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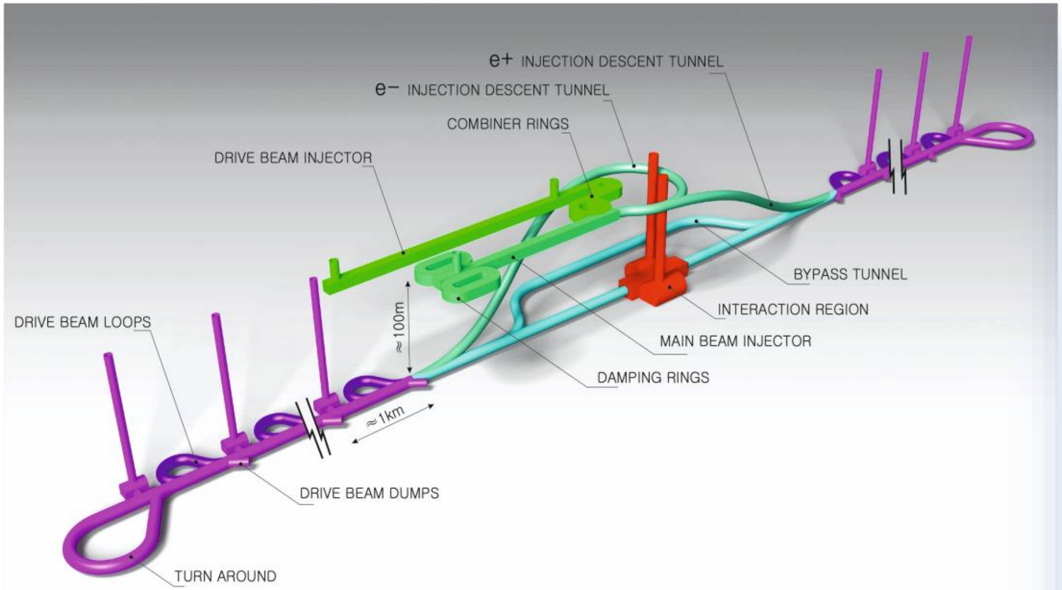
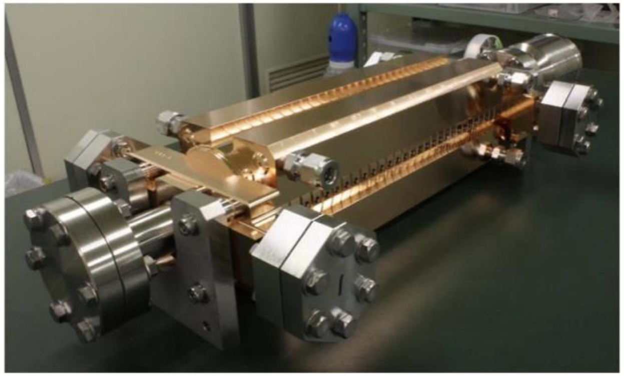
Surface heating in HTS-based high field pulsed RF cavities

Sergio Calatroni

CERN

The European Strategy for Particle Physics : Linear Colliders are within the high-priority future initiatives





The CERN-CLIC accelerator studies, started in the late '80, are now mature:

- **Optimised design for cost and power**
- **Technical developments of most key elements**

To reach the goal of 250Gev energy, the accelerating cavities will operate in very high rf power (100MV/m or more accelerating field). Copper cavities operating at room temperature are presently considered. Pulsing with low duty factor allows reducing the average consumption for NC copper accelerating cavities down to the SC level.

Cooling at 77K is considered to increase Q and reduce fatigue by thermally induced stress.

A factor 10÷20 improvement in Q factor using HTS in place of copper at 77K would end up in a significant energy saving.

A wide international collaboration has been established to study and verify whether, at 77K, a HTS layer set on NC Cu operating in pulsed RF mode can allow a further power consumption reduction.

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

EXCELENCIA SEVERO OCHOA

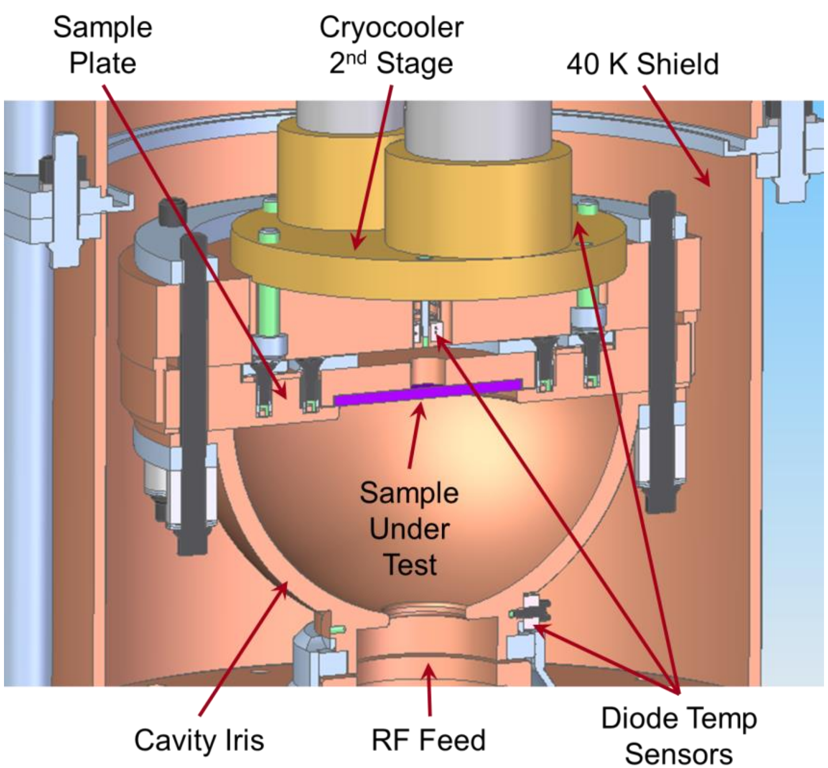
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

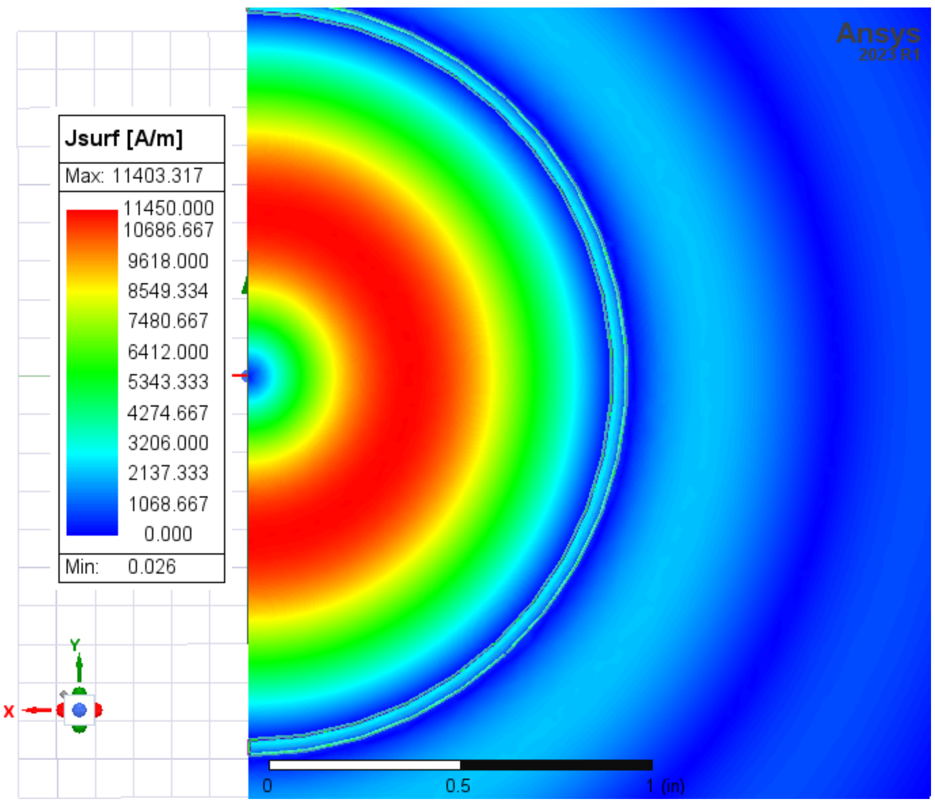
KIT Campus TRANSFER

The goal is to demonstrate high-gradient pulsed operation of HTS at cryo-temperatures.

