Linac4 RFQ issues

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Linac4 RFQ – Introduction

- Linac4 RFQ Facts
- How it all came about that we looked into the structure…
- Linac4 RFQ Inspections on 7 and 8 January 2020
- Linac4 RFQ Inspections on 11 February 2020
- Irradiation of Cu collimator mask and inspection
- The material and construction quest
- The way forward

Linac4 RFQ – Facts

- The L4 RFQ performs according to the original specification
- The RFQ has received beam on the vanes
- The RFQ shows surface modification
- The surface profile could not be measured
- The surface variation is less than could optically be resolved
- The RFQ worked fine in the last test run
- RFQ voltage was reduced slightly to ease operation
- Breakdown recovery needed to and will be improved
- The RFQ was vented and will need reconditioning
- There is no reason to expect immediate degradation

Linac4 RFQ – How it all came about…

- **It is well known from other institutes that RFQs degrade with time**
- **However**
  - The Linac4 RFQ operates at low duty cycle <0.1%
  - So far no degradation in operation seen
  - Linac2 RFQ had a spare that was never used
- **Strategy: no inspection to avoid venting of the RFQ – Linac4 is an operational machine**
- **However**
  - Beam induced surface damage on chopper beam dump found
  - Coloration in the LEBT found
  - Surface damage on test masks on the test stand (w/o RFQ)
- **Decision to continue endoscopy into the RFQ**

Linac4 RFQ – What is the risk?

- **4-vane RFQ is built "monolithically" – there are no individual spare parts**
- **Prior thoughts and preparation:**
- The only Linac4 structure with a detailed risk analysis – EDMS1560355 (2015)
- Budget for spare manufacturing was reserved
- Material was purchased in advance
- **Manufacturing requires 20 months**
- **Spare had not been built yet due to pending studies on a new geometry**
- **Other study clarified that the current RFQ is close to reasonable BD limits**

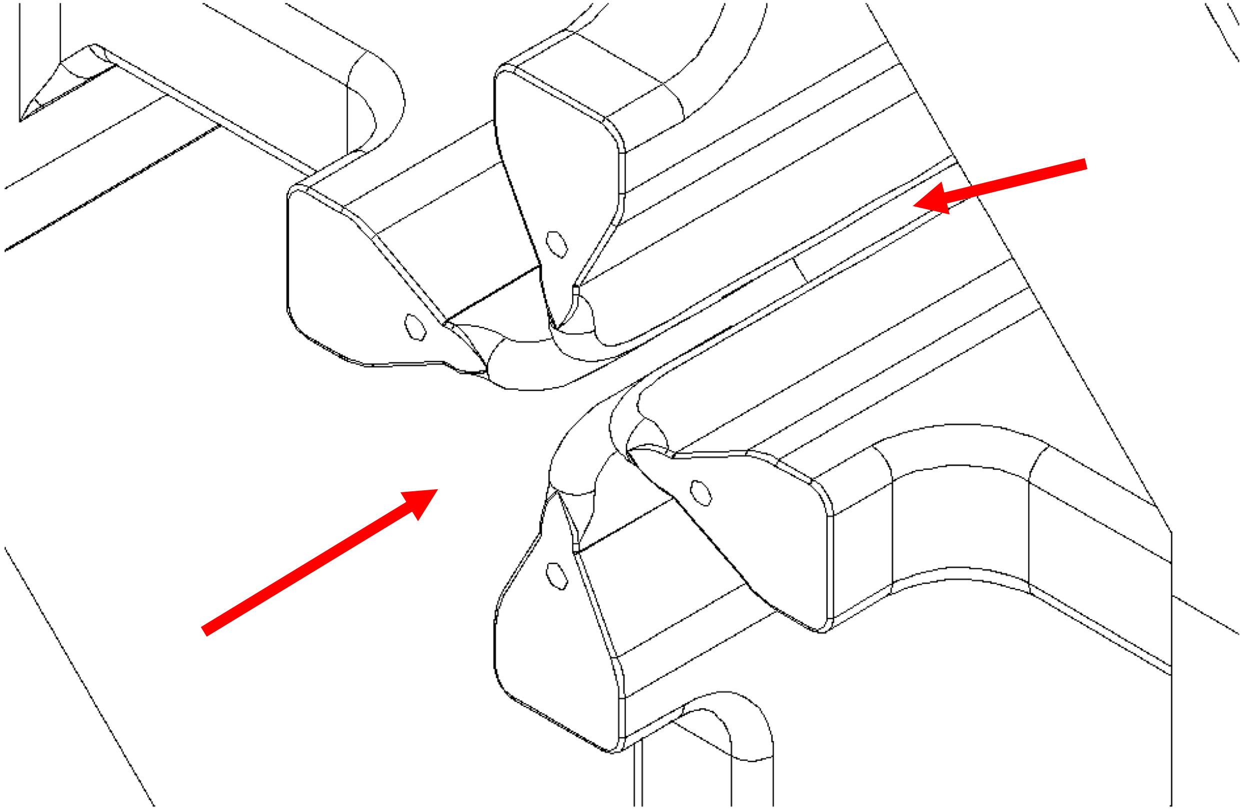
Linac4 RFQ Inspection

- RFQ inspection on 7 and 8 January 2020:
- Endoscopy of RFQ via entry at pre-chopper, beam stopper, vacuum valve and solenoid
- Endoscopy through vacuum ports of RFQ

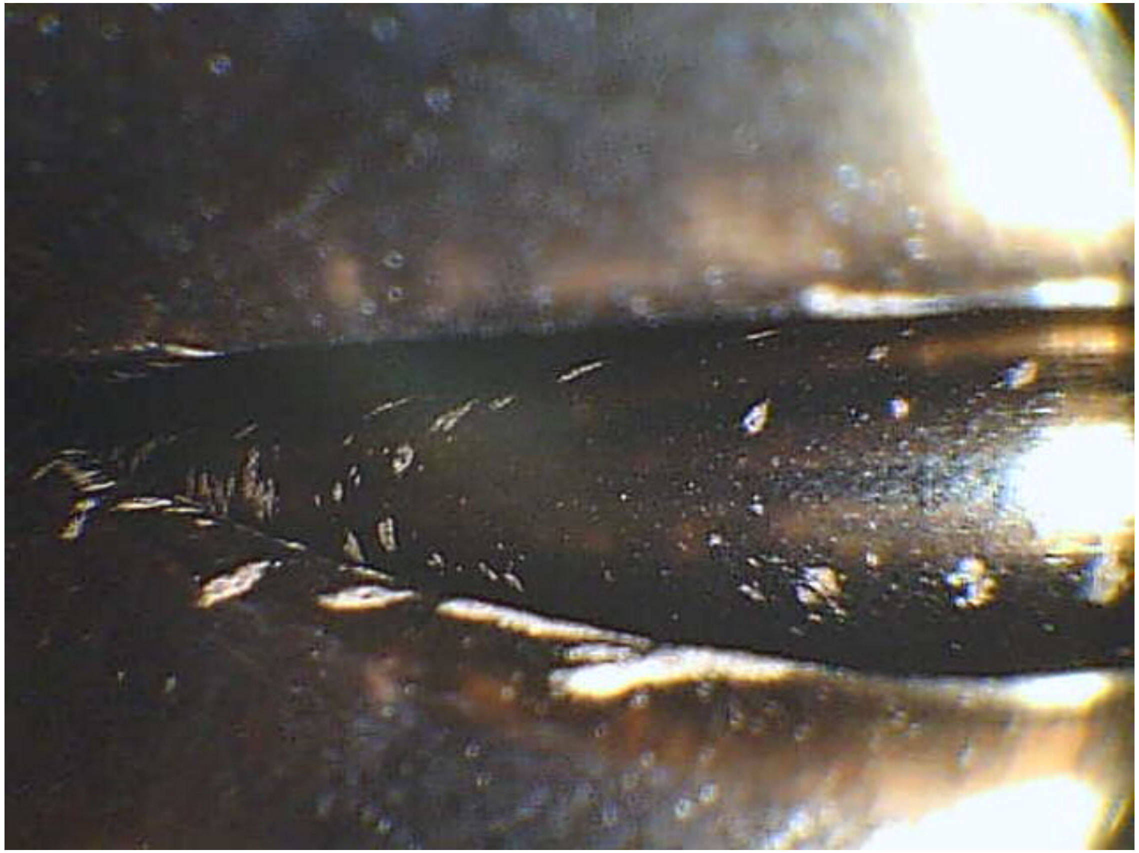
- Found usual craters all along the RFQ vanes
- Craters are a typical signature of breakdowns
- Breakdowns are part of conditioning of a structure

