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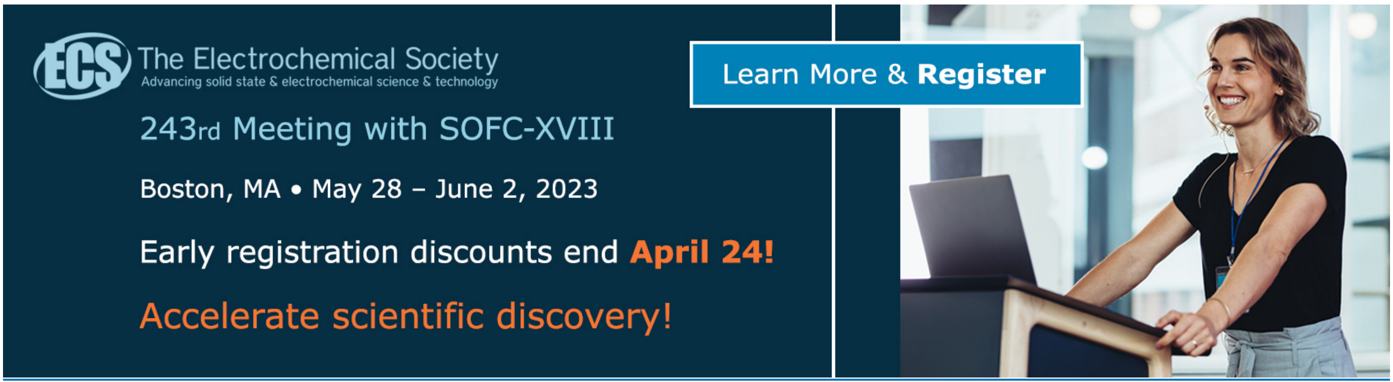

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Evaluation of geometrical precision and surface roughness quality for the additively manufactured radio frequency quadrupole prototype

T Torims[1], A Cherif[2], N Delerue[6], M Foppa Pedretti[3], D Krogere[1], T Otto[7], G Pikurs[1], M Pozzi[3], A Ratkus[1], M Thielmann[4], M Vedani[5], M Vretenar[2] and P Wagenblast[4]

[1] Riga Technical University, Riga, Latvia
[2] CERN, Geneva, Switzerland
[3] Rösler Italian S.R.L, Concorezzo, Italy
[4] TRUMPF Laser und Systemtechnik GmbH
[5] Politecnico di Milano, Italy
[6] IJCLab, Orsay, France
[7] TalTech, Tallinn, Estonia

E-mail: `toms.torims@rtu.lv`

Abstract. A multidisciplinary collaboration within the I.FAST project teamed-up to develop additive manufacturing (AM) technology solutions for accelerators. The first prototype of an AM pure-copper Radio Frequency Quadrupole (RFQ) has been produced, corresponding to ¼ of a 4-vane RFQ. It was optimised for production with state-of-the-art laser powder bed fusion technology. Geometrical precision and roughness of the critical surfaces were measured. Although the obtained values were beyond standard RFQ specifications, these first results are promising and confirmed the feasibility of AM manufactured complex copper accelerator cavities. Therefore, further post-processing trials have been conducted with the sample RFQ to improve surface roughness. Algorithms for the AM technological processes have also been improved, allowing for higher geometrical precision. This resulted in the design of a full 4-vane RFQ prototype. At the time of the paper submission the full-size RFQ is being manufactured and will undergo through the stringent surface quality measurements. This paper is discussing novel technological developments, is providing an evaluation of the obtained surface roughness and geometrical precision as well as outlining the potential post-processing scenarios along with future tests plans.

1. RFQ by additive manufacturing

The RFQ is a crucial accelerator component down-stream the particle source, providing simultaneous and efficient focusing, bunching and acceleration of a particle beam before injection into the linear accelerator [1]. Conventionally it is manufactured from highly conductive materials and consists of four complex shape segments with modulated vanes. To ensure optimum beam optics and radio-frequency properties, all internal surfaces of the RFQ are designed with high-precision tolerances and fine surface roughness parameters. Consequently, the standard RFQ manufacturing routine is complex; each sequence is costly, time consuming and requires expensive technological operations. Among other things, this involves series of multiple high-precision machining operations followed by specialized brazing and material stress-release treatment [2, 3]. Thus, there is an opportunity to re-evaluate established manufacturing approaches and to consider other emerging technologies.

