CAS

Mechanical & Materials Engineering for Particle Accelerators and Detectors

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Vacuum Brazing

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EN/MME

Outline:

Introduction
- Brazing / Soldering
- Wetting
- Vacuum Brazing
- Vacuum Furnace

Vacuum Brazing assembly
- Metal/Metal Vacuum Brazing Examples
- Case of Glidcop
- Brazing and partial Diffusion Bonding

Vacuum Soldering Examples

Case of the RFQ

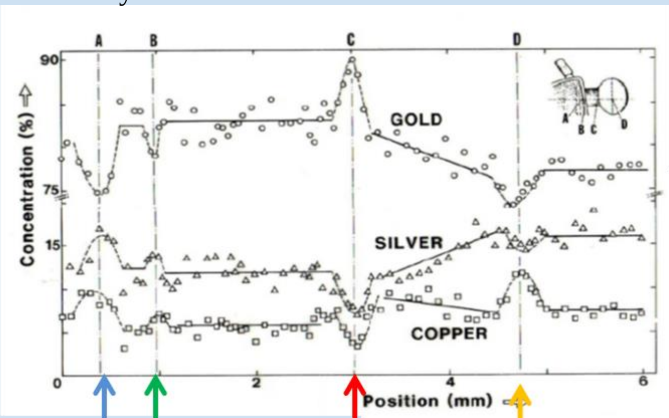
Vacuum Brazing of Alumina (Ceramic)
- With Metallisation
- With Active Alloys

Vacuum Brazing by Diffusion Brazing

Vacuum Brazing of large quantities

Brazing – a “old” story

PIXE analysis – LARN

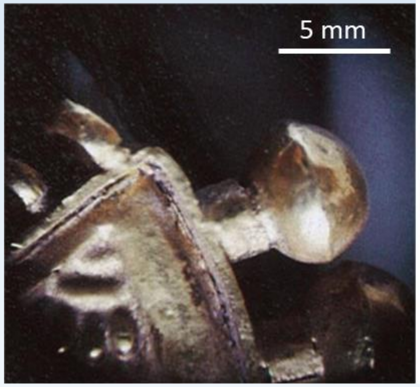


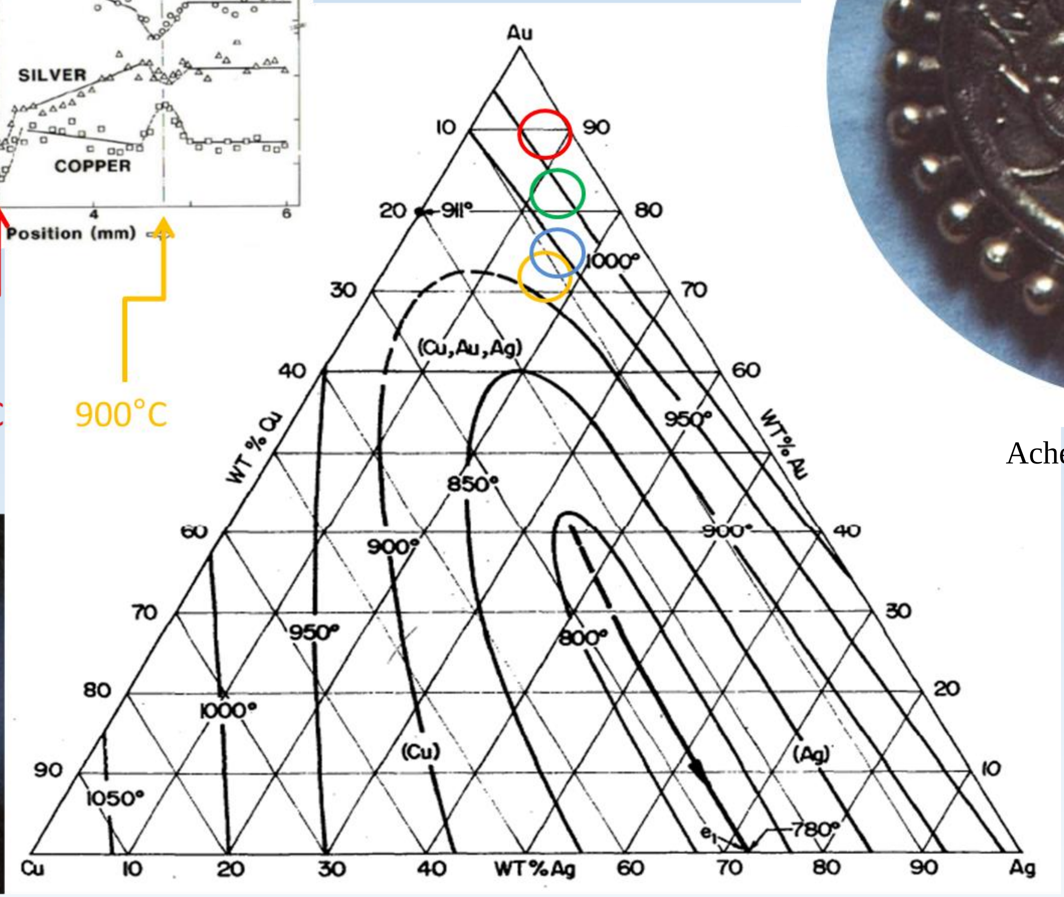
950°C

1000°C

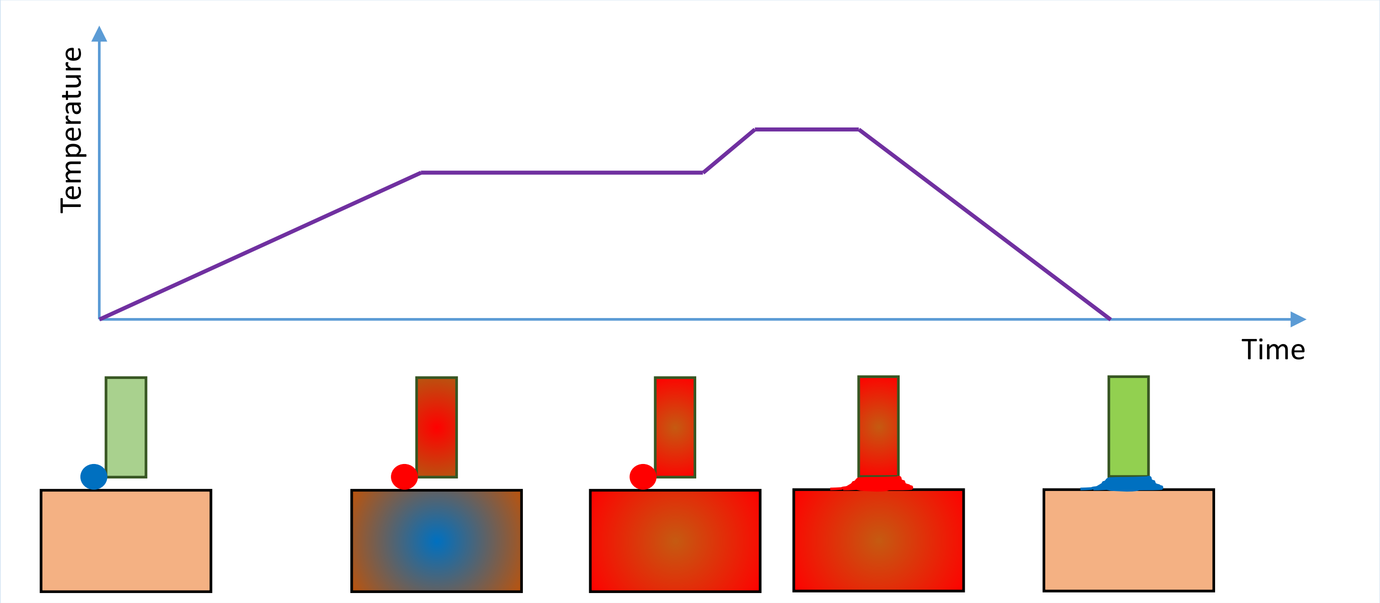
>1000°C

900°C





Achéménide pendant - 4° s. B.C. (Louvre)



- Brazing & Soldering: Assembly with a filler metal having a melting point lower than for the assembled materials
- Soldering: Melting point of the filler metal < 450 °C, Brazing: > 450 °C.

- Allow the assembly of different metals and no-metals (ceramics).
- Allow high precision assembly.
- Mechanical resistance generally less than for welding.

- Wetting of the filler metal obtained using a flux or with vacuum / reductive atmosphere (and coating if needed).

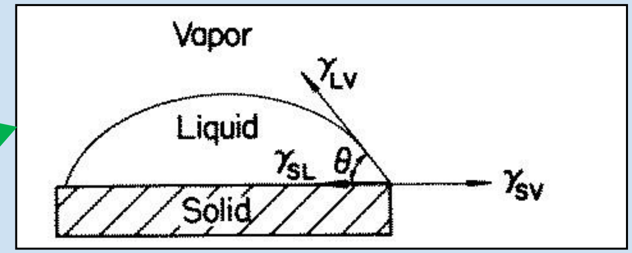
Air brazing & soldering — Vacuum brazing & soldering

The Wetting

$$\gamma_{SL} + \gamma_{LV} \cos(\Theta) = \gamma_{SV}$$ *(Young's relation)*

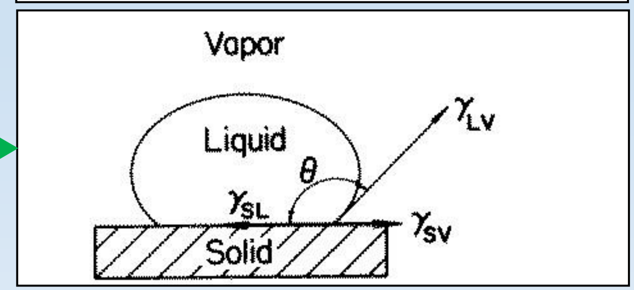
- Interaction
$\Rightarrow \gamma_{SL} \downarrow$
(Ex.: Cu-Ag on Cu)

- $\cos(\Theta) \uparrow$
$\Theta \downarrow$



- Pas d'interaction
$\Rightarrow \gamma_{SL} \uparrow$
(Ex.: Cu-Ag on Alumina)

- $\cos(\Theta) \downarrow$
$\Theta \uparrow$, $\cos(\Theta) > 90°$



Brazing / Soldering: $\theta < 30°$ …. Ideally 0° for good brazing by capillarity.

What prevents good wetting (*a good interaction*) on a metal is <u>oxidation!</u>

Two solutions: the flux or the vacuum

Main objective of the vacuum brazing: Oxide reduction at high temperature / low O_2 partial pressure

Example with Copper (Cu):

Gibbs energy of metal oxide formations: **G = H – TS** **H = U + PV**

For the reaction: $2\,Cu_2O \leftrightarrow 4\,Cu + O_2$

$$\Delta G^0 = \Delta H - T\Delta S \quad \rightarrow \quad \Delta G^0 \cong A + BT$$

$$\Delta G^0 = \int \Delta C_p dT - T \int \frac{\Delta C_p}{T} d_T$$

For **CuO_2**, A= -169881 and B= 74.43 [Source: CRC Handbook]

At 800°C, ΔG = -90 kJ → ΔG = -180 kJ for 1 mole of O_2.

At equilibrium, for the production of one mole of O_2:

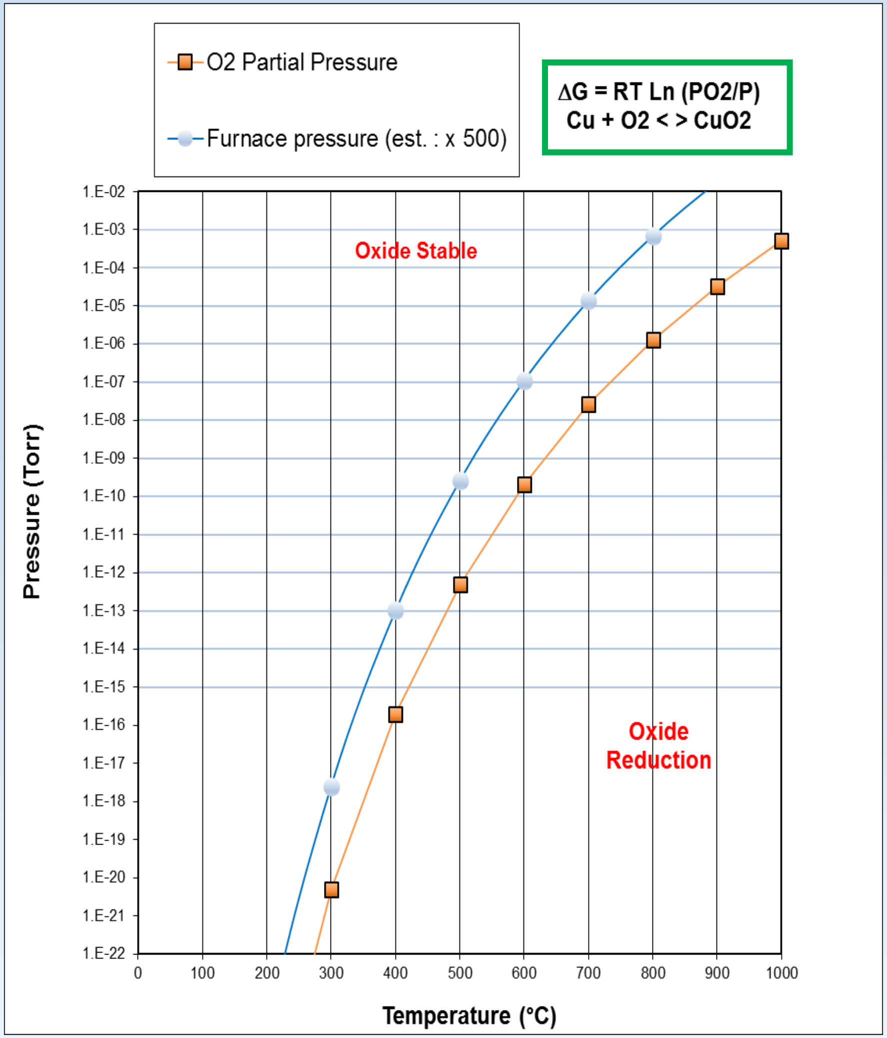
$$2\Delta G^0_{(T)} = RT \ln \frac{P_{O_{2(eq.,T)}}}{P}$$

With ΔG = -180 kJ, $\frac{P_{O_{2(eq.)}}}{P} = 1.7\ 10^{-9}$

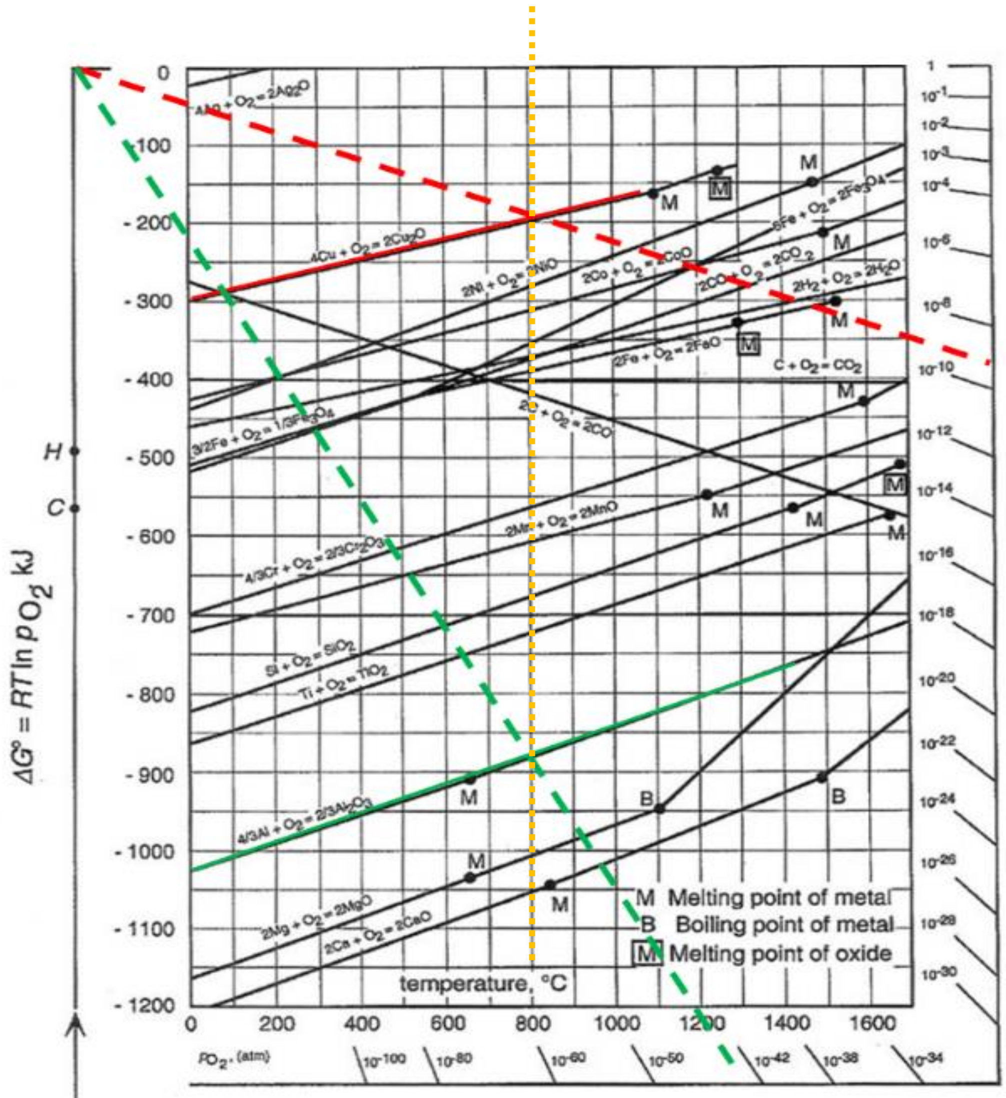
With P = 760 Torr, $P_{O_2(eq.)} = 1.3\ 10^{-6} (Torr)$

