The Additive Manufactured RFQ prototype: results and perspectives

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on behalf of the whole AM team of WP10

How RFQ emerged in Task 10.2

T10.2: Additive Manufacturing – Survey of applications and potential developments

(M1-M36)

- Review current AM applications in accelerators.
- Identify needs of the accelerator community and **technology barriers and challenges**.
- Define R&D directions to enhance impact of AM on accelerator applications (sterilisation, medicine, industry).

Achieved deliverables and milestones:

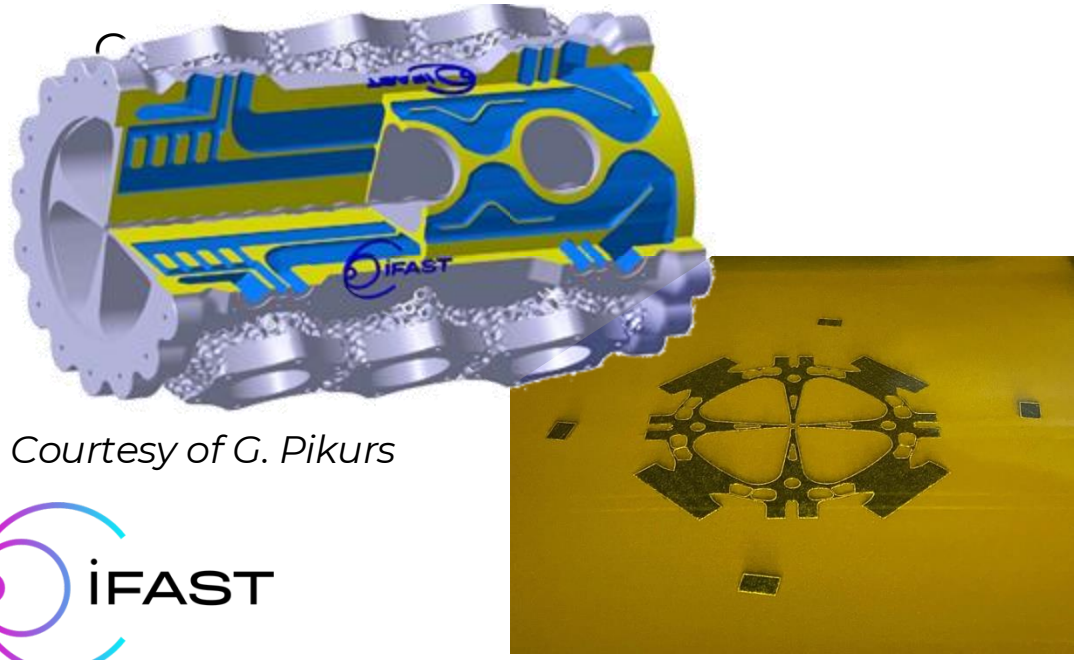
- **D10.1**: Potential AM applications in accelerators (M30)
- **D10.2**: Survey of AM applications and strategies for repairing component by AM (M24)
- **MS44**: Survey on current AM applications in accelerators and expected new developments (M30)

https://doi.org/10.1103/PhysRevAccelBeams.27.054801

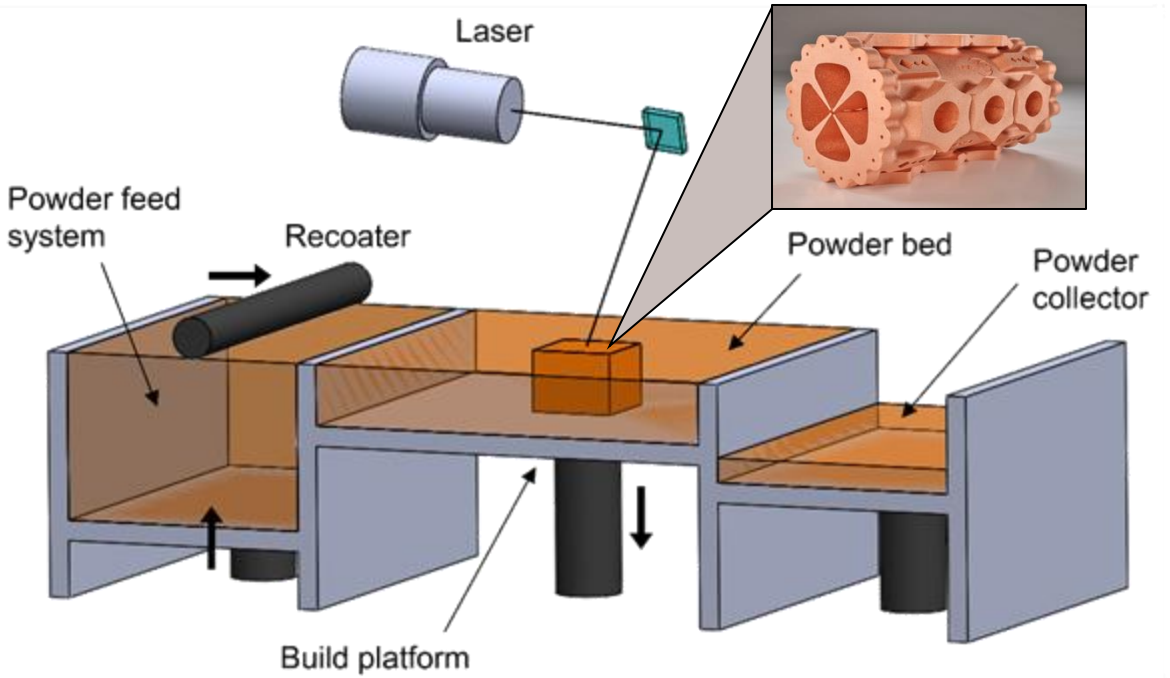
The design process of the RFQ prototype

Leverage the capabilities of most advanced **Laser Powder Bed Fusion** systems:

- **One-step printing** of complex geometry with integrated flanges and connections, without joining issues.
- Integrate conformal **cooling channels and lattice structures** for temperature control and material saving.
- **Green laser** for improved printability with pure copper.



Courtesy of G. Pikurs



http://dx.doi.org/10.5772/intechopen.107233

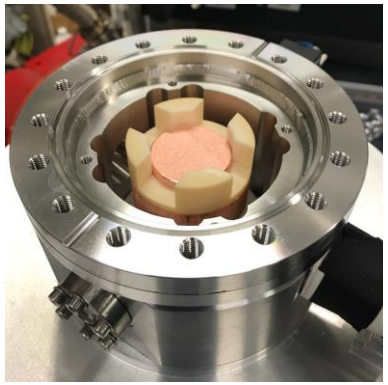
Qualification of the RFQ prototype

Material characterisation

- Microstructure
- Density and purity
- Mechanical properties
- Electrical and thermal conductivity

Qualification testing

- High-voltage and breakdown behaviour
- Vacuum tightness



Full module testing

- Vacuum tightness of full module
- Electromagnetic behaviour
- Surface finishing

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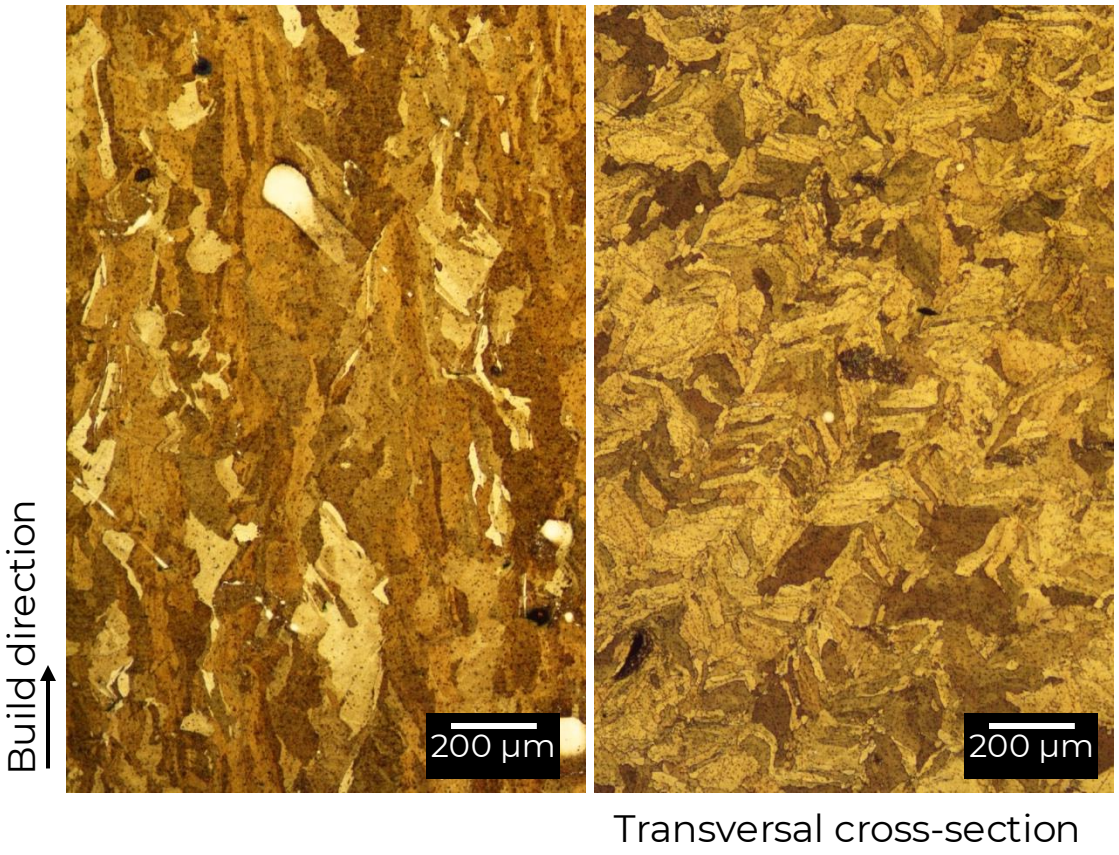
Properties of LPBF copper