Additive Manufacturing (AM) is a natural candidate, as one of the enabling technologies that has reached the required maturity level to be applied within the accelerator community. The comprehensive study carried out by the I.FAST project confirms the opportunities provided by AM technology [4, 5]. Initial results of the survey have revealed that metal AM activities within the community started already in 2007 and since, the number of applications is growing exponentially. This is explained by the virtues of AM technology: it is accessible, has wide applications within aerospace, medical and automotive industries and is changing the technological paradigm and way of thinking within the engineering wing of the accelerator community. Indeed, AM is offering valuable opportunities, such as the capability to work with a wide range of materials and to provide new design options [6]. Proliferation of the AM has led to the standardisation of this technology. For instance, today the ISO 52900:2021 standard [7] provides for general terms and common language for the growing AM community. Subsequently, series of the standards are being compiled within the Guide to AM Standards [8].

Furthermore, it has been demonstrated [9] that AM can contribute to the manufacturing routines of the RFQ's, e.g., is enabling for design optimisation and improved general properties. The biggest advantage is that AM allows for the RFQ to be built in a single piece, thereby avoiding the complex technological operations, and permitting the design of more efficient internal cooling channels. Recent attempt to produce with AM the pure copper drift tube linac components, is showing that cavity parameters (e.g. quality factor Q and shunt impedance per unit length R_L) are of comparable values to the conventionally machined elements [10].

At the same time, it is important to note that the pure copper, applied for RFQs, is a challenging material for laser-based AM processes itself. It requires state-of-the-art equipment and expertise which is not yet self-evident within the community. For instance, the high thermal conductivity of copper also results in rapid heat diffusion away from the melt area, generating local thermal gradients, hence the risk of the significant residual stresses and part distortion [9].

The limited energy absorption provided by infrared laser radiation on copper is another issue to consider [11]. In the case of laser powder bed fusion (L-PBF) technology, due to the high reflectivity of copper, most of the energy provided by the laser during manufacturing is reflected instead of being absorbed by the powder. This may lead to incomplete fusion of the powder when employing conventional infrared fibre laser sources [12 – 14]. It has been recognized [15 – 17] that increasing the laser power above 500 W can lead to increased part densities. However, high-power lasers can also generate unstable melt tracks due to the different absorptivity of the powder and the molten material. In addition, the large amount of reflected energy that irradiates the optical mirror of the machine during the printing process may damage it [18].

There have been three promising strategies to solve energy absorption issue: increase laser power up-to 1 kW; increase the absorption of the particles through coating; or switch to a green laser source where absorption is almost three times higher. Recent research results [11, 19] are showing that the use of green laser sources are effectively enabling higher absorbance for copper. In case of L-PBF, this leads to relative material densities exceeding 99.8% and which almost eradicates the indicated drawbacks.

2. The additive manufacturing process and equipment

The above-mentioned approach has led to the development of the TruPrint1000 Green Edition by TRUMPF - this machine is based on a modified L-PBF system with an integrated TruDisk1020 1kW frequency doubled 515nm thin disk green laser as energy source for the copper powder bed fusion of 10-45μm particle size (m4p PureCu). At 1 μm wavelength the absorptivity of copper powder is below 10%, whereas at around 500μm it rises 6x to ~60% [20].

With short wavelength, the fusion process becomes more stable and productive in the resulting quality of the parts, compared to a 1 μm laser process, yielding density of > 99,5% and electrical conductivity of >100% International Annealed Copper Standard - IACS (corresponding to >58 MS/m). It is important to note that this matches the properties of conventionally manufactured annealed electrolytic-tough pitch (ETP) copper [21] and falls well within the requirements set for the RFQ, i.e. >90% IACS. The very first demonstration of an AM pure-copper RFQ, corresponding to ¼ of a 4-vane, has been performed on TruPrint1000 Green Edition at IWS Fraunhofer [9].