If : $P_{O_2(T)} > P_{O_2(eq.,T)}$ → The oxide is stable

$P_{O_2(T)} < P_{O_2(eq.,T)}$ → The oxide decompose


O2 Partial Pressure
Furnace pressure (est. : x 500)
ΔG = RT Ln (PO2/P)
Cu + O2 < > CuO2
Oxide Stable
Oxide Reduction
Pressure (Torr)
Temperature (°C)
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
1.E-15
1.E-16
1.E-17
1.E-18
1.E-19
1.E-20
1.E-21
1.E-22
0
100
200
300
400
500
600
700
800
900
1000

Vacuum Brazing – The Ellingham diagram



Ellingham diagram

$$2\,Cu_2O \leftrightarrow 4\,Cu + O_2$$

For CuO_2, A= -169881 and B= 74.43 [Source: CRC Handbook]

At 800°C, ΔG = -90 kJ → ΔG = -180 kJ for 1 mole of O_2.

With ΔG = -180 kJ, $\frac{PO_{2(eq.)}}{P} = 1.7\ 10^{-9}$

With P = 760 Torr, $P_{O_2(eq.)} = 1.3\ 10^{-6} (Torr)$

Reduction of the Copper Oxyde **possible** at 800 °C in a vacuum furnace.

$$\frac{2}{3} Al_2O_3 \leftrightarrow \frac{4}{3} Al + O_2$$

For Al_2O_3, A= -1689572 and B= 328.66 [Source: CRC Handbook]

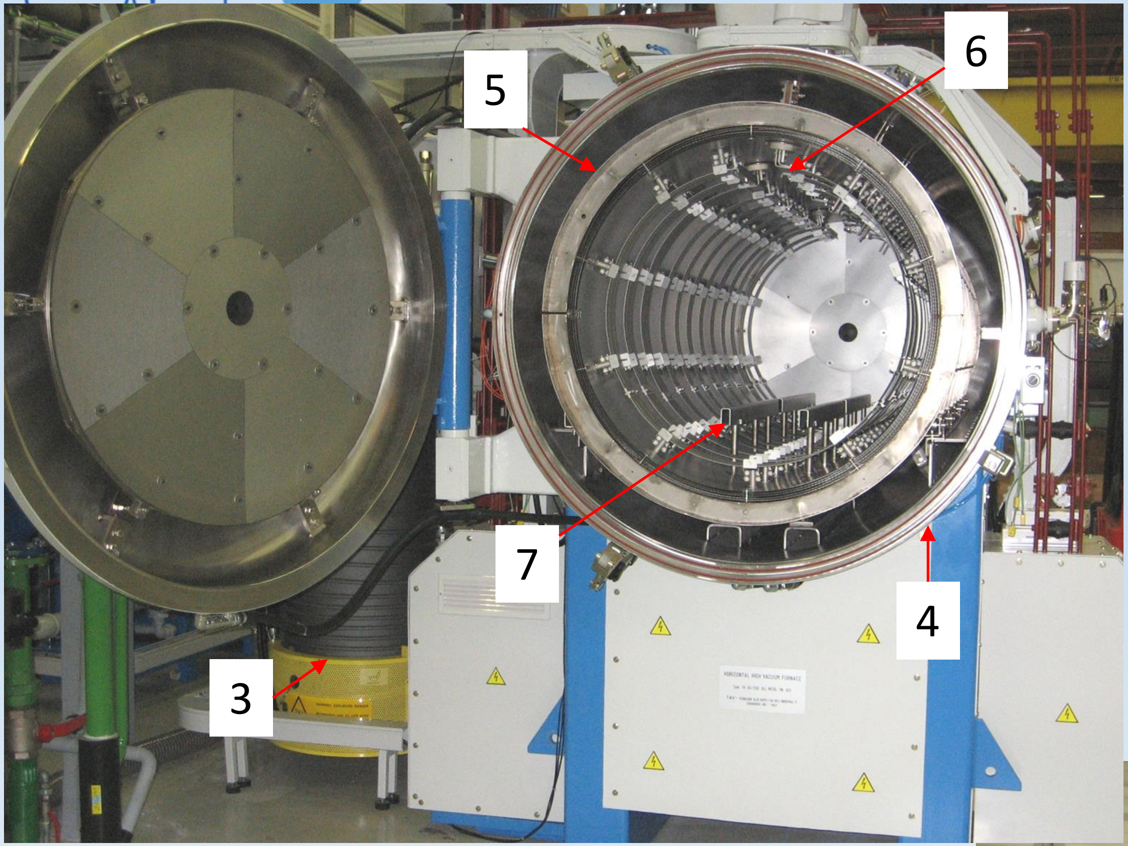
At 800°C, ΔG = -1337 kJ → ΔG = -891 kJ for 1 mole of O_2.

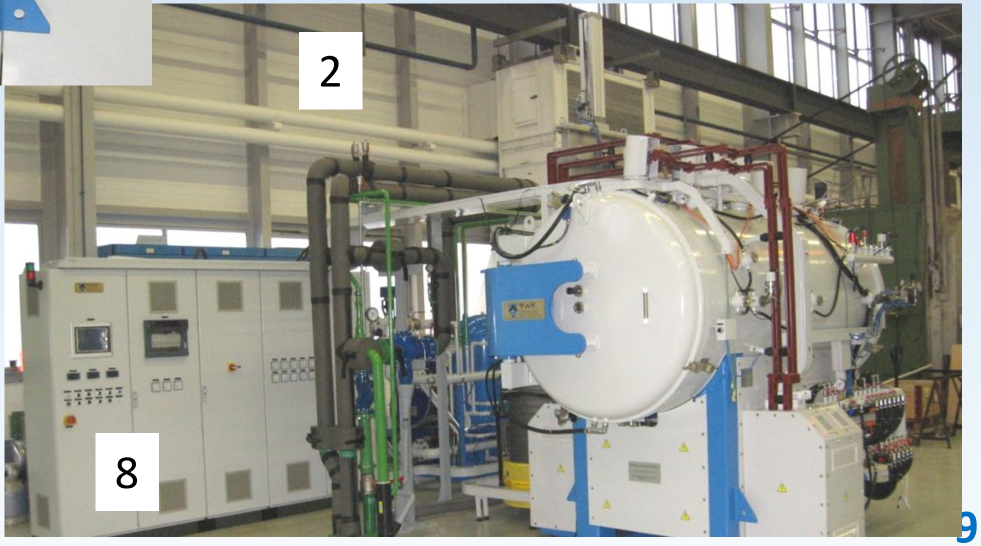
With ΔG = -893 kJ, $\frac{PO_{2(eq.)}}{P} = 3.4\ 10^{-44}$

With P = 760 Torr, $P_{O_2(eq.)} = 2.5\ 10^{-41} (Torr)$

Reduction of the Alumiun Oxyde (Alumina) **impossible** in a vacuum furnace.

Vacuum **Furnace**

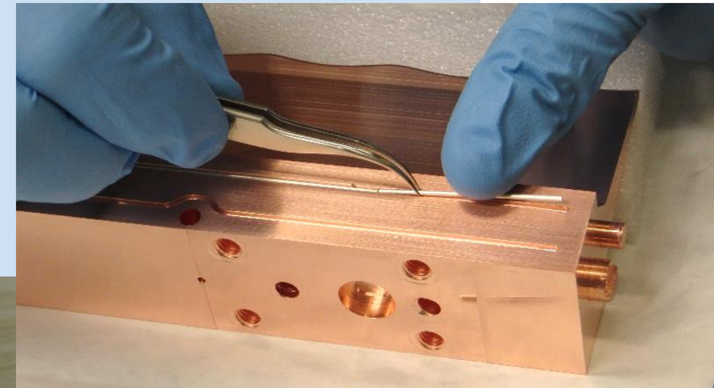


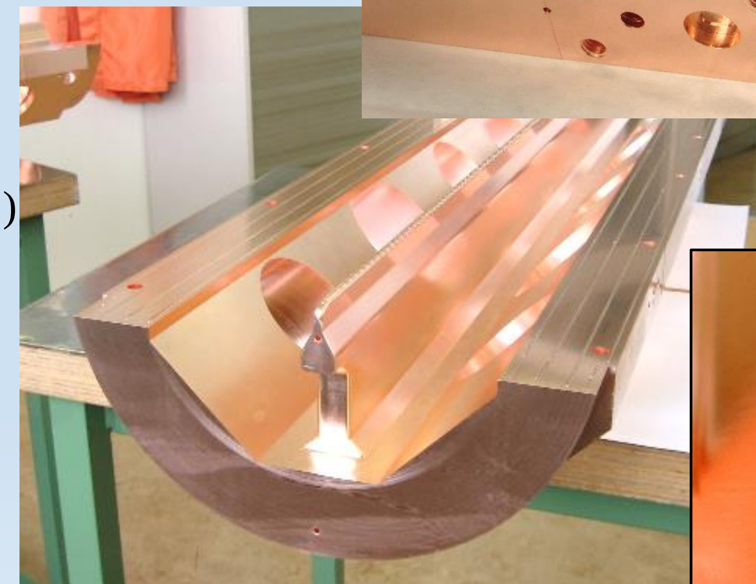


Vertical(1) or Horizontal(2) configuration, made of a high-speed vacuum pump (diffusion pump)(3), vacuum chamber with double walls water cooled(4), stainless steel / molybdenum screens(5), molybdenum heaters(6), molyddenum support(7), electrical cabinet(8).
(case for a all-metal vacuum furnace)

Visit 112-R-A10

Vacuum Brazing assembly



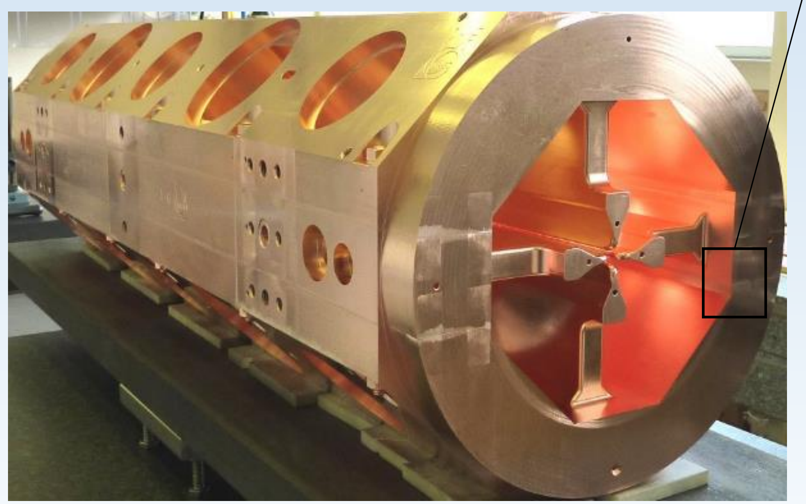


- Wetting is generally excellent.
- Brazing on large surfaces possible.
- Allow very good thermal and electrical contacts.
- Assembly clean and UHV compatible.
(Filler metal and material with low vapor pressures!)
- Dissimilar materials can be join.
- Allow high precision assembly with little or no distortion of the components

But:

- Heat treatment can affect the properties of the base materials.
- Mechanical tolerances are tight

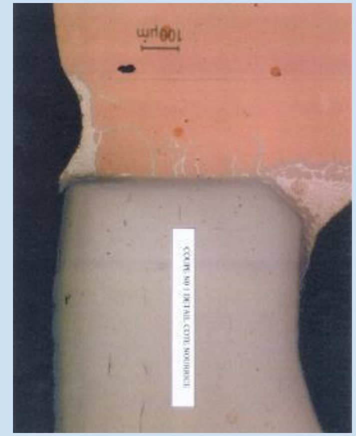
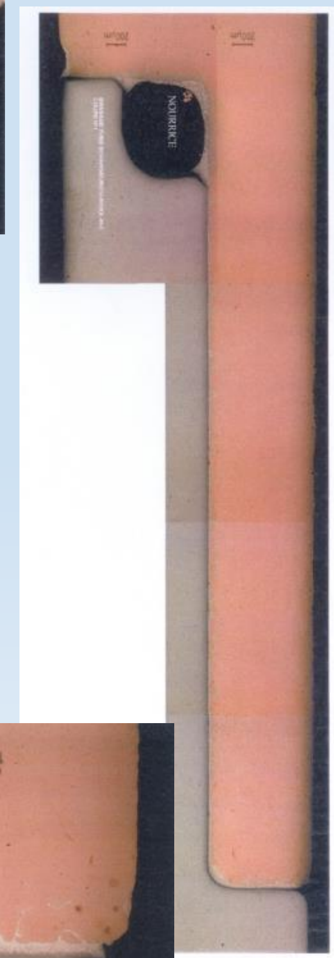
Filler Metal	**Gap** *(mm)*	**Ideal** *(mm)*	**Brazing Temp.** *(°C)*
Cu	0-0.05	0.025	>1083
Ag-Cu (Pd)	0-0.05	0.025	795 - 820
Au-Cu	0.03-0.1	0.05	>920
Ni-Cr	0.03-0.1	0.05	>1050



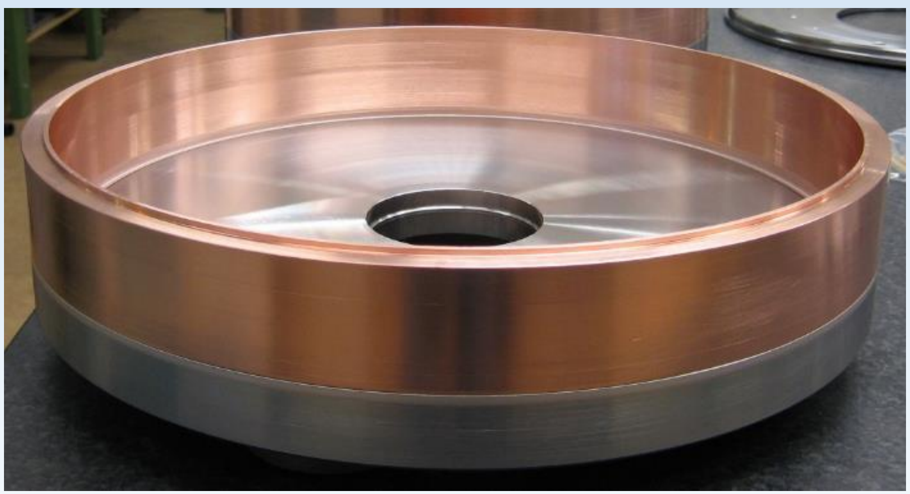
Filler metal seen on the vacuum side

Metal/Metal Vacuum Brazing Examples

Joint configuration:
- Groove, no gap (Ra ≈ 0.8 µm)
- Groove on a diameter
- Chamfer
- Foil
- Paste

