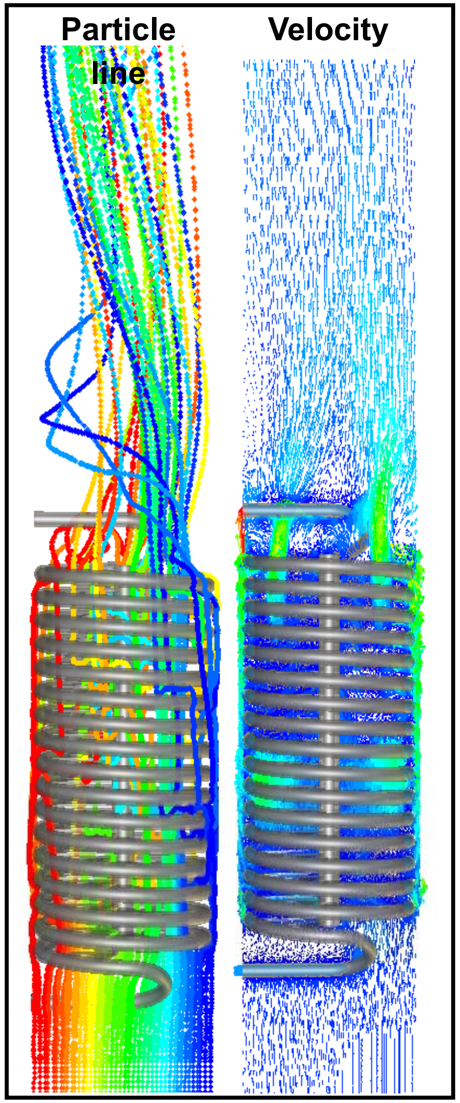
FIGURE 4. SNLS perforated copper plate with holes (SC channels) and slots (VLP channels), and completed heat exchanger.

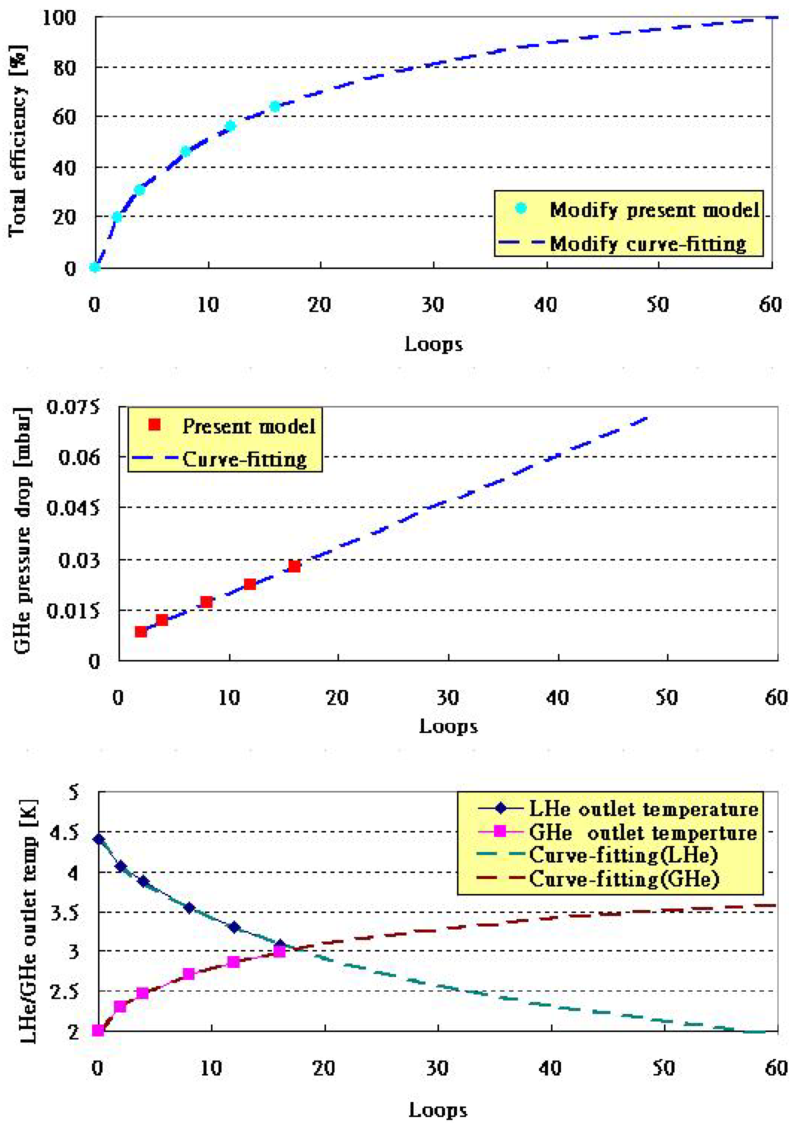
PERFORMANCE TESTS OF INDUSTRIAL PROTOTYPE SUBCOOLING HELIUM HEAT EXCHANGERS FOR THE LARGE HADRON COLLIDER