Transversal cross-section

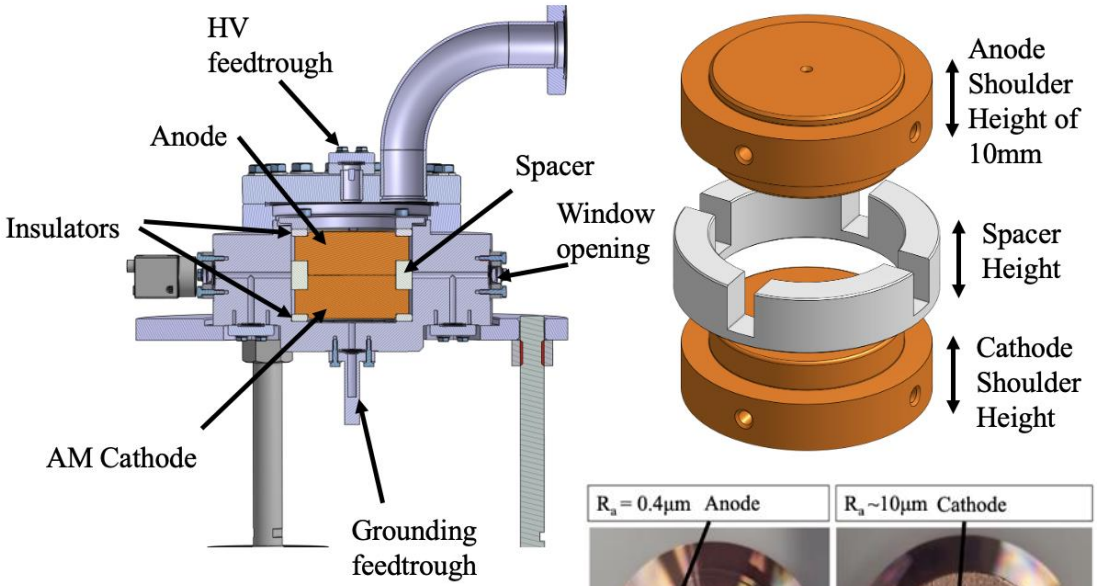
Specimens printed by green LPBF exhibit **microstructural anisotropy** and properties in line with **pure copper standards**.

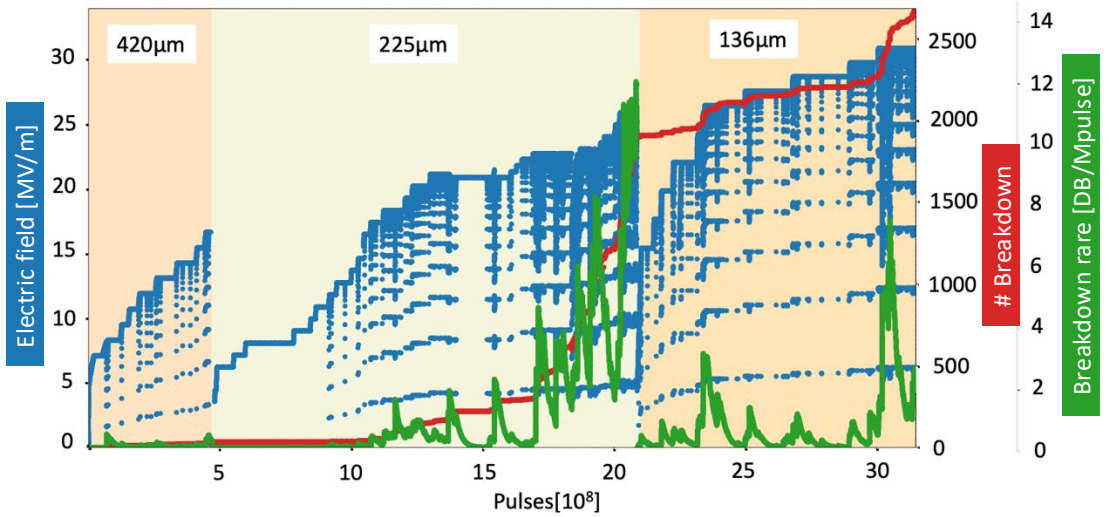
- Oxygen content: 0.044 ± 0.004 wt.%
- Density: ~99.6%
- Microhardness: 75.5 ± 3.2 $HV_{0.05}$
- Electrical conductivity: 58.01 ± 0.22 MS/m (~100% IACS)
- Thermal diffusivity:
  - 1.172 ± 0.007 cm^2/s (~100.3%) along BD
  - 1.167 ± 0.006 cm^2/s (~99.7%) along TD

https://doi.org/10.1016/j.vacuum.2024.113995

High-voltage behaviour of LPBF copper

- High-field gradient tests performed with **pulsed high voltage DC system** at CERN, using smooth anode and **as-built LPBF cathode**.
- Average gap distance between electrodes estimated from **capacitance**.





