Prof. Toms TORIMS, Riga Technical University

I.FAST Period 2 Review, 15.07.2024

The progress as of Oct 2022

- Very good results in all Tasks of WP10
- This is deep tech with the **great impact** to the whole accelerator community
- Additive Manufacturing Tasks are pioneering technology, we are holding **strategic leadership**
- **New partners** are being engaged; new collaborations are created
- **Numerous** outreach activities and highest level **Q1/Q2 scientific publications**
- Technology “heavy weight” WP

WP10 Milestones in P2

Task 10.2	MS44	Survey on current AM applications in accelerators and expected new developments	10.2	30	Report	**Achieved**
Task 10.3	MS45	Survey on current AM repair technologies for accelerator and list of possible applications	10.3	24	Report	**Achieved**

Achieved - links to reports:

- MS45 - Survey on current **AM repair** technologies for accelerator and list of possible applications
- MS44 - Survey on current **AM applications** in accelerators and expected new developments

WP10 Deliverables in P2

	Deliverables related to WP10	
Task 10.2	**D10.1:** Potential AM applications in accelerators. *Report on output of the survey on AM applications, further needs for the accelerator community, and perspective developments.*	30 **Achieved**
Task 10.3	**D10.2:** Survey of AM applications and strategies for repairing accelerator components by AM. *Report listing possible strategies and technologies for repairing of parts.*	24 **Achieved**
Task 10.5	**D10.4:** First PSD data from NEG coating. *First PSD data from NEG coating reported.* **Ongoing – delay to month 44**	36
Task 10.6	**D10.5:** Technical Report on machine learning at ESS. *Evaluation and verification results, architecture of the final implementation, and achieved performance at the ESS facility.* **Ongoing – delay to month 46**	34
Task 10.7	**D10.6:** Electro-optic performance report. *Final report on the performance of the electro-optic pick-up prototype with beam.*	24 **Achieved**

WP10 Deliverables in P2

Achieved - links to reports:

- D10.2 - Survey of AM applications and strategies for repairing components by AM
- D10.6 - Electro-optic Performance Report
- D10.1 - Potential AM applications in accelerators

Ongoing:

- D10.4 - **First PSD data from NEG coating** – responsibility of Task 10.5 (UKRI) - **technical problems** cause 1-year delay to test during yearly shutdown – *see info by Dr Oleg Malyshev (UKRI/STFC Daresbury Laboratory)*
- D10.5 – **Technical Report on machine learning at ESS** - waiting for data after **shift in ESS** facility commissioning **schedule**

Task 10.2

AM – Survey of applications and potential developments

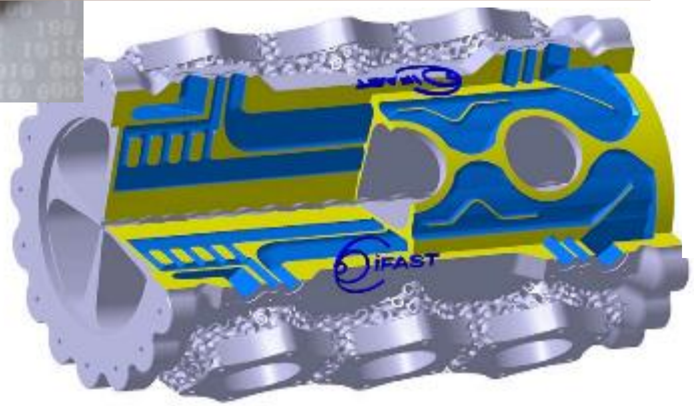
- *Survey of **current** Additive Manufacturing (AM) **applications** in accelerators and identification of **needs for future** development and research actions*
- *Promote initiatives to identify **how AM can address** the needs of the accelerator community*
- *Define **strategic directions** for future AM technologies and foster their impact on accelerator applications (inc. societal), identifying technology barrier and challenges.*

AM in the accelerator community - survey

Courtesy of Guntis Pikurs

Task 10.2 - RFQ related activities

The main demonstrator for WP10, after printing two versions of the full-section RFQ, tests have been done on one of the samples to investigate surface treatments, machining of functional surfaces, He leakage, …



Test passed, threshold value at: $1\cdot10^{-10}$mbar·l·s^{-1}

Courtesy of CERN TE-VSC, Cedric GARION and Hendrik KOS

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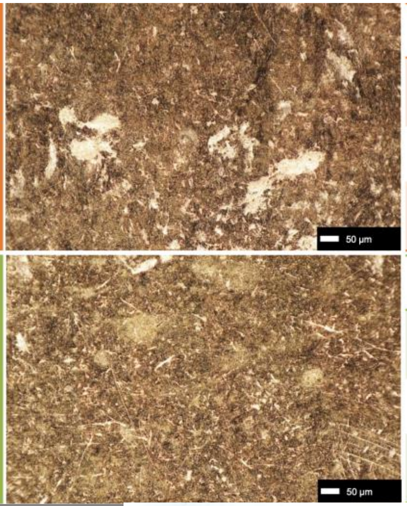
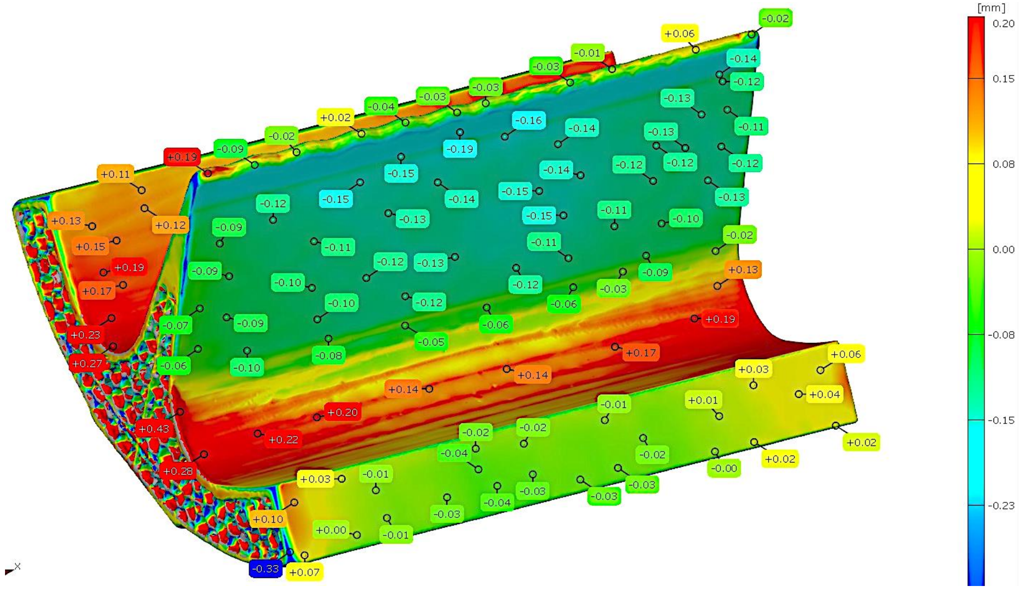
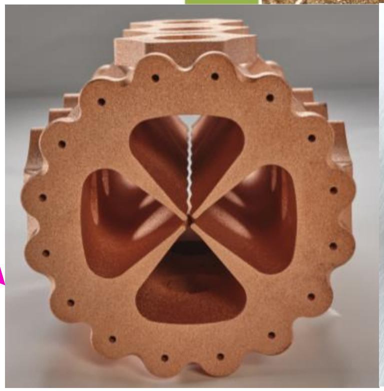
Indicative sample of RFQ

