DEVELOPMENT OF ADDITIVELY MANUFACTURED 750 MHz RFQ*

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Abstract

Additive manufacturing (AM) technologies, especially powder bed fusion, are rapidly taking their place in the technological arsenal of the accelerator community. A wide range of critical accelerator components are being manufactured additively today. However, there is still much scepticism as to whether additive manufacturing can address the stringent requirements set to complete accelerator components. Therefore, as an advanced proof-of-principle, a full-size, pure-copper Radio Frequency Quadrupole (RFQ) prototype was developed and additively manufactured in the frame of the I.FAST EU project. Gradually improved RFQ prototypes and related pure copper samples manufactured by laser powder bed fusion were submitted to a series of standard tests at CERN to demonstrate that this novel technology and suitable post-processing can deliver the required geometrical precision, surface roughness, voltage holding, vacuum tightness, and other relevant parameters. The results obtained are very promising and could be of great benefit to the linac community at large. The paper is outlining the technological developments and RFQ design improvement process along with the obtained results and future endeavours.

DEVELOPMENT OF RFQ BY AM

AM solutions are becoming an integral part of the accelerator community technological portfolio. A dedicated survey revealed that several challenging parts of accelerator components already are already produced by AM, mainly through powder bed fusion technology [1]. Nonetheless, there is still scepticism on the possibility for AM parts to attain some challenging requirements of accelerator components, i.e. surface roughness, geometrical precision, vacuum-tightness, etc [2].

The RFQ is considered as one of the most complex and arduous part and for this reason was considered as an excellent test bed for AM technologies because of its very stringent mechanical requirements [3]. The recent development of high-frequency RFQ structures at 750 MHz [4-6] provides an excellent opportunity for AM since their reduced dimensions are compatible with modern AM machines. A summary of specific requirements for a 750 MHz RFQ is presented in Table 1.

Initially, an *iteration 1* prototype RFQ section was additively manufactured by Fraunhofer IWS, corresponding to one-quarter of a 750 MHz 4-vane RFQ – see Fig. 1 [7]. To achieve the required surface roughness parameters, three samples were post-processed by three different surface treatment technologies.

Table 1: Standard RFQ Requirements

Requirement	Value
Geometrical accuracy	20 µm on vane tip 100 µm elsewhere
Surface roughness	$R_a < 0.4$ µm for all inner surfaces
Porosity, degassing	Vacuum 10^{-7} mbar
Peak electric field on surface	~40 MV/m
Electrical conductivity	90% IACS

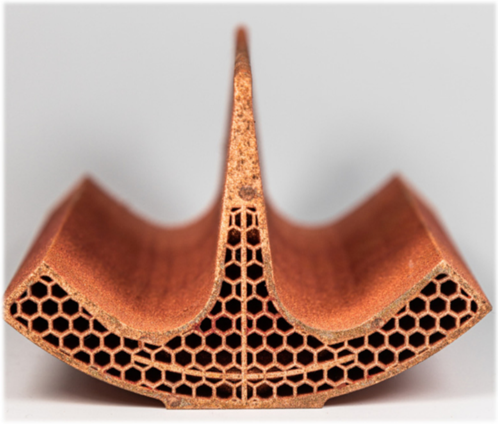

Figure 1: *iteration 1* - 95 mm ¼ RFQ.

Subsequently, a complete 4-vane RFQ prototype *iteration 2* was designed by RTU and manufactured by TRUMPF. The design was optimised for AM production and involved improved features – see Fig. 2 [8]. Based on results obtained with *iteration 1*, the printed part was treated with a two-step mass finishing process by Rösler, aiming to address hard-to-reach areas, such as the vane tip.

Benefiting from the valuable experience gained by the I.FAST WP10 partners [9] and excellent collaboration, an *iteration 3* of the RFQ was manufactured with a length of 390 mm, considered as an optimum to realise segmented RFQ's – see Fig. 3. Its design was optimised by RTU and realised by TRUMPF [10].