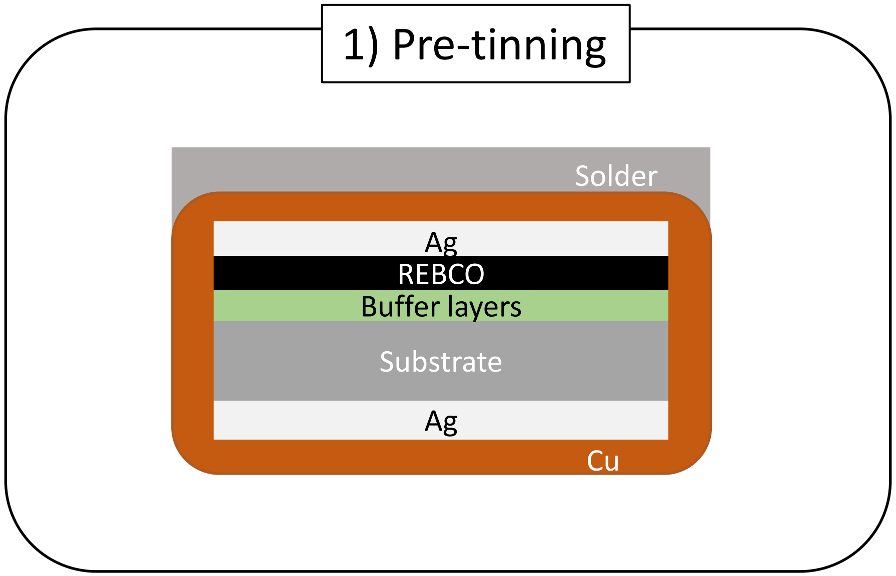
At SLAC a test facility based on a 11.5GHz “mushroom” cavity is available that can produce a maximum B_{rf} of about $350mT$ (H_{rf}~ 280KA/m, corresponding to E_{rf}~100MV/m for a plane wave and E_{acc}~80MV/m for standard electron cavities)

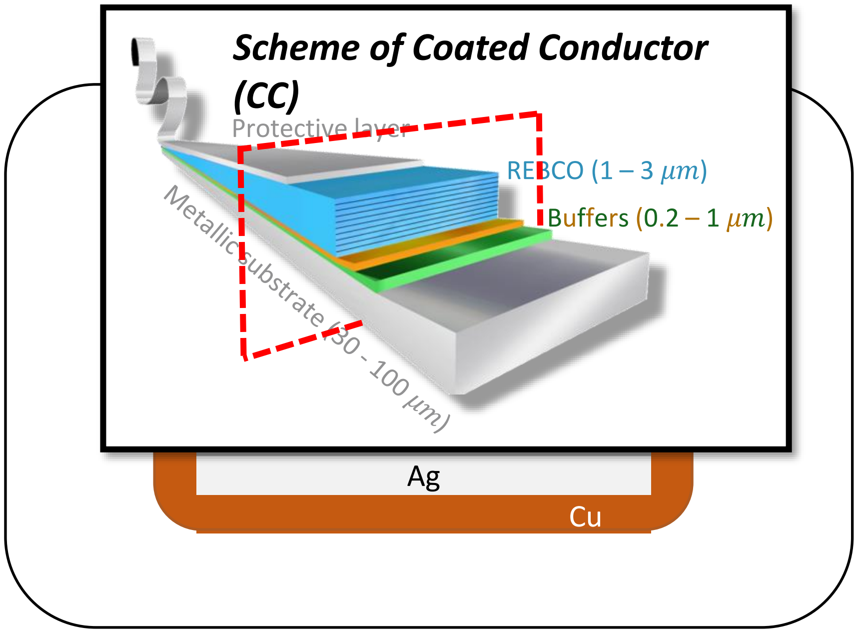
The cavity is operated in pulsed regime (1μs long pulses, 10^{-5} duty cycle)

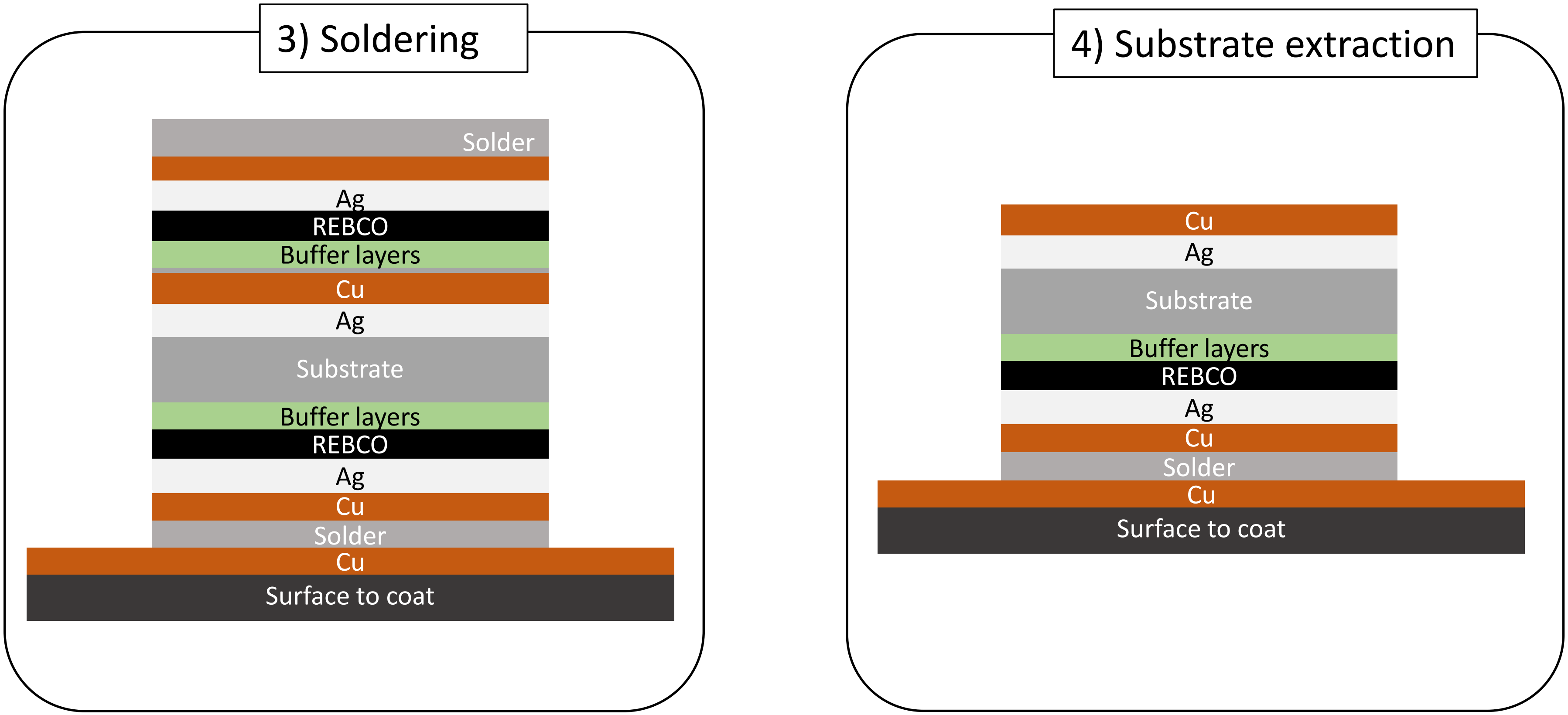




The idea is to use the commercial REBCO tapes soldering technique on copper developed by ICMAB in the frame of the FCC-CERN project for beam-screen coatings

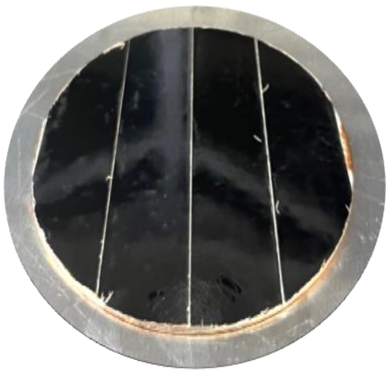


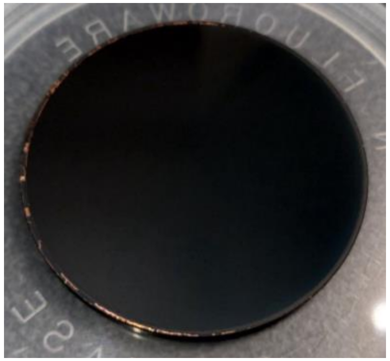



3) Soldering
Solder
Ag
REBCO
Buffer layers
Cu
Ag
Substrate
Buffer layers
REBCO
Ag
Cu
Solder
Cu
Surface to coat
4) Substrate extraction
Cu
Ag
Substrate
Buffer layers
REBCO
Ag
Cu
Solder
Cu
Surface to coat

Preliminary measurements have been already performed at low rf field using REBCO tapes. REBCO films grown on MgO/Cu have been also measured for comparison

Soldered REBCO on copper (Fujikura by ICMAB)

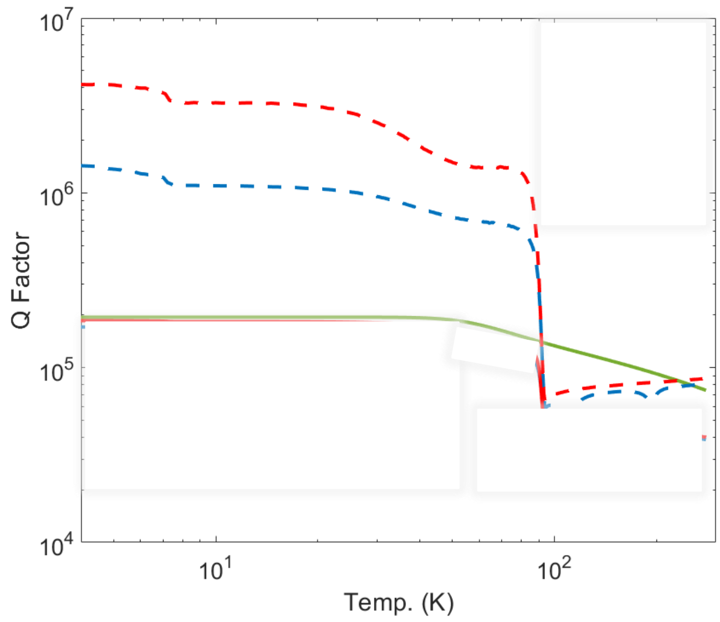




REBCO on MgO/Cu (CERACO)

77K

R_s Cu ≅ 17 mΩ
R_s REBCO tapes ≅ 1.7 mΩ
R_s REBCO PVD ≅ 1.0 mΩ



REBCO tapes results might be influenced by currents through tapes joints. Larger tapes (4cm) are currently under production at KIT (using previous Bruker equipments).