- *Promote initiatives to identify* ***how AM can address*** *the needs of the accelerator community*



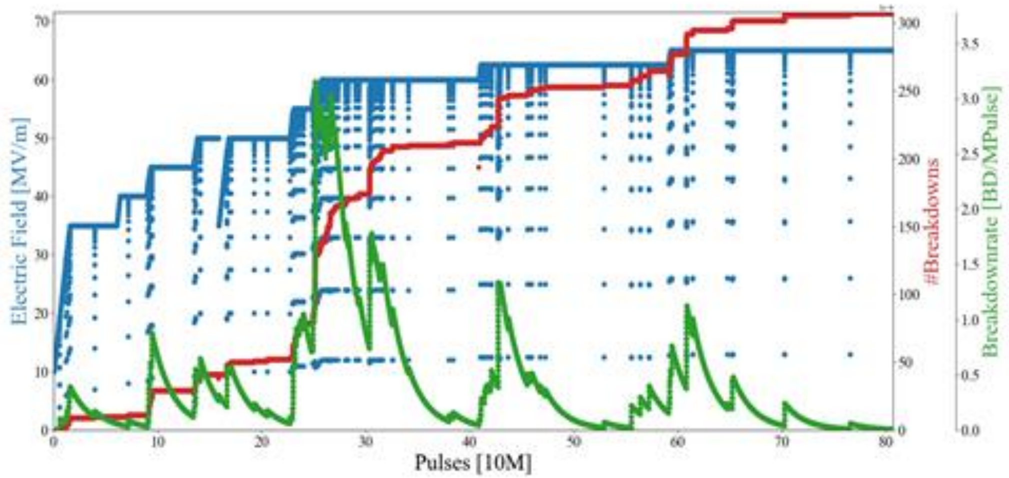
	Ra (µm)	Rz (µm)
#1: mechanical treatment	0,28 ± 0,12	2,09 ± 0,89
#2: chemically assisted process	0,28 ± 0,09	1,56 ± 0,50



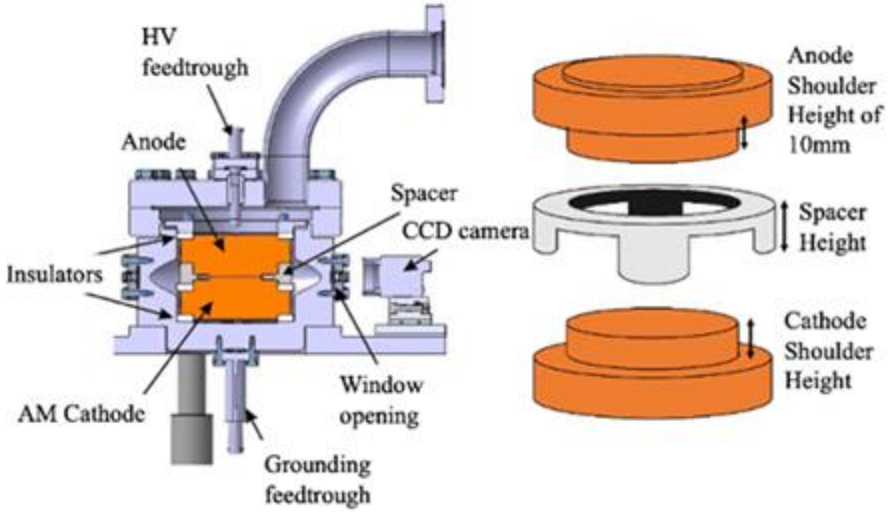


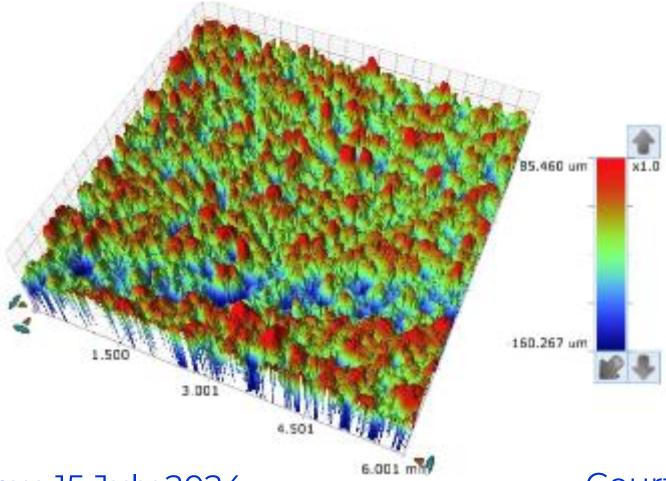
High-voltage behaviour of AM Copper

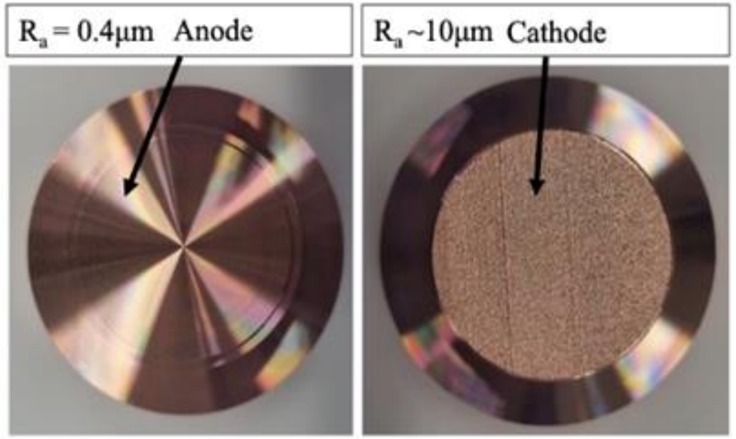
Different surface conditions are under investigation



CERN's pulsed high-voltage DC system





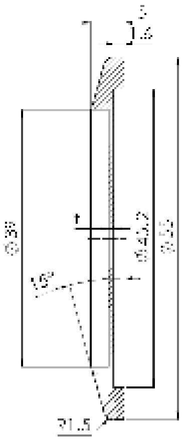


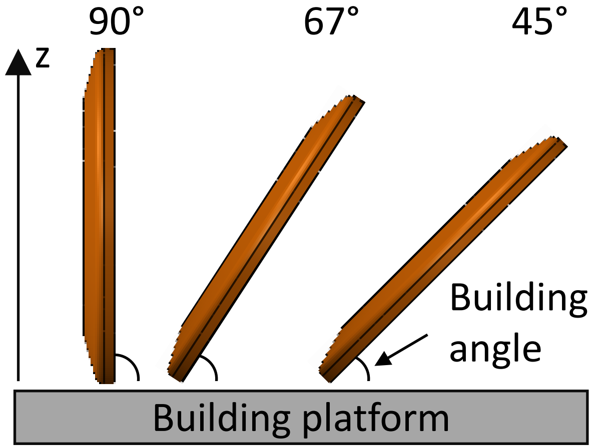
Courtesy of CERN SY-RF team W. Wuensch and V. Bjelland

UHV tests on Cu printed membranes

Standard test membranes printed by a green laser with different thickness and print orientation

- Nominal thickness: 2,5, 5, 1,5, 1, 0,75, 0,5 mm
- Building orientation: 90°, 67°, 45°