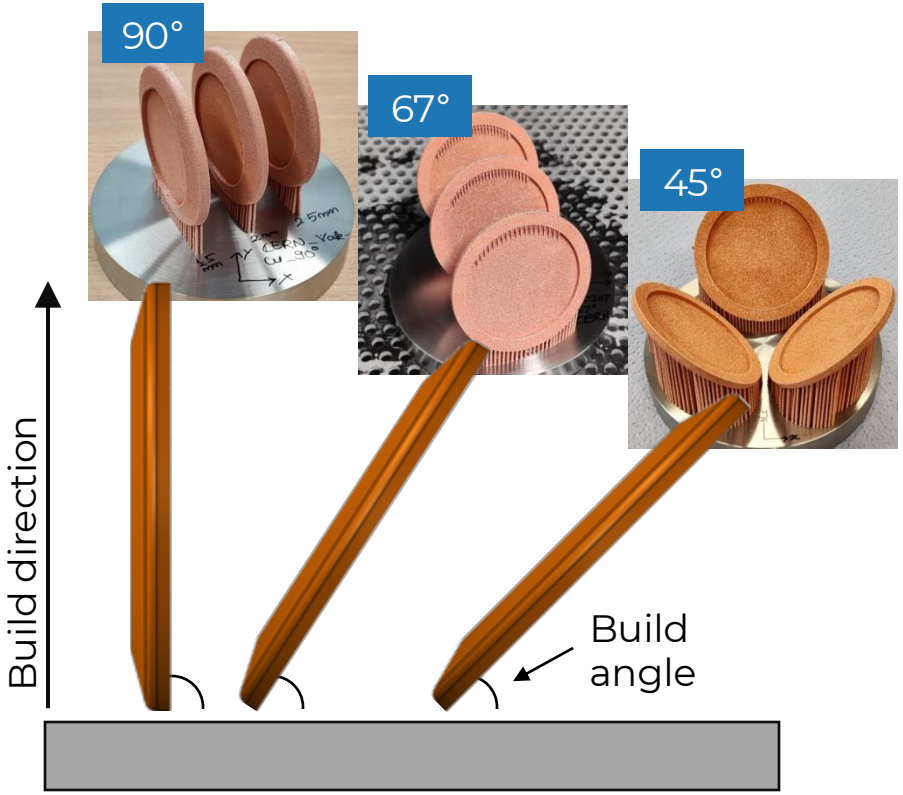
ΔV_{max}	Gap	E_{max}
7 kV	420 µm	~17 MV/m
7 kV	225 µm	~26 MV/m
7 kV	136 µm	~31 MV/m

CERN compact 750 MHz RFQ operates at 40 MV/m.

https://meow.elettra.eu/81/pdf/THPB051.pdf

Vacuum tightness of LPBF Cu membranes

Helium leak testing (10^{-10} mbar l s^{-1} detection limit) performed on standard test membranes printed with different **wall thicknesses** and **build orientations**.



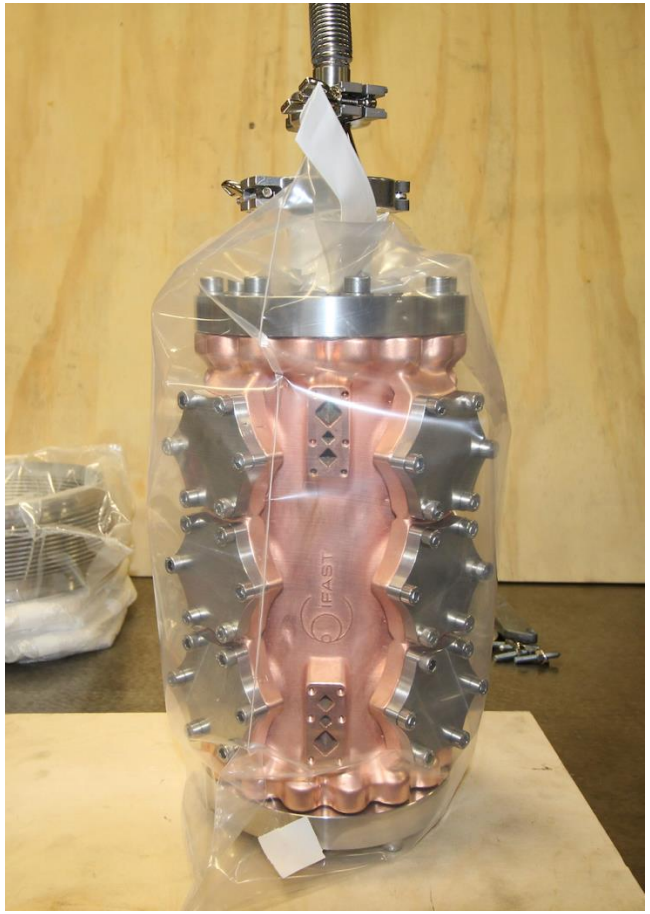
- Compact thickness lower than design.
- Higher inclination leads to longer scan length and thicker compact layer.
- **Design compensation** for complex parts with varying feature orientations.

Wall thickness \ Build angle	Effective thickness (mm)			He leak rate (mbar l s^{-1})		
	45°	**67°**	**90°**	**45°**	**67°**	**90°**
1 mm	0.73	0.69	0.69	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$
0.75 mm	0.65	0.50	0.36	$<10^{-10}$	$<10^{-10}$	$\sim10^{-6}$
0.5 mm	0.38	0.31	0.17	$<10^{-10}$	$\sim10^{-3}$	$\sim10^{-2}$

https://doi.org/10.1016/j.vacuum.2024.113995
https://doi.org/10.1088/1742-6596/2687/8/082046

Vacuum tightness of RFQ module

Helium leak test passed (10^{-10} mbar l s^{-1} detection).



