A15 Superconductors:
Alternative to Nb for RF Cavities

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Outline

- **Theory**: *Surface Resistance*
  - **Mo-Re system**: *Deposition Technique and Results*
  - **V_3Si**: *Thermal Diffusion in Reactive SiH_4 Atmosphere*
  - **Nb_3Sn**: *Liquid solute diffusion tecnique*
  - **6 GHz cavities**: *RF Measurements*
- **Conclusions and future plan**

Surface Impedance and Surface Resistance

For a **normal metal** in the **normal regime**:

$$Z_n = \frac{1-i}{\sigma_n \delta} = (1-i)\frac{\rho_n}{\delta}$$

$\sigma_n = 1 / \rho_n$ = dc conductivity at T

δ = skin depth

Extension to Superconductors:

$\sigma_1 - i\sigma_2$ in place of σ_n

As derived by **Nam**, for **$T < T_c / 2$, R_s** can be approximated by:

$$\frac{R_s}{R_n} = \frac{1}{\sqrt{2}} \frac{\frac{\sigma_1}{\sigma_n}}{\left(\frac{\sigma_2}{\sigma_n}\right)^{\frac{3}{2}}}$$

Mattis and Bardeen Integrals

In the framework of the **BCS theory**, for $\omega < 2\Delta$, the **complex conductivity of a superconductor is**:

$$\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}\left[f(E) + f(E+\hbar\omega)\right]g^{+}(E)\,dE$$

$$\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega,-\Delta}^{\Delta}\left[1-2f(E+\hbar\omega)\right]g^{-}(E)\,dE$$

The two integrals σ_1/σ_n and σ_2/σ_n are easily **numerically calculated**.

$$\frac{\sigma_1}{\sigma_n} = \left[\frac{\frac{2\Delta}{K_B T}}{\left(1+e^{-\Delta/K_B T}\right)^2}\right] e^{-\Delta/K_B T}\ln\frac{\Delta}{\hbar\omega}$$

$$\frac{\sigma_2}{\sigma_n} = \frac{\pi\Delta}{\omega}\tanh\frac{\Delta}{2K_B T}$$

In the **normal skin effect** regime, for $\hbar\omega \ll 2\Delta$

R_{BCS}

Then, if **$T < T_c / 2$**

$$R_{BCS} \cong \frac{R_n}{\sqrt{2}}\left(\frac{\hbar\omega}{\pi\Delta}\right)^{\frac{3}{2}} \frac{\sigma_1}{\sigma_n} = A\sqrt{\rho_n}\, e^{-\frac{\Delta}{K_B T}}\left(1 + O(\Delta, \omega, T)\right)$$

Empirically, **R_{res}** is found to be **dependent on** ρ_n too.

Essence of the previous slides

For low rf losses,

a high T_C value is not sufficient

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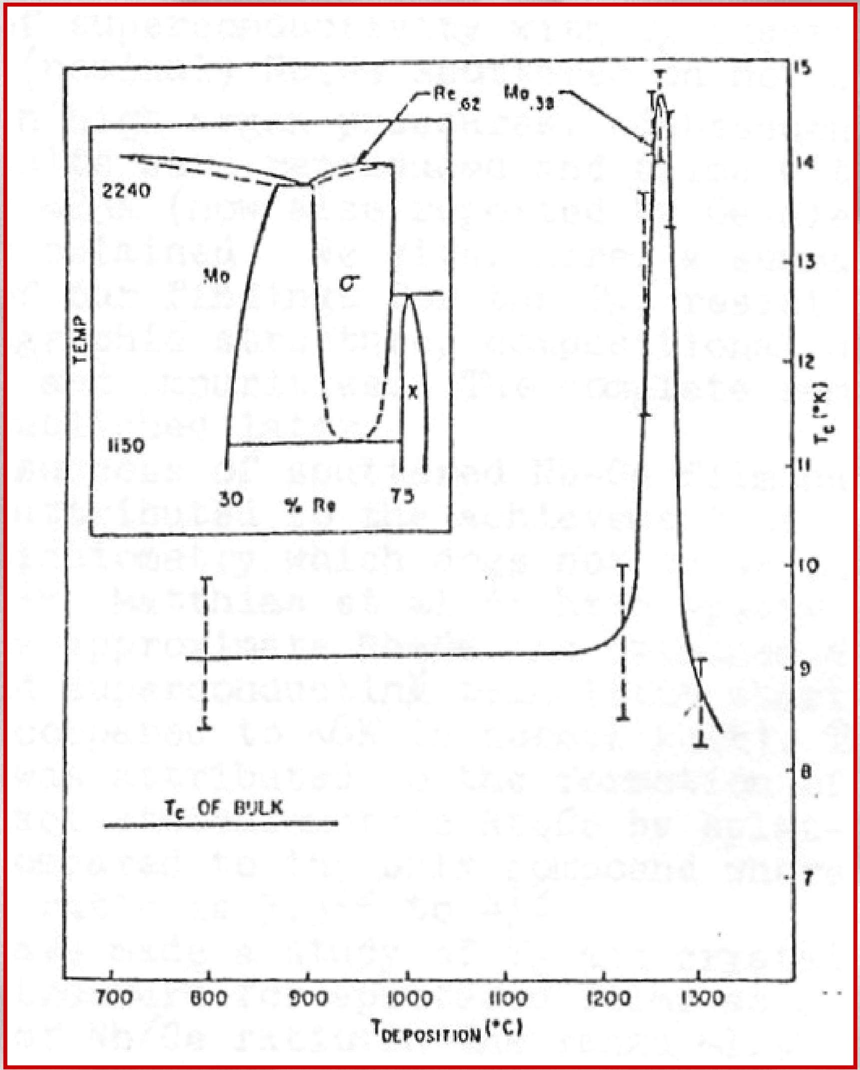
A metallic behaviour in the normal state is mandatory

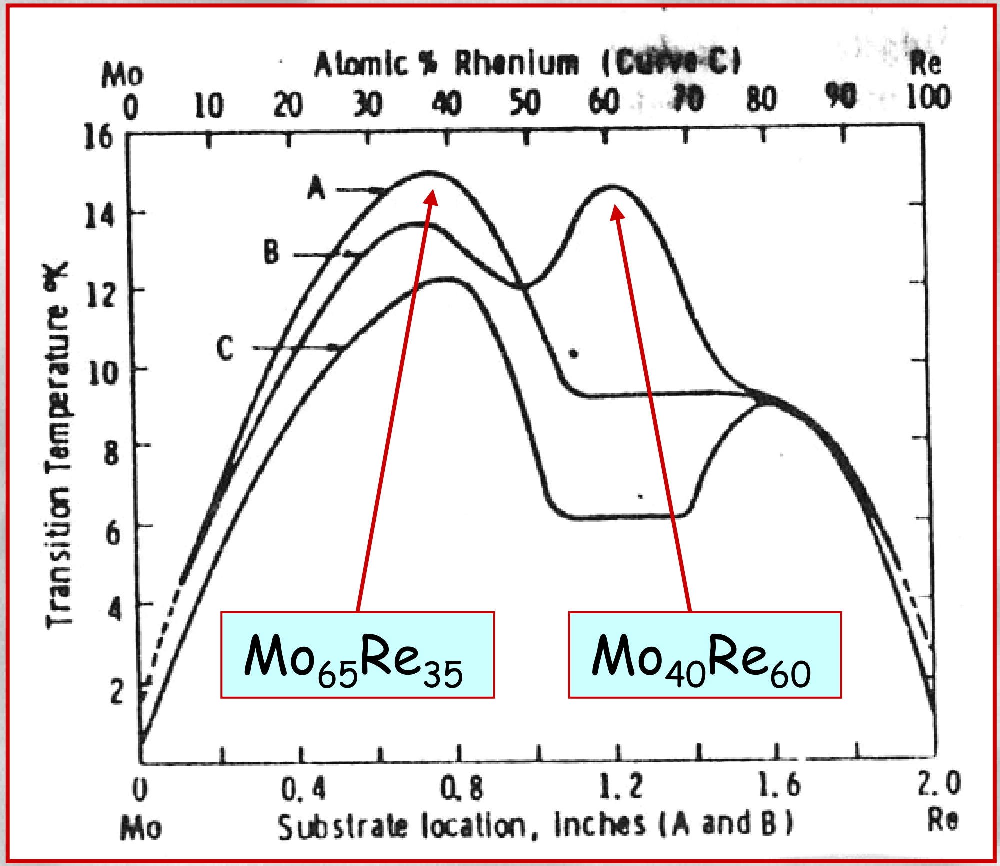
Literature: Mo-Re system



$Mo_{38}Re_{62}$

Testardi, 1975

Literature: Mo-Re system



A – Sputtering v ~ **500 Å/min**, deposition T = **1000 °C**, **B** – Sputtering v ~ **1000 Å/min** deposition T = **1200 °C**, **C** – Mo-Re **bulk samples**

Gavaler et al.

Mo-Re system: deposition tecnique

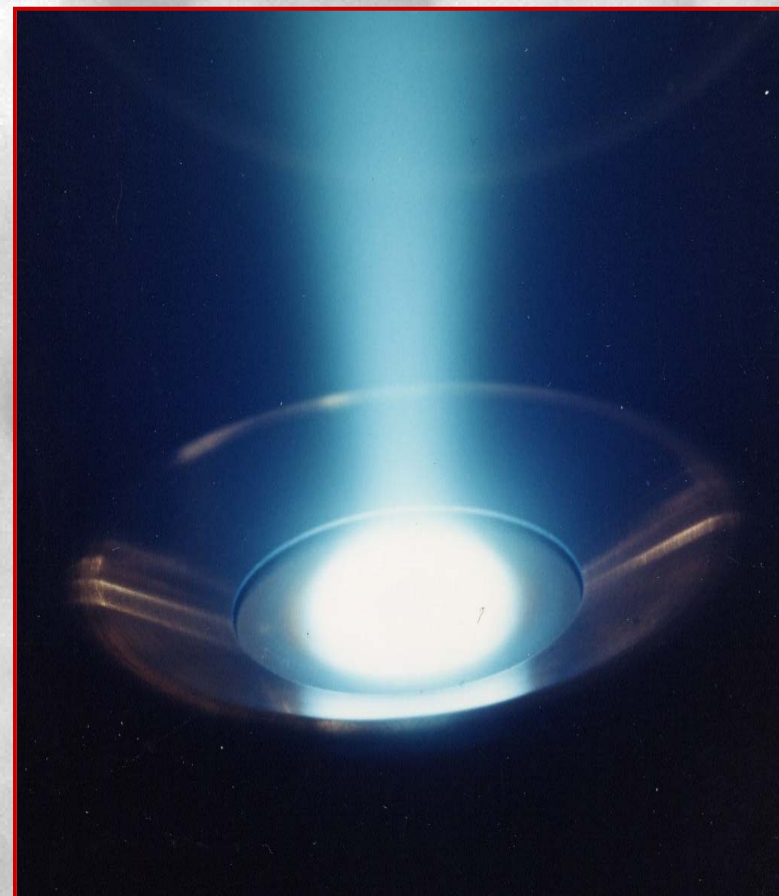
Magnetron Sputtering at high T

3 Target Compositions

$Mo_{75}Re_{25}$

$Mo_{60}Re_{40}$

$Mo_{38}Re_{62}$



$Mo_{75}Re_{25}$

26 SPUTTERING RUNS

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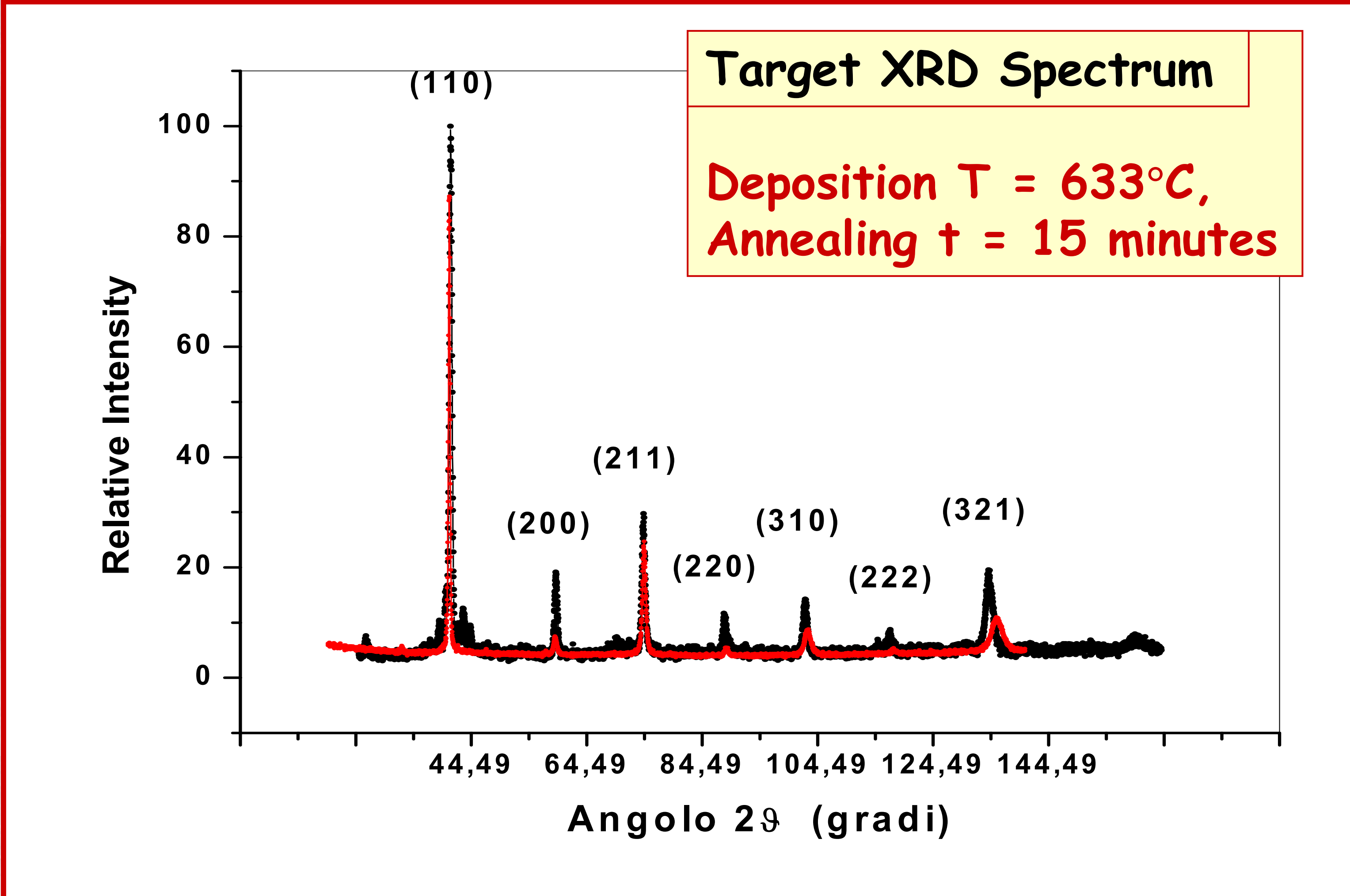
More than 60 samples

