Novel methods of vacuum chamber production:

Applications of electroforming to accelerator components

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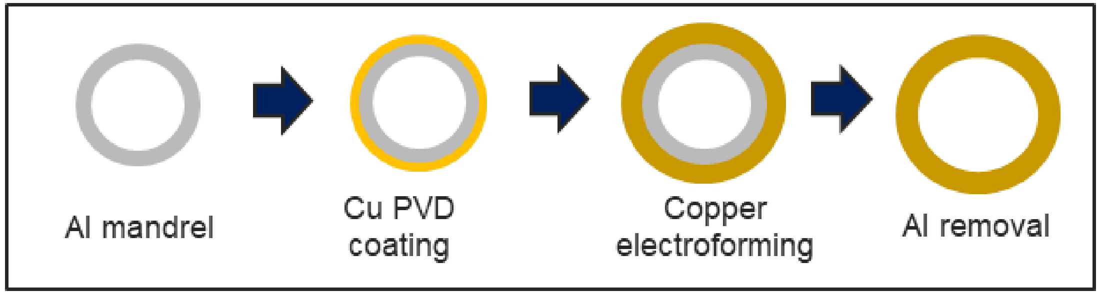
Outline

1. Electroforming process and copper properties

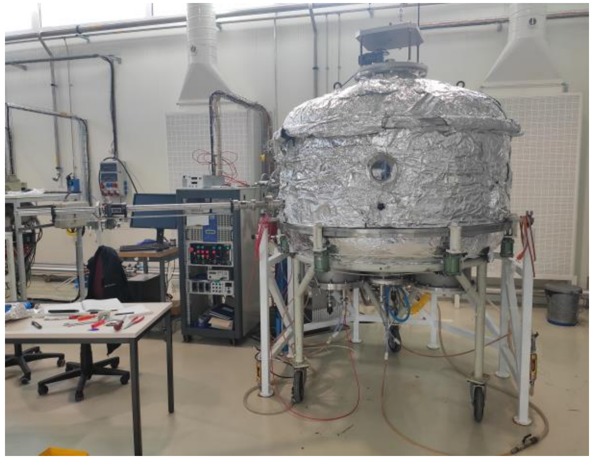
2. Development of thin-walled copper electroformed vacuum chambers for undulators

3. Electrodeposition of copper applied to the manufacture of seamless SRF cavities

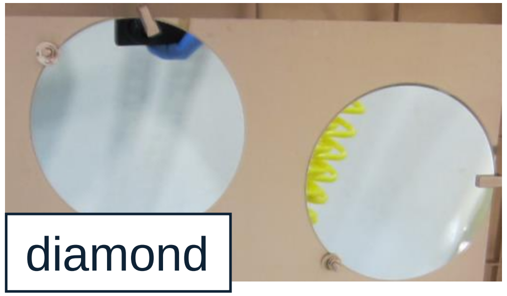
Electroforming process

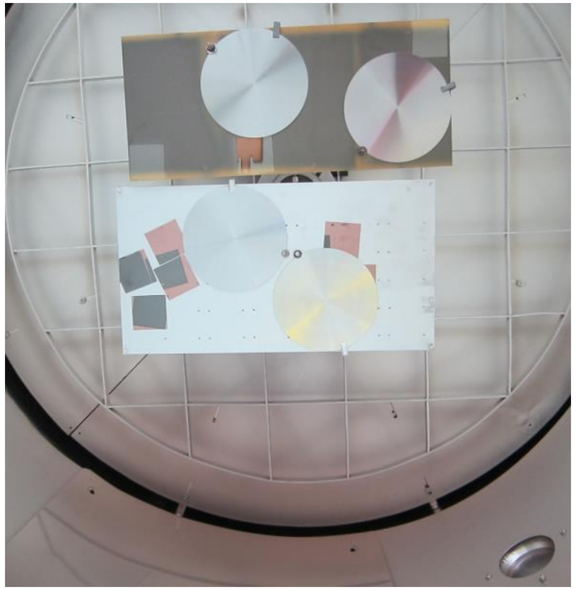


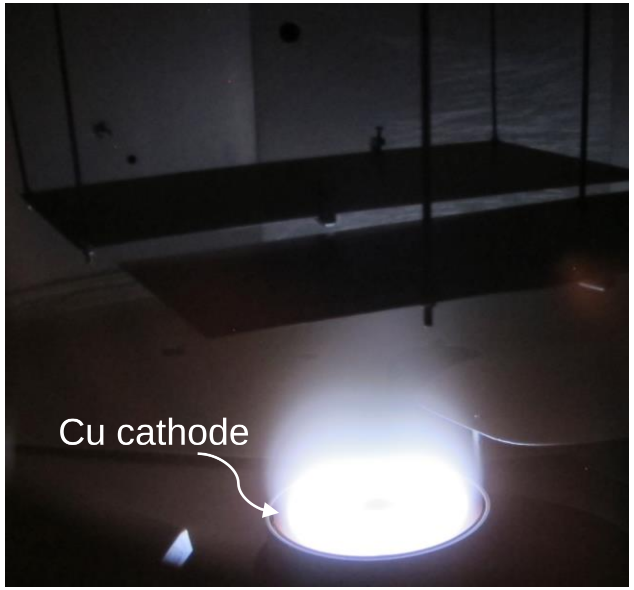
Process: copper electroforming around a sacrificial aluminium mandrel which is pre-coated with a copper thin film.



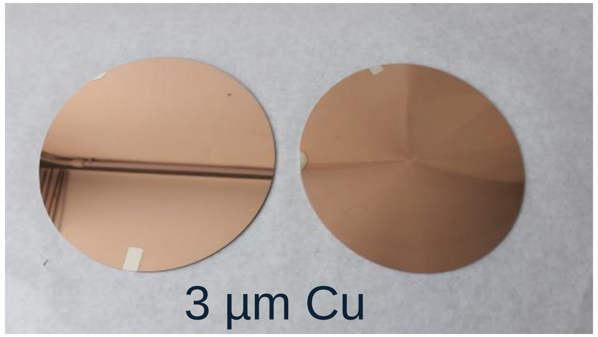
Cu PVD coating







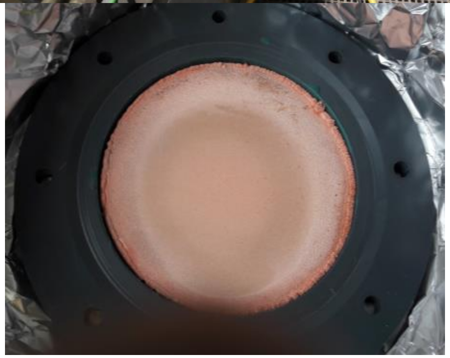
Cu coating by plannar magnetron sputtering



Electroforming process

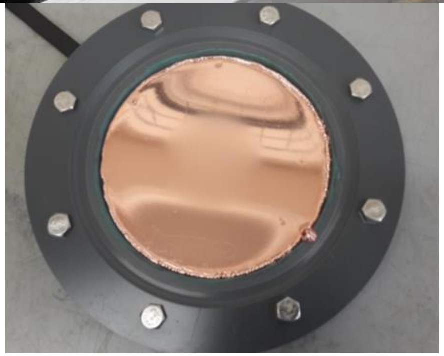
Two copper sulphate-sulphuric acid baths

Bath without additives



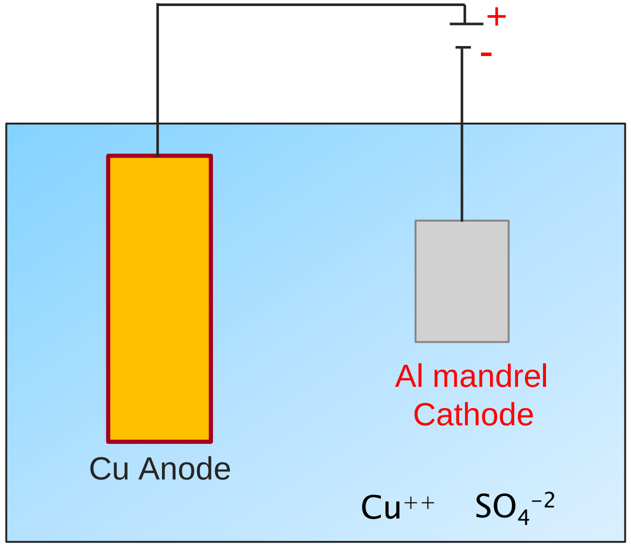
Pulse plating

Bath with brightener



DC plating

Setup Schematic



Chemistry

Cathode (reduction):

$$Cu^{2+} + 2e^{-} \rightarrow Cu$$

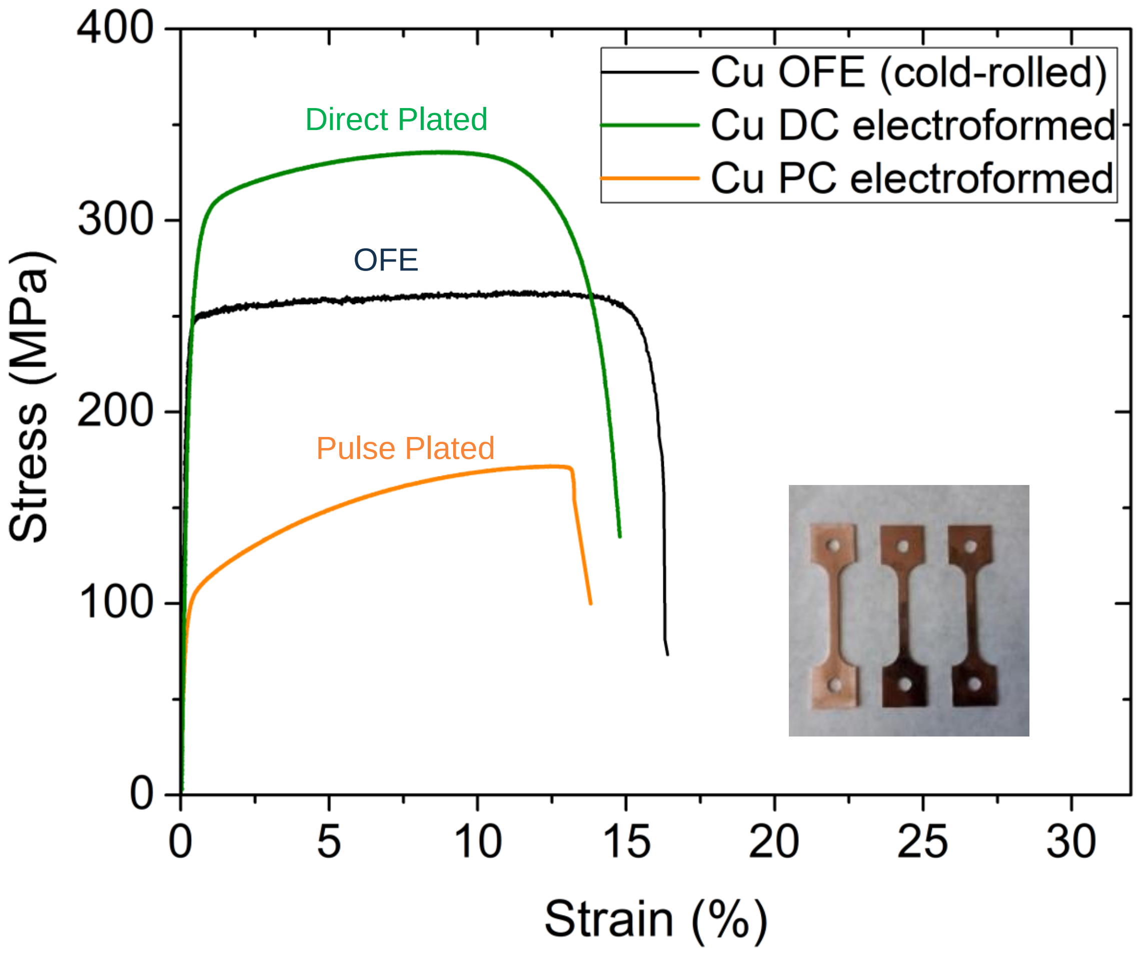
Anode (oxidation):

$$Cu \rightarrow Cu^{2+} + 2e^{-}$$

- Electrodeposition of Cu, 2 A/dm^2
  96 hours, 1.5 mm electroformed layer
- Aluminium removal dissolution

Electroformed copper properties

UTS/ Young modulus



- DC electroforming stronger than copper OFE cold-worked
- PC electroforming similar to copper OFE annealed

Ultimate tensile strength (UTS)