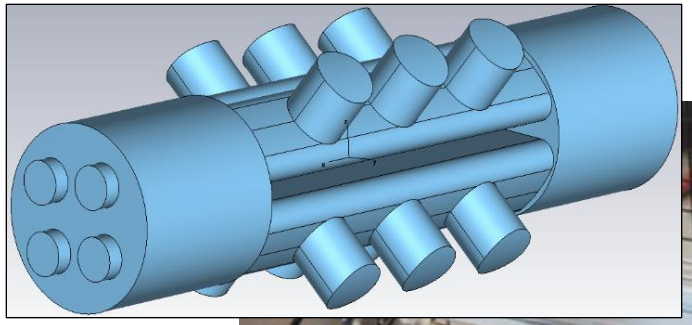
Thanks to CERN TE-VSC, C. Garion, and H. Kos

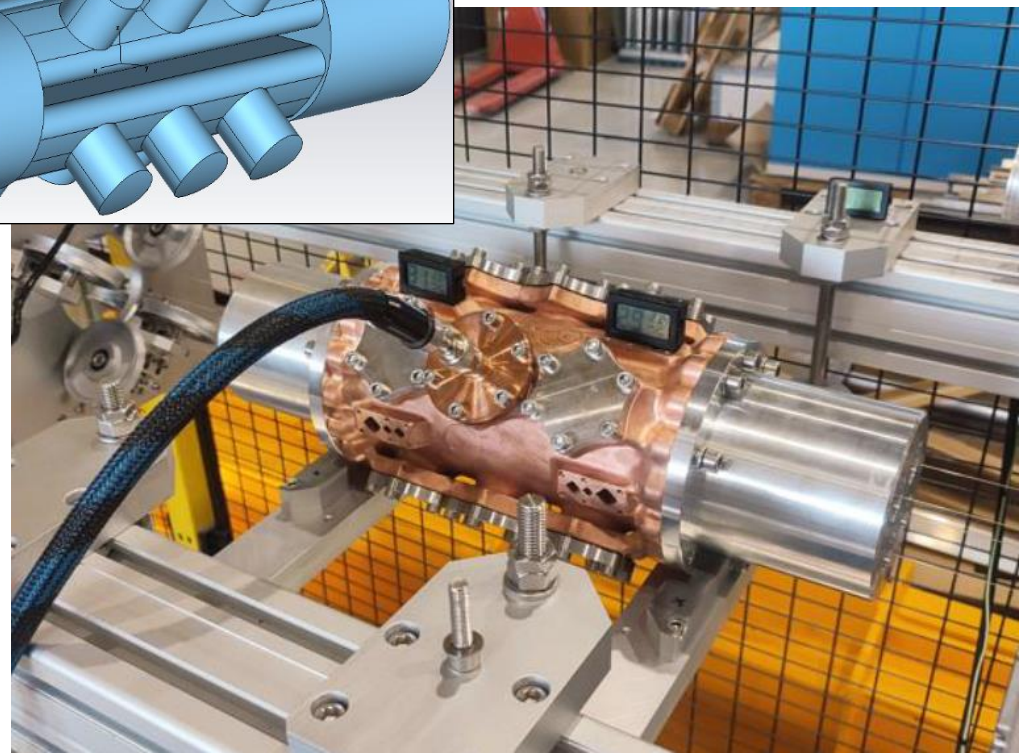
https://inspirehep.net/files/ce28c0d1284c283028b07146d9c5a2b6

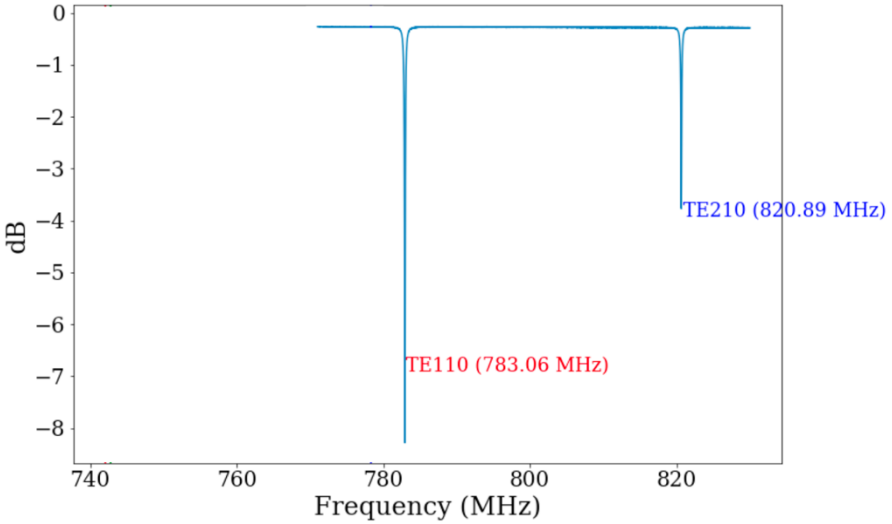
Electromagnetic behaviour of RFQ module

Original RFQ module design targeted an operating frequency of **750 MHz**.