2.1. Design and manufacturing of the full-size RFQ

Subsequently, collaboration within the I.FAST project continued with the design of full size 4-vane RFQ. This demonstrator has been manufactured by TRUMPF on the extended AM system prototype like the one described in [22], yet with a much larger build volume of 300 mm in diameter and 400mm in height. This meant a full RFQ segment could be built, with the cross-section of Ø148 mm and 248 mm in length (see figure 8).

The system is based on the general design of a TruPrint 5000 and is similarly equipped with a TruDisk 1020. Process chamber inertisation down to 100ppm of oxygen and an efficient gas flux system for the removal of processing by-products are key enablers to achieving the high material quality in a highly productive process with melting rates of typically 16-21 cm^3/h.

Thanks to the availability of the state-of-art AM technological equipment and experience acquired with ¼ sample RFQ sections design, production and measurement results the following major technological improvements were done (see figures 1 and 2):

- High resolution modelling and increased mesh-size;
- Flanges for the vacuum tests;
- Orifices for the RF tests;
- Enhanced internal lattice structures;
- Design optimisation of the cooling channels.

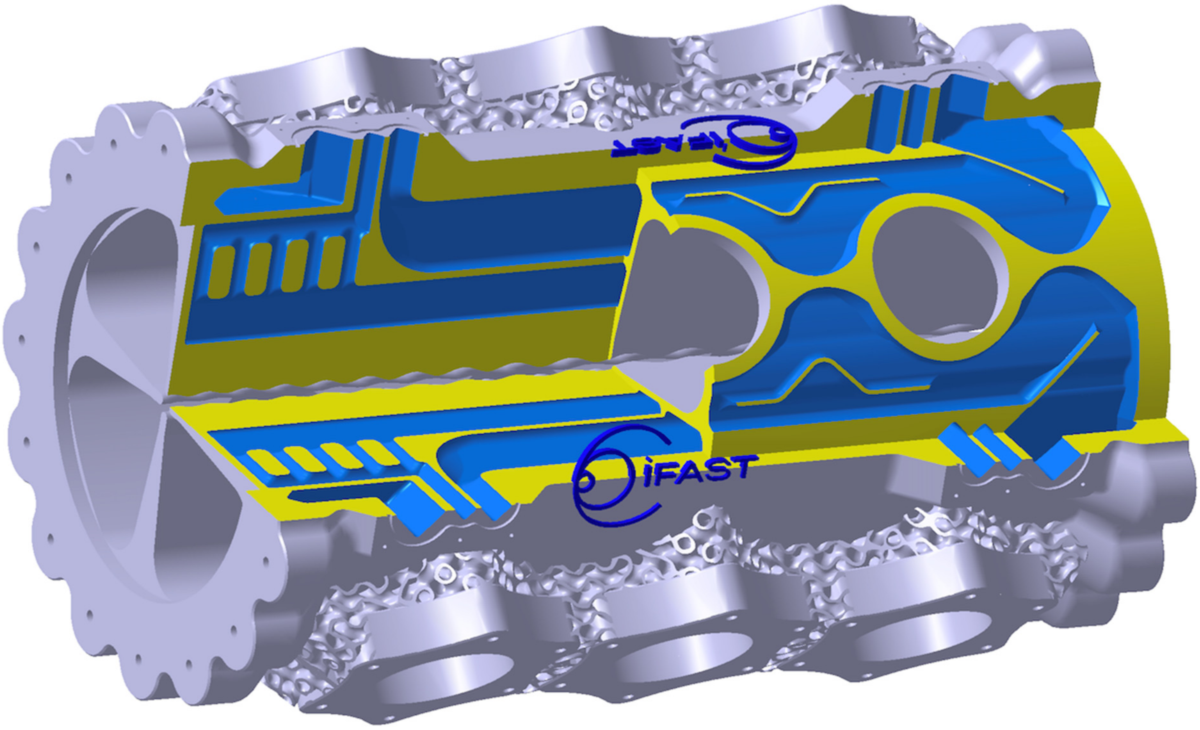

Figure 1. Full-size optimised RFQ.

The overall build duration for the full RFQ demonstrator at TRUMPF amounted to □110 hours, with 6400 layers of 40μm layer thickness and the laser power of 650W with scan velocity at 800 mm/s.

