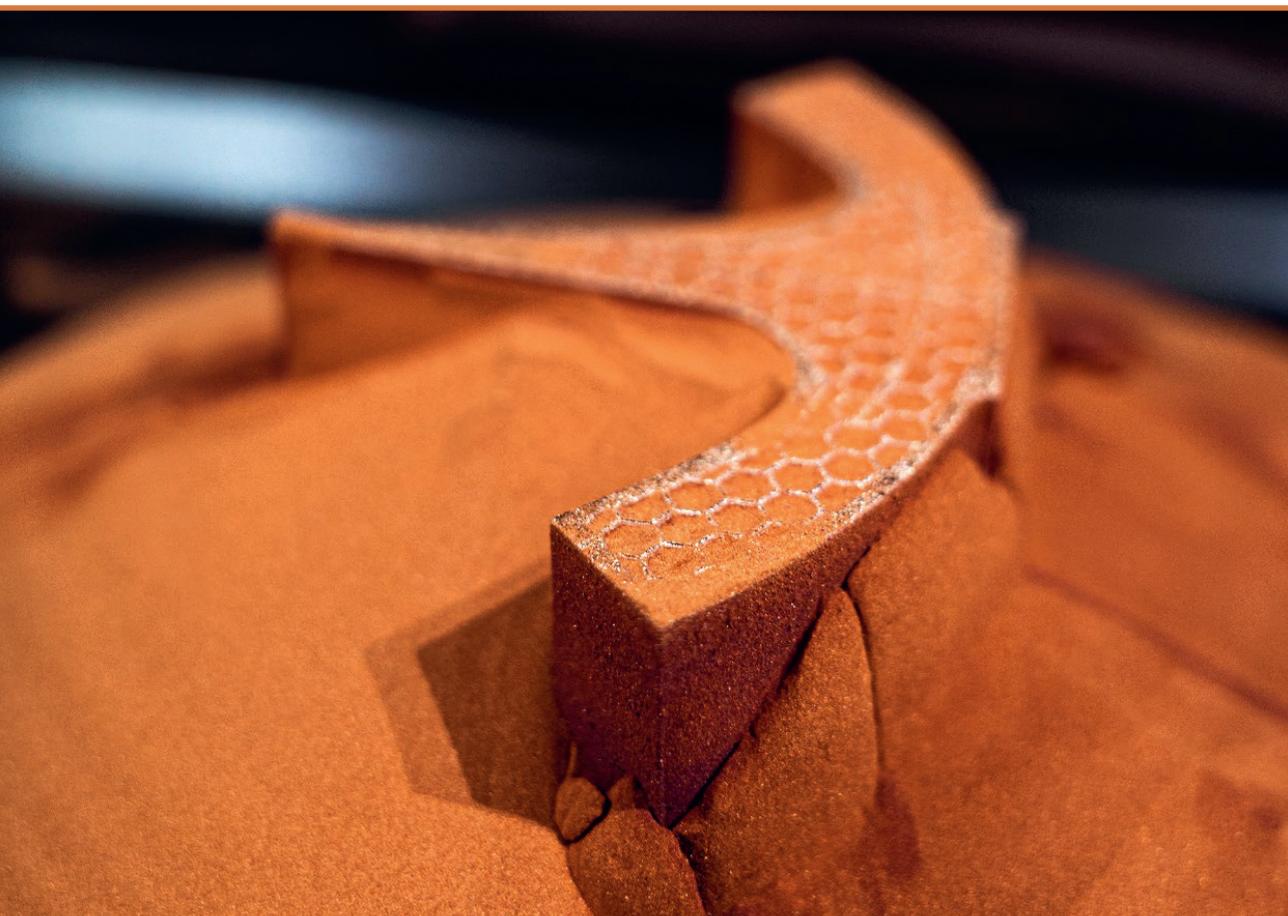


Guntis Pikurs

**RESEARCH ON THE NOVEL MANUFACTURING
TECHNOLOGY FOR COMPACT RADIO FREQUENCY
QUADRUPOLE DESIGN AND PRODUCTION**

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

Faculty of Civil and Mechanical Engineering
Institute of Mechanical and Biomedical Engineering

Guntis Pikurs

Doctoral Student of the Study Programme “Mechanical Engineering and Mechanics”

**RESEARCH OF THE NOVEL ADDITIVE
MANUFACTURING TECHNOLOGY FOR COMPACT
RADIO FREQUENCY QUADRUPOLE DESIGN AND
PRODUCTION**

Summary of the Doctoral Thesis

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RTU Press

Riga 2024

Pikurs, G. Research on the Novel Manufacturing Technology for Compact Radio Frequency Quadrupole Design and Production. Summary of the Doctoral Thesis. – Riga: RTU Press, 2024. – 50 p.

Published in accordance with the decision of the Promotion Council “P-03” of 18 October 2024, Minutes No. 04030-9.3.2/1.

The research was carried out within the framework and with financial support of the following projects:

- State Research Programme (SRP) “High-energy physics and accelerator technologies” VPP-IZM-CERN-2020/1-0002; VPP-IZM-CERN-2022/1-0001;



- Horizon 2020 project “Innovation Fostering in Accelerator Science and Technology” (I.FAST) WP10.2. This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under grant agreement No. 101004730.



Cover photo by Christoph Wilsnack/Fraunhofer IWS

<https://doi.org/10.7250/9789934371400>

ISBN 978-9934-37-140-0 (pdf)

**DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY
FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF
SCIENCE**

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of the RTU Promotion Council on December 27, 2024, at the Faculty of Civil and Mechanical Engineering of Riga Technical University, 6B Ķīpsalas Street, Room 417.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Guntis Pikurs/signature/
Date

The Doctoral Thesis has been written in English. It consists of an Introduction, 11 chapters, Conclusions, 56 figures, 13 tables and 8 appendices; the total number of pages is 110, not including appendices. The Bibliography contains 117 titles.

ABBREVIATIONS

Abbreviation	Meaning
AI	Artificial Intelligence
AM	Additive Manufacturing
AIDA	Advanced European Infrastructures for Detectors and Accelerators
AMAZE	Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products
AMCM	Additive Manufacturing Customized Machines GmbH, EOS group company
APAE	Applications of Particle Accelerators in Europe
ARIES	Accelerator Research and Innovation for European Science and Society
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CATIA	Computer Aided Three-Dimensional Interactive Application
CERN	European Organization for Nuclear Research
CORDIS	Community Research and Development Information Service
CMM	Coordinate Measurement Machine
DfAM	Design for Additive Manufacturing
EDMS	Engineering Data Management Service
EuCARD ²	European Coordinated Accelerator Research and Development
H2020	Horizon 2020
HEP	High Energy Physics
HF-RFQ	High Frequency Radio Frequency Quadrupole
IACS	International Annealed Copper Standard
I.FAST	Innovation Fostering in Accelerator Science and Technology
IJCLab	Irene Joliot-Curie named Laboratorie in Orsay
ISO	International Standard Organisation
JACoW	Joint Accelerator Conferences Website
KEK	Japanese High Energy Accelerator Research Organization
MMP	Micro Machining Process
NIMMS	Next Ion Medical Machine Study
PAM ²	Precision Additive Metal Manufacturing
PBF	Powder Bed Fusion
PIXE	Proton-Induced X-ray Emission[1]
PLM	Product Lifecycle Management
RFQ	Radio Frequency Quadrupole
STL/ .stl	Stereo Lithography/ .stl file format used for Stereo Lithography