- Found damage on front face & start of the RFQ vanes
- Beware: endoscopy images can be misleading
- The analysis is based on more images than shown

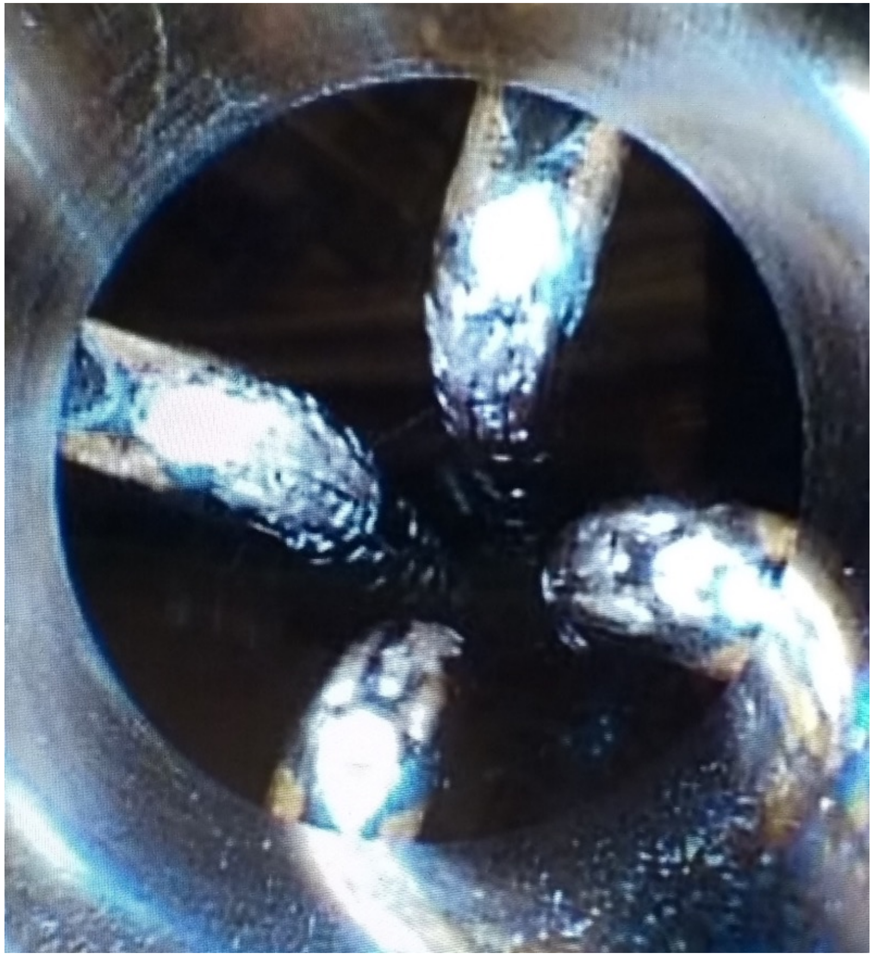
L4 RFQ vane front face



Breakdown craters



L4 RFQ vane front face



Vane front face damage

Vane front face damage

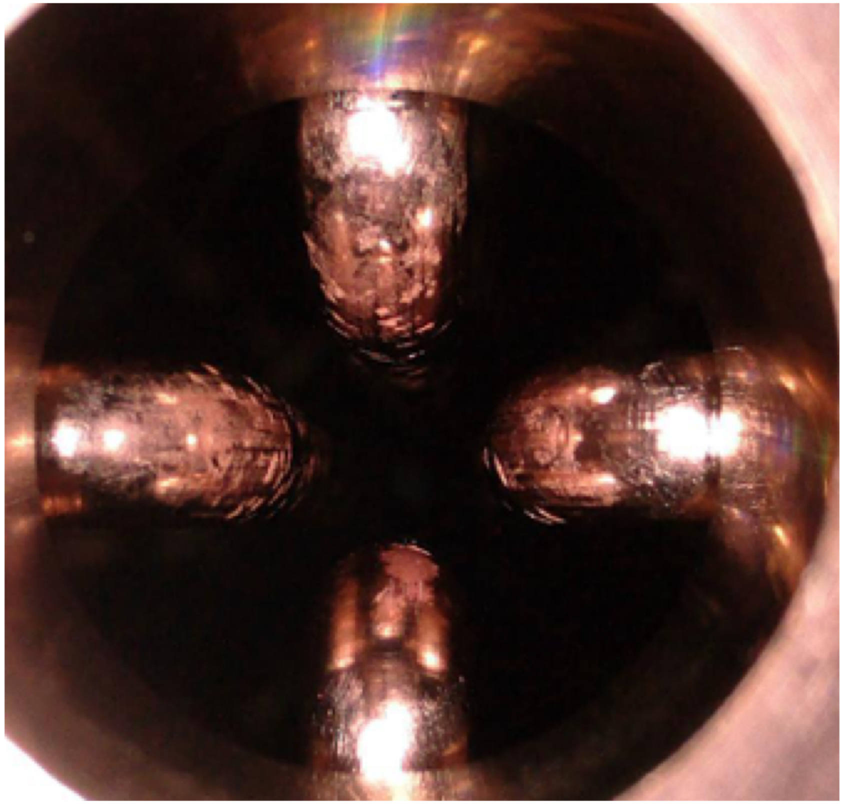
Vane entrance damage – groove?

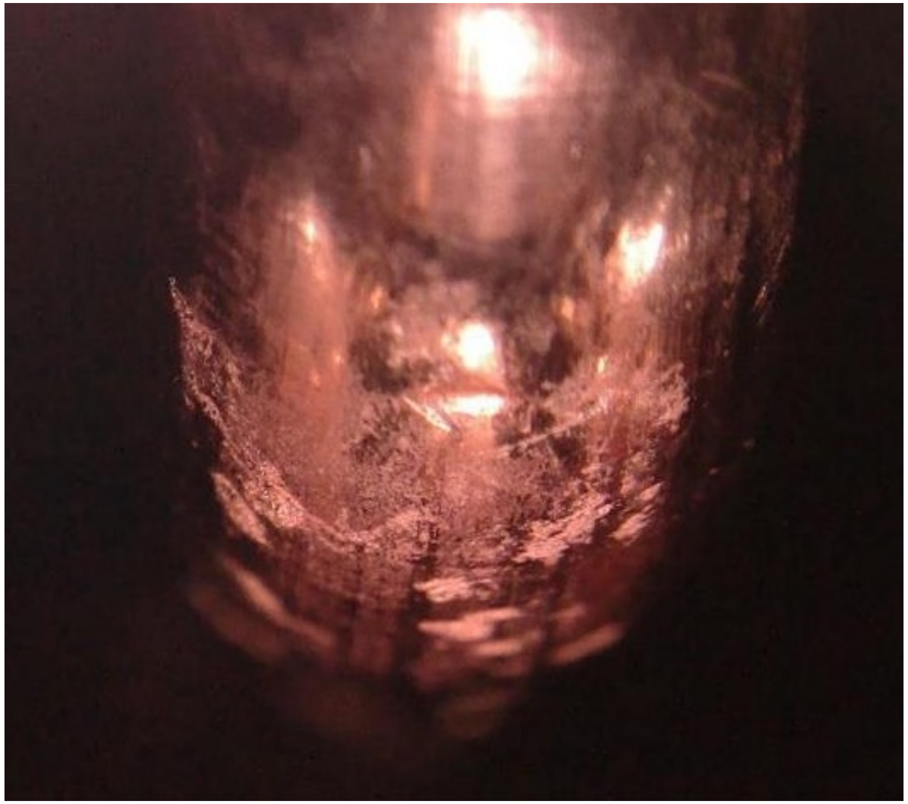
Linac4 RFQ – Inspection 07.01. – 08.01.2020