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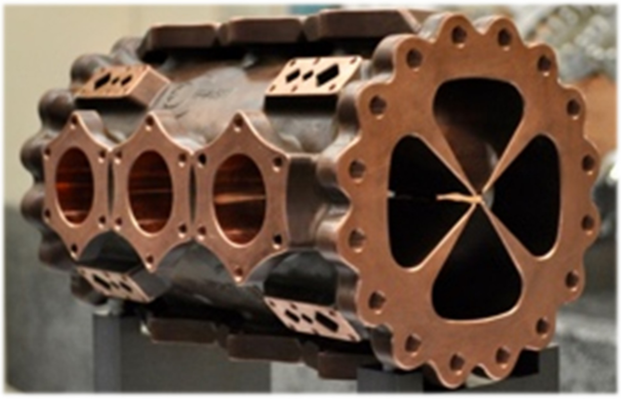

Figure 2: *iteration 2* - 750MHz RFQ, Ø148x250 mm.

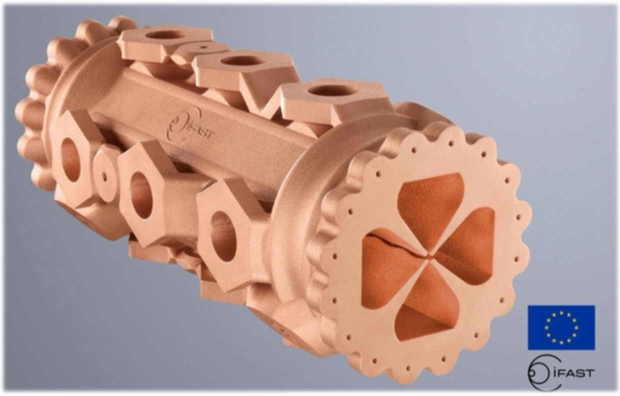

Figure 3: *iteration 3* - full-segment RFQ Ø148x390 mm.

IMPROVED DESIGN POSSIBILITIES

Thanks to its unique features, AM technology is unlocking great potential for the optimisation of a complex accelerating cavity like the RFQ. The RFQ geometry can be improved based on accelerator physics and functional requirements without considering major limiting factors on tolerances, shape, size and configuration imposed by conventional manufacturing techniques. Furthermore, complex cooling channels and connection flanges can be integrated in the structure, with a gain in installation and operation flexibility [11]. This is a true change of paradigm – one can start to design RFQs and other complex linac components solely based on accelerator physics considerations without being limited by machining and assembly considerations, as seen in Fig. 4 that shows the optimisation of the cooling channels for RFQ prototype *iteration 3.*

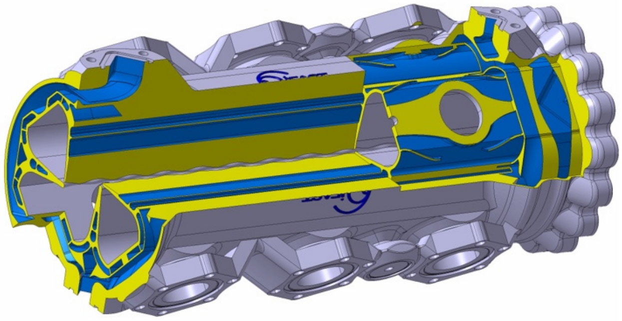

Figure 4: Improved iteration 3 RFQ.

GEOMETRICAL PRECISION

Geometrical precision of all prototypes in *iterations 1* [7, 8] and *2* [11] were determined before and after their post processing. Measurements were performed at different technological stages this has been done by Fraunhofer IWS, Rösler and most rigorously by CERN metrology lab – employing 3D optical surface scanners and established contact measurement methods, through a Coordinate Measuring Machine.

The results indicated an overall surface shrinkage in the range of 200 µm. This can be attributed a general shrinkage of the body volume in the order of 100 µm related to the AM process itself and additional 100 µm of material removed during post-processing steps. This aspect was considered in the analysis process and relevant calculations, which confirmed that AM can provide the overall 100 µm geometrical accuracy required by the RFQ. In the upcoming prototype *iteration 4* this 200 µm discrepancy shall be compensated for with the appropriate surplus tolerances. Only the outer parts of vanes were measured and analysed by CERN metrology lab. Limited measurements of the vane tips (as far as accessible, on outer surfaces near the flanges) indicated that the required precision of <20 µm is generally attainable – as illustrated in Fig. 5.