DC	PP
352 ± 41 MPa	174 ± 6 MPa

E modulus – impact excitation

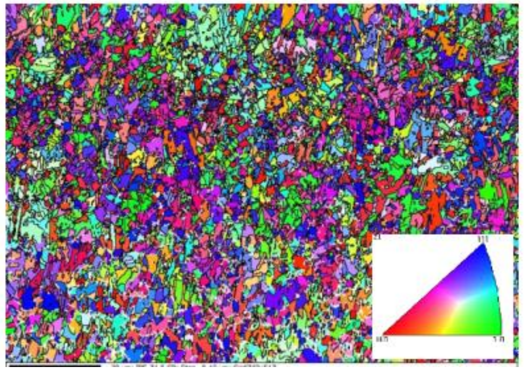
DC	PP
124 ± 15 GPa	131± 15 GPa

Electroformed copper properties

Microstructure and EBSD

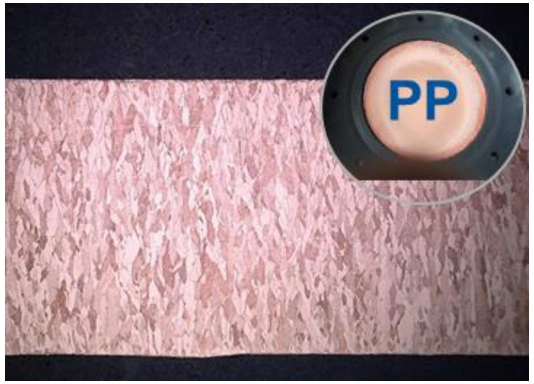
DC plated
with additive

100 µm

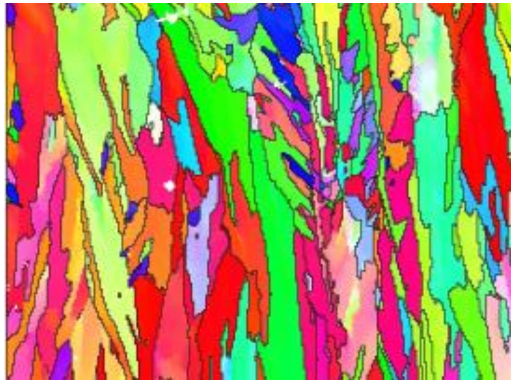


20 µm

Pulse plated
w/o additives



100 µm



20 µm

- **Tensile strength:**

  DC>PP : grains morphology

- **Grain size:**

  DC plating = 1-3 µm

  Pulsed plating =30-70 µm

  Cu OFE = 13-17µm

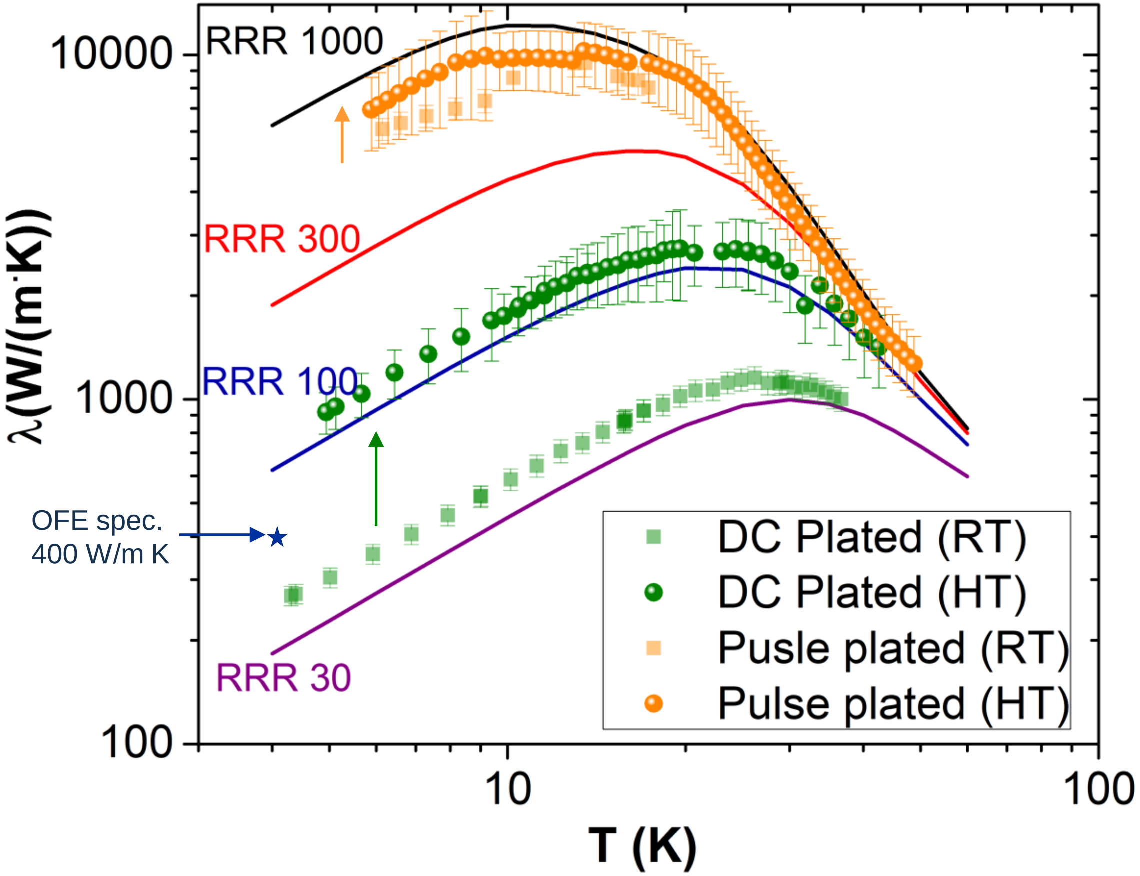
- **Different grain growth**

- EBSD shows no preferential grain orientation.

Electroformed copper properties

Thermal conductivity

- Samples measured after deposition
- Pulse plated sample conductivity 5 times larger than OFE spec.

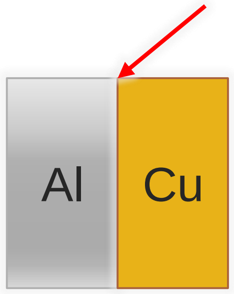


- After 2h at 400°C
- Triplicated conductivity for DC plated after thermal treatment

- Pulse plated layer is very pure (less than 2 ppm of Oxygen measured by IGA) in comparison with OFE copper (5 ppm) and DC plated copper (6.2 ppm)

Electroformed copper properties

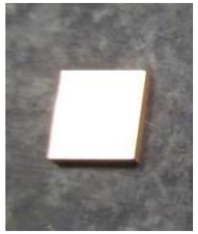
Roughness of internal layer

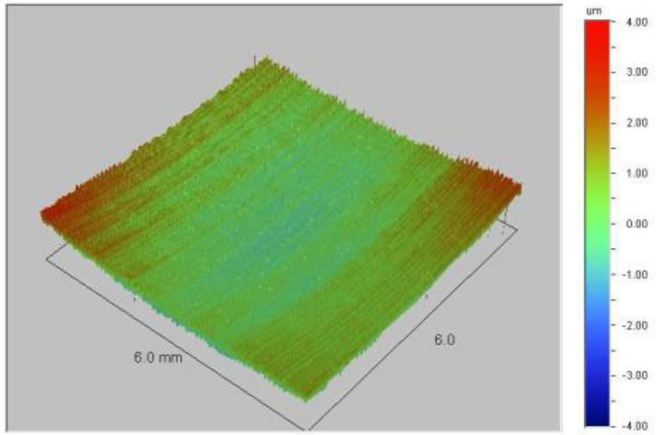


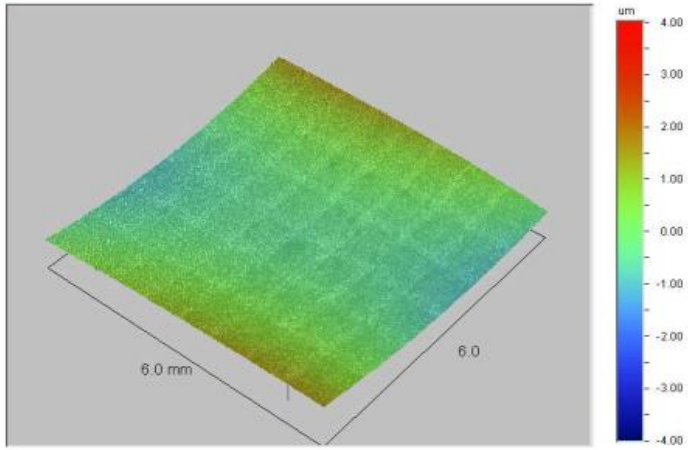
Standard mandrel machining
(Ra 0.49 µm)

Diamond mandrel machining
(Ra 0.002 µm)

Ra (µm)	DC plated	Pulse Plated	DC plated	Pulse Plated
Cu	0.39	0.65	0.023	0.028







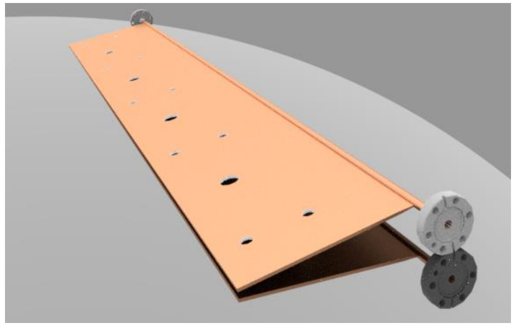
Cu layer reproduces mandrel topography

Electroformed copper properties

More suited for

DC plated with additive

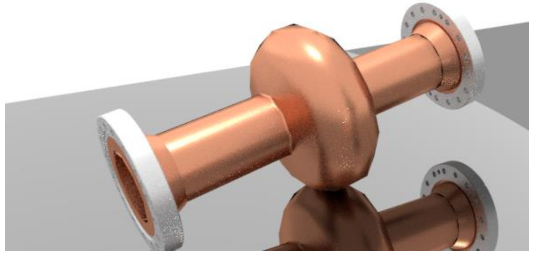
- High mechanical strength
- Very small grain size



Thin-walled vacuum chambers

Pulse plated w/o additives

- High thermal conductivity
- Very pure layer



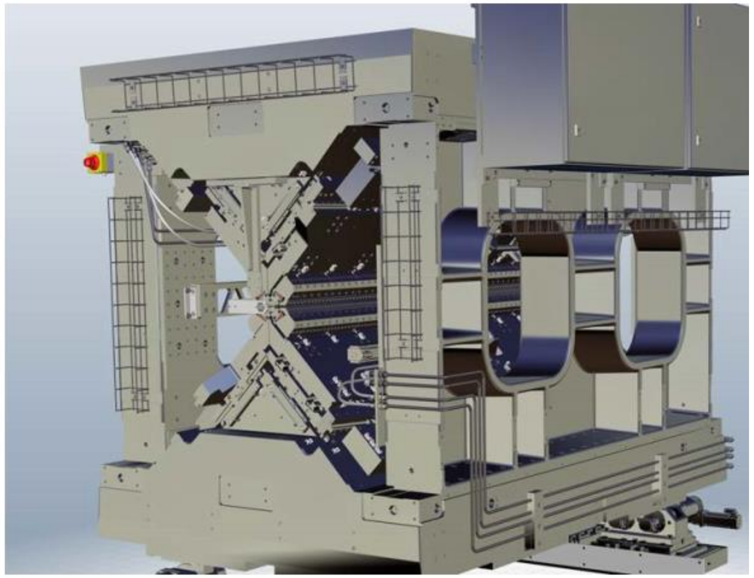
SRF copper substrates

Both

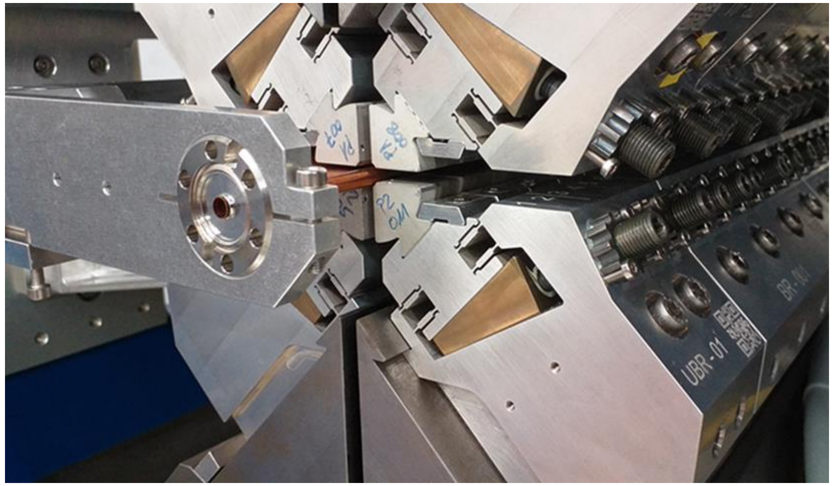
- Replicates surface mandrel state

2. Development of thin-walled copper electroformed vacuum chambers for undulators

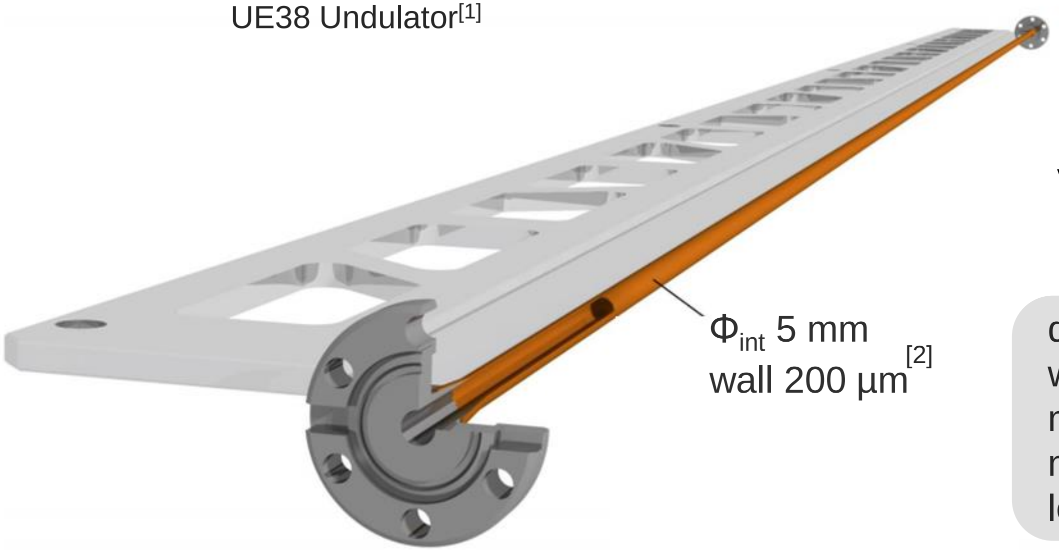
Electroformed undulator vacuum chamber (SwissFEL)