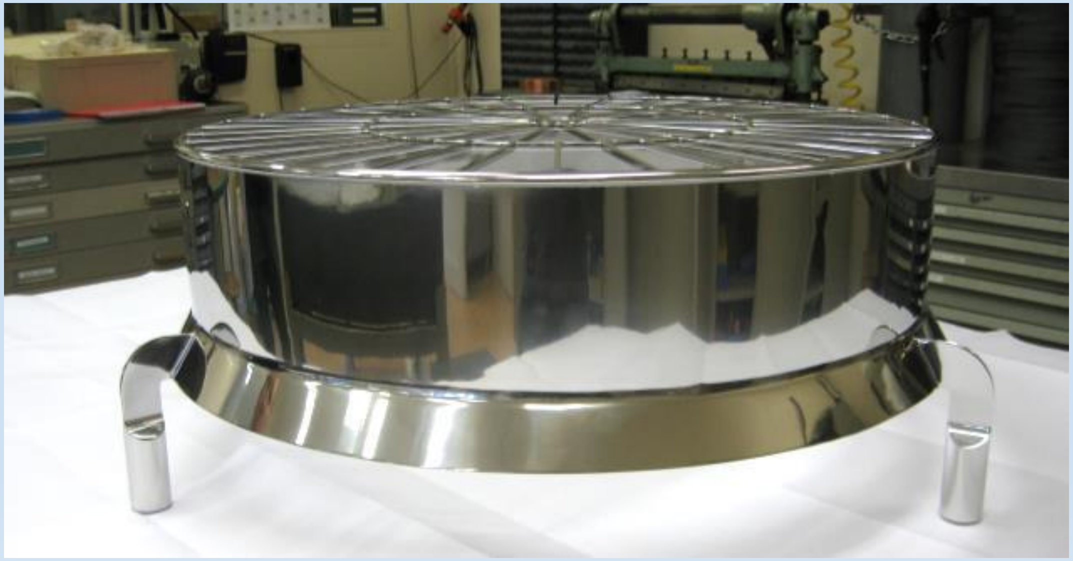




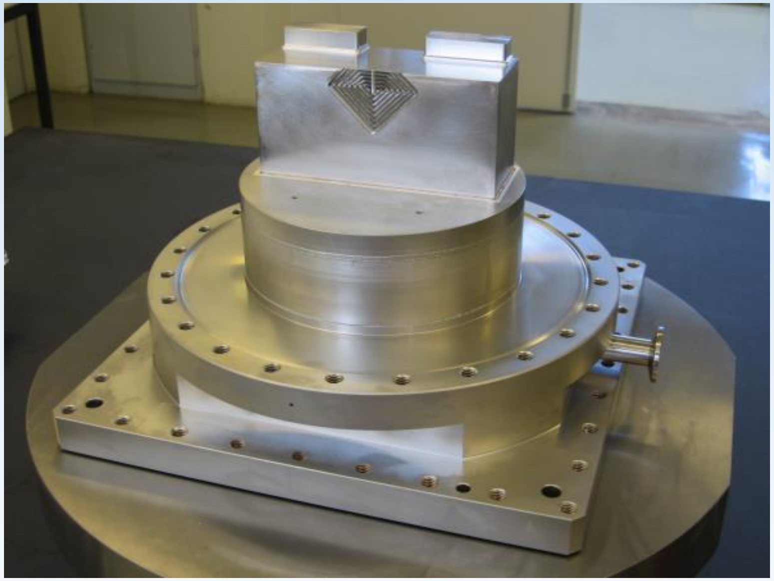
Copper (OFE) / Stainless Steel (316LN)

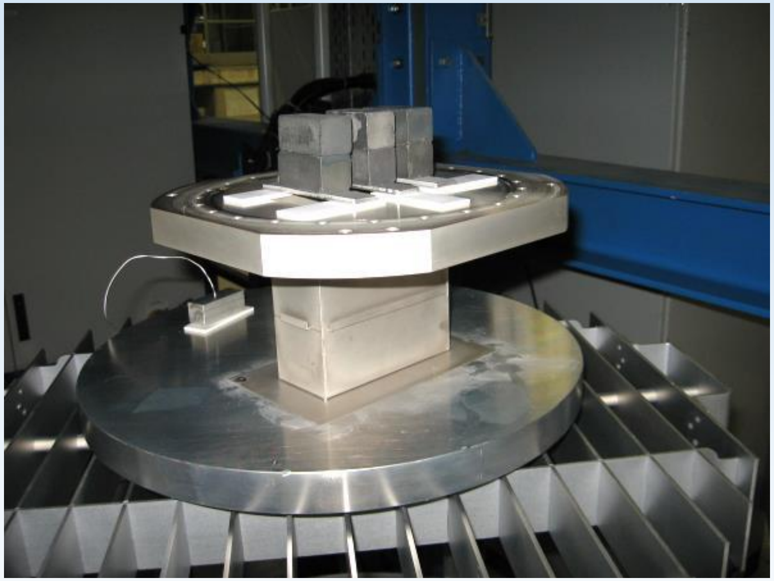


Metal/Metal Vacuum Brazing examples

Stainless Steel / Stainless Steel (316LN)



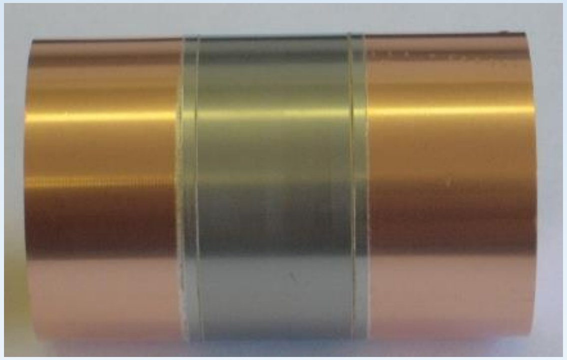




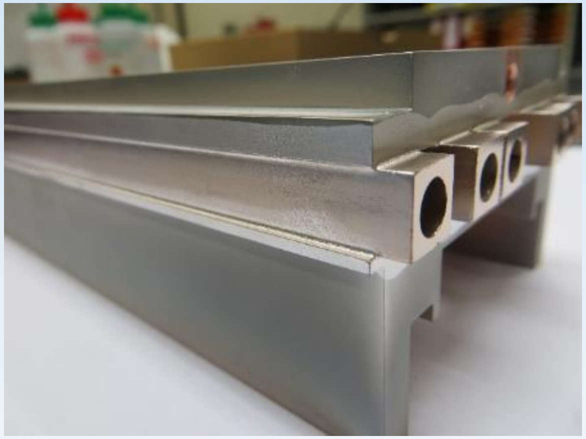
Metal/Metal Vacuum Brazing examples

Nb – Stainless steel

Mo – Stainless steel



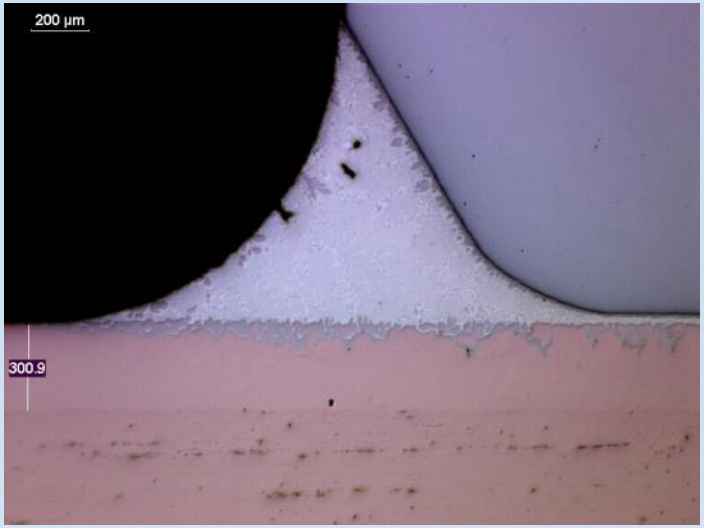
Cu – Stainless steel - Ti

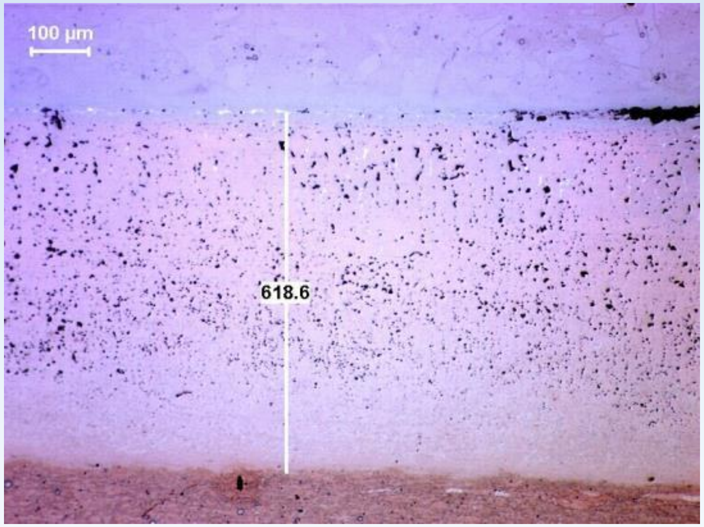


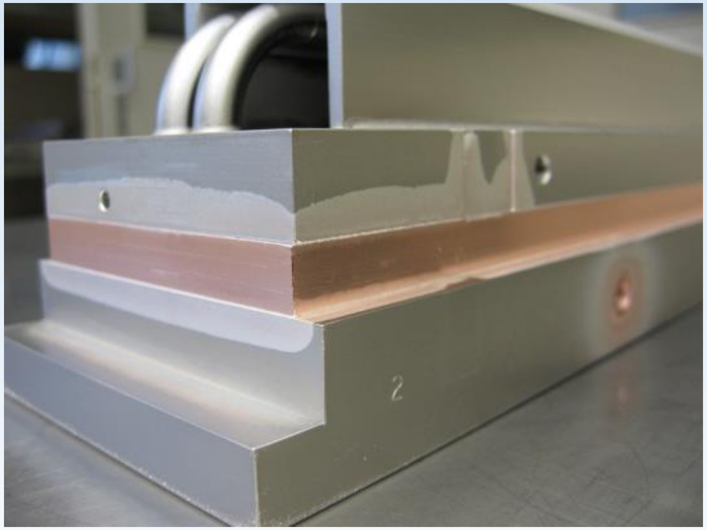
Glidcop - CuNi

Metal/Metal Vacuum Brazing examples

Case of Glidcop

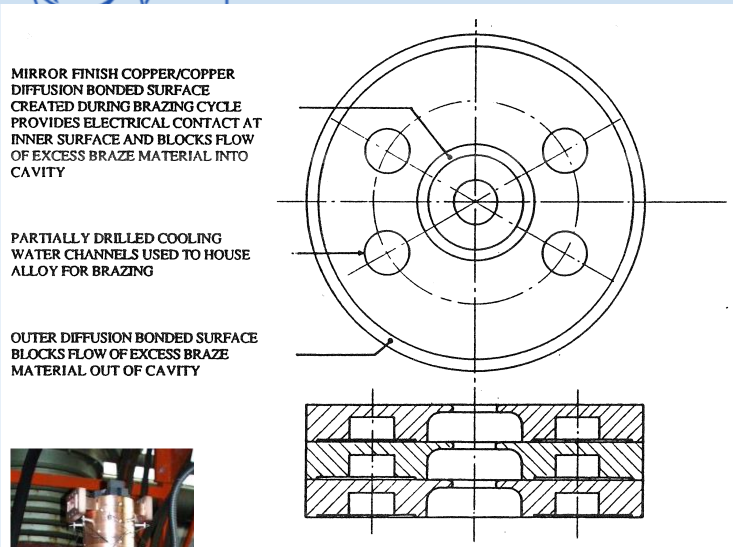


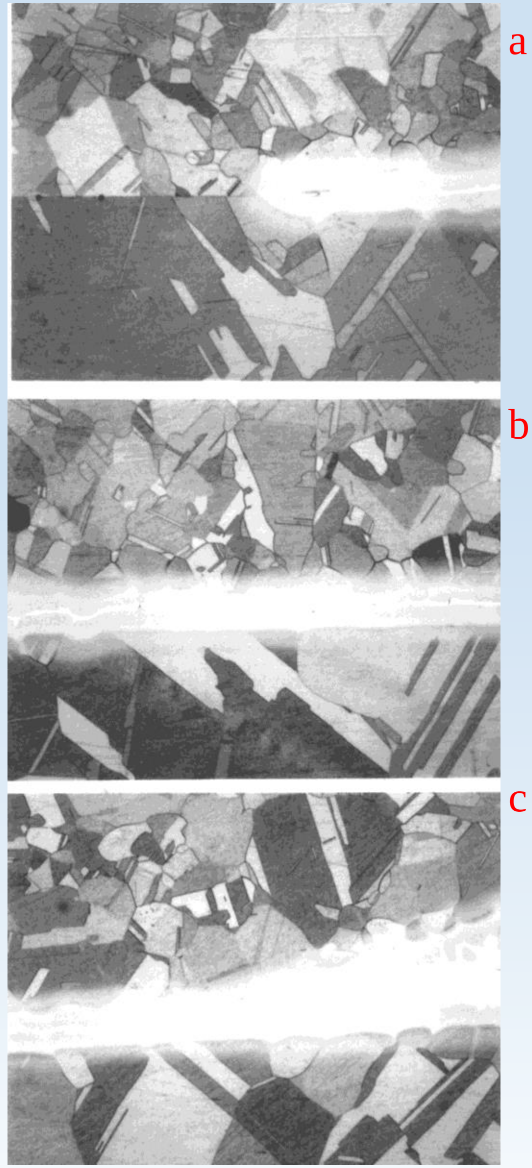


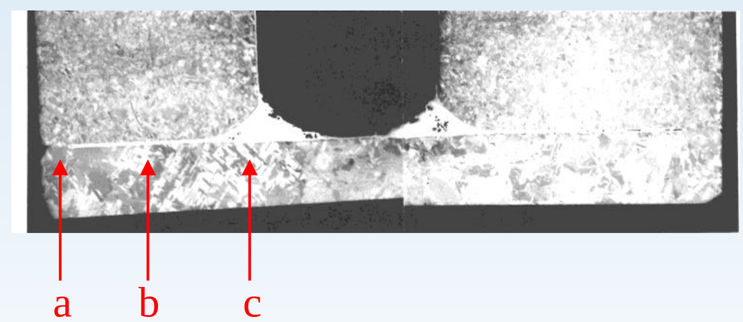


Metal/Metal Vacuum Brazing examples

Brazing & Partial Diffusion Bonding

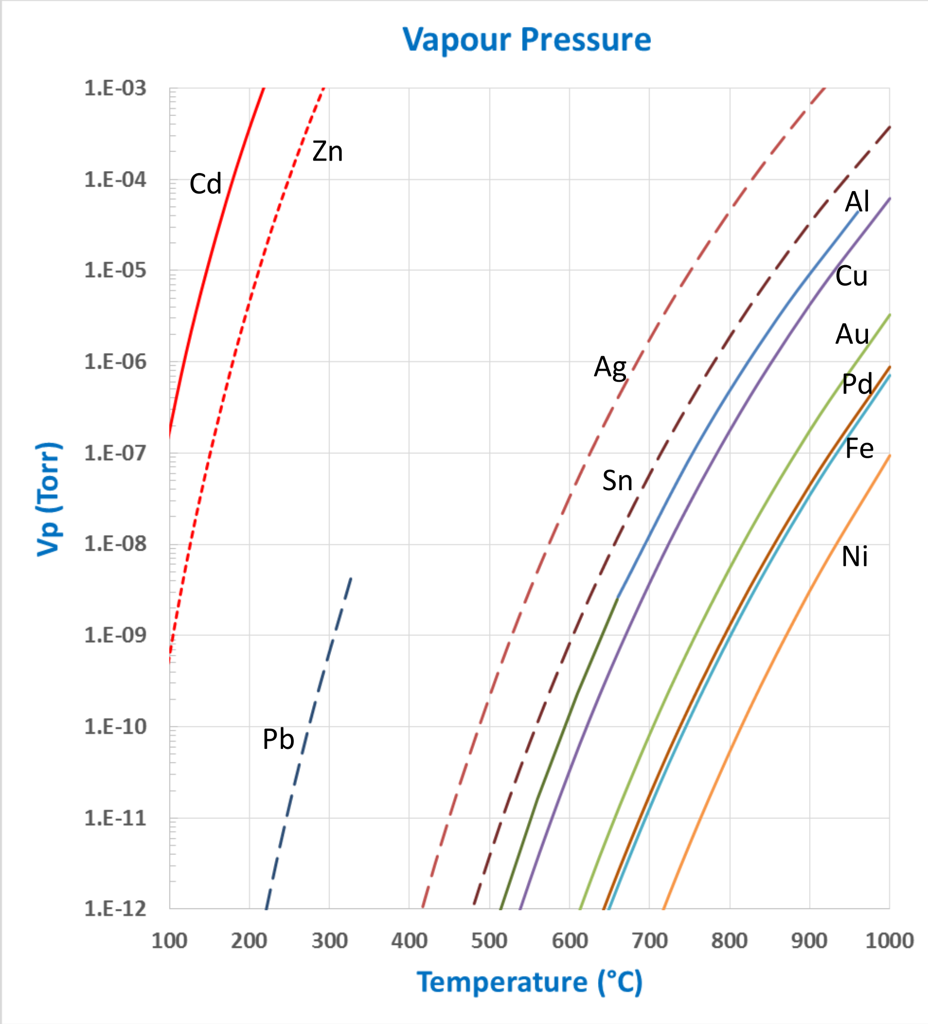






Metal/Metal Vacuum **Soldering** examples

◦ High purity SnAg or SnPb solders can be used in vacuum …



- Typical solders:

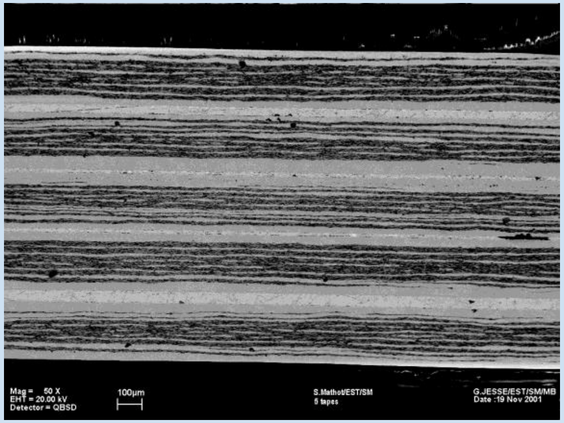
  SnAg (eutectic): m.p. 221°C
  SnPb (eutectic): m.p. 183°C

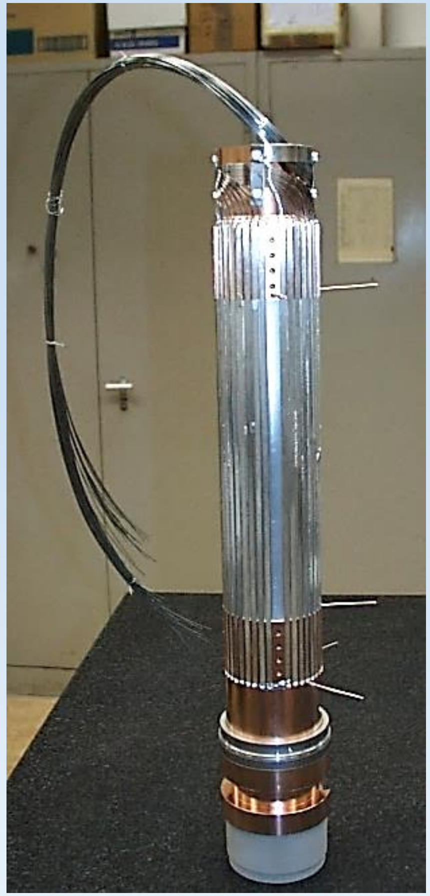
- Wetting acceptable on:

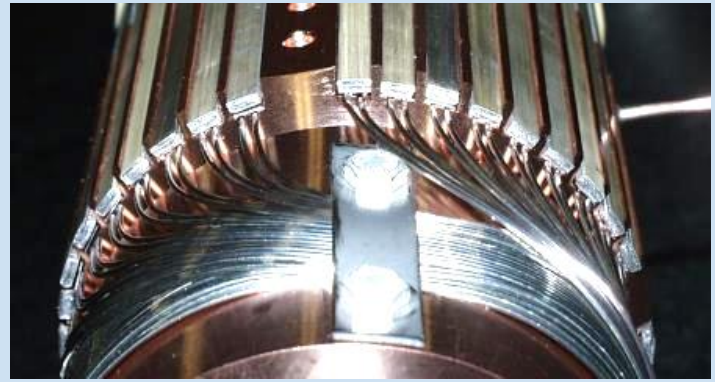
  Cu and Ag

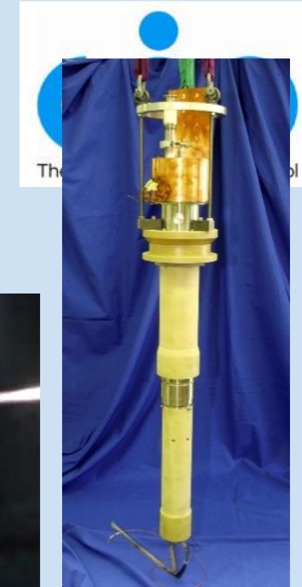
Metal/Metal Vacuum **Soldering** examples

Vacuum soldering of High Temperature Superconductor (HTS) tapes for the LHC current leads.

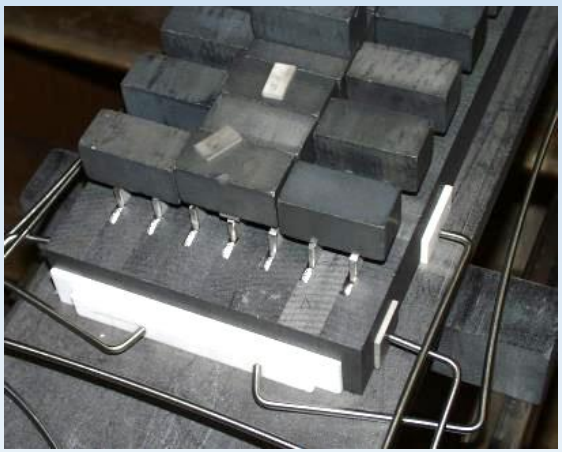




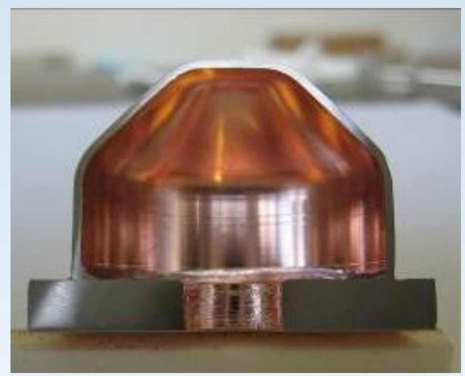


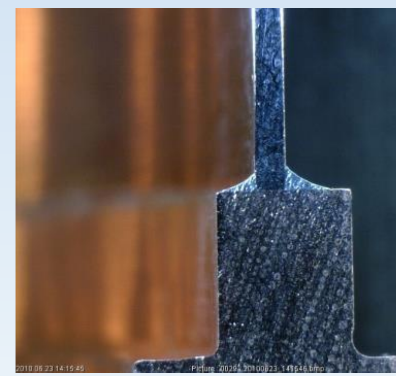


HTS stacks soldering – SnPb



HTS tapes soldering – SnAg

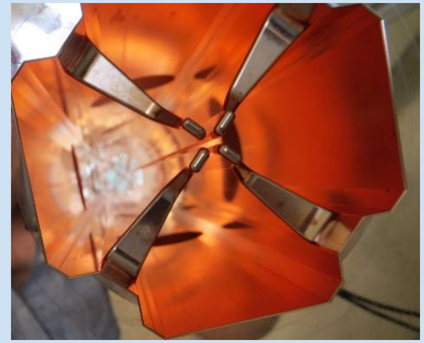




Kovar “boxes” – SnAg

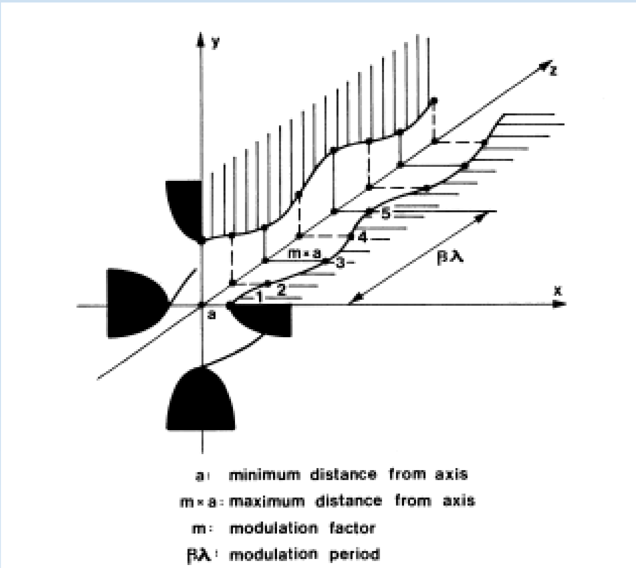
Metal/Metal Vacuum brazing examples

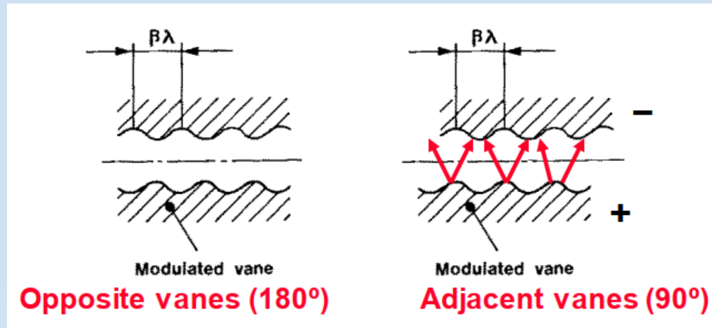
Case of the RFQ



4-Vanes

The RFQ (Radio Frequency Quadrupole)





4-Rods

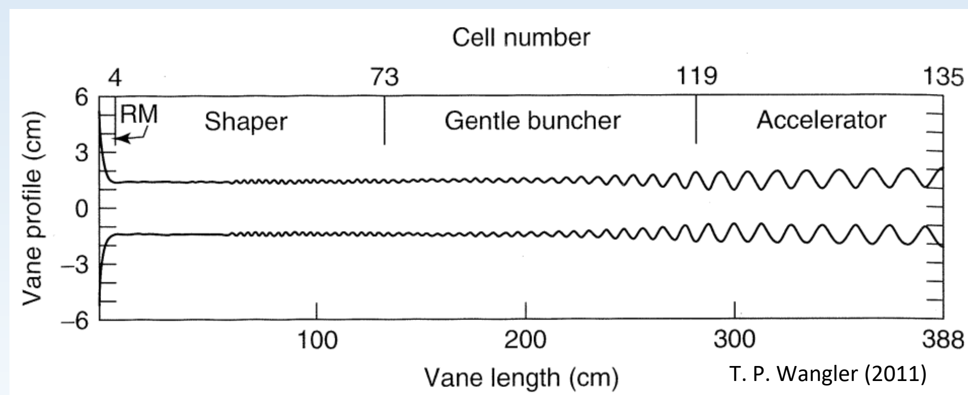
Perturbation (**Modulation**) of the Electrodes (**Vanes**) produces a longitudinal electric field for the acceleration of the ions.

RFQ Performances:

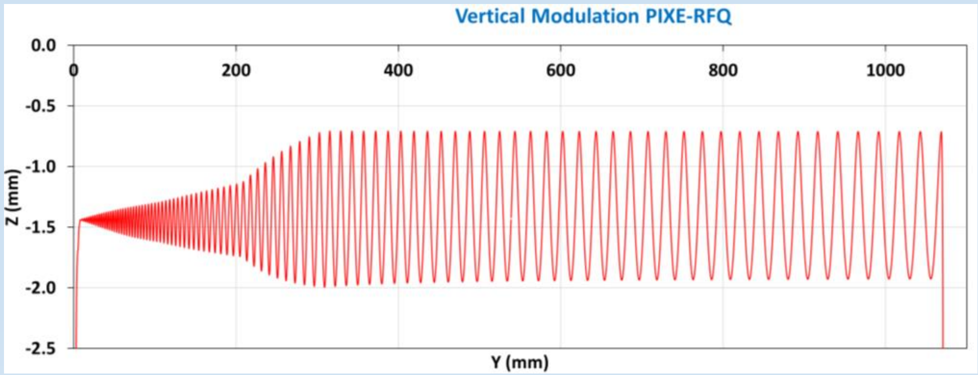
- The RF field allows the Focusing, Bunching and Acceleration

- Is the only linear accelerator accepting a low energy continuous beam

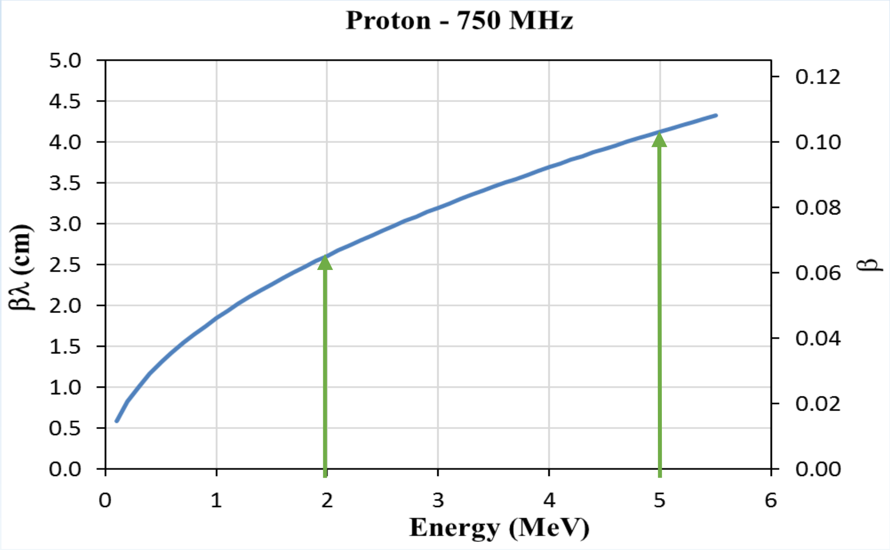
- Acceleration up to 5 - 10 MeV for protons

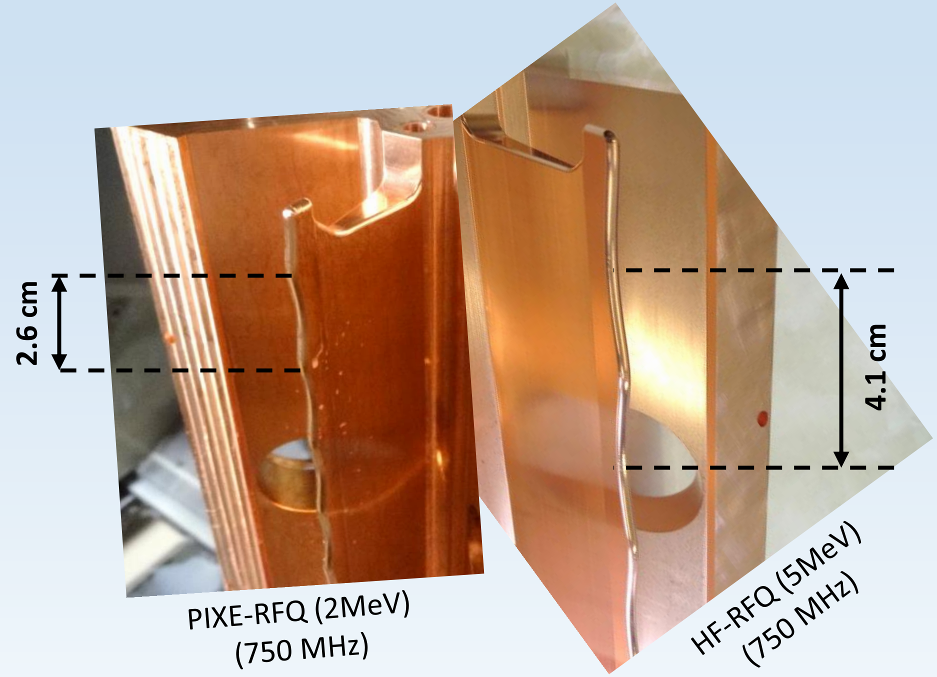


Synchronism between the modulation and
the velocity of the particle in an RFQ



Views of the high energy side (last cells) of the vane for two RFQ's at same frequency, same ion but different end-energy.

