

METAL ADDITIVE MANUFACTURING FOR ACCELERATOR TECHNOLOGIES (MAAT PROJECT AT INFN)

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Abstract

The MAAT (Metal Additive Manufacturing for Accelerator Technologies) project is a three-year INFN research programme launched in 2026, aimed at establishing Additive Manufacturing (AM) as a validated production route for high-performance accelerator components. MAAT brings together three INFN units: Legnaro (LNL), Padova (PD), and Milano LASA, combining complementary expertise in superconducting RF, materials science, and advanced manufacturing. This paper reports on the activities and preliminary results during the first year of the project, in particular covering:

1. the Design for Additive Manufacturing (DfAM) of 6 GHz cavities produced by Laser Powder Bed Fusion (LPBF).
2. the preliminary tests of the Wire Laser Additive Manufacturing (WLAM) combined with CNC machining for the fabrication of a 1.3 GHz RF cavity prototype in CuCrZr.

INTRODUCTION

The design of next-generation particle accelerators including the Future Circular Collider (FCC-ee) and the Muon Collider imposes unprecedented requirements on critical components such as accelerating cavities, current leads, and cryogenic magnet end spacers. These facilities will demand thousands of highly integrated, geometrically complex, and thermally stable components that conventional manufacturing methods, based on spinning [1], hydroforming, or electron-beam welding, struggle to supply at the required scale, cost, and performance. Additive Manufacturing (AM) has emerged as a transformative technology capable of addressing these challenges. In particular, Laser Powder Bed Fusion (LPBF) enables the direct fabrication of complex internal geometries such as conformal cooling channels, while Wire Laser Additive Manufacturing (WLAM), combined with CNC machining of internal surfaces, offers a hybrid route for large, near net shape components. However, the application of AM to accelerator components remains technologically immature. Critical open issues include high as-built surface roughness incompatible with RF quality factor (Q_0) requirements, residual porosity and powder contamination in internal channels, and the absence of validated end to end manufacturing workflows.

The MAAT project directly addresses these gaps through a coordinated three-year programme structured in three Work Packages (WPs): WP1 Materials Research and Development, WP2 Process Engineering and Design for AM, and WP3 Characterisation and Post-Processing Treatments. This paper presents the status of first year activities (January - May 2026).

PROJECT STRUCTURE

MAAT is organised in three Work Packages, each led by a different INFN unit and addressing a specific technological layer of the AM workflow for accelerator components.

WP1 - Materials Research and Development (Leader: MI-LASA)

WP1 targets the development and optimisation of novel copper-based alloys for AM processes. The key objective is to identify materials that offer superior performance compared to the baseline Oxygen-Free Electronic (OFE) copper, currently the reference material for normal-conducting RF cavities, by improving mechanical strength and high temperature resistance while preserving thermal and electrical conductivity. The alloys of primary interest for MAAT are Cu-Ag, Cu-W, and, as an established reference, Cu-Cr-Zr. Table 1 summarises selected properties compared to OFE copper.

Table 1: Key Properties of Copper Alloys Under Investigation in MAAT

Material	Thermal Cond. (W/m·K)	Tens. Strength (MPa)	High-T Resistance
OFE Cu	~398	220–250	Limited
Cu-Cr-Zr	~320-340	400–550	Good
Cu-W	140-250	200–850	Excellent
Cu-Ag	330-390	200–600	Improved

The first-year activities focus on Task 1.1 (powder blend formulation and characterisation): copper-based alloy

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powders are produced either as pre-alloyed materials or by mechanical blending of pure elemental powders. The powder blends are characterised by Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) to assess particle morphology, size distribution, and phase composition parameters that directly control packing density and, ultimately, component density after printing.

WP2 – Process Engineering and Design for AM (Leader: INFN-PD)

WP2 covers the development of two complementary AM manufacturing pathways for seamless RF cavities and novel cooling channel architectures. The first pathway is the Wire Laser Additive Manufacturing (WLAM) combined with CNC machining a hybrid approach developed at LNL in collaboration with the industrial partner MELTIO [2], based on INFN patent application no. 102024000017647. The experimental forming procedure follows a precise production flow consisting of alternating forming and machining steps. Initially, the cavity is grown to approximately 60% of its final geometry. At this stage, the internal surface is machined using a CNC milling machine to achieve the required surface finish and dimensional accuracy. Subsequently, the remaining 40% of the cell geometry is deposited by WLAM, and a final CNC machining pass is performed on the complete internal surface. This four step sequence (60% cell wire printing, internal cell machining, 40% cell wire printing, final cell machining) ensures that all internal RF surfaces meet the stringent electromagnetic requirements while exploiting the geometric freedom of additive manufacturing. The inert manufacturing cell under development by MELTIO is essential to prevent oxidation during copper and copper alloy deposition. The first-year priority is the fabrication of a 1.3 GHz cavity prototype in CuCrZr (Milestone M1.2, Month 8). The second pathway, coordinated by PD and MI-LASA, uses Laser Powder Bed Fusion (LPBF) to produce 6 GHz cavities [3] and current leads featuring fully integrated cooling channels. The LPBF workflow encompasses three main phases. In the Project Phase, design freedom is exploited through topology optimisation software to create lightweight yet strong structures and to integrate internal cooling channels directly within the component; the output is an STL file ready for processing. In the Data Preparation phase, the digital design is prepared for the physical process: the optimal part orientation is defined, supports for overhanging surfaces are designed (including innovative strategies to improve as built internal surface quality), and process parameters are assigned before the file is sliced into a printer readable format. In the Production and Post Processing phase, a laser selectively melts the metal powder layer by layer inside the build chamber; once the part is built and the platform is cleaned, the components undergo heat treatment to relieve internal stresses, part removal and cleaning, and surface finishing to meet the functional requirements.