GLOSSARY

Symbol Meaning

A	– total quadrant area of cavity, mm^2
B	– magnetic field in the quadrant, T
c	– the specific heat, $\text{J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$
C_ℓ	– shunt capacitance for unit length, F/m
C'	– cavity quadrant shunt capacitance per unit length, F/m
CI	– statistics confidence interval
I	– peak current, A
k	– the coefficient of thermal conductivity
Ku	– statistics kurtuosis value
κ	– coefficient, which covers OFE-Cu 750 Mhz cavities specifics
L	– perimeter of cavity quadrant, mm
l_V	– vane(cavity) length, mm
L'	– quadrant shunt inductance, $\text{H} \cdot \text{m}$
μ_0	– permeability of free space (physical constant), Tm/A
P	– power dissipation, W
P_ℓ	– power per unit of length, W/m
π	– mathematical constant that is the ratio of a circle's circumference to its diameter, approximately equal to 3.1415
r	– circle radius, mm
Ra	– arithmetic mean deviation of roughness profile, μm
Rz	– arithmetic mean deviation of roughness profile, μm
ρ	– the density of the studied solid material, kg/m^3
Q_0	– unloaded cavity quality factor
$Q_{0,2D}$	– unloaded two dimensional cavity quality factor
\dot{q}	– the internal heat generation rate, per unit volume, per unit time, $\text{W/m}^3/\text{h}$
s	– statistics standard deviation
S	– cavity quadrant area, mm^2
SE	– statistics standard error value
Sk	– statistics skewness value
σ	– electric conductivity, S/m
t	– time, s
T	– the variable temperature for the coordinates x , y , z and time t
x, y, z	– coordinates, mm
\bar{x}	– arithmetic mean for x_i values
ω_0	– resonant frequency of cavity, Hz
W_0	– stored energy for unit length, J/m

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GENERAL OUTLINE OF THE THESIS

Actuality of the topic

Modern particle accelerators consist of diverse constituent parts and necessitate advanced technological solutions to operate at their intended parameters. Currently, the majority of accelerator components are produced through the utilization of conventional (subtractive) high-precision machining techniques. Typically, traditional machining techniques necessitate substantial material removal rates, resulting in a considerable amount of material being transferred to chips. Moreover, conventional machining procedures and technologies are considerably time-intensive, with machine time and human labour contributing substantially to manufacturing expenses. A noteworthy and intricate subject for further inquiry pertains to a crucial component of the accelerator, namely the radio frequency quadrupole (RFQ). This component necessitates the usage of oxygen-free pure copper (OFE-CU, C10100) in its manufacturing process. The chemical purity of RFQ material must exceed 99.98 % to ensure good conductivity of cavity "skin layer" and the accelerator effectiveness. The failure to meet this threshold may result in a significant decrease in efficiency and increased heat losses. The intricate nature of geometric shapes and the need for high precision and surface quality have resulted in significant costs associated with traditional manufacturing methods. As a result, there has been a growing impetus to explore the potential of additive manufacturing (AM) technology for producing accelerator components.

As Horizon 2022 EuCARD² [2] summarized in key recommendations for applications of particle accelerators - advances in the development and applications of particle accelerators have involved a significant R&D effort over the past 50 years and have substantially benefited society to continue the progress made. It is essential to encourage R&D across the wide range of disciplines that are associated with accelerator physics. More specifically, the following recommendations were made for compact accelerator development, which is a critical element in most applications. Improved designs and cost-effectiveness, more superficial and lower-cost designs and concepts, with higher efficiency, reliability, robustness, and reduced costs of operation, are needed in many accelerator applications, especially in medical, industry and security; even the ready mobility of accelerator equipment is a growing need for some applications [2].

Goal and objectives

The objective of the Thesis is to develop the design and manufacturing technology of RFQ for AM-based technology to reach enhanced performance. The following tasks were identified to reach the mentioned objective:

1. To identify benefits of novel RFQ manufacturing technology – to propose possible RFQ design and performance improvement options as well as validation methods;
2. To manufacture a novel RFQ prototype with AM technology, encompassing the proposed design improvements.
3. To perform the required technological post-processing steps for the RFQ prototype.
4. To perform metrological evaluation of attained geometrical parameters and surface roughness quality – at all technological stages of RFQ prototype production.
5. To evaluate RFQ design/performance improvements by using scientific validation tools - to model RFQ performance, thermal management and geometrical precision.
6. To conduct a quantitative comparison of RFQ production between conventional technology and AM.
7. To identify future research issues and provide practical recommendations for RFQ manufacturing technology advancements.

Applied research methods

The set aim and tasks were achieved through the utilization of various research methods:

- Field studies encompass collecting data from various sources about AM application cases in different accelerator systems. Field studies were primarily based on exploring literature and communication with area experts.
- Surveys and questionnaires – for gathering data from project partners and conference participants. Questionnaires were utilized to collect data regarding user preferences, opinions, and predictions about AM applications in the accelerator community. Surveys included quantitative or qualitative data, contingent upon the nature of the questions.
- Quantitative and qualitative research methods were applied for survey and result analysis, while the quantitative methods dominated mostly for research steps. Qualitative methods, such as surveys and communication with accelerator and AM community experts, were employed to gain insight into specific questions, such as design considerations and software applications throughout the research process.

- Design for Additive Manufacturing (DfAM) – implementing DfAM guidelines and principles can be employed to improve the design of components for Powder Bed Fusion with Laser Beam (PBF-LB) technology. Investigate the extent of design freedom facilitated by AM, specifically focusing on its ability to create intricate geometries lattice structures and optimize topology. This study aims to assess the influence of design modifications on the performance of parts, the efficient utilization of materials, and the feasibility of manufacturing processes.
- The Comparative Design Analysis – to conduct a comprehensive comparative analysis between the designs produced through Powder Bed Fusion with Laser Beam (PBF-LB) technology and traditional manufacturing methods. The parameters to be evaluated encompass various aspects, including structural integrity, weight optimization, performance enhancement, and manufacturability. Employ software tools such as computer-aided design (CAD) and finite element analysis (FEA) in order to conduct a comparative evaluation of the designs.

Scientific novelty

Significant contribution to the mechanical engineering and accelerator technology sub-sector:

- An innovative AM RFQ model has been created and validated based on the developed manufacturing method, providing improved performance and heat transmission.
- An alternative calculation method for Q value based on the RFQ cavity geometry parameters and a coefficient containing the physical properties of the manufacturing material has been developed and validated.
- The development and validation of an innovative technological process and method for the production of RFQ.
- For the first time in the world, the production of high purity, complex design and geometric accuracy copper component (RFQ prototype), with AM technology, has been demonstrated and scientifically justified.
- A comparison of the developed technological process with the traditional manufacturing technology has been carried out, and the advantages of the new technology have been demonstrated.