P. Roussel[1], A. Bézaguet[2], H. Bieri[3], R. Devidal[4], B. Jager[1], R. Moracchioli[5], P. Seyfert[1] & L. Tavian[2].

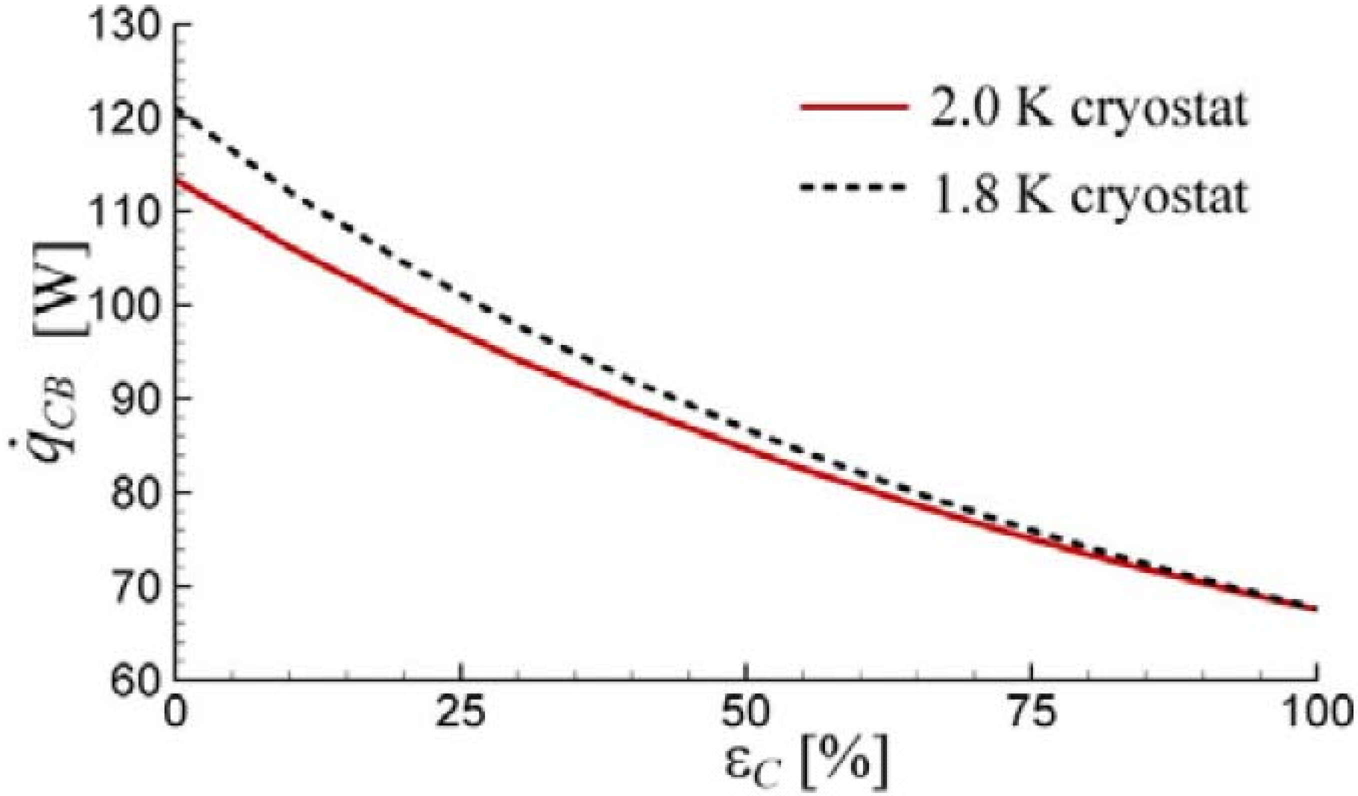
Fluent Simulation for 2K Heat Exchanger

Design by K. Hosoyama (KEK)





Efficiency of Cold Heat Exchanger



Equivalent cryogenic loading on the 4.5K cryo-plant at NSRRC for a cryogenic load of 12W at 2K (1.8K) as function of efficiency of cold HEX.

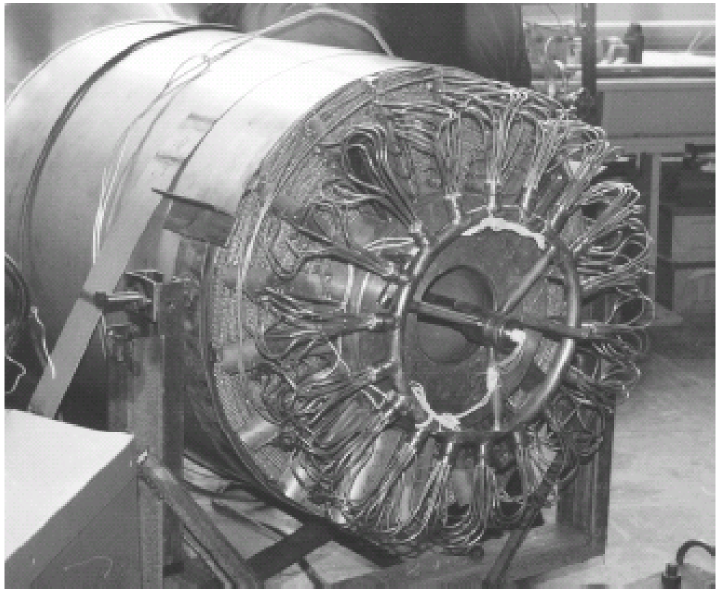
Warm Heat Exchanger for 2K Operation (FLASH Linac at DESY)

External low pressure heat exchanger (IHEP,Russia)

counter-flow heat exchanger:

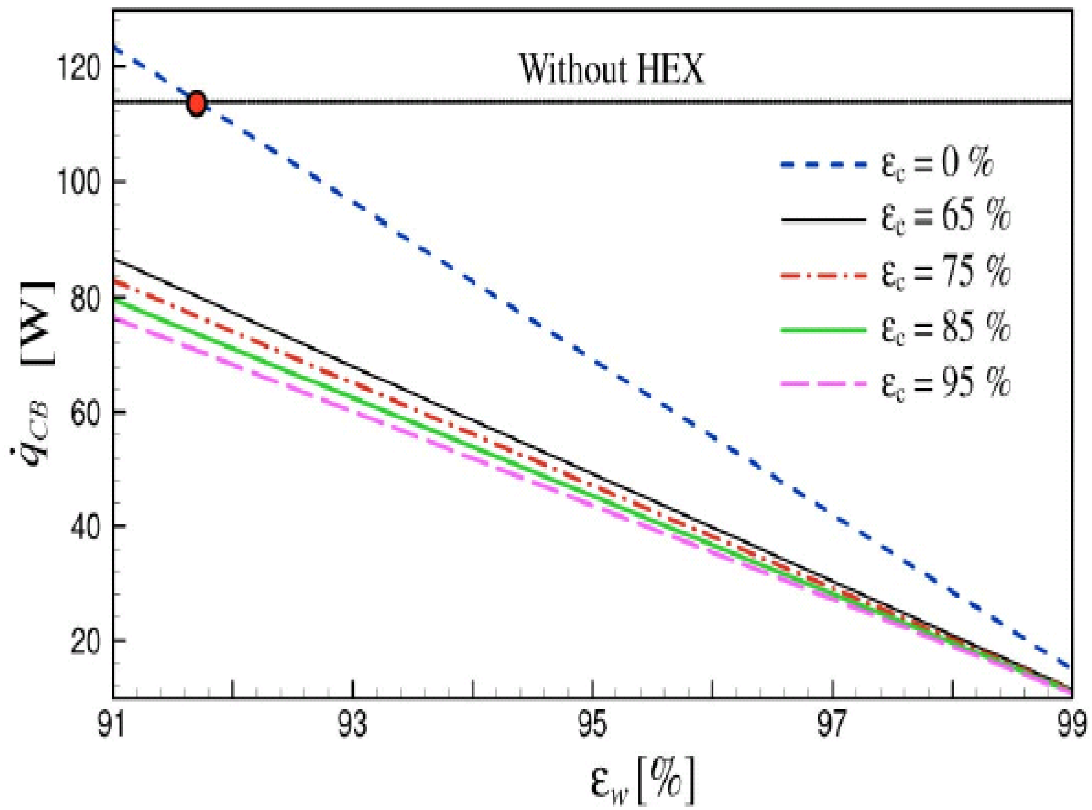
3,5 K / 31 mbar -> 280 K / 29 mbar

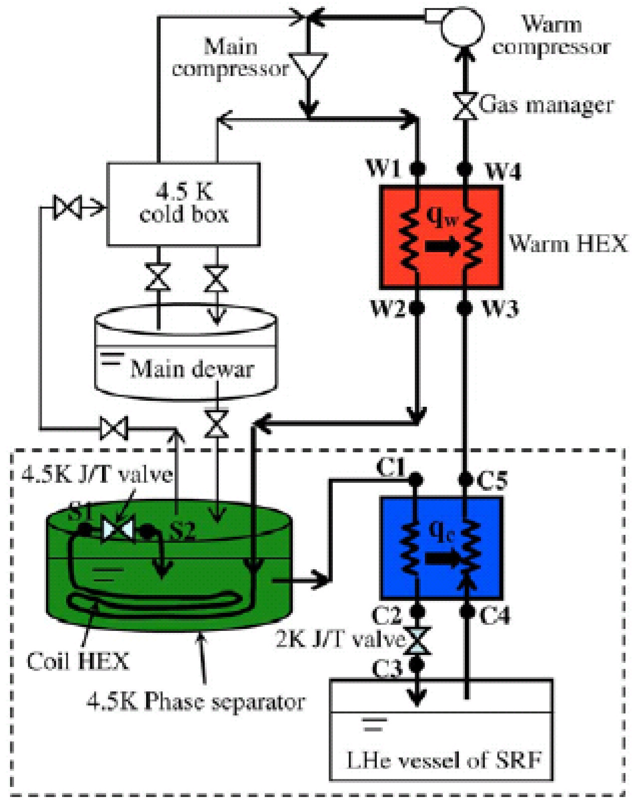
7,5 K / 12 bar <- 300 K / 12 bar



(Courtesy of B. Petersen)

Efficiency of Warm Heat Exchanger





Equivalent cryogenic loading on the 4.5K cryo-plant at NSRRC for a cryogenic load of 12W at 2K (1.8K) as function of efficiency of cold and warm HEX. Note that the efficiency of warm HEX must be very high (The warm HEX for TTF is 97%). Otherwise, it brings disadvantage.

Cold Compressor (> 100W @ 2 K) or Warm Vacuum Pump

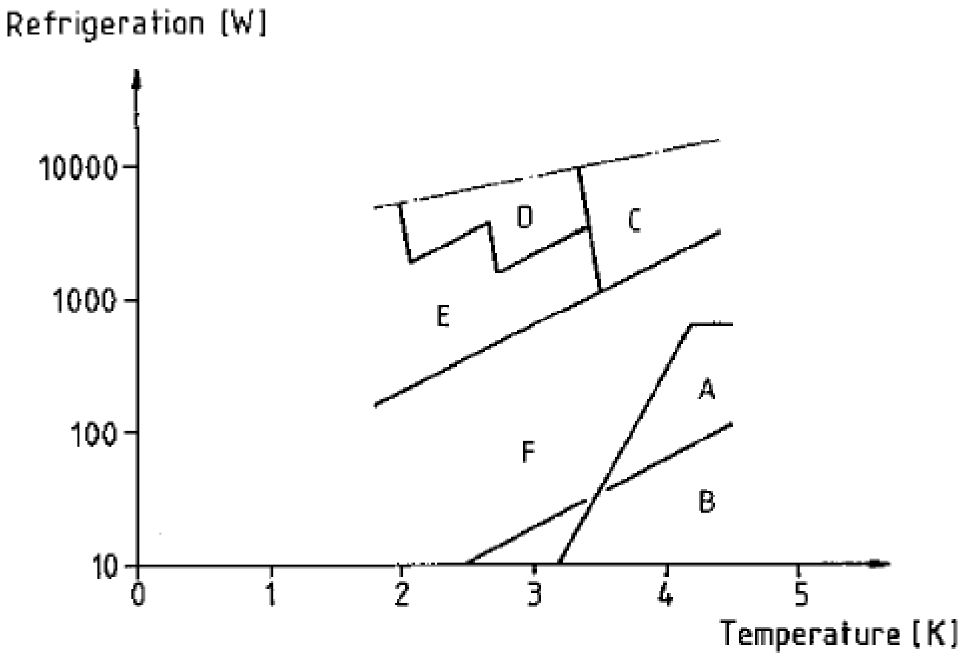


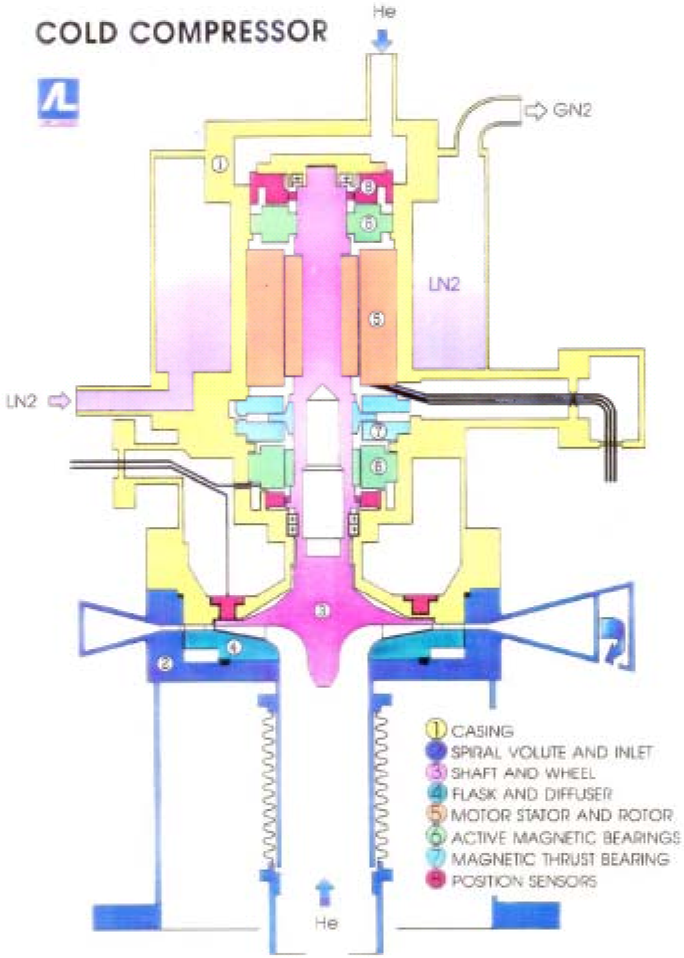
Fig. 3

Range of application of different types of cold compressors

A: Ejector
B: Piston compressor
C: Turbo compressor one stage to 1.2 bar
D: Turbo compressor multi stage to 1.2 bar
E: Turbo compressor last stage to below 1.2 bar
F: No cold compressor

H. Quack, "Cryogenic System for Large Research Projects", IEEE Trans. On Appl. Super., Vol. 12, p. 1355 (2002); H. Quack, "Cold Compression of Helium Refrigeration below 4 K", Adv. Cryog. Eng. Vol. 33, p. 647.