11 samples SETS

↓

Annealing treatment

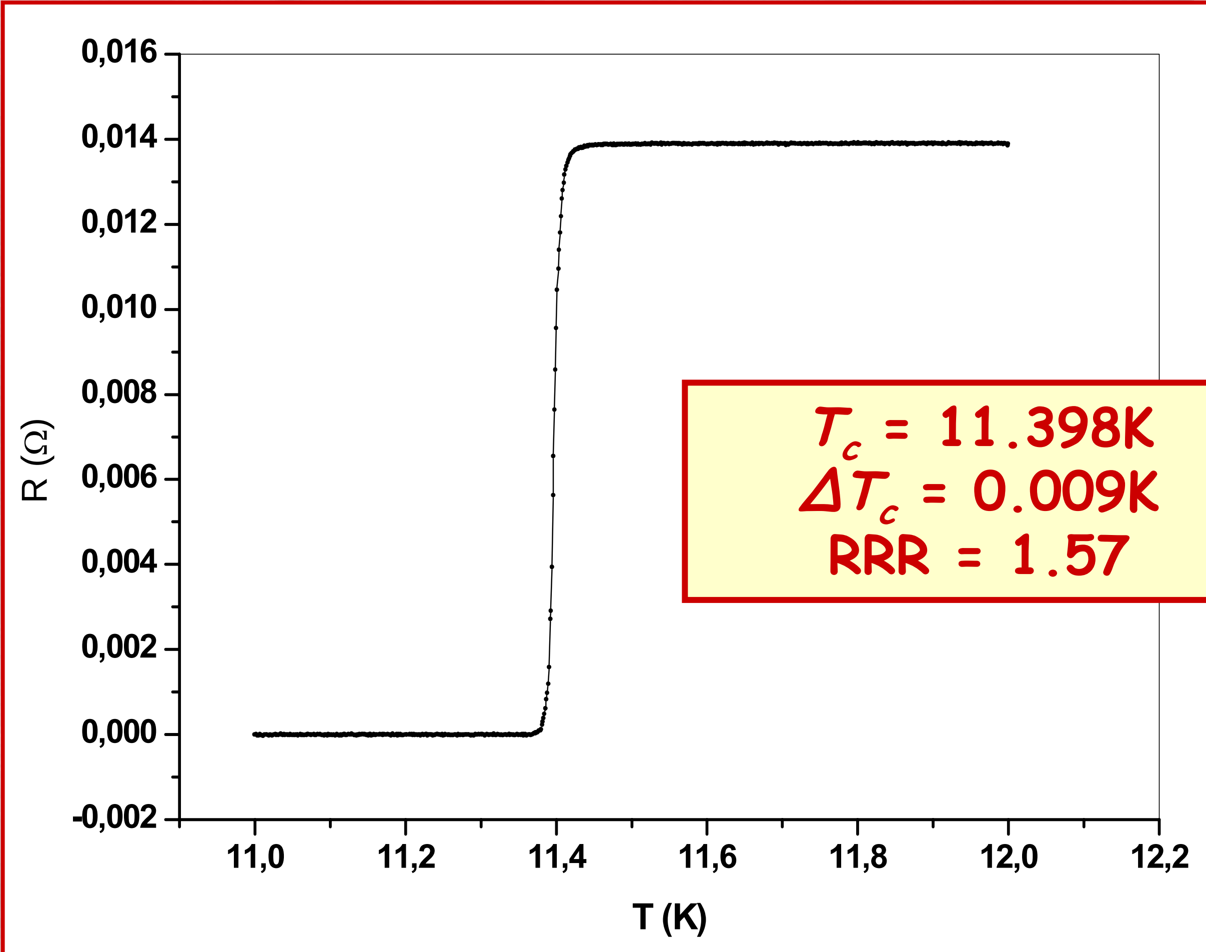
$Mo_{75}Re_{25}$: XRD Spectra



$Mo_{75}Re_{25}$: A Superconductive Transition Curve

Deposition T = 633°C

Annealing t = 15 min

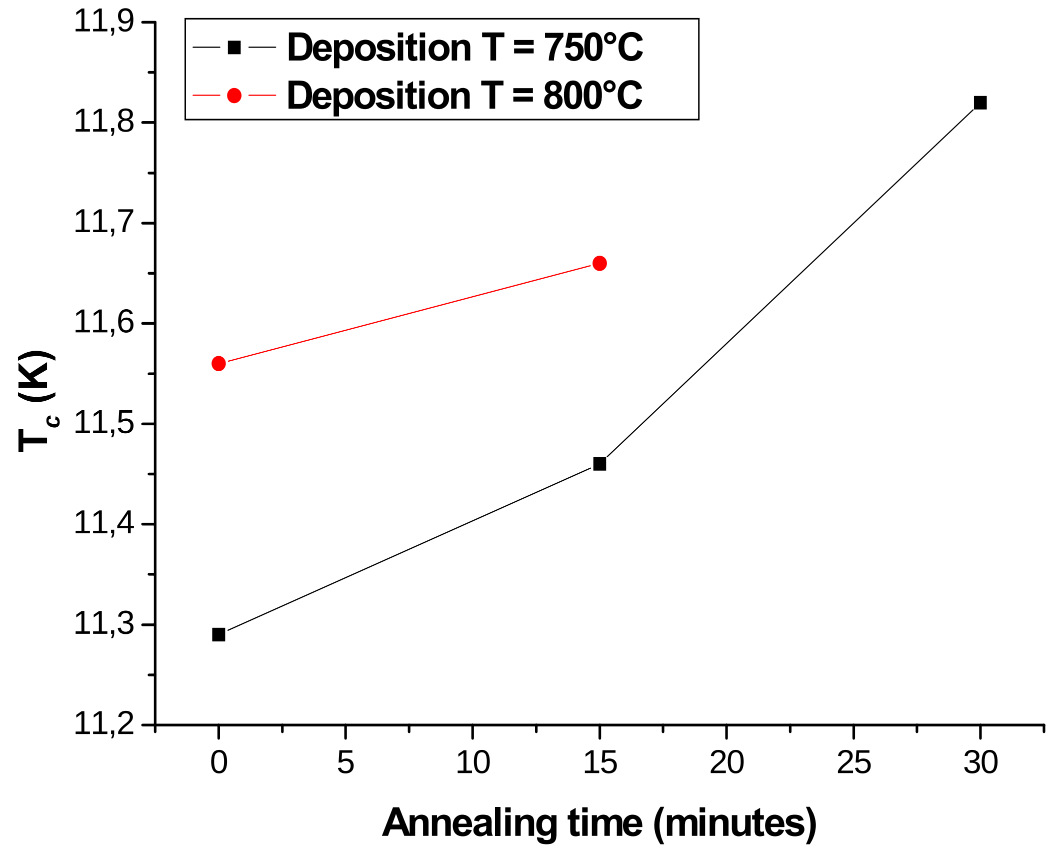


T_c = 11.398K

ΔT_c = 0.009K

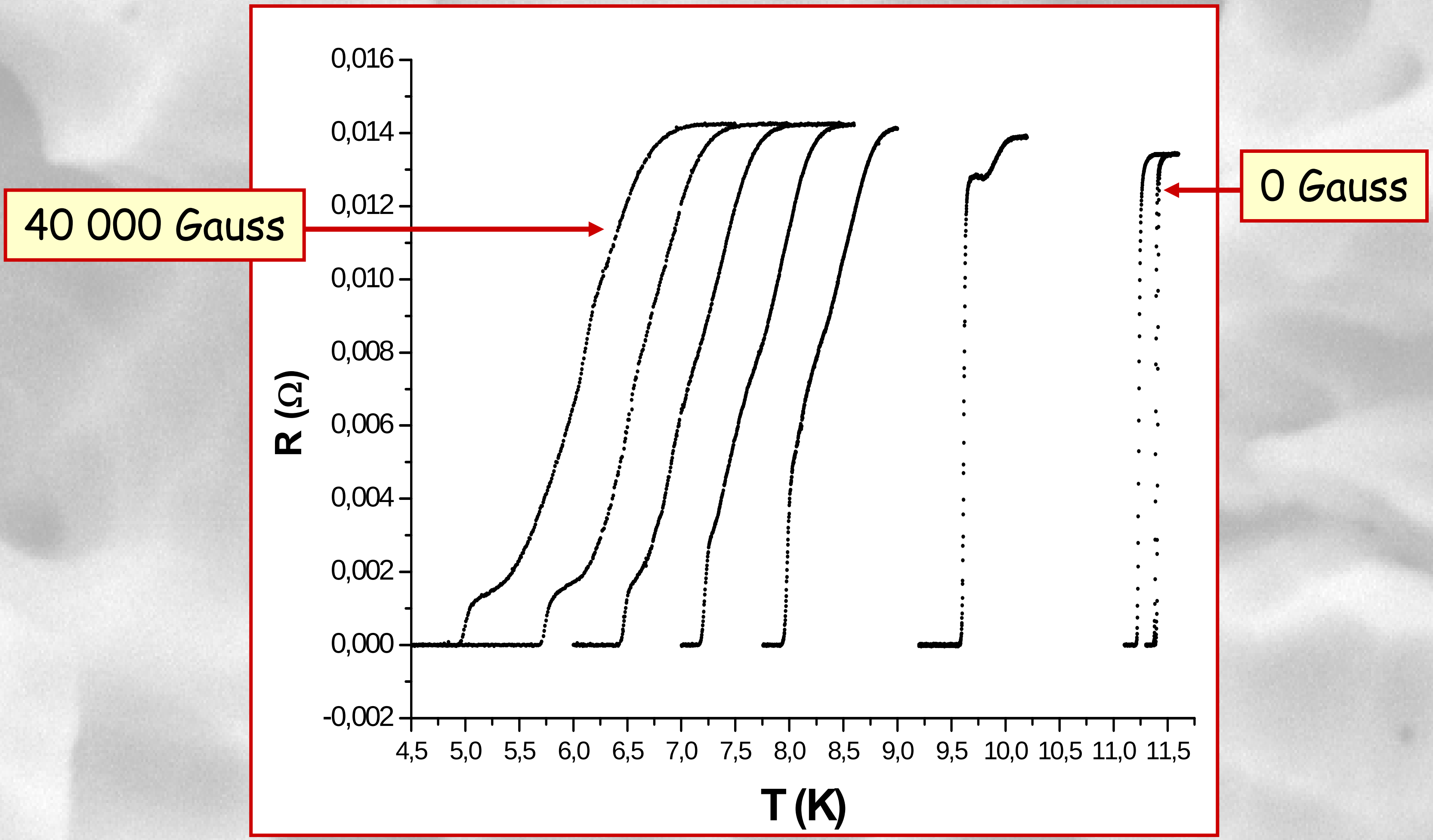
RRR = 1.57

$Mo_{75}Re_{25}$: T_c vs Annealing Time

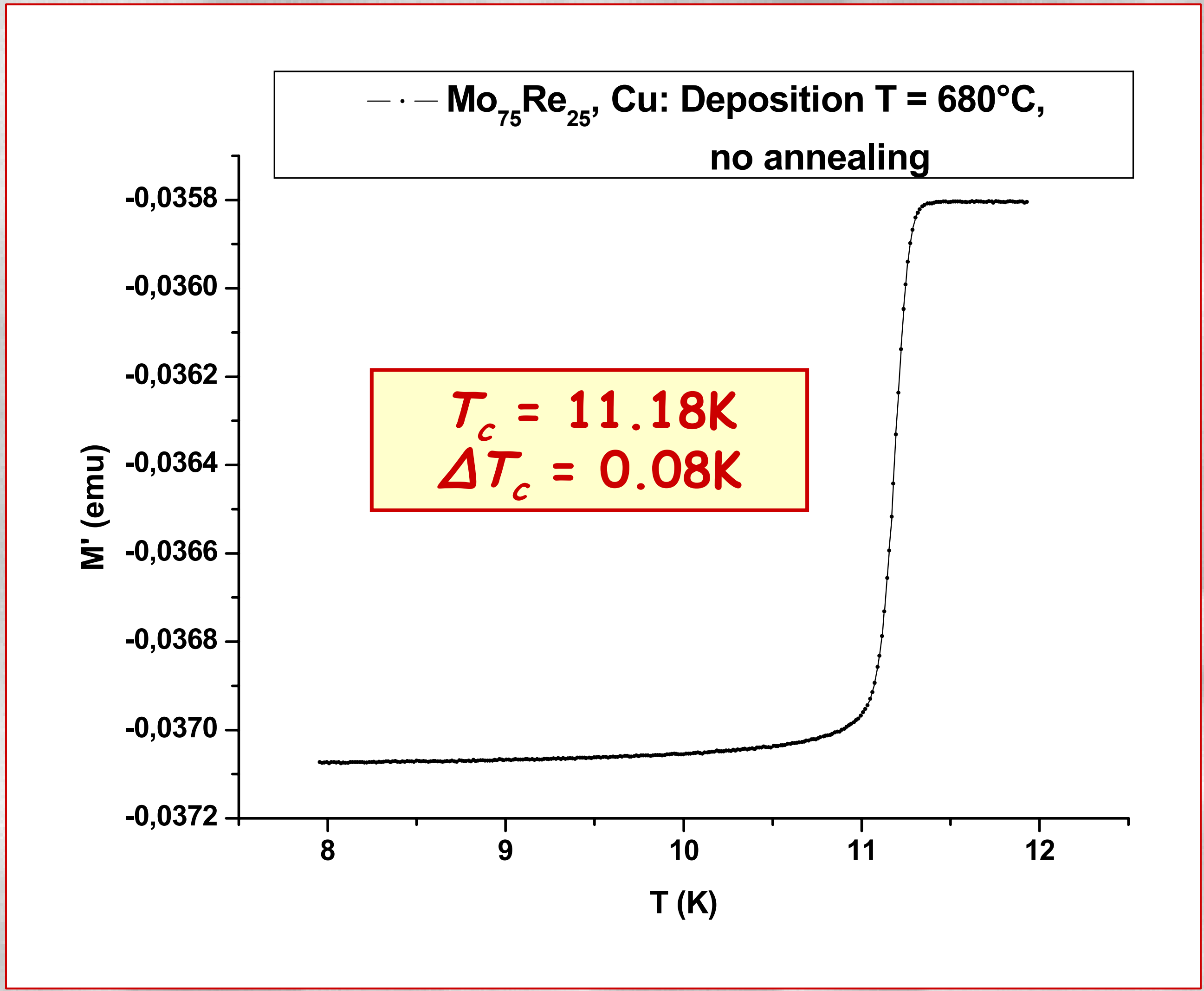


$Mo_{75}Re_{25}$: *R* vs T at Increasing H

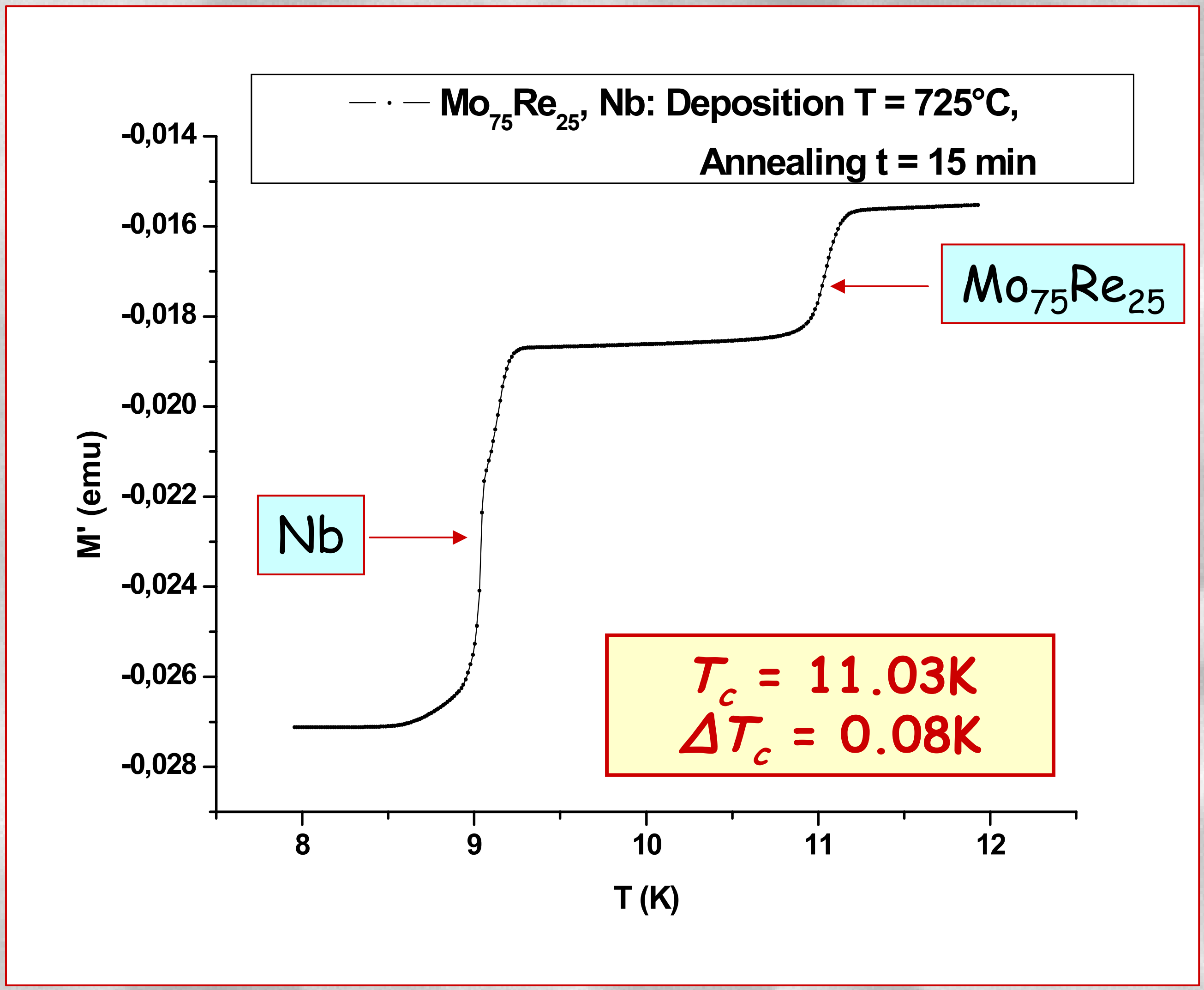
Deposition T = 633°C, Annealing t = 15 minutes