- **Damage on the surface layer of front face – first ideas**
- **Appears to be beam induced**
- **Superficial hydrogen implantation in Cu >10^{18}ions/cm^2**
- **No hydride formation in copper, instead H-bubbles**
- **Literature: blistering & exfoliation by heat deposition**

- **Detailed analysis at Peking University (2017) shows**
  - Visual material damage by 40 keV beam ~10^{18}ions/cm^2
  - Simulations show dislocations at ~0.2μm depth
  - Higher beam energy, less visible damage
- **Literature on the phenomenon is sufficiently available**

Linac4 RFQ – Inspection 11.02.2020

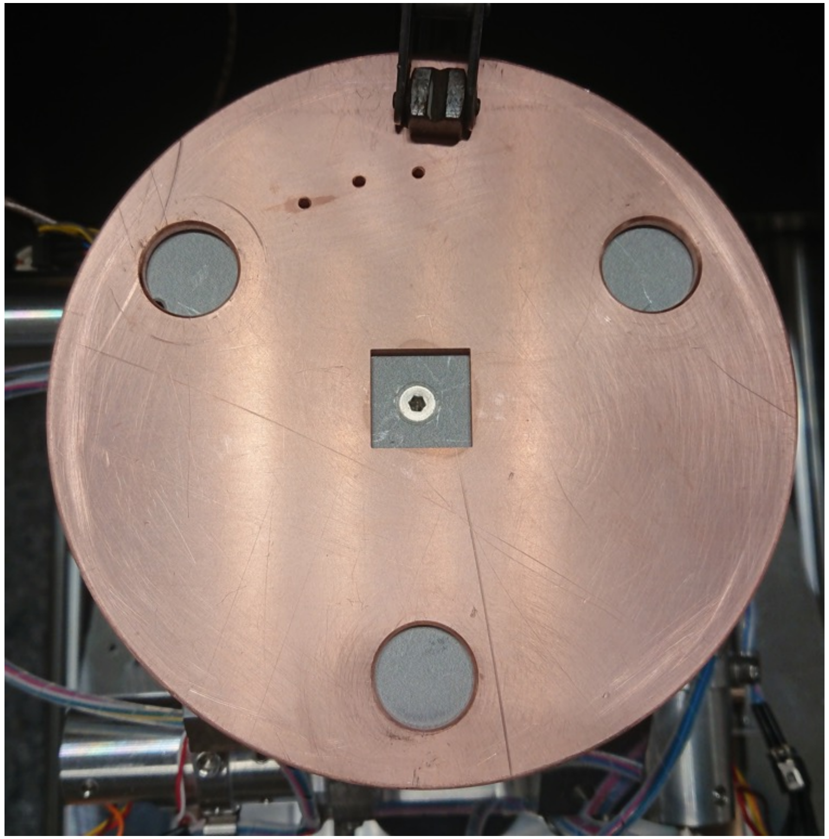


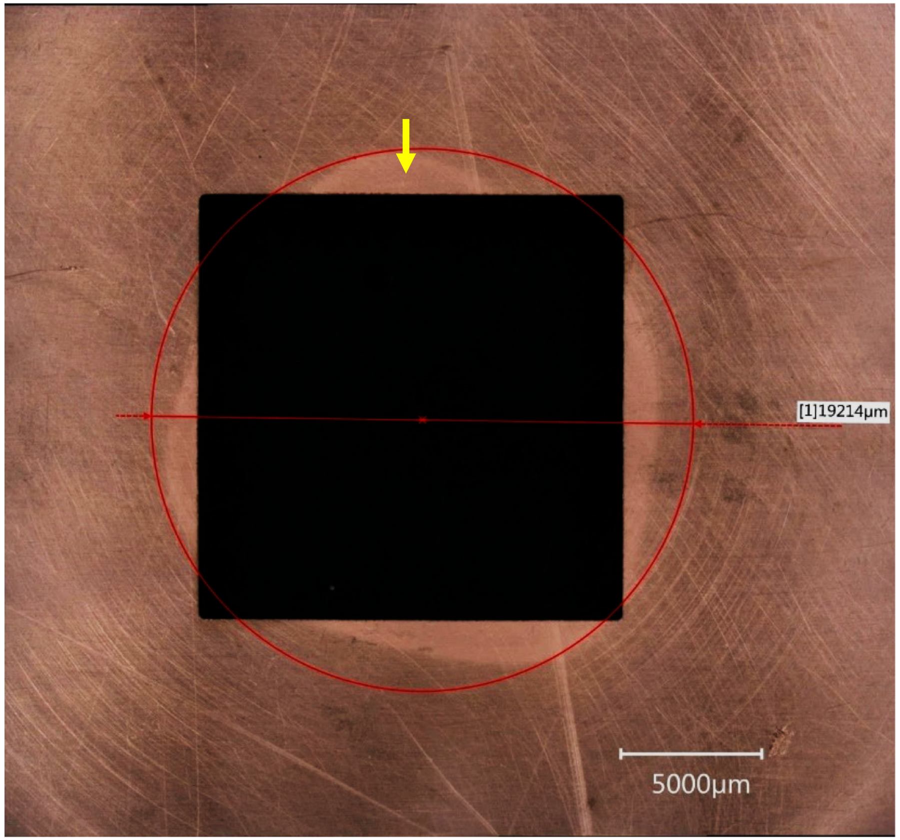


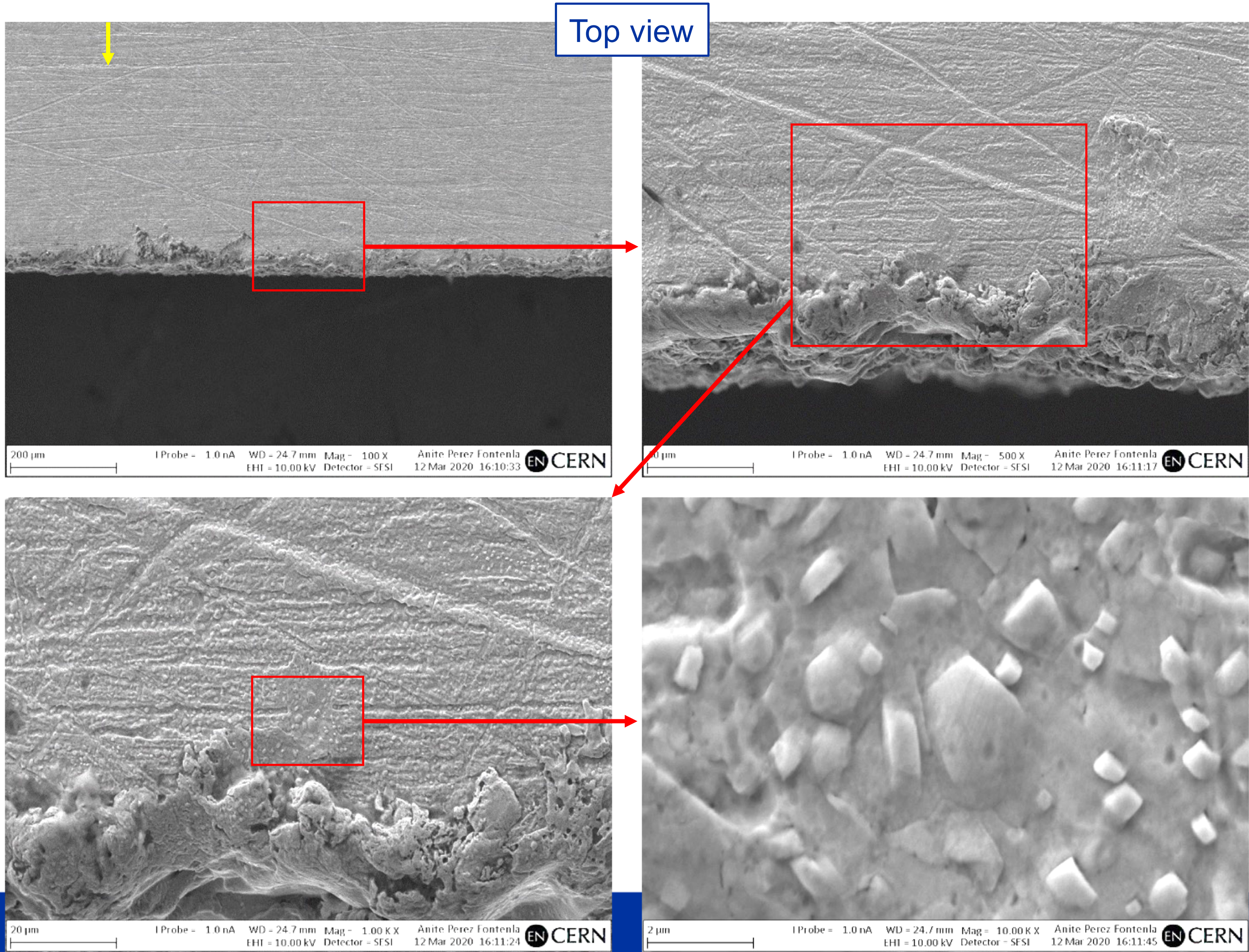
Linac4 RFQ – Inspection 11.02.2020

- **Solenoid removal, pictures taken by normal camera:**
- **Presumed damage turns out to be mostly variations in surface texture**
- **No profound features were found**
- **Surface profile could not be measured**
- **Aperture of opening too small to use hand held laser metrology devices**