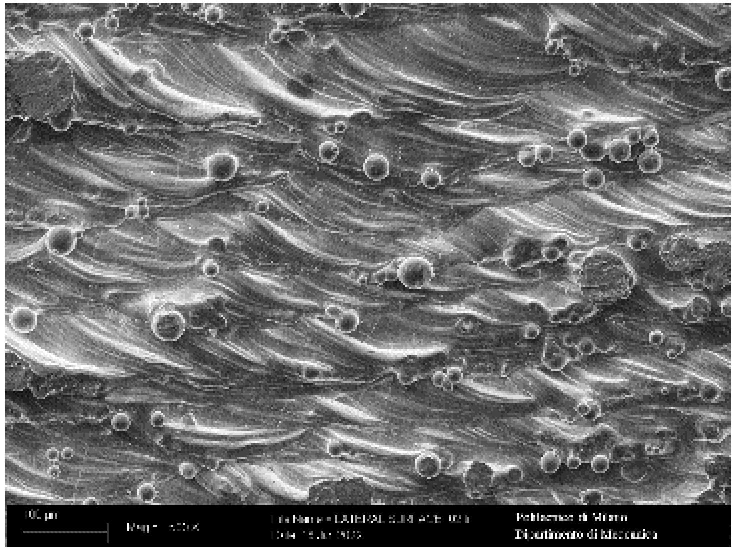


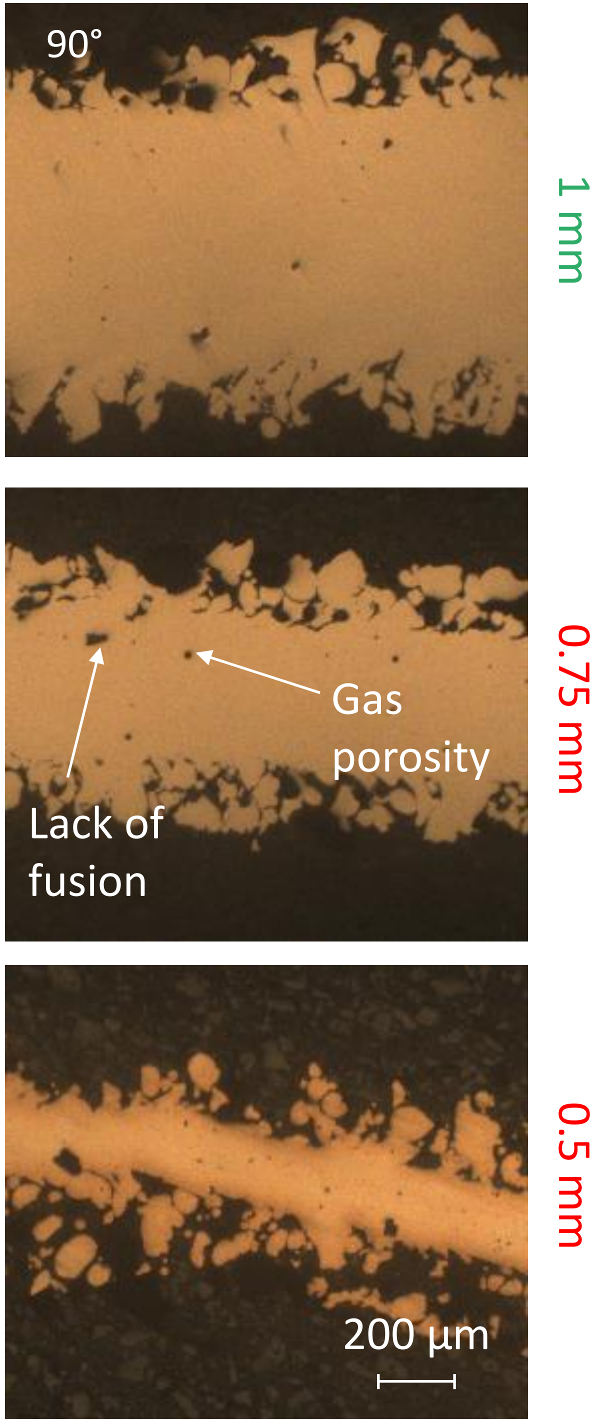
Courtesy of CERN TE-VSC, Cedric GARION and Hendrik KOS

UHV tests on Cu printed membranes

Only small-thickness membranes at highest angles failed the test due to actual thickness related to roughness

Nominal thickness (mm) \ Building angle	Helium leak rate (mbar l s^{-1}) 45°	67°	90°
2.5	PASS	PASS	PASS
2	PASS	PASS	PASS
1.5	PASS	PASS	PASS
1	PASS	PASS	PASS
0.75	PASS	PASS	$1.0 \cdot 10^{-6}$
0.5	PASS	$2.5 \cdot 10^{-3}$	$5.0 \cdot 10^{-2}$





Some recent publications

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27**, 054801 (2024)

Review Article

Metal additive manufacturing for particle accelerator applications

Tobia Romano,[1,2,*] Guntis Pikurs,[2,3] Andris Ratkus,[2] Toms Torims,[2,3] Nicolas Delerue,[4] Maurizio Vretenar,[3] Lukas Stepien,[5] Elena López,[5] and Maurizio Vedani[1]

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[3]*The European Organization for Nuclear Research (CERN), 1211 Meyrin, Switzerland*
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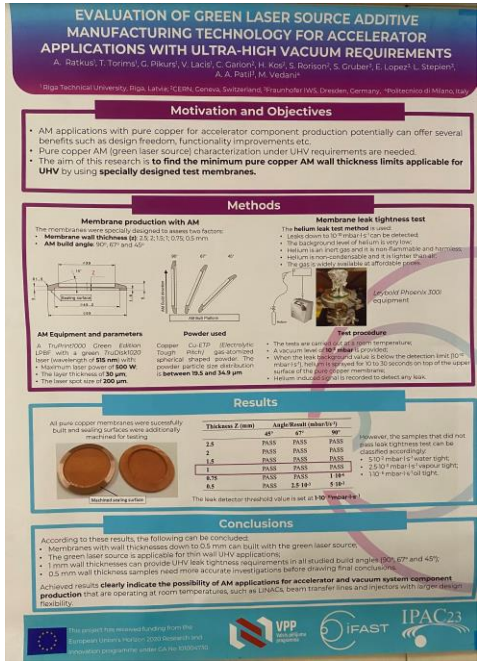
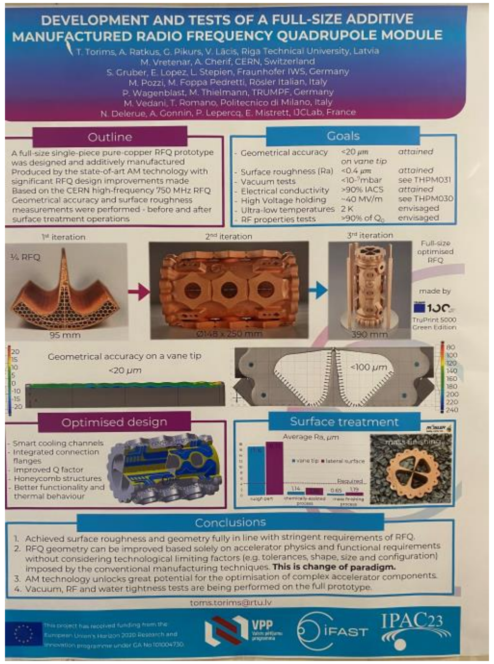
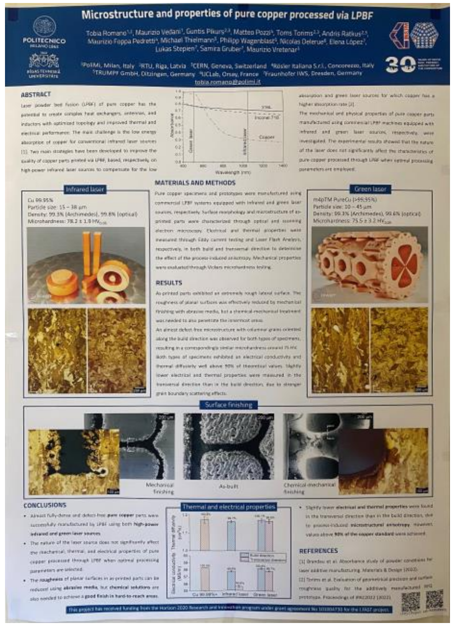
(Received 22 February 2024; accepted 23 April 2024; published 17 May 2024)