Theses to be defended

- The developed **mathematical model** for 2-dimensional Q-factor calculation for the design stage **is applicable for 750 MHz pure copper RFQ cavities** and

can be scaled.

- The **AM 1/4 RFQ design with balanced smooth transition geometry** leads to Q-factor improvement by **2.81 %** versus the conventionally designed HF-RFQ.
- The design of cooling channels, which provides **32 % in average and more than ten times reduced thermal deformation for vane tip region**.
- The used **AM and post-processing techniques are capable of providing geometrical tolerances that are practically within the 20 μm on RFQ waveguide profile and modulation region**. Furthermore, applied methods are capable of providing **surface roughness profile values of $R_a = 0.4 \mu\text{m}$** .
- The AM method **significantly reduces the number of RFQ production operations** from 58 to 30 and the production time by 75 %.

Practical significance and application

The Thesis research represents a significant advancement explicitly targeted at the AM of compact-size RFQ, a highly intricate part of accelerators. The manufacturing process of HF-RFQ demands exceptional geometric accuracy and surface quality due to stringent requirements for beam optics. The Thesis findings can serve as a valuable reference for the future advancements of AM technology in the context of RFQs and other intricate components of accelerators. The Thesis encompasses a comprehensive guide for applying AM technology in rapid functional prototype development. The current Thesis can be used as a guide for further developments and includes the initial design development concepts, concluding with the evaluation of the geometrical shape and surface quality of the prototype through several types of tests. The Thesis represents a significant and valuable contribution to the H2020 I.FAST project, serving as an essential component of the deliverable for the I.FAST WP10 collaboration. In addition, the Thesis has continued with the development of a full-size RFQ [3].

Approbation of the results

Presentations in international scientific conferences and seminars:

1. Pikurs, G. Additive manufacturing applied to particle accelerators, IJCLab, report. [Online]. Available: https://indico.cern.ch/event/1126958/contributions/4730216/attachments/2393754/4124387/I.FAST_Paris_G.pdf. 18/03/2022.
2. Pikurs, G., Delerue, N. Additive Manufacturing applied to Particle Accelerators. [Online]. Available: https://indico.cern.ch/event/1133254/contributions/4853087/attachments/2438320/4176612/I.FAST_1st_Annual_WS_GP_ND.pdf. 05/05/2022.

3. Pikurs, G., Torims, T., Vretenar M. Research on design improvement of accelerator components by AM. National Centre of Physical and Technological Sciences, Report. [Online]. Available: https://indico.cern.ch/event/1147717/contributions/5082259/attachments/2526799/4346280/CBC2022_GP.pdf. 12/10/2022.
4. Ratkus, A. Pikurs, G. Torims, T. Seminar: Additive Manufacturing technologies within the Accelerator Community/ progress with the RFQ. Orsay, Paris, IJCLab. Available: <https://indico.cern.ch/event/1246711/> 30/01/2023.
5. Pikurs, G., Torims, T., Vretenar, M. Research on the design development of accelerator components by AM. 2nd CERN Baltic Conference, National Centre of Physical and Technological Sciences, Vilnius, Lithuania. 12/10/2022.
6. Torims, T., Ratkus, A., Pikurs, G. Proliferation of Additive Manufacturing technologies within the Accelerator Community. Seminar on AM at the Goethe University Frankfurt. 20/01/2023.
7. Torims, T., Ratkus, A., Pikurs, G. Additive Manufacturing technologies within the Accelerator Community. Seminar on AM at the Paul Sherrer Institute, Willingen, Switzerland. 16/03/2023.
8. Torims, T., Ratkus, A., Pikurs, G. Additive Manufacturing technologies within the Accelerator Community. Seminar on AM in the Laboratory of Subatomic Physics and Cosmology, IN2P3 (CNRS), University of Grenoble Alpes, Grenoble, France. 6/04/2023.
9. Pikurs, G., Torims, T., Vretenar, M. Mechanical design optimization of an RFQ (particle) accelerator prototype made by AM. 3rd CERN Baltic Conference, Riga Technical University, Latvia. 11/10/2023.
10. Pikurs, G., Torims, T., Vretenar, M. Research on AM (AM) technology development for Radio frequency quadrupole (RFQ) fabrication and performance improvement. 64th International Scientific Conference of RTU, Riga Technical University, Latvia. 12/10/2023.

Publications:

1. T. Torims, G. Pikurs, S. Gruber, et al., First Proof-of-Concept Prototype of an Additive Manufactured Radio Frequency Quadrupole. *Instruments*, vol. 5, no. 4, p. 35, 2021. <https://doi.org/10.3390/instruments5040035>
2. T. Torims, A. Ratkus, G. Pikurs, D. Krogere, A. Cherif, S. Gruber, et al., "Evaluation of geometrical precision and surface roughness quality for the additively manufactured radio frequency quadrupole prototype," *Proceedings of IPAC2022*, pp. 787–791, 2022. <https://doi.org/10.18429/JACoW-IPAC2022-TU0XSP3>

3. A. Ratkus, T. Torims, G. Pikurs, V. Bjelland, S. Calatroni, R. Peacock, C. Serafim, M. Vretenar, W. Wuensch, M. Vedani, T. Romano, M. Pozzi, M. Foppa Pedretti, Initial high electric field – vacuum arc breakdown test results for additively manufactured pure copper electrodes. Proceedings of IPAC2023, pp. 3184–3186, 2023. <https://doi.org/10.18429/JACoW-IPAC-23-THPM030>
4. A. Ratkus, T. Torims, G. Pikurs, V. Lacis, C. Garion, H. Kos, S. Rorison, S. Gruber, E. Lopez, L. Stepien, A. A. Patil, M. Vedani, Evaluation of green laser source AM technology for accelerator applications with ultra-high vacuum requirements. Proceedings of IPAC2023, pp. 3187–3190, 2023. <https://doi.org/10.18429/JACoW-IPAC-23-THPM031>
5. T. Romano, G. Pikurs, A. Ratkus, T. Torims, N. Delerue, M. Vretenar, L. Stepien, E. López, and M. Vedani, Metal AM for particle accelerator applications. Phys. Rev. Accel. Beams 27, 054801 – Published 17 May 2024. <https://doi.org/10.1103/PhysRevAccelBeams.27.054801>

1. METAL AM REVIEW AND STATE OF ART ANALYSIS

In order to explore the current state of the art in the field of metal AM and, more specifically, on applications in the field of high energy physics, a number of public and institutional databases were explored, such as Google Scholar; JACoW Publishing; ScienceDirect/Elsevier; Springer; MDPI; IEEEExplore; arXiv.org; ResearchGate; indico.cern.ch; CORDIS etc. Focused search keywords were used: *metal AM, metal 3D printing, powder bed fusion, solid freeform fabrication, accelerator, linear accelerator, LINAC, radio frequency quadrupole, and pure copper*. As well, international patent and intellectual property searches were executed by European Patent Office and World Intellectual Property Organization search engines.

