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# PURE COPPER AND STAINLESS STEEL ADDITIVE MANUFACTURING OF AN IH-TYPE LINAC STRUCTURE*

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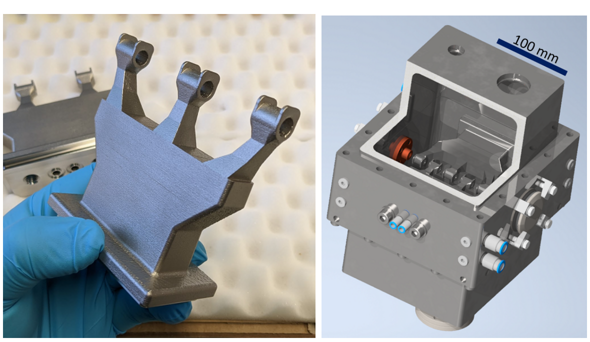
*Abstract*

Additive manufacturing ("AM" or "3D printing") has become a powerful tool for rapid prototyping and manufacturing of complex geometries. A 433 MHz IH-DTL cavity has been constructed to act as a proof of concept for additive manufacturing of linac components. In this case, the internal drift tube structure has been produced from 1.4404 stainless steel, as well as pure copper using AM. The Prototype cavity, as well as stainless steel AM parts have been copper plated. We present results from low level rf measurements of the cavity with and without copper plating, as well as the status of preparations for high power rf tests with a 30 kW pulsed power amplifier.

## INTRODUCTION

Additive manufacturing (AM) of metal parts will provide an interesting new way to manufacture accelerator components. As technology is evolving, the quality and accuracy of parts manufactured this way is improving. The technology especially allows for more complex parts design, including extensive water cooling of components. Recently, a number of studies on the topic of AM for linear accelerator components have been published [1–6].




(a) (b)

Figure 1: Overview of the cavity geometry and printed parts. (**a**) First 3D printed girder drift tube structure. (**b**) Cross section of the assembled cavity model.

Based on these promising results, we aim to evaluate the suitability of AM parts for direct manufacturing of normal conducting linac structures. To that end, a reproduction of the beam pipe vacuum tests in [2, 3] was performed [7, 8]. Motivated by these successful preliminary experiments, a prototype cavity with a fully printed drift tube structure was constructed (see Fig. 1). The cavity is designed to be UHV capable and includes cooling channels reaching into the stems of the drift tube structure for power testing with a pulsed 30 kW rf amplifier.

The prototype cavity was designed for a resonance frequency of 433.632 MHz, which is a harmonic of the GSI UNILAC operation frequency [9]. In combination with a targeted proton beam energy of 1.4 MeV this scenario allows for a compact accelerator at the limits of feasibility and is therefore a good benchmark for the new approach. For the idealized design model, the simulated effective shunt impedance is $Z_{eff} = 287.13\,\mathrm{M\Omega/m}$, showing the high efficiency of such an IH-type structure.

Since the first construction of the cavity in late 2020 to early 2021, several experiments have been conducted to evaluate certain aspects of the cavity suitability for linac operation. First results from materials testing, vacuum testing (successfully demonstrated $1.4 \times 10^{-7}$ mbar) and low level rf measurements can be found in [7, 8, 10]. In the following, we will focus on the progress made since the reports in [10].

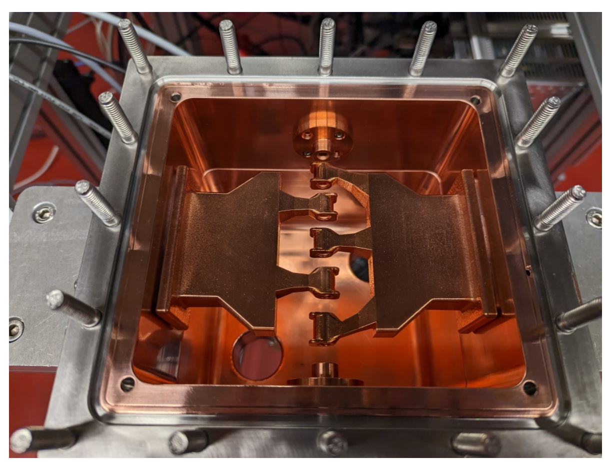


Figure 2: Copper plated cavity with copper plated stainless steel AM structures mounted.