3. Post-processing of RFQ

The initial results of [9] revealed that high-precision accelerator components require post-processing technological operation to ensure the stringent surface roughness requirements of R_a=0.4 μm.

Two sets of the ¼ of a 4-vane were manufactured, measured and then one of them was cut into the smaller segments to allow for the post processing with the three different technologies.

3.1. Conventional surface mass finishing

This process was performed by Rösler in vibrating and rotating machines, where samples have been inserted together with abrasive media, water, and compounds. The surface finishing has been obtained mainly by the mechanical abrasion of the media on the component, due to the relative speed among them. For the finishing of ¼ RFQ a three-step process was designed:

1. Grinding: 12h with Rösler media RXX 07/14 ZS and compound ZF 113 at 1% vol.
2. Smoothing: 6h with Rösler media RKH/4 10/20 DK and compound ZF 113 at 1% vol.
3. Polishing: 1h with Rösler media RP 3/5 ZS and compound ZF 113 at 1% vol.

3.2. Chemically assisted surface finishing

Differently from conventional processes, the surface machining was obtained through the combination of the mechanical abrasion on the surface and the chemical reactions mediated by the compound. Likewise, a three step process was applied - grinding: 1h with Rösler media RXX 07/14 ZS and compound CMP 03/21 L + steps 2 and 3 - idem to the above - see the figure 2.

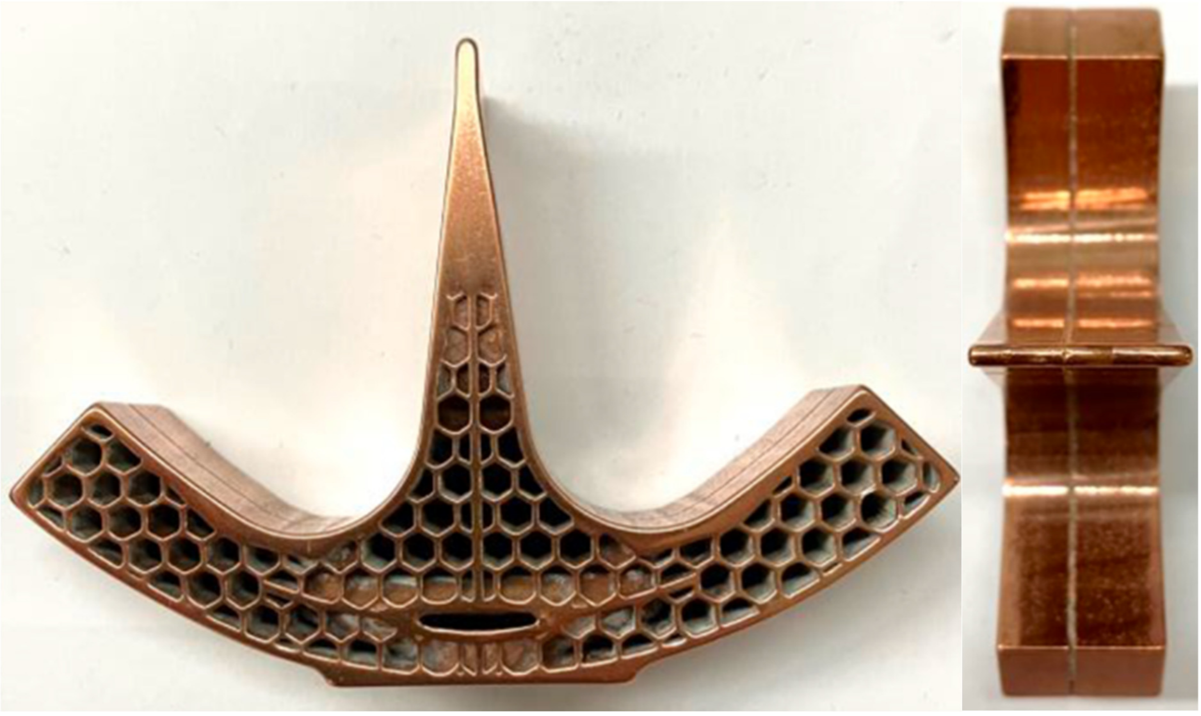

Figure 2. ¼ RFQ sample - chemically assisted finishing.