UE38 Undulator[1]



UE38 Undulator[1]



Φ_{int} 5 mm
wall 200 µm[2]

Vacuum chamber dimensions

diameter	5.0 mm
wall thickness	0.2 mm
magnet aperture	6.5 mm
minimum gap	3 mm
length	2040 mm

Other requirements

Cu Stiffener	2 mm
Ra (internal)	0.3 µm

[1] H. Joehri at al., MEDSI 2018

[2] Thomas Schmidt, Apple-X undulator for SwissFEL Athos and EU-XFEL (SASE 3)

Electroformed undulator vacuum chamber (SwissFEL)

Chamber manufacturing process by conventional methods

1. Extruded Cu tube of 200 µm wall thickness
2. Welding of the copper tube to the stainless steel flanges

Stiffener can not be welded! (penetrated groove will damage the smooth inner surface)

3. Stiffener is glued
   - Poor mechanical performance
   - Glue cannot be heated up at high temperature
   - Unknown glue behaviour under radiation

Can the thin-walled chamber be produced by electroforming?

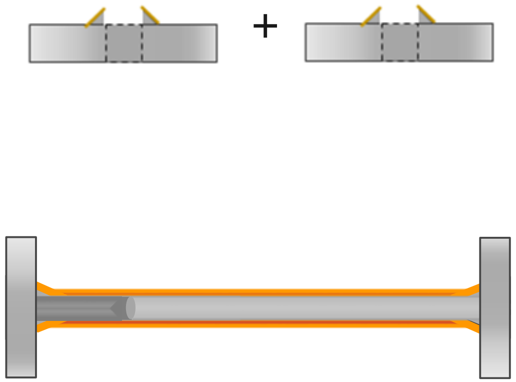
Chamber electroforming approach

1. Preparation of Al mandrel

⌀ 5mm

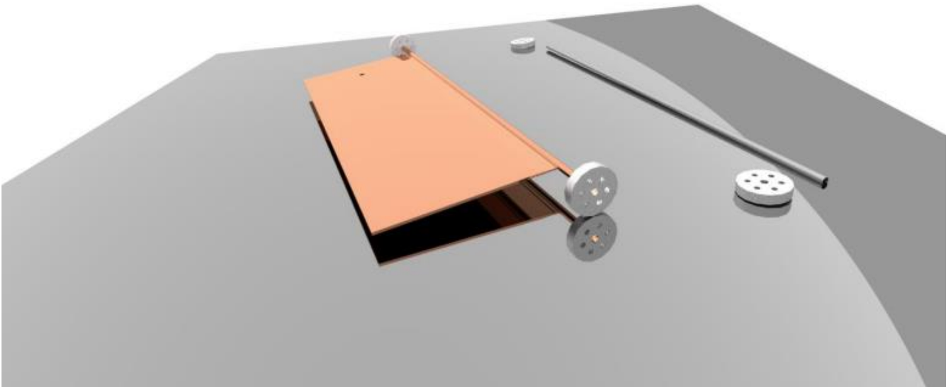
Cu PVD thin film

2. Cu electrodeposition 200 µm (step1)



3. Cu electrodeposition Stiffener addition (step2)

4. Mandrel etching



Starting point: 400 mm long chamber

Goal: 2 m length

Chamber electroforming approach

Preparation of Al mandrel

Cu coating (3 microm)

Cu coating process is performed by planar magnetron sputtering.

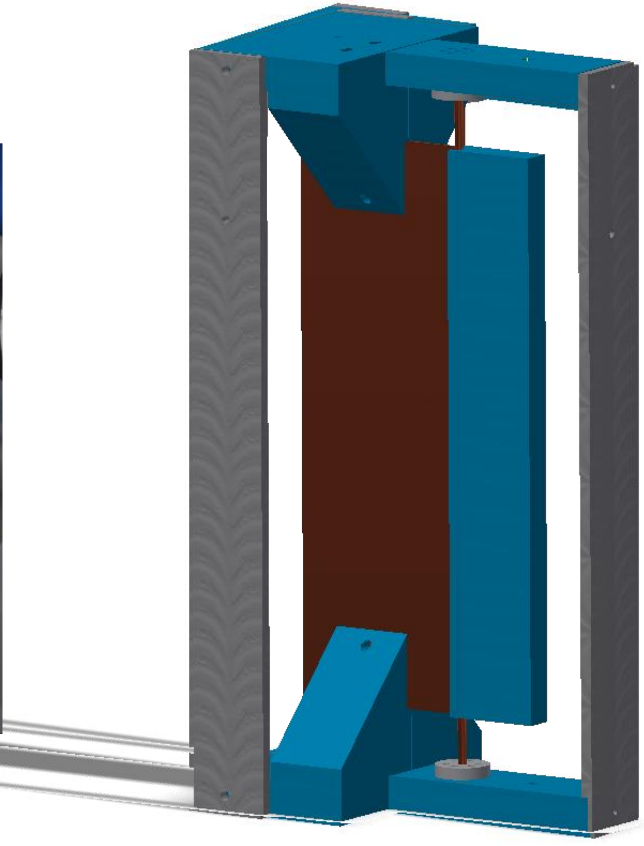
- Kr sputtering gas 1x10^{-3} mbar
- 2 coating steps with rotation of the mandrel (350W average)

Preparation of the flanges

Modified DN16 flanges

Cu plating is not adherent on SS. We need a Ni flash plated layer

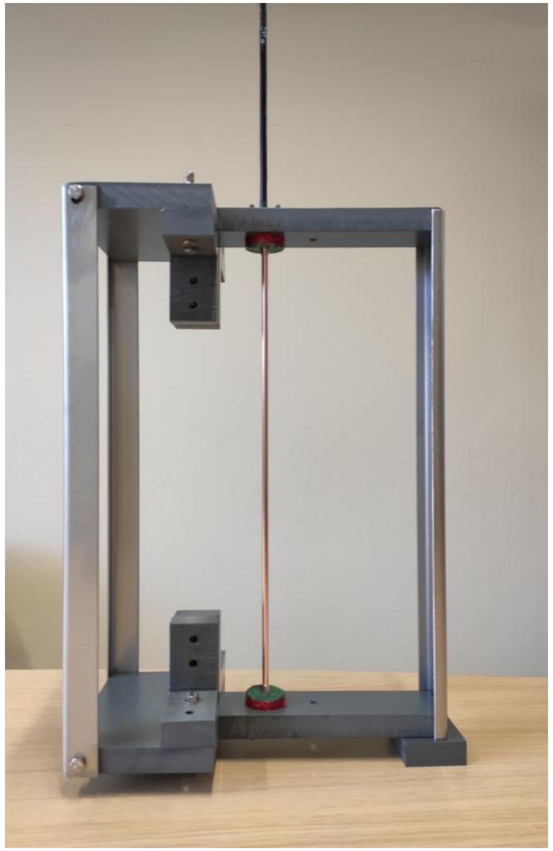
Ni and Cu plating on stainless steel



Chamber electroforming approach

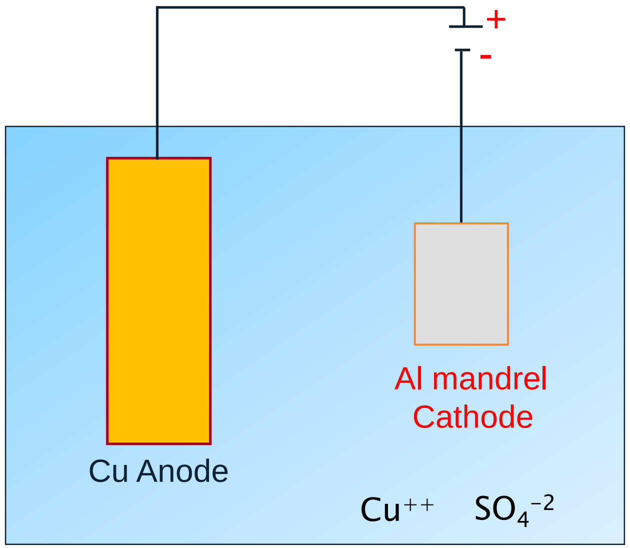
First plating: 200 µm thickness on the tube

Acidic copper sulphate with brigthener bath



6 hours at 2.4 A/dm^2

Direct Plating



Cathode (reduction):

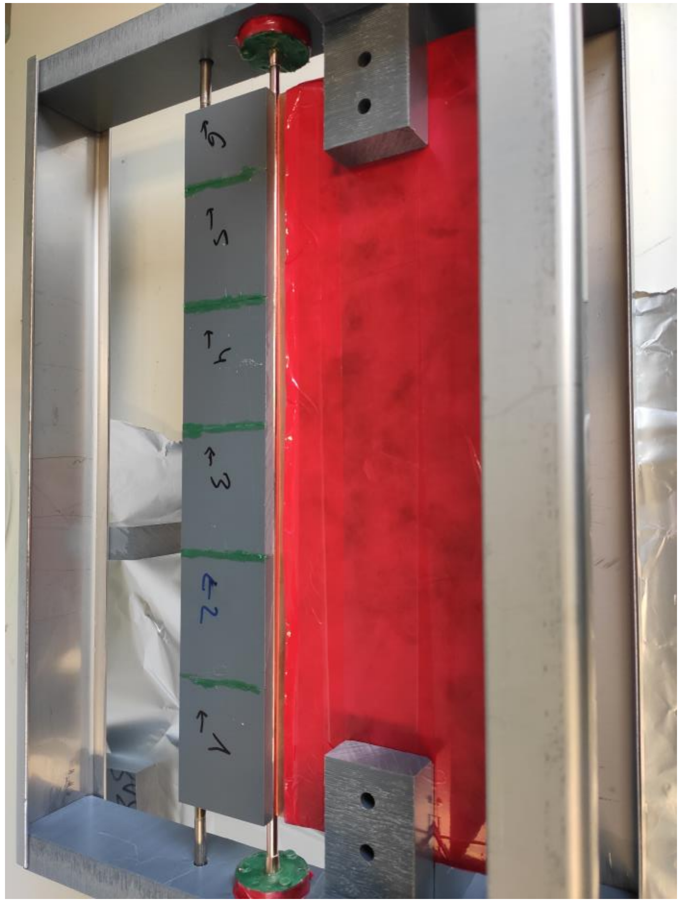
$Cu^{2+} + 2e^{-} \rightarrow Cu$

Anode (oxidation):

$Cu \rightarrow Cu^{2+} + 2e^{-}$

Chamber electroforming approach

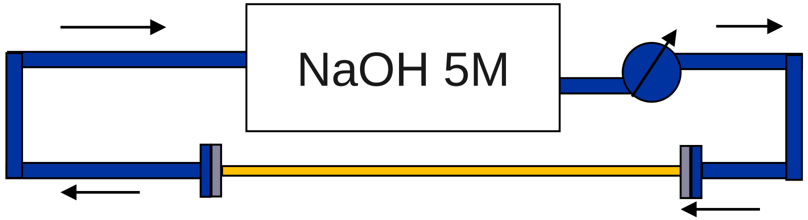
Second plating: Addition of the stiffener



Mask-tube-stiffener

24 hours at 1.6 A/dm^2

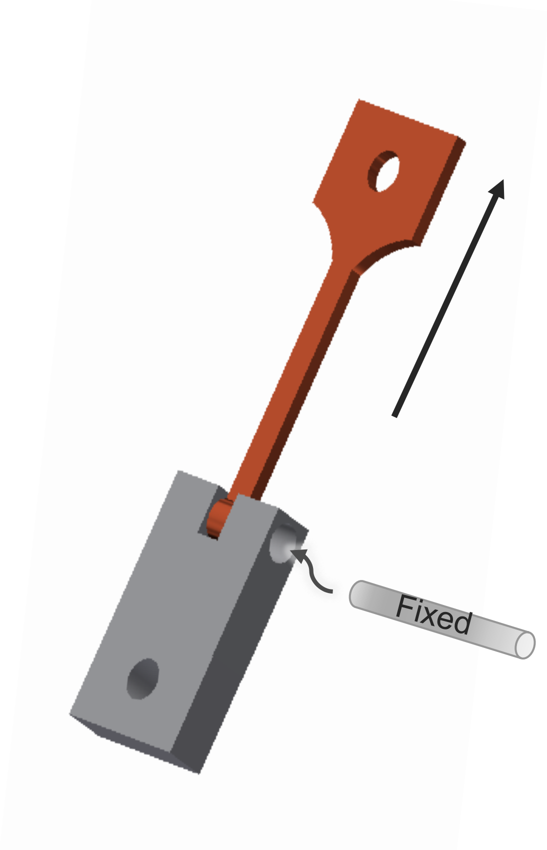
Mandrel etching: Aluminium dissolution NaOH 5M



Main challenges

The stiffener-tube junction has to be mechanically strong.