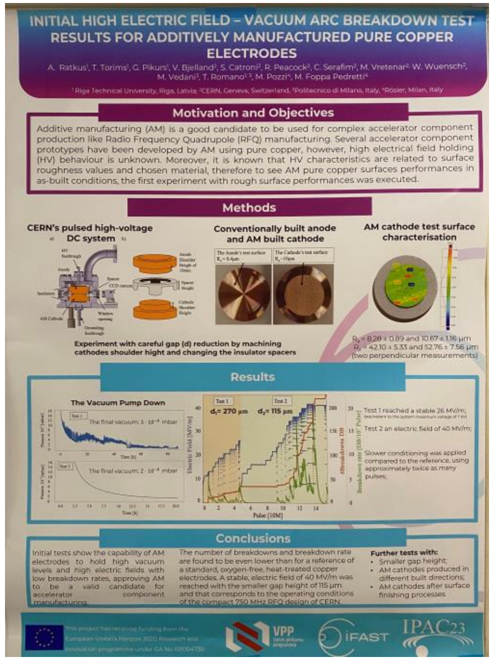
Metal additive manufacturing technologies are rapidly becoming an integral part of the advanced technological portfolio for the most demanding industrial applications. These processes are capable of fabricating three-dimensional components with near-net shape quality by depositing the constituent materials in a layer-by-layer fashion. This fabrication approach provides numerous advantages over conventional manufacturing methods, including enhanced design flexibility, reduced production costs and lead times, rapid prototyping, and the possibility to repair damaged parts. In recent years, the growing demand for novel accelerator components with improved performance characteristics, integrating structures such as drift tubes and internal cooling channels, has prompted the exploration of additive manufacturing in the field of particle accelerators. Radio-frequency components, beam intercepting devices, and vacuum systems have been prototyped using various metallic materials and additive manufacturing technologies, demonstrating performance levels comparable to the conventionally manufactured counterparts in preliminary tests. However, the absence of established qualification protocols and the uncertain reliability of additively manufactured parts under the demanding conditions typical of accelerator applications pose significant challenges to the integration of additive manufacturing processes into the fabrication practices of these components. This paper provides a comprehensive review of documented applications of metal additive manufacturing in particle accelerators, highlighting benefits, challenges, and opportunities for future improvements. The main requirements and currently available test setups for the assessment of additively manufactured components in applications involving ultrahigh vacuum and intense electromagnetic fields are also discussed.

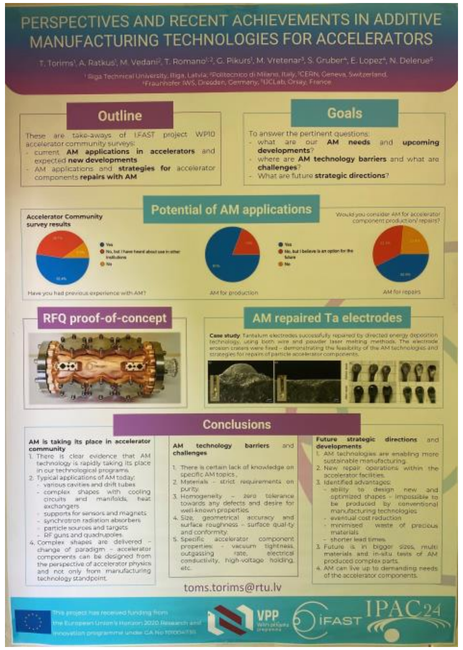
DOI: 10.1103/PhysRevAccelBeams.27.054801











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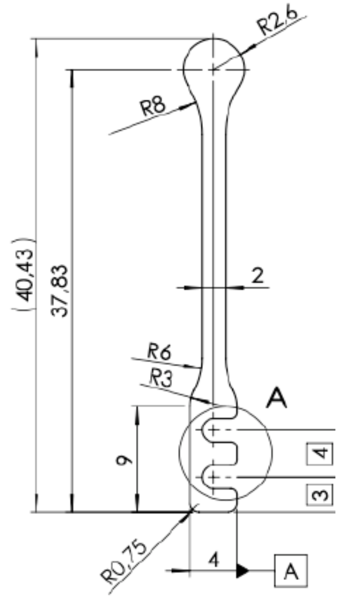
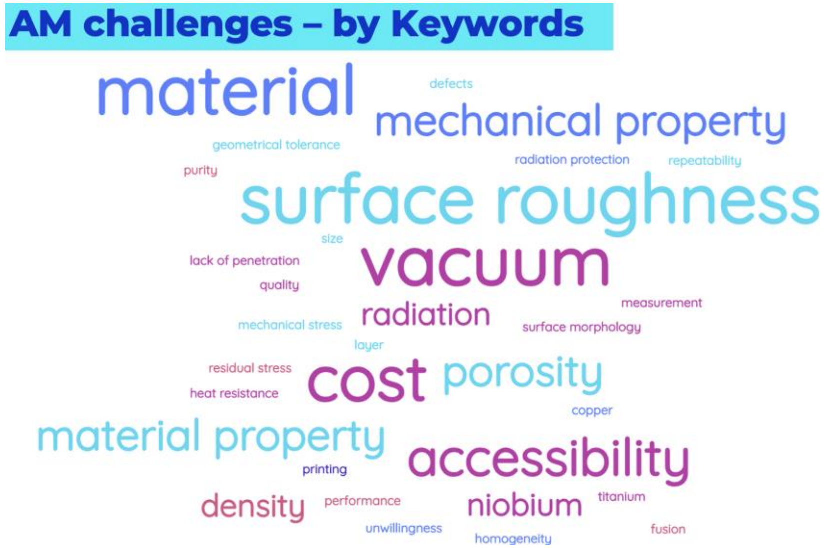
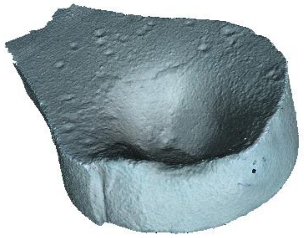
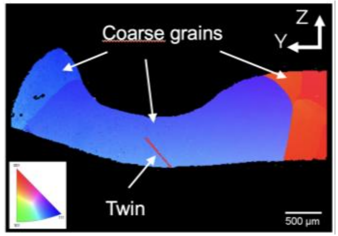
Task 10.3 - highlights