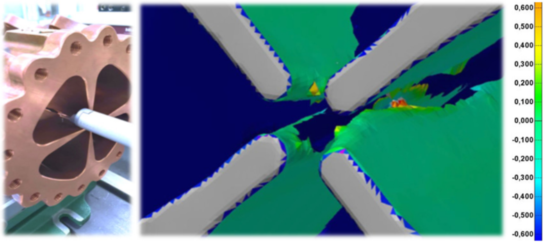

Figure 5: Limited measurements of geometrical accuracy (µm) on the RFQ vane tips, by EN-MME-MM of CERN.

However, conclusive results on the vane tip geometrical precision will only be available after sectioning the *iteration 2* RFQ prototype and conducting comprehensive measurements in the vane tip areas.

SURFACE ROUGHNESS

Similarly to geometrical accuracy, surface roughness was measured and analysed [7, 8, 11], with particular attention to the RFQ vane tips. The initial roughness of the *iteration 2* prototype ranged between 17 and 18 µm in both vane tip and lateral positions – as shown in Fig. 6. Post-processing performed by Rösler, smoothened the surfaces to Ra = 0.65 ± 0.08 µm close to the tip vane and to 1,19 ± 0,39 µm on the lateral position – see Fig. 7. Final measurements on the vane tip will be conducted after sectioning the *iteration 2* RFQ prototype for full investigation.

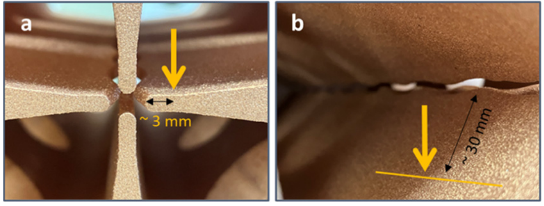

Figure 6: a) vane tip position; b) lateral surface position.

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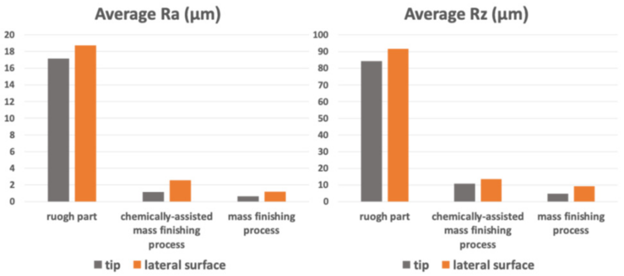

Figure 7: Roughness measurements of as-built and post-processed RFQ – iteration 2, by Rösler.

VOLTAGE HOLDING

High voltage holding is crucial for any HF RFQ. Therefore, the voltage holding capability of additively manufactured pure copper is a critical parameter to be tested. Vacuum arc breakdown tests are being performed by the RF Group at CERN, using a pulsed high-voltage DC system that was developed for testing the CLIC accelerating structures [12]. The aim is to characterize the properties of the sample pure-copper electrodes manufactured by PoliMi trough laser powder bed fusion, deliberately maintaining high surface roughness values. Initial tests were conducted under high vacuum 10^{-8} mbar. The electric breakdown rate was monitored to ensure a maximum breakdown limit of 10^{-5} breakdowns per pulse [13]. Preliminary results indicate the capability of AM electrodes to hold a required electric field, while having low breakdown rates – an electric field of 60 MV/m was reached – as shown in Fig. 8. Detailed analysis of the tests results is ongoing at the time of the submission of the paper. Further tests are envisaged.