- **Space is tight for the installation of a laser measurement head with XY table**
- **Copper surfaces have strong reflections**
- **3d endoscope had major issues with surface texture**
  - AI image reconstruction in the visible freq. range has similar shortcomings as our eyes.

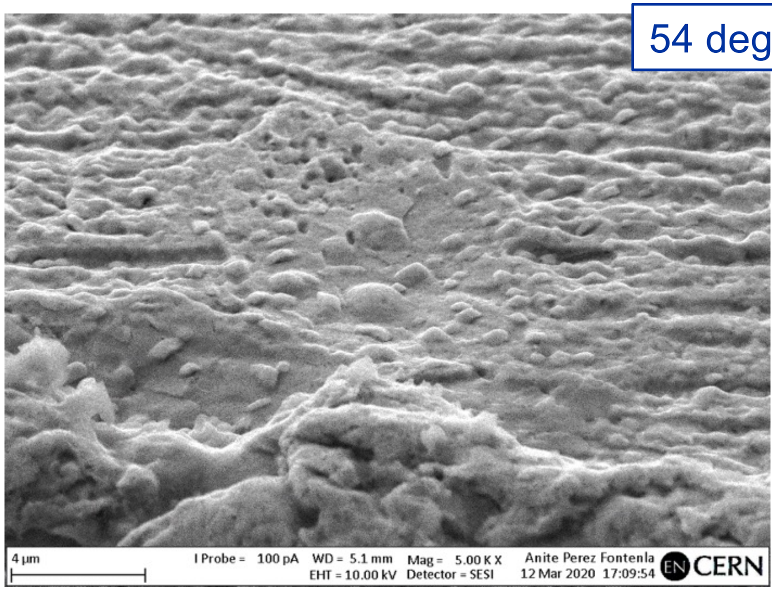
Material tests on copper mask - (A. Perez Fontenla)

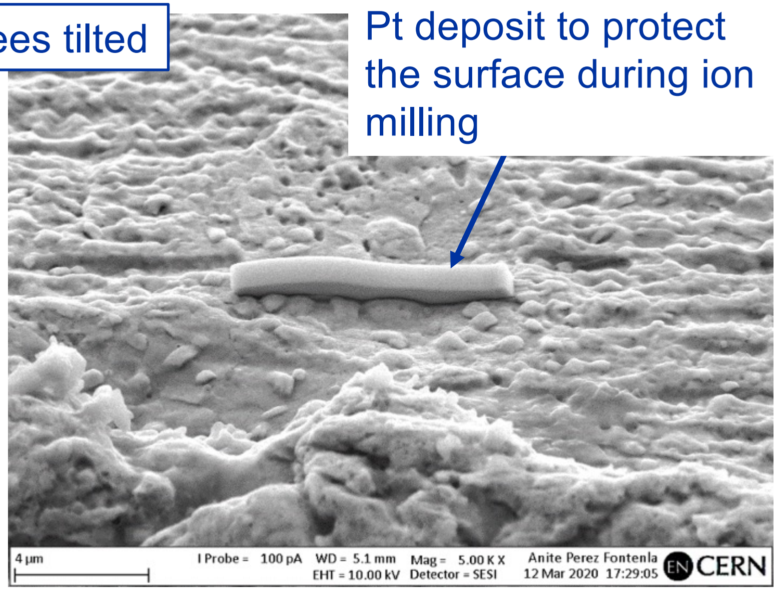




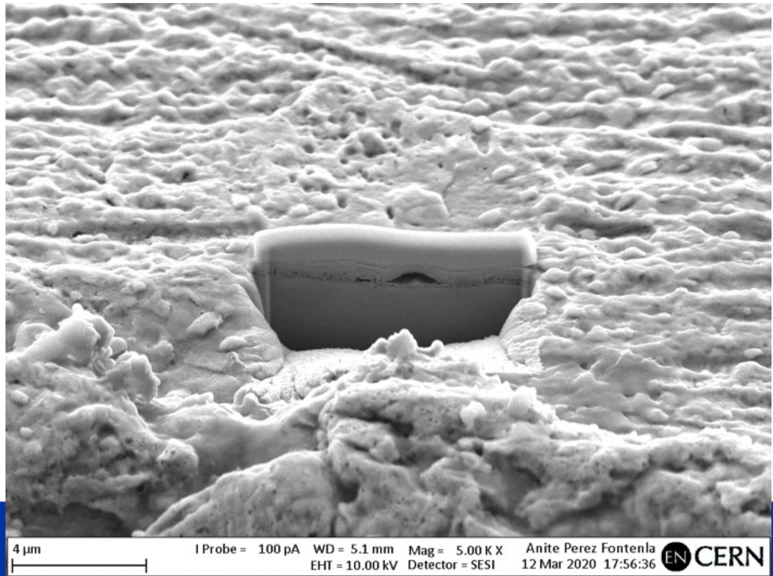

Top view
200 µm
I Probe = 1.0 nA
WD = 24.7 mm
EHT = 10.00 kV
Mag = 100 X
Detector = SESI
Anite Perez Fontenla
12 Mar 2020 16:10:33
CERN
I Probe = 1.0 nA
WD = 24.7 mm
EHT = 10.00 kV
Mag = 500 X
Detector = SESI
Anite Perez Fontenla
12 Mar 2020 16:11:17
CERN
20 µm
I Probe = 1.0 nA
WD = 24.7 mm
EHT = 10.00 kV
Mag = 1.00 K X
Detector = SESI
Anite Perez Fontenla
12 Mar 2020 16:11:24
CERN
2 µm
I Probe = 1.0 nA
WD = 24.7 mm
EHT = 10.00 kV
Mag = 10.00 K X
Detector = SESI
Anite Perez Fontenla
12 Mar 2020 16:11:45
CERN