WP3 – Characterisation and Post-Processing Treatments (Leader: INFN-LNL)

WP3 ensures that manufactured components meet the stringent RF, thermal, vacuum, and quality standards required for accelerator applications. The post processing strategy developed at LNL is multi step: an initial vibrotumbling stage homogenises surfaces and removes macroscopic asperities, followed by Plasma Electrolytic Polishing (PEP), which achieves very low surface roughness levels and chemically stable surfaces compatible with ultra-high vacuum (UHV) requirements. Chemical cleaning protocols are also being developed to remove residual LPBF powder from narrow internal cooling channels. Non-destructive inspection by X-ray Computed Tomography (CT) is used to verify internal structural integrity.

PRELIMINARY RESULTS

WP1 – Powder Blend Formulation

Powder blend activities were initiated at INFN-PD and INFN-LNL in Q1 2026. Cu-Ag blends with Ag content ranging from 0.1 to 6 wt% and Cu-W blends with W fractions of 20-50 wt% are under preparation. A dedicated powder mixer installed at LNL enables controlling blending without contamination. Moreover, SEM and XRD analysis are planned at LNL to confirm the final blend composition.

WP2 – WLAM+CNC Cavity Prototype

The WLAM+CNC forming procedure (Fig. 1) is being developed by LNL in collaboration with MELTIO. The four-step process sequence: 60% cell wire printing, internal cell machining, 40% cell wire printing, and final cell machining has been validated at the prototype level in stainless steel prior to the start of MAAT. The 1.3GHz stainless steel cavity is reported in Fig. 2, Fig. 3.

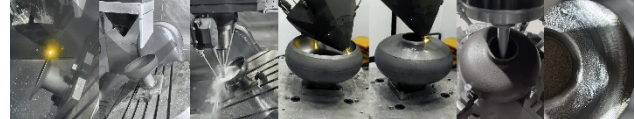


Figure 1: production flow of creating the 1.3 GHz cavity prototype.



Figure 2: lateral view of the 1.3 GHz stainless steel cavity prototype



Figure 3: top view of the 1.3 GHz stainless steel cavity prototype after the final CNC machining

The specification and procurement process for the first 1.3 GHz CuCrZr cavity has been initiated continuing the collaboration with MELTIO. The cavity design follows the standard TESLA 1.3 GHz single-cell geometry to allow direct benchmarking against the established state of the art. The novel MELTIO inert manufacturing cell, enabling WLAM deposition of copper and copper alloys without oxidation, is a key enabling technology for this milestone and is currently working for the prototype production. The delivery of the first CuCrZr prototype is expected by Month 8 of 2026.

On the LPBF side, the three phase production workflow (Project, Data Preparation, Production and Post-Processing) is being established in parallel at MI-LASA and PD. At MI-LASA, the EOS AMCM M290-1 1 kW system dedicated to reflective materials including pure copper is being used to produce the project components. First 6 GHz copper cavity prints incorporating purpose designed support structures are under development (Fig. 4); the support geometry is conceived to stabilise the build process and simultaneously improve internal surface homogeneity by promoting controlled heat dissipation during solidification, resulting in superior surface quality as built. At PD, the DfAM activity for integrated cooling channel geometries is progressing using finite-element thermal simulations, with the goal of delivering the design reports for 6 GHz cavities and current leads by Month 12 of 2026.

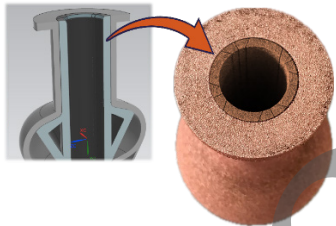


Figure 4: design of internal support structures under development for the 6 GHz cavities (left) and Cu cavity 3D printed with internal supports (right)

WP3 – Post-Processing and Inspection Preparation

At LNL the CT scan qualification of the first 1.3 GHz stainless steel cavity prototype has been done in collaboration with the external metrology provider (Labormet due srl), evidencing both defects in the internal walls of the cavity (Fig. 5), and differences in dimensions between the product built and the 3D CAD model, ranging from 1 to 2 mm along the axis of the cavity (Fig. 6). The dimensional difference is accounted for by the material's contraction after the laser melting. To produce the CuCrZr 1.3 GHz cavity, MAAT includes an initial phase of printing parameter simulation to compensate for the material's contraction effects.

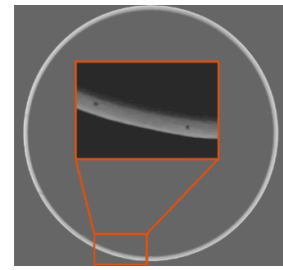


Figure 5: defects presents in the internal walls of the 1.3 GHz stainless steel cavity

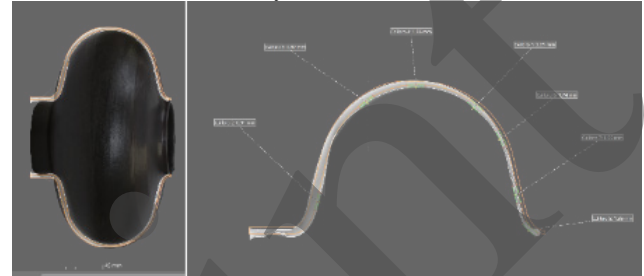


Figure 6: dimensional comparison between the product built and the 3D CAD model

CONCLUSIONS

MAAT is currently in the early phase of a three-year research project. The results obtained from the first 1.3 GHz stainless steel cavity prototype have identified key areas for improvement in the component manufacturing process. Simulations accounting for material contraction during metal wire melting will be essential for producing cavities that meet the required dimensional specifications.

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