3.3. High precision surface finishing with MMP TECHNOLOGY®

This technology is based on a mechanical-physical-catalyst surface treatment and was applied to ¼ RFQ which was placed inside a treatment tank [23].

4. Evaluation of geometrical precision and surface roughness

4.1. Geometrical accuracy

The metrology measurements were performed at Fraunhofer IWS with the 3D scanner ATOS GOM Core 135 (see figure 3) and subsequently at CERN by the EN-MME-MM group using Creaform METRASCAN Elite Black and ZEISS Prismo Ultra 12-18-10 (see figure 4). Two sets of measurements were taken: before and after of the post-processing steps.

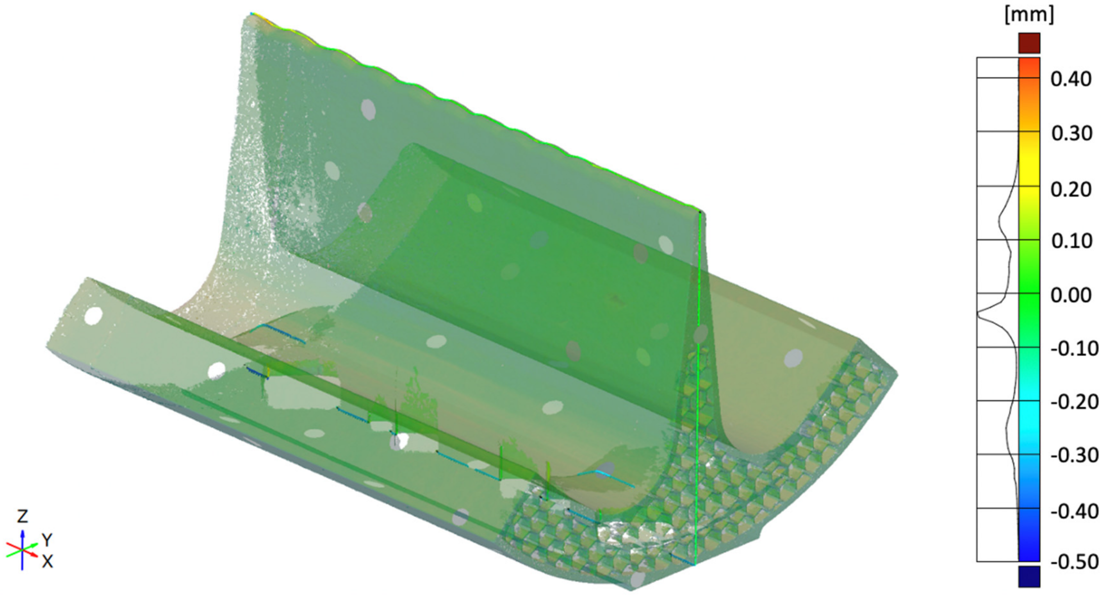

Figure 3. Deviation measurements of ¼ RFQ sample No.1 – prior post-processing.