Cold Compressor

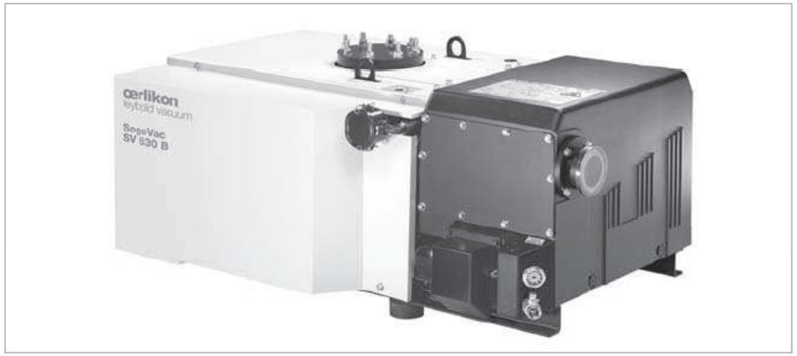


Example of a cold compressor with active magnetic bearings used at Tore Supra, CEBAF and Oak Ridge

Source: Air Liquide

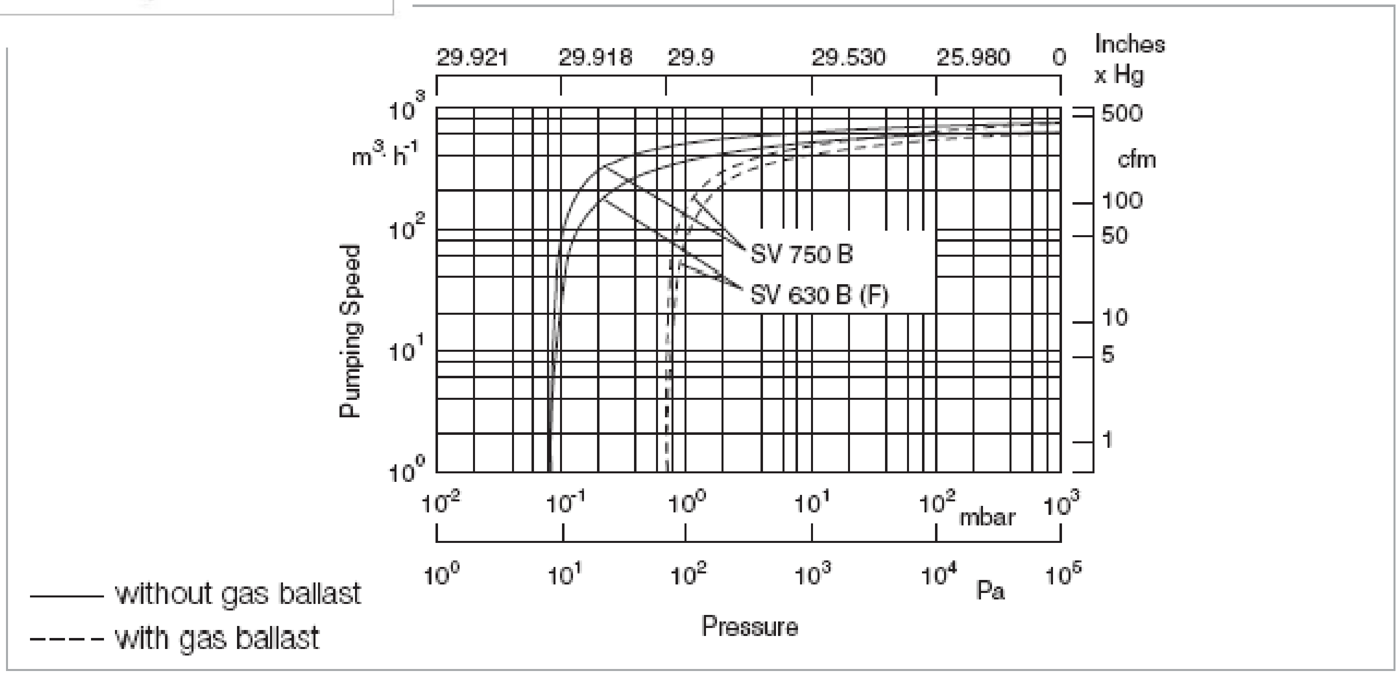
Vacuum Pump for Helium

-工作溫度只差0.2K，vacuum pump的尺寸差很多!