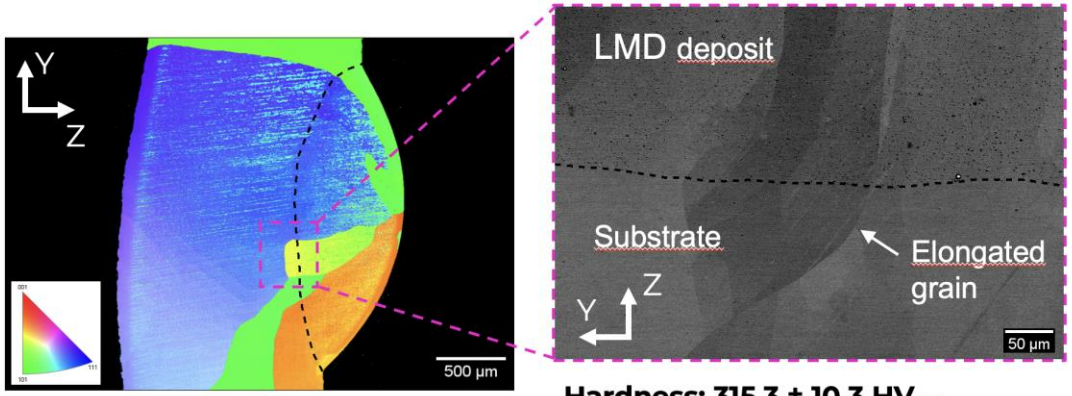
Refurbishment of accelerator components by AM technologies



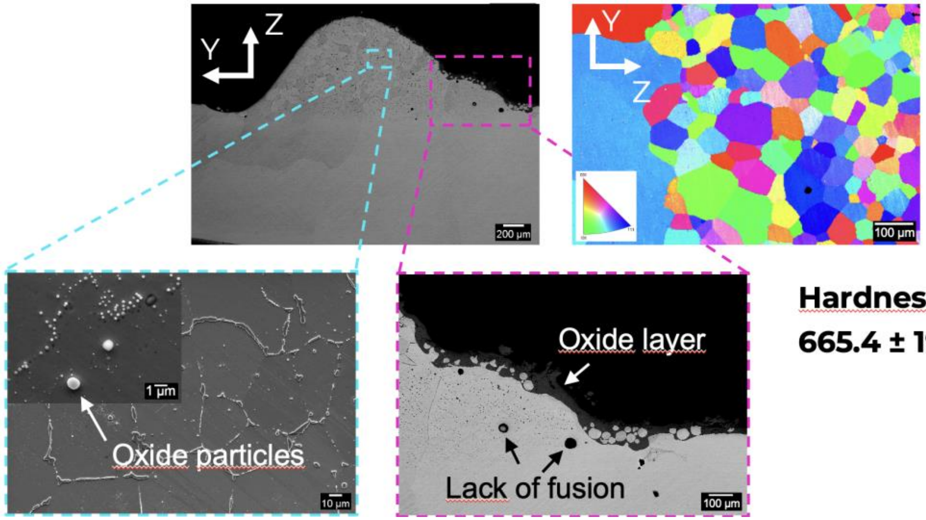








Hardness: 315.3 ± 10.3 $HV_{0.05}$



Hardness:
665.4 ± 19.0 $HV_{0.05}$

Task 10.3 results

Accelerator community response to the use of Additive Manufacturing (3D printing) in the production and repairs of accelerator components

- Targeted survey for accelerator community
- Explored strategies for AM repairs

- Demonstrated AM abilities with exotic material
- Successfully used two DED AM technologies
- Tested several repair strategies

www.pearson.com

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Task 10.4: Development of AM-manufactured superconductive RF cavities

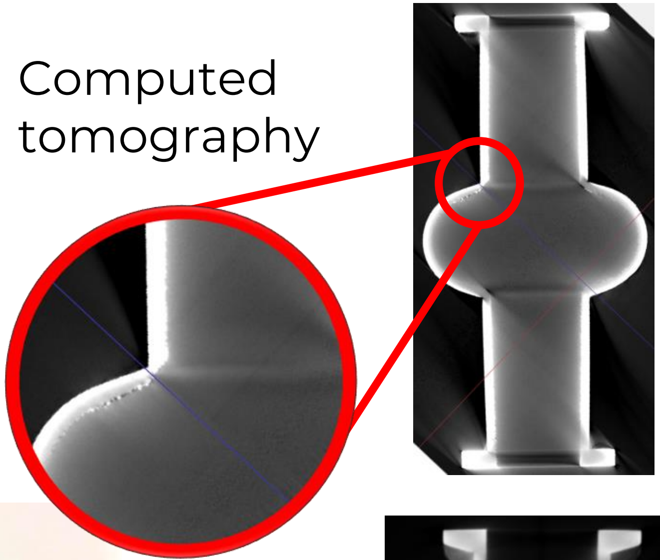
- *Develop the **design approach and test** relevant properties of **AM-manufactured Niobium RF cavities***
- *Develop the **design approach and test** relevant properties of **AM-manufactured Ultra-Pure Cu-made RF** body cavities - coated by a Niobium thin layer at the inner surface*
- *Both to be tested at room and at cryogenic temperature*

Task 10.4 AM of Nb and Cu SRF cavities

Cu

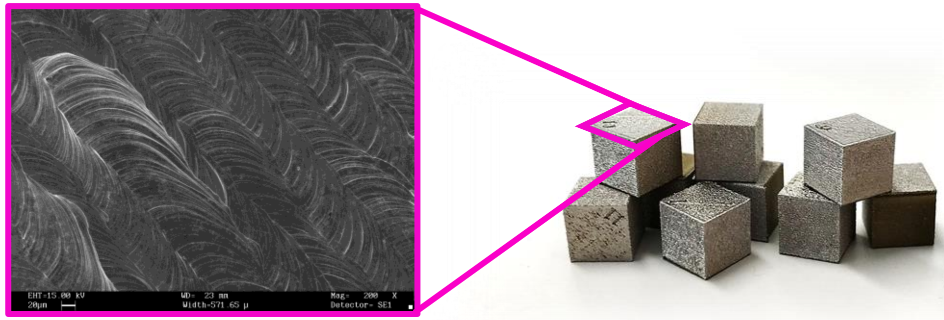
Green laser (515 nm)

Computed tomography

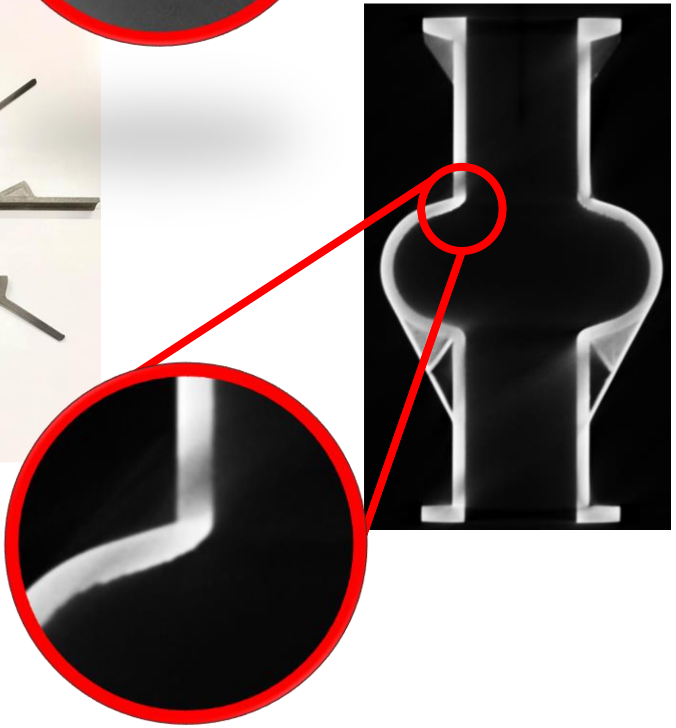


Build direction

Nb



Maximum density achieved: 99.9%



Build direction

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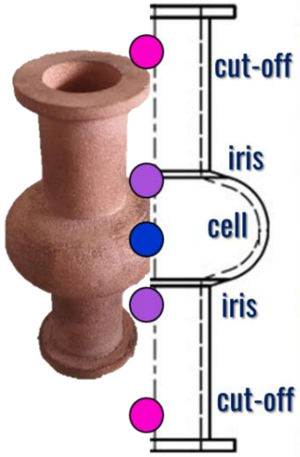
Surface Treatments

