

PERFORMANCE EVALUATION OF ADDITIVELY MANUFACTURED PURE COPPER RADIO FREQUENCY QUADRUPOLE BY LOW-POWER RF AND HIGH-FIELD GRADIENT TESTS *

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Abstract

This paper presents the continuous results of investigations on additive manufacturing (AM) in the field of particle accelerators, conducted within the framework of the I.FAST (Innovation Fostering in Accelerator Science and Technology) EU project. AM, particularly Laser Powder Bed Fusion (LPBF), is demonstrating unique production capabilities for accelerator components.

As a proof-of-principle, a full-size pure copper Radio Frequency Quadrupole (RFQ) was successfully manufactured earlier. Low-power RF tests and bead-pull measurements performed on this prototype confirmed the precise electromagnetic field distribution, validating design accuracy and repeatability. Furthermore, high field gradient tests conducted in the CERN's DC pulsed measurement system showed that AM copper electrodes can sustain gradients higher than 31 MV/m for 136 μm gap. These promising results highlight the transformative potential of AM in producing high-frequency accelerator components, advancing both precision and reliability.

INTRODUCTION

AM technologies have been increasingly considered as a tool for prototyping and manufacturing accelerator components due to their ability to build complex designs with a simplified workflow and reduced material usage [1]. Specifically, LPBF has been used for prototyping a 250 mm long pure copper RFQ within the I.FAST project [2].

To demonstrate the suitability of AM for RFQ fabrication, designed tests have been conducted to assess its performance under typical operating conditions.

Initial high-field gradient tests were performed using the CERN's pulsed high voltage DC system, indicating that AM cathodes can sustain a stable electric field of up to 42 MV/m with an estimated gap of 115 μm [3]. This gap distance was derived from cathode shoulder height measurements. However, a reassessment of the gap measurements was deemed necessary to validate these results. This was done in the present work through capacitance measurements, which provided an independent estimate of the gap distance.

Furthermore, low-power RF tests and bead-pull measurements were performed to determine the electromagnetic

field distribution, providing direct information on the operational capabilities of the RFQ prototype.

MATERIALS, EQUIPMENT AND METHODS

Reassessment of High Voltage Test Results

The CERN's pulsed high voltage DC system consists of a vacuum chamber containing two electrodes, separated by a ceramic ring providing a controlled gap distance (Fig. 1).

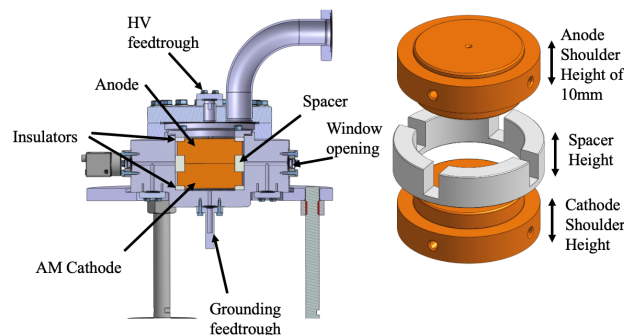


Figure 1: Schematic of pulsed high voltage DC system [4].

The applied electric field can be calculated as:

$$E = V/d \quad (1)$$

where V is the voltage applied between the two electrodes and d is the gap distance. With conventionally machined electrodes, the gap distance is defined by the height of the cathode shoulder and the ceramic spacer, as shown in Fig. 1 [4]. However, for as-built AM cathodes, the high surface roughness substantially affects the effective gap distance. Therefore, capacitance measurements were performed to estimate the average effective distance as:

$$d = \epsilon_0 \pi R^2 / C \quad (2)$$

where ϵ_0 is the vacuum permittivity (8.854 pF/m), R is the electrode radius, and C is the measured capacitance.

These values were used to revise the previously reported field gradients, providing a more accurate assessment of the breakdown strength achievable by AM cathodes.

Electromagnetic Simulation

Electromagnetic simulations of the AM RFQ module were carried out using CST Studio software to compare the design frequencies with experimental measurements.

The simulation was run in a vacuum with a perfect electric conductor (PEC) background, incorporating the two lateral aluminium cylinders used in bead-pull measurements to set the same boundary conditions (Fig. 2). A finer mesh was used in the curved regions of the vanes to ensure accurate simulations, reaching one million cells per mesh.

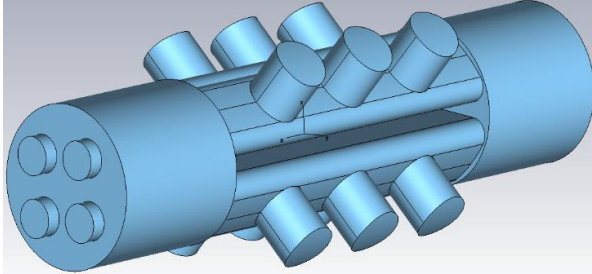


Figure 2: Simulated model incorporating auxiliary cylinders.