A $Mo_{75}Re_{25}$ Film Deposited on Cu



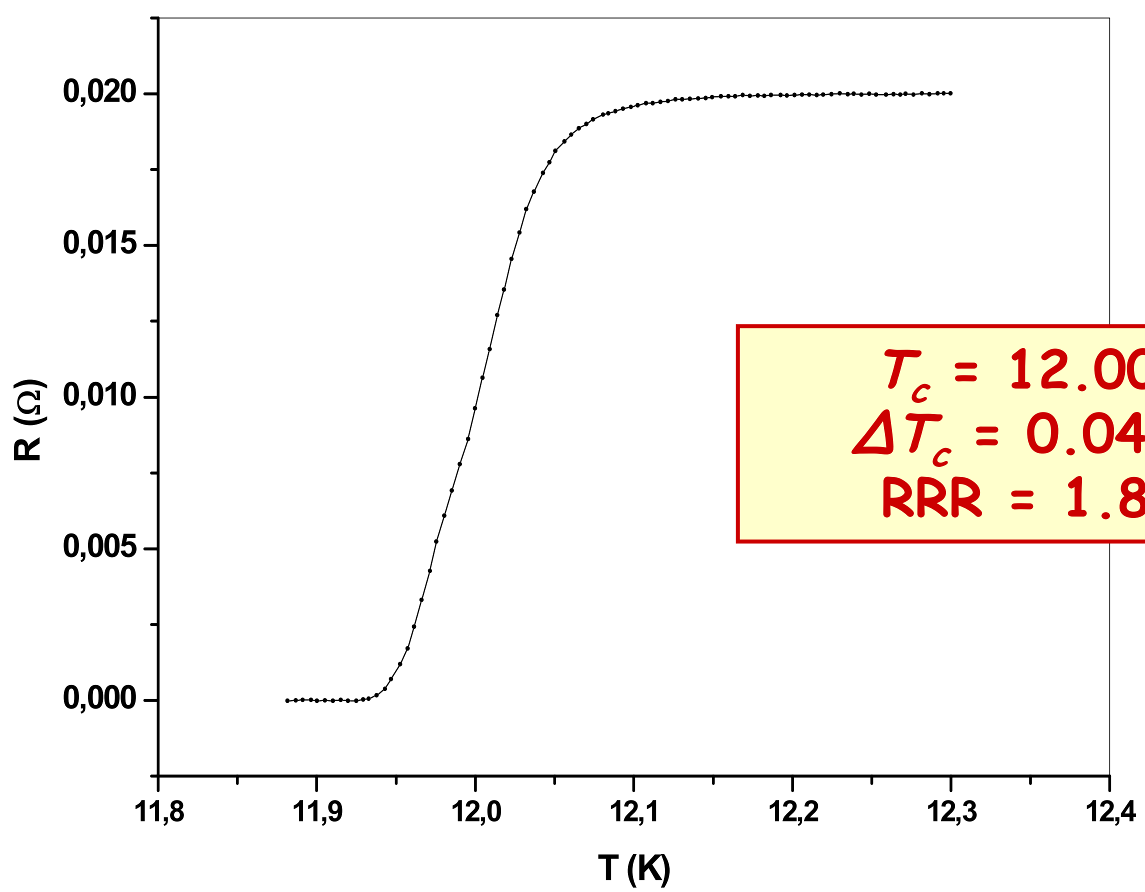
A $Mo_{75}Re_{25}$ Film Deposited on Nb



$Mo_{60}Re_{40}$: A Superconductive Transition Curve

Deposition T = 750°C

Annealing t = 60 min

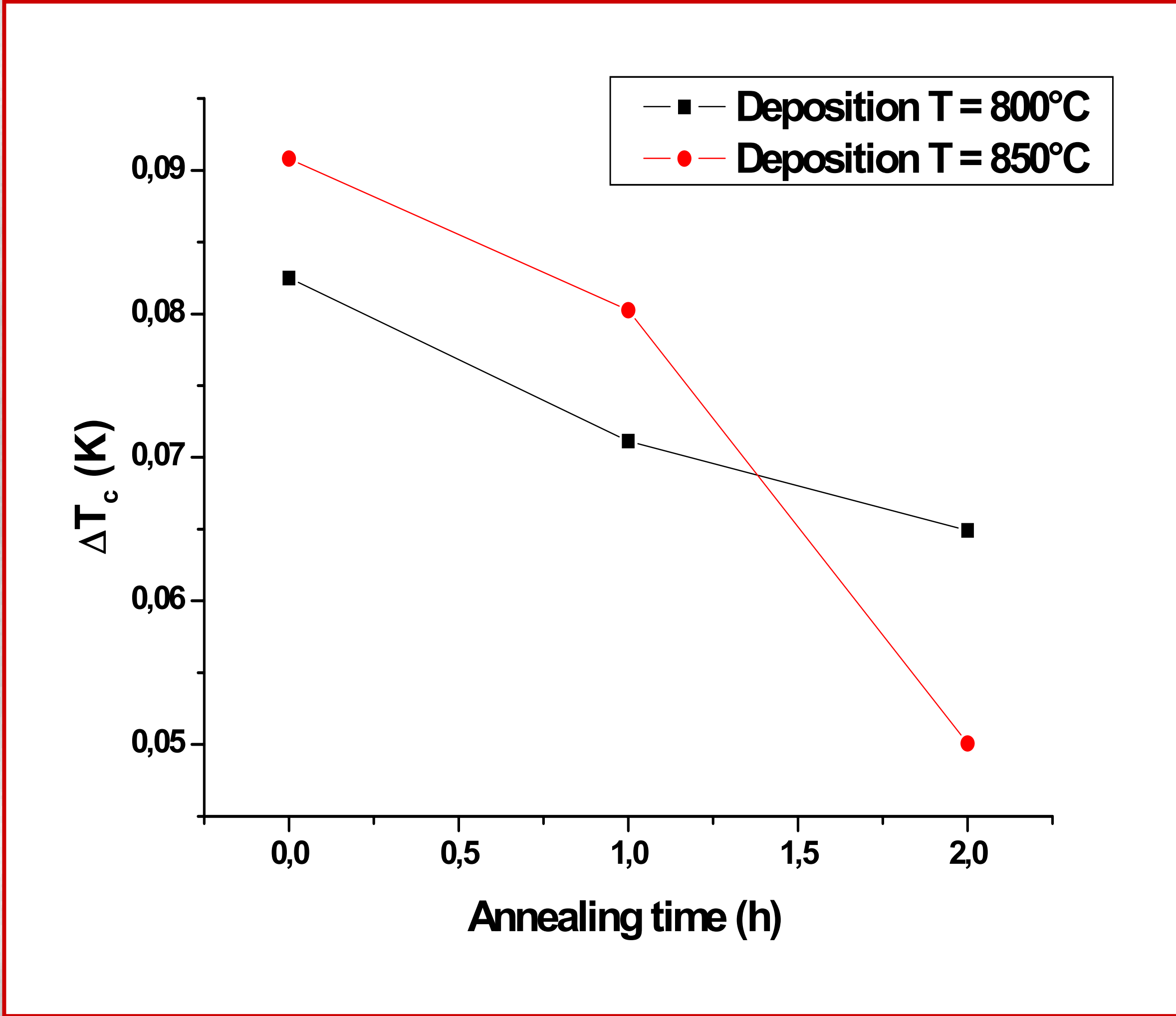


T_c = 12.00K

ΔT_c = 0.041K

RRR = 1.88

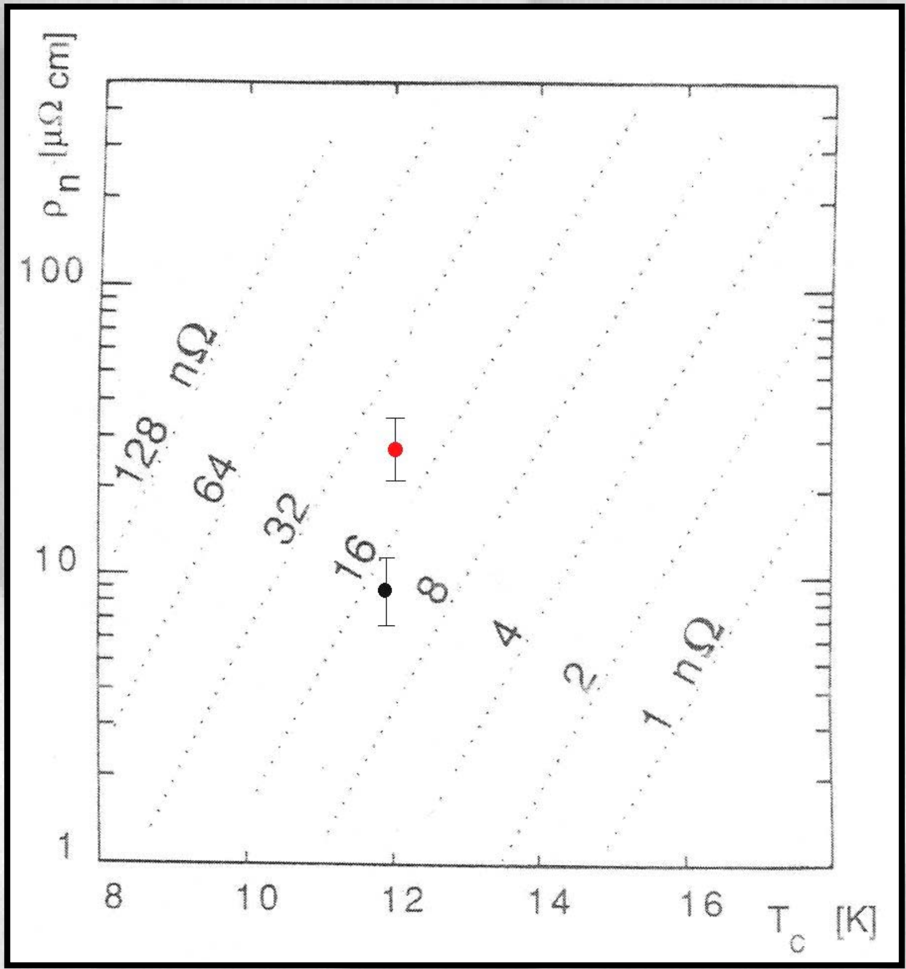
$Mo_{60}Re_{40}$: ΔTc vs Annealing Time



Nomogram

Lines of equal R_{BCS}. At T = 4.2 K, f = 500 MHz, s = 4

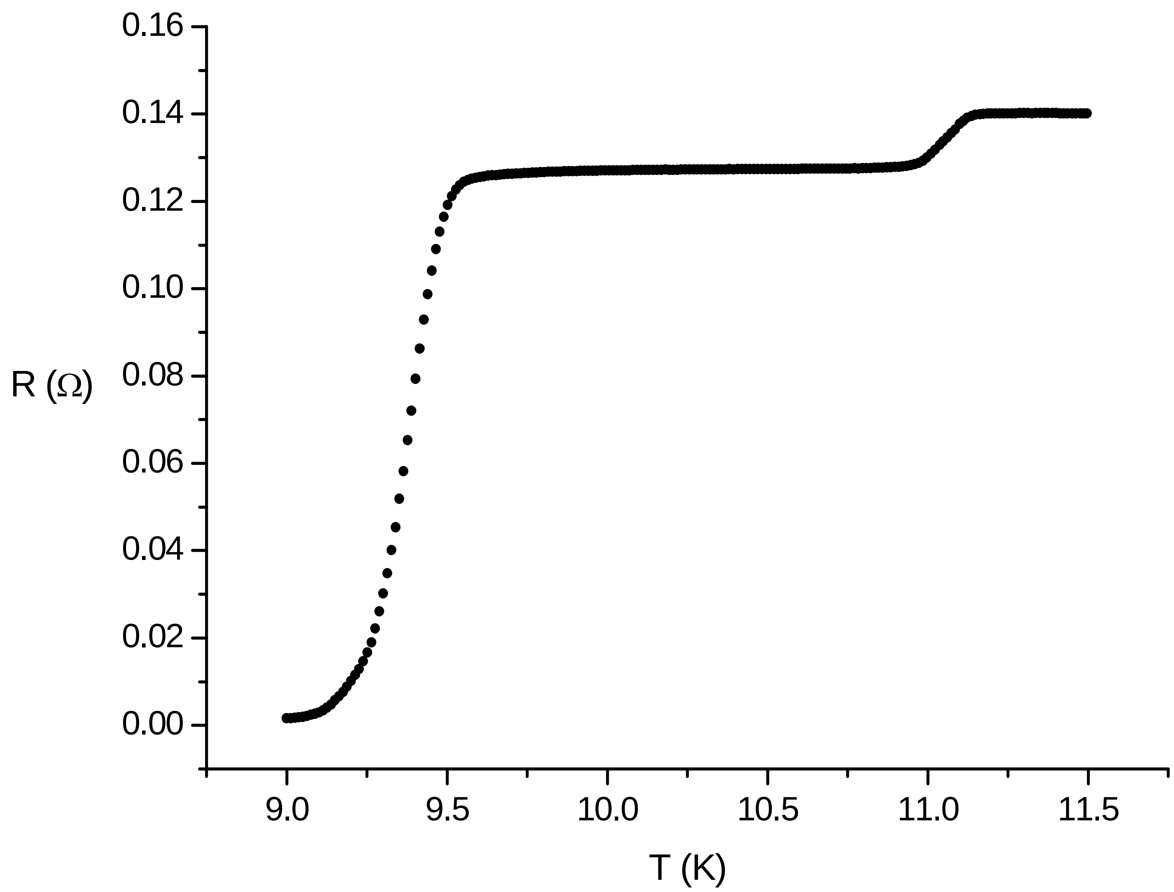
R_{BCS} depends on Δ and ρ_n



- $Mo_{60}Re_{40}$ (T_c = 12.13, RRR =1.3, ρ_n ~ 30μΩcm),
- $Mo_{75}Re_{25}$ (T_c = 11.82, RRR =1.71, ρ_n ~ 10μΩcm).

$Mo_{38}Re_{62}$: A Superconductive Transition Curve

Deposition T = 750°C, Annealing t = 60 minutes