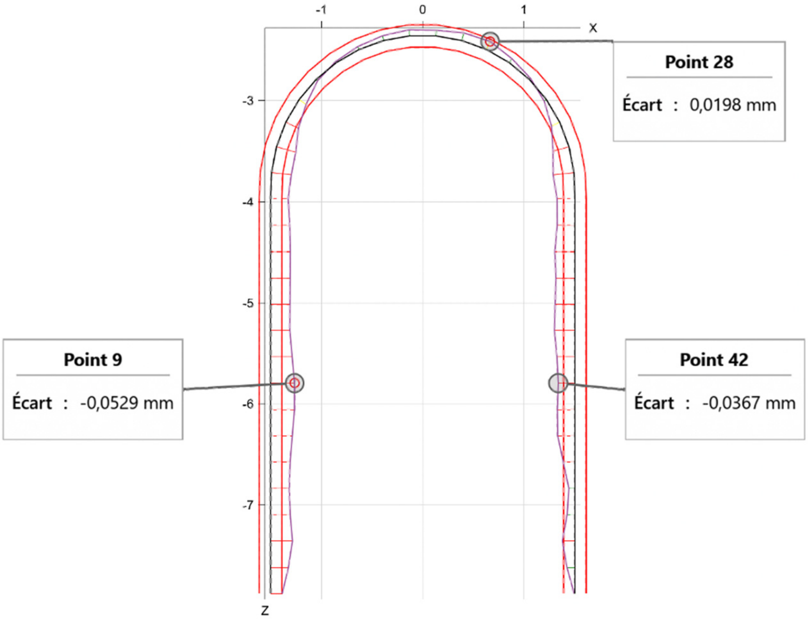

Figure 4. Vane-tip and side measurements of ¼ RFQ sample No.1 – prior post-processing.

Post-processed ¼ RFQ samples were consequently measured in the Rösler and CERN metrology labs with GOM ATOS compact scan and Creaform METRASCAN respectively (see figure 5).

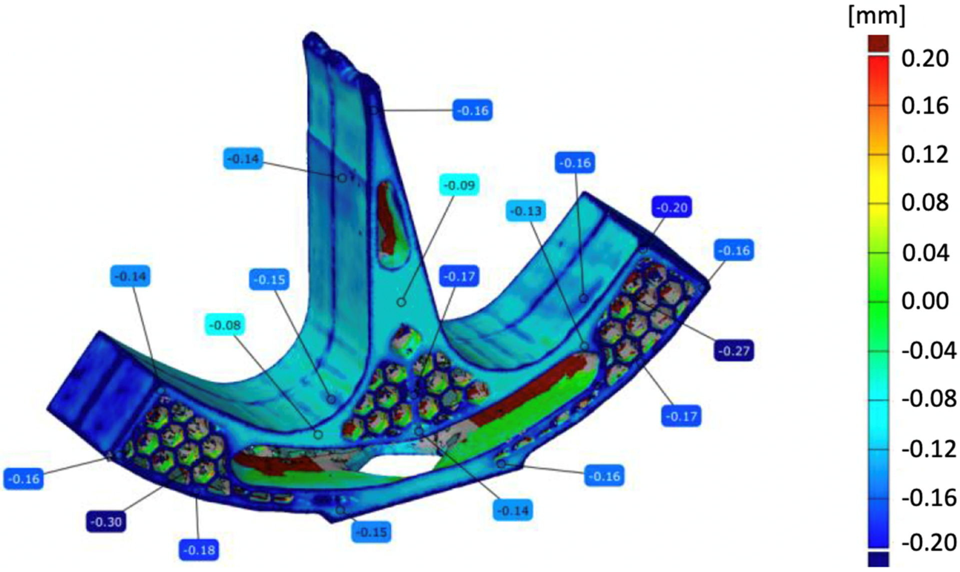

Figure 5. Measurements of ¼ RFQ segment sample No.1 - post-processed.

4.2. *Surface roughness*

Correspondingly, the surface roughness measurements were carefully planned and were performed in the critical parts of the RFQ. These measurements were done prior and after post-processing operations at CERN and at Rösler by the Mitutoyo 3000 stylus surface roughness measuring equipment, ensuing the comparable protocols (see figure 6).