Tensile tests of the junction



Tensile specimens

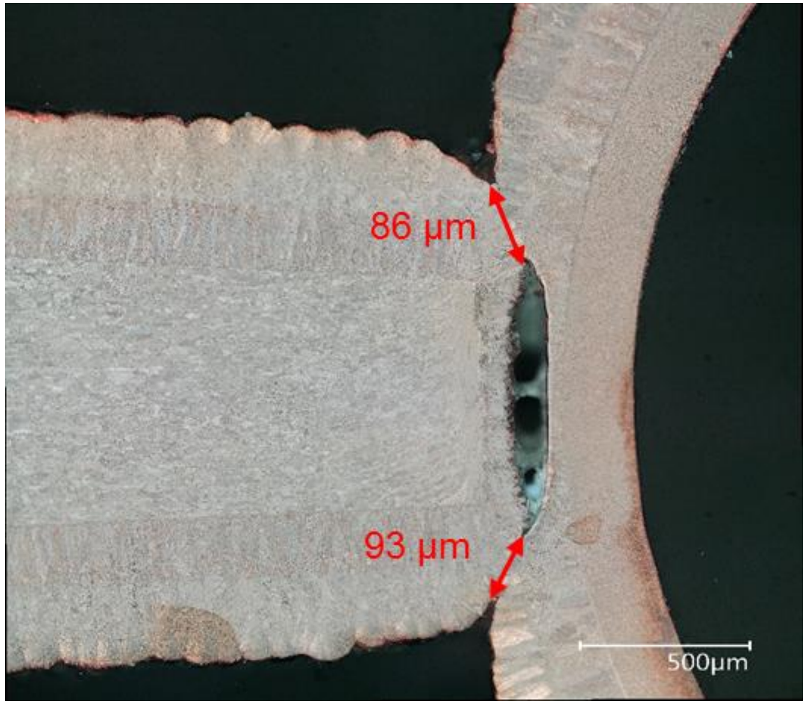
- No standard specimens
- No values of strain but values of stress

Metallographic cuts

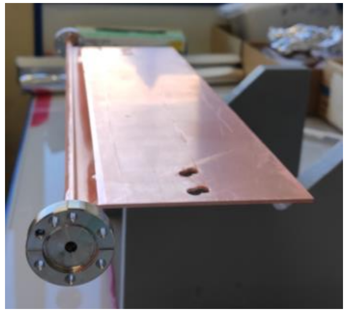
- Microstructure observation
- Junction properties

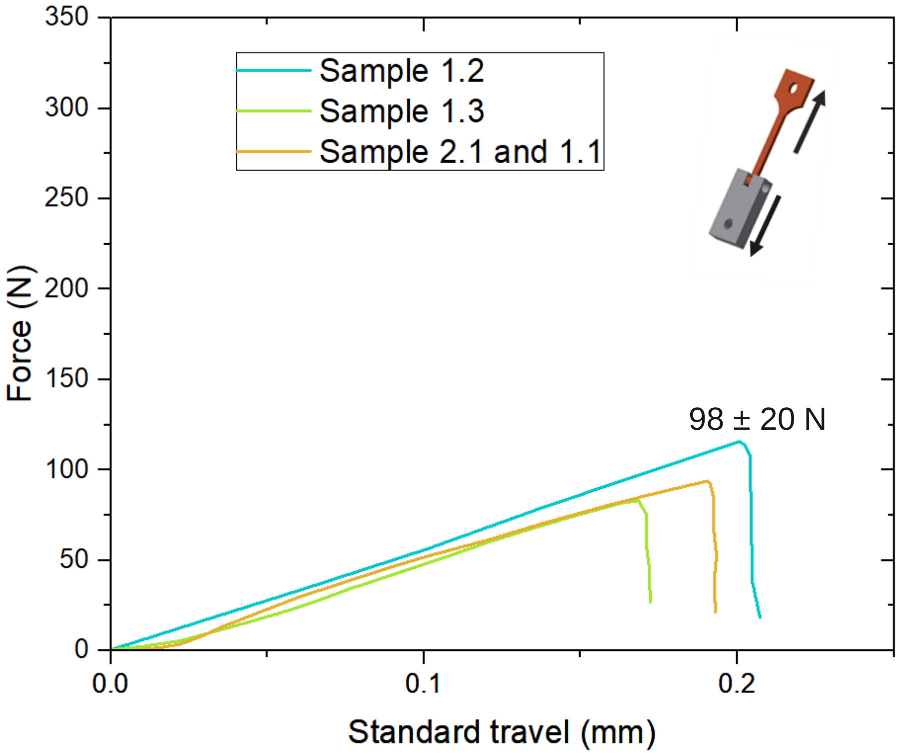
Tensile tests of the junction

Prototype 1- Starting point (10 hours)



Connection of
2 x 90 µm



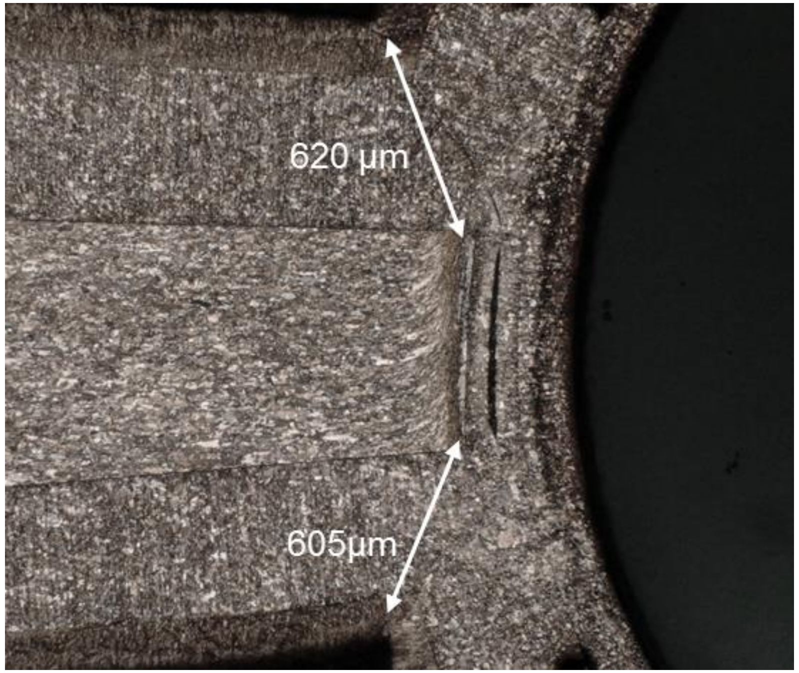


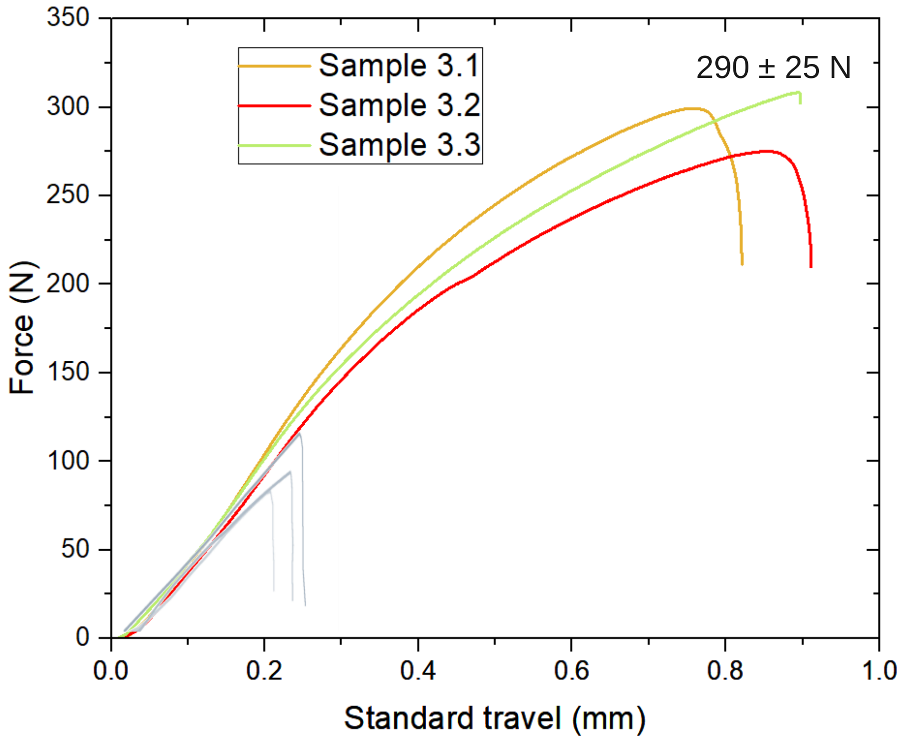
- Samples broke on the junction
- For a 34 cm stiffener, this translates on a max. load of 8000N.

It holds the chamber

Tensile tests of the junction

Prototype 2 - Towards optimization (40 hours)





Connection of
2 x 612 µm

- Samples broke on the tube

Always for a thickness greater than 200µm (tube wall).

- **Triplicated max. load**: 24000N.