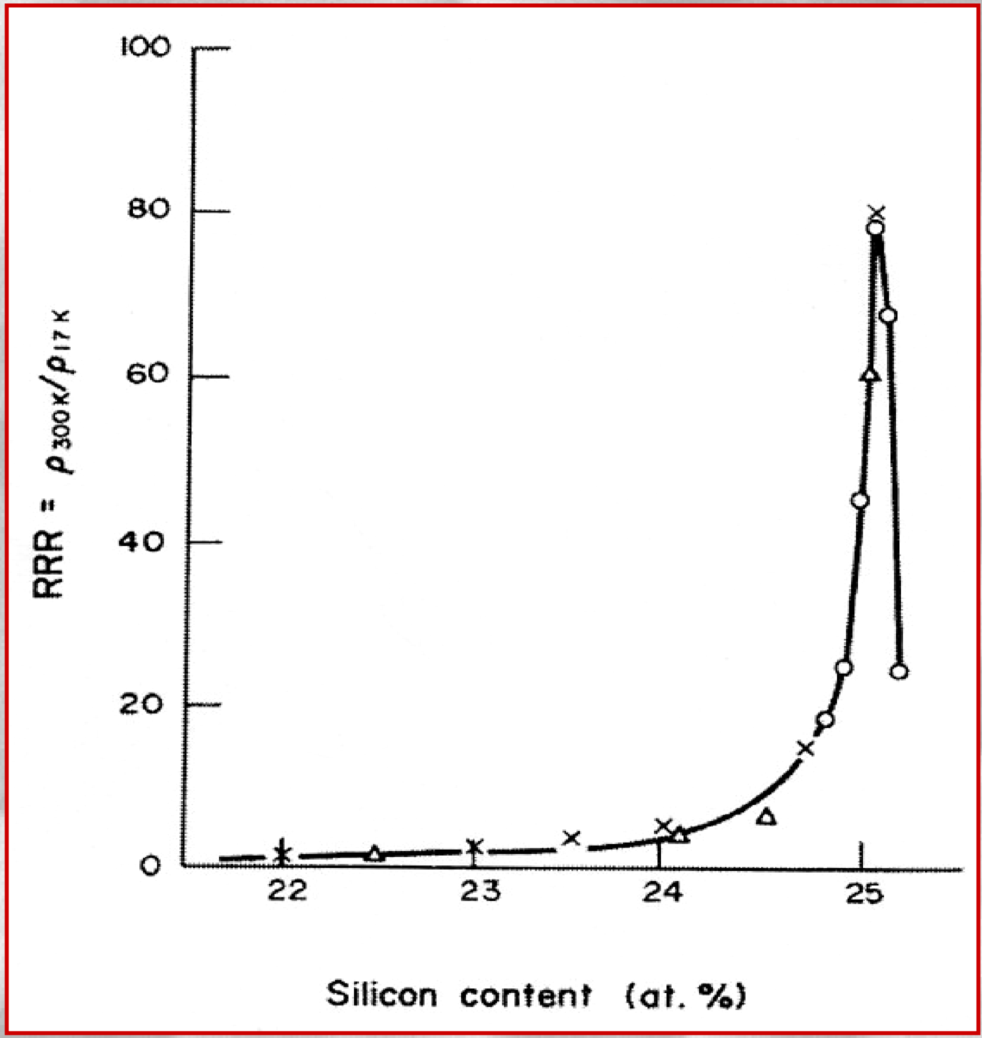
T_c = 9.47K
ΔT_c = 0.029K
RRR = 1.11

Essence of the previous slides

- We **deposited** more than **100 films**
- **Annealing** treatments give surprising results: **>T_c, <ΔT_c**
- **T_c is higher than 12K ($Mo_{60}Re_{40}$)**
- **R_{BCS} is around 16 nΩ ($Mo_{75}Re_{25}$, $Mo_{60}Re_{40}$)**

of the most meaningful parameters. **A sharp superconducting transition corresponds to a high ξ_0.**

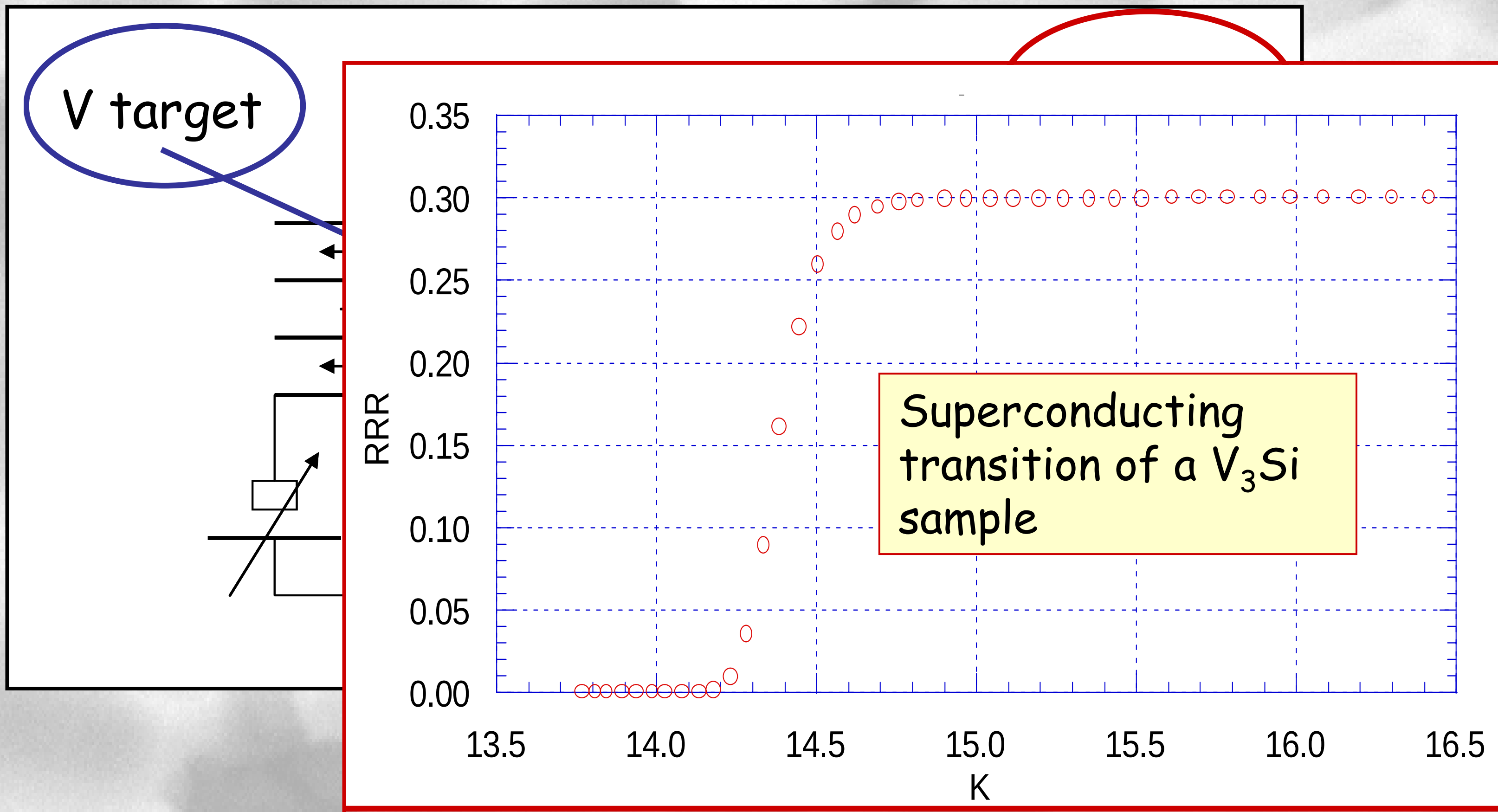
V_3Si: RRR vs Silicon content



Preliminary results on cosputtering of V_3Si films by the facing-target magnetron technique

Y. Zhang, V. Palmieri, R. Preciso, W. Venturini, Legnaro National Laboratory, ITALY

Schematic diagram of the facing-target magnetron.