Overall, the highest number of scientific articles (39 articles on 16/05/2023) about applications of AM for accelerators are published by JACoW Publishing. It is intelligible because JACoW stands for Joint Accelerator Conferences Website.

1.1. Evolution of the technology and recent advances

AM is already part of modern manufacturing however, at the same time, it is still a relatively new and continuously progressing technology which is developing in a close loop with the latest inventions in the industry. AM has numerous advantages over conventional manufacturing technologies. One of the most crucial advantages is its exceptionally high potential for manufacturing top-performance and high-complexity parts [4].

The Thesis research is focused on metal powder bed fusion(PBF-LB/M) technology, where the part is built in a powder bed, and the material is melted by a laser beam(LB). The current development of the PBF technique is giving a promising look for the near future to reach highly specific demands for accelerator parts. Meanwhile, most industries are already using metal PBF technology with excellent results. However, the standardization process and implementation of even more precise monitoring techniques to ensure consistent results is continuously improving. Presently, consistency and outcome quality, as well as repeatability is still a challenging task for some areas of the applications mainly due to safety reasons.

Despite to challenges, scientific and industrial communities are working on solutions to address potential issues and improve the AM product quality. The European AM community is the second largest after the U.S. and includes several strong AM technology groups. These groups primarily focus on new developments to advance in technology. Among leaders are H2020 I.FAST WP10 project partners Fraunhofer I.W.S. (Dresden), PoliMi(Milano), INFN DIAM(Padova), TRUMPF SE+Co. K.G. (holding), Rösler Italiana S.r.l. and RTU (Latvia). TRUMPF SE+Co.K.G. is a laser source and AM machine manufacturing company famous in the metal industry as a leader in laser processing

technology and system development. In 2018, TRUMPF SE+Co.K.G. presented the world premiere of green laser application for AM. By inspiration of the latest developments, a decision was taken to use “green laser” technology developed by TRUMPF SE+Co.K.G.

1.2. Current applications within accelerator community

The first known proposal on applying metal AM in high energy physics appeared in 2003, with ARIES Compact Stellarator coil structure development. In 2012, the first AM projects appeared at CERN. These activities at CERN can be tracked by public documents in CERN’s Indico, EDMS and CDS servers. CERN’s engineers started to promote the first application ideas, and it looks like the beam instrumentation group’s idea about fast beam scanners is the first official AM project at CERN. Meanwhile, several developments started in other European accelerator centres: INFN, CRNS and IJCLab.

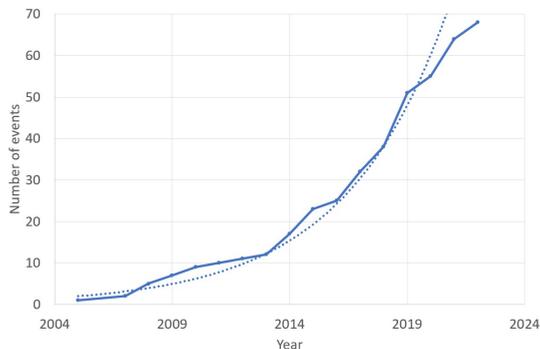


Fig. 1.1. Cumulative number of AM events and developments in the accelerator field [5], [6].

1.3. Conclusions

During the last decades, the number of metal AM applications increased significantly, see Fig. 1.1.. However, the number of successful and industrialized cases in HEP field still is surprisingly low compared to other industries. Generally, the main reason for low-level AM activities and success stories is stringent quality requirements and a strongly conservative community. Despite that, most AM projects carried out are showing signs of the significant potential of AM application in the near future. It is well visible that the AM technology can become a provider of high-performance accelerator part manufacturing in aviation, medicine and the automotive industry. The most attractive qualities of AM are high design freedom, availability for topology improvements at low costs, structural performance tuning, manufacturing flexibility, high level of production automation, minimized number of processing steps affected by human errors, and high digitization level.

2. RESEARCH METHODOLOGY

The research on potential RFQ design development by metal AM application is based on in-depth scrutiny research of the accelerator and AM field. Literature and state-of-the-art analysis implies using mixed structure by time and project topic. This includes a comprehensive analysis of several types of resources: literature, databases, conference proceedings, standards, patents and EU co-financed projects, as well as prior publicly known studies of AM applications within the accelerator community, in general, most of design improvement research is based on comparative study basis; by using quantitative and qualitative analysis tools.

2.1. Analysis methods and tools

Quantitative tools used in reserch are Poisson/SUPERFISH(LANL) codes [7] utilized to validate cavity geometry; CAD software Catia V5R27 was used for the part design-redesign stage, as well as to find 2D cavity geometry coordinates for application in Poisson/SUPERFISH codes (in CATIA mostly used workbenches were part design, generative shape design, rapid prototyping and digital shape editor workbenches); ANSYS'2019 (Steady State Thermal, Static Structural and Fluent workbenches) was used in design validation as well as in designing process and finally, ZEISS GOM Inspect'2018 and 2022 version metrology software were used in final stages for metrology data analysis. At several research stages, concepts were validated by Autodesk Fusion 360, NetFabb Premium 2023 and eDrawings'2021 x64 software to explore major visual details of models.

Qualitative tools. Comparative analysis and simulations were used for result interpretation and validation of results. Targeted survey was carried out to better understand the needs of the community.

Design, inspection and public information research tools and methods were used to ensure detailed level of research. Sources were used: CERN EDMS; CERN PLM SmarTeam; INDICO(CERN); INDICO(INFN); INDICO(IN2P3/CNRS); JACoW Publishing; ResearchGate; Espacenet; Google Scholar; Autodesk Netfabb Premium 2023 etc.

Result validation tools. The results at different development stages of prototype were obtained by various tools. At the initial stage, the concept design validation was carried out by Poisson/SUPERFISH codes to check quality parameters of RFQ, then, ANSYS Static Structural and Steady State Thermal workbenches were used for validation and designing of internal cooling channels. Catia V5R27 – /Mechanical Design/Part Design, Shape/Generative Shape Design, Shape/Digitized Shape Editor, Shape/Sketch Tracer and – Machining/Rapid Prototyping workbenches were utilized during whole design workflow. Optical scanning of the prototype and comparison with the as-designed CAD model, as well as surface geometry validation on ZEISS GOM Inspect'2022 and Polyworks MS2020 software were carried out.

For HF-RFQ geometry development, evaluation and calculations Poisson/SUPERFISH

(LANL) codes were used. Further CAD models were developed, inspected, and STL file (mesh) preparation in CatiaV5R27(Dassault Systems) environment. During the CAD model development, ANSYS'2019 Steady State Thermal, Static Structural and CFD workbenches were used to evaluate the cooling channel design and static structural behaviour. Model preparation for build job on Truprint1000 machine was carried out in Materialise Magics [8] software.