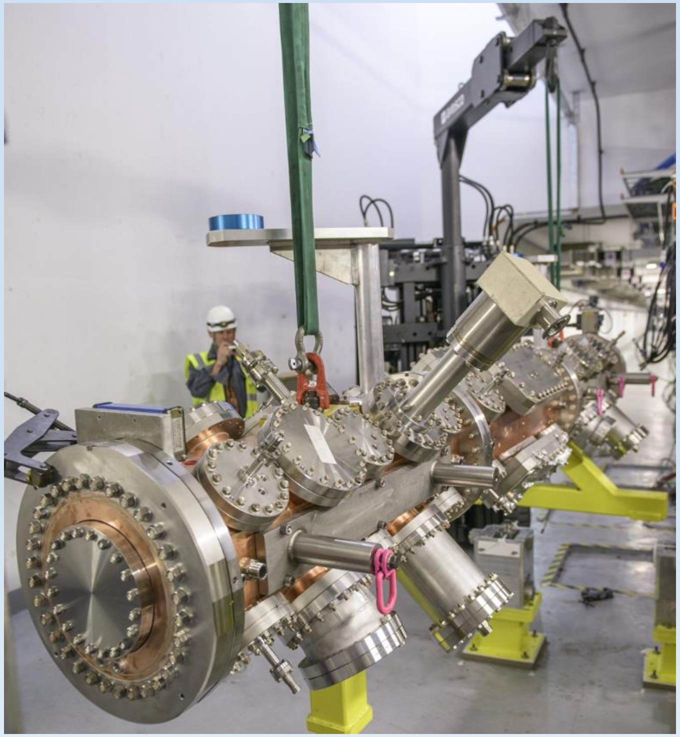


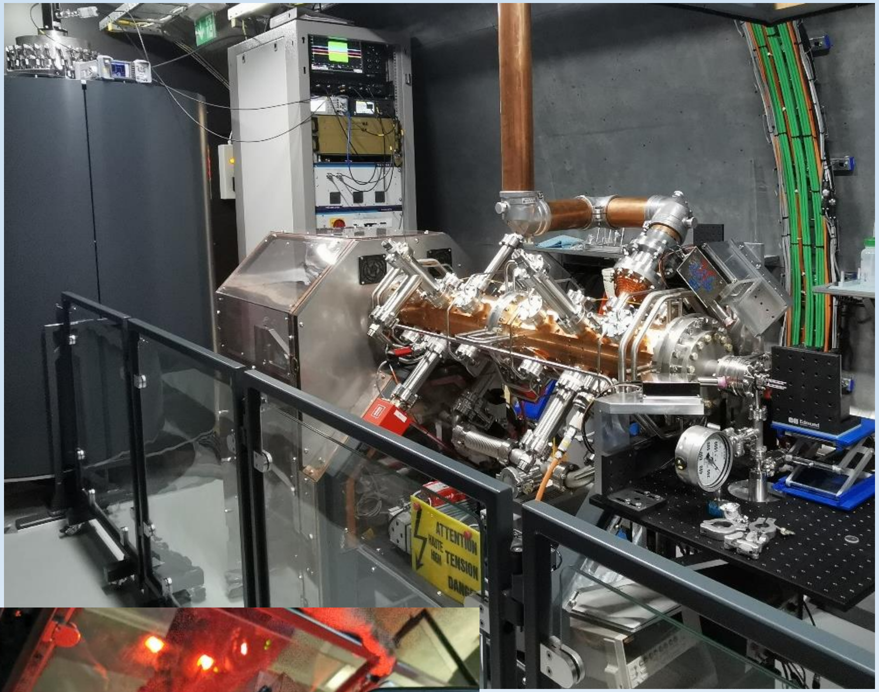


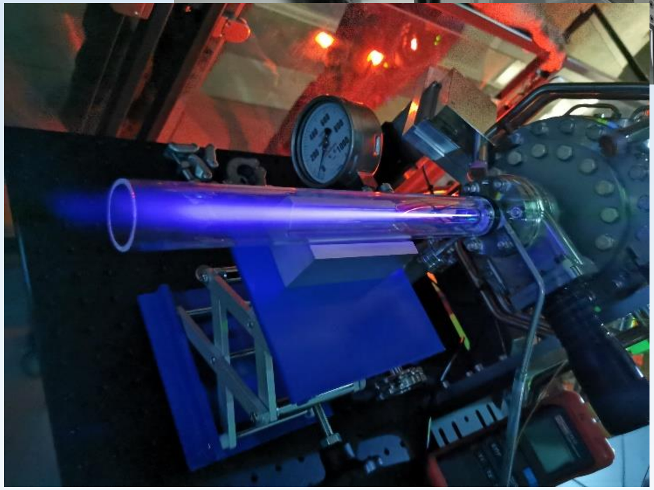
Metal/Metal Vacuum brazing examples

Case of the RFQ

RFQ are generally used as an injector (LINAC4), but (recently) can be used as well as stand alone accelerator (ELISA)





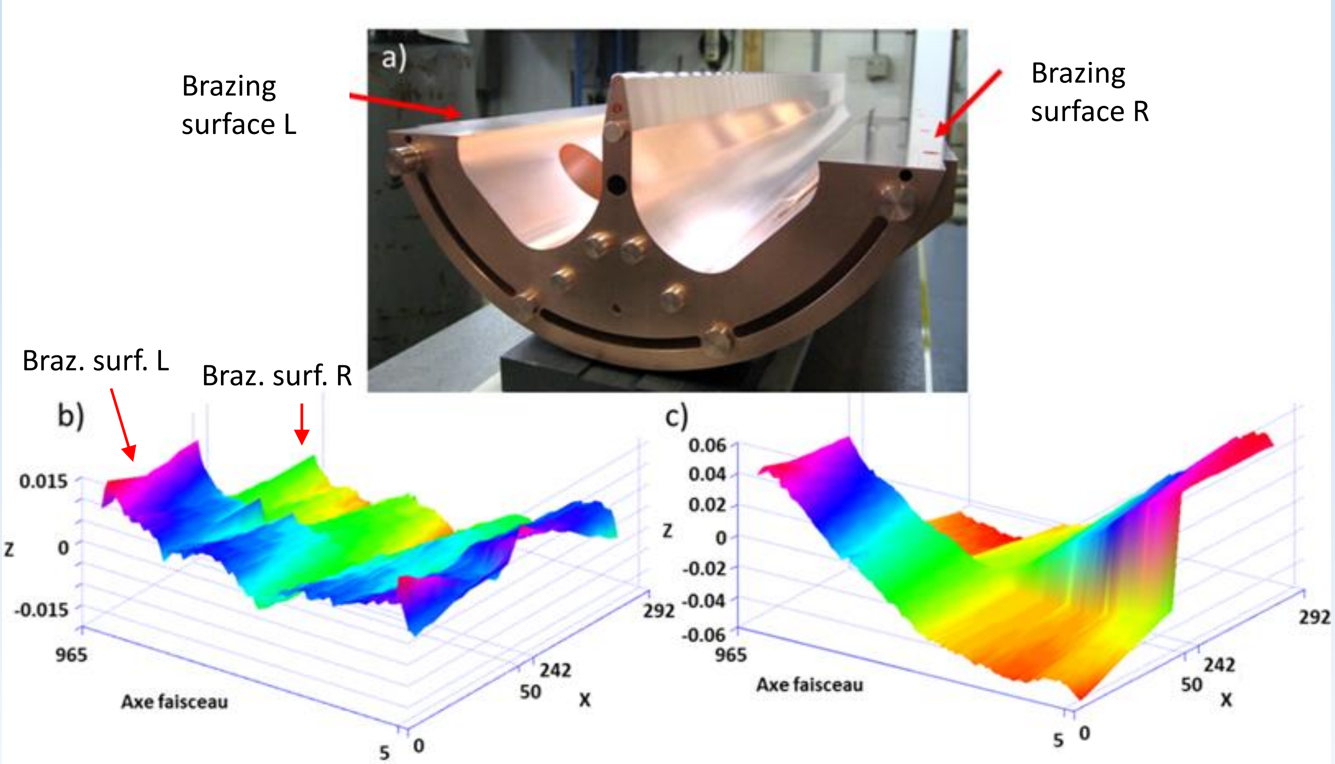


Metal/Metal Vacuum brazing examples

Case of the RFQ

Mechanical Tolerances

	RFQ Linac4 – 352 MHz (2011)	HF-RFQ – 750 MHz (2016)
Vane (Shape)	± 10 µm	± 5 µm
Vane (Position)	± 30 µm	± 15 µm
Cavity (Shape)	± 20 µm	± 10 µm
Displacement max. (X-Y)	± 50 µm	± 25 µm
Displacement max. (Z)	± 50 µm	± 20 µm
Module gap	± 15 µm	± 10 µm



Flatness of the Left and Right brazing surfaces: After machining and after heat treatment at 800 °C

Tolerances are very tight for an RFQ … but good machining and good alignment are not enough.
Deformations during brazing must be anticipate!

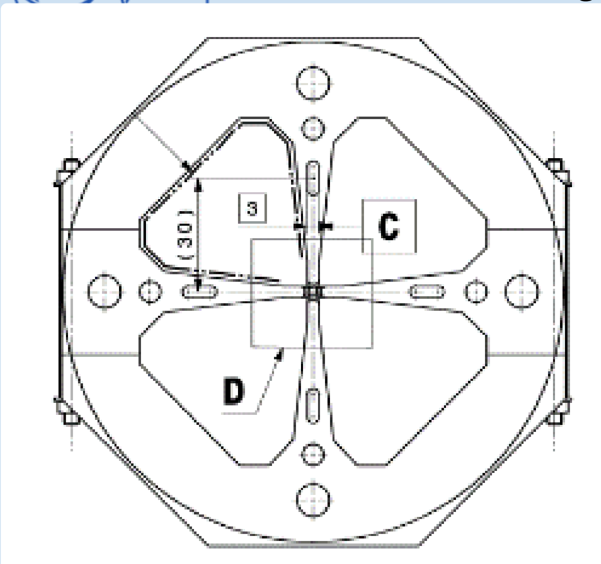
Recipe:

1. Discuss a cavity design which reduce the machining time and constraints and limit the risks during brazing.
2. Alternate machining and heat treatment steps, last machining before brazing must be very “light”.
3. Have a good alignment strategy (and good metrology).
4. Have a good tooling reducing possible movement during brazing.
5. Use a thermal cycle adapted to the size of the piece.