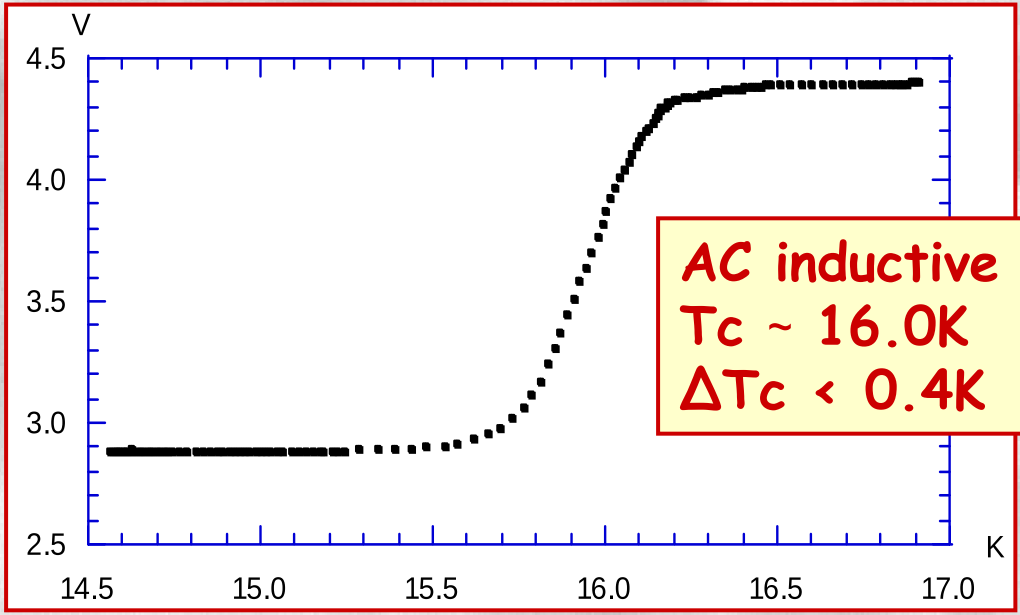


Thermal diffusion of V_3Si films

Y. Zhang, V. Palmieri, W. Venturini, F. Stivanello, R. Preciso, Legnaro National Laboratory, ITALY

Diffusion Parameters:

Silane pressure	Heat power	Temperature	Diffuse in silane	Anneal in vacuum
$1.2 \cdot 10^{-4}$mbar	300W	900°C	20h	40h

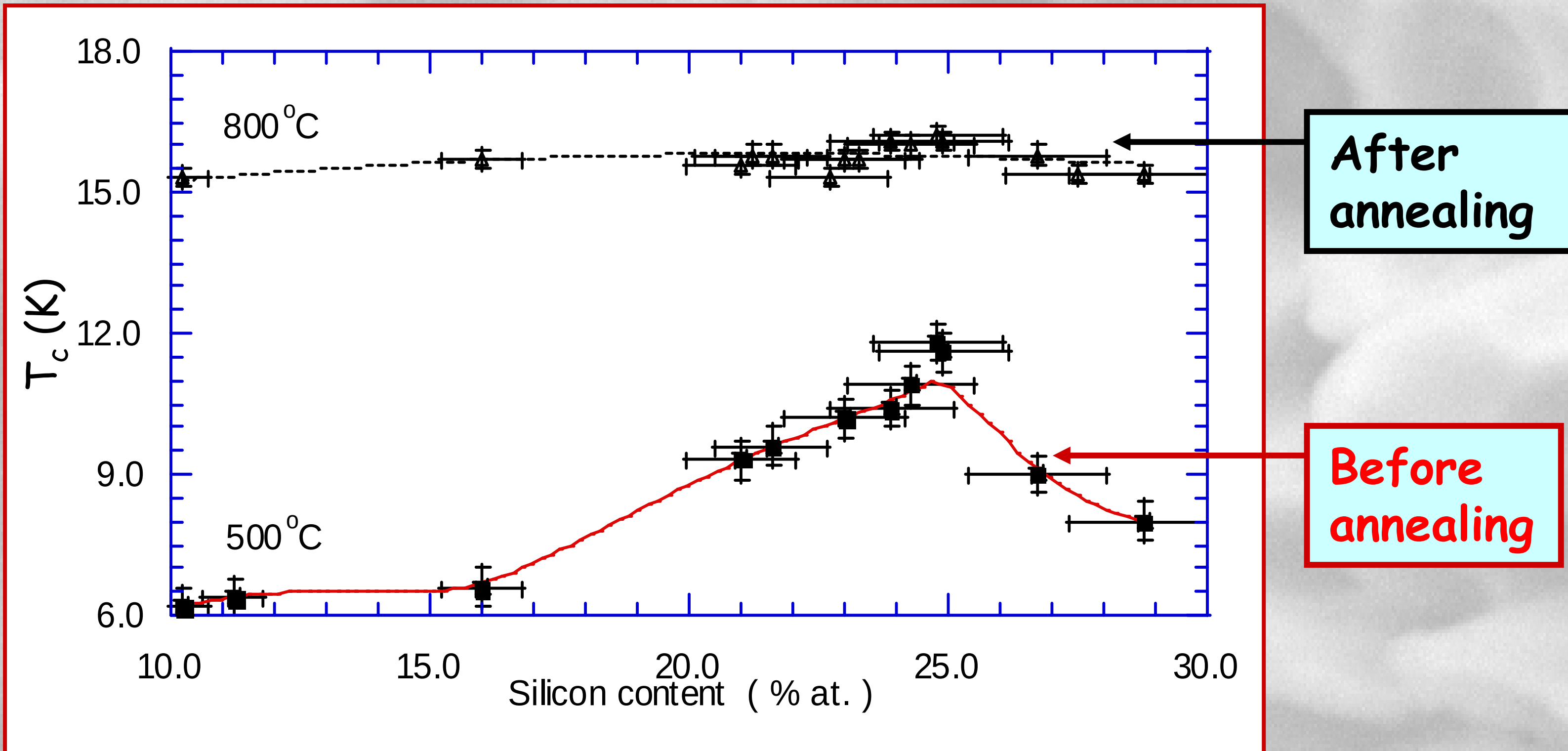


AC inductive measurement:
Tc ~ 16.0K
ΔTc < 0.4K

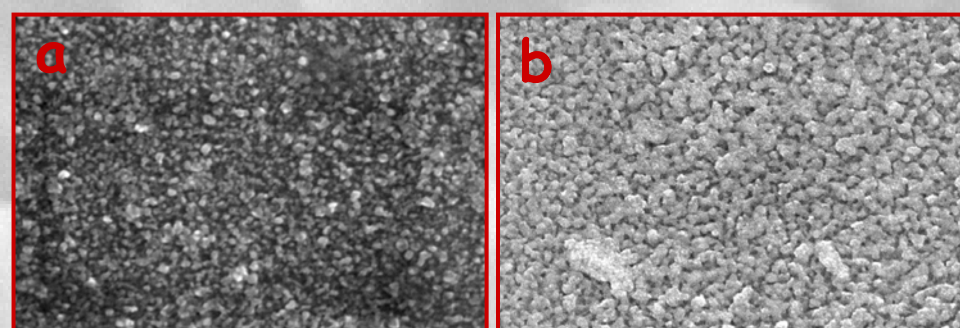
There is room to **improve the film quality** by **higher thermal diffusion temperature** or by **longer annealing time in vacuum**.

Reactive sputtered V_3Si films

Y. Zhang, V. Palmieri, W. Venturini, R. Preciso, Legnaro National Laboratory - INFN, Italy



Surface of two annealed samples under SEM: Grain size, (a) 0.2μm, (b) 0.5μm



Essence of the previous slides

No matter how **good** the initial **superconducing properties of the film** are

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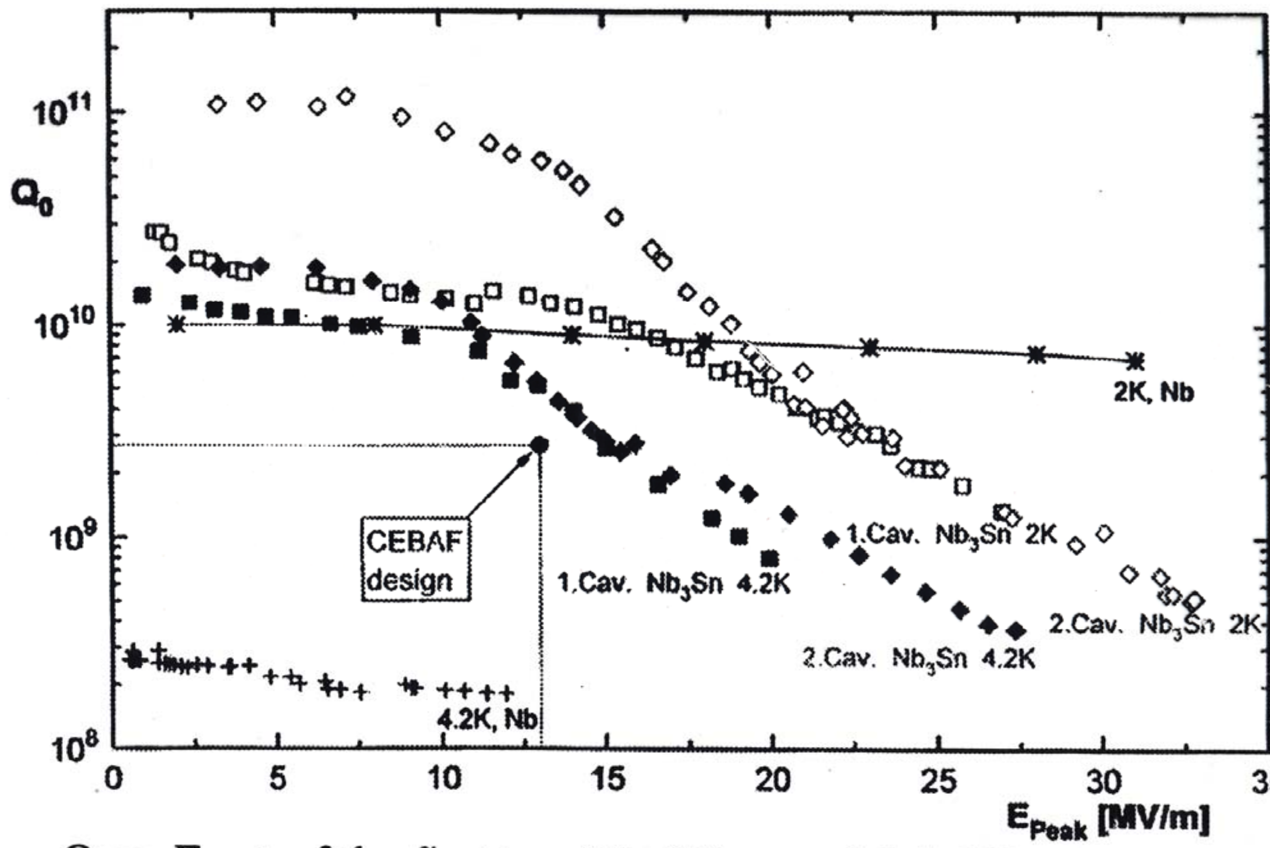
T_cs of **17 K** and **RRR** values of **18** have been recovered by **annealing in SiH_4** atmosphere

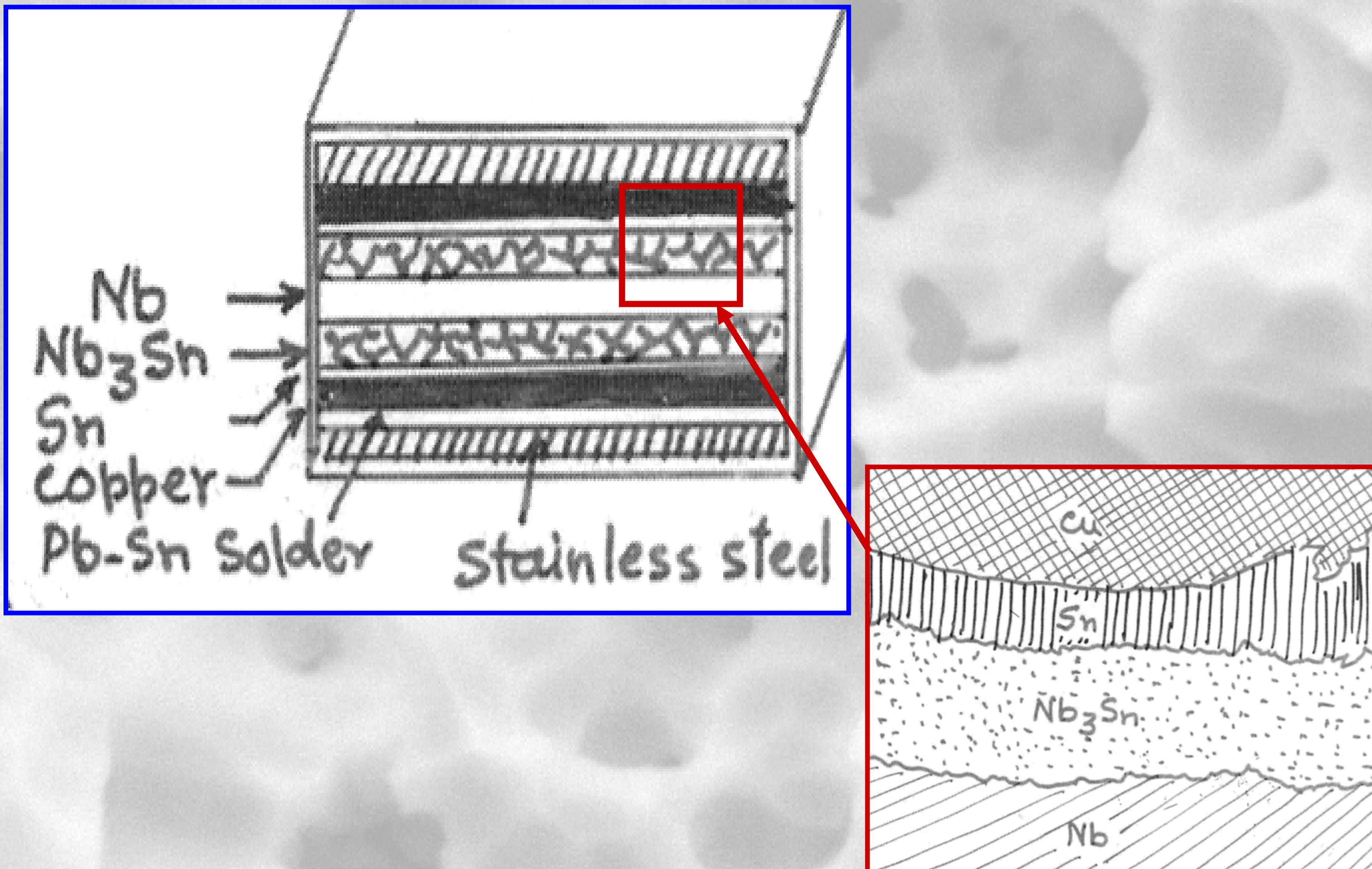
We are **ready** to **apply** the **thermal diffusion** method to **6 GHz** cavities