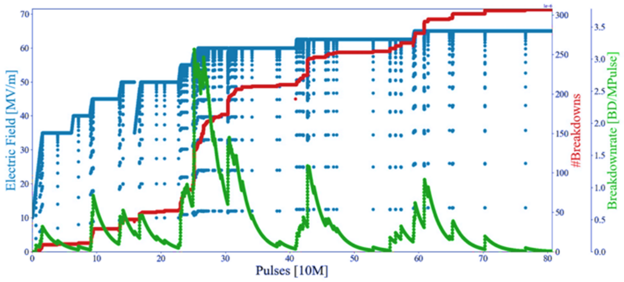

Figure 8: Preliminary results of the pure-copper AM electrode voltage-holding tests, by SY-RF-MKS of CERN.

HELIUM LEAKAGE TESTS

Ultra-high-vacuum capability is another fundamental parameter to be measured - the outgassing rate and the leak rate, determine the attainable ultimate system pressure. Frequently, AM made parts present some outgassing, because of high surface area and porosity which is promoting the absorption of contaminants. Therefore, specific testing is required to demonstrate UHV compatibility of materials processed with AM methods.

A dedicated study was conducted to evaluate the above-mentioned properties. Sample vacuum membranes of pure-copper were produced by AM, with different thicknesses and build angles – see Fig. 9.

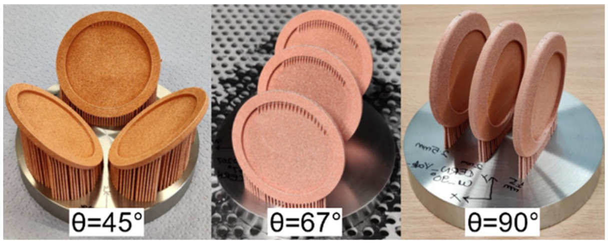

Figure 9: AM manufactured test membranes, by Fraunhofer IWS.

Samples membranes were subjected to standard helium leakage test procedures, it was confirmed that 1 mm wall thickness ensures UHV leak tightness for all build angles, while 0,75 mm thickness is appropriate for 45° and 67° angles [14].

Concurrently, the vacuum tests of *iteration 2* RFQ prototype were performed initially at IJCLab and then completed at CERN. Preliminary testing using the standard CERN procedure confirmed that the AM RFQ appears leak tight at $1 \cdot 10^{-10}$ mbar/l/s^{-1} – see Fig. 10.

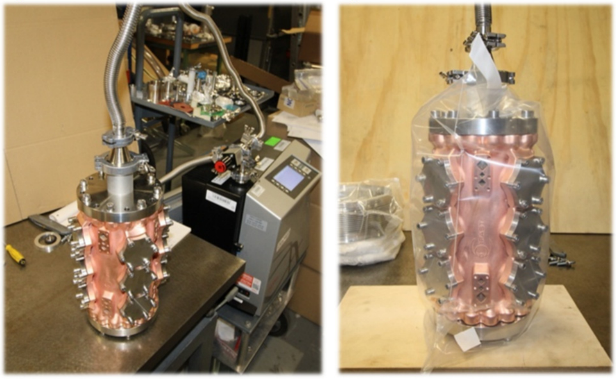

Figure 10: AM made RFQ vacuum test-setup at CERN.

CONCLUSIONS

Throughout the development process of the 750 MHz additively manufactured RFQ – involving *iterations 1, 2 and 3*– valuable lessons were learned, successively implemented in each successive *iteration,* and shared with the accelerator community. The I.FAST project multidisciplinary team is coming closer to the production of a truly functional AM optimised RFQ module of 400 mm length. It is envisioned that next – *iteration 4* – will be AM produced and tested at CERN with RF power and eventually with a real beam.

The initial series of standard tests shows that state-of-art AM powder bed fusion technology complemented by suitable post-processing can meet the required geometrical precision and surface roughness parameters of RFQ. The results of DC voltage holding, vacuum tightness and leakage tests concluded at CERN suggest that AM technology, is in principle, a viable solution to produce technologically complex accelerator components.

Furthermore, it was demonstrated that features of AM technology are allowing to considerably improve the RFQ design – particularly its complex cooling channels. Dedicated RF tests are now planned as next step for the RFQ *iteration 2*.

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