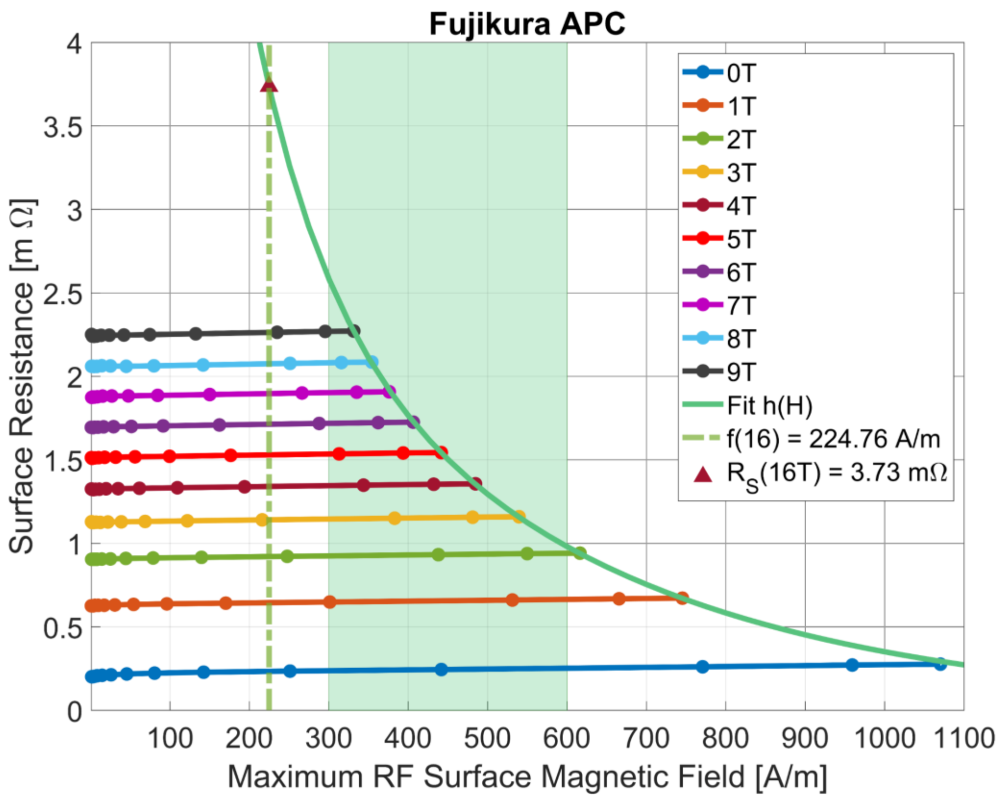
HIGHEST - R&D on wide HTS REBCO conductors

Bernhard Holzapfel, Nadja Bagrets, Ruslan Popov, Sukanya Baruah
Institute for Technical Physics, Karlsruhe Institute of Technology,

IBAD on Hastelloy

There are two major conceptual possible problems concerning such high rf field applications of HTS :

1) High rf fields can possibly significantly reduce cavity performances due to HTS superconductor “intrinsic” nonlinear behavior. (equivalent to the Q-slope problem)



Only few data are currently available (recent ICMAB results lead to a moderate optimism)

2) A temperature increase due to the very high rf power at the HTS surface can occur. A surface temperature increase would produce an increase in R_s and, in turn, of the dissipated power ($P_a = 1/2 R_s H_{rf}^2$; $P_a(T) \sim R_s\,(T)$ is a good approximation for highly coupled cavities, as those foreseen for CLIC)

This can result in a thermal runaway process (the same effect would not occur using copper cavities).

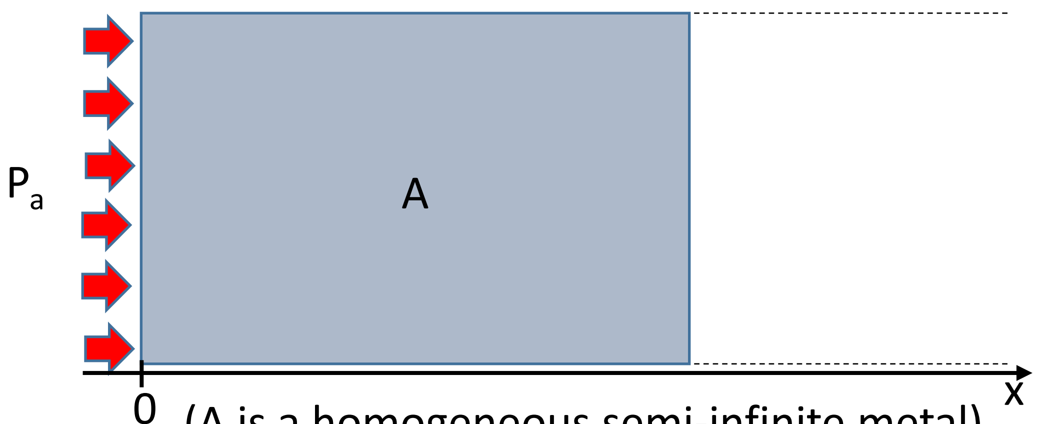
In the following I will discuss this last effect !

Temperature increase at a metal surface in the presence of a pulsed rf electromagnetic field :

1D heat equation:

$$\frac{\partial^2 T(x,t)}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} = 0$$

$$\left(\alpha = \frac{k}{C_P \rho} = \frac{k}{C_V} : \text{diffusivity}\right)$$

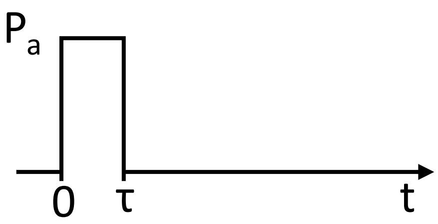


(A is a homogeneous semi-infinite metal)

Boundary conditions:

$$T(x,0) = T_o \quad ; \quad -k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} = P_a$$

$$T(\infty,t) = T_o$$



(k and α are assumed here to be temperature independent;
P_a is deposited at x=0 as a «delta function»)

The heat equation, with these boundary conditions, can be solved using the Laplace transform method

$\mathrm{U}(x,s) = L_t[T(x,t)](s) = \int_0^\infty T(x,t)e^{-st}dt$

Applying the transform to the Heat equation we get:

$$\frac{\partial^2 U(x,s)}{\partial x^2} = \frac{1}{\alpha}\left[sU(x,s) - \frac{T_0}{s}\right] \qquad (T(x,0) = T_o)$$

which is an ordinary, simple, differetial equation, whose solution is:

$$\mathrm{U}(x,s) = C_1 e^{x\sqrt{\frac{s}{\alpha}}} + C_2 e^{-x\sqrt{\frac{s}{\alpha}}} + \frac{T_0}{s}$$

$T(\infty,t) = T_o$ ⇒ $\mathrm{U}(\infty,s) = \frac{T_0}{s}$ and $C_1 = 0$

$$\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} = -\frac{P_a}{k}$$

$$\left.\frac{\partial U(x,s)}{\partial x}\right|_{x=0} = -\sqrt{\frac{s}{\alpha}}C_2$$

⇒ $$C_2 = \frac{P_a\sqrt{\alpha}}{k}\frac{1}{s\sqrt{s}}$$

Finally :

$$U(x,s) = \frac{P_a\sqrt{\alpha}}{k}\frac{1}{s\sqrt{s}}e^{-x\sqrt{\frac{s}{\alpha}}} + \frac{T_0}{s}$$