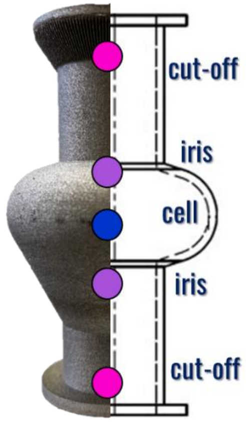
Treatment details	copper T1	copper T2
Mass-finishing @ Rösler Italiana S.r.l.	✔	✔
Vibro-tumbling @ LNL-INFN	VT1: 60 min; 15 µm	✗
	VT2*: 35 min; 23 µm	
Electropolishing @ LNL-INFN	EP1: 80 min; 116 µm	EP1*: 70 min; 92 µm
	EP2: 67 min; 105 µm	✗
Total average thickness removed	259 µm	92 µm

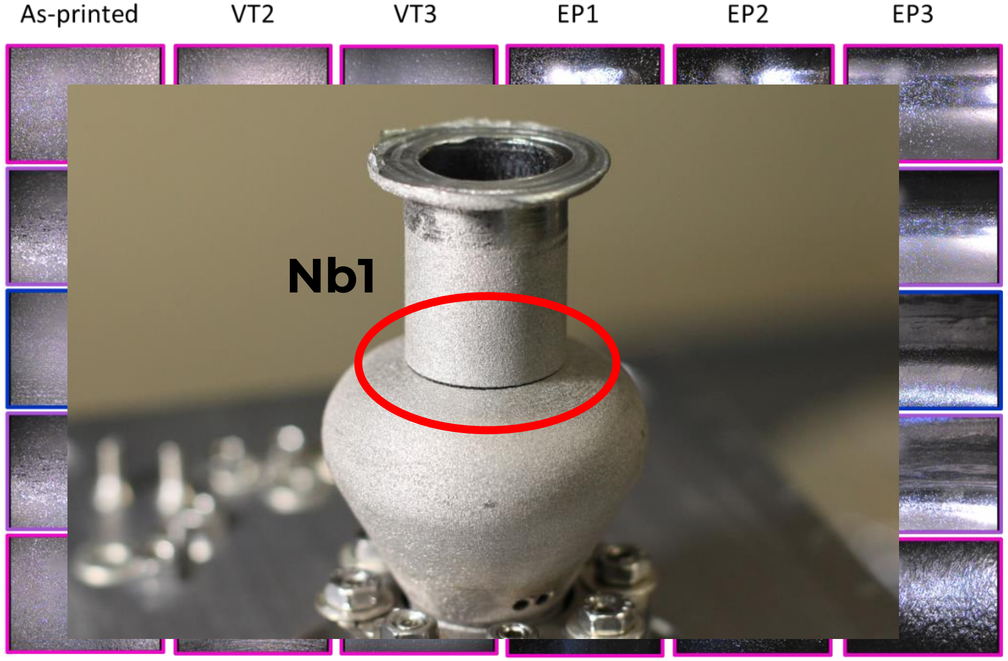
Treatment details	niobium Nb1	niobium Nb2
Vibro-tumbling @ LNL-INFN	VT1: 180 min; 15 µm	VT1: 120 min; 13 µm
	VT2: 300 min; 12 µm	VT2: 90 min; 6 µm
	VT3: 24h min; 18 µm	✗
Electropolishing @ LNL-INFN	EP1: 60 min; 90 µm	EP1: 45 min; 55 µm
	EP2: 90 min; 150 µm	EP2: 45 min; 70 µm
	EP3: 90 min; 150 µm	✗
Total average thickness removed	445 µm	144 µm
Resonant frequency	**5,995 GHz**	**6,04 GHz**
	~20 K ✗	*Test*

RÖSLER finding a better way ...



INFN LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro





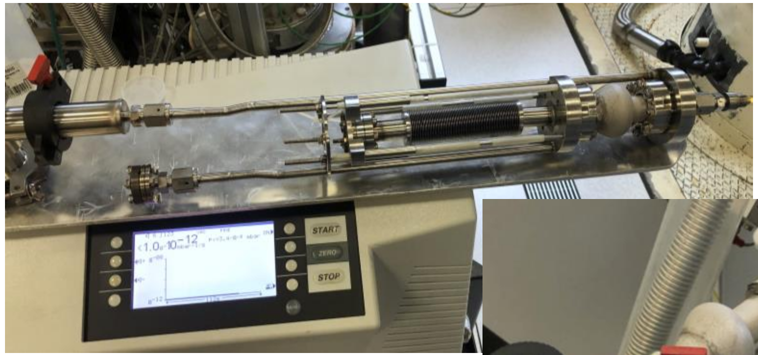
Test Procedure

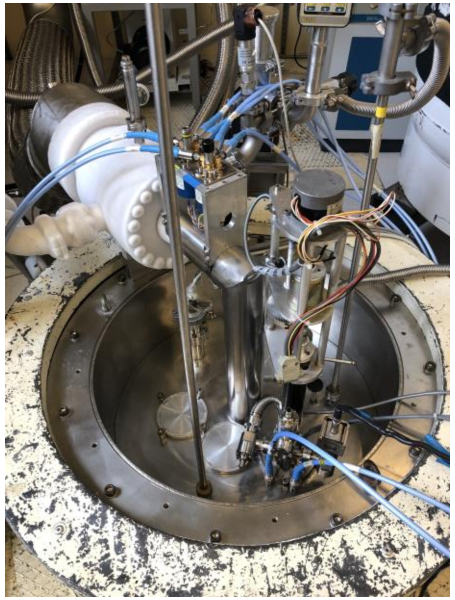
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

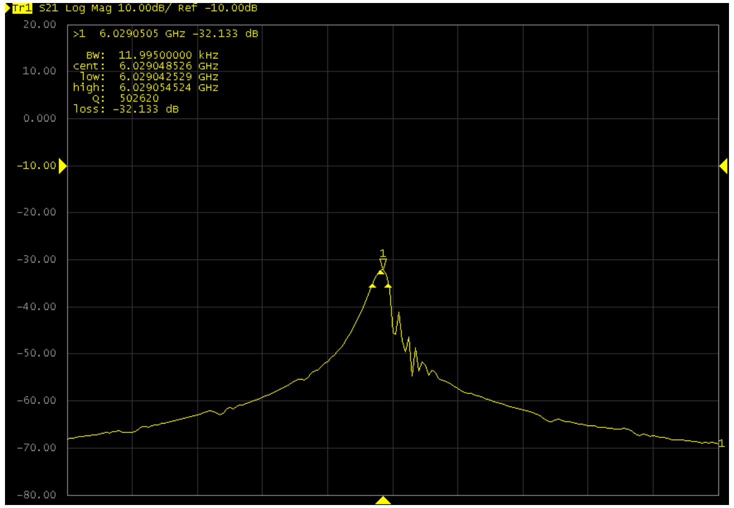
- ✓ AM Production Process
- ✓ Surface treatments

- Multiple leak tests
  - ➢ After each Surface Treatments
  - ➢ before assembly in the cryostat
- Resonant frequency measurement
  - ➢ Measured after S.T. → **6,04 GHz**
- Assembly in the cryostat
- LHe leak test
- Q_{Loaded} @ zero field with Network Analyzer
  - ✓ $Q_{Loaded} \simeq 5,03 \cdot 10^5$

Approximately 5 times better than as-printed ($Q_{Loaded} \simeq 1,36 \cdot 10^5$)
… But still to improve!



