Additive Manufacturing for SRF Technology - State of the Art and New Perspectives

TSRF2024

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Université Paris-Saclay, France

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Classic forming techniques for SRF cavities

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Electron Beam Welding

EBW is still **one of the most used techniques** for manufacturing particle accelerators components (*expecially cavities*).

- ✓ **Well established** technique
- ✓ **State of the art** for now
- × **High cost** process
- × **Long time process**

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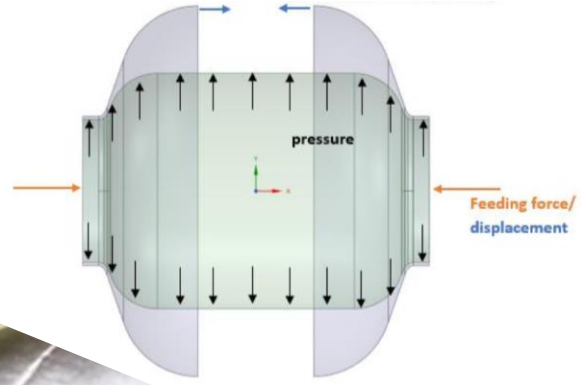
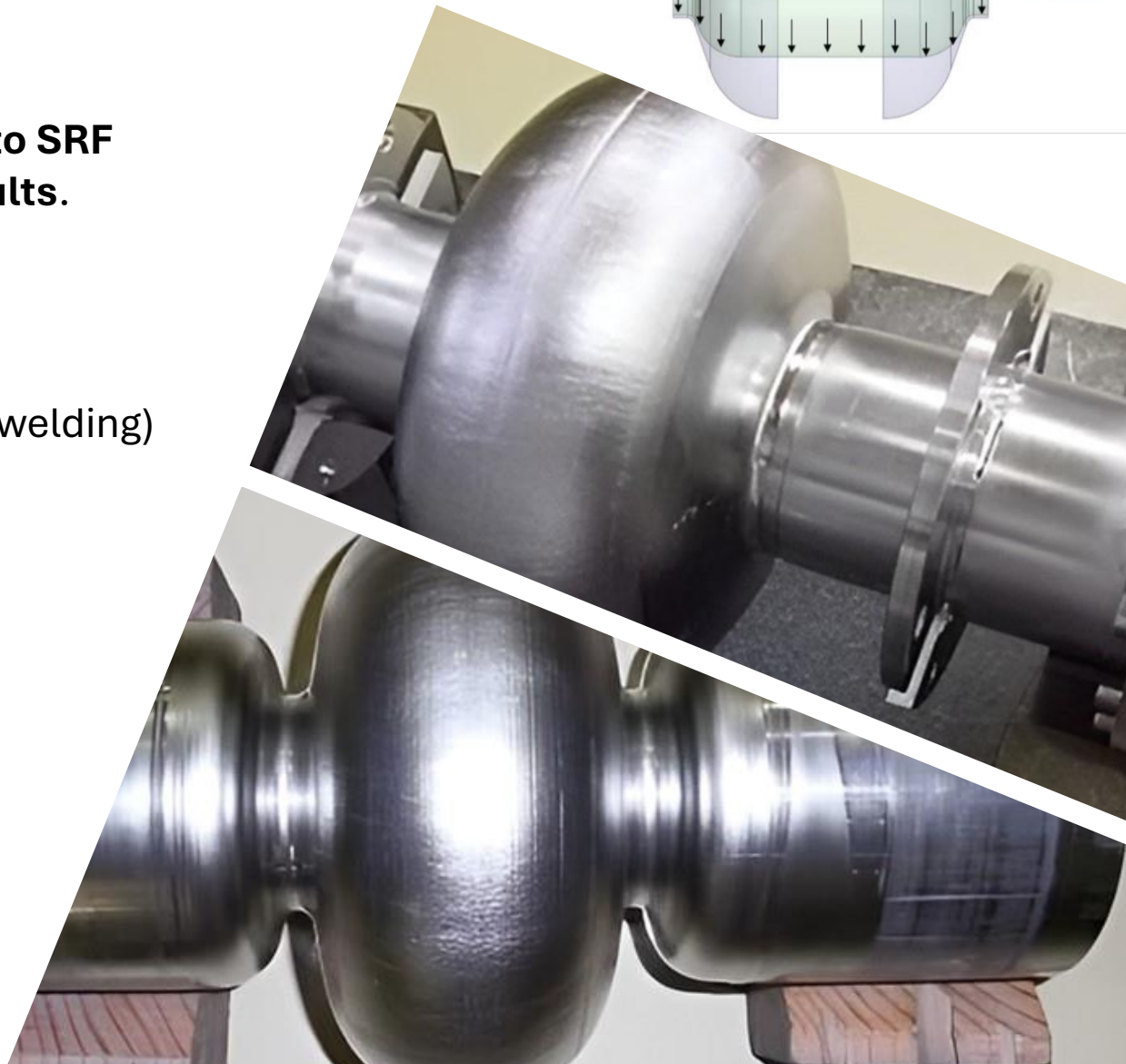
Seamless manufacturing: Hydroforming

Well established technique for industrial use, **applicable to SRF** components (*expecially elleptical cavities*) **with good results**.