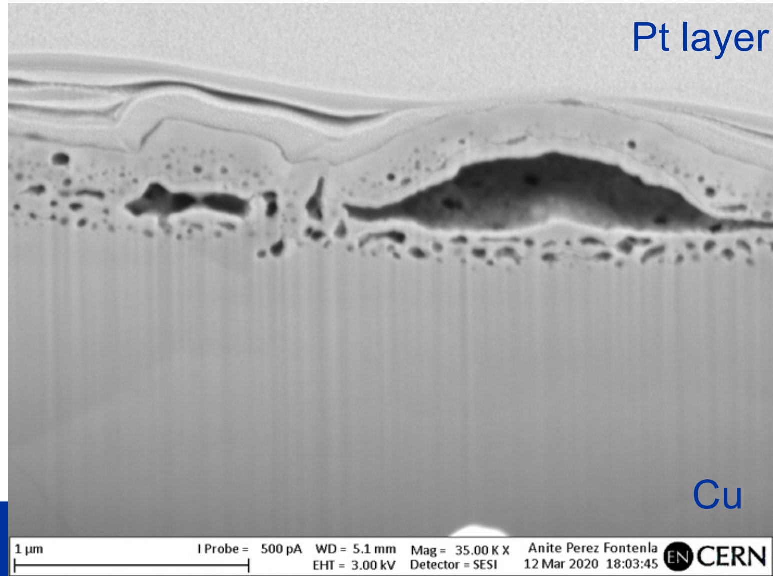
54 degrees tilted



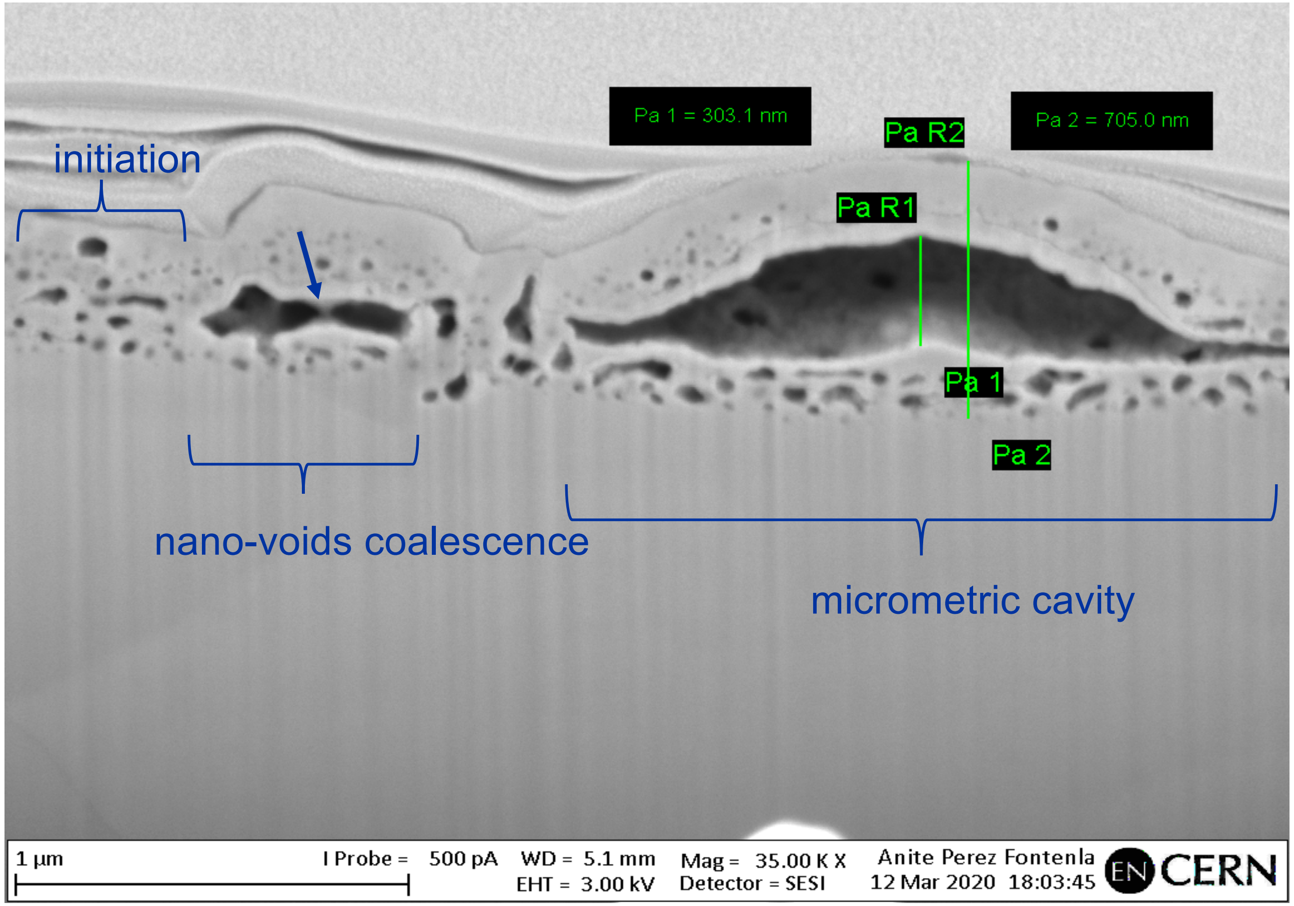


Pt deposit to protect the surface during ion milling





Spongy copper layer



Material tests on copper mask

Material received beam on the L4 source test stand exactly in place of an RFQ

What appears as a change in coloration are:

- **Changes in surface roughness with micron-sized features**
- **Little hydrogen cavities under every bump in the surface**
- **Spongy material areas going 400nm into the surface**
- **The Bragg peak at the proton implantation energies is expected at 200nm**
- **Areas w/o coloration have 400nm of perturbed non-spongy structure**
  - Probably due to material production
- **The material is not representative for the RFQ – more beam tests required**
- **More care will need to be taken to reproduce the situation on the RFQ**

The material quest – Copper (Cu-OFE)

- 99.99% copper
- Has been used in the Linac4 RFQ design
- Yield strength strongly dependent on grain size: <300 N/mm^2, hardness: HV <100
- High conductivity: 59.6 S/m, 101% IACS (International Annealed Copper Standard)
- Loses strength with thermal treatment due to grain growth
- Can be brazed