Strong connection

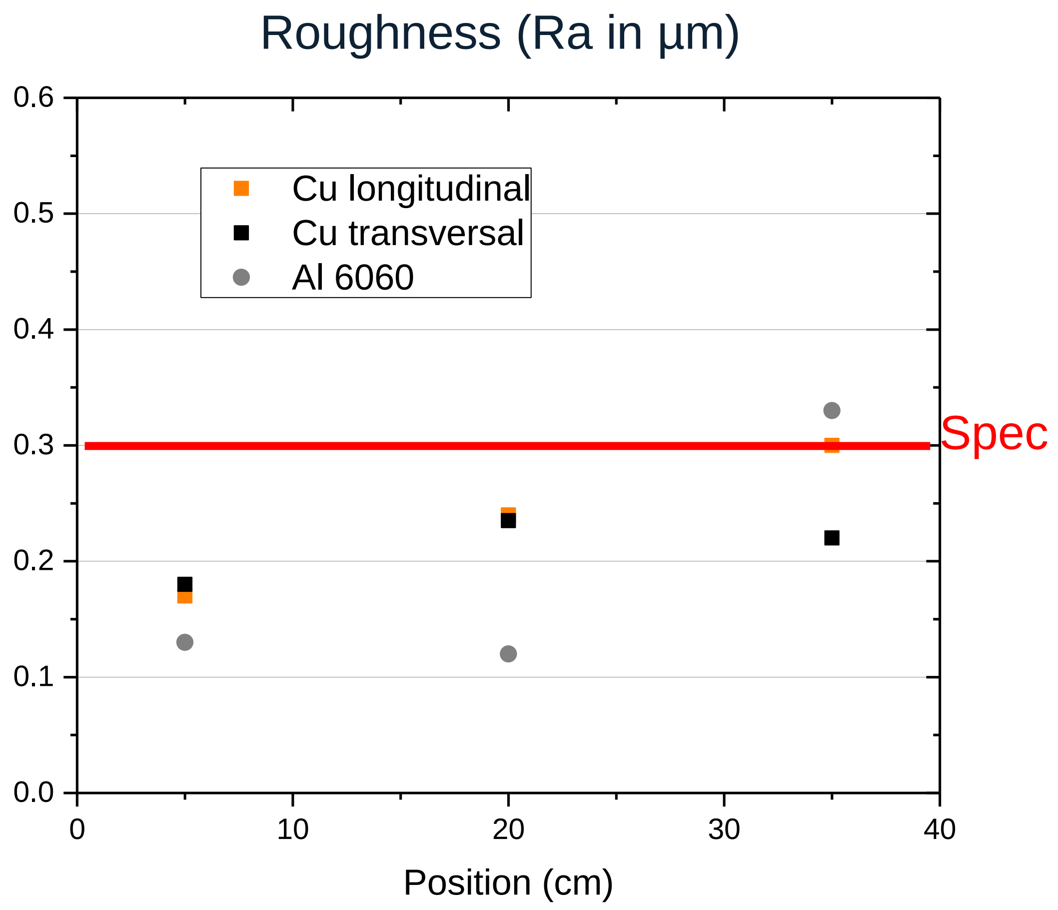
Main challenges

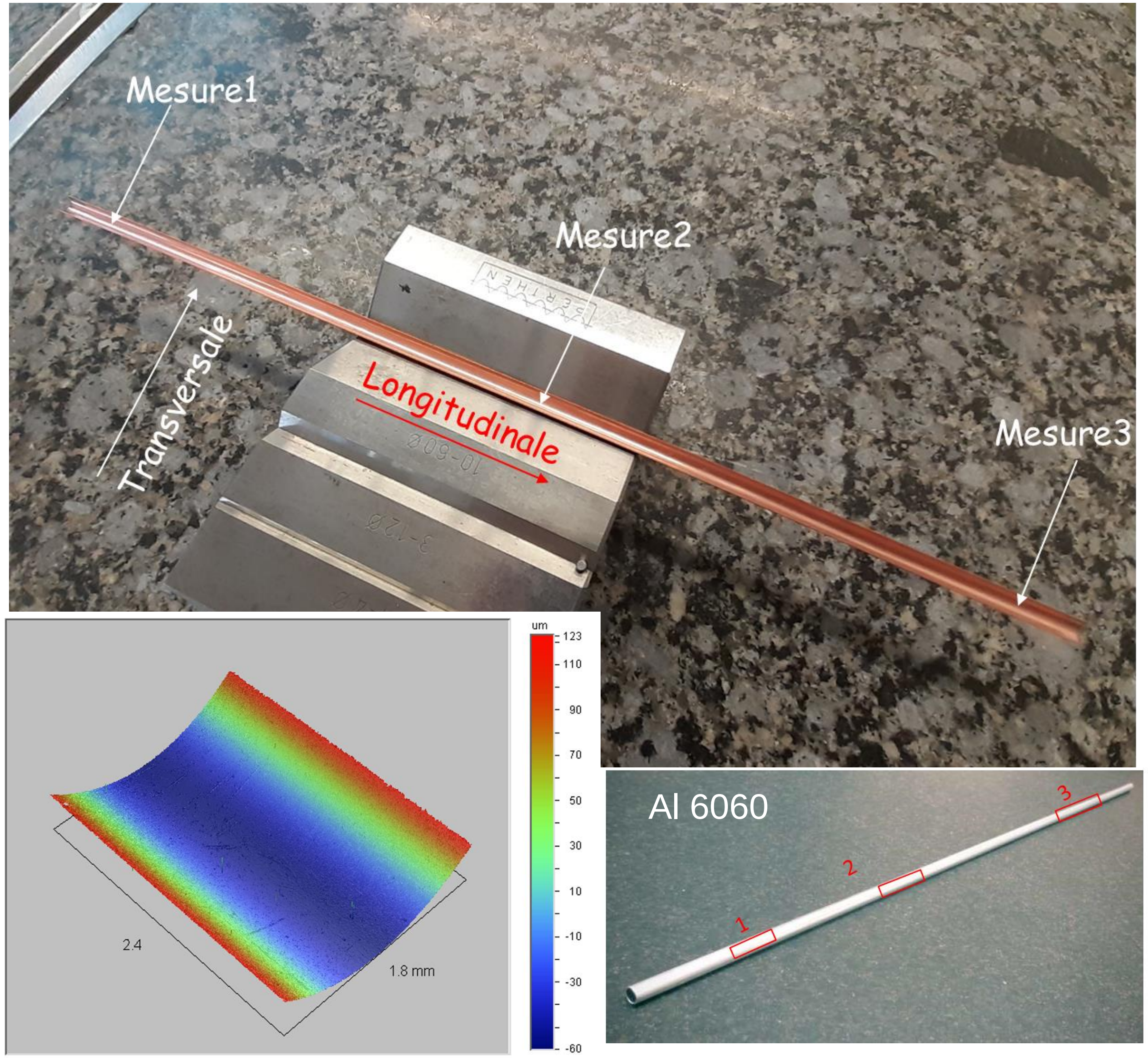
The stiffener-tube junction has to be mechanically strong.

The inner surface must guarantee a roughness of less than 0.3 µm over the length of the tube.

Roughness of inner copper tube surface

Measure on surface optical profiler (non-contact)





It replicates the roughness of the aluminium

Successful prototypes

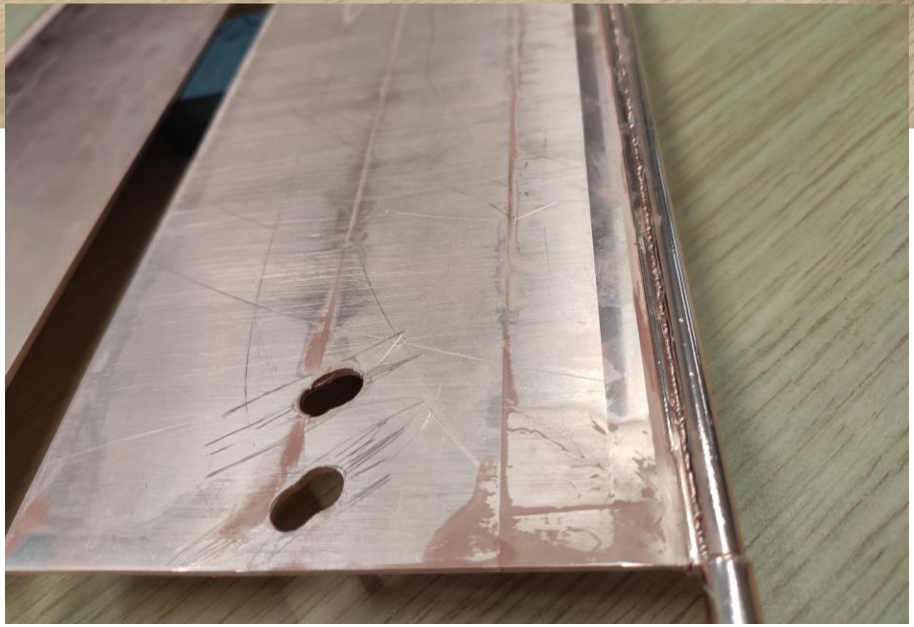
Reproducibility

Several prototypes meet the specifications

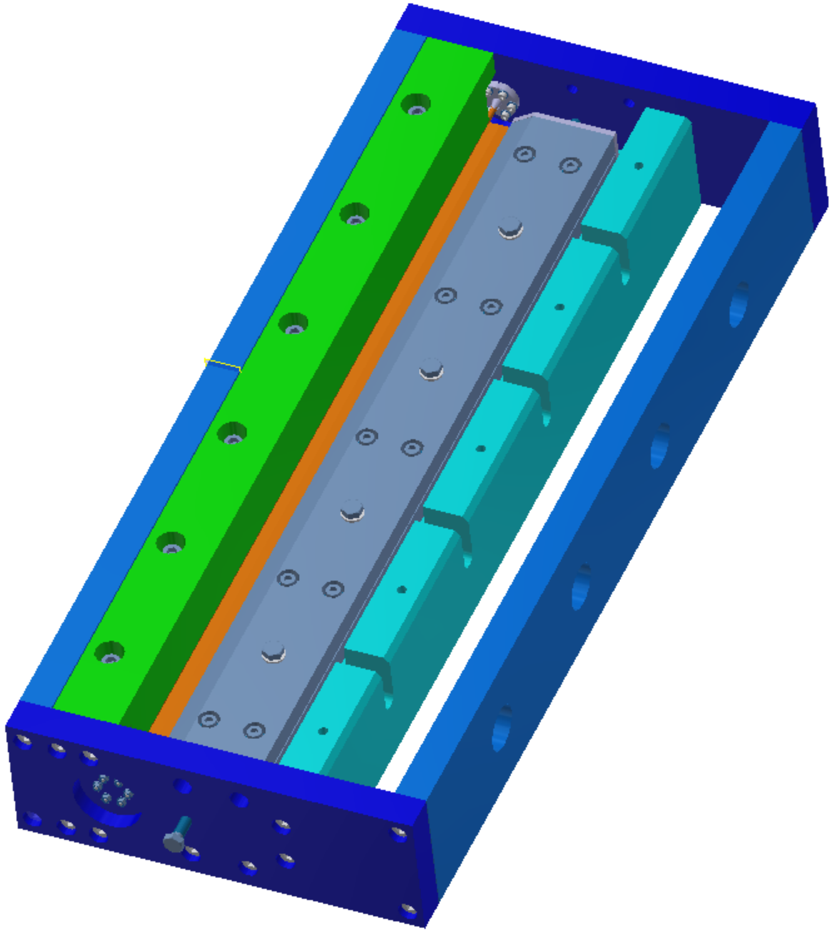
Strong connection

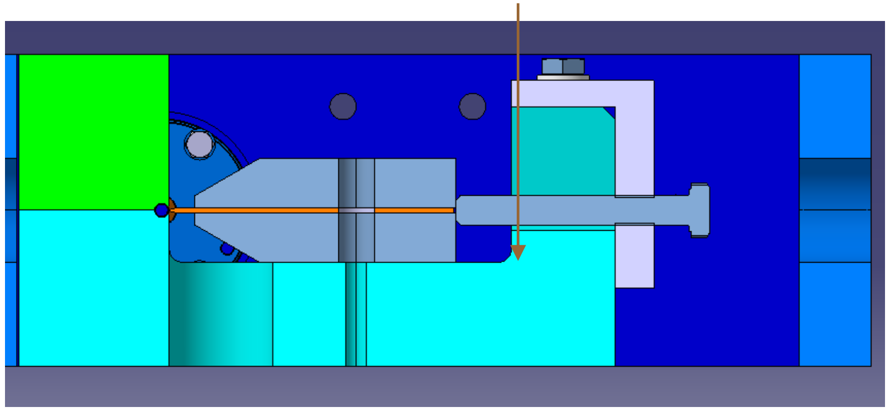
Wall thickness tube 200 µm

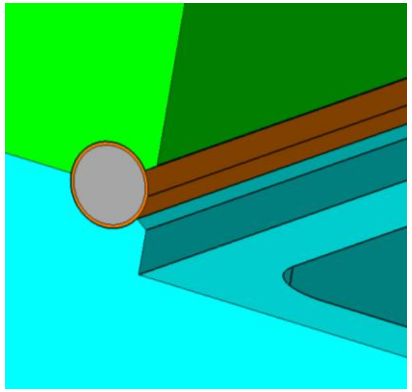
Smooth inner surface



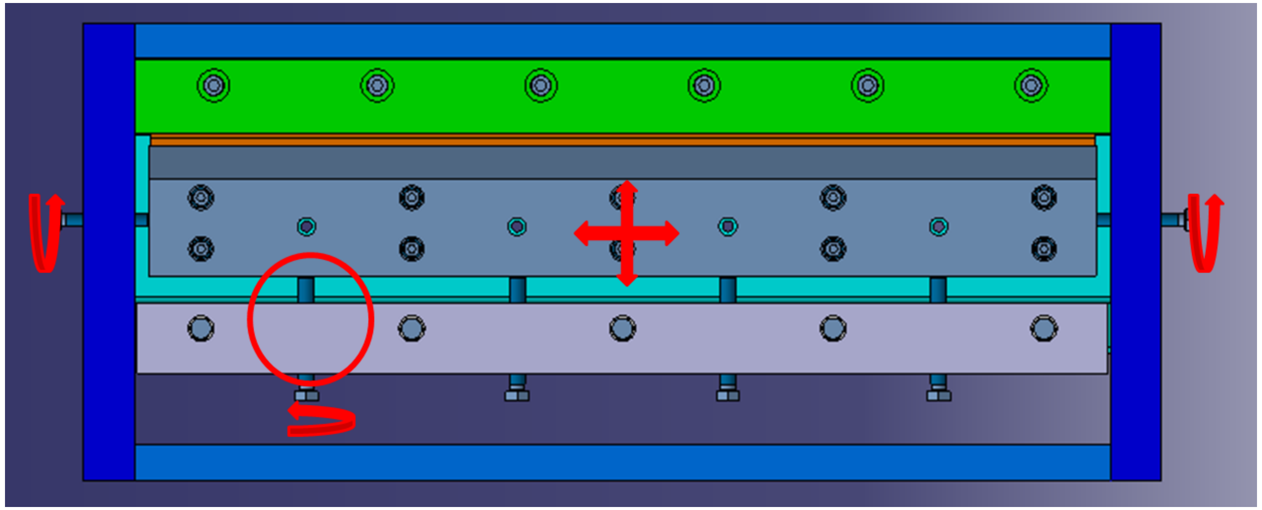
Towards meter-length chamber



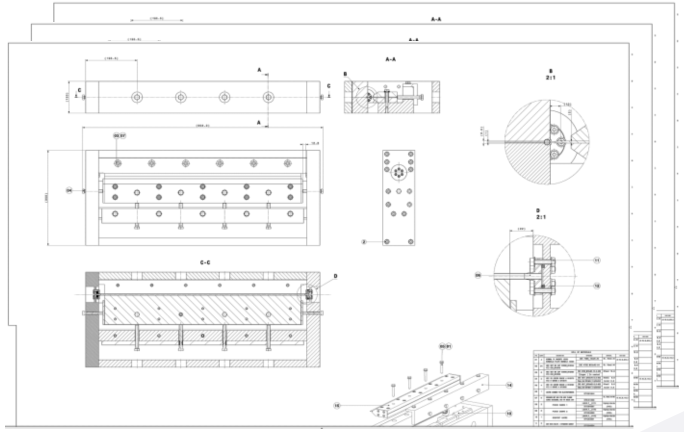




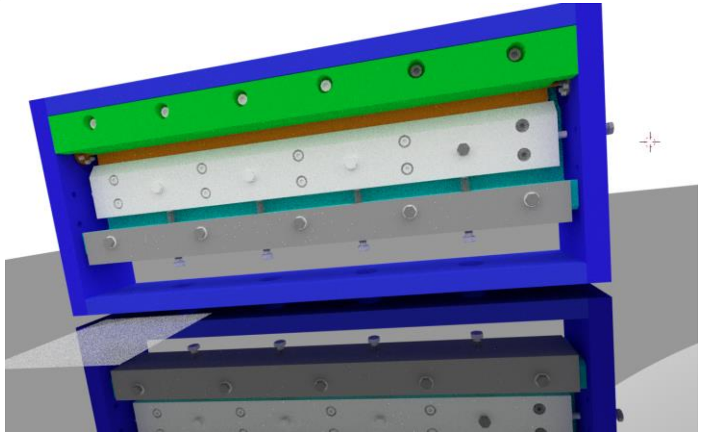
- Improved alignement stiffener-tube
- Improved masking