- ✓ Fewer defects (**no welding joint on equator**)
- ✓ **Reduced cost**
- ✓ **Less contaminants and porosity** (due to absence of welding)
- ✓ **Fast process**
- ✓ Could be a solution for **mass production**
- × Prototyping expensive
- × Mass production not ready yet
- × Not suitable for complicated shapes





KEK

M. Yamanaka *et al*, Hydroforming SRF Cavities From Seamless Niobium Tubes, *Proceedings of SRF2015, Whistler, BC, Canada*

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Seamless manufacturing: CNC Spinning

Established technique to produce R&D elliptical SRF cavities with good performance.

- ✓ **Low cost**
- ✓ **Less contaminants and porosities** (due to absence of weld lines)
- ✓ **Already validated** for R&D, **not yet industrialized**
- ✕ Not uniform thickness
- ✕ Not suitable for complicated shapes

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F. Sciarrabba *et al*, 1.3 GHz Seamless Copper Cavities Via CNC Spinning Technique, *Proceedings of SRF2021, East Lansing, MI, USA*

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Any alternatives?

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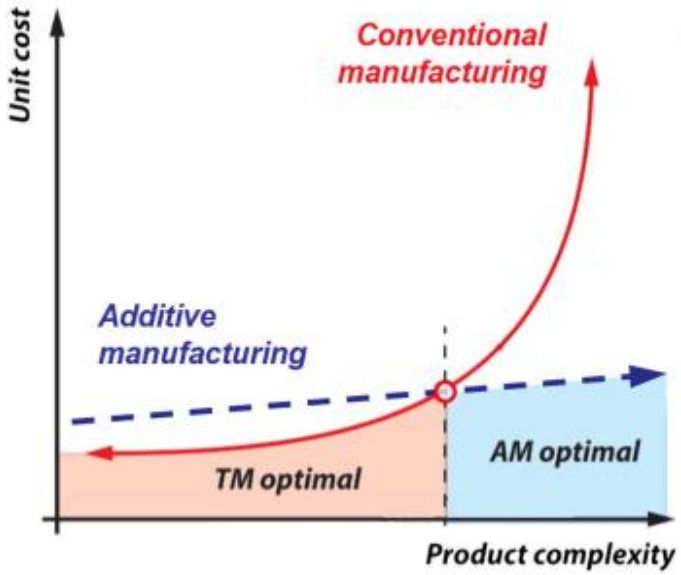
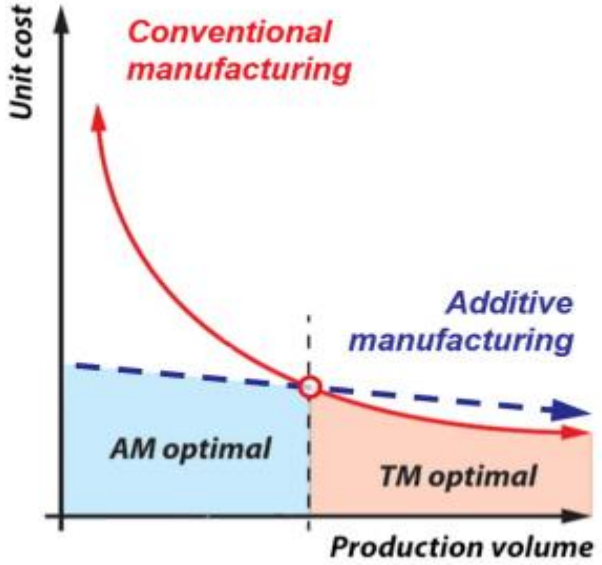
Additive Manufacturing

One-step fabrication that simplifies production processes with **possible reduced costs and almost no design constraints** of conventional methods, which is ideal for:

- ✓ Rapid and cheap **prototyping**
- ✓ Creating geometrically **complex parts in one go**
- ✓ **High savings** on expensive materials (such as Nb and high purity Cu)
- ✓ Fabrication of **seamless structures**
- ✓ …

This comes with many challenges…





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Tobia Romano *et al*, Metal additive manufacturing for particle accelerator applications, *PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 054801 (2024)*

Many process types!

Powder Bed Fusion – Electron Beam (PBF-EB)

Laser Metal Deposition (LMD)

Powder Bed Fusion - Laser Beam (PBF-LB)

Binder Jetting (BJT)

Wire Arc Additive Manufacturing (WAAM)

Cold Spray Additive Manufacturing (CSAM)

Bound Metal Deposition (BMD)

Ultrasonic Additive Manufacturing (UAM)