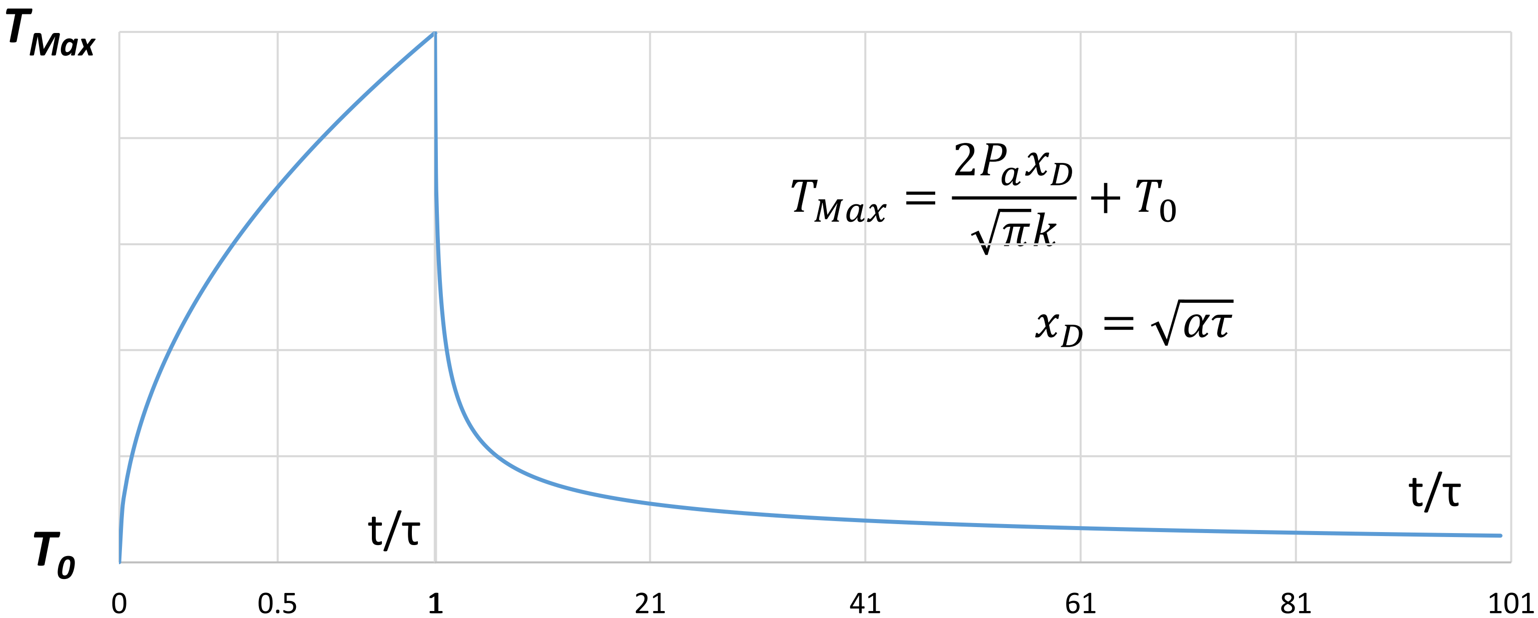
and : $T(x,t) = L_t^{-1}[U(x,s)\,]t$

$$T(x,t) = \frac{2P_a}{k}\sqrt{\alpha t}\left[-\text{ierfc}\left(\frac{x}{2\sqrt{\alpha t}}\right)\right] + T_o$$

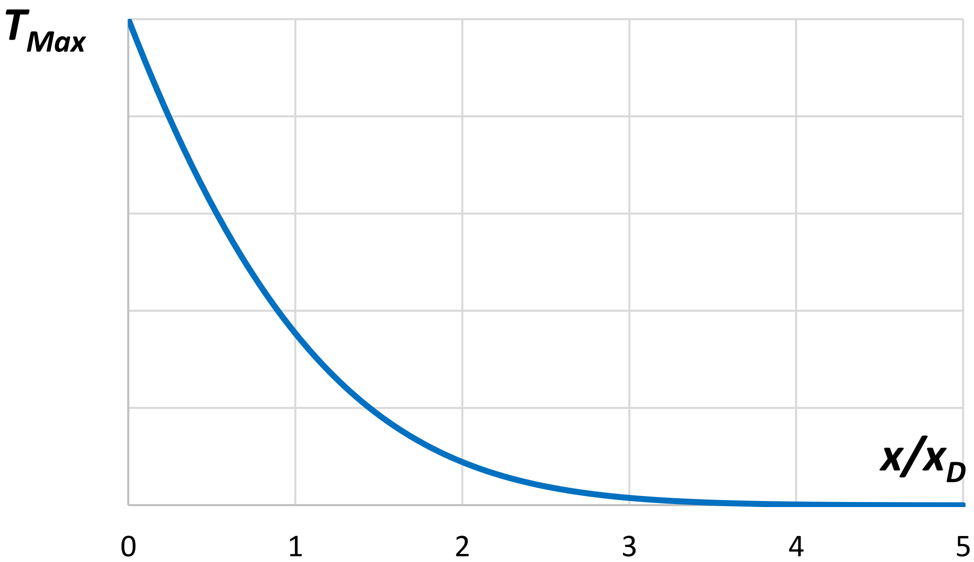
($erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-z^2}\,dz;$ $erfc(z) = 1 - erf(z);$ $ierfc(z) = z\,erfc(z) - \frac{e^{-z^2}}{\sqrt{\pi}}$)

The espression [ ] is the same reported by I.Wilson , CLIC Note 52 (15.10.87) Wilson was interest to determine the copper surface temperature increase (over room temperature) in the CLIC foreseen operating conditions, to evaluate the effects of fatigue cycling under thermally induced stress. He found ΔT ~ 5°C for E_{acc} =80MV/m. Mainly due to the reduction of the thermal expansion coefficient, the effect should be negligible at 77K.

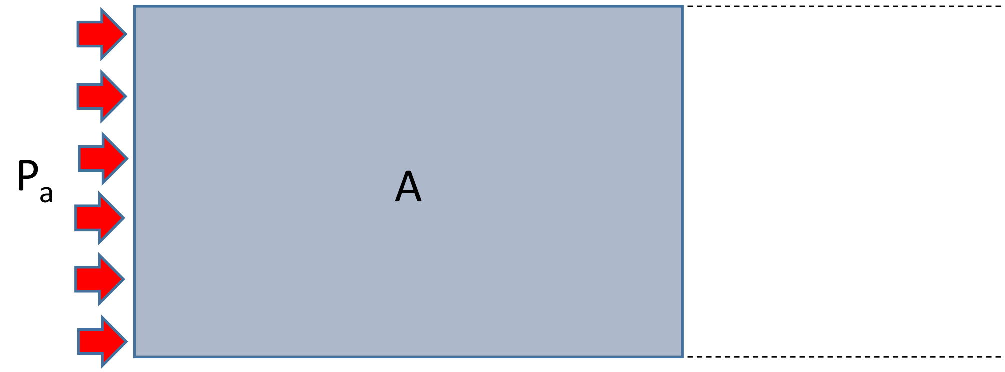
The t dependence, at *x=0,* is :



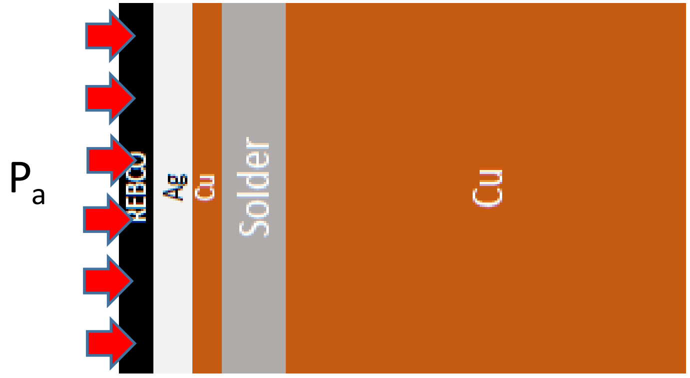
The x dependence for t=τ is :



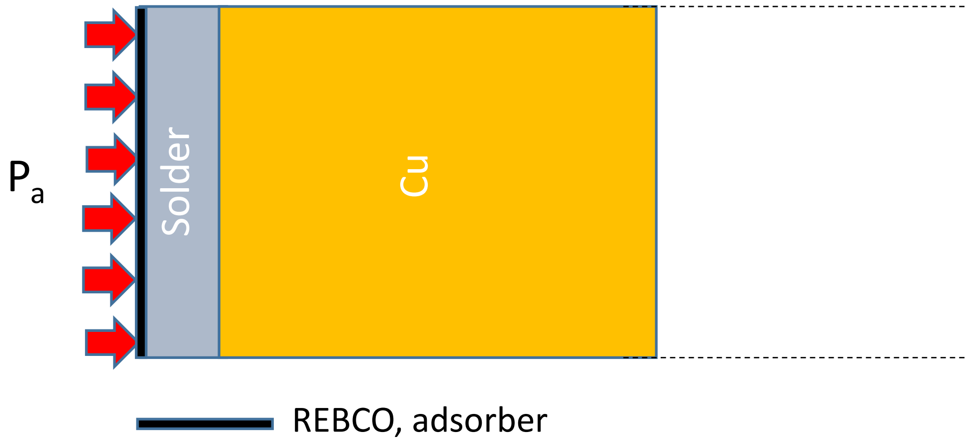
Uniform metal (Cu case):
Exact analytical solution,
with the assumed
boundary conditions.