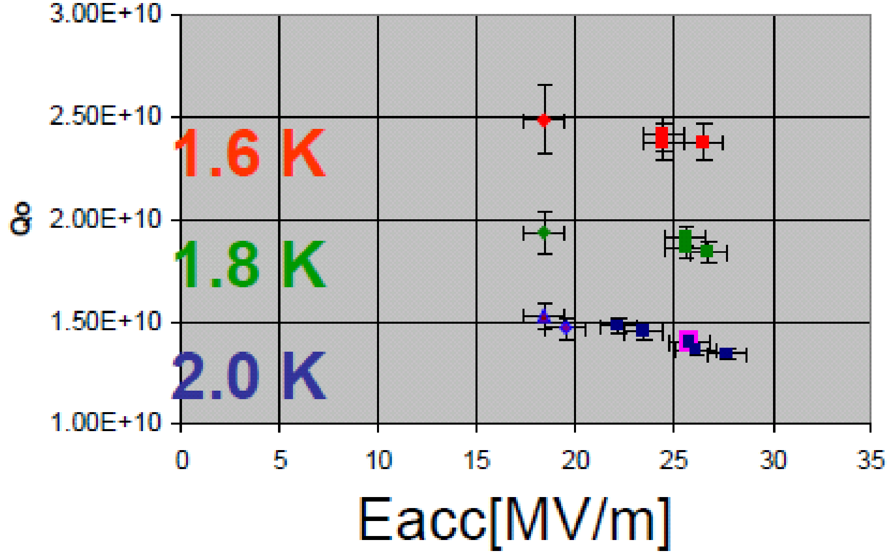
SOGEVAC SV 630 B

- 2.0K: 31 mbar
- 1.8K: 16 mbar

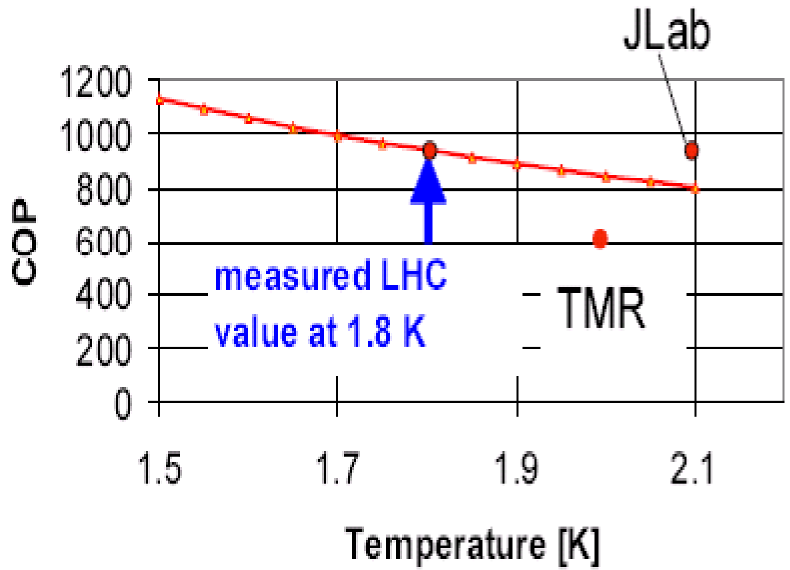


Pumping speed characteristics of the SOGEVAC SV 630 B(F)
(60 Hz curves at the end of the section)

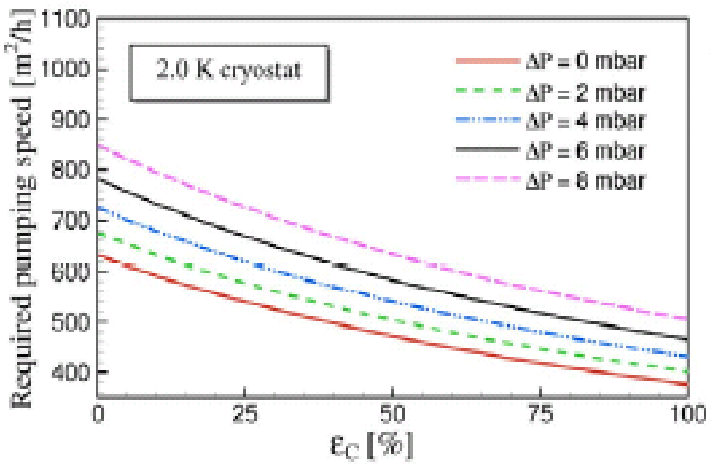
1.8K(16 mbar) or 2K (31 mbar)?

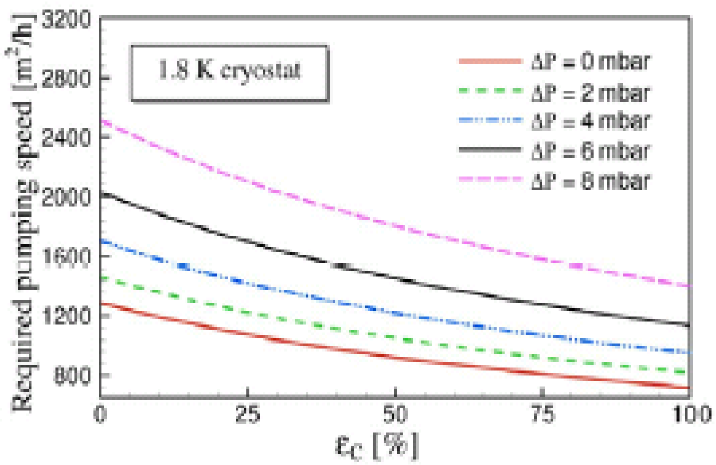


(Courtesy of R.Lange et al. DESY MKS)



ERL2005 Bernd Petersen DESY





Outlines

- Historical Remark
- Basic of Superconducting RF
- SRF Performance: Achievement and Challenge
- Cryogenic Plant for SRF Operation

- SRF Operation and Maintenance

SRF Operation: Many trips…

- Roughly 50% of machine trips of light source cause by RF operation;
- Machine trip rate may be even higher after using SRF modules.
- The recovery time is usually very short – just push the reset bottom.
- Or, it will cause a long downtime.
  - RT cavity: one week for the worst case;
  - SRF module: at least one month (using spare module).