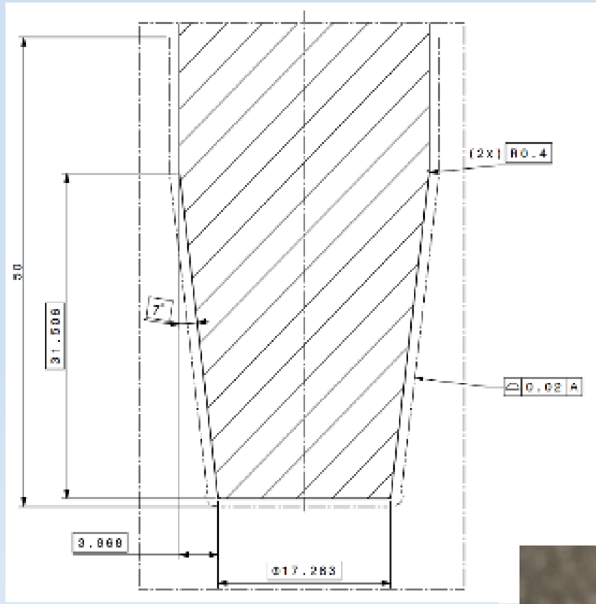
Metal/Metal Vacuum brazing examples

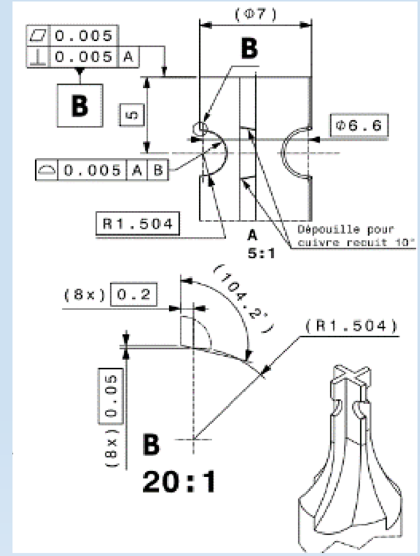
4-Vanes design

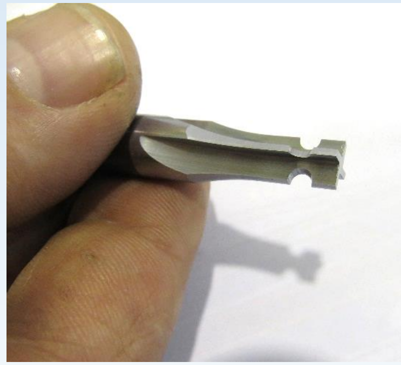
Case of the RFQ

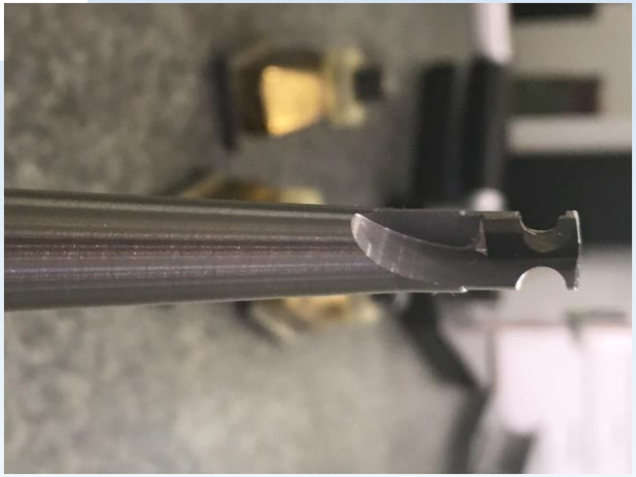


Machining with shape tools





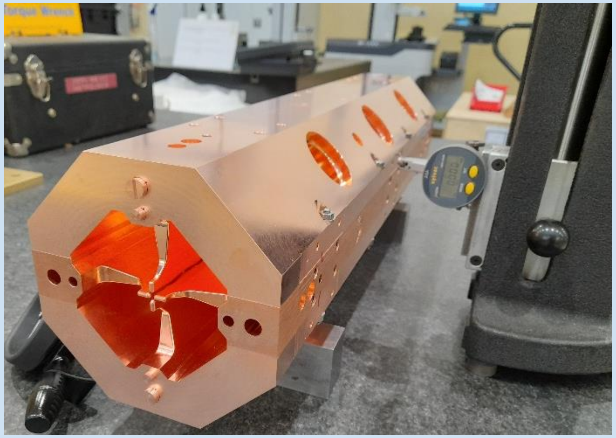


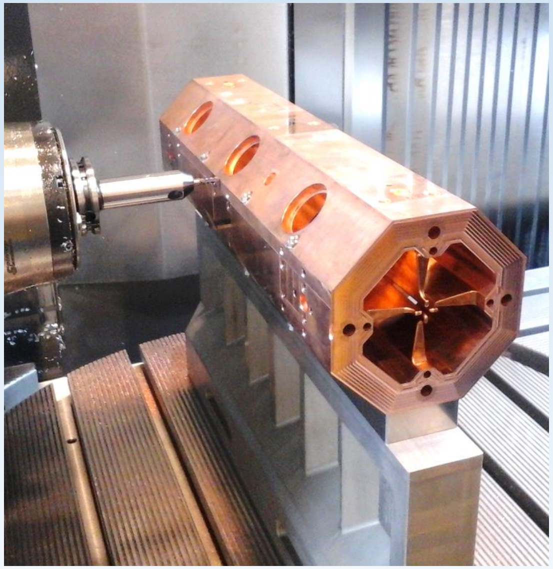


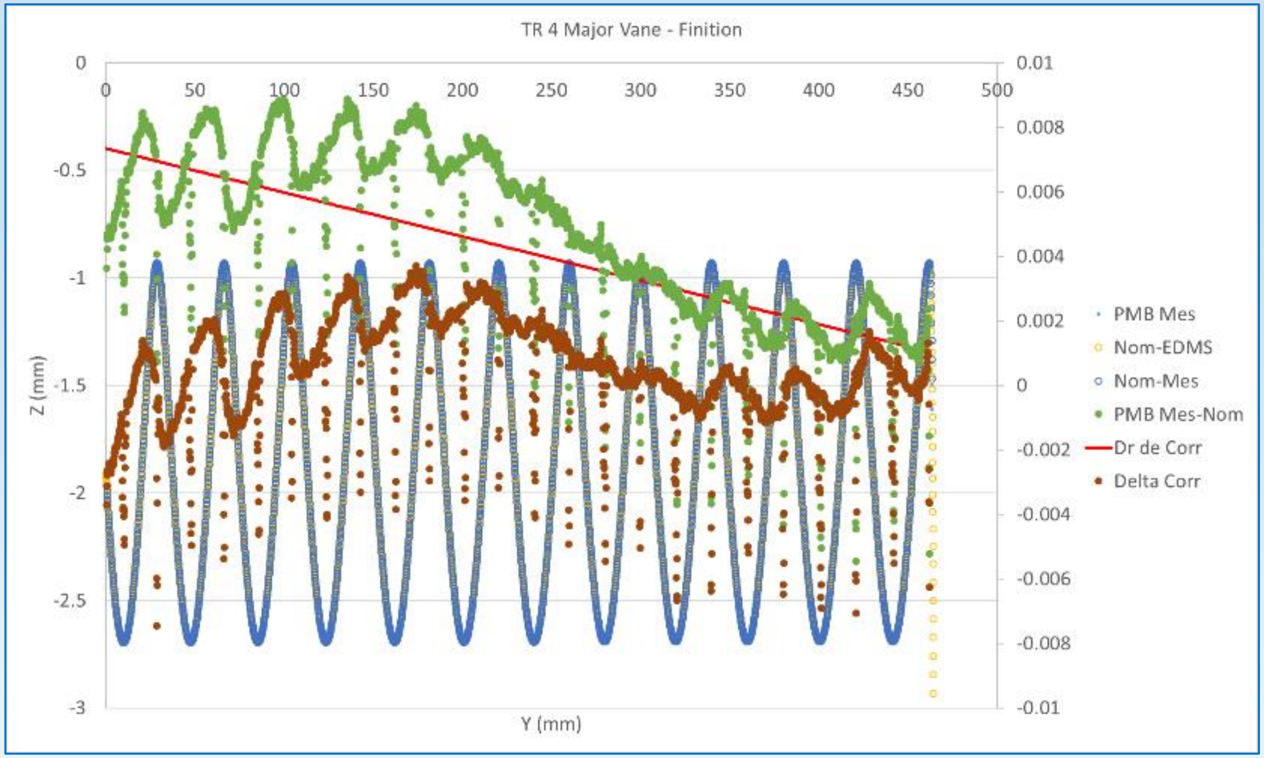
Metal/Metal Vacuum brazing examples

Case of the RFQ

Metrology – Alignment –Machining of reference surfaces



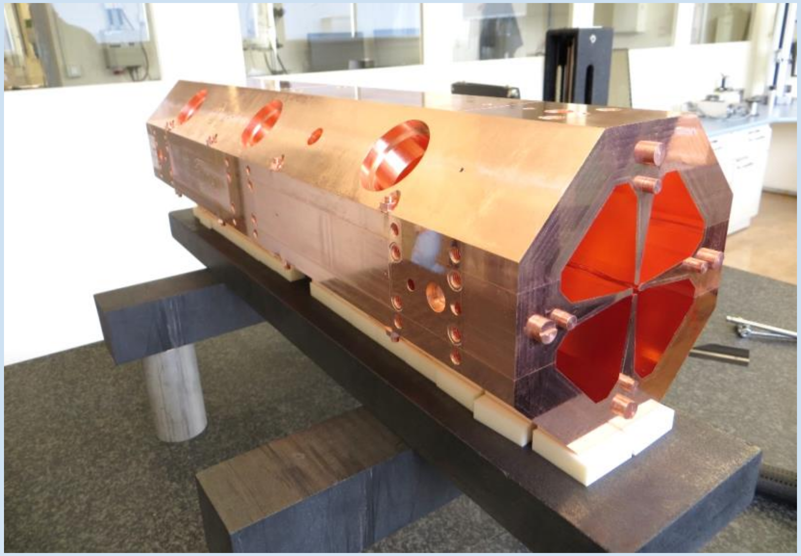


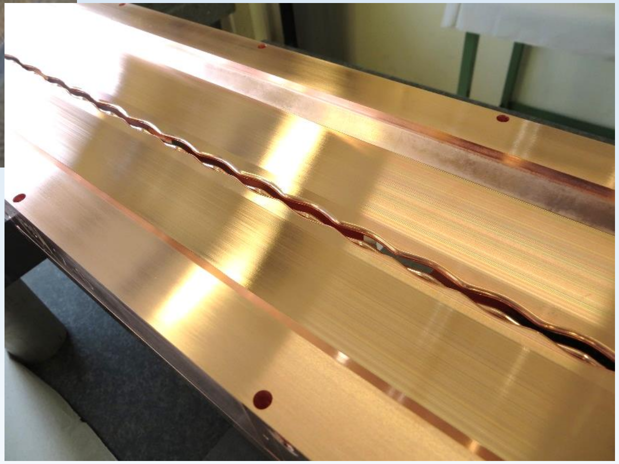


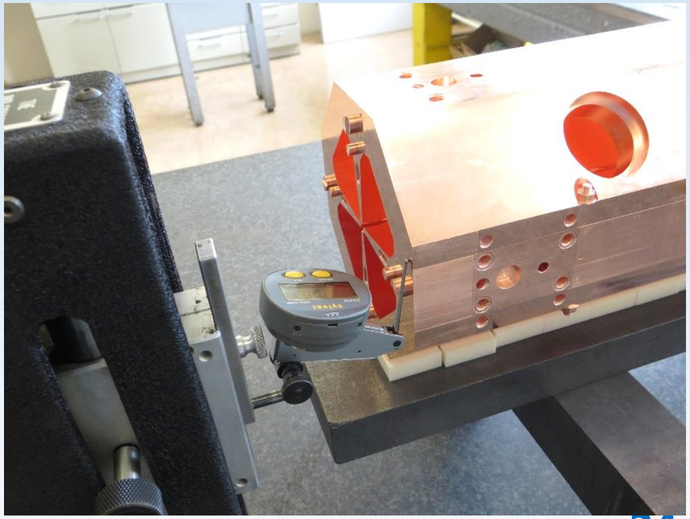
Metal/Metal Vacuum brazing examples

Case of the RFQ

First brazing : alignment and assembly



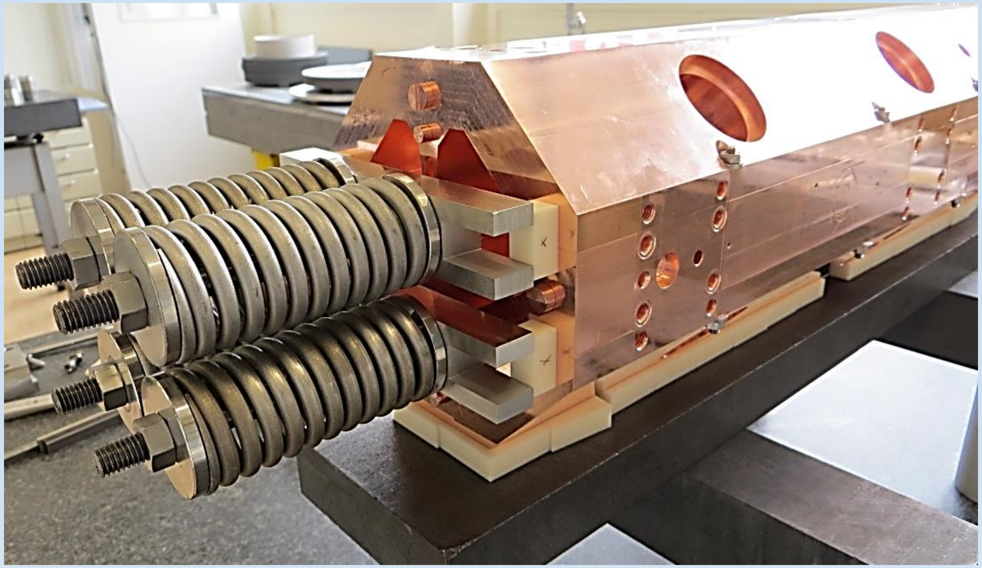


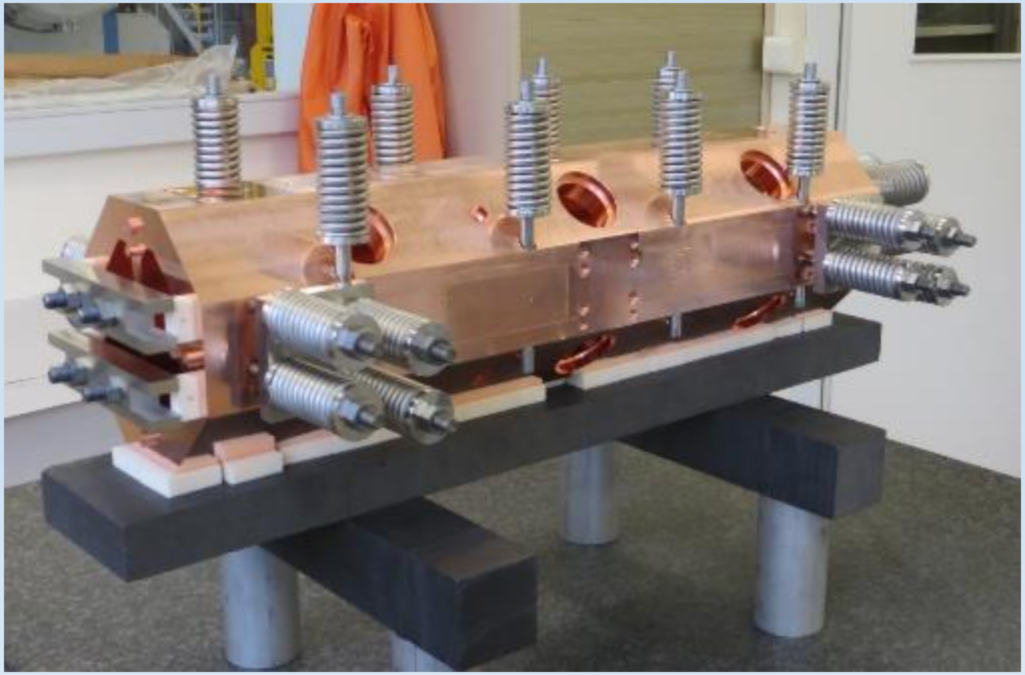


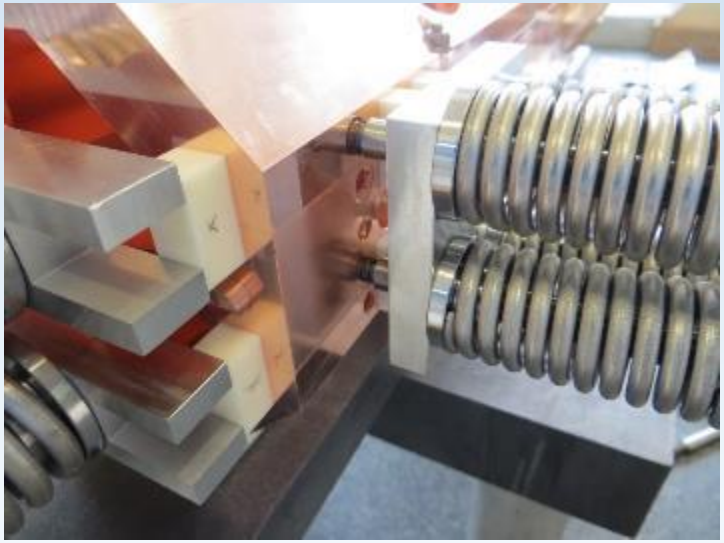
Metal/Metal Vacuum brazing examples

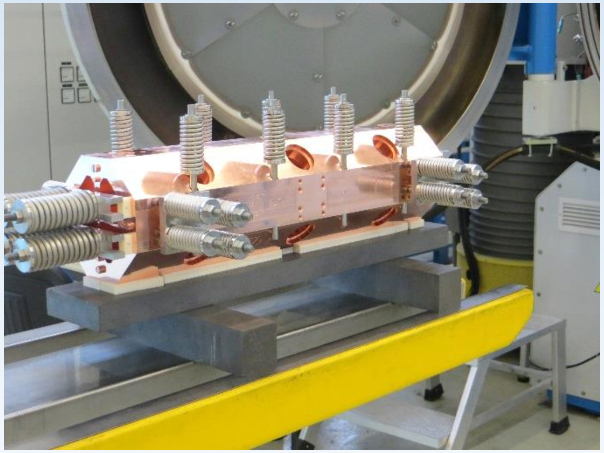
Case of the RFQ

First brazing : Fixture and brazing





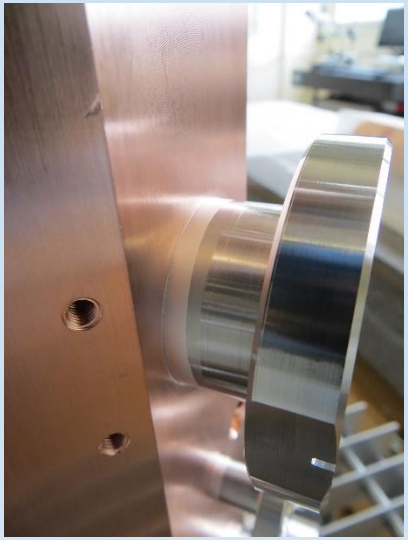


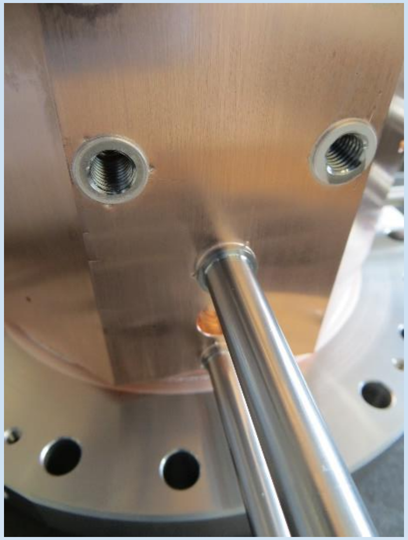


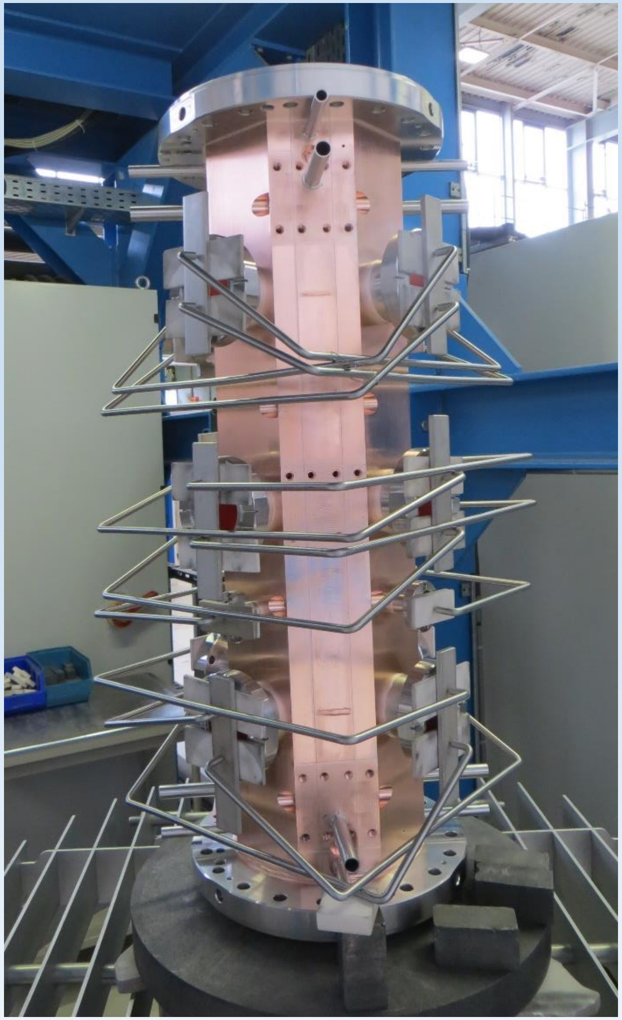
Metal/Metal Vacuum brazing examples

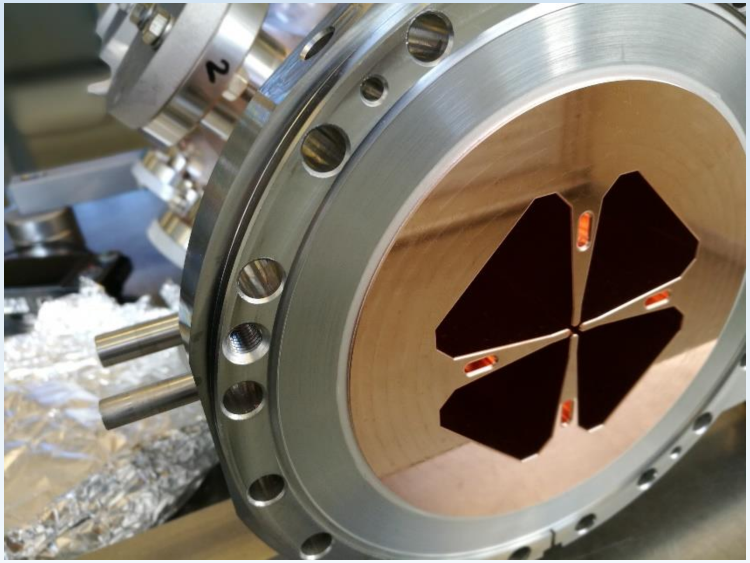
Case of the RFQ

Second brazing : Fixture and brazing





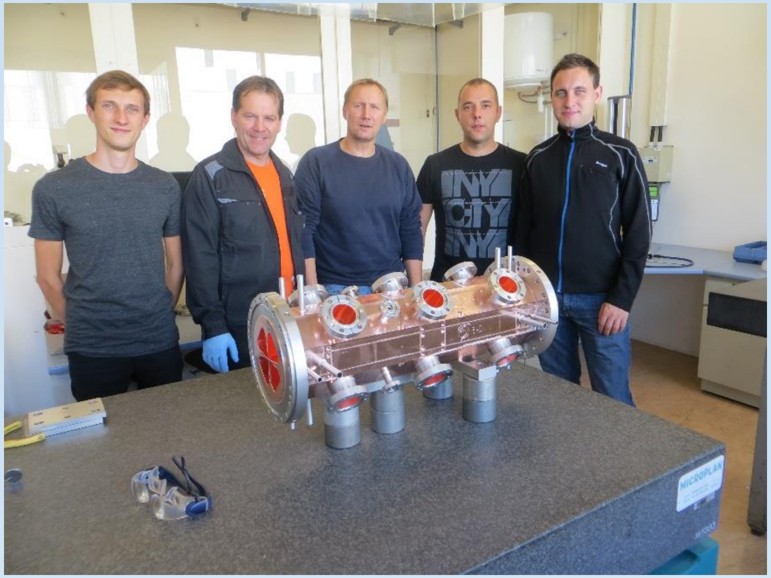


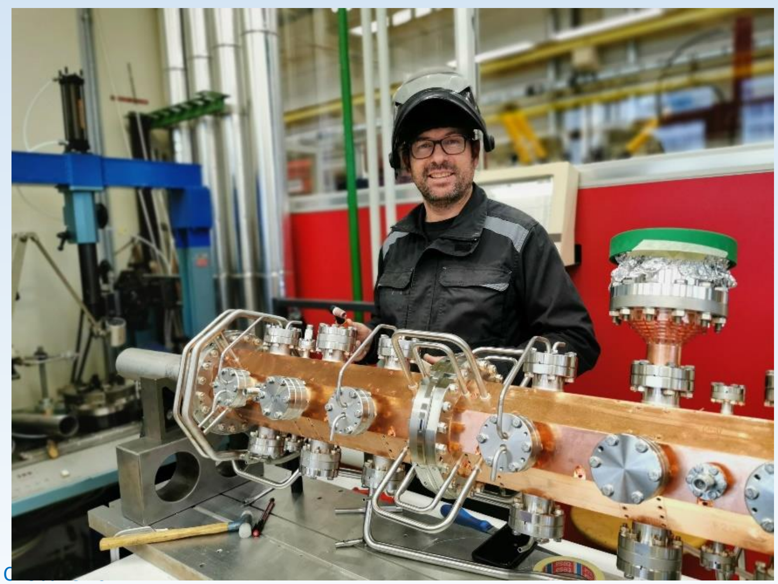