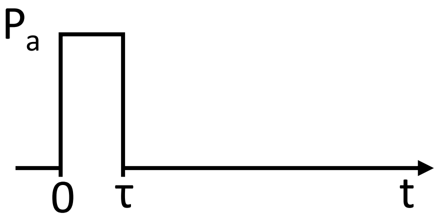
Real system of our interest:
Numerical solutions!

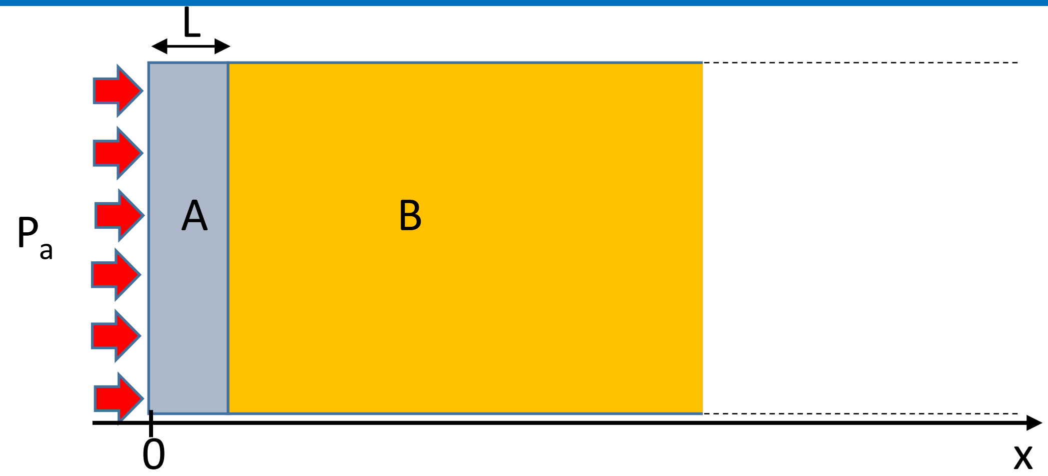


Approximate analytical
solutions for this simplifyed
model system are possible !



Let's consider the case of an A/B interface, where A is a metal of thickness L and B is a homogeneous semi-infinite metal:





We need to solve two coupled 1D heat equations:

$$\frac{\partial^2 T_A(x,t)}{\partial x^2} - \frac{1}{\alpha_A}\frac{\partial T_A(x,t)}{\partial t} = 0 \qquad \frac{\partial^2 T_B(x,t)}{\partial x^2} - \frac{1}{\alpha_B}\frac{\partial T_B(x,t)}{\partial t} = 0$$

with the boundary conditions:

$$T_B(\infty,t) = T_o$$

$$-k_A \left.\frac{\partial T_A\,(x,t)}{\partial x}\right|_{x=0} = P_a$$

$$T_A(L,t) = T_B(L,t) \quad \text{(neglecting Kapitza resistance)}$$

$$-k_A \left.\frac{\partial T_A\,(x,t)}{\partial x}\right|_{x=L} = -k_B \left.\frac{\partial T_B\,(x,t)}{\partial x}\right|_{x=L} = P_{a/b}$$

$P_{a/b} = P_{a/b}\,(t)$ is the power crossing the A/B interface

The two coupled A/B equations, with the given boundary conditions, cannot be exactly solved analytically. An approximate solution can be obtained considering for the solutions the same form of the homogeneous case :

$$T_A(x,t) \cong C_{1A}\sqrt{\alpha_A t}\ \ ierfc\left(\frac{x}{2\sqrt{\alpha_A t}}\right) + C_{2A} \qquad (0 \leq x \leq L)$$

$$T_B(x,t) \cong C_{1B}\sqrt{\alpha_B t}\ ierfc\left(\frac{x-L}{2\sqrt{\alpha_B t}}\right) + C_{2B} \qquad (x \geq L)$$

The boundary conditions imply :

$$\begin{cases} C_{1A} = -\dfrac{2P_a}{k_A} \\[2ex] C_{1B} = -\dfrac{2P_a}{k_B} erfc\left(\dfrac{L}{2\sqrt{\alpha_A t}}\right) \end{cases} \qquad \begin{cases} C_{2A} = \dfrac{2P_a}{k_B}\sqrt{\dfrac{\alpha_B t}{\pi}} erfc\left(\dfrac{L}{2\sqrt{\alpha_A t}}\right) + \dfrac{2P_a}{k_A}\sqrt{\alpha_A t}\ ierfc\left(\dfrac{L}{2\sqrt{\alpha_A t}}\right) + T_0 \\[2ex] C_{2B} = T_0 \end{cases}$$

$$T_{Max} \cong T_A(0,\tau) = \frac{2P_a x_{AD}}{\sqrt{\pi} k_A}\left[1 + \frac{k_A}{k_B}\sqrt{\frac{\alpha_B}{\alpha_A}} erfc\left(\frac{L}{2x_{AD}}\right) + \sqrt{\pi}\ ierfc\left(\frac{L}{2x_{AD}}\right)\right] + T_0$$

What happens if the adsorbing layer is a superconductor ?

$$P_a = P_a(T) = \frac{1}{2} R_s(T) H_{rf}^2$$

The temperature dependence of R_s can be well described, for a superconductor, by the two-fluid formula, that can be written as:

$$R_s(T) = R_s(T_0) \left(\frac{T}{T_0}\right)^{\alpha} \left[\frac{1-\left(\frac{T_0}{T_c}\right)^{\alpha}}{1-\left(\frac{T}{T_c}\right)^{\alpha}}\right]^{\beta}$$

where $R_s(T_0)$ is the surface resistance of the superconductor at the initial temperature and α=4 , β =3/2 for a BCS superconductor and α ~ 2 , β ~ 0.3 for HTS

The problem can be easily faced dividing the pulse time lenght τ into N small intervals $\Delta\tau$ (so that $\tau = N\Delta\tau$) sufficiently small that R_s can be considered constant in that interval. The solution can than be found by a iteration procedure.

$$T_{Max} \cong \frac{R_s(T) H_{rf}^2 x_{AD}}{\sqrt{\pi} k_A} \left[1 + \frac{k_A}{k_B}\sqrt{\frac{\alpha_B}{\alpha_A}}\, erfc\left(\frac{L}{2x_{AD}}\right) + \sqrt{\pi}\, ierfc\left(\frac{L}{2x_{AD}}\right)\right] + T_0$$

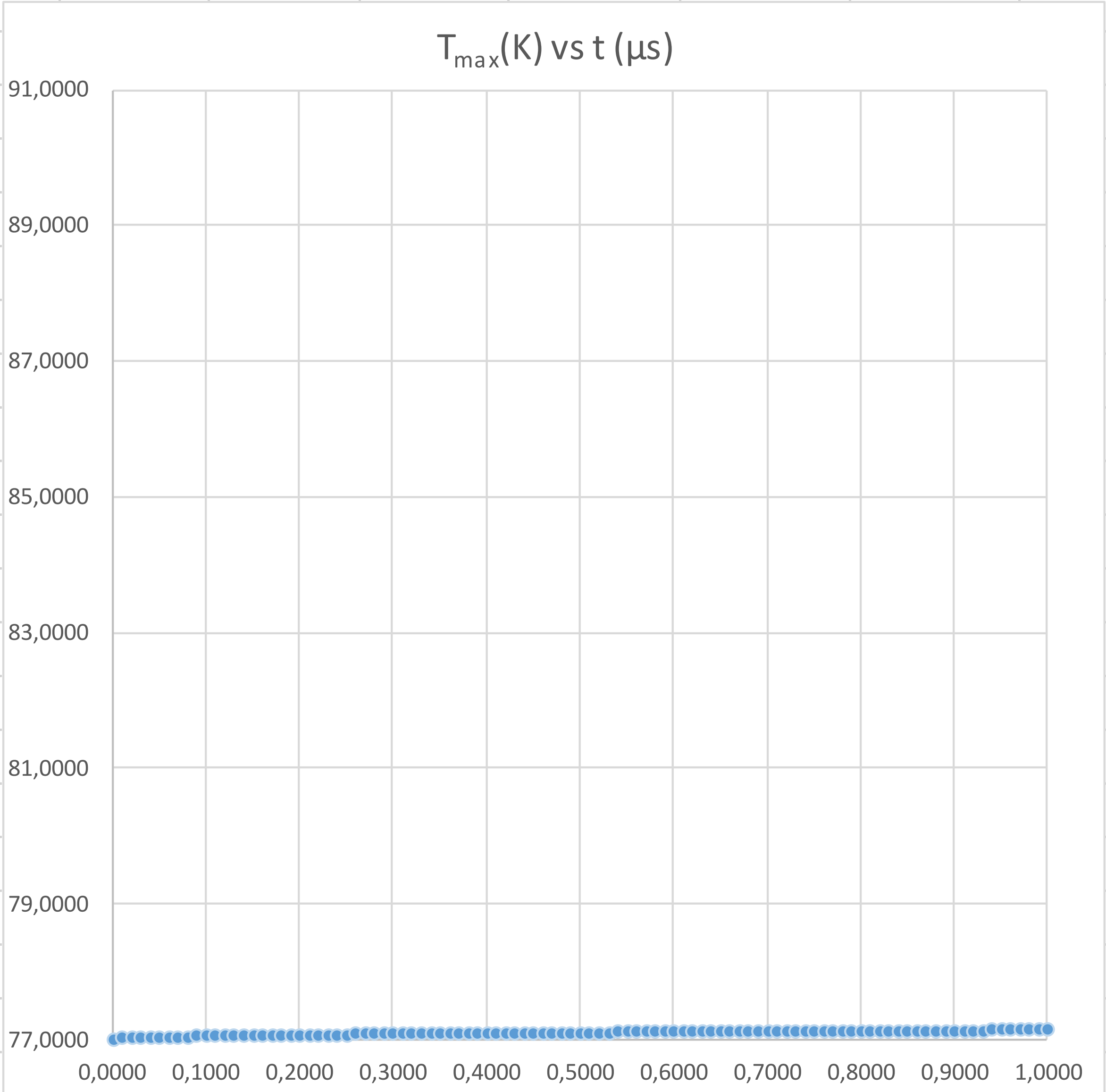
This iterative calculation has been implemented using excel.