SRF Operation: Many trips…

-Machine Operation of TLS w/ SRF Module

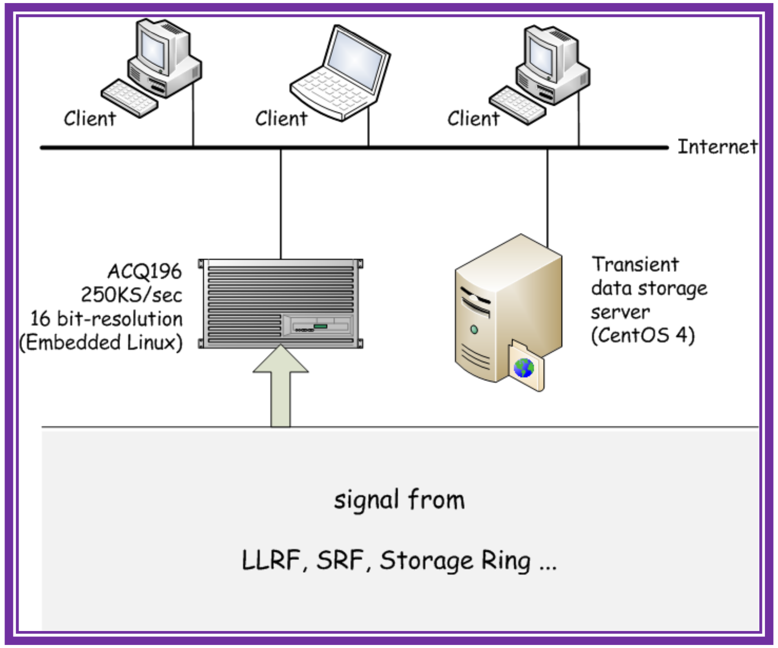
2008		Number of beam trip		Accumulated downtime	
Sag/Falling of AC line voltages		5	(9.8%)	21.08Hr	(31.8%/17.6%)
SRF (43.1% of beam trips, 22.7% of down time due to beam trip)	RF transmitter	5	(9.8%)	4.0Hr	(6.0%/3.3%)
	EMI (false arcing)	6	(11.8%)	3.08Hr	(4.7%/2.6%)
	AC power station	1	(2.0%)	1.85Hr	(2.8%/1.5%)
	Mechanical vibrations	2	(3.9%)	1.17Hr	(1.8%/1.0%)
	Insulation vacuum	3	(5.9%)	2.08Hr	(3.1%/1.7%)
	unknown	5	(9.8%)	2.83Hr	(4.3%/2.4%)
Power suppler		7	(13.7%)	12.88Hr	(19.4%/10.7%)
Vacuum/front end		1	(2.0%)	0.98Hr	(1.5%/0.8%)
feedback systems (GFB, TFB, ebpm)		4	(7.8%)	5.17Hr	(7.8%/4.3%)
Unknown partial beam loss		8	(15.7%)	7.60Hr	(11.5%/6.3%)
Kicker		3	(5.9%)	1.85Hr	(2.8%/1.5%)
Others (simulated earthquake)		1	(2.0%)	1.67Hr	(2.5%/1.4%)
		Total of 51		Total of 70 Hr	(100%/55%)

At TLS in 2008, about 50% of (22 of 51) unscheduled beam dumps is caused by the trips of RF system.

SRF Diagnostic System

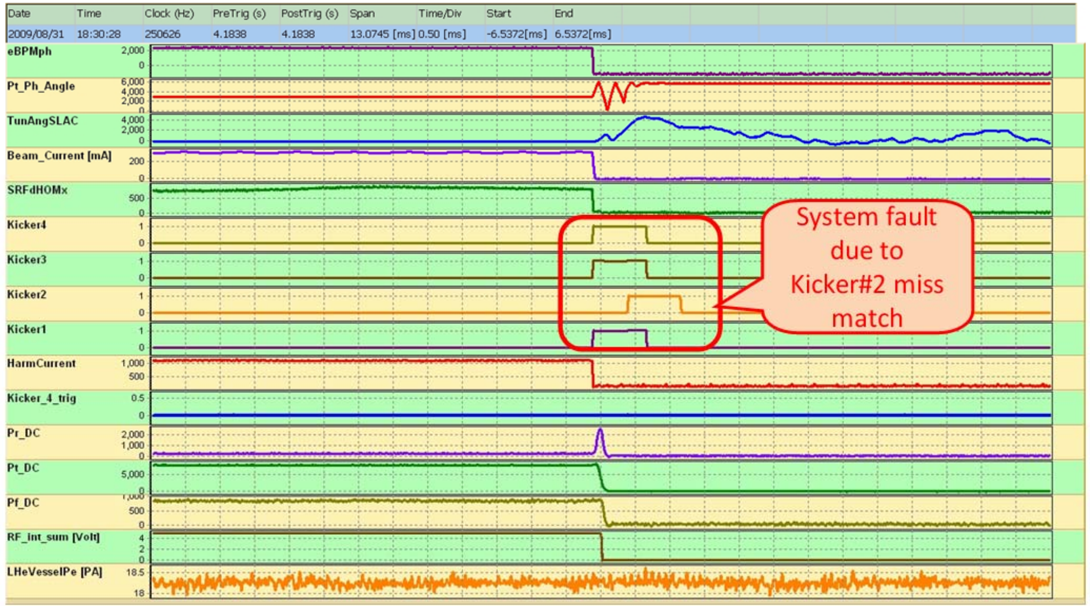
- A short Cut to Improve the Reliability of SRF Operation

- More Channels (96#), Higher Sampling Rate (250 kHz), Support EPICS

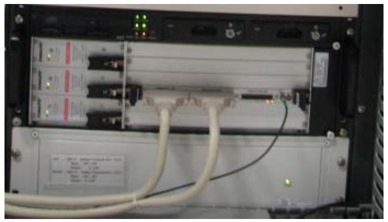


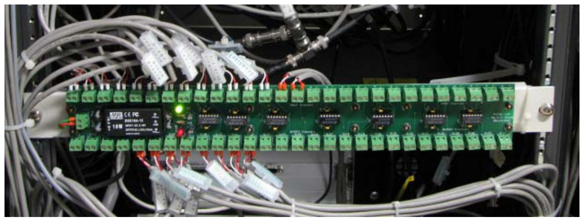
Commercially available hardware

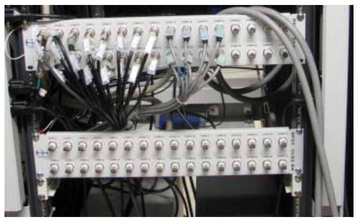
A trip event at 18:28 2009/08/31 (MON)