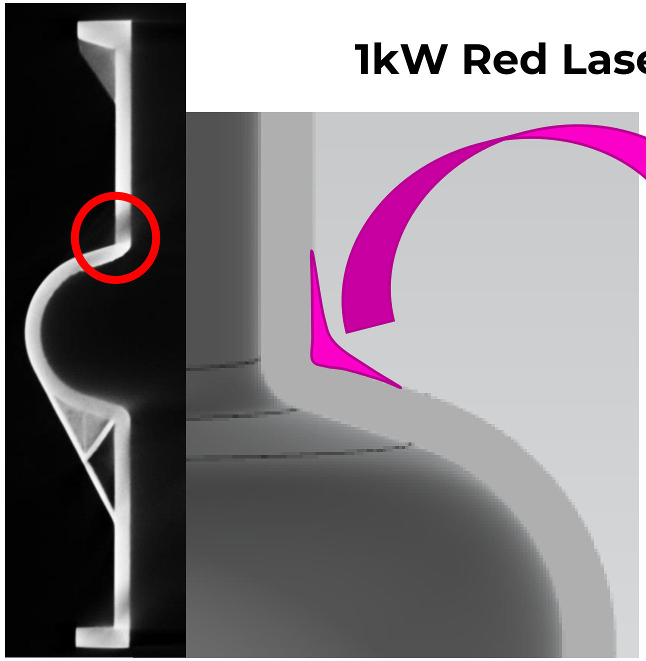


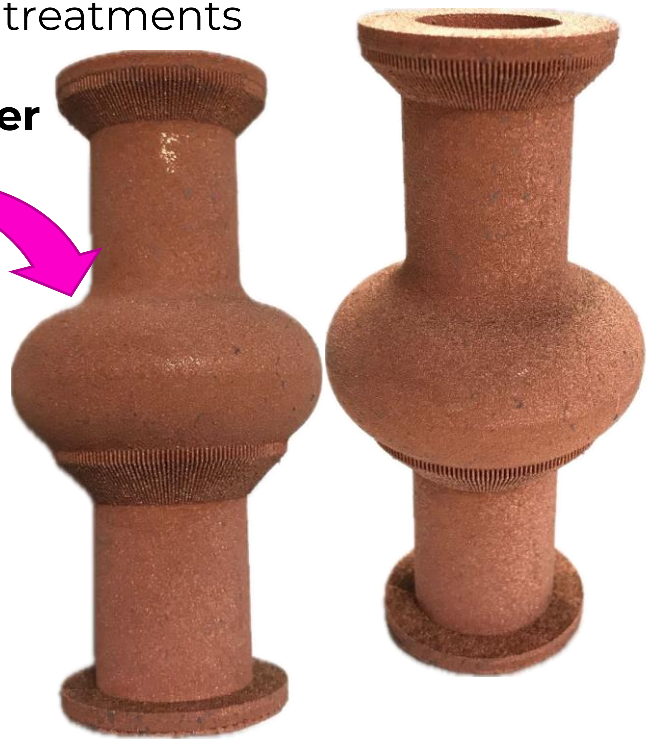


Optimized SRF cavities production and test

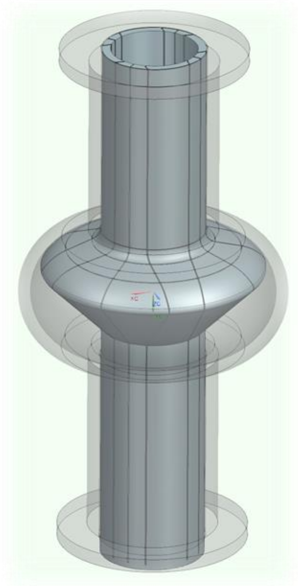
✓ **NEW DESIGN**: Thickened area to ensure resistance in the iris area during surface treatments

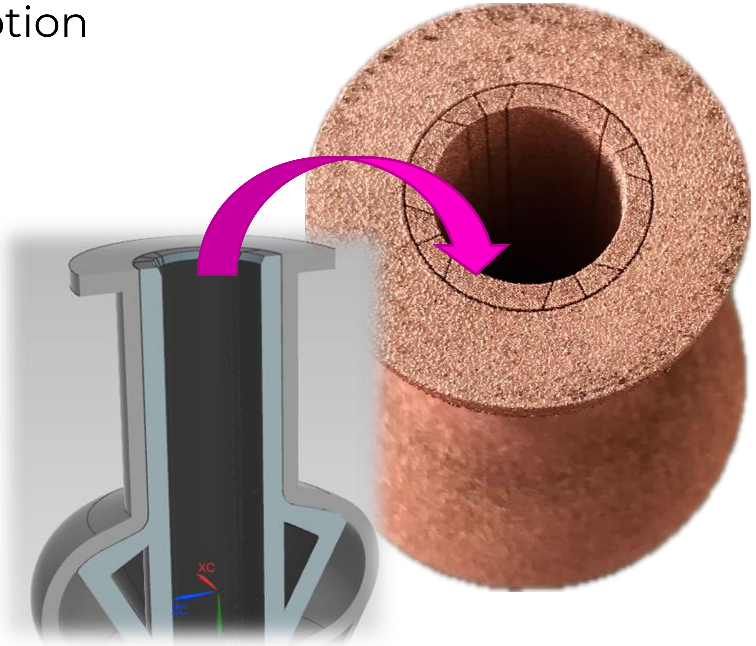
1kW Red Laser





✓ **IMPROVED QUALITY of the INNER as-built SURFACE** Contactless supporting structures and external support optimized to reduce the building time and material consumption





- **SURFACE TREATMENTS** optimization studies of the quantity of material removal are needed to understand the minimum average surface thickness removal and maximum values to avoid rupture @ IRIS area
  - **HEAT TREATMENTS** (in particular annealing) can as well contribute to the final performance
    - optimization of **PRINTING PARAMETERS** & use of machine with **HIGH POWER and SMALL LASER SPOT** can potentially improve the down-skin region quality, thus enhancing the final RF performance.