- **Electromagnetic simulations** followed by **bead-pull measurements**.
- Mismatch between simulated and measured frequencies due to **post-processing**.







Mode	Simulated *f*	Measured *f*
TE210	749.41 MHz	820.89 MHz
TE110(1)	714.12 MHz	783.06 MHz
TE110(2)	715.09 MHz	

Thanks to CIEMAT Accelerator Unit, C. Oliver, G. Moreno, and P. Calvo

https://meow.elettra.eu/81/pdf/THPB051.pdf

Surface finishing of RFQ module

Mass finishing based on mechanical abrasion from vibrating media, tuned via:

- Type, size, and shape of media
- Water and chemical compounds
- Operating conditions

As-built

Post-processed

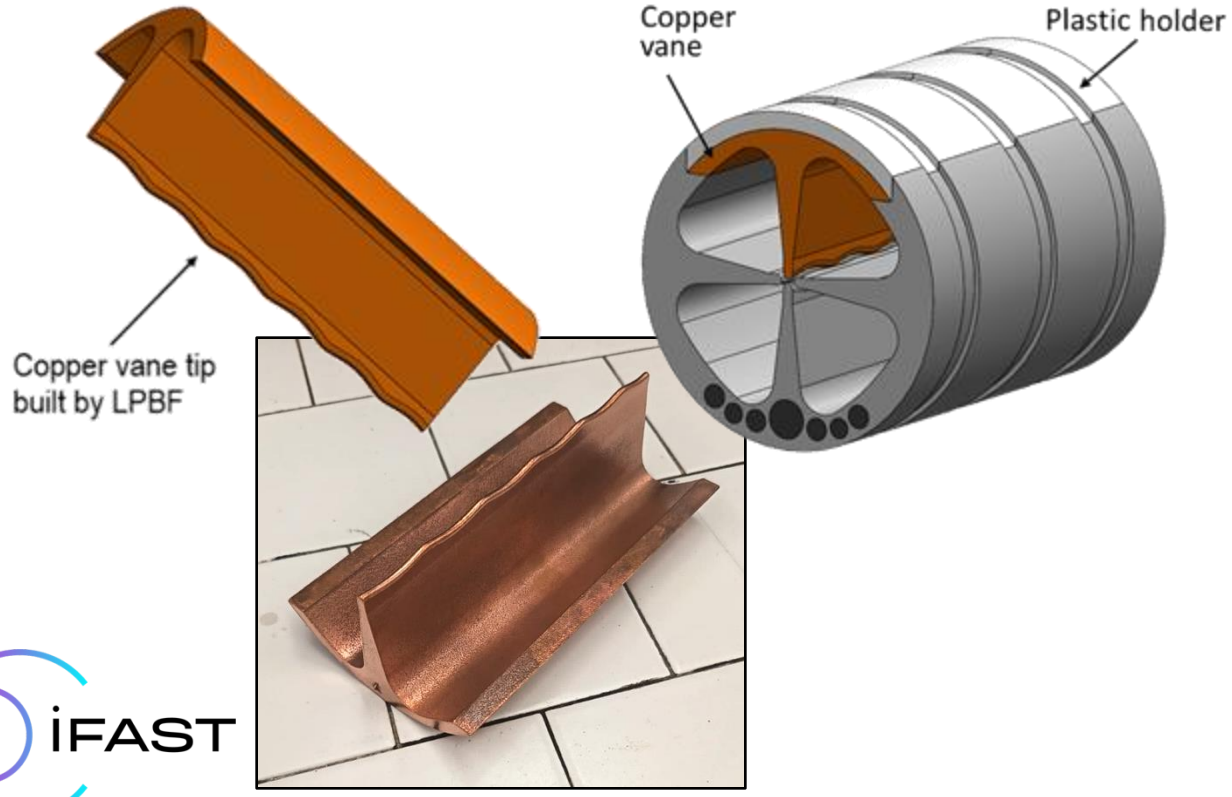
	Close to tip		Lateral surface	
	Ra (µm)	Rz (µm)	Ra (µm)	Rz (µm)
As-built	17.16 ± 2.84	84.30 ± 16.20	18.73 ± 3.59	91.59 ± 11.28
Coarse finishing	1.14 ± 0.43	10.87 ± 5.71	2.55 ± 0.77	13.49 ± 3.77
Fine finishing	**0.65 ± 0.08**	**4.85 ± 0.57**	**1.19 ± 0.39**	**9.33 ± 2.74**