Home-developed software

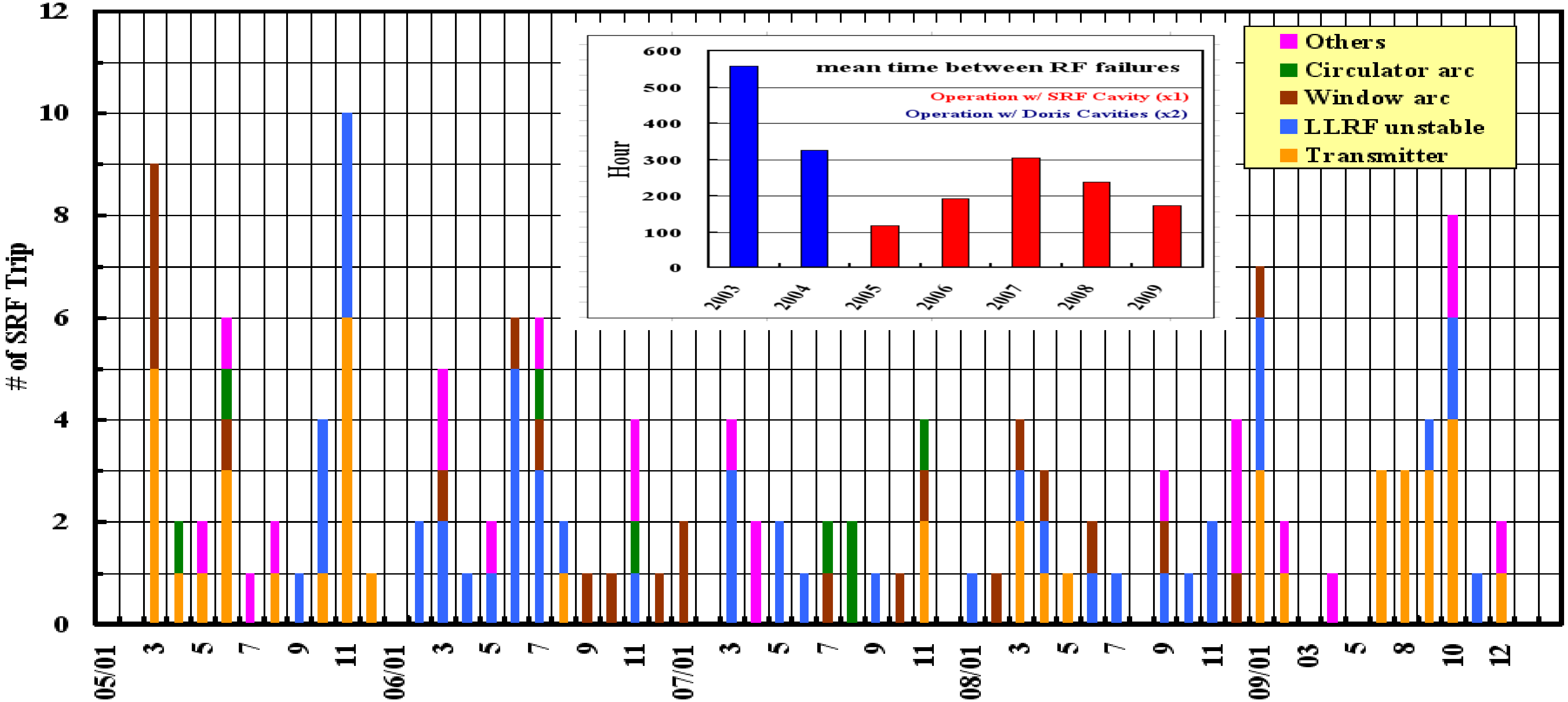






Operation Statistics of TLS

	Year	User Time			Opertion Mode	0.2% Merit of I0 Stability (%) ($\Delta I_0/I_0$<0.2%)
		Scheduled Annual User Time (hr)	Up-time (%)	MTBF (hr)		
TLS	2002	4785	95.8%*	154.4	Decay Mode	47%
	2003	5017	97.2%*	313.6	Decay Mode	86%
	2004	4235	97.5%*	69.4	Decay Mode	85%
	2005	4576	96.8%*	83.2	Top-up Mode(3/12)/SRF	76%
	2006	5552	96.7%*	40.8	Top-up Mode/SRF	98.1%(81.3% of $\Delta I_0/I_0$<0.1%)
	2007	5219	98.1%*	85.6	Top-up Mode/SRF	98.6%(39.9% of $\Delta I_0/I_0$<0.1%)
	2008	5726	97.9%	112.3	Top-up Mode/SRF	98.6%(95.7% of $\Delta I_0/I_0$<0.1%)
	2009	5358	98.2%	78.8	Top-up Mode/SRF	99.3%(88.8% of $\Delta I_0/I_0$<0.1%)



SRF Maintenance

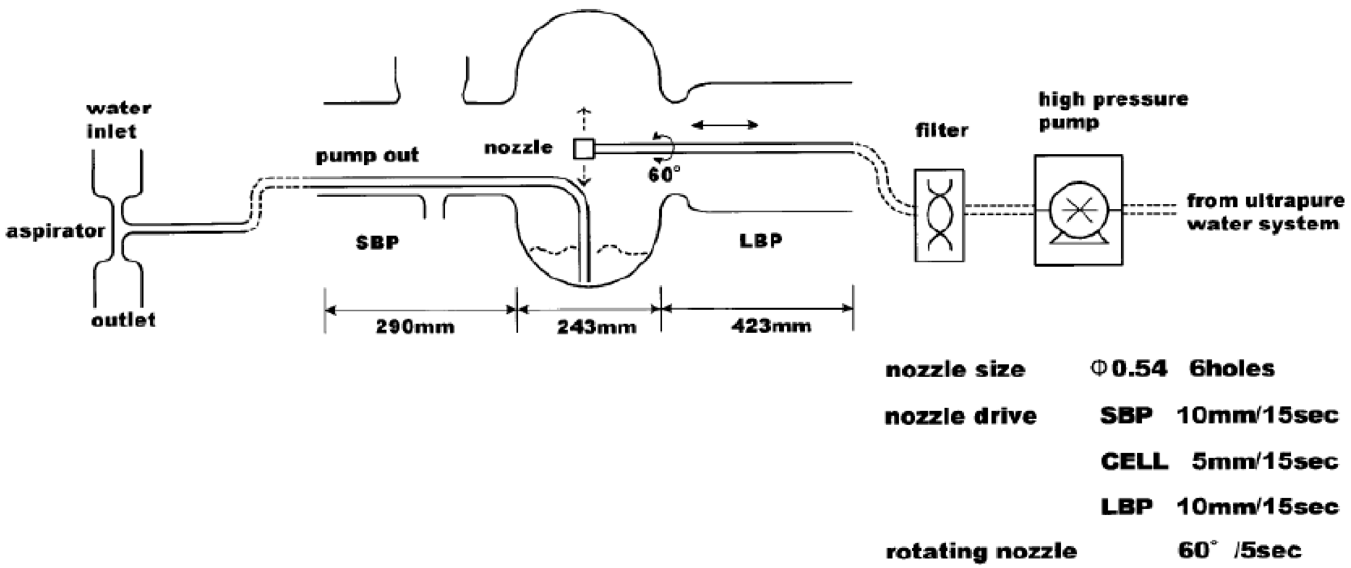
- Nothing can be done…
- Most busiest group when the cryogenic plant needs to maintain…
  - Warm-up/cool down of SRF module before/after maintenance of cryogenic plant;

About 50% of Operating 500-MHz SRF Modules Got Leak…

- Where?
  - from helium volume into cavity vacuum
  - from helium volume into insulation vacuum
  - from ambient into insulation vacuum
- Small leak
  - pump down periodically or continuously
- Big leak
  - re-tighten part of indium sealing
  - re-assemble everything

What Happens after Vacuum Accident?