Input parameters are T_0, $k_{A/B}$, $\alpha_{A/B}$ (or C_p and ρ), τ , L_A, R_{s0}, T_c and B_{rf}

77K	K (W/mK)	C_p (J/KgK)	ρ (Kg/m^3)	α (m^2/s)	τ (μs)	X_D (μm)	L_A(μm)	R_{s0} (mΩ)	B_{rf} (mT)	T_0	T_c
Solder	50	100	8650	0,000058	1,00	7,60	20	1	50	77	91
Copper	600	200	8940	0,000336		18,32					

T_{max} = 77,13 K

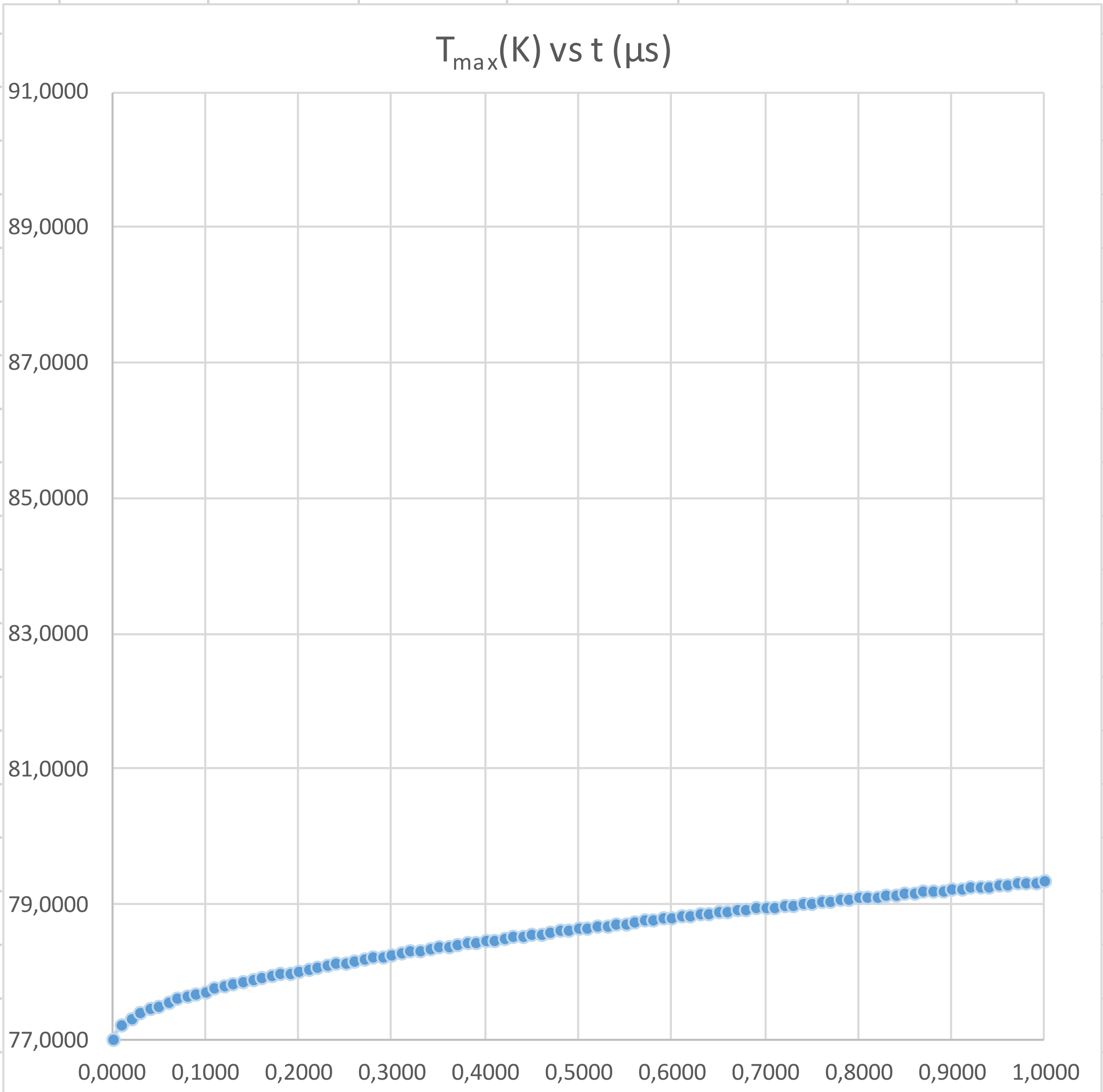
R_{smax} = 1,01 mΩ



77K	K (W/mK)	C_p (J/KgK)	ρ (Kg/m^3)	α (m^2/s)	τ (μs)	X_D (μm)	L_A(μm)	R_{s0} (mΩ)	B_{rf} (mT)	T_0	T_c
Solder	50	100	8650	0,000058	1,00	7,60	20	1	200	77	91
Copper	600	200	8940	0,000336		18,32					