Bead-Pull Measurements

A bead-pull system was used to characterize the electromagnetic field distribution inside the RFQ cavity by measuring the phase disturbance induced by a small conductive bead moving along each quadrant of the structure. Signal coupling was made with a low-coupling copper wire, which allowed stabilizing the input and reception of the signal inside the cavity.

Before measurements, the RFQ was post-processed by Rösler's chemical-assisted and conventional mass finishing[2] to reach the roughness values of $R_a = 0.65 \pm 0.08 \mu\text{m}$ close to the tip vane and to $1,19 \pm 0,39 \mu\text{m}$ [5].

Iterative measurements were conducted to eliminate noise from the signal and possible errors introduced by the experimental system.

During the tests, the phase shift of the cavity relative to the resonance value was measured as the bead passed through. The combination of the displacements q (phase shifts produced by the bead-pull passage in each quadrant of the RFQ) allows calculating the quadrupole (Q), sagittal dipole (D_s), and transverse dipole (D_t) components of the cavity as:

$$Q = \frac{q_1 - q_2 + q_3 - q_4}{4} \quad (3)$$

$$D_s = \frac{q_1 - q_3}{2} \quad (4)$$

$$D_t = \frac{q_2 - q_4}{2} \quad (5)$$

RESULTS

Effective Gap and Reassessment of HV Test

Three average effective gap distances (420 μm , 225 μm , and 136 μm) were obtained from capacitance measurements. Figure 3 shows the results of conditioning tests run with these gap distances, with the electric field values calculated using Equation (1).

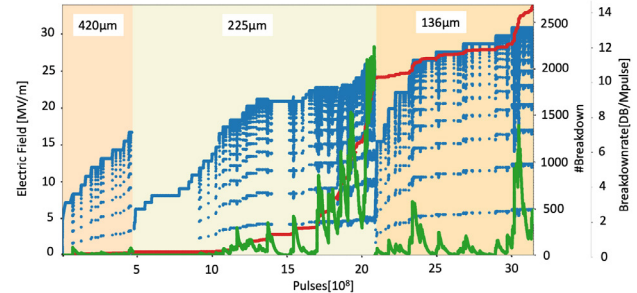


Figure 3: Conditioning of AM electrode with different gaps.

A maximum electric field of $\sim 17 \text{ MV/m}$ was reached with a gap of 420 μm , corresponding to the system maximum voltage of 7 kV. Under the same conditions, the maximum electric field increased to $\sim 26 \text{ MV/m}$ and $\sim 31 \text{ MV/m}$ for 225 μm and 136 μm gap distances, respectively.

Radio Frequency Measurements

Table 1 summarizes the results of RF simulations, identifying two dipole modes (TE110) and one quadrupole mode (TE210).

Table 1: Simulated RFQ Frequencies

Mode	Simulated frequency
TE210	749.41 MHz
TE110(1)	714.12 MHz
TE110(2)	715.09 MHz

The frequency values measured experimentally are shown in Fig. 4. The TE210 mode exhibits a vacuum frequency of 820.89 MHz, which is $\sim 71 \text{ MHz}$ higher than the value predicted by simulation. Notably, only a single dipole mode is observed at 783.06 MHz, in contrast to the two distinct TE110 frequencies obtained from simulation.

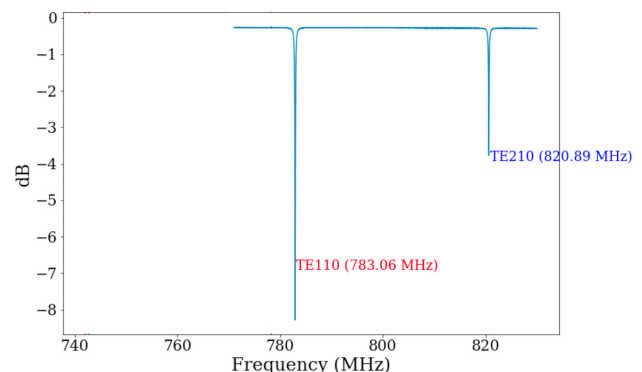


Figure 4: Frequencies measured in the range 760–840 MHz.

Figure 5 shows the average phase shift produced by the bead-pull passage in each quadrant of the RFQ. These values were used to calculate the relative amplitudes of the field components Q , D_s , and D_t using Equations (3–5). In Fig. 6, the values of field components are normalized to the maximum quadrupole component of the cavity.