And more…

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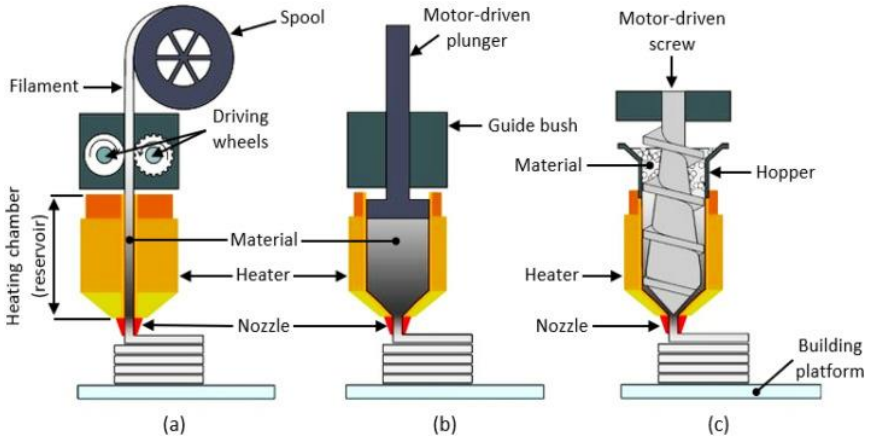
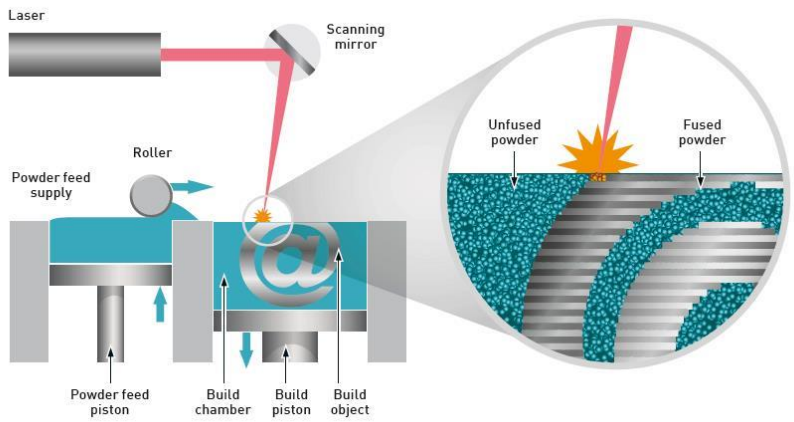
Extrusion based process



Powder Bed process



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AM state of the art for accelerators

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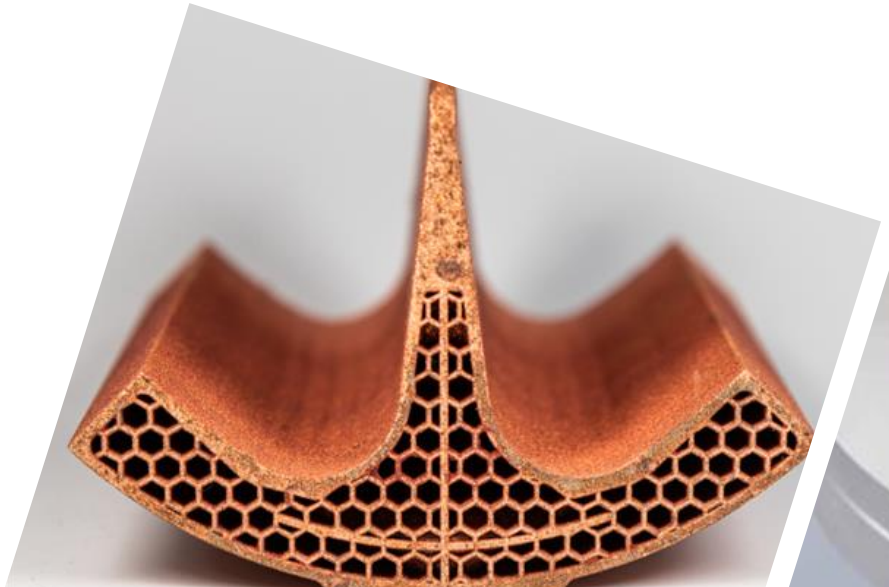
First AM Radio Frequency Quadrupole

New opportunities for commercial production of portable linear accelerators (medical and industrial use).
Integrated cooling channels and internal honeycomb structure that **saves 37% of material.**
No complex and time consuming brazing operations
Geometrical accuracy of 20 µm achieved.



T. Torims *et al*, First Proof-Of-Concept Prototype Of An Additive-Manufactured Radio Frequency Quadrupole, *CERN-ACC-NOTE-2021-24*

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AM IH-type Drift Tube structures

Stainless Steel prototypes, copper plated

- Stainless steel and pure copper prototypes with flanges and RF coupler for testing.
- **Integrated cooling channels**
- **Good ultimate pressure** (10-7 mbar) **and Q factor** (up to 6400 with post processing, with room for improvements).

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Hendrik Hähnel *et al,* Additive Manufacturing of an IH-Type Linac Structure from Stainless Steel and Pure Copper, *Instruments 2023, 7, 22*

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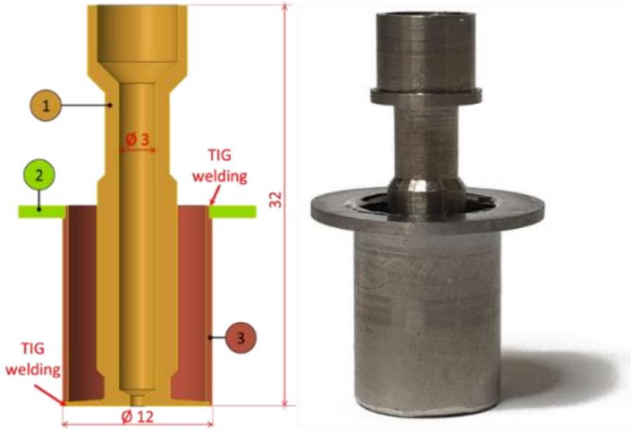
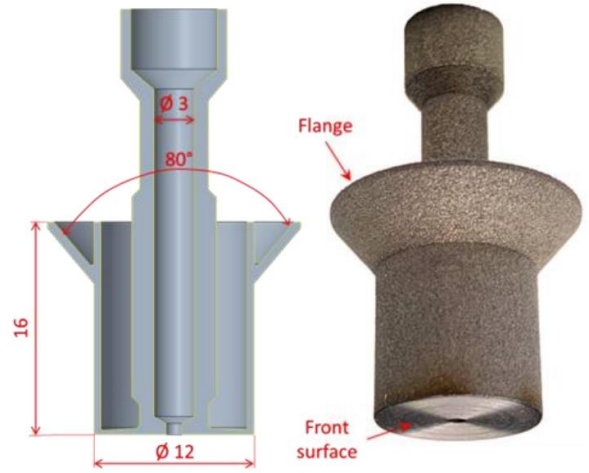
Ion sources via AM