T_{max} = 79,33 K

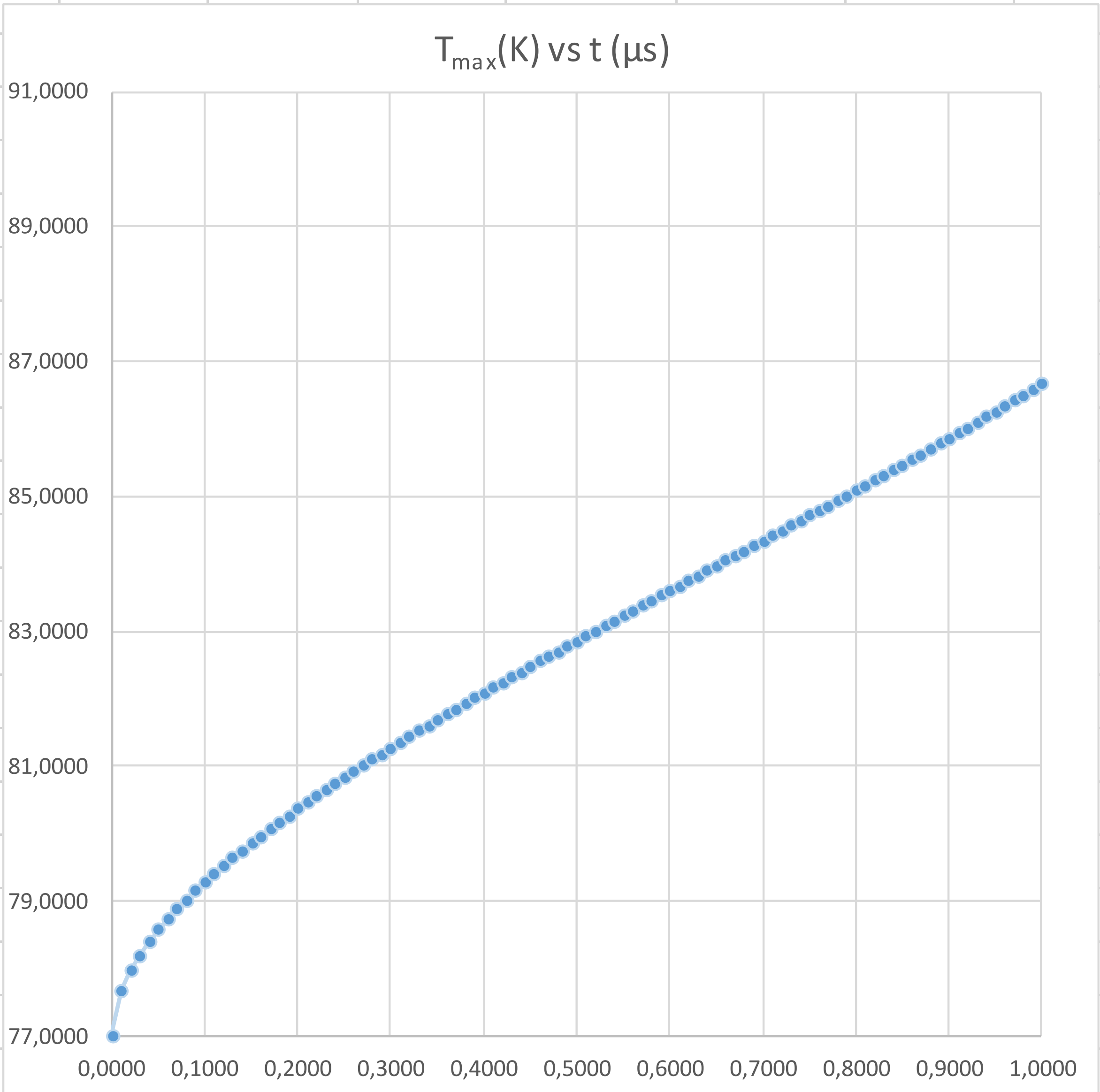
R_{smax} = 1,12 mΩ



77K	K (W/mK)	C_p (J/KgK)	ρ (Kg/m^3)	α (m^2/s)	τ (μs)	X_D (μm)	L_A(μm)	R_{s0} (mΩ)	B_{rf} (mT)	T_0	T_c
Solder	50	100	8650	0,000058	1,00	7,60	20	1	350	77	91
Copper	600	200	8940	0,000336		18,32					

T_{max} = 86,66 K

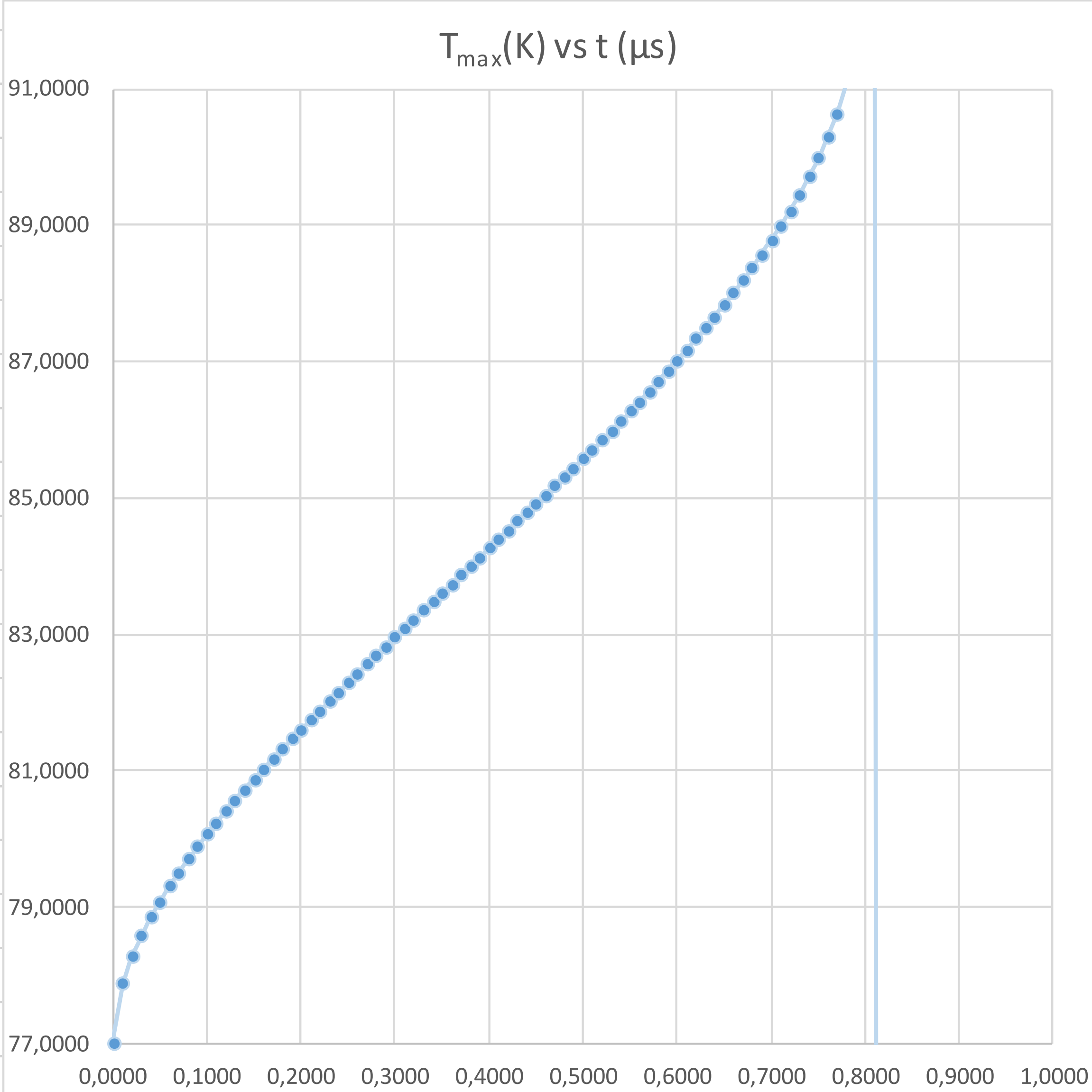
R_{smax} = 1,77 mΩ



77K	K (W/mK)	C_p (J/KgK)	ρ (Kg/m^3)	α (m^2/s)	τ (μs)	X_D (μm)	L_A(μm)	R_{s0} (mΩ)	B_{rf} (mT)	T_0	T_c
Solder	50	100	8650	0,000058	1,00	7,60	20	1	400	77	91
Copper	600	200	8940	0,000336		18,32					

T_{max} = #NUM! K

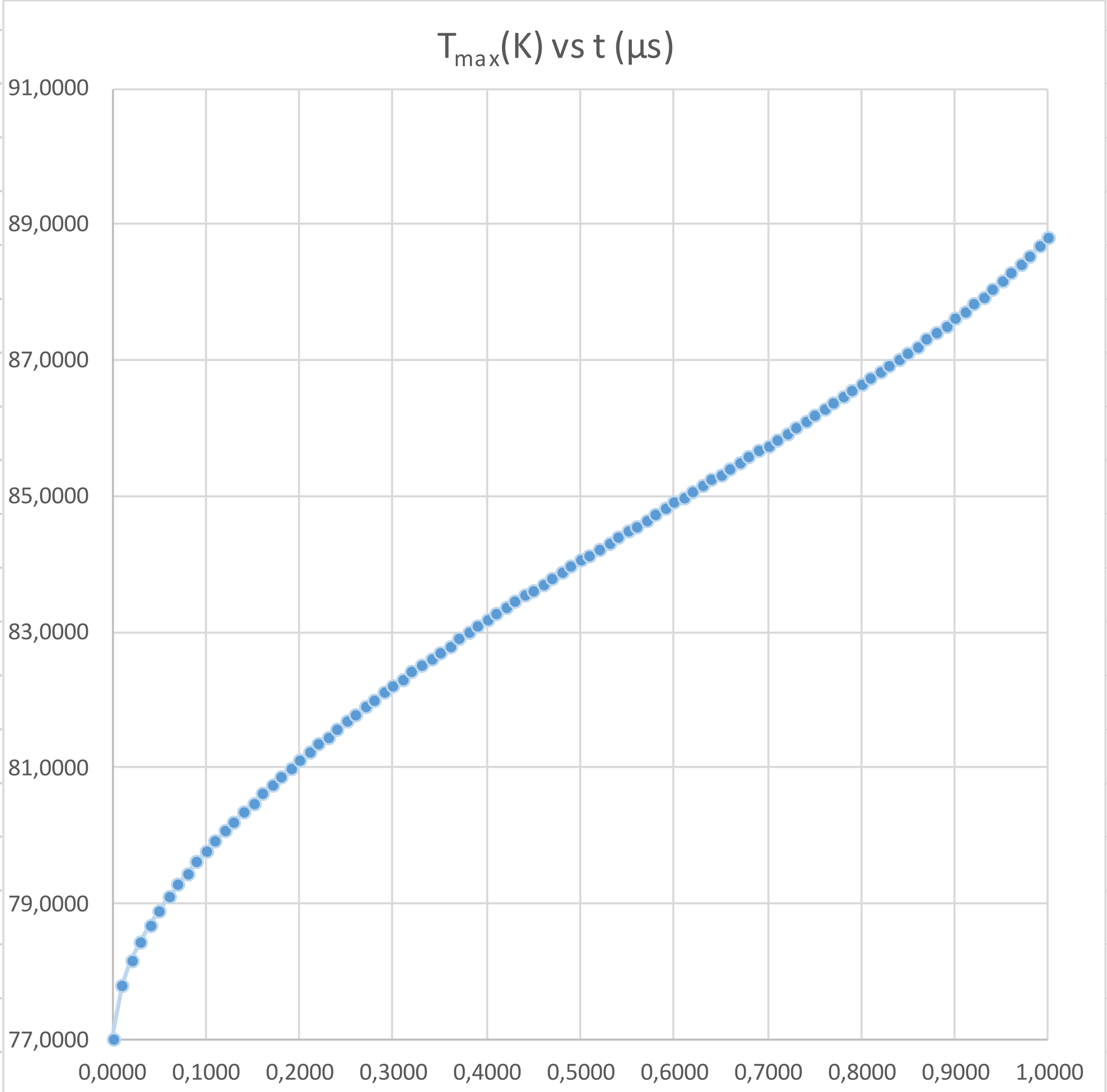
R_{smax} = #NUM! mΩ



77K	K (W/mK)	C_p (J/KgK)	ρ (Kg/m³)	α (m²/s)	τ (μs)	X_D (μm)	L_A (μm)	R_{s0} (mΩ)	B_{rf} (mT)	T_0	T_c
Solder	60	100	8650	0,000069	1,00	8,33	12	1	400	77	91
Copper	600	200	8940	0,000336		18,32					

T_{max} = 88,80 K

R_{smax} = 2,27 mΩ



Conclusions :

- Coating with REBCO tapes high rf field pulsed accelerating Cu cavities at 77K for linear colliders is presently considered.