## SURFACE FINISHING INVESTIGATIONS

The initial batch of AM IH-structures has been polished in a slide grinding machine. Following the surface polishing, the structures have been copper plated with an approximate layer thickness of 50 µm. Optical inspection shows a very clean result of the copper plating [10]. Additionally, the entire cavity has been copper plated and assembled for testing (see Fig. 2).

After these initial polishing attempt for the first printed parts, it became clear, that more advanced post-processing techniques will be required to ensure good surface quality

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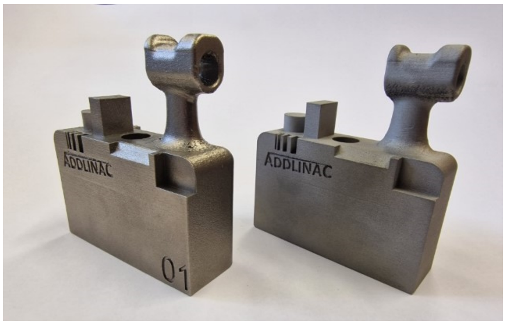


Figure 3: Test geometries printed from stainless steel by a contractor (left), as well as in a high quality setting by colleagues from THM Friedberg (right).

in combination with good dimensional accuracy. Therefore, a dedicated program to investigate the surface finishing quality and performance was started. To this end, a test geometry was designed, that includes the characteristics of the drifttube structure, while also providing well defined geometric features that can be utilized to asses the surface roughness of the part, as well as the dimensional material loss after polishing. These test parts were manufactured on two different AM machines with different process settings (see Fig. 3). Pairs of these test parts will be post-processed with different techniques to determine the best outcome for linac applications.

## GIRDER DESIGN IMPROVEMENTS

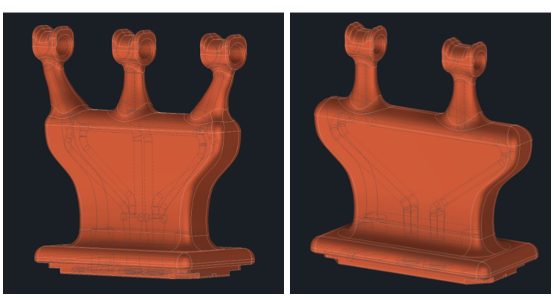

Figure 4: CAD models of the improved geometry for the AM IH-structure.

From polishing and copper plating tests, as well as rf simulations, it was clear, that the original geometry of the printed parts (see Fig. 1) would not be suitable for high power testing. Therefore, a significant redesign of the structure was performed. The new design significantly is smoothing the overall geometry without sacrificing the rf performance (see Fig. 4). Some hard to reach corners in the model were eliminated to better facilitate post-processing (polishing) of the parts. Peak fields for the new design are significantly reduced, which will be beneficial for copper plating, as well as high power rf operation. A CAD view of the improved geometry is shown in Fig. 4. The new geometry also includes improved cooling channels for better flow in the thin stems on the top of the structure.

Figure 5: New geometry printed in 1.4404 stainless steel. Bottom surface and beam aperture have been CNC machined.

Figure 5 shows the new geometry printed from stainless steel. Bottom sealing surfaces and the beam aperture have been CNC milled. The remaining surface of the part will be polished and copper plated, as soon as a suitable technique for the surface finish has been identified.

Figures 6 and 7 show the parts printed from pure copper before and after CNC post-processing. In this case, the whole part was CNC machined to produce the sealing surfaces, as well as to remove the outermost layer of the printed part (100 µm). The results show a near mirror finish of the pure copper parts. While these results are certainly impressive, machining the whole surface of the part is an expensive option and may also not be possible for all geometries. Following tests with copper parts will focus on polishing instead of CNC post-processing, to produce the most cost-effective solution.

Figure 6: New geometry printed from pure copper before CNC post-processing.