Tantalum machining is difficult and postwelding distortions result in poor dimensional accuracy.
AM simplifies the manufacturing process of ISOL ion sources (no separate part machining and welding)
Monolithic AM tantalum prototypes with a **dimensional deviation of less than 100 µm** (structural integrity maintained also at high T testing)

Conventional manufacturing method (welding)



Seamless AM manufactured source



A Girotto *et al,* Additively manufactured tantalum cathode for FEBIAD type ion sources: production, geometric measurements, and high temperature test, *J. Phys.: Conf. Ser. 2687 082047*

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Integrated cooling channels

Next talk by **Thomas Proslier**

3D additive fabrication of Cu cavity with cooling channeling at CEA

6GHz Niobium cavities

Previous work by CERN

2 half cells produced via LBF-LB, EB welded

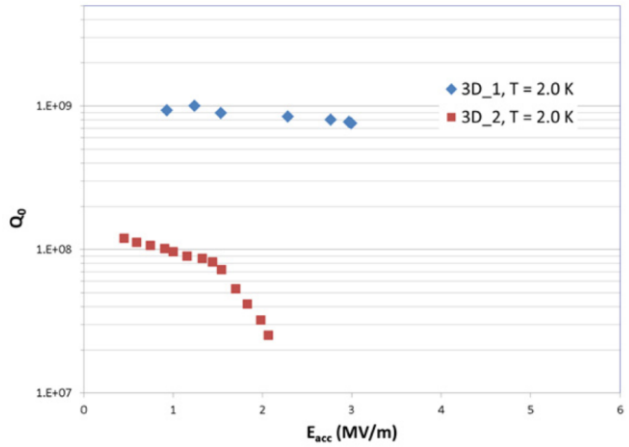
Romain Gerard
https://indico.cern.ch/event/725106/contributions/2982999/attachments/1639125/2618793/additive_Manufacturing_2.pptx

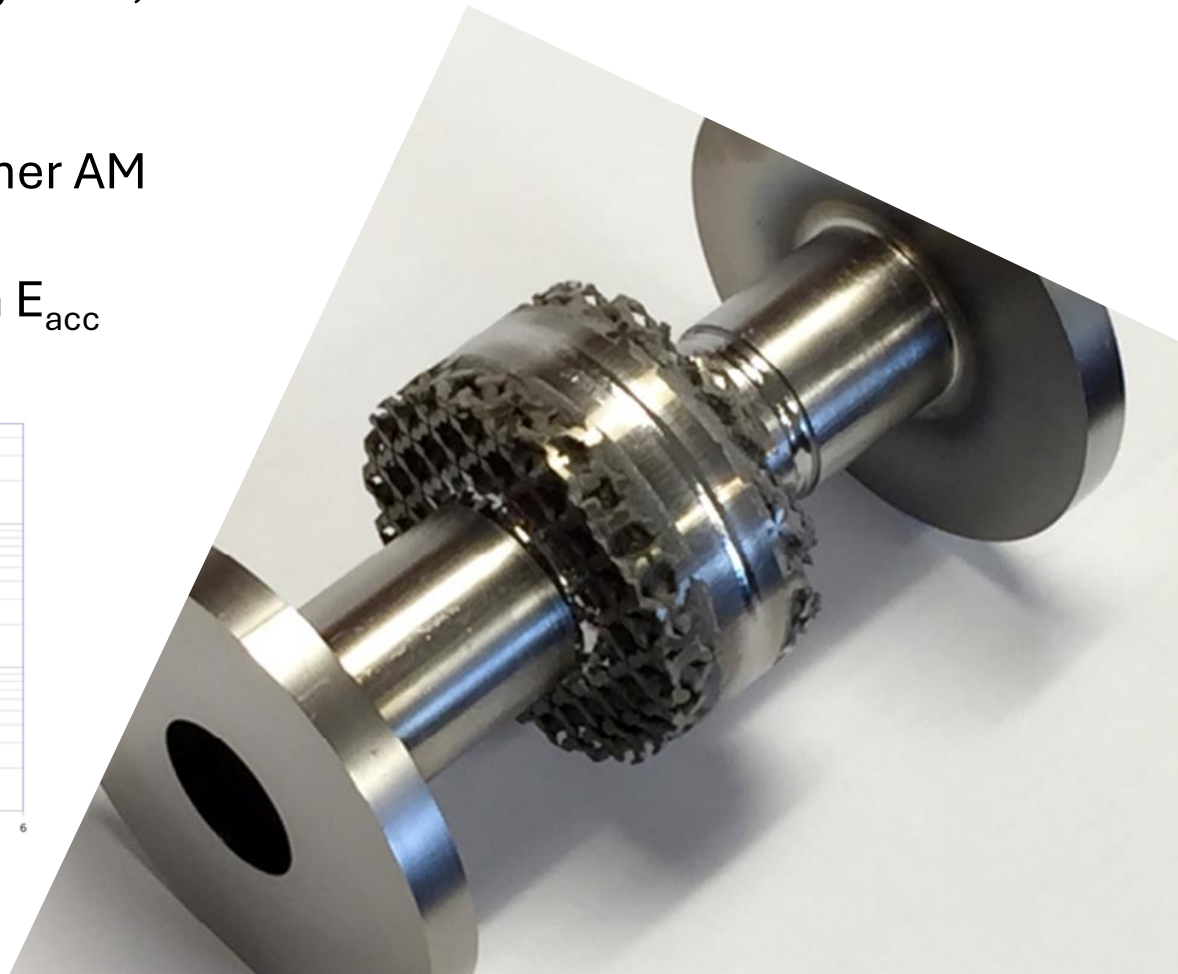
6GHz Niobium cavities

Previous work by RadiaBeam Technologies (2015)

2 half cells produced via EBM AM, joined and flanged by EBW, machined and chemical finished to improve *Ra*.