The initial surface roughness profiles were measured at Fraunhofer IWS by perthometer Surfcom Touch 50, which is a contact profilometer from Accretech (Japan). Similarly, the first "as-built" part optical scan was also performed in Fraunhofer's IWS metrology lab. After that, a cross check was done at CERN EN-MME metrology lab on Creaform MetraSCAN BLACK™-Elite scanner with a 0.025 mm measurement accuracy and volumetric precision of 0.064 mm at 9.1 m³ [9], and the software Polyworks MS2020 was applied for optical scan inspection at lab. Further more detailed alignment and analysis were carried out independently by ZEISS GOM Inspect 2022 software.

Several series of measurements by ZEISS Prismo Ultra 12-18-10, which is Bridge type CMM with a moveable bridge, were executed in CERN's MME metrology laboratory. ZEISS Prismo Ultra 12-18-10 can provide readings up to 1 µm accuracy [10].

2.2. Design of the AM process (design of experiments)

AM technology workflow, in general, is similar to most technologies and is a multi-step process. However, for complex shapes and smaller tolerances than ISO 2768 fine-machining can provide, AM technology development can offer a significantly reduced number of manufacturing steps compared to same-level subtractive machining, where it is necessary to implement accurate assembly and re-machining steps. A general workflow of detailed process-planning for metal AM technologies is described by several authors such as Dotcheva [11]. The core work is primarily associated with the model development and the AM workflow. The first steps focus on the 3D model development, further workflow directs to the quality assessment tasks, and lastly to planning and post-processing.

2.3. Validation of results

Research results validation is mainly based on the comparative and statistical analysis between actual conventionally manufactured HF-RFQ critical values retrieved from CERN's EDMS and PLM systems and results from scientific conferences and articles where manufacturing accuracy and precision of additively manufactured prototype samples were presented. At the initial stage of AM prototype design, SUPERFISH codes were used to validate the geometrical shape of the cavity. Further, Ansys19.0 Mechanical Static Structural and Steady State Thermal were applied to validate the thermal performance and impact on structural stability, which is a critical factor for stable accelerator operation.

3. MECHANICAL DESIGN AND PRODUCTION DEVELOPMENT OF RFQ ENABLED BY ADDITIVE MANUFACTURING TECHNOLOGY ADVANTAGES

Additive manufacturing is a technology which changes paradigm, already initially it is a far more natural way of manufacturing. The process is similar to natural phenomena. Material adding takes place only in regions where it is necessary, it is similar as plants and animals are growing. AM is the technology of future, where material is not wasted in chips and energy to remove them from workpiece. The technology allows us to manufacture complex parts more easily with minimum number of processing steps if compared to conventional subtractive machining and complex vacuum brazing technologies.

Furthermore, AM allows design solutions which are completely impossible and mind-blowing for conventional technologies. Those complex and high performance focused design parts, manufactured by additive technology are less expensive than the same level performance parts which are manufactured by conventional methods. AM is a completely different manufacturing method, which enables higher level of design freedom and high level manufacturing process control and automation, eliminating impact of human errors during manufacturing process.

3.1. Mathematical model and cavity Q factor optimization

The theory of designing and calculation steps of RFQ cavities are described by several authors. Detailed equations are described by T. P. Wangler [12] and H. W. Pommerenke [13]. Traditionally, in most of cases, designing starts with classical idealized assumption that the cavity's effective quadrant area consists of three quarters of a circle with radius r , and a square with sides of the same length, see Fig. 3.1. which represent the area nearest the beam axis, yielding a total quadrant area [12] of

$$A = (4 + 3\pi)r^2/4, \tag{3.1}$$

where r – circle radius, mm; π – mathematical constant that is the ratio of a circle's circumference to its diameter, approximately equal to 3.1415.

The quality factor Q is a ratio of the energy stored in the cavity to the energy dissipated in the walls per RF cycle. A high Q is desirable if it means low power dissipation, but is not necessarily desired if it means large stored energy because it implies a sensitivity to frequency errors. For pulsed systems, high Q also implies a long time constant for filling the cavity with RF energy. The power loss of an eigenmode is commonly quantified by

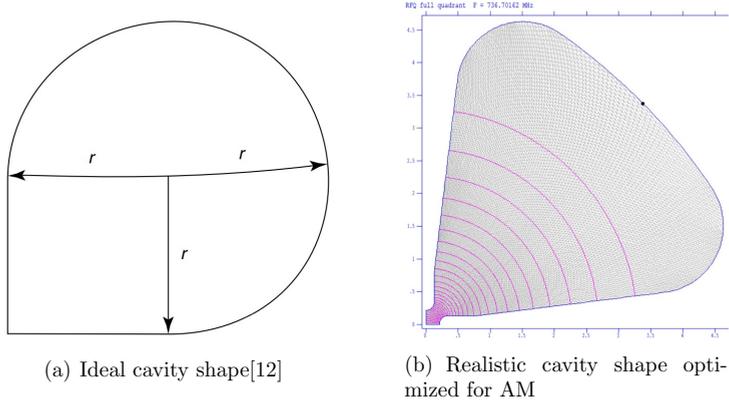


Fig. 3.1. Ideal and realistic cavity shapes.

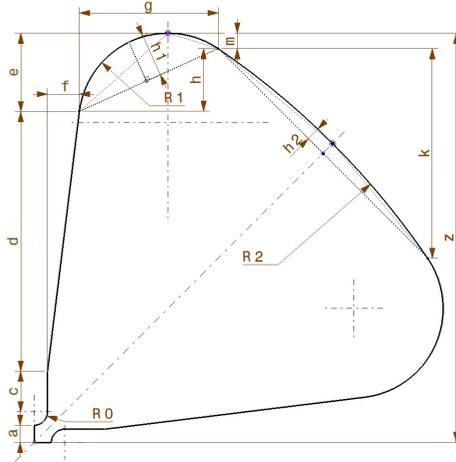


Fig. 3.2. Geometrical shape and elements of the AM RFQ cavity 2D profile developed in this research.

the unloaded quality factor [12]:

$$Q_0 = \frac{\omega_0 W_0}{P_0}, \quad (3.2.)$$

where W_0 is stored energy for unit length, J/m;

P_0 is power dissipation(power loss), kW, and r is the cavity radius r [12]:

$$Q_0 = \sqrt{\frac{8\delta}{(4 + 3\pi) \sqrt{\frac{16}{\mu_0(4+3\pi)r^2 C_\ell}} C_\ell}}, \quad (3.3.)$$

and further, by adding known values, the equation becomes dependable from the cavity

radius.

2D cavity shape optimization aims to achieve a feasible high Q-factor value, as it is a cornerstone of RFQ structure efficiency. In general, it is a task to push the realistic shape of the cavity closer to the ideal one, see Fig. 5.2. The main optimization restrictions for 2D cavity geometry are:

- vane tip aperture radius;
- the vane thickness, to ensure vane stability and general cooling performance;
- minimum material thickness of copper between the water and the vacuum media to avoid degrading the vacuum due to water diffusion.