## LOW-LEVEL RF TESTS

At first, low-level rf measurements were performed with a network analyzer to confirm the frequency and Q-factor of the cavity without any copper plating. For comparison, CST simulations were performed with the final design CAD geometry of the components, to get as close to the manu-

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Table 1: Comparison of CST Microwave Studio rf simulation based on the final CAD model and low level rf measurements for different configurations of unplated steel, copperplated steel and bulk Cu parts. Cavity: (C), AM girder-drifttube structure: (G), new geometry AM parts (GV3).

| Parameter | Simulation | Measurement steel (C+G) | Measurement steel (C), plated (G) | Measurement plated (C+G) | Measurement plated (C), Cu (GV3) |
|---|---|---|---|---|---|
| $f_{res}$ | 433.445 MHz | 433.524 MHz | 427.3 MHz | 428.33 MHz | 436.03 MHz |
| $Q_0$ (steel) | 1321 | 1132 | - | - | - |
| $Q_0$ (copper) | 8715 | - | 2600 | 7076 | 5337 |
| $Z_{eff}$ (copper) | 241.2 MΩ/m | - | - | - | - |

factured cavity as possible. Simulations were performed with an electrical conductivity of $\sigma_{Cu} = 5.8 \times 10^7$ S/m and $\sigma_{1.4404} = 1.3 \times 10^6$ S/m for copper and stainless steel respectively.

Thanks to the modular design of the prototype cavity, several combinations of cavity and drifttube structures have been performed since then. Table 1 compares the simulation results with the performed measurements. For the original components, without any copper plating, the measured resonance frequency is only 79 kHz higher than simulated. The measured unloaded quality factor of the cavity $Q_0 = 1132$ is also reasonably close to the simulated value of $Q_0 = 1321$ for stainless steel. Calculating the quality factor for stainless steel relies on the actual conductivity value of the steel used during manufacturing an can therefore only be approximated based on spec-sheets.

Figure 7: New geometry printed from pure copper after CNC post-processing.

Subsequent measurements with copper plated parts will be compared to the theoretical $Q_0 = 8715$ for a cavity made fully of copper. As can be seen in Table 1, the resonance frequency in these measurements is lower than expected. This can be explained by the geometrical changes to the parts due to copper plating and was reproduced in CST Simulations for some cases. All measurements were performed without any tuning bodies in the cavity. The first of these measurement was performed with the copper plated drifttube structure mounted in the plain steel cavity (Table 1, "steel (C+G)"). As expected, the quality factor was improved by the increased conductivity of the AM structures. With a quality factor of over 7000, the best results so far were achieved with the combination of copper plated cavity and copper plated steel AM parts. The most recent results were produced with the pure copper AM parts inside the copper plated cavity. The measured quality factor is much lower than expected, which may indicate a lower conductivity than expected. Simulations showed no difference in quality factor for the different girder geometries. Further experiments to investigate this behaviour are necessary. Similar results were reported in [11] for a 3 GHz DTL. So far, the AM stainless steel parts with copper plating show the best performance of the tested parts.

## RF COUPLER PROTOTYPE

As the largest coupling port on the cavity is CF40, a compact rf coupler is needed for power tests. A prototype for a CF40 power coupler has been designed and tested (see Fig. 8. Critical coupling (no reflections) could be demonstrated in low-level measurements.

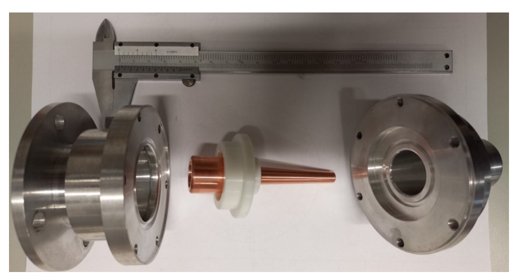

Figure 8: CF40 power coupler prototype disassembled.

## CONCLUSION

Most recent vacuum tests showed, that a cavity pressure of $1.4 \times 10^{-7}$ mbar could be reached without issue. First low-level rf measurements of the steel parts confirmed the operating frequency and also showed good agreement for the stainless-steel Q-factor of the cavity. Detailed measurements with different part combinations show a promising trend for the usability of 3D printed parts as main components for accelerators. For the first time we could also test printed parts from pure copper, which will probably be the most promising development for manufacturing of linear accelerators.

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