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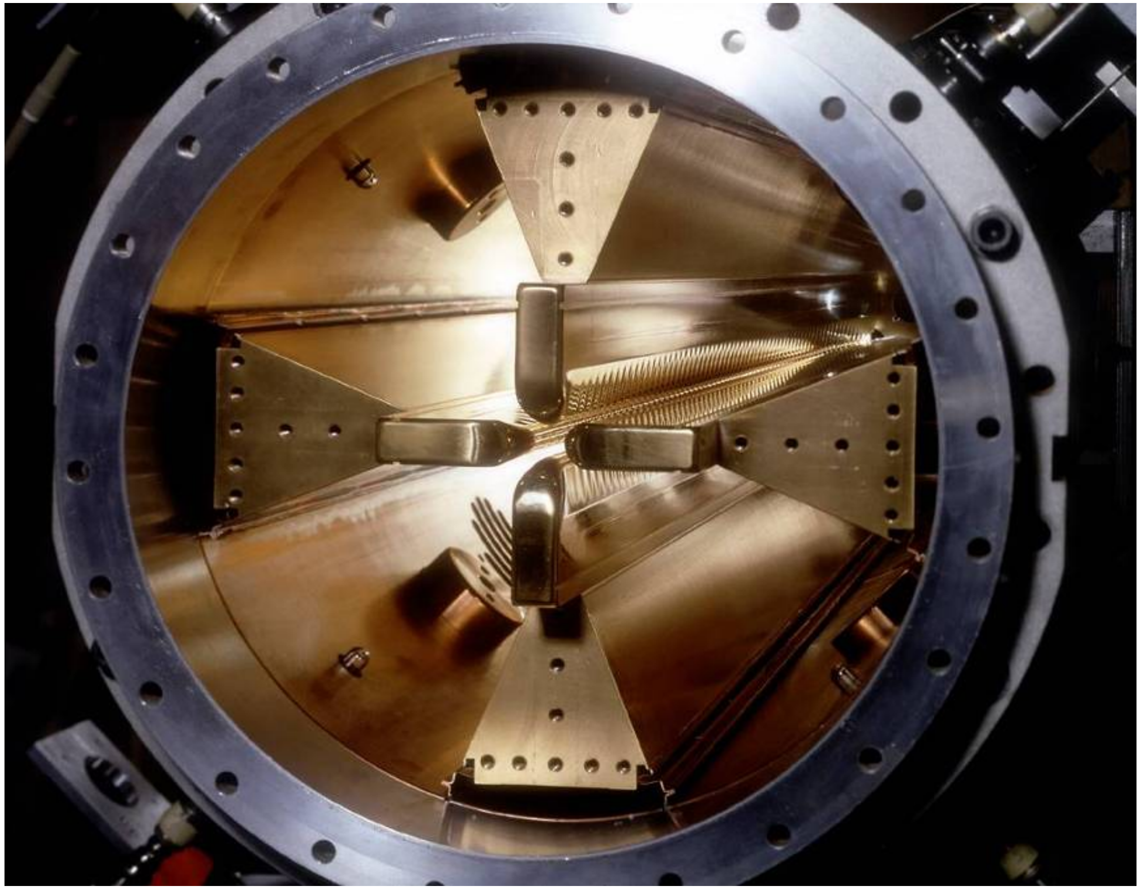
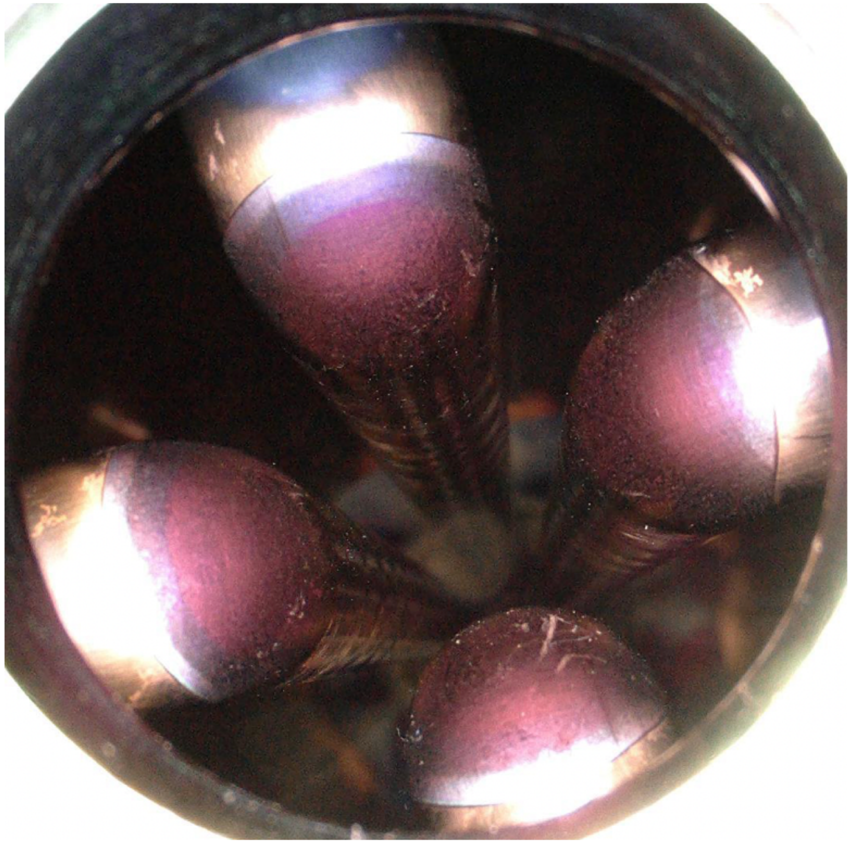
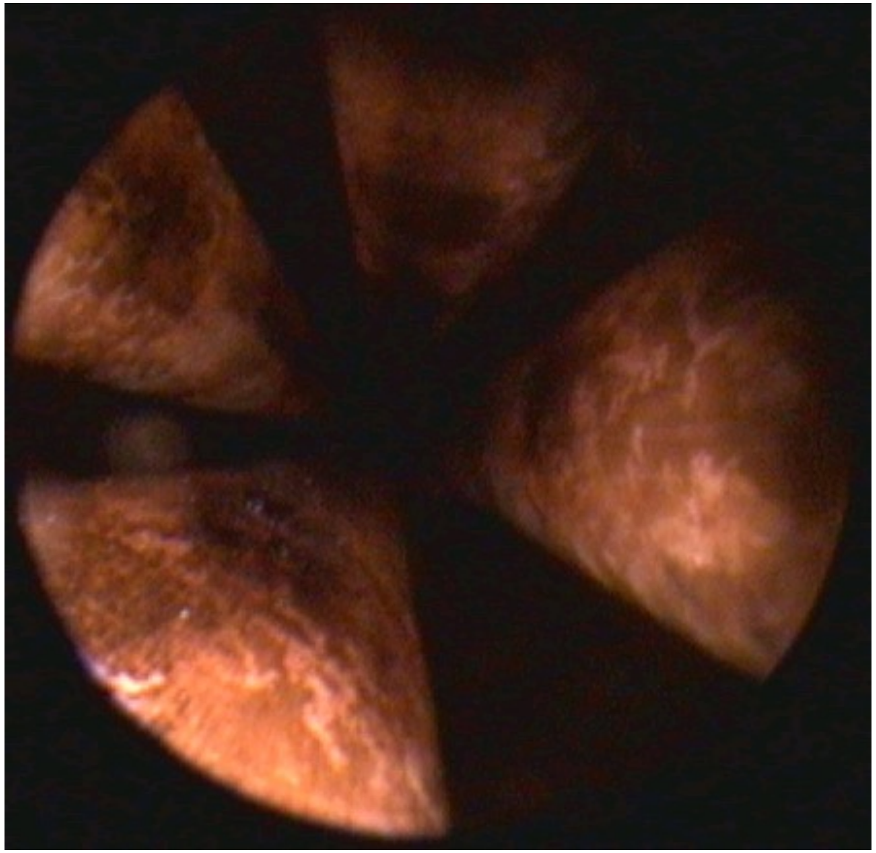
Linac2 RFQ – for comparison



Linac2 RFQ – for comparison





Copper-Chromium-Zirconium (CuCr1Zr)

- ~1% Chromium, ~0.1% Zirconium
- A standard alloy available from various manufacturers
- Hot forging, precipitation hardening and thermal ageing
- Has been used in the Linac2 RFQ design: Elmedur X, Thyssen, Stuttgart
- Higher yield strength: >300 N/mm^2, higher hardness: HV <160
- Relatively high conductivity of ~80% IACS
- Zirconium forms hydride, might inhibit blistering
- Can be brazed in general

wieland
duro

Elmedur X (for universal applications)

Technical Datasheet

Short Name	CW106C	Chemical Composition (Reference values in %)	Cr	Zr	Cu
Code	CuCr1Zr		0.8	0.08	balance
Material-Nr.(old)	2.1293				