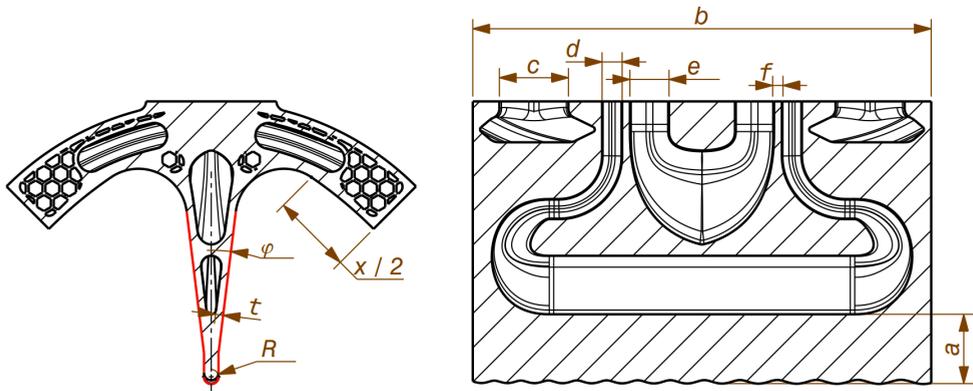


Fig. 3.3. Optimized cavity and cooling model for the AM RFQ quarter sector prototype.

Cooling channel design development and optimization. The cooling system of the RFQ aims to remove heat produced due to power loss in the skin layer and transport it to a heat exchanger – outside of the RFQ body. The idea is to try to keep the temperature in the whole RFQ structure in a possibly narrow band, thus limiting thermal distortions. There are several important factors which impact the cooling efficiency of an RFQ:

- the concept of cooling channel routing;
- contact surface between cooling and cooled medias;
- channel shape and crossection values along the channel length.

It is important to note that the heat flux on cavity walls varies considerably, from 0 up to almost $3 \text{ W} / \text{cm}^2$, depending on the specific location – see Fig. 3.7.

In addition to previously mentioned aspects, it is worth mentioning AM design limitations for internal structures to avoid support structure necessities and keep respect for fluid mechanics rules.

Mathematical model for 2-dimensional quality factor $Q_{0,2D}$. Geometrically the quality factor of RFQ cavity is proportional to cross section area and perimeter deviation multiplied by coefficient which includes specifics of the RFQ cavity:

$$Q_{0,2D} = \frac{S}{L}\kappa, \quad (3.4)$$

where

S – cavity cross section area, mm²:

$$S = z^2 - (a + R_0 + c + d + e)^2 - \frac{1}{2}\pi R_0^2 - 2R_0c - 2R_0d - df - 2R_0ef - 2(eg - (gh + R_1^2 \cos^{-1}(\frac{R_1 - h_1}{R_1}))) - (R_1 - h_1)\sqrt{2R_1h_1 - h_1^2} - 2(k + \frac{l}{2})m - (k^2 - (\frac{1}{2}k^2 + R_2^2 \cos^{-1}(\frac{R_2 - h_2}{R_2}))) - (R_2 - h_2)\sqrt{2R_2h_2 - h_2^2}; \quad (3.5)$$

L – cavity cross section perimeter, mm:

$$L = a + \frac{\pi R_0}{2} + c + \sqrt{d^2 + f^2} + 2R_1 \cos^{-1}(\frac{R_1 - h_1}{R_1}) + R_2 \cos^{-1}(\frac{R_2 - h_2}{R_2}) \quad (3.6)$$

κ – coefficient adopted for 750 MHz RFQ design baseline, $\kappa = 890.9$;

$a, c, d, e, f, g, h, k, l, m, z, R_i$ – geometrical elements of cavity, see Fig. 3.2.

Result validation table POISSON/SUPERFISH vs mathmodel S/L

Table 3.1.

Cavity $Q_{0,2D}$ values S/L vs. SUPERFISH

Design name	New mathmodel (NM) & SUPERFISH (SF) design parameters						$Q_{0,2D}$ value NM	$Q_{0,2D}$ value SF	Q value deviation, %
	Perimeter, mm	Area, mm ²	Area/Peri meter	R. Frequency, MHz	Tip R, mm	Aper ture R, mm			
HF-RFQ	151.34	1397.89	9.237	716.56	1.504	1.935	8044.26	8028.51	0.19
PIXE	139.9	1148	8.206	728.97	1.439	1.439	7146.45	7156.49	-0.14
Carbon	142.15	1202	8.456	709.78	1.411	1.411	7364.17	7273.45	1.25
RoundDesign	143.04	1397.89	9.773	714.75	1504	1.935	8511.03	8608.20	-1.13
Tangency+F	154.84	1397.89	9.028	716.59	1.504	1.935	7862.43	7811.74	0.65
AM390	149.72	1397.87	9.337	716.44	1.504	1.935	8131.18	8138.77	-0.09
AM 1/4 RFQ	151.38	1445.7	9.550	703.25	1.504	1.935	8317.19	8254.51	0.76
AM250-200 μ m	152.1	1475.2	9.699	736.70	1.304	2.135	8446.73	8569.27	-1.43

From Table 3.1. it is clearly visible that **AM 1/4 RFQ** is designed with compromise to allow full capability of tuning options by plungers, but with features of AM it is feasible to rise static Q factor even by ≈ 7.2 % in case of “round” design.

3.2. Challenges of RFQ AM

Conventionally the pure copper RFQ's are manufactured by multistep machining and brazing technology. Several literature sources are referencing on complex multistep manufacturing technologies for linear accelerators [14]. Fourteen step development of pure copper PIXE-RFQ was introduced at CERN by S. Mathot more than 10 years ago, but over the time conventional manufacturing technology has evolved in line with the latest advances in machining and brazing technologies. The last published version was presented and updated by the development team in 2018 [15].

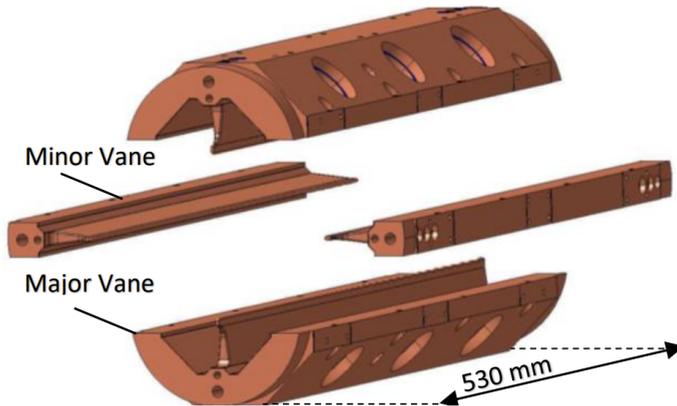


Fig. 3.4. Exploded view of PIXE-RFQ module assembly, two major vanes and two minor vanes [16].

An RFQ is a critical component of particle accelerators featuring strict technical requirements in order to be able to successfully operate. At first glance, it appears that its stringent requirements (see Table 3.2.) are unreachable by the current state-of-the-art of AM systems. However, the continuous developments in AM systems and related post-processing technology are steadily approaching the levels of precision, surface quality, and manufacturing predictability required by RFQs. The experimental testing activity of this proof-of-concept was performed by commercially available, state-of-the-art laser-based AM technology, which is suitable for pure copper manufacturing. Table 3.2. and Fig. 3.5. summarizes the main parameters of the design and manufacturing of the pure copper RFQ.