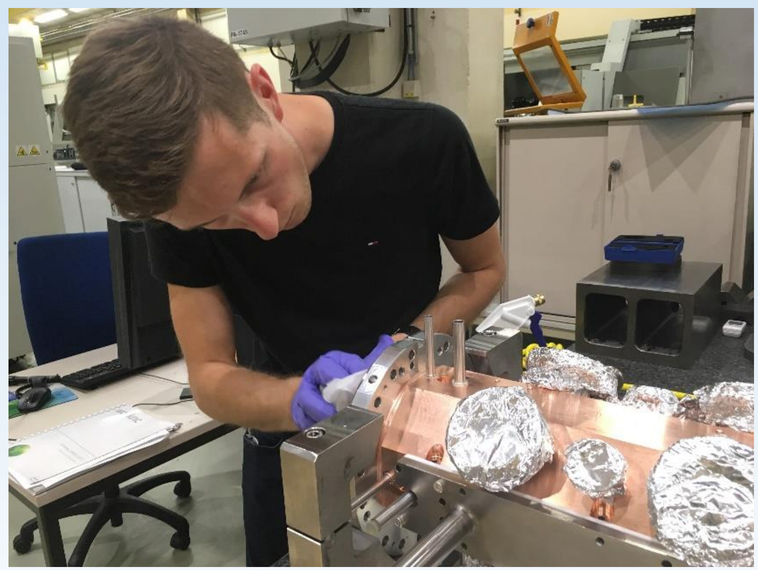
Metal/Metal Vacuum brazing examples

Case of the RFQ

Good job …. One module finished ….





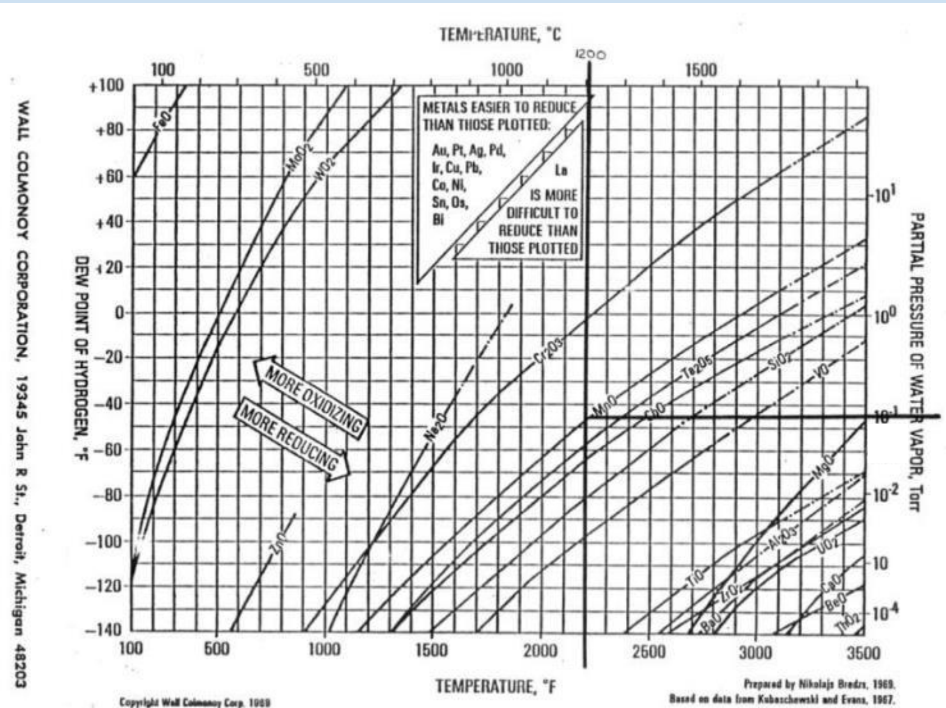


Vacuum brazing of Alumina (Ceramic)

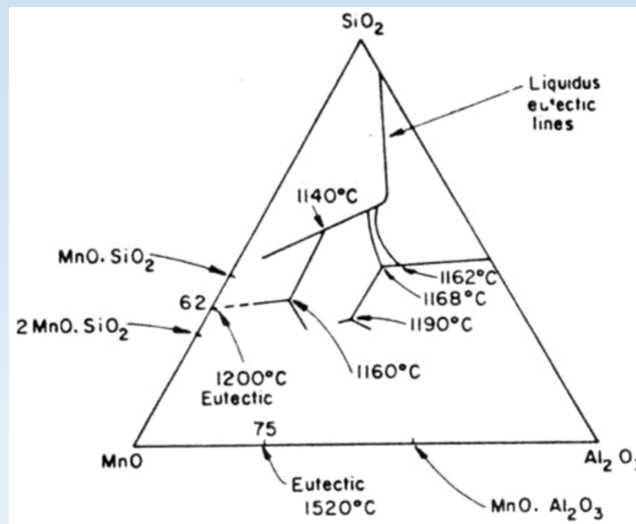
First process = Mo-Mn metallization

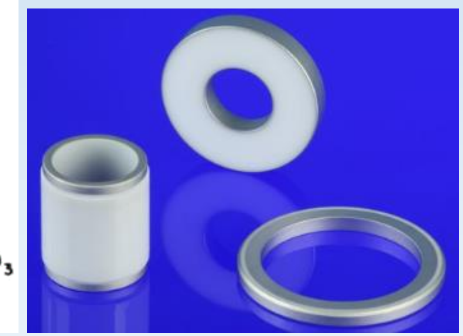
Mo + MnO (Mn) powder on alumina (Al_2O_3) @ T > 1200 °C and P_{H2O} / P_{H2} > 10^{-4} induce:

- Mo reduction and $MnO/Al_2O_3/SiO_2$… vitreous phase formation.
- Interaction with the Alumina base material and the binder.
- Sintering of the Mo powder in the vitreous phase during cooling.
- Formation of Mo-Mn layer strongly adhering the support.
- Ni layer added to improve the brazing.



4. Metal-metal oxide equilibrium in pure hydrogen atmospheres as a function of dew point showing molybdenum to be present always as the metal and manganese always as the oxide.





Vacuum brazing of Alumina (Ceramic)

TCF = Thermomechanical Compatibility Factor

$$TCF \cong \frac{\epsilon_y}{\sigma_y * \epsilon_T}$$

With

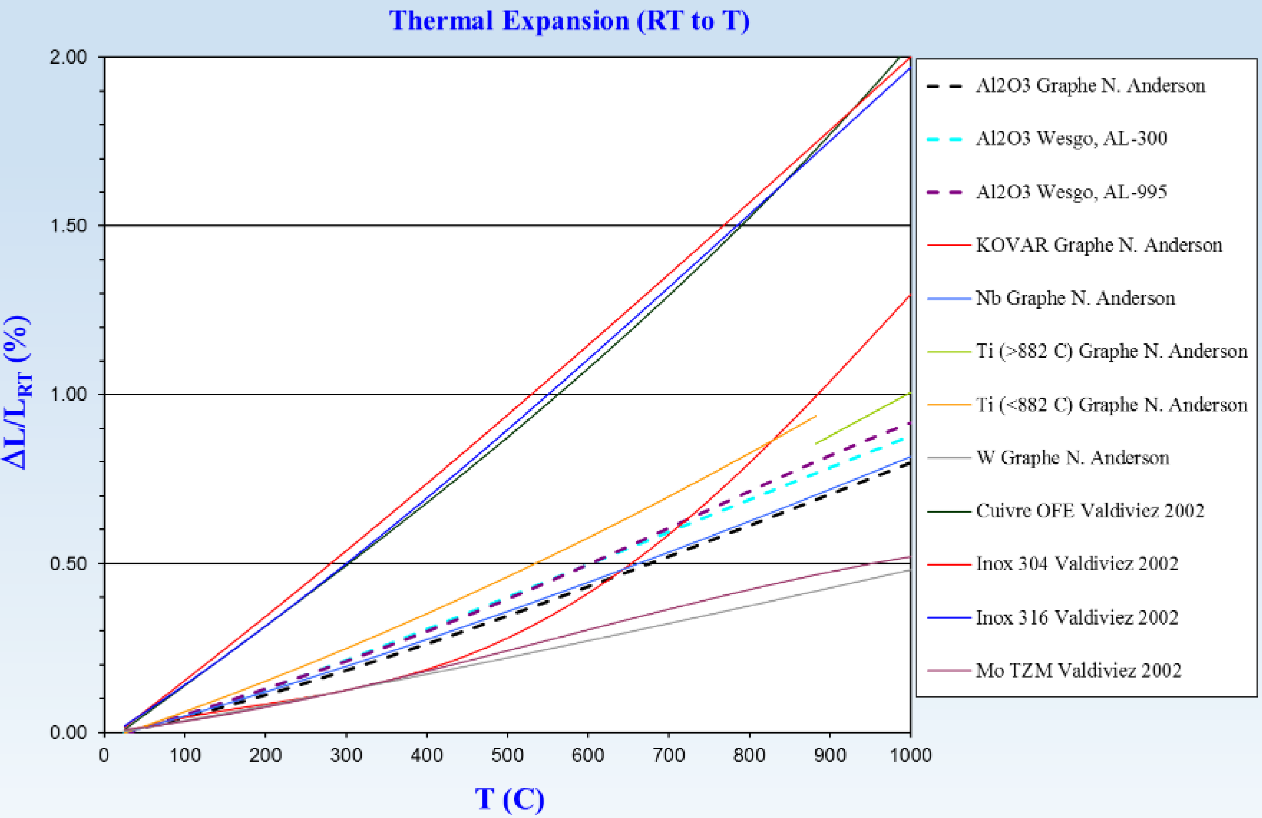
$\epsilon_y = Metal\ elastic\ elongation\ at\ brazing\ temp.$

$\sigma_y = Metal\ yield\ strength.$

$\epsilon_T = Delta\ elengation\ between\ metal\ and\ ceramic$

Metal thermal expansion AND metal yield strength should be taken into account for Metal / Alumina brazing.