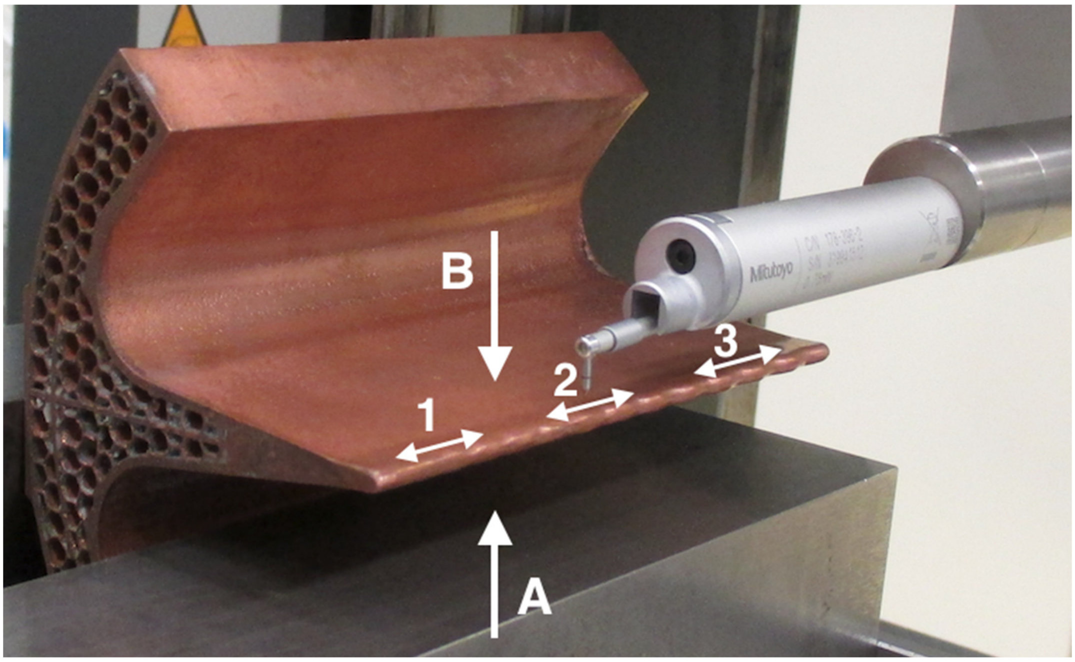

Figure 6. Measurements of ¼ RFQ segment sample No.2 - post-processed with MMP TECHNOLOGY®

To assess the overall results, the obtained surface roughness amplitude values were comprehensively evaluated in an aggregated way: R_a - average, of profile height deviations from the mean line and R_z - maximum peak to valley height of the profile, within a single sampling length.

Table 1. Surface roughness of ¼ RFQ before and after post-processing.

Post processing method	Side	R_a, µm	R_z, µm
Before post-processing		13.82	48.86
Trad. mass finishing	A	0.09	0.83
	B	0.07	0.58
Chemically assisted	A	0.07	0.67
	B	0.12	0.97
MMP TECHNOLOGY®	A	0.30	3.24
	B	0.11	1.03
Target roughness		0.4	not set

5. Conclusions and way forward

5.1. Attained geometrical accuracy

The I.FAST AM collaboration has previously con-firmed [8] that even without surface finishing operations, the surface precision of the AM manufactured RFQ's is approaching the required precision of 20 µm on the vane-tip and fully reaching 100 µm on other surfaces. Certain accuracy deviations exceeding 20 µm, on the vane-tip, are attributed to the features of the standard AM techno-logical process and could be effectively eradiated by enhancing (increasing source file mesh-size) of the RFQ vain-tip design and optimising the AM technological settings (process parameters).

Still, even without the RFQ design and AM process improvements, impact of the applied post-processing operations has proved to be beneficial for attainment of the required geometrical accuracy. Measurements of the geometrical precision revealed encouraging results – post-processing has improved surface accuracy by eliminating excess peaks and is opening valuable surface engineering features. At the same time, it must be noted that - post processing has removed extra surface layer below pre-set values. Chemically assisted finishing has removed surplus of 115-135 µm and finishing with MMP TECHNOLOGY® has reduced surface volume by 40-70 µm. This must be considered and appropriately compensated within the design and technological process for AM manufactured and post-processed parts.

5.2. Post-processing and achieved surface roughness

Required R_a values < 0.4µm were successfully accomplished by the three different post-processing methods. For the conventional surface mass finishing, processing time was longer, however, material removal was smaller, in comparison with chemically assisted process, where process time was smaller and material removal was higher finishing (see figure 7).

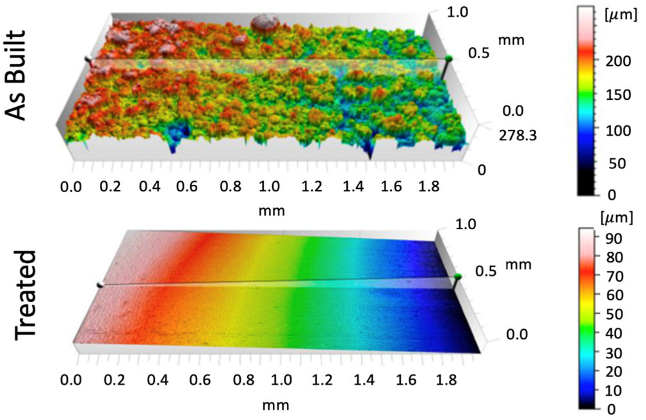

Figure 7. 3D surface roughness of the post-processed ¼ RFQ sample.