- EBM showed **great homogeneity** compared with other AM techniques
- Residual resistance of 170 nΩ, Q_0 ~ 8*10^8 at 3 MV/m E_{acc}





RadiaBeam Jefferson Lab UTEP NC STATE UNIVERSITY

P. Frigola *et al*, Advance Additive Manufacturing Method for SRF Cavities of Various Geometries, Proceedings of SRF2015, Whistler, BC, Canada THPB042

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6 GHz cavity prototypes at INFN

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Proof of concept AM SRF cavities

Why **6GHz cavities**?

- **Small prototypes** (fast manufacturing and less material)
- Infrastructures to **polish and test the cavities** already present
- **Direct comparison to seamless spinning** manufactured cavities
- Possible **coating** of Cu cavities with **Nb or Nb3Sn film** via **PVD**

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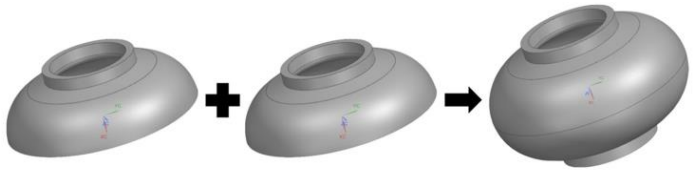
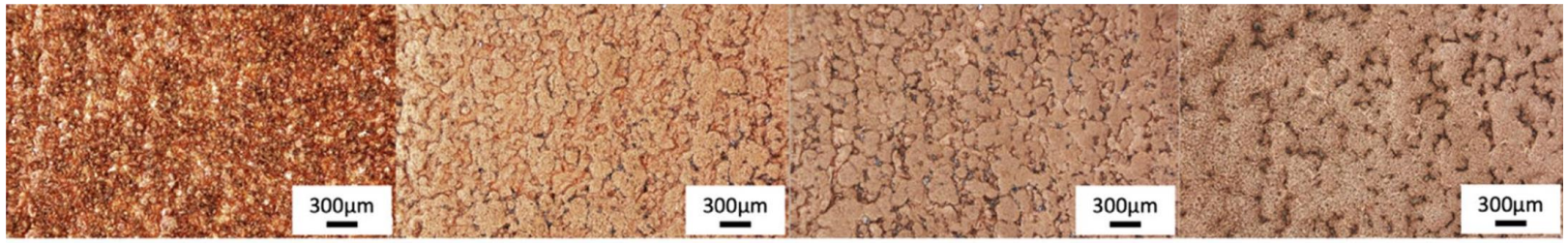
Smoothening inner surfaces

Mechanical process (on half cavity)

As-printed condition Ra = 30-35 µm on down-skin regions (worst case scenario)

- Just mechanical processes **ideal to reduce initial roughness**.
- **Ra does not go below 9 µm**
- Very slow process (10 step, 24h each)
- Peaks are cut but **valleys remain**





a
As-built

b
After 5 steps

c
After 8 steps

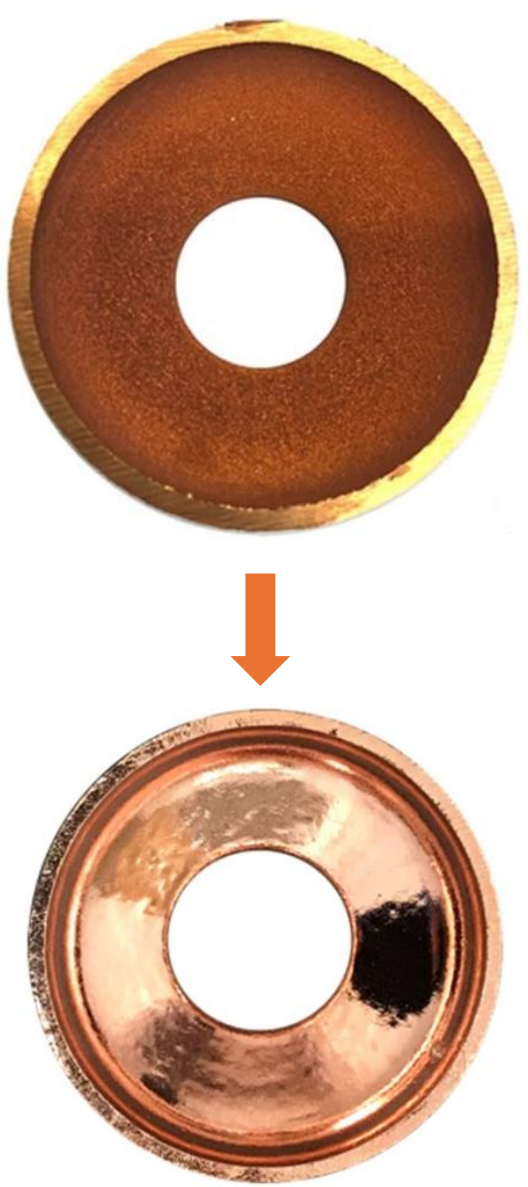
d
After 10 steps

V. Candela *et al*, Smoothening of the down-skin regions of copper components produced via Laser Powder Bed Fusion technology, *The International Journal of Advanced Manufacturing Technology (2022) 123:3205–3221*