Wuppertal: Nb_3Sn cavity (1.5 GHz) obtained trough Sn vapour phase diffusion ('90s)

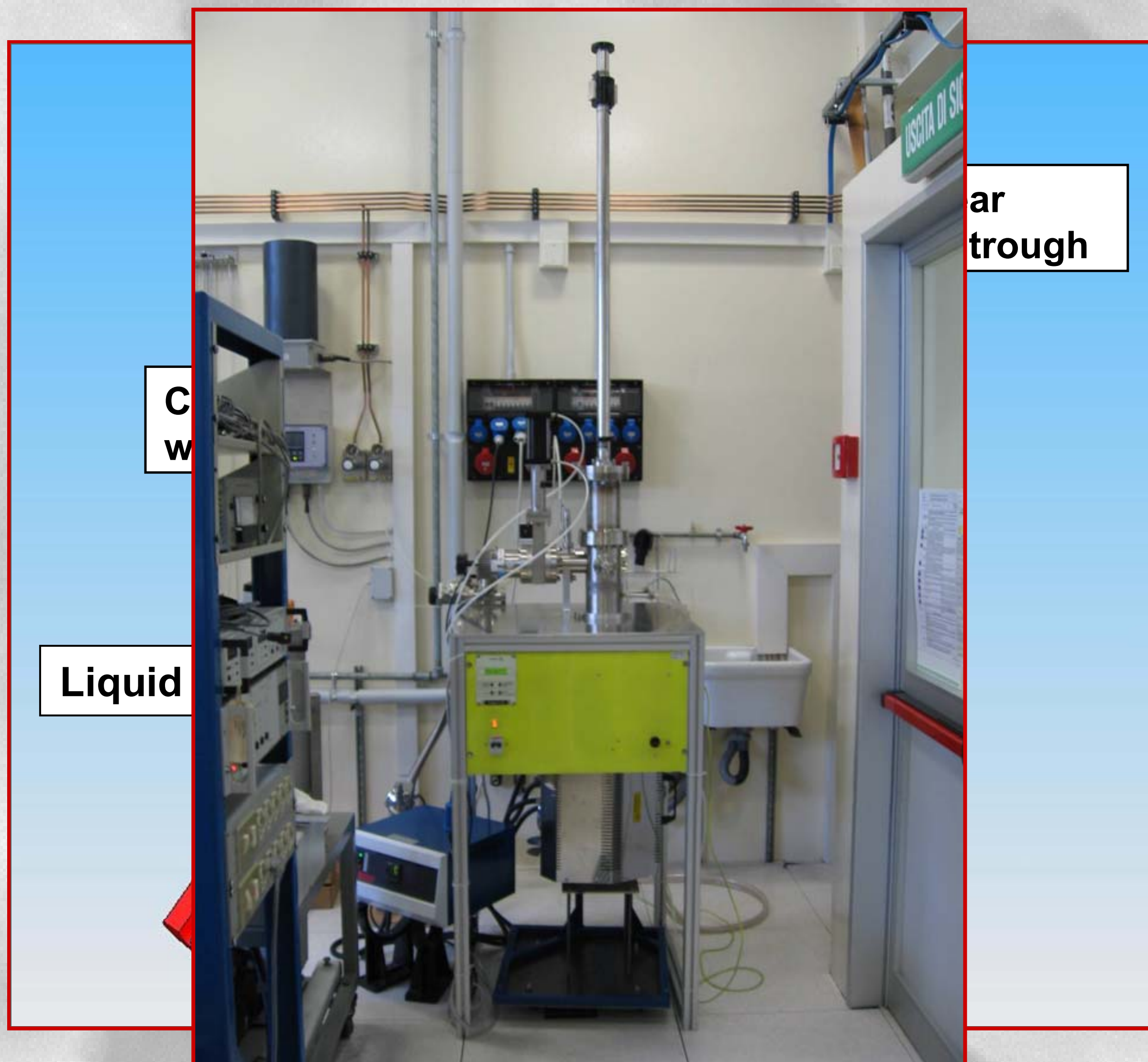


Q vs. Epeak of the first two Nb3SN-coated 1.5 GHz single-cell cavites in comparison to pure Nb at 4.2 K and 2 K frcm CEBAF.