Recent publications

1. V. Candela, M. Pozzi, E. Chyhyrynets, et al. Smoothening of the down-skin regions of copper components produced via Laser Powder Bed Fusion technology, Int J Adv Manuf Technol (2022), DOI:10.1007/s00170-022-10408-8
2. S. Candela, P. Rebesan, D. De Bertoli, S. Carmignato, F. Zanini, V. Candela, R. Dima, A. Pepato, M. Weinmann, P. Bettini Pure niobium manufactured by Laser-Based Powder Bed Fusion: infuence of process parameters and supports on as-built surface quality, The International Journal of Advanced Manufacturing Technology (2024) DOI: 10.1007/s00170-024-13249-9

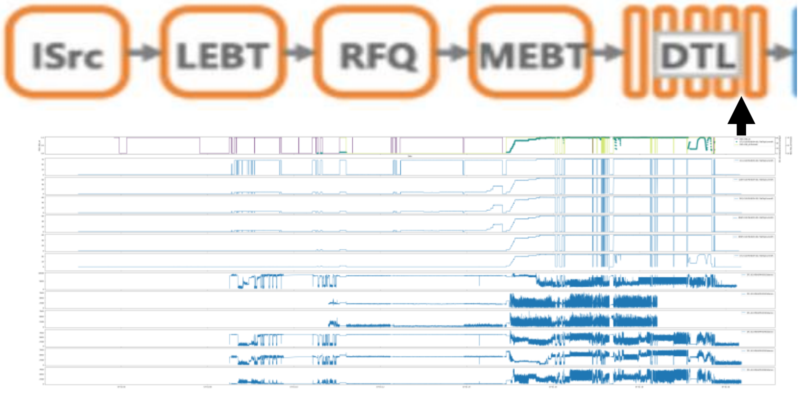
Task 10.6 - highlights
Machine learning techniques for accelerator and target instrumentation

- **developing** low-latency **ML techniques** to control parameters at the *ms* level
- **improving performance** and availability of high-power facilities, with immediate application on ESS or MYRRHA
- **Focus areas** during Period 2
  - ML **algorithm development** and **off-line validation** with ESS data
  - Enabling activities - **preparation of the platform** to support low-latency data communication and ML algorithm execution

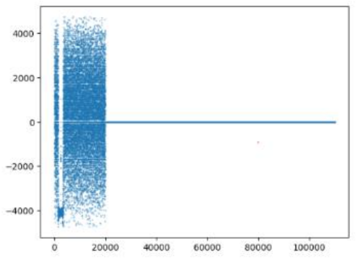
ML Algorithm Development

- **Data from ESS** warm linac commissioning
- Performed data extraction: **~400 GB from archived** dataset (about 10%)
- Performed curation
- Applied K-shape clustering **algorithm** including dynamic time warping
- Developing Random Forest **prediction algorithm**

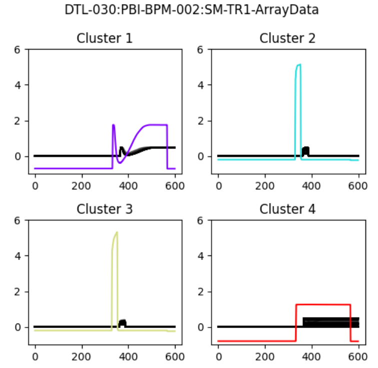
74 MeV protons



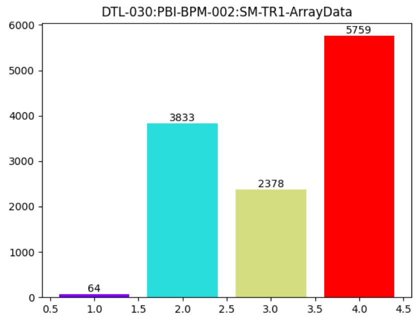
Trend & interlock status over a day



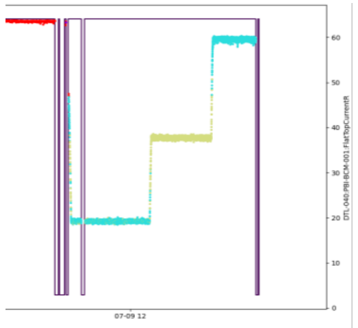
Typical waveform



Time series examples for each cluster type



Distributions over cluster type



Trend plot: Interlock and current with cluster color

Courtesy of Kārlis Berkolds, RTU

I.FAST - coordinates and leverages external activities

- **MOU** signed **with Oak Ridge** National Laboratory covering Machine Learning collaboration and data sharing
- I.FAST 10.6 experience with ESS archiver and data systems is **setting requirements** for upgrades
- Collaboration with WUT in Poland on Minimum-latency optical data acquisition link (Modal), hardware and firmware

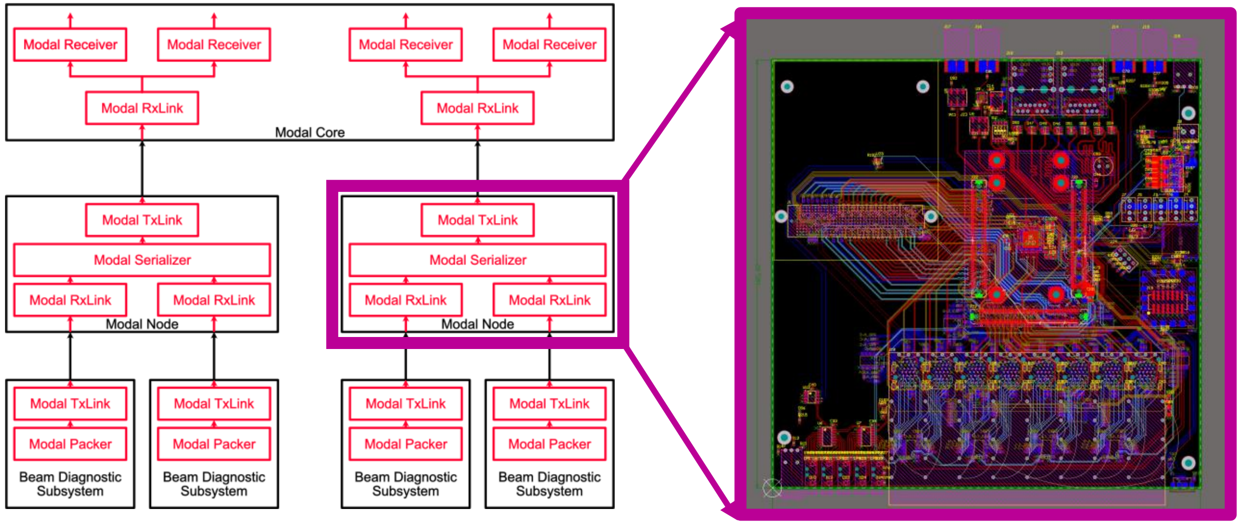
Modal Node designed

Data Flow

FPGA platform for I.FAST ML models (up to ~0.3 Terabits/s)

Data concentrator nodes

Beam Instrumentation Systems installed at ESS



Courtesy of Maciej Grzegrzółka, WUT

Resources – in P2

- No major deviations from the planned resources – all milestones achieved; deliverables are on track – M44/M46
- Strong industrial engagement and significant in-kind contributions

- For some partners higher number of PM than envisaged – *this is technology "heavy weight" WP*
- New partners engaged: TRUMPF and Goethe University – attracting additional resources

Take away messages

- Our **strategy was right** – as predicted **AM is proliferating fast** also in our community. Technology is in our labs and on our *menu* today – several WP's and Tasks are now working with AM

- Challenges and bottlenecks are being addressed as a collective effort and we will be having **more AM and applications in future**

- In the open and collaborative spirit, we are uniting our efforts, exchanging knowledge within I.FAST and far beyond – **strong human and institutional framework** is established

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Thank you for your attention!

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