Smoothening inner surfaces

Chemical processes (on half cavity)

- *Best of both worlds*: combination of an **initial mechanical treatment** and finishing **chemically assisted** steps to achieve target *Ra*
- Final chemical treatment with a solution of SUBU5 or EP were investigated. EP treated samples showed better surface finish.
- **From down skin roughness of 30-40 µm to less than 1 µm.**
- **Very high material loss compared to VT (ca. 3 times more).**
- **Very fast process** (1h to remove 40 µm of material)



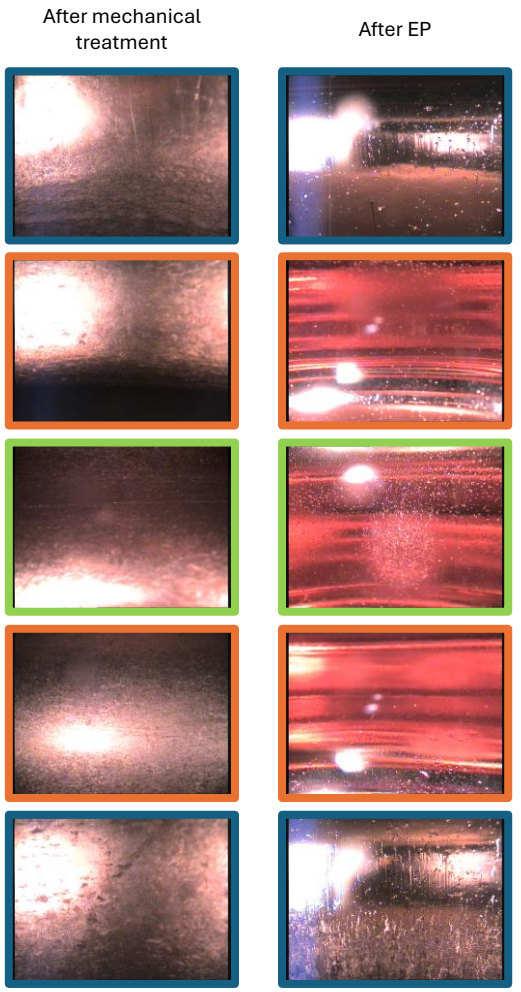
V. Candela *et al*, Smoothening of the down-skin regions of copper components produced via Laser Powder Bed Fusion technology, *The International Journal of Advanced Manufacturing Technology (2022) 123:3205–3221*

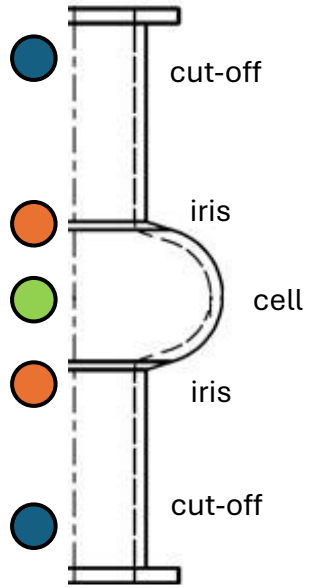
Smoothening inner surfaces

Chemical process (on a full AM 6GHz cavity)

Electro-Polishing technique used with the **full cavity**:
EP in H_3PO_4 : Butanol = 3:2
Vertical configuration
2 steps, 1h each

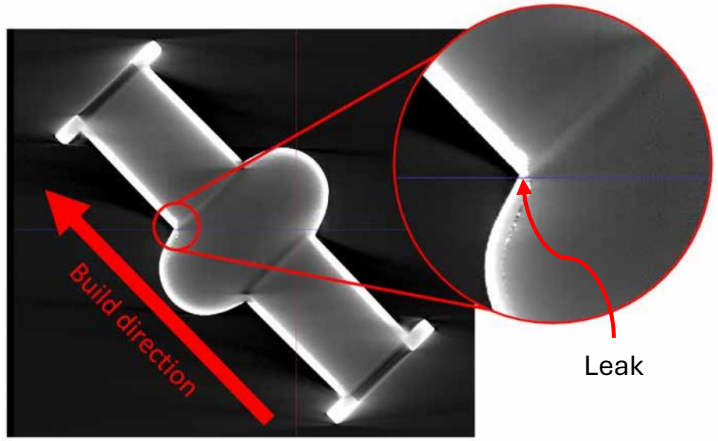
- ✓ **Fast process**
- ✓ Great surface finish (**mirror-like**)
- × Some stains and minor pitting still visible