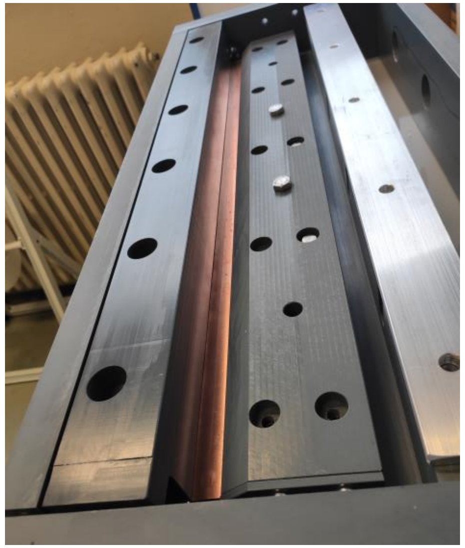


Towards meter-length chamber

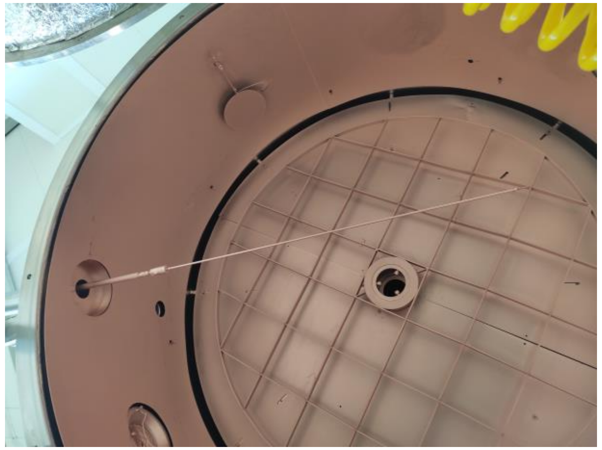


- Design
- Procurement tubes and stiffeners
- Fabrication tooling
- Prototyping campaign (March-July 2021)



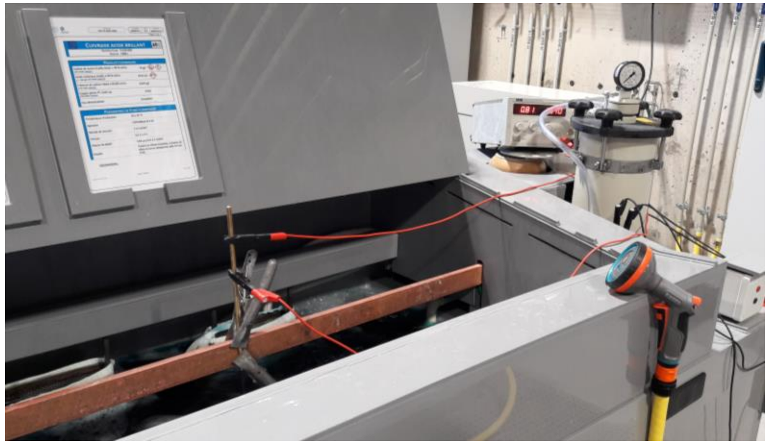


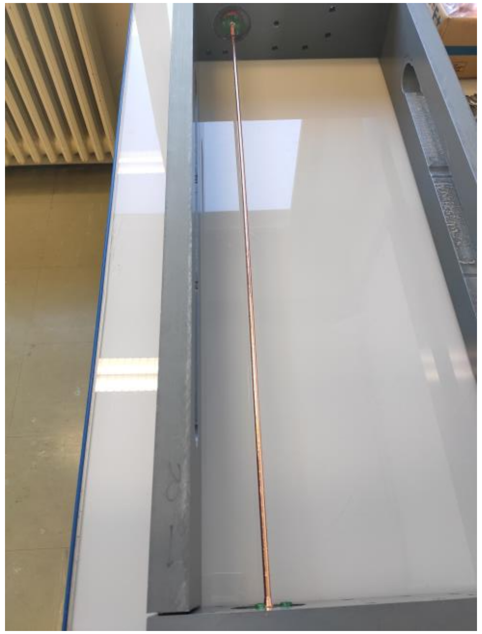
Thin-walled meter-length chamber



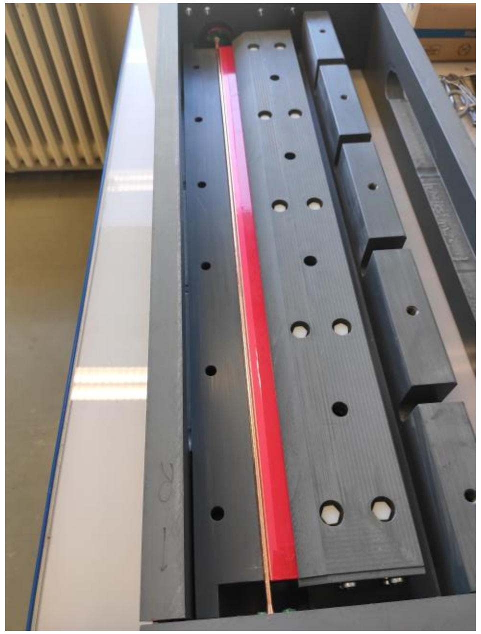
Cu PVD

Assembly





200 µm plated tube



Towards adding the stiffener

- First 1m prototype ongoing
- Measurements
  - Straigthness
  - Pump down
  - Bake-out

Conclusions

- The feasibility of producing the thin-wall chambers, up to half a meter, was demonstrated.
- The strength of the junction to the stiffener is large enough to hold and handle the chamber.
- The specified wall thickness of 200 µm is achieved.
- The roughness of the inner surface is within specifications.

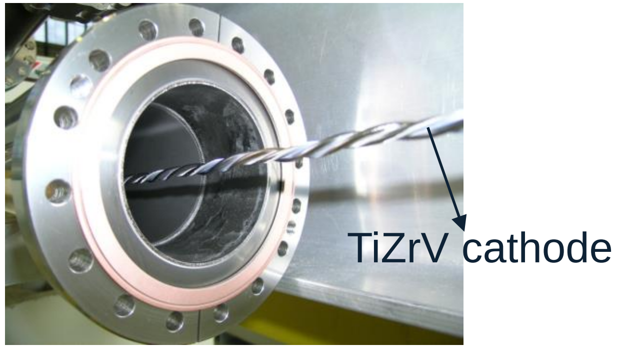
Perspectives

- Production of 1 meter length chambers.
- Extend to 2 m length.
- Inverse NEG scheme could be used for the future upgrade.

Inverse NEG coating

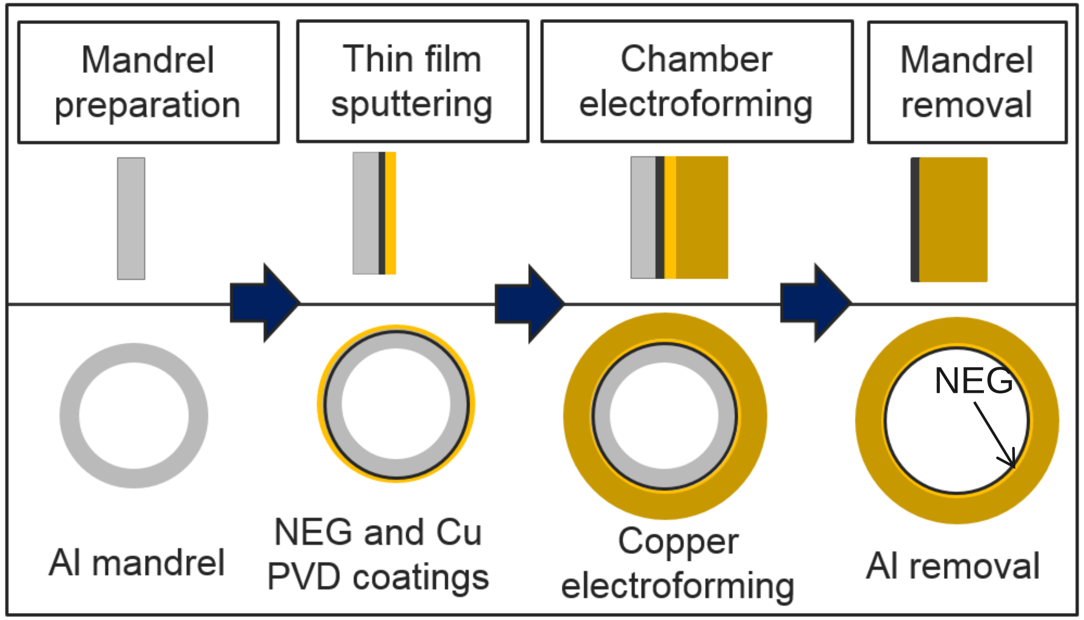
Future upgrades will require of NEG coated vacuum chambers for the undulators

NEG thin film coating, is usually performed by DC magnetron sputtering from a TiZrV wire cathode that is positioned in the vacuum chamber centre.



Problem: Physical vapor deposition techniques are difficult to apply to few-mm diameter pipes that are several meter long.

Solution: Integrate the NEG coating on the production step



Inverted NEG process

Next talk by Mauro Taborelli

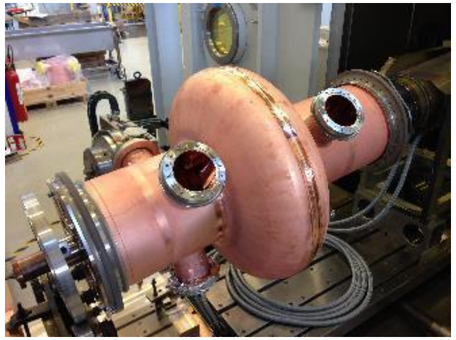
3. Electrodeposition of copper applied to the manufacture of seamless SRF cavities