- Problems can arise both from the nonlinear high field behavior of REBCO tapes or from surface heating (leading to thermal runaway).

- Approximate calculations based on a simplified system thermal modeling have been presented here, showing that surface heating can be a serious problem only at very high field. The operation limit can be further raised improving the overall system thermal properties.

- Numerical calculation for a system more close to the effective experimental situation will be performed to confirm these indications.

Walter Venturini notes

Energia e.m. in cavità corrispondente ad una data P_f (potenza diretta RF) ed ad un dato accoppiamento β:

$$U_0 = \frac{4\beta P_f}{(\beta+1)^2}\,\frac{Q_0}{\omega} = k\,E_0^2$$

$$Q_0 = \frac{\omega U_0}{P_c} = \frac{\Gamma}{R_s} \quad ; \quad \beta = \frac{Q_0}{Q_e} = \frac{\Gamma}{Q_e R_s}$$

$$U_0 = \frac{4\,\frac{\Gamma}{Q_e R_s}\,P_f\,\frac{\Gamma}{R_s\,\omega}}{\left(\frac{\Gamma}{Q_e R_s}+1\right)^2} = \frac{4\,\frac{\Gamma^2}{Q_e\omega}P_f\,\frac{1}{R_s^2}\,(Q_e R_s)^2}{(\Gamma + Q_e R_s)^2}$$

$$= \frac{\frac{4\Gamma^2 Q_e P_f}{\omega}}{(\Gamma + Q_e R_s)^2} = k\,E_0^2$$

quindi $$E_0^2 = \frac{\frac{4\Gamma^2}{k\,\omega}Q_e P_f}{(\Gamma + Q_e R_s)^2}$$

mentre $$P_c = \frac{\omega U_0}{Q_0} = \frac{4\Gamma^2 Q_e P_f}{(\Gamma + Q_e R_s)^2}\,\frac{R_s}{\Gamma}$$

To estimate the error of the approximate solutions, we can set A=B in the solution for T_{Max} :

$$T_{Max} \cong T_A(0,\tau) = \frac{2P_a x_{AD}}{\sqrt{\pi}k_A}\left[1 + erfc\left(\frac{L}{2x_{AD}}\right) + \sqrt{\pi}\, ierfc\left(\frac{L}{2x_{AD}}\right)\right] + T_0$$

We already know that , for a uniform material (A), it is : $T_{Max} = T_A(0,\tau) = \frac{2P_a x_{AD}}{\sqrt{\pi}k_A} + T_0$

So that the difference between the approximate solution and the exact in this case is :

$$erfc\left(\frac{L}{2x_{AD}}\right) + \sqrt{\pi}\, ierfc\left(\frac{L}{2x_{AD}}\right)$$

The approximation made overestimates the maximum surface temperature up to a maximum of about 12% when $L = x_{AD}$

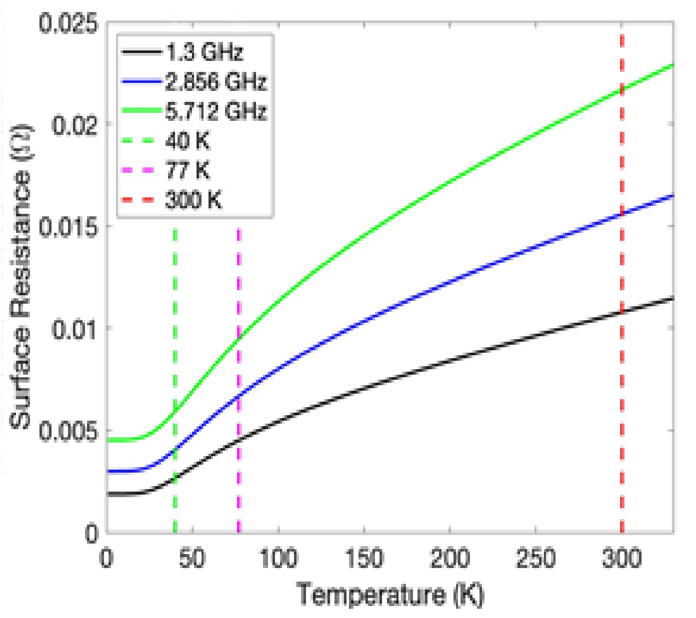
Cold Copper

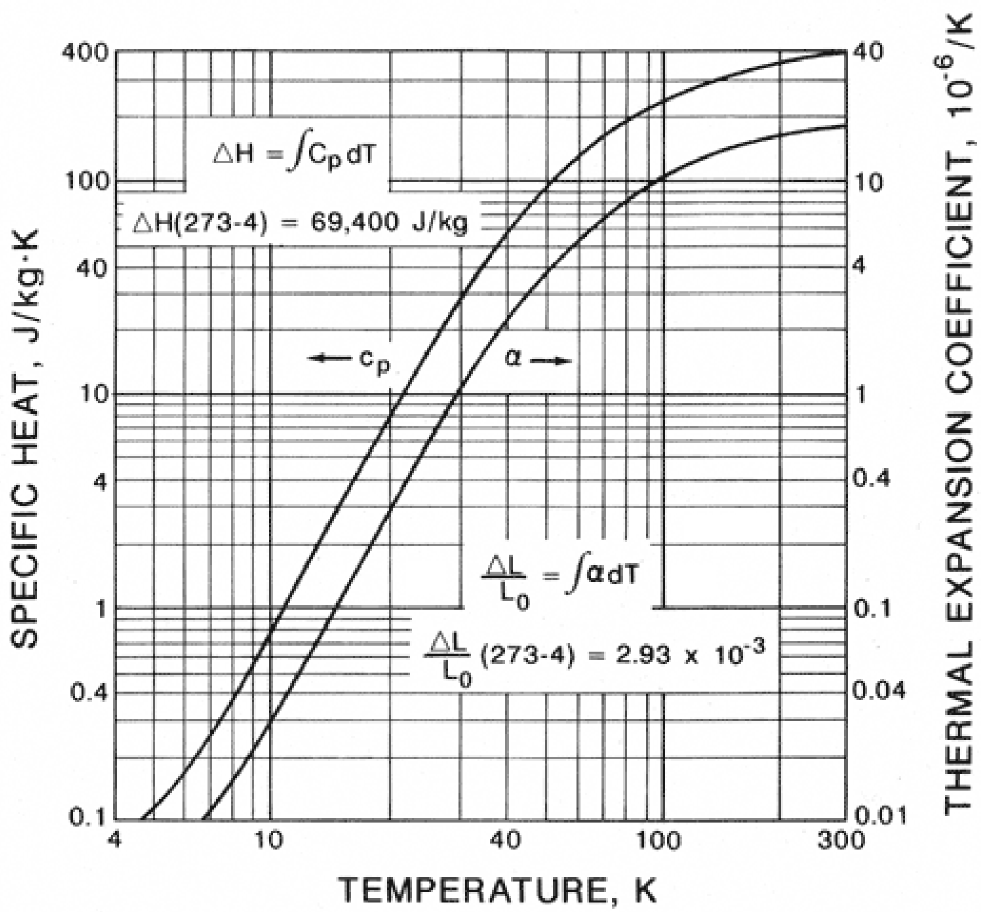
Cryogenic temperature elevates performance in gradient

- Material strength is key factor
- Improved conductivity reduces material stress
- Increases rf efficiency

Operation at 77 K with liquid nitrogen is simple and practical

- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency*





SPECIFIC HEAT, J/kg·K
THERMAL EXPANSION COEFFICIENT, 10^{-6}/K
TEMPERATURE, K
$\Delta H = \int C_p \, dT$
$\Delta H(273\text{-}4) = 69{,}400$ J/kg
← c_p
α →
$\frac{\Delta L}{L_0} = \int \alpha \, dT$
$\frac{\Delta L}{L_0}(273\text{-}4) = 2.93 \times 10^{-3}$
400
100
40
10
4
1
0.4
0.1
40
10
4
1
0.4
0.1
0.04
0.01
4
10
40
100
300