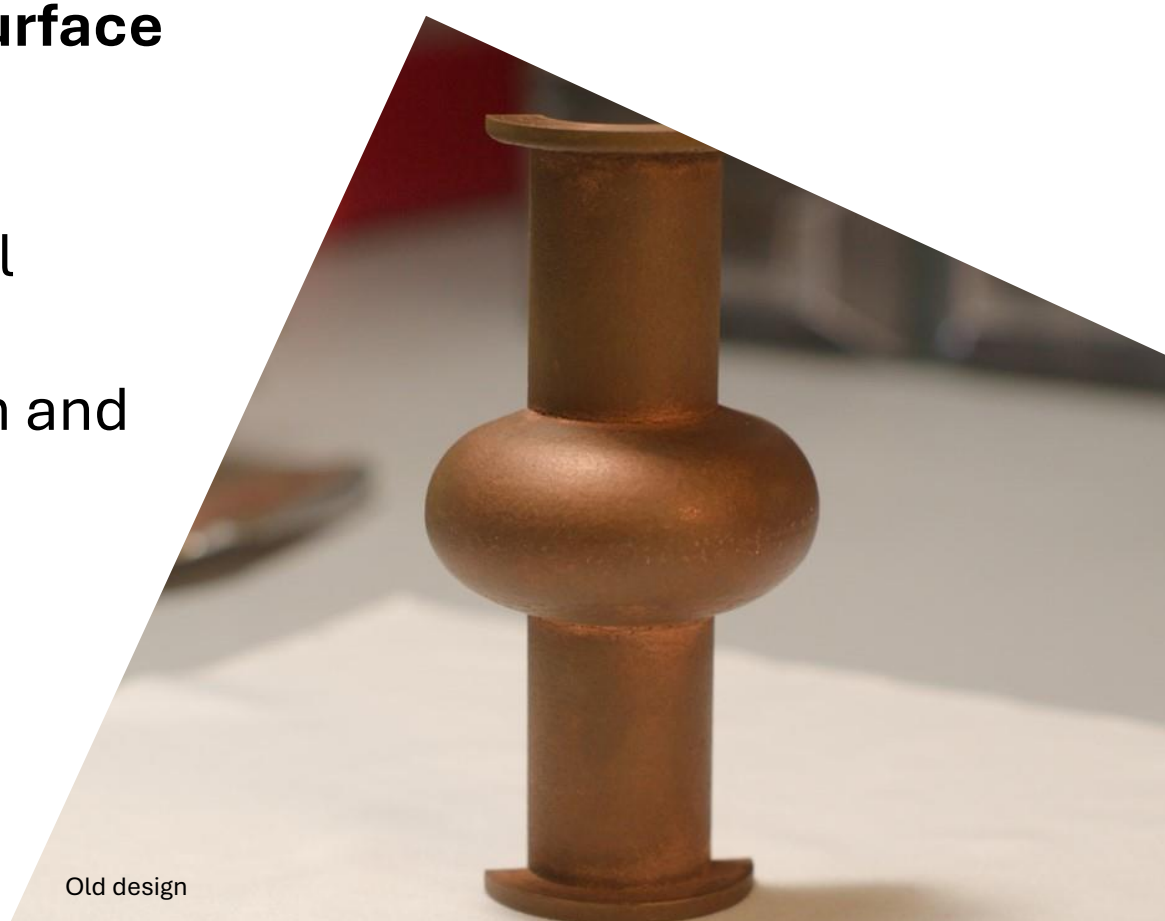




Challenges

- ✕ **Difficult to manufacture** due to intrinsic geometry of elliptical cavities (very low down-skin angles)
- ✕ **Cracking on first samples on iris during surface polishing**, due to insufficient material
- ✕ **High porosity and surface roughness**
- ✓ Good results with mechanical and chemical surface polishing techniques
- ✓ Research is constantly upgrading the design and solving the issues




Old design

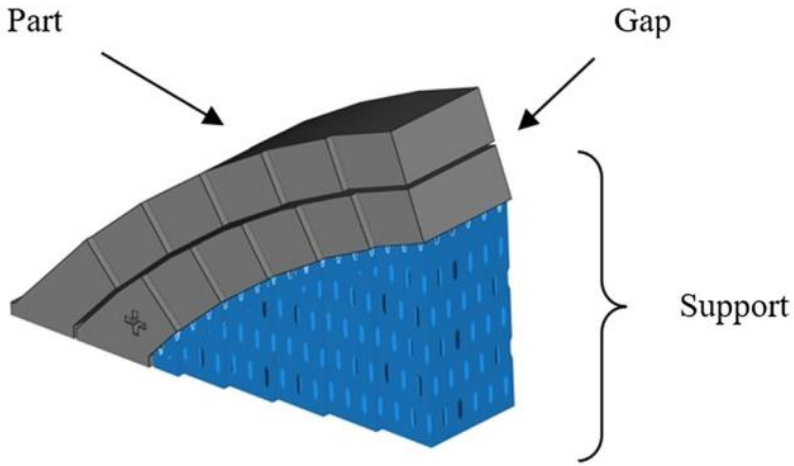
Challenges

Support structures

The high removal of material from polishing processes could lead to **breakage of part**, expecially on the iris of the cavity (thinner section).

- ✓ A new design is being tested to solve the issue
- ✓ An innovative **internal support** has been already tested to **reduce roughness on down-facing structures**

Internal *contactless* support structures



New design

S. Candela *et al,* Pure niobium manufactured by Laser-Based Powder Bed Fusion: influence of process parameters and supports on as-built surface quality, *The International Journal of Advanced Manufacturing Technology (2024) 131:4469–4482*

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Plasma Electrolytic Polishing?