In the framework of **Superconducting radio frequency niobium coated cavities**

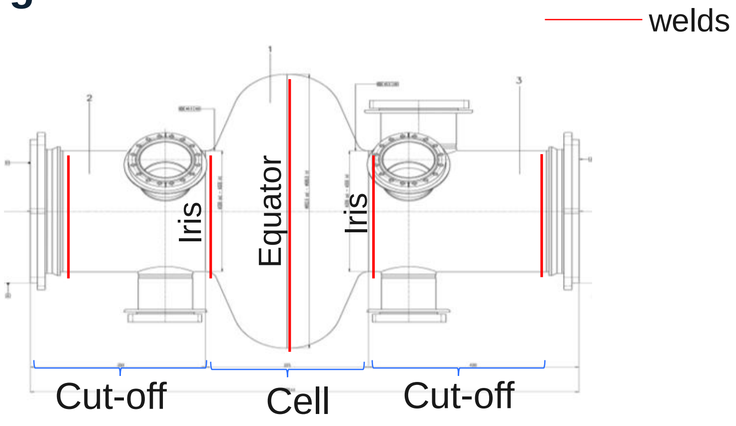
Production of copper SRF substrates

STANDARD METHOD - Half cell spinning and welding

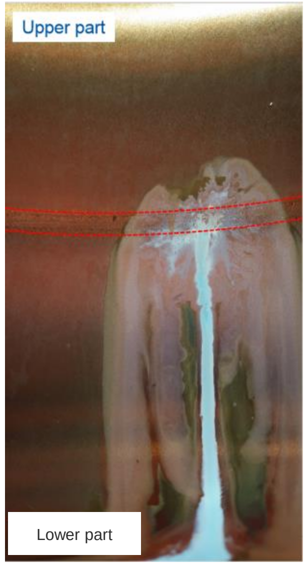
Half cell spinning

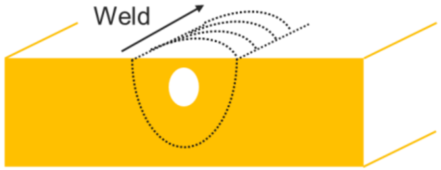


Welding



Possible defects



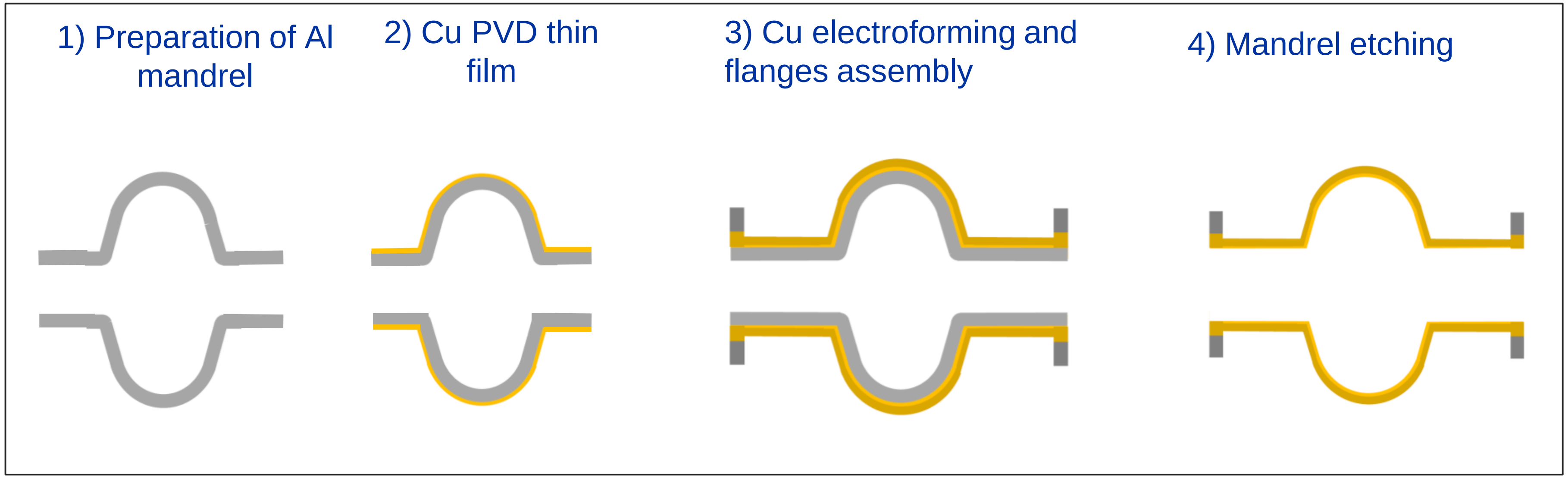


Weld porosities

- Presence of porosities along the junction caused by the welding process
- Welding grooves are localized in critical regions which are very important for RF performance.
- Copper sheets can contain defects.

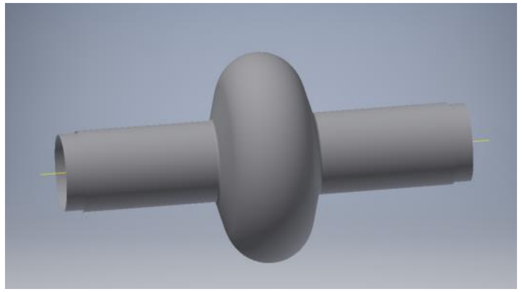
Cu electroforming - approach

The cavity is produced by copper electroforming around a sacrificial aluminium mandrel which is pre-coated with a copper thin film.



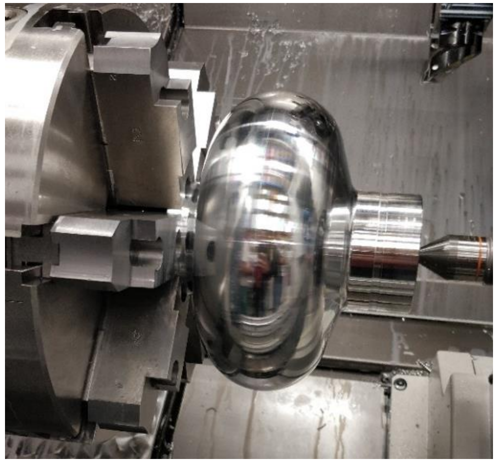
- Seamless cavities (**No EB welding**)
- Stainless steel flanges assembled during electroforming

1.3 GHz Mandrel production

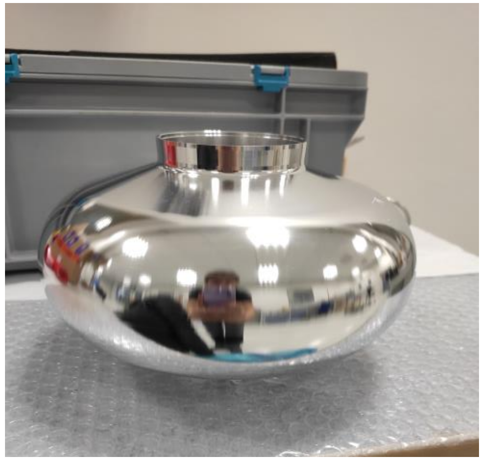


How to produce such an aluminium mandrel?

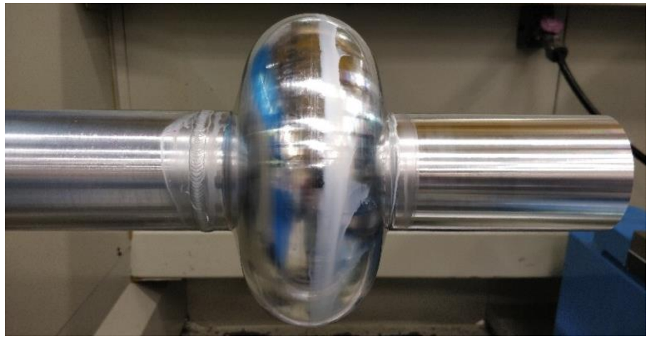
Machined from bulk aluminium



Mandrel cell turning



Mechanical finishing

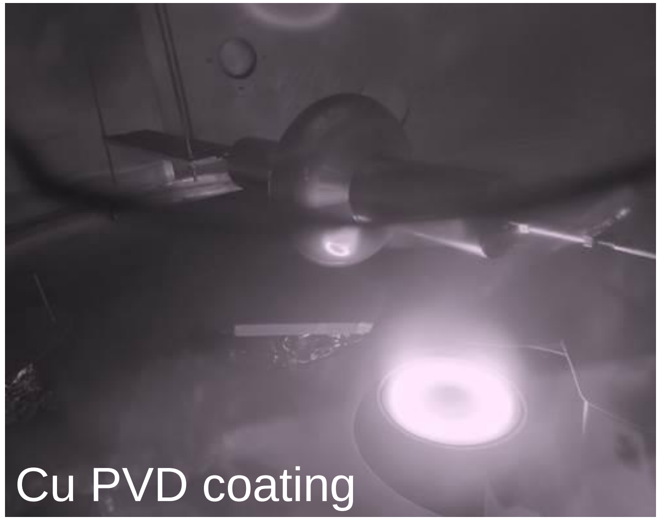


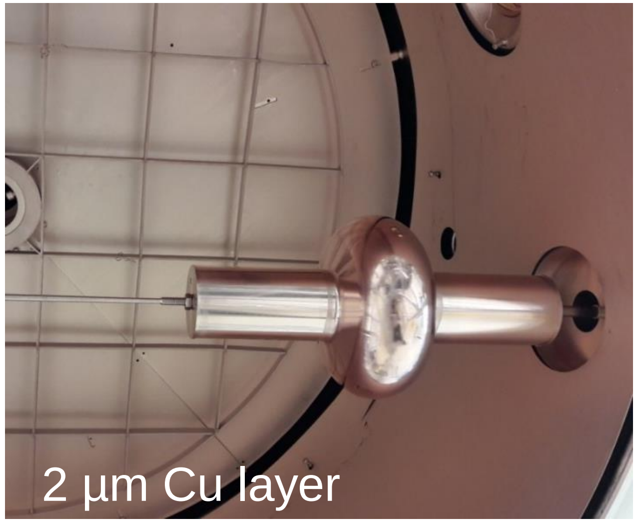
Tubes welding/machining

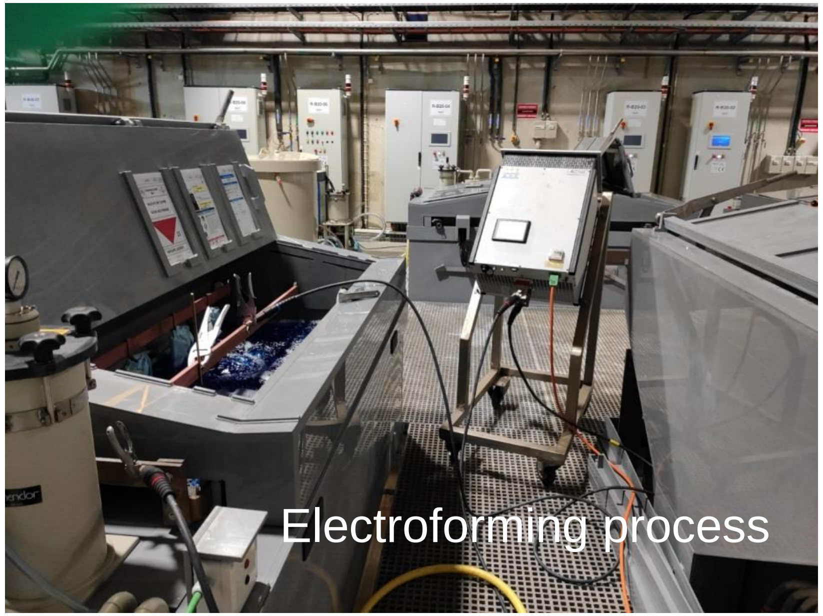
Final Mandrel

For the moment: Standard machining finishing

1.3 GHz cavity production

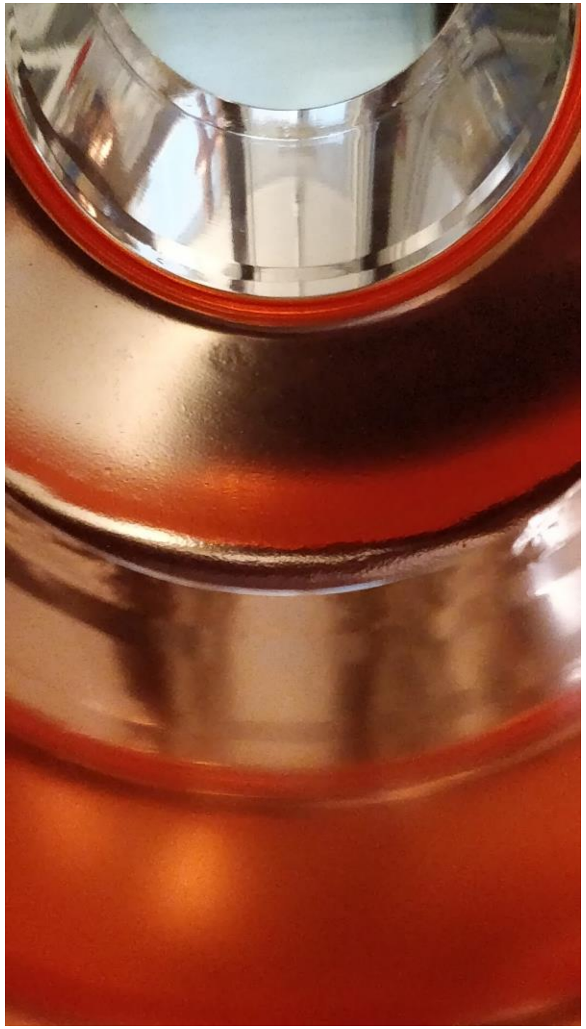






336 hours of plating
(192 h pulse plating,
144 h DC plating)