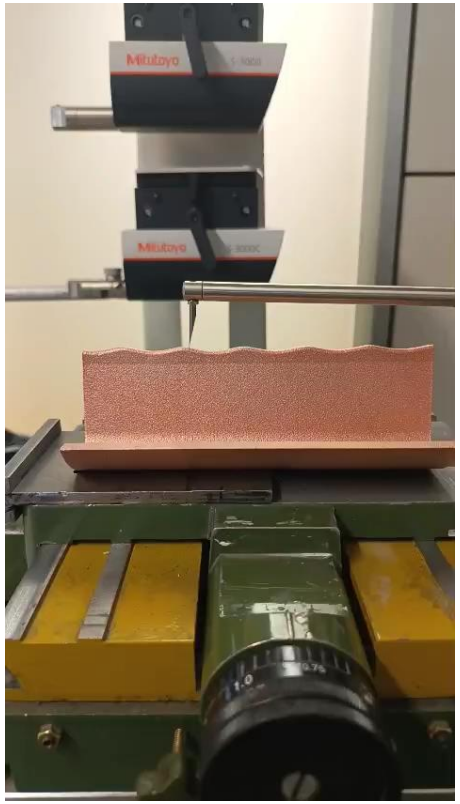
https://inspirehep.net/files/ce28c0d1284c283028b07146d9c5a2b6

Surface finishing of RFQ vane tip

Activity conducted in Aug – Oct 2025 at Rösler Italiana within the **I.FAST Industry Training**.

- Evaluate the effect of post-processing in **hard-to-reach vane tip**.
- Copper vane printed by green LPBF + plastic holder to replicate full RFQ.
- Test different treatments and durations.

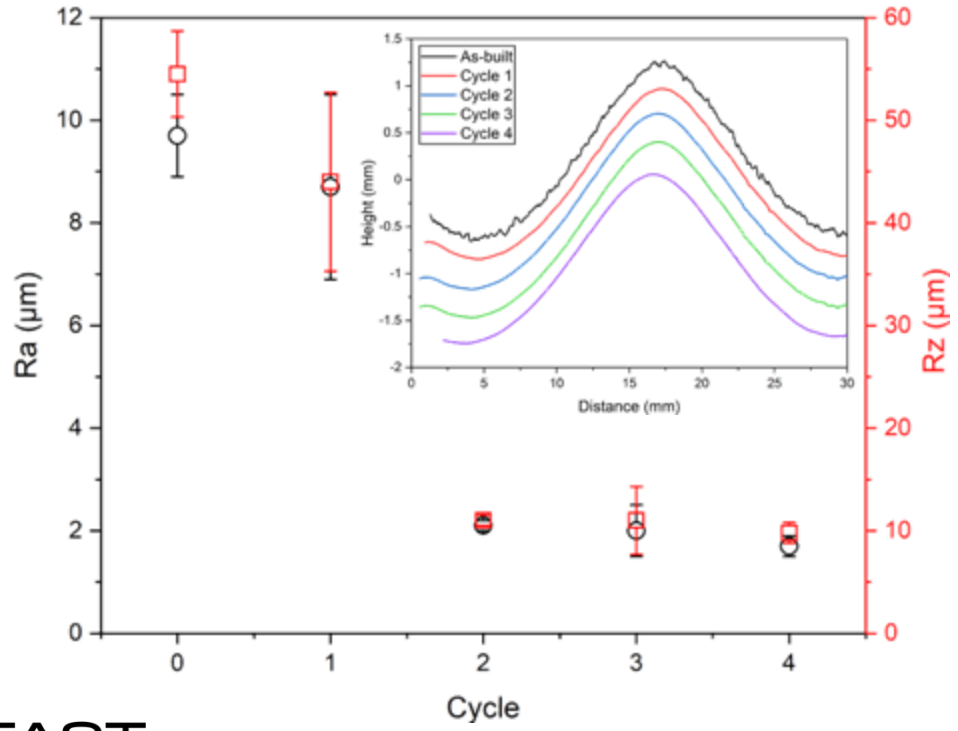




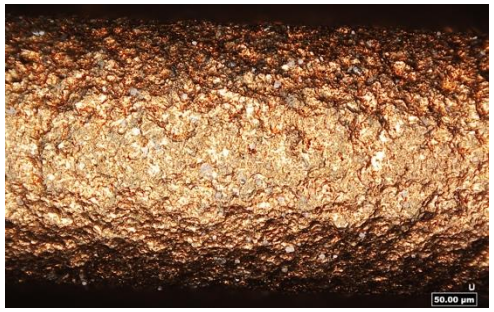
Surface finishing of RFQ vane tip

Four sequential post-processing cycles with intermediate characterisation:

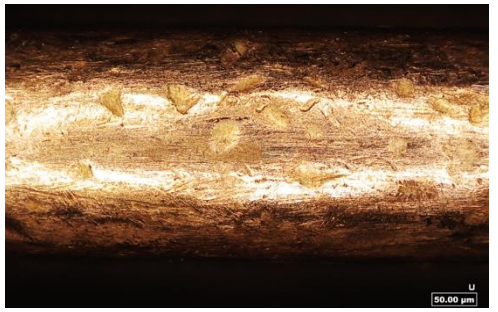
- Material removal
- Stereomicroscopy
- 2D/3D roughness
- Profilometry



As-built



Cycle 3



Step	Ra (µm)	Rz (µm)	Δmass (g)
As-built	9.7 ± 0.8	54.5 ± 4.2	–
Cycle 1	8.7 ± 1.8	44.0 ± 8.7	8.8
Cycle 2	2.1 ± 0.1	11.0 ± 0.5	11.3
Cycle 3	2.0 ± 0.5	11.0 ± 3.3	17.3
Cycle 4	1.7 ± 0.2	9.8 ± 1.0	10.0

Some lessons learned

- No need for «precursors» of holes in the printed part – harder to centre final holes during machining.
- Define and preserve **reference surfaces** for clamping during post-processing and machining.
- Account for material removal and shrinkage during **post-processing** to ensure proper **design compensation** and final dimensional accuracy.
- Optimize contour parameters to improve **as-built roughness**, especially on functional surfaces (e.g., vane tips).