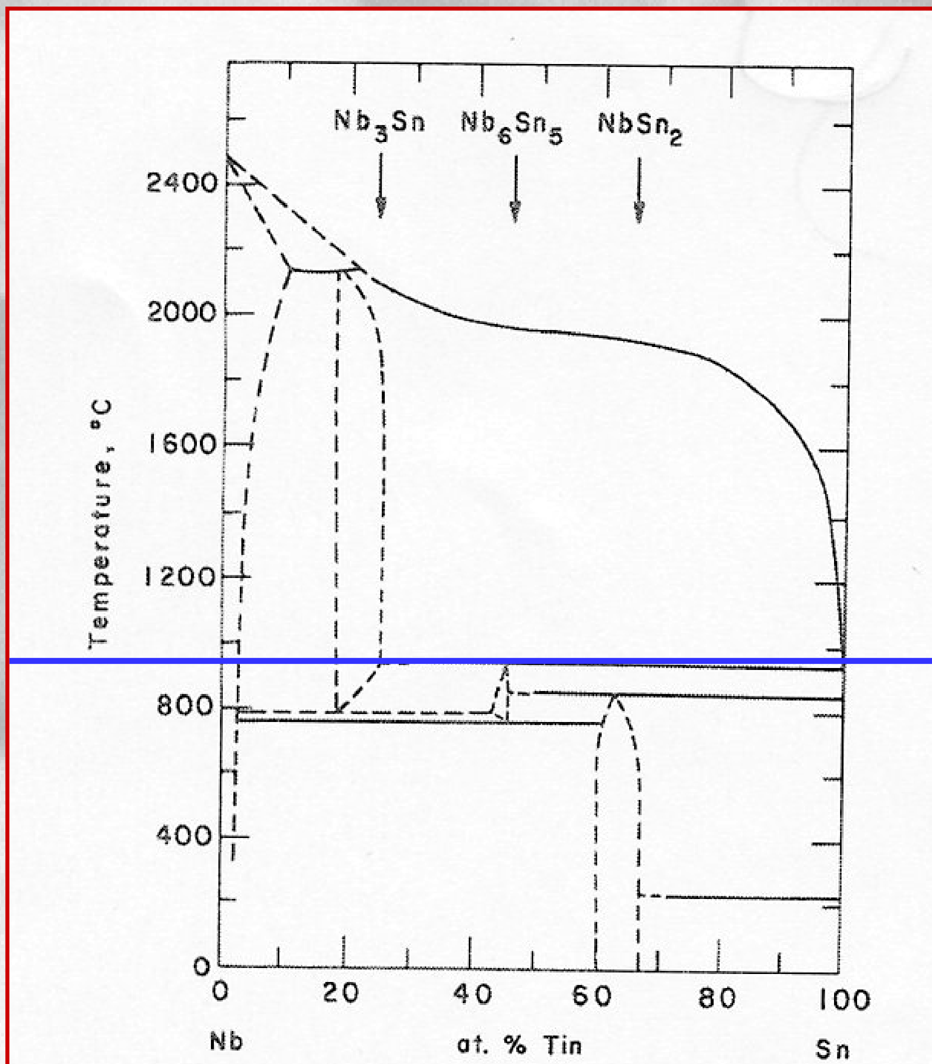
Nb_3Sn: Liquid solute diffusion



Nb_3Sn: Used System



Nb_3Sn: Phase Diagram

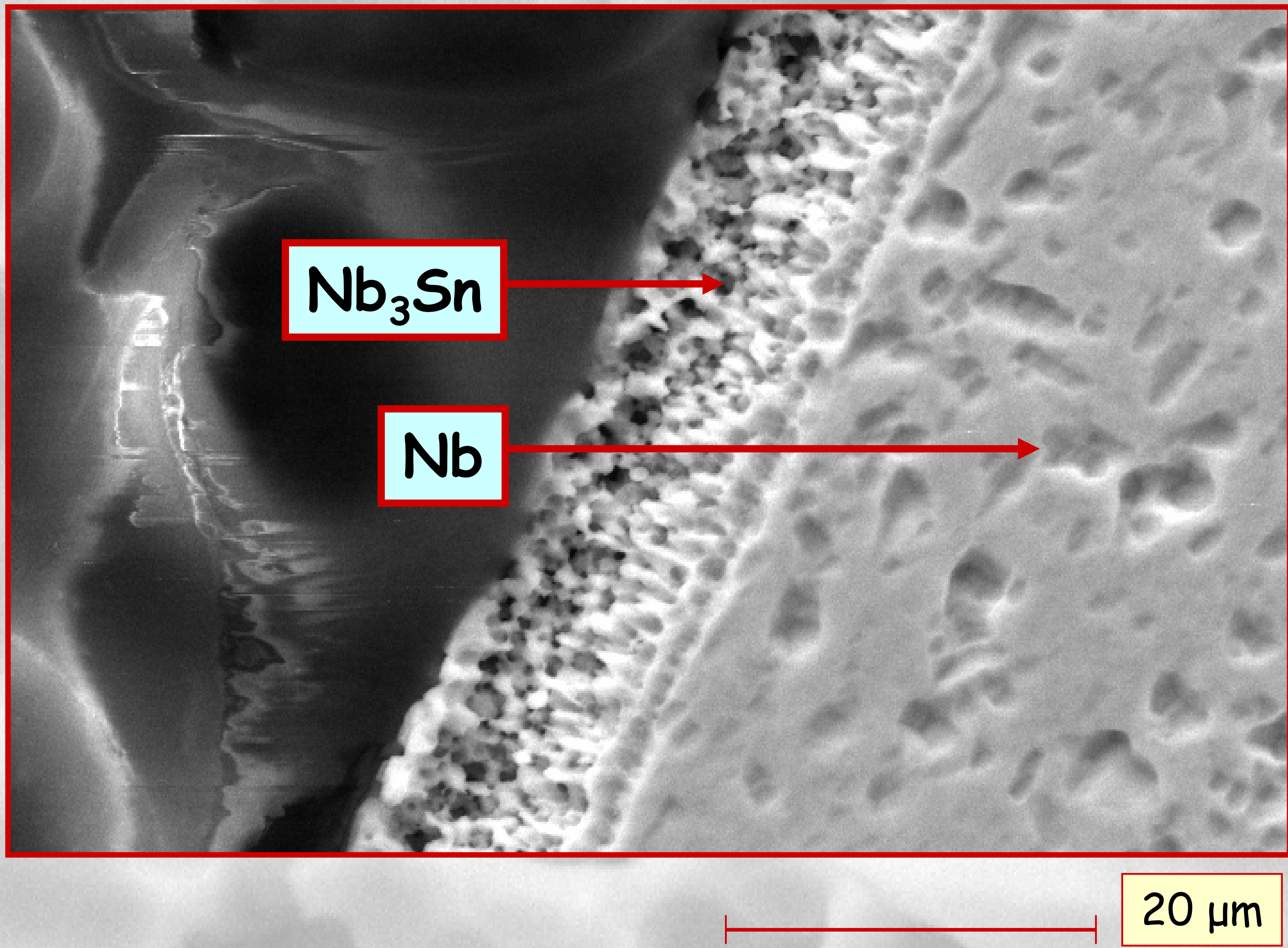


Nb_3Sn

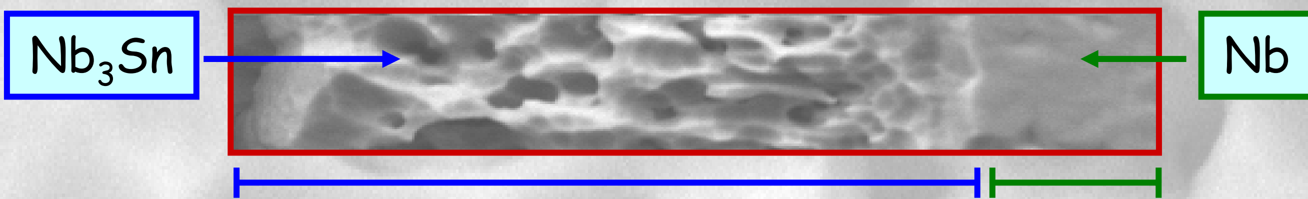
930°C

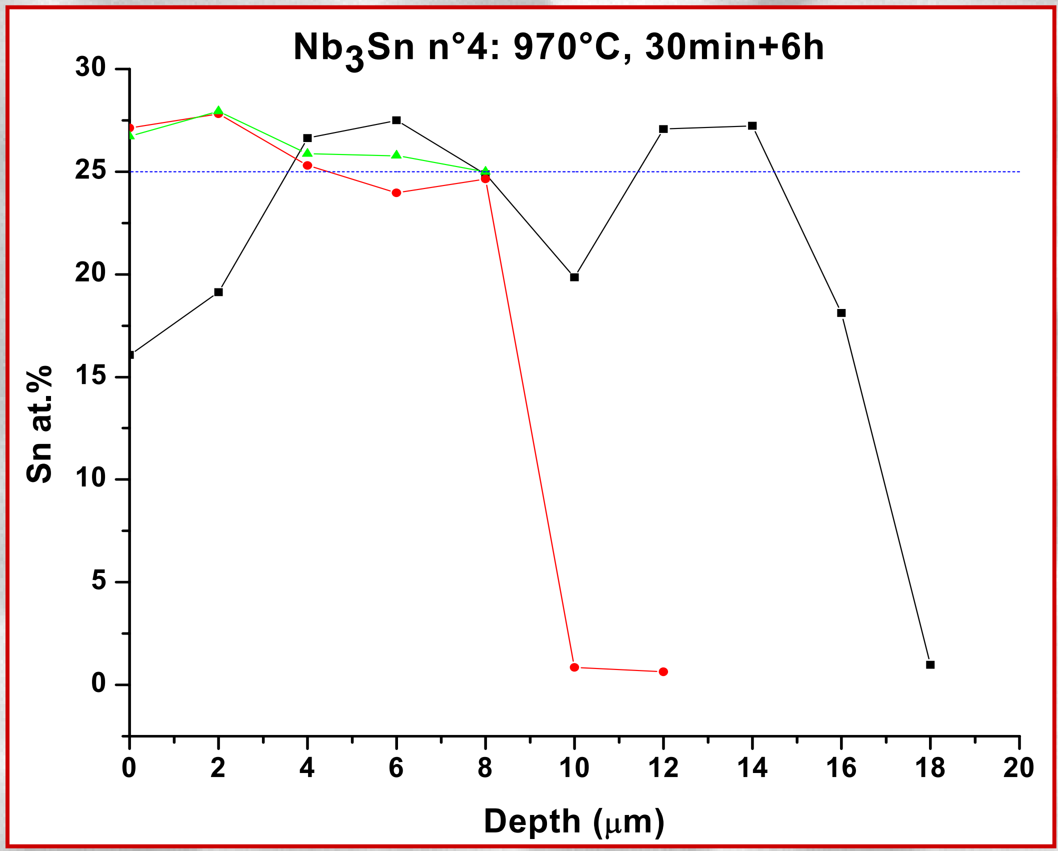
$<T_c$ phases

Nb_3Sn: SEM Image

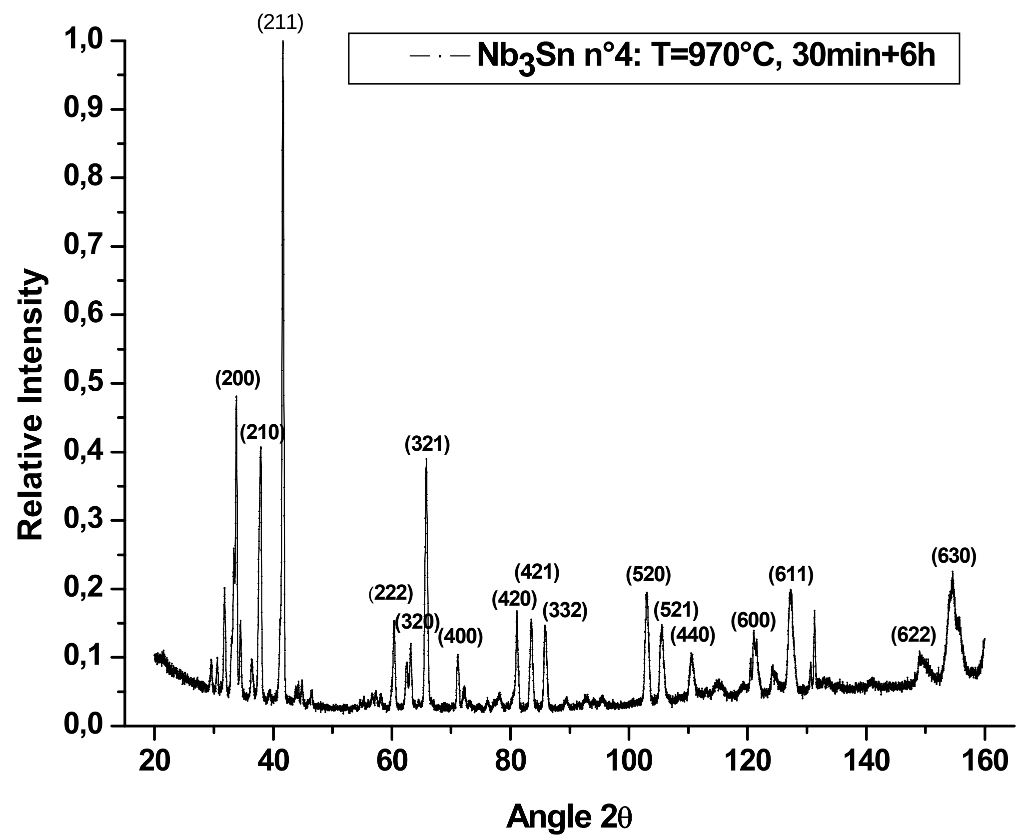


Nb_3Sn: Sn at.% vs Depth



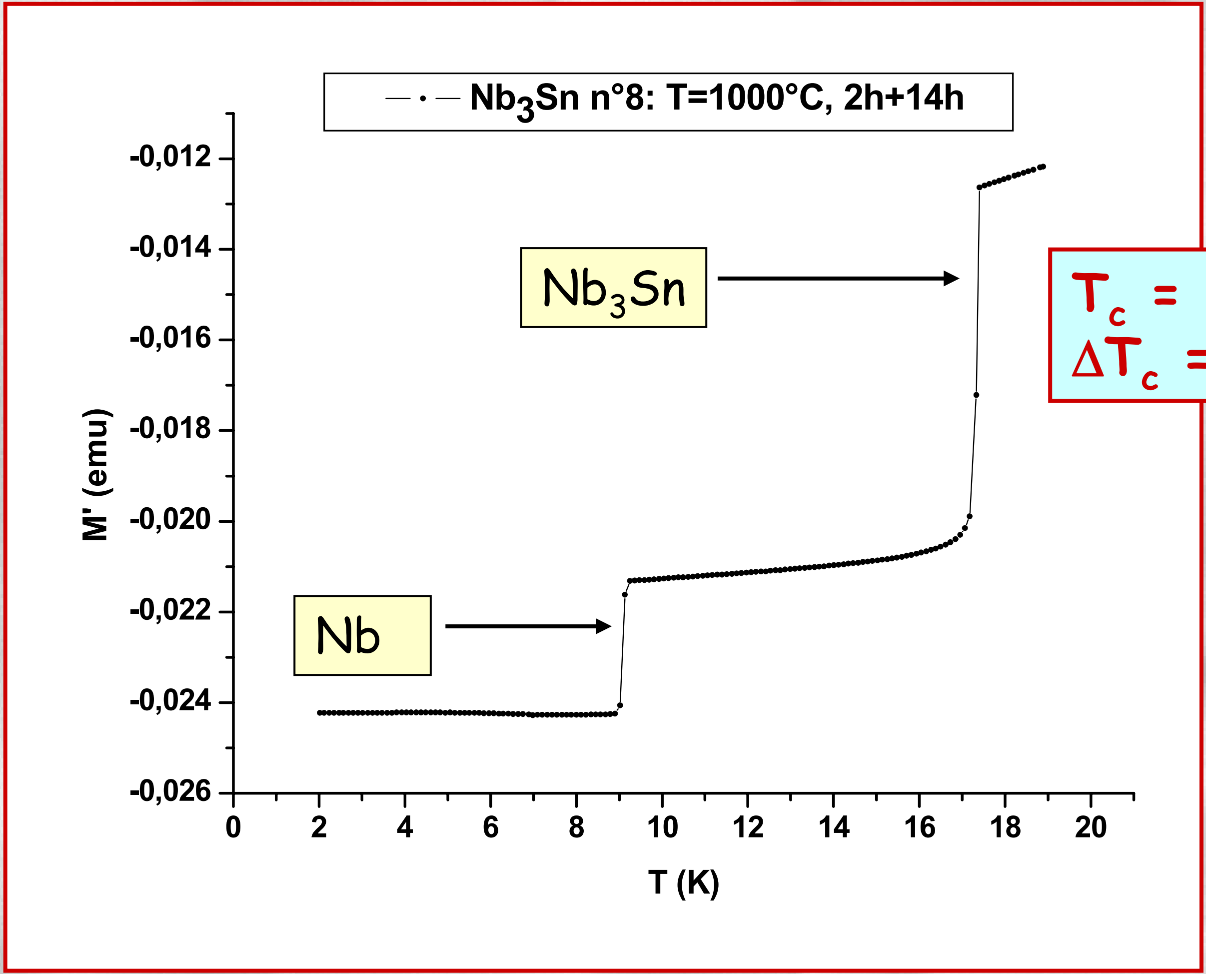


Nb_3Sn: XRD



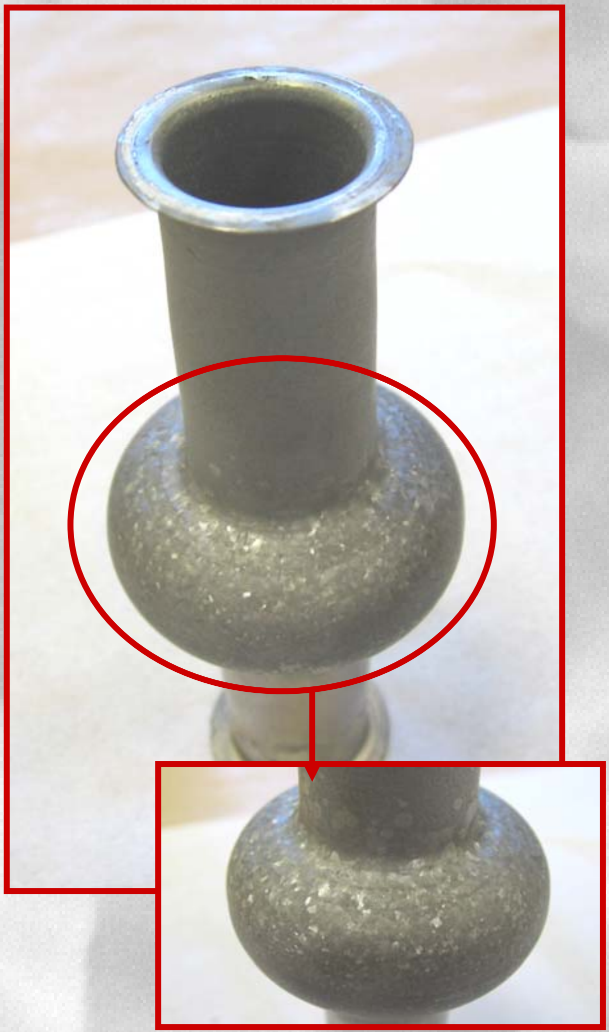
Nb3Sn n°4: T=970°C, 30min+6h
Relative Intensity
Angle 2θ
(211)
(200)
(210)
(321)
(222)
(320)
(400)
(420)
(421)
(332)
(520)
(521)
(440)
(600)
(611)
(622)
(630)
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
20
40
60
80
100
120
140
160

Nb_3Sn: A Superconductive Transition Curve



T_c = 17.3 K
ΔT_c = 0.1 K

Nb_3Sn: A 6 GHz Cavity



Nb_3Sn Process Parameters:

T = 970°C
Dipping time = 1h
Annealing time = 1h

Nb_3Sn Surface Treatment:

Pure HCl (55-66°C)
for 15 minutes

Essence of the previous slides

• **Uniformity** of Nb_3Sn film ensured and **stoichiometry** mantained

• We can **avoid Nb-Sn low T_c phases**:

- **manteining T > 930°C** during the experiment
- **reducing T** very **fast** at the **end** of the process

• A possible **Sn outer layer** has to be **removed**: we are able to **get rid of it** by prolonged **post annealing**

And now?

We can **produce** a large amount of **samples but** it is **difficult** to **measure** their **RF resistance**

⬇

6 GHz seamless cavities

obtained by the spinning technique:

- are made from scrap material
- do not need welding (even for flanges)
- are directly measured inside a Liquid He dewar

6 GHz Cavities

1. Spinning Technique
2. Surface Treatments
   - Mechanical polishing
   - Chemical polishing
   - A15 obtainment
3. Q Factor Measurement