Classification	DIN ISO 5182	Class A 2/2
	R.W.M.A.	Class 2
	UNS	C18150

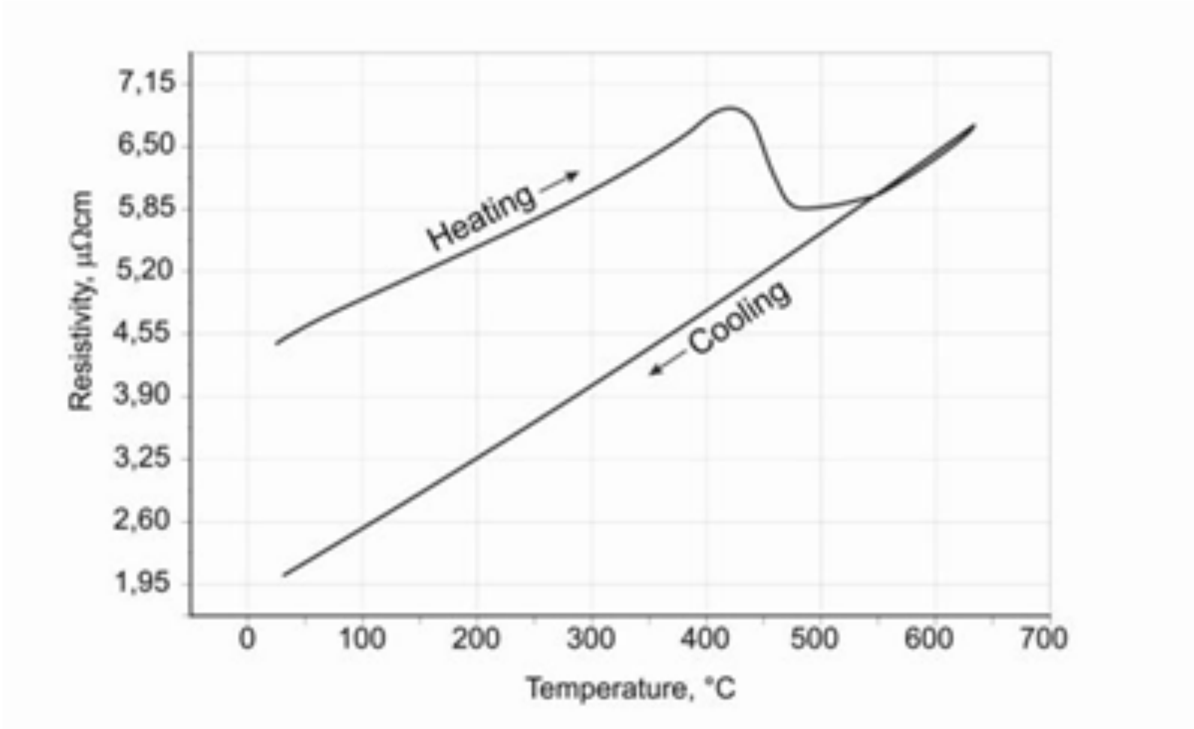
Material-Properties	Precipitation hardened copper alloy with excellent hardness and high electrical and thermal conductivity.

Applications

- Electrodes and cap tips for spot welding as well as for spark erosion
- Contact tips for MIG/MAG welding
- Parts in electrical equipments under high stress conditions if high electrical conductivity is required
- Application predominantly at low mechanical load if simultaneously very high heat elimination is desired

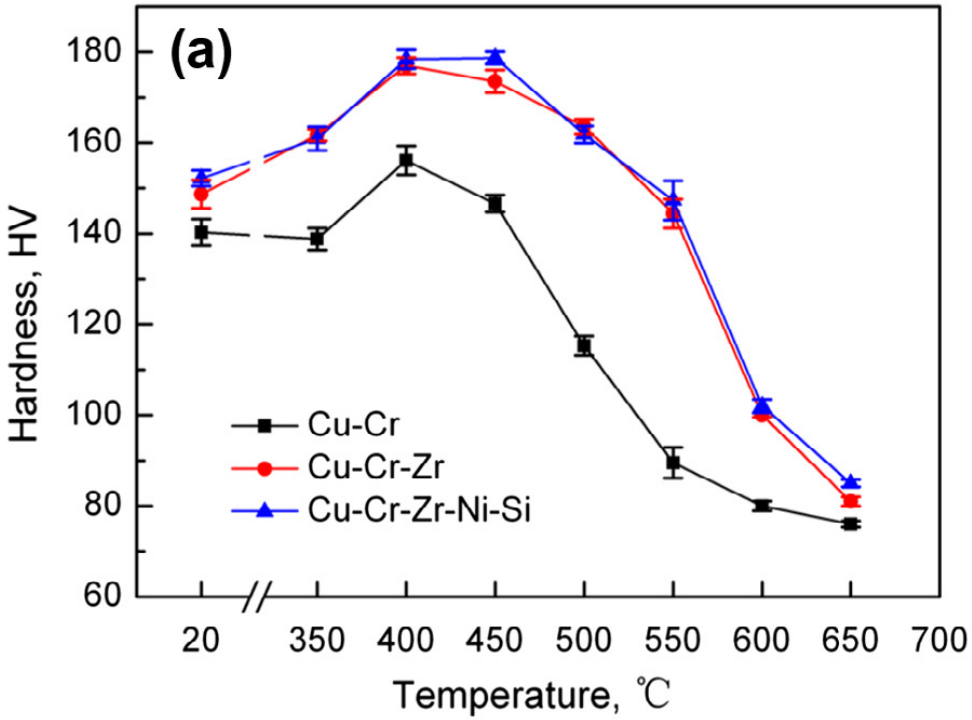
CuCr1Zr Raw Material Hardening

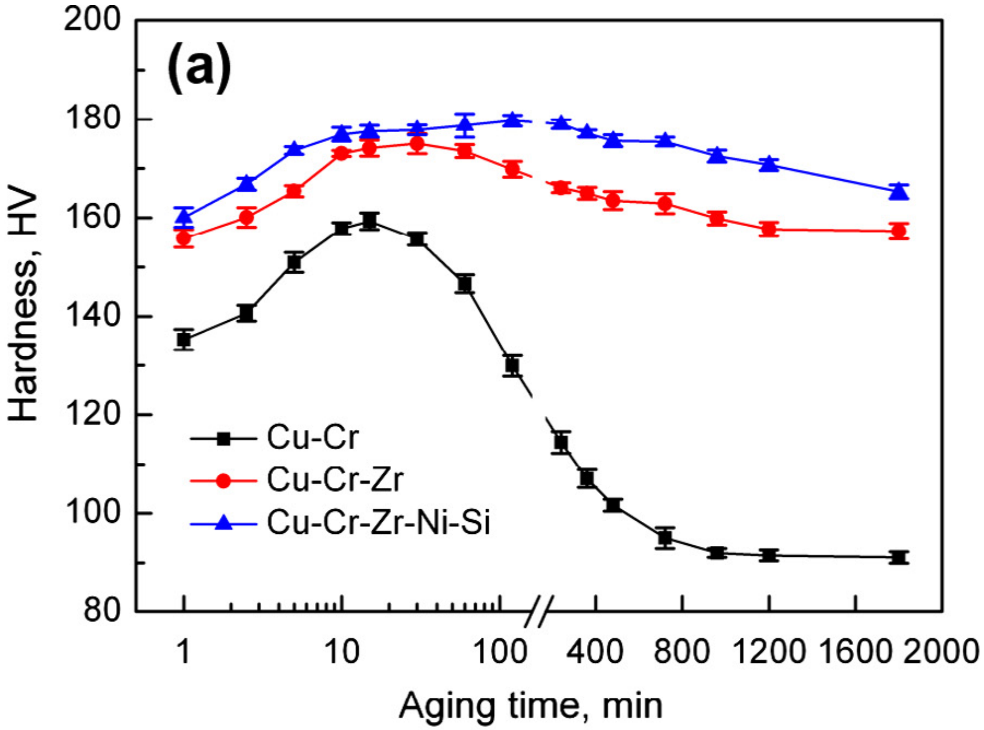
- **Solution annealing at 980–1000°C for 30–60 min.**
- **Water quench**
- **Aging at 460–500°C for 2–4 h**



- **Note: the curves have been collected from various sources and CuCr1Zr materials and should just serve for illustration**

CuCr1Zr Heat Treatment (Cr 0.42%, Zr 0.18%)





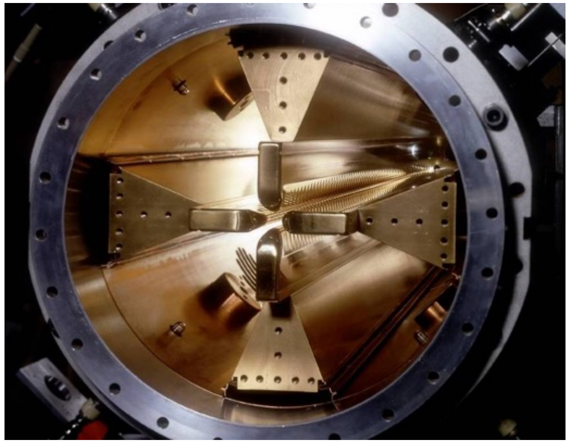
- **Hardness after heat treatment: 60min at various Ts and 450ºC with various durations**

Pang et al.: Effects of Zr and (Ni, Si) additions on prop. and microstr. of CuCr alloy