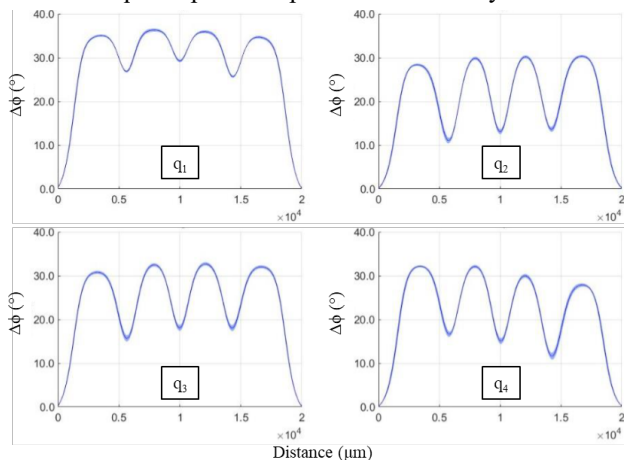


Figure 5: Relative phase shift in each RFQ quadrant.

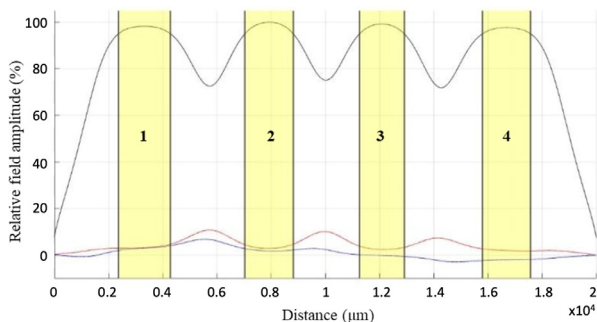


Figure 6: Relative amplitude of the fields in the RFQ.

The electromagnetic field distribution inside the cavity is significantly affected by asymmetries in the cavity walls introduced by the presence of ports, as evidenced by hill-valley pattern of the field components. To mitigate this effect, measurement regions were identified where the fields are uniform within the RFQ, as evidenced in Fig. 6. The values reported in Table 2 correspond to sampling points within these regions.

Table 2: Average Relative Field Components in the Sampling Regions

Point	Q (%)	D_s (%)	D_t (%)
1	98.26 ± 0.2	3.41 ± 0.35	3.02 ± 0.38
2	100.00 ± 0.3	3.41 ± 0.40	2.01 ± 0.44
3	99.24 ± 0.3	2.80 ± 0.38	-0.19 ± 0.48
4	97.70 ± 0.2	2.06 ± 0.36	-2.01 ± 0.45

DISCUSSION

Capacitance measurements revealed that the average effective gap distances during high-voltage tests were significantly larger than the previously estimated values[3]. The

maximum electric field achieved was 31 MV/m with an effective gap distance of 136 μm , approximately 10 MV/m lower than the value calculated with the nominal gap distance of 115 μm defined by the ceramic spacer used in the test [3]. For comparison, the operating condition of CERN's compact 750 MHz RFQ is 40 MV/m[6]. However, it should be noted that, due to the relatively high surface roughness of as-built AM electrodes, only average gap distance and electric field could be calculated, while their spatial distributions remain unknown. The maximum surface electric field is expected to exceed the estimated average value. To obtain more representative results, tests should be repeated on post-processed cathodes, enabling a more accurate assessment of the electric field limits.

Regarding RF characterization, the discrepancy between bead-pull test results and simulation predictions can be primarily attributed to post-processing, which altered the part dimension relative to the nominal design. Based on experimental measurements, an initial calculation indicated that approximately ~ 0.5 mm of material was removed from the RFQ vanes during post-processing, given the initial vane gap of 2.6 mm.

It can also be observed that the quadrupole field exhibit errors among quadrants lower than 1.7%, indicating a very homogeneous material removal during post-processing. Dipole components of $\sim 3\%$ can be attributed to local deviations introduced by post-processing operations. Although dipole components should ideally be negligible, they may be compensated during cavity tuning.

CONCLUSION

This work presents the results of high voltage and RF tests conducted on pure copper components fabricated by AM using LPBF technology.

Capacitance measurements highlighted the need to carefully consider the influence of as-built surface roughness on the effective gap distance during high voltage testing and, thus, the intensity of the established electric fields. Further testing on post-processed electrodes is expected to provide more accurate data regarding the high voltage behavior of AM components.

Low-power RF and bead-pull measurements performed on a post-processed AM RFQ prototype, complemented with RF simulations, demonstrated good electromagnetic performance, with acceptable field components at the quadrupolar resonance. The discrepancy between the simulated and measured frequencies was attributed to the effects of post-processing, which altered the RFQ dimensions compared to the original design. Nonetheless, the low quadrupole field errors among quadrants ($<1.7\%$) indicated that a uniform material layer of ~ 0.5 mm was removed during post-processing operation.

These results establish a foundation for the integration of LPBF in the manufacturing routes of pure copper RF cavities, highlighting the potential of this AM technology for particle accelerators applications. Further analyses and experimental activities are planned to thoroughly evaluate the impact of surface post-processing on RFQ geometry and its resulting RF performance.

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