1.3 GHz cavity production



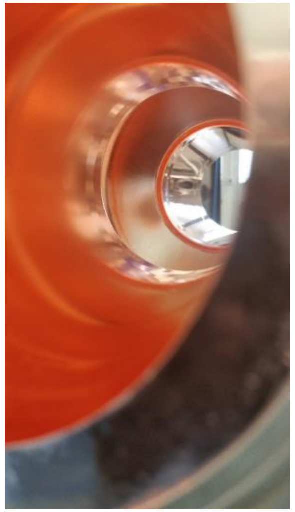
Aluminum dissolution NaOH 5M

Surface preparation: SUBU

First 1.3 GHz cavity

Workflow succesfully evaluated on electroformed cavity

Surface preparation

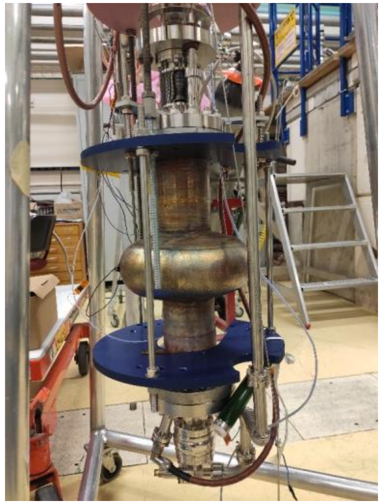


HPR

Nb Coating

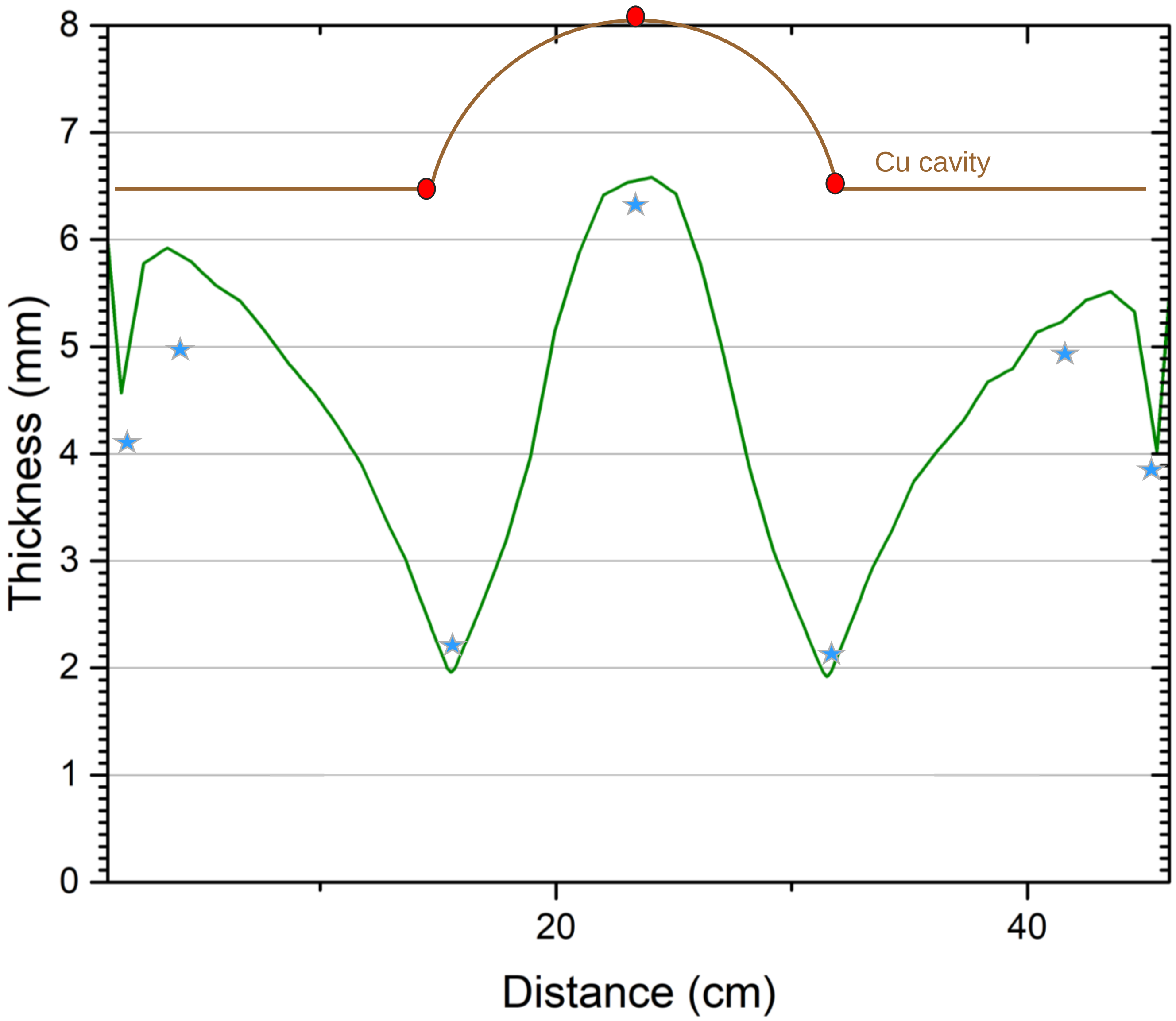
HPR

RF testing



Nb stripping

First 1.3 GHz cavity

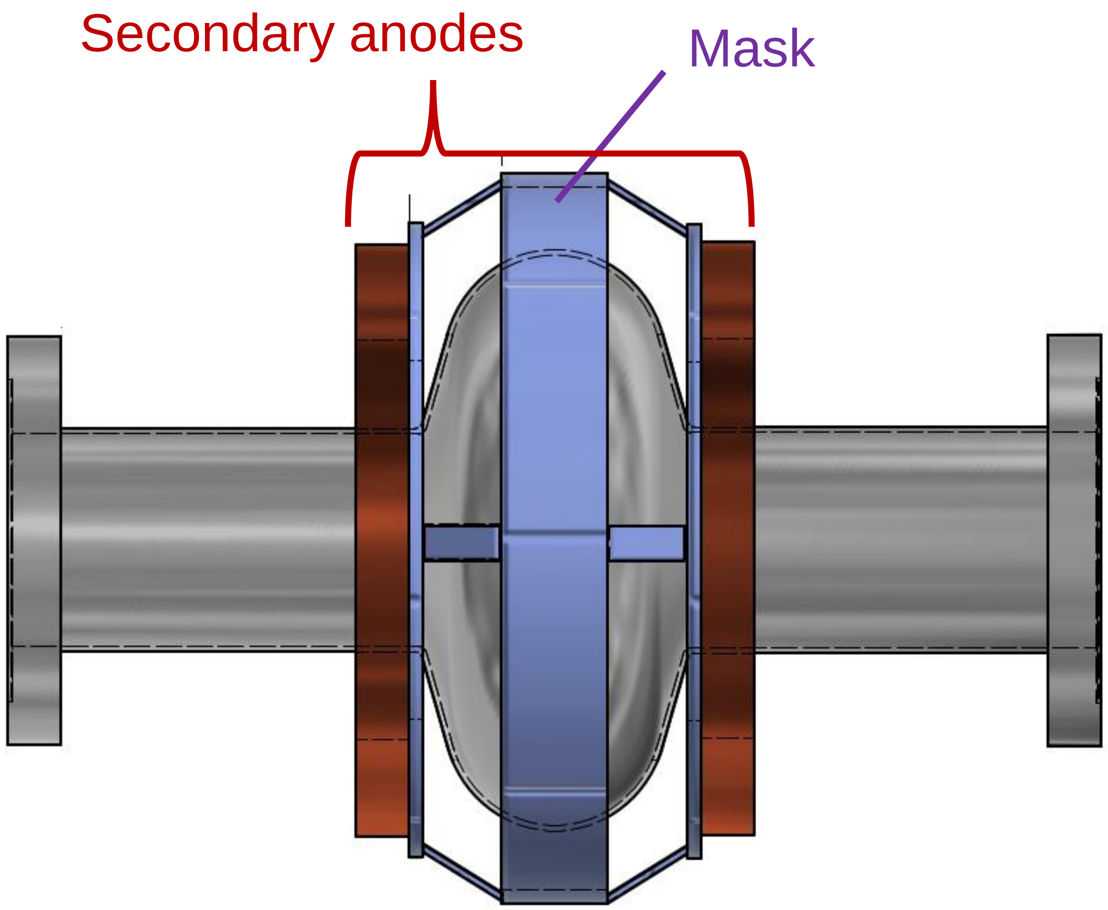


- 2 mm plating at the iris
- 6.4 mm plating at the equator

- Simulation can be used for optimization of anodes and mask.

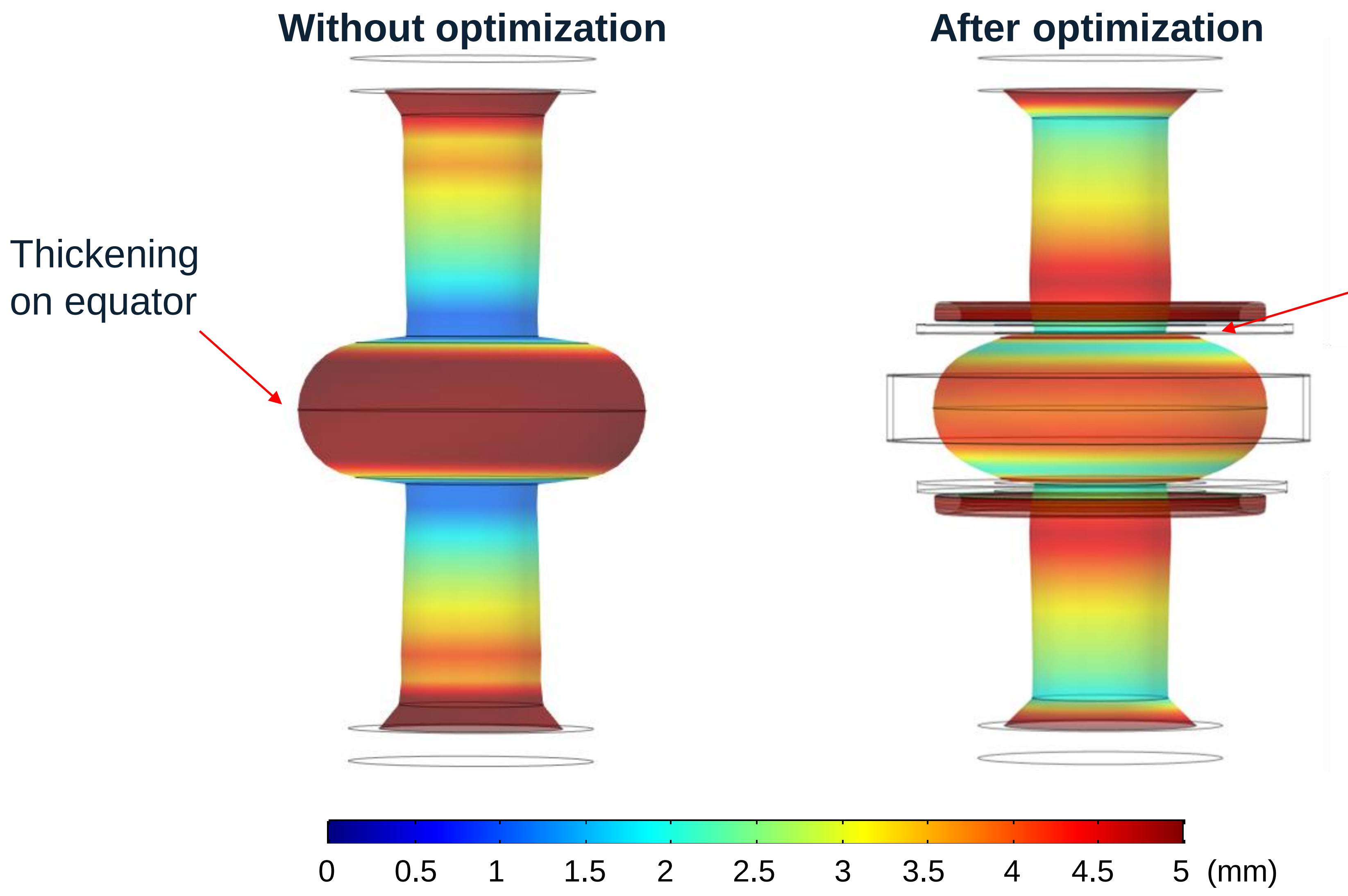
Design of secondary anodes and masking

- Solution for uniformity: Secondary anodes positioned at the iris to promote plating, mask at the equator to reduce the deposition.



Design of secondary anodes and masking

Thickness profile simulated with COMSOL



- 175 hours plating time for 2 mm at the iris
- Decrease plating time in half

Summary

- Cavity lifecycle (production-coating-rinsing-testing-stripping) feasibility has been demonstrated with the electroformed 1.3 GHz cavity.

- The main drawback of the electroforming approach is the non-uniform thickness distribution along the cavity.

  Solution: secondary anodes and masking to the cavity. The plating time will be reduced by half.

Future steps

- 1.3 GHz cavity production and validation of the secondary anodes support.
- Nb thin film coating using best recipe and RF testing.
- Different mandrels surface state: electroforming on polished mandrels.

Publications

- L. Lain Amador, P. Chiggiato, L. M.A Ferreira, V. Nistor, A. T. Perez Fontenla, M. Taborelli, W. Vollenberg, M-L Doche, J-Y Hihn, J. Vac. Sci. Technol. A, 36, 021601 (2018).

- L. Lain Amador, J Rolet, M-L Doche, P. Massuti-Ballester, M-P Gigandet, V. Moutarlier, M. Taborelli, L. M. A. Ferreira, P. Chiggiato, J-Y Hihn, ECS Transactions 85(13): 815-822 (2018).

- L. Lain Amador, J. Rolet, M-L Doche, P. Massuti-Ballester, M-P Gigandet, V. Moutarlier, M. Taborelli, L. M. A. Ferreira, P. Chiggiato, J-Y Hihn. Journal of The Electrochemical Society 166:10, D366-D373 (2019) .

- L. Lain Amador, CERN-THESIS-2019-160, (2019) "https://cds.cern.ch/record/2693564"

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Thank you for your attention!