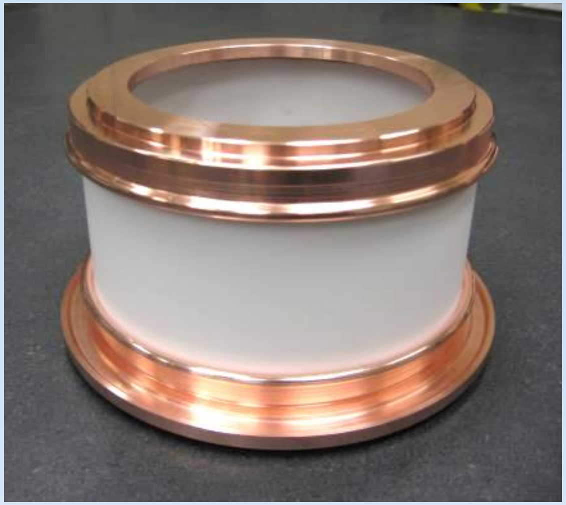
Max. TCF => Min. Stress

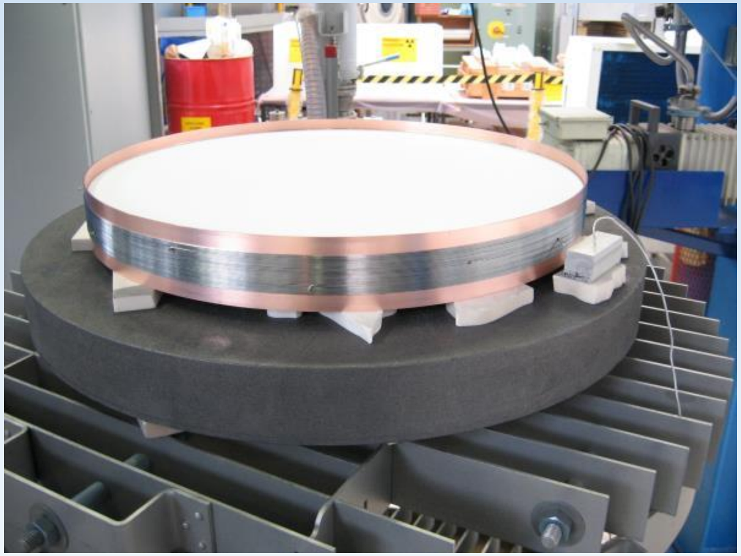


Métal	TCF
Niobium	88
Platine	33
Tantale	28
Cuivre	20
Titane	8.8
Kovar	7.7
Nickel	6.7
CuNi	4.8
Fe-42Ni	4.5
Monel	4.0
Invar	3.7
Molybdène	3.5
Inox 304	2.9
Inconel 600	2.1
Tungstène	2.0

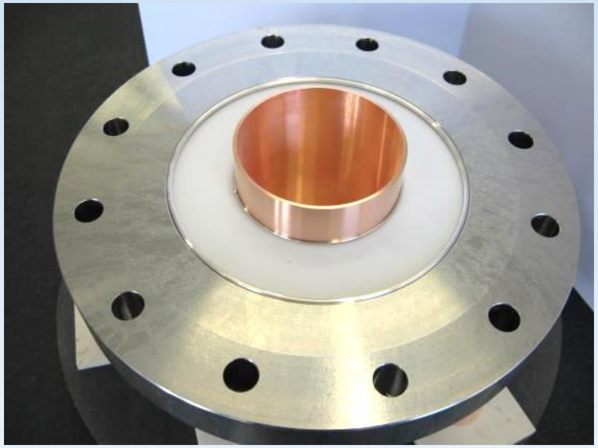
Vacuum brazing of Alumina with Metallization - Examples

Kovar (Dilver) – Alumina





Cu – Alumina (up to diameter 400 mm!)



Ti – Alumina – Cu

Vacuum Brazing of Ceramic

Second process = Active Brazing

- Brazing alloy containing reductive metal: Ti, Zr, Be, …

- At brazing temperature, under high vacuum, strong interaction with oxides (alumina), carbide, nitrite, ….

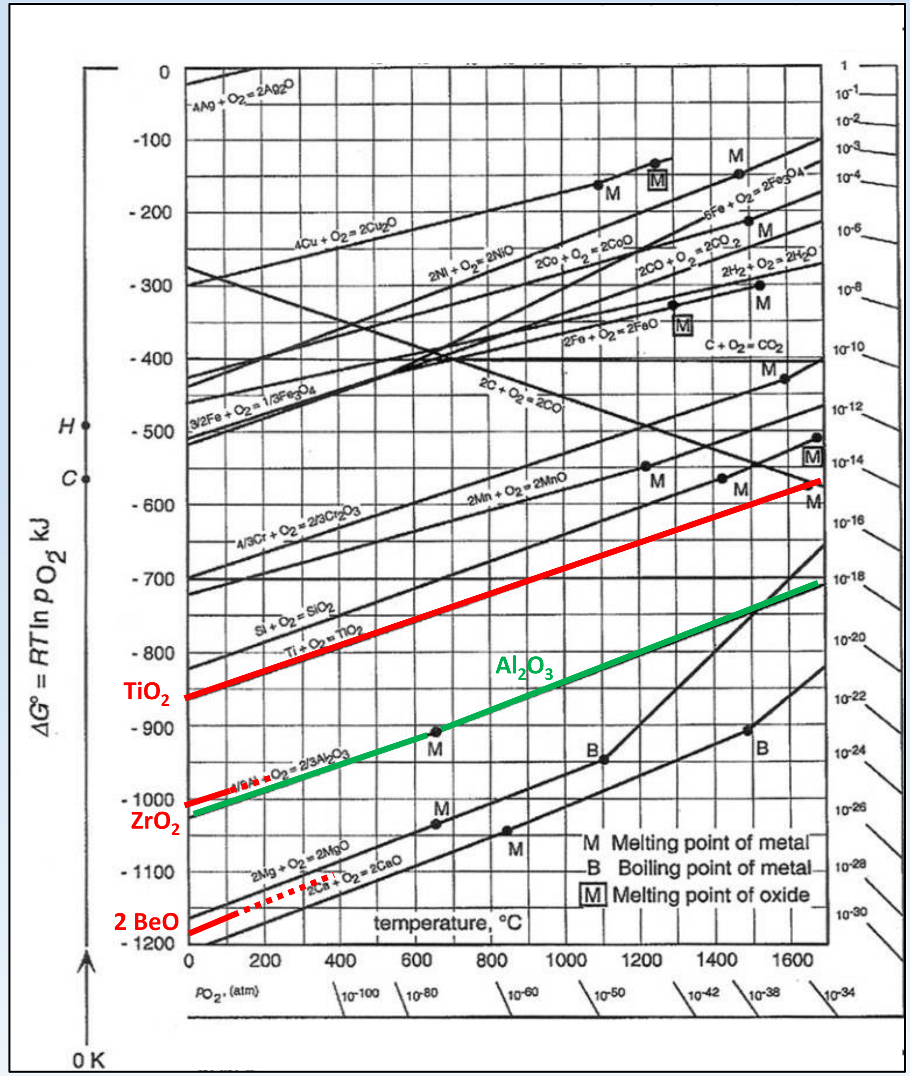
- Complex chemical reactions formed at the ceramic / brazing metal interface. Ex.: SiC/Ti > Ti_3SiC_2, Ti_5Si_3C, $Ti_5Si_3C_x$,….

- ↑ Interaction (wetting) possible with several types of ceramics.

- ↓ Possible formation of brittle phases.

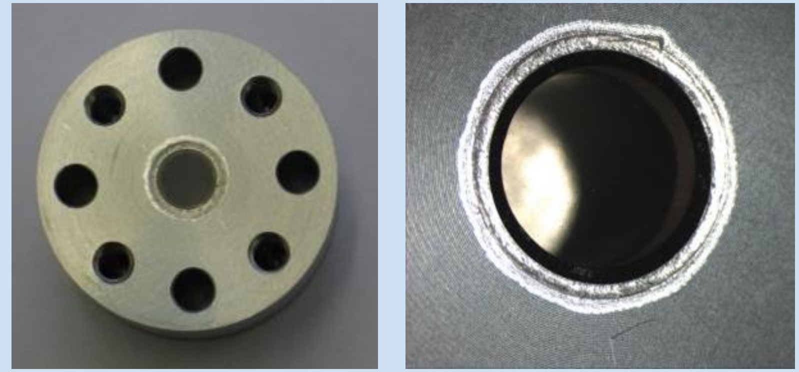
- Example of Active Brazing Alloys:

  CuSil ABA (Ag 63, Cu 35.25, Ti 1.75)
  Silver ABA (Ag 92.75, Cu 5, Al 1, Ti 1.25)
  Gold ABA (Au 96.4, Ni 3, Ti 0.6)

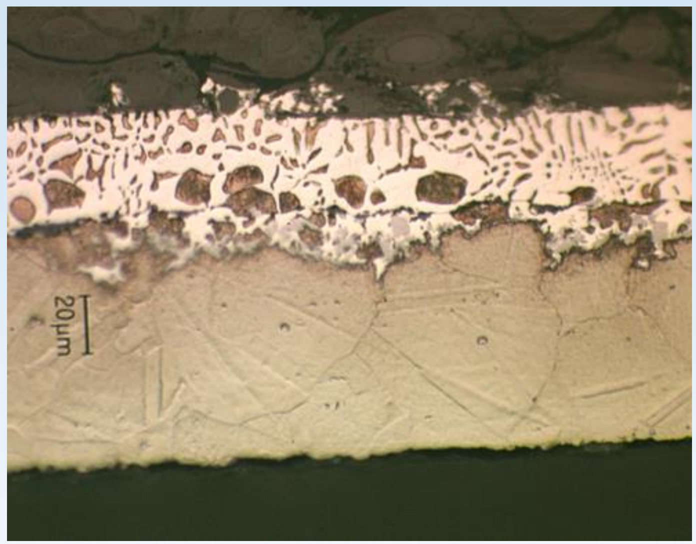


Ellingham diagram

Vacuum Brazing of Ceramics with Active Alloy - Examples



Diamond (Φ 5 mm) – Ti



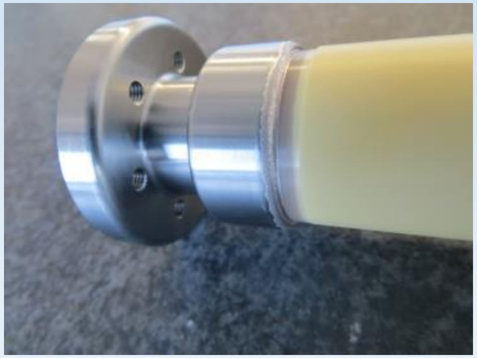
Carbon – CuSil ABA – CuNi

AlN – Dilver

- Active brazing on ceramics

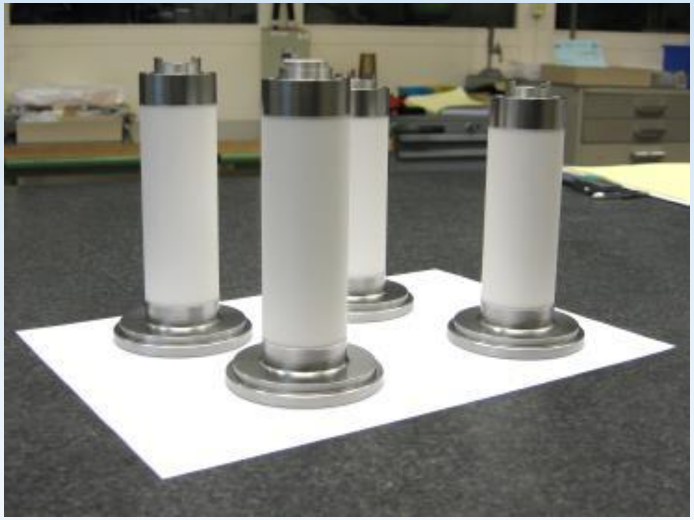
Alumina – Ti

Alumina – Cu



ZrO_2 – Ti

Alumina – Monel



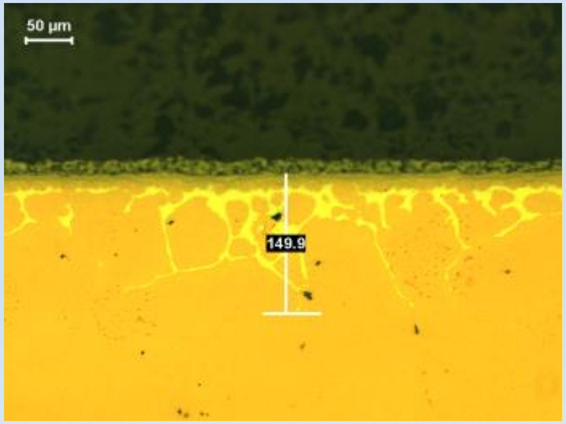
Alumina – Ti

Vacuum Brazing of **Metals** with Active Alloy - Examples

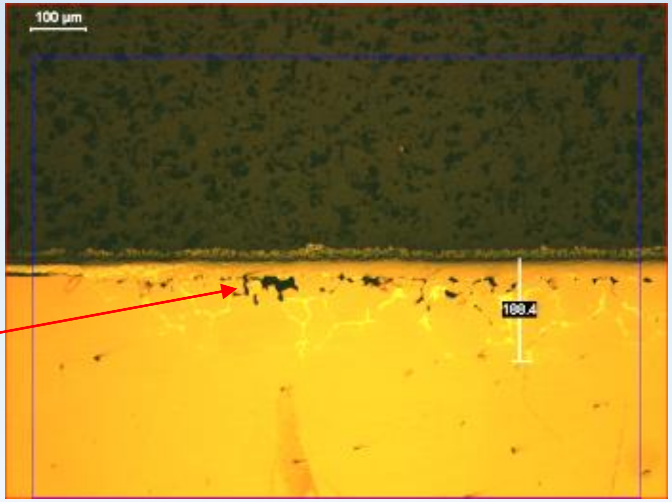
Ta tube /316LN with CuSil ABA
(A. Gerardin)

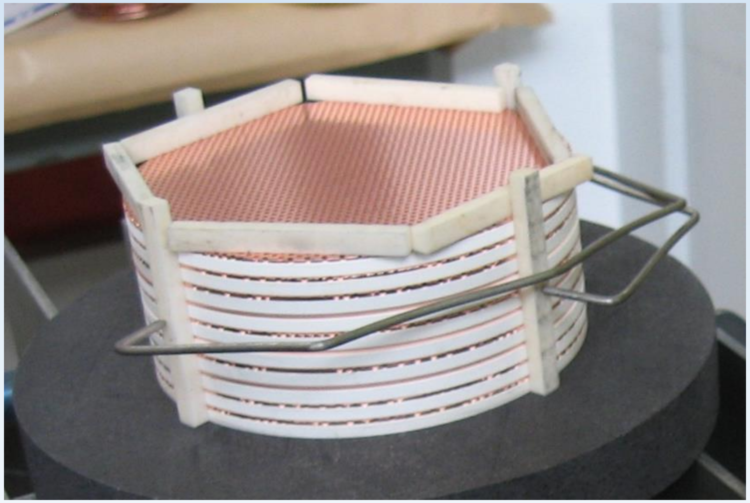
Cu – W
(CuSil ABA)

Diffusion brazing: The filler metal is form by diffusion during the heat treatment.
Example: Alumina/Cu, Metallized ceramic with a Silver layer, Cu with Silver layer

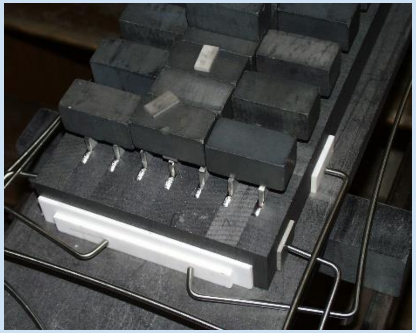


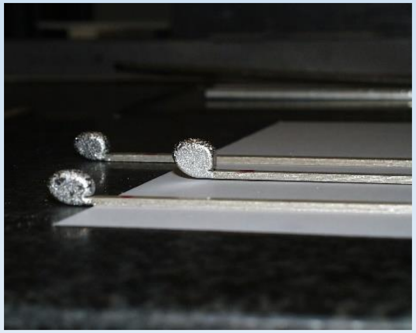
Porosities



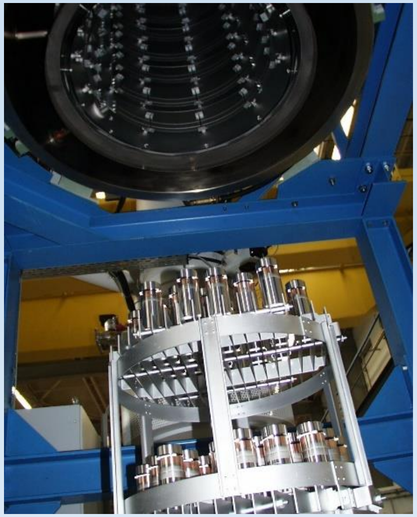


Vacuum brazing (and vacuum furnaces) are adapted to produce large quantities of similar pieces. Not common at CERN, but why not when needed ….

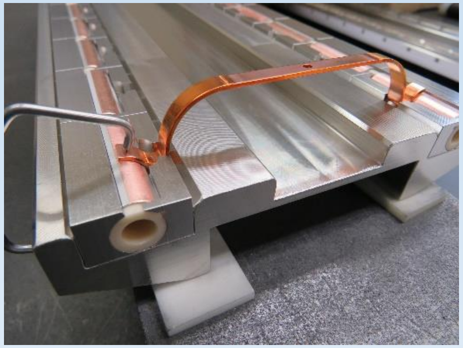




23 km of HTS tapes vacuum soldered in stacks



Hundreds of Cu/Stainless steel junctions



18000 brazing for the thermal links

Final remarks - comments

Vacuum brazing is a technique that allows highly precision assemblies, which allows different materials, including ceramics, to be assembled.

The preparation of parts and machining is always high precision. But success begins with the discussion of the design and the follow-up of a very precise procedure, including for surface treatments.

High temperature brazing always modifies the properties or even the dimensions of the parts... this must always be taken into account.