- Re-assemble everything (half to one year!)
- In-situ high-pressure rinsing



HORIZONTAL HIGH PRESSURE WATER RINSING FOR KEKB SUPERCONDUCTING CAVITY

Proceedings of SRF2009, Berlin, Germany

(S. Mitsunobu, KEKB)

Better SRF Performance after Cryostat Assembly

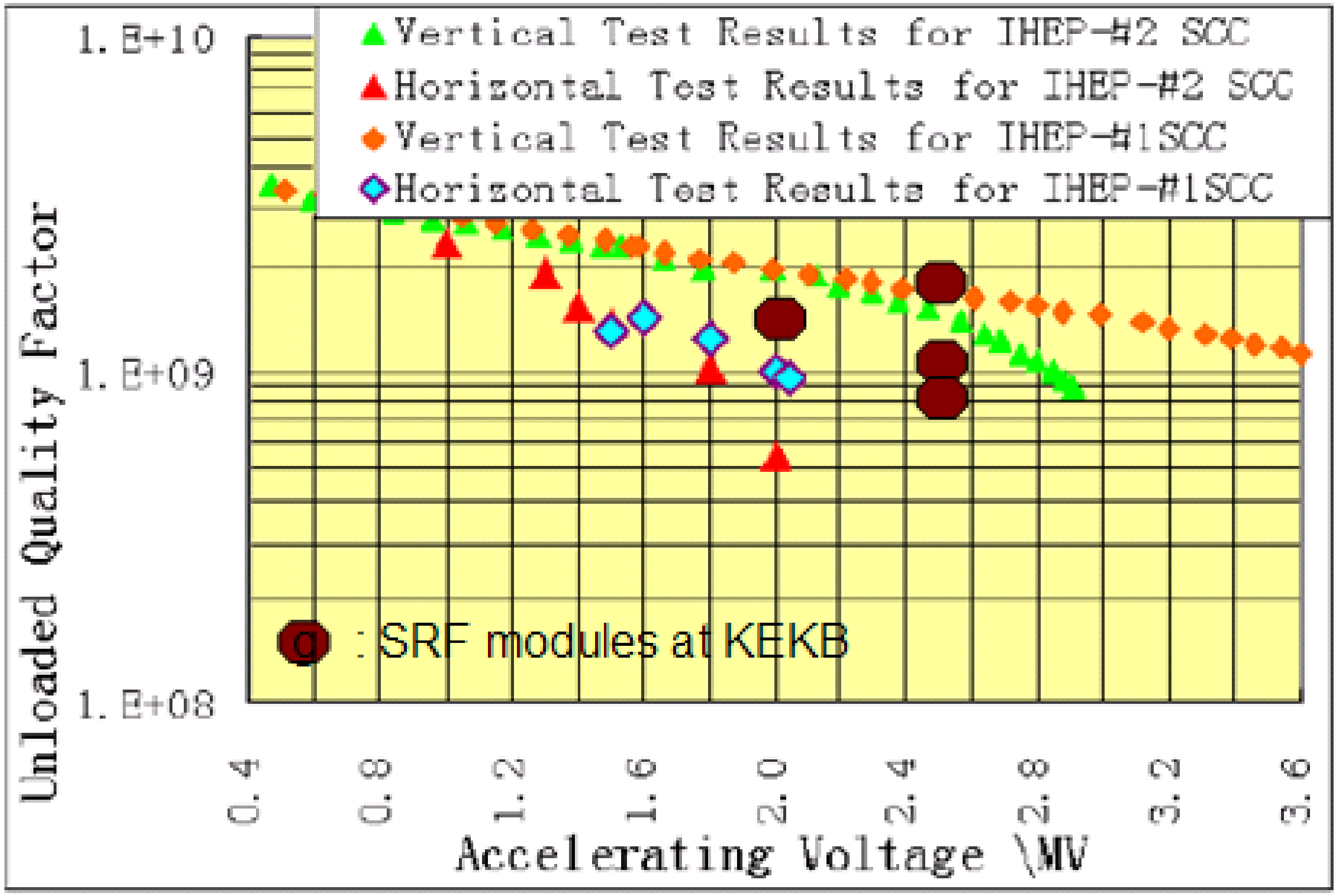
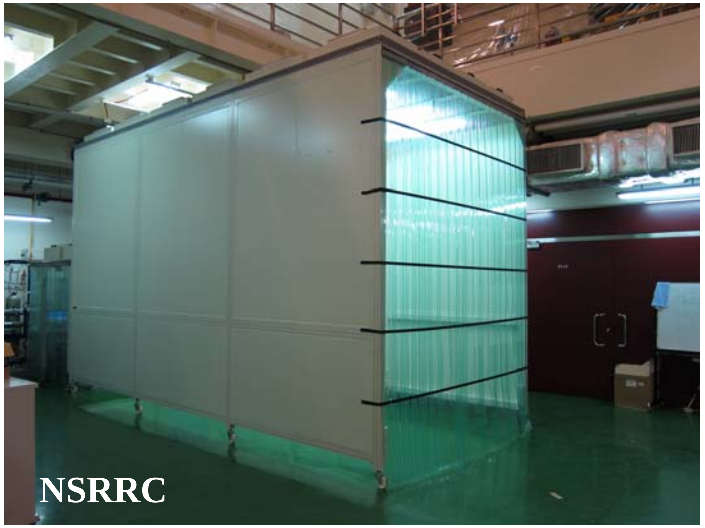


Chart 1: Unloaded quality factor vs. accelerating voltage.

(Y. Sun et al.)

High-Pressure Rinsing & Clean-Room Operation

- Infrastructure:
  - ✓ Class 10 cleanroom
  - ✓ Ultrapure water system
    - 17.5~18.2 MOhm-cm
      - 18.5 MOhm-cm at DESY
    - 50 counts/l (0.2um) at NSRRC
      - 25 counts/l (0,2 um) at DESY
    - TOC of 11 ppb at NSRRC
      - < 3 ppb at DESY
  - Ultrasonic rinsing system
    - Water circulation with fine filter;
    - Operation within clean–room;
    - Foil test after usage.
  - High pressure rinsing system
    - Horizontal design
    - Vertical design
    - Water particle measurements



Further Reading

- H. Padamsee et al., RF Superconductivity for Accelerators, John Wiley & Sons, Inc.
- H. Padamsee, RF Suuperconductivity: Science, Technology and Applications, John Wiley & Sons, Inc.

Questions:

1. Why the superconductor has a non-zero rf resistance?
2. What is the difference between the superconductor and the perfect conductor (w/ infinitive conductivity)?
3. What are the challenges of applying SRF technology to light sources nowadays?
   a) from high beam power point of view;
   b) from high rf gap voltage point of view;