The limiting factor for mass finishing processes is the presence of deep valleys on the surface. It is because the mechanical abrasion provided by the media occurs preferentially on peaks and they remain on the surface also at the end of the process. Instead, chemically assisted surface and presumably also MMP TECHNOLOGY®, is enabling much higher material removal. In this case, the external surface layers, where defects are most prevailing, could be completely removed and thus issues related to the presence of valleys shall be mitigated.

Although feasibility of the pure-copper AM production and its surface treatment approach has been fully con-firmed, other methods of the surface finishing, such as laser smoothening will be considered in the future re-search. This will be studied in the context of the 3D sur-face roughness parameters and surface texture requirements.

5.3. AM produced full-size RFQ and the next steps

I.FAST AM collaboration has developed a full-size RFQ design which was optimised for AM and improved features. The RFQ demonstrator has been AM printed on TruPrint 5000 machine by TRUMPF (see figure 8). This segment has reached dimensions of 250 mm in length and cross-section of Ø148 mm. This falls within the real size limits of the compact linear accelerator RFQ's [24]. This is confirming the feasibility of large-size pure-copper AM printing capabilities for the accelerator community at large.

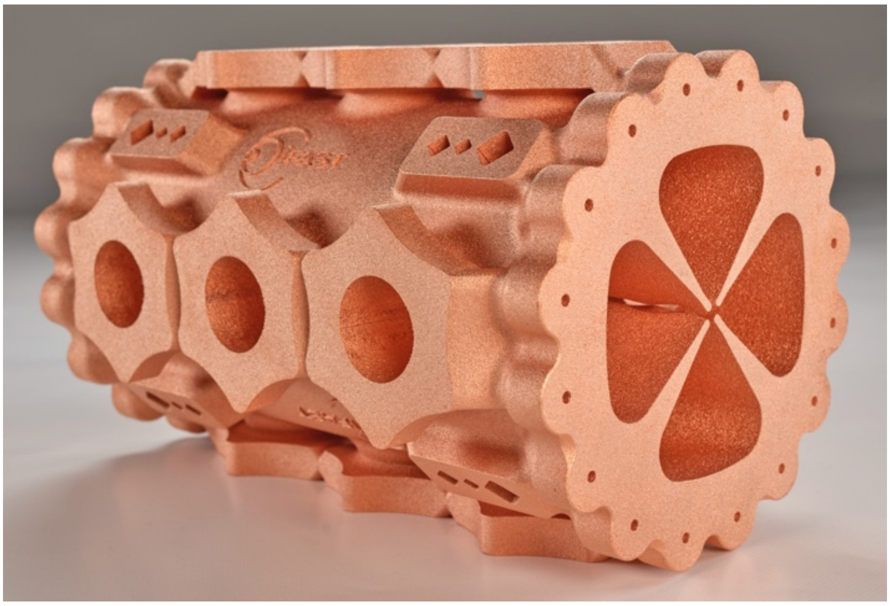

Figure 8. Full-size AM produced RFQ of pure copper.

This demonstrator will undergo the same geometrical accuracy and surface roughness measurements as ¼ of a 4-vane RFQ. This will be complemented with vacuum, water-tightness, and RF tests which are planned at IJCLab, and are integral part of the I.FAST project AM package. An AM produced RFQ demonstrator has been designed and equipped with the flanges and orifices enabling these tests. Separately, pure copper AM sample High Voltage Holding tests are planned at CERN.

Even though required geometrical accuracy and surface roughness of ¼ RFQ have been achieved, on the inner and outer surfaces, attention will remain on the vane-tip as a crucial and most challenging element of the RFQ. Post-processing will be applied to the full-size RFQ demonstrator with the subsequent analysis routines described in this paper.

Acknowledgments

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