The manufacturing experiment was carefully designed and planned, keeping in mind the requirements mentioned in Table 3.2.. To ensure the functionality of the RFQ, the geometrical accuracy and shape of the manufactured surfaces are of utmost importance, as indicated by the values of 20 μm for the vane tip and 100 μm for all other cavity surfaces. The most relevant target value here is the RFQ vane tip and its modulation profile, which is the core element for beam transport; therefore, particular attention and careful measurements should be devoted to the vane tip. It is clear that, if AM cannot

Requirements for the Prototype RFQ [17]

Challenge	Target
Geometrical accuracy	20 μm on vane tip, 100 μm elsewhere
Surface roughness	$R_a = 0.4 \mu\text{m}$ for all inner surfaces
Cavity Quality factor	$> 90 \% Q_0$
Cooling performance	$\Delta L < 2 \mu\text{m}$
Vacuum	10^{-7} mbar
Electrical conductivity	95 % of pure copper IACS
Peak electric field on surface	$\sim 40 \text{ MV/m}$

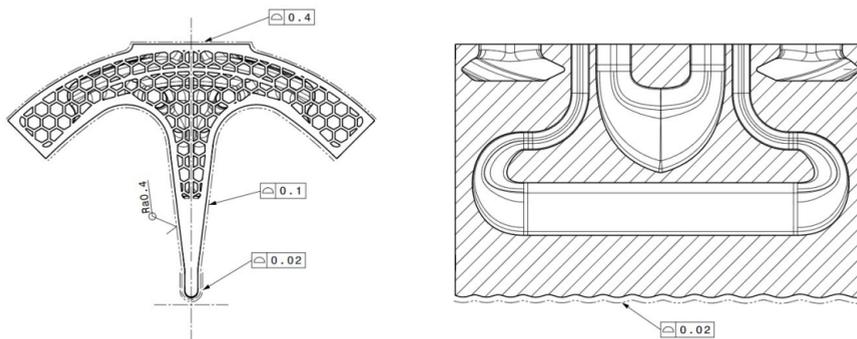


Fig. 3.5. Geometrical accuracy target for prototype.

provide enough precision for the modulation geometry, beam transport and acceleration cannot be ensured. Furthermore, the surface arithmetical mean roughness value R_a has to be kept at a level of about $0.4 \mu\text{m}$. The surface roughness has to be shallower than the penetration of high-frequency currents in the metal “skin depth” to avoid considerable reductions in the Q factor value of the RFQ resonator and proportional increases in its power consumption and in the cost of the radio frequency system. Moreover, large values of R_a might increase the sparking probability of surfaces subject to high electric fields. Although surface roughness is critical for the functionality of RFQ, such values are rather difficult to maintain with conventional AM technology and might require post-processing of the surfaces transporting the radio frequency current. The vacuum value of 10^{-7} mbar was set to minimum required value for the RFQ, as reference circular accelerators often require higher vacuum values. The electrical conductivity is of utmost importance and has a decisive impact on RFQ efficiency. The highest electrical conductivity can be reached only with high chemical purity and density of the base material, e.g., copper. In the case of AM, the chemical purity of the final product depends not only on chemical cleanness of powder, but also on the manufacturing chamber’s protection against oxidation. It is important to note that the oxygen-free pure copper powder grains tend to oxidize in a standard room environment and at room temperature. The lower electrical conductivity

of the RFQ, in turn, will proportionally increase the required operational power of the accelerator, in a similar way to the roughness, and will generate extra heat on the vane surfaces. Therefore, the target value for the electrical conductivity for this proof-of-concept was set to 90 % that of ideal copper according to the International Annealed Copper Standard (IACS). Finally, the voltage holding properties are crucial for the successful operation of the RFQ. Naturally, these properties are directly affected by any mechanical and chemical inclusions, and the homogeneity of the RFQ material itself. Considering some existing RFQ designs, a target value can be empirically defined at about 40 MV/m peak surface field. However, it was clear that not all RFQ-specific requirements could be achieved at this initial proof-of-concept stage (e.g., roughness, degassing, and voltage holding). In the proposed prototype, design emphasis was given to the verification of AM capabilities for the RFQ geometrical accuracy (manufacturing tolerances) and surface quality (roughness), and to the demonstration of improved mechanical design advantages.

3.3. Comparison of practically achievable versus original HF-RFQ Q-factor value

From a practical point of view, maximum Q-factor value, which is practically achievable, relates to “round design”, see Fig. 3.6. In comparison to existing conventionally manufactured HF-RFQ, which was designed and built between 2016 – 2018 and has already highly optimized 2D geometry, but by AM application, theoretically could be improved from 8028.5 to 8608.2, which is 7.2 %. In practical values, it means cost reduction on RF power source by 7.2 % as well as reduced electricity consumption by the same ratio.

In general, physical accelerator lifetime cost reduction is directly relates to the Q factor value and depends on:

- RF power source size;
- accelerator lifetime power consumption.

Sample calculation was done based on HF-RFQ design, where the average RF power consumption is 16 kW and the peak power is around 400 kW [18]. The average industrial RF power source costs approximately 1 Euro per Watt, resulting in a price of 400,000 Euros for a 400 kW RF power source. In the case of the most economically viable “round design” cavity, the theoretical savings on capital costs are estimated to be approximately 28,000 Euros. Further exploitation economy gained from annual power consumption, based on 300 days 24 hour operation and electricity cost 0.2 Eur/kWh reaches 1659 Eur/year, which is rather a negligible gain if compared to capital investments used to build accelerator facility. However “round design” creates complexities for frequency tuning, tuners design and calculations therefore, for the first prototype, the **AM 1/4**

RFQ design was chosen. Further, was calculated economical gain over the conventional HF-RFQ, where the Q value advantage of AM 1/4 RFQ is approximately **2.81 %**, which in capital costs is 11 240 EUR, but the exploitation cost reduction is 647 EUR/year. In fact, in different regions of our planet, electricity cost varies widely due to market demand, and 0.2 EUR/kWh price is rather close to the lowest price offer, in addition overall tendency of electricity prices is constantly growing therefore, economy of the exploitation for some periods can easily rise up to five times.

3.4. Optimization of geometry design and thermal management

Geometric properties. From technical point of view, in most of the RFQ design cases, the development and validation of structure starts with input parameters for general design, like: type of accelerating structure, application field, used materials, then further steps arriving to the cavity shape development of potentially most effective structure, which is tuned for specific performance. However, for current study, the development is different: the initial source for design was CERN's developed HF-RFQ, which already is proven and accepted by field experts [19]. Certain changes in shape were designed to be able improve static quality value by application of AM advantages. However, most significant improvements there were gained on internal shapes.