Could be an effective **alternative to conventional methods**:

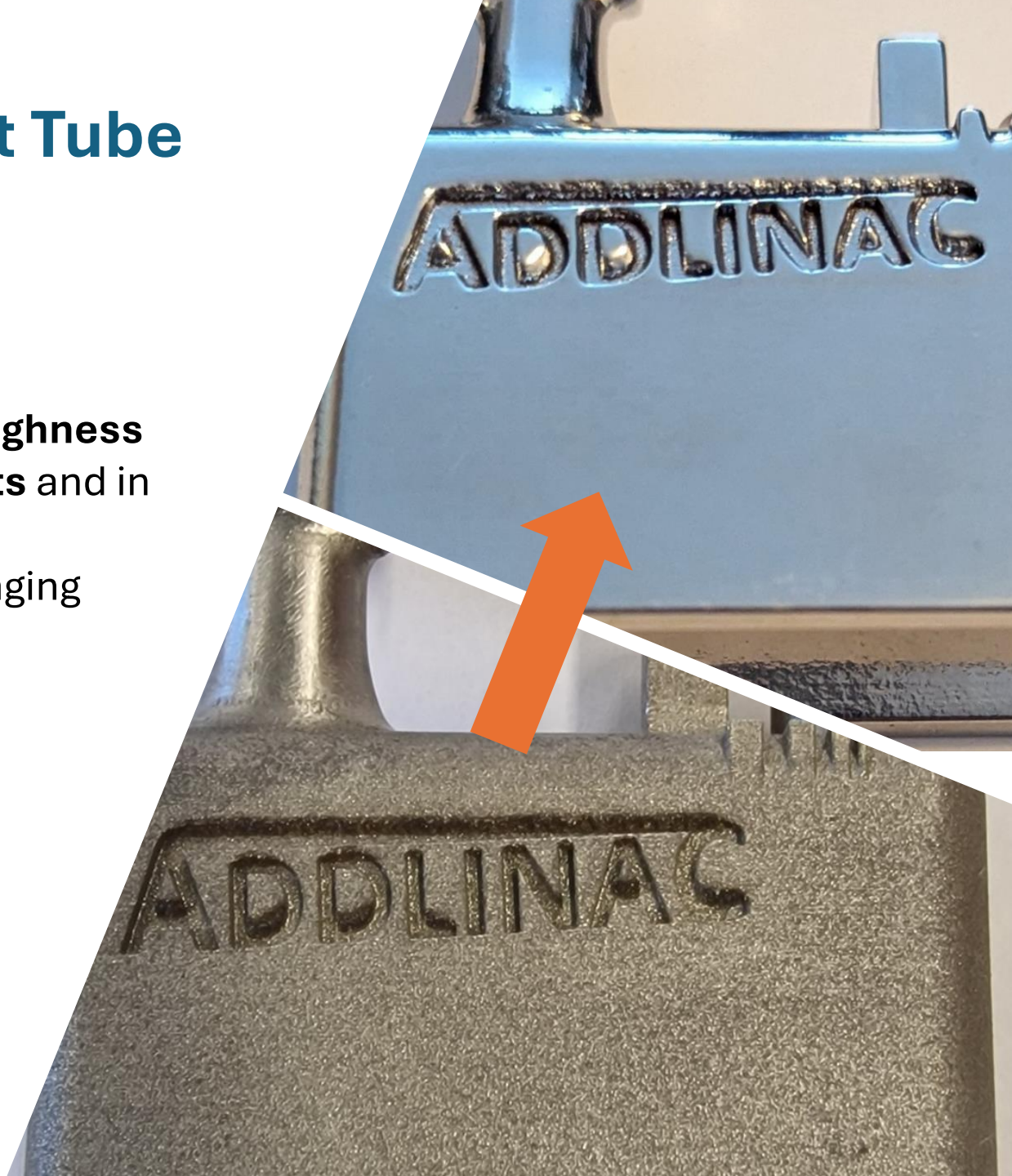
- ✓ **One-step-process** from initial as-printed condition to target Ra
- ✓ **No use of aggressive chemicals**
- ✓ Already great results on planar samples (cylinders and cavities tests still on-going)
- ✓ Mirror-like finish
- ✓ **Very fast** process
- ! Highly depends on material (**high purity required**)
- ! High material removal

Talk by **Eduard Chyhyrynets**
Plasma Electrolytic Polishing for SRF

AM Stainless Steel IH-type Drift Tube structures

PEP treatments

- **PEP** treatments capable of **reducing surface roughness** by an **order of magnitude** with **no pre-treatments** and in a **fraction of the time**
- Tested various polishing techniques with encouraging results
- Copper plating possible after surface treatment



H. Hähnel *et al*, Surface finishing of additive manufacturing parts for particle accelerators, *32° Linear Accelerator Conference - LINAC'24, August 25-30, 2024, Chicago, IL, USA*

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Nb bulk 6GHz cavities tests

3 **Nb bulk cavities** were produced and tested as proof of concept:

- ✓ Vacuum leak **under 10^{-12} mbar l/s**
- ✓ Tc of AM Nb cavity according to bulk Nb
- ✓ **Measured Q_0 of $5*10^5$** (@4.5 K) with mechanical and EP processes

↓

Can not replace Nb in applications where low Rs is needed

↓

Interesting solution for SC «low performace» components

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Conclusions

- ✓ Several possible application explored
- ✓ Significant **benefits in terms of design possibilities**, costs and production time
- ✓ **Conformal cooling** has enhanced heat dissipation on RF components (**enabling operation at higher powers**)
- ✓ **Component weight**
- ✓ Technical gaps gradually filled by continuous research
- ✓ *Ra* is **still a limiting factor** and post-process is required, but new polishing techniques are being investigated

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Thank you!