CuCr1Zr Heat Treatment / Brazing

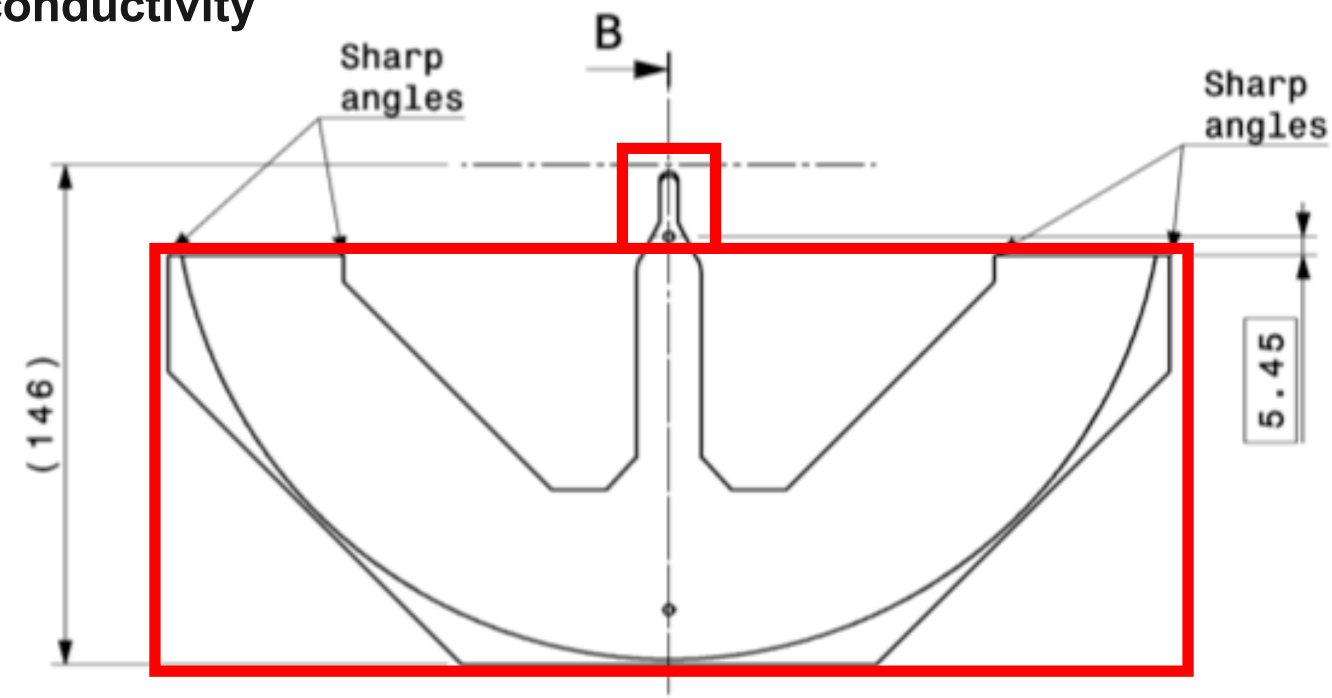
- **Zirkonium reduces the chromium diffusion coefficient, but…**
- **Heat treatment and brazing for the current Linac4 RFQ was undertaken at ~800ºC**
- **Material will not keep its properties if treated at temperatures >500ºC**
- **There is no advantage in using CuCr1Zr if brazing destroys the material properties**

- **Alternatives:**
  - Soldering instead of brazing
  - mechanical assembly and welding, e.g. the Linac2 RFQ



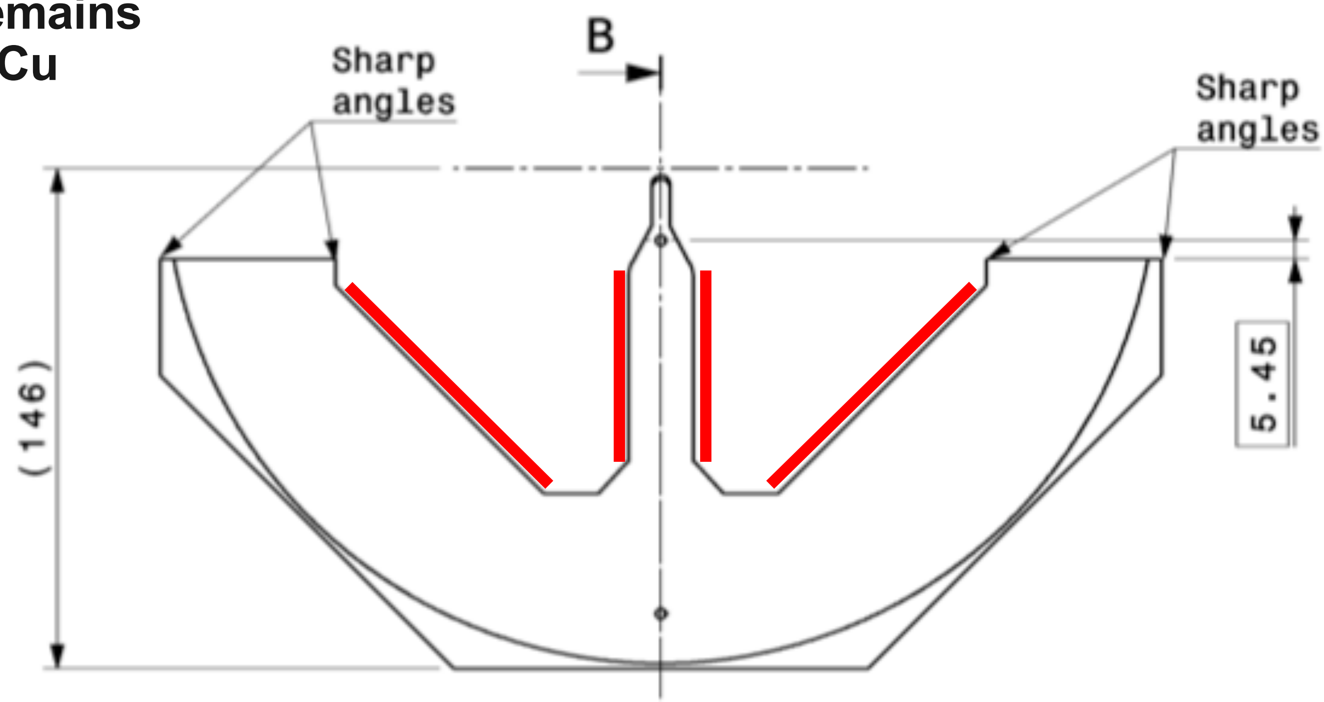
Further Mechanical Design Studies

- Can we join a CuCr1Zr tip to a Cu-OFE body before final machining?
- Joint requires good thermal conductivity
- But no leak tightness
- The area with high currents remains in Cu-OFE
- Can we weld the poles together?
- We need RF continuity inside



Further Mechanical Design Studies

- Can we copper plate a CuCr1Zr structure before final machining?
- The area with high currents remains plated with high conductivity Cu
- Can we weld CuCr1Zr?
- We need RF continuity inside



The way forward…

The Linac4 spare RFQ project (Richard Scrivens)

- **Protect the existing RFQ (RFQ1) – interlock on reflected power**
  - Implementation by Rolf Wegner and Bartosz Bielawski with support from Lee Millar
- **Collect more data in a permanent installation – Anna's thesis work**
  - With support from high gradient colleagues
- **Further material studies**
  - Walter Wuensch, Sergio Calatroni, Anité Fontenla, Ruth Peacock, Alexej Grudiev, Edgar Mahner
- **Build and test spares – a 1:1 copy (RFQ2) and a new design (RFQ3)**
  - Alexej Grudiev, Serge Mathot, Hermann Pommerenke plus …

Acknowledgements

All findings presented here are the result of a strong collaborative effort of many colleagues from various groups

- **BE-ABP for the Linac4 and test stand source operation and studies**
- **EN-MME and TE-VSC for the material analysis and studies**
- **BE-RF for RF operation, breakdown analysis**

Knowledge accumulated and techniques developed in the CLIC and high gradient study and the network of experts will be key to move forward on the RFQ spare project

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