6 GHz Cavities: Q Factor Measurement

Conclusions

From scrap material and by a seamless technique

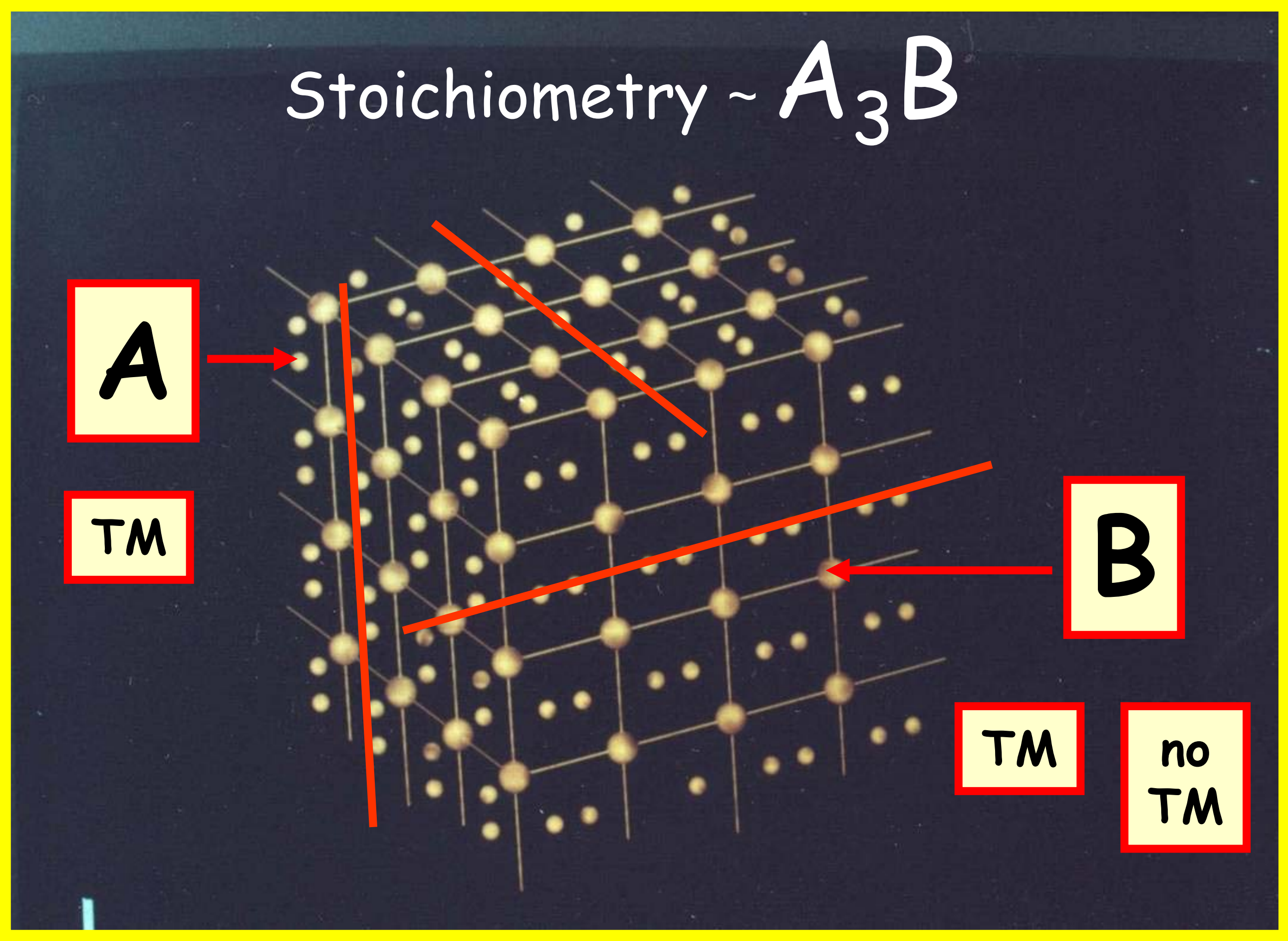
we are planning

A 6 GHz CAVITIES MASS PRODUCTION TO

***INVESTIGATE* A15 INTERMETALLIC COMPOUNDS**

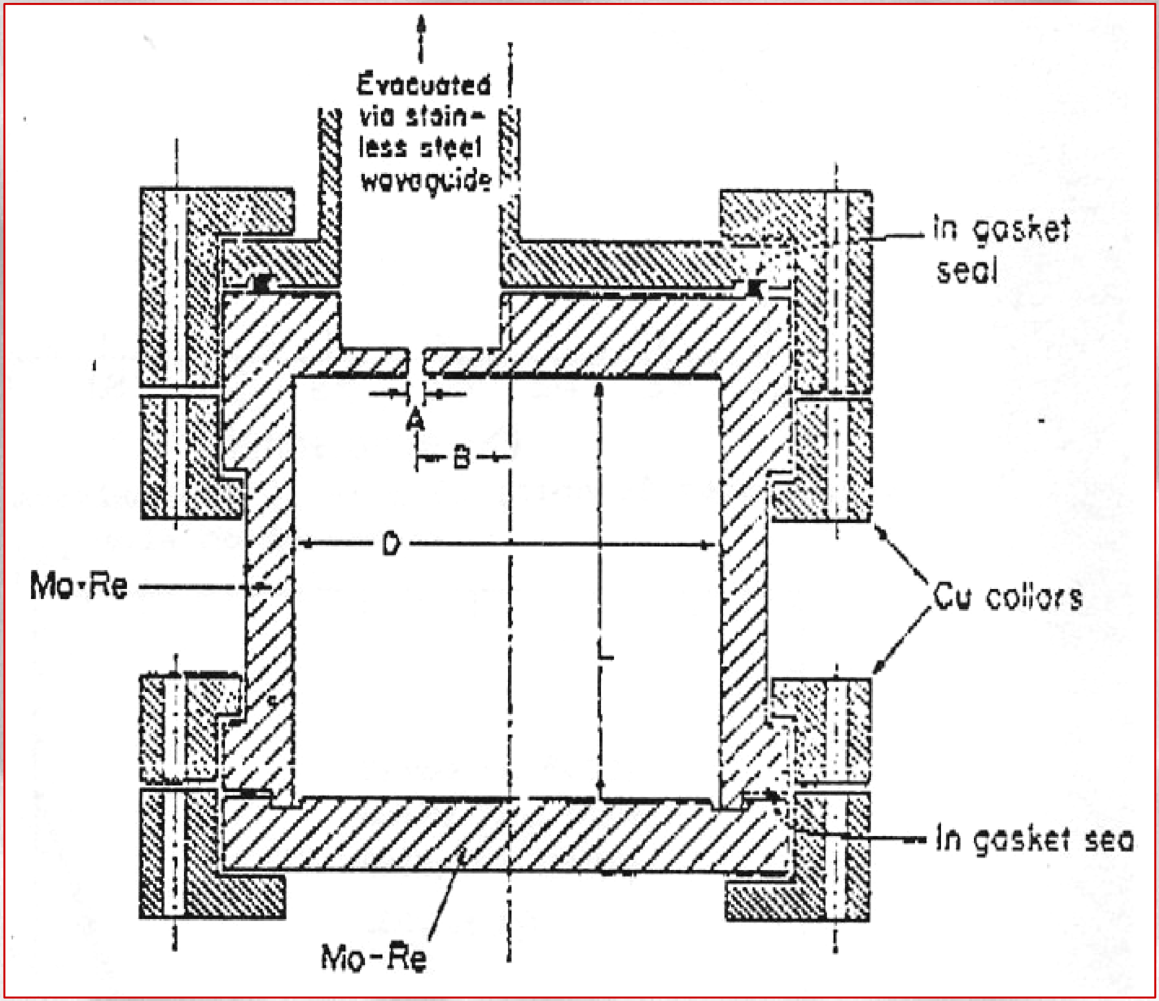
The end

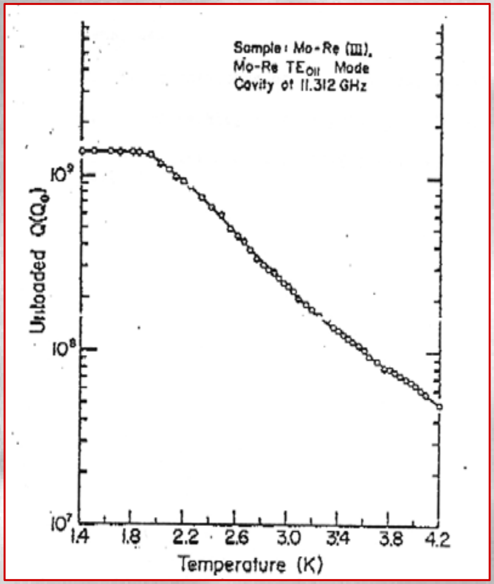
A15 Compounds Structure



A atoms form **linear chains**: they are parallel
to the 3 crystallographic directions [100], [010], [001]

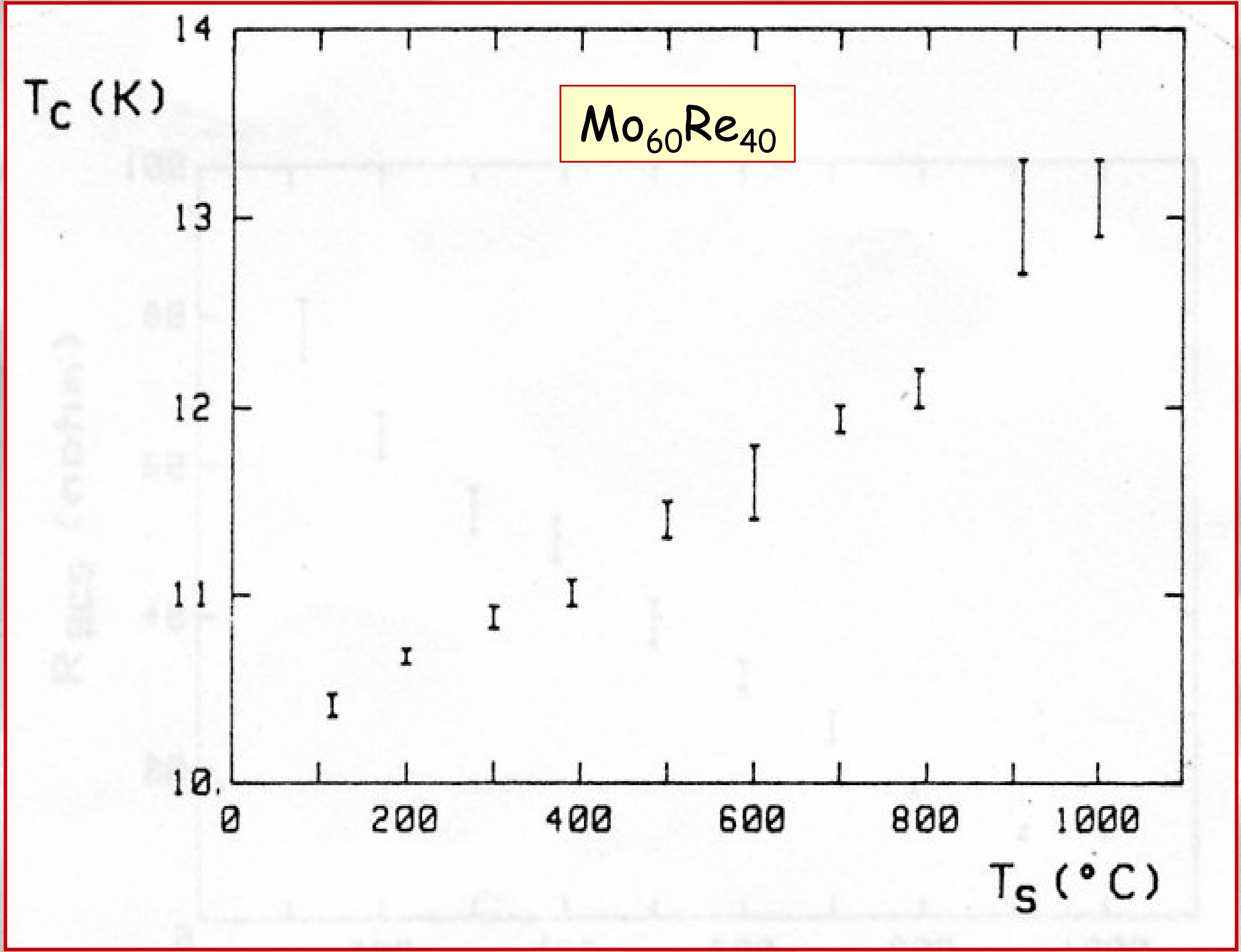
$Mo_{75}Re_{25}$ Cavity (MIT 1978)





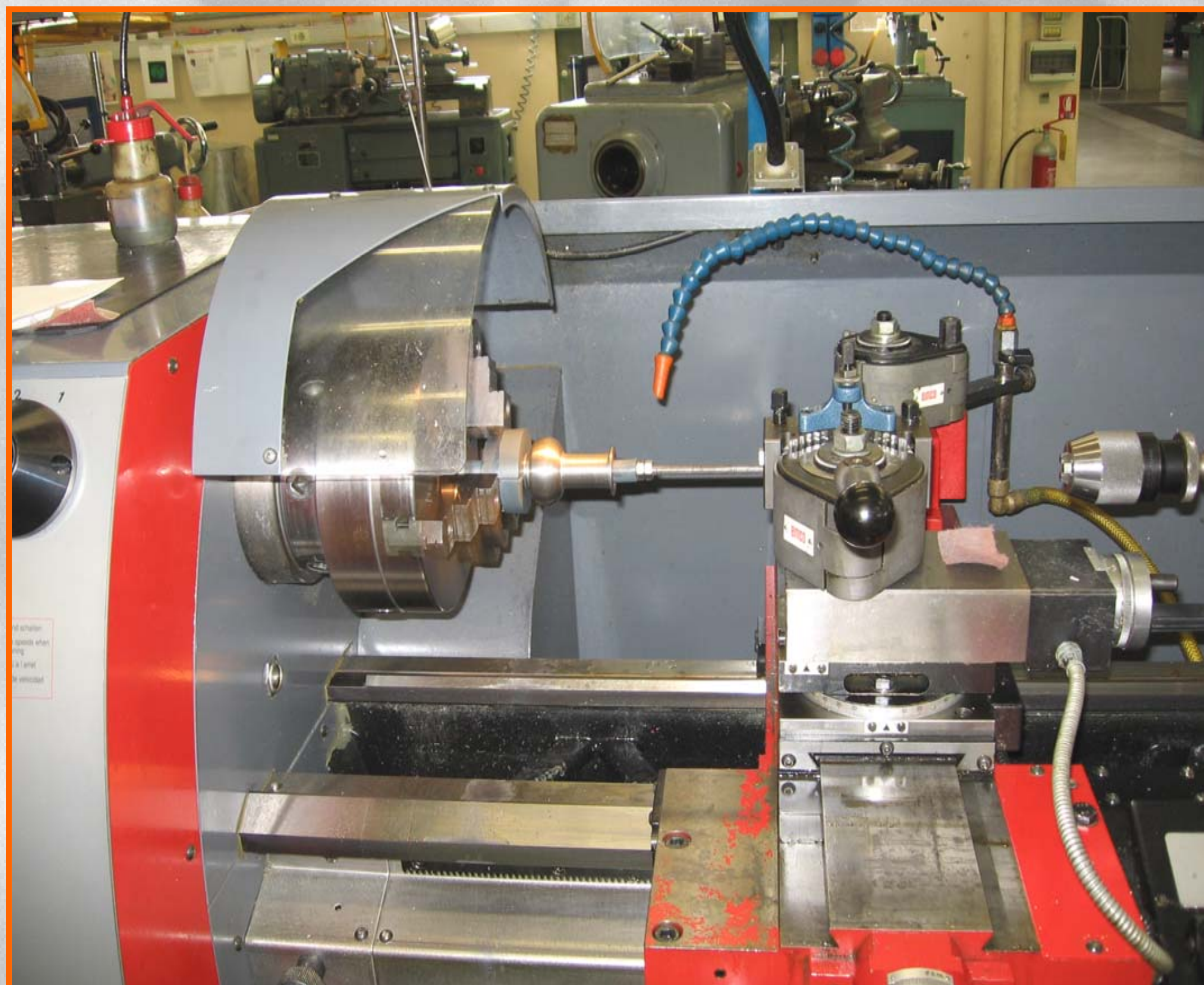
K. Agyeman, I. M. Puffer, J. A. Yasaitis and R. M. Rose, "Superconducting $Mo_{0.75}Re_{0.25}$ cavities at X-band"

Literature: Mo-Re system



A.Andreone, A.Barone, A.Di Chiara, G.Mascolo, V.Palmieri, G.Peluso, U.Scotti, 1988

6 GHz Cavities: Mechanical Polishing



6 GHz cavities: Chemical Polishing