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Final remarks

Outcomes: demonstrate feasibility of AM of accelerator components and identify most strategic directions for future research, (possibly 🤞) during **EPITA** project.

- Improve material performance: conductivity, cooling efficiency, vacuum compatibility.
- Design, manufacture, and validate a **750 MHz RFQ prototype** using **LPBF**:
  - Optimize design / process for post-printing operations, surface quality, and accuracy.
  - Improve surface finishing with combined technologies for critical areas.
- Reach **TRL4 – Prototypes tested with beam in lab**
  - **Success metrics in EPITA**: achieve >85 % of nominal Q-value and stable RF operation at nominal design power, demonstrating proton acceleration up to 0.5 MeV.

Impacts: enable adoption of AM for low-cost industrial production of **custom-made compact accelerators for societal applications** (cancer therapy, industry, and security).

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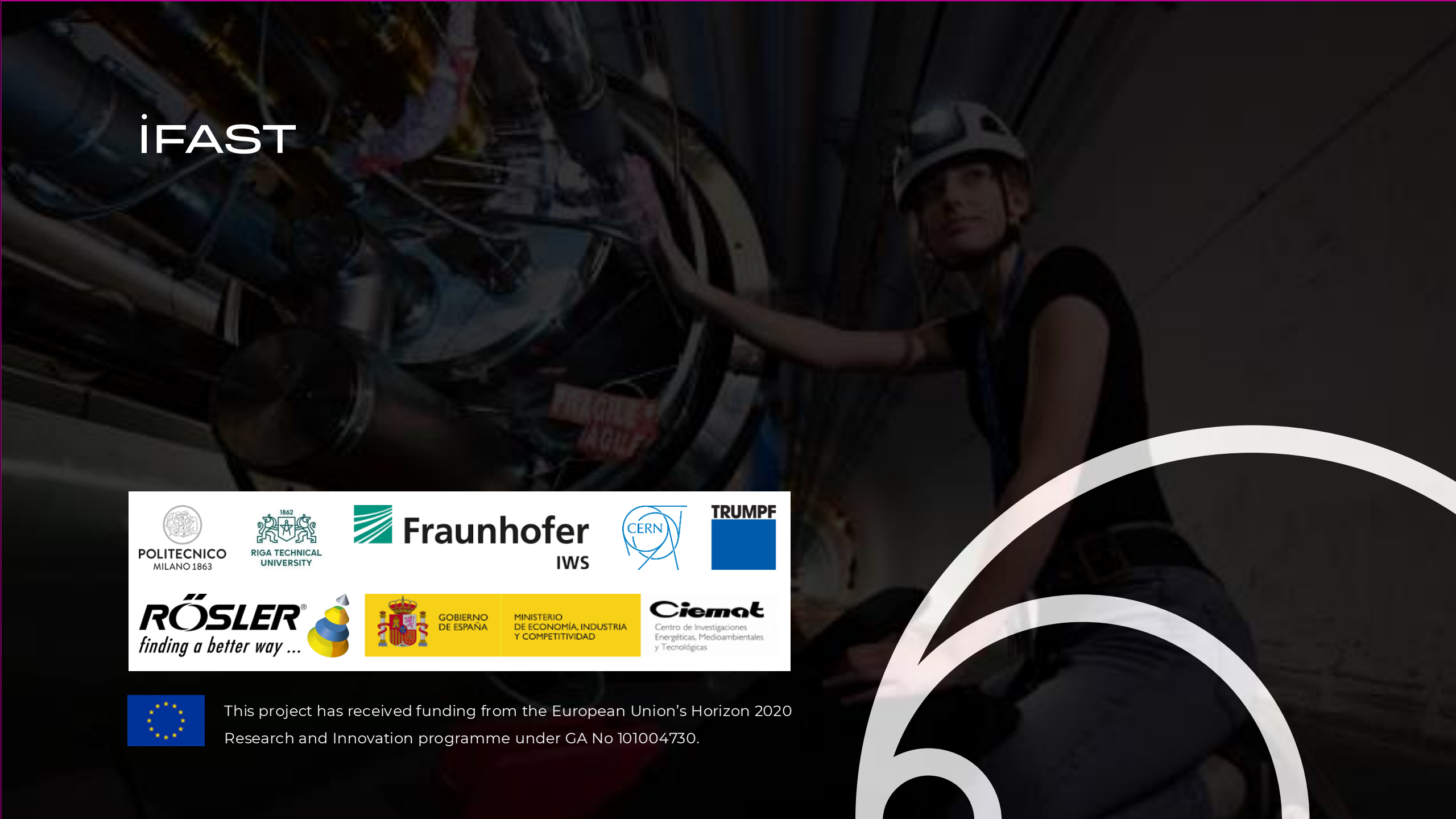

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