As it is well known in accelerator community, LANL did significant contribution and pioneering in the field of RF devices. In eighties of the last century, the Los Alamos Accelerator Theory and Simulation Group (AT-6) maintained and distributed a standard version of the Poisson-Group codes (LATTICE, AUTOMESH, TEKLOT, POISSON, PANDIRA, MIRT, FORCE, SUPERFISH, and SF01). In general, these codes are the product of man-decades of development under the guidance of R. F. Holsinger and K. Halbach. Most of RF system developers still are using these codes, which are available from the LANL homepage by registration and are free of charge [20]. The first step to enter in SUPERFISH calculation is to propose approximate cavity size and shape. It could be done by using previous, already working design samples and modify them by scaling or geometrical shape improvements tuned to application case. The calculations are summarized in Table 3.3..

The current Thesis is based on CERN's 750 MHz HF-RFQ design line. These are most widely used RFQ's with common applications in medicine and industry. Therefore, improvement could give higher economical and societal effect for human well-being. The CERN's compact size RFQ's are relative recent development, and it becomes already as a design line wich includes HF-RFQ, PIXE and carbon-ion RFQ. The SUPRFISH calculation results for above mentioned 750MHz structures are given in Table 3.3..

Thermal design development. The basic concept of the thermal management

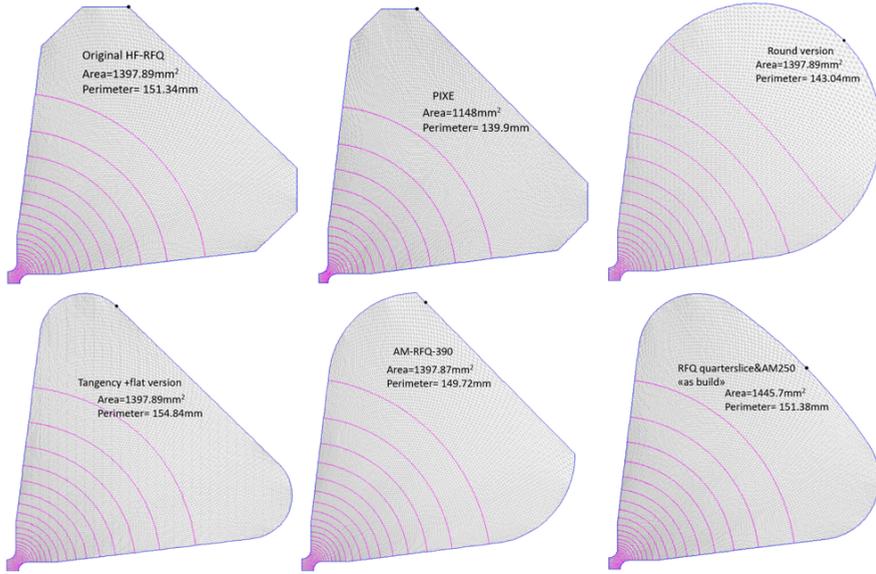


Fig. 3.6. SUPERFISH solutions for 750MHz cavity 2D geometries.

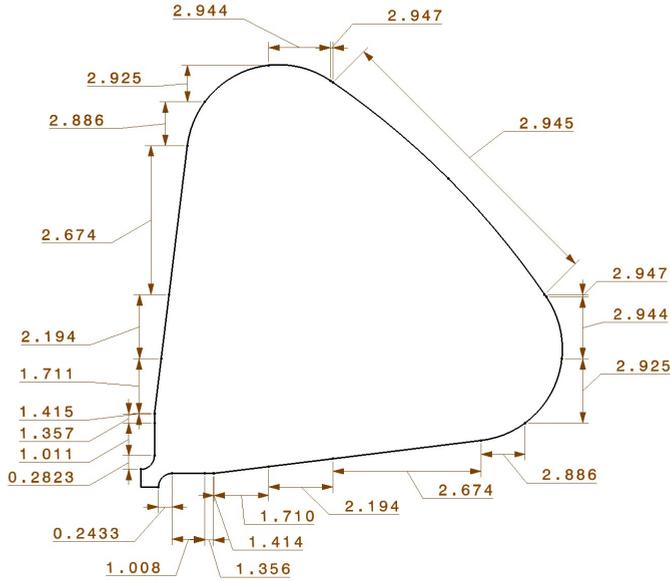
for AM produced RFQ was modeled on the ANSYS 19.1 Steady-State Thermal analysis workbench. Input data for ANSYS simulation were based on general approximations and assumptions from the recently built at CERN 750 MHz PIXE RFQ [22]. The initial analysis was based on a number of crucial input data points. The cooling channel temperature was maintained at 22 °C, the heat flux on the vane tip was 2×10^{-3} W/mm², the flux on the vane and internal walls was 8×10^{-3} W/mm², and additional negligible values for heat convection from the outer surfaces. The sample results of the thermal analysis are presented in Figure 3.8.. Both CAD models were tested with the same heat flux values to highlight the thermal advantages of the AM prototype. The initial results of the Steady-State thermal analysis demonstrated that the difference of 0.8 °C, does not pose any risk to the RFQ functionality. Further development and simulations were based on heat loss calculations by SUPERFISH code (Fig. 3.7.) and applied as constrains for simulations to both designs (Fig. 3.8.). The proposed design concept, particularly the internal honeycomb structure and enhanced cooling channels, could prove highly beneficial for the AM-manufactured RFQs and other complex (in terms of shape and structure) accelerator components.

In order to address the heat flow distribution in the RFQ model and the thermal stresses dispersion, and the construction of the generated deformation state, in any of its locations, the energy conservation law (Fourier law), described by the differential equation,

Table 3.3.

SUPERFISH Calculation Results for 750MHz RFQ Cavities [21]

Design name	Peri-meter, mm	Area, mm ²	Area/ Peri-meter	R. Fre-quency, MHz	$Q_{0,2D}$ value	Tip R, mm	Aper- ture R, mm	Shunt im-pedance, M Ω /m	Stored energy, $\times 10^{-5}$ J/cm
HF-RFQ	151.34	1397.89	9.237	716.56	8028.51	1.504	1.935	6303.89	6.8775
PIXE	139.9	1148	8.206	728.97	7156.49	1.439	1.439	6286.239	6.87484
Carbon	142.15	1202	8.456	709.78	7273.45	1.411	1.411	6620.685	6.87443
RoundDesign	143.04	1397.89	9.773	714.75	8608.20	1504	1.935	6737.561	6.91407
Tangency+F	154.84	1397.89	9.028	716.59	7811.74	1.504	1.935	6133.634	6.90091
AM390	149.72	1397.87	9.337	716.44	8138.77	1.504	1.935	6388.894	7.55072
AM 1/4 RFQ	151.38	1445.7	9.550	703.25	8254.51	1.504	1.935	6578.903	6.90091
AM250-200 μ m	152.1	1475.2	9.699	736.70	8569.27	1.304	2.135	6574.460	4.36554

Fig. 3.7. Graphical representation of SUPERFISH calculation result for power distribution on cavity walls, average values for length sections, W/cm²

is used [23], [24];

$$\rho c \frac{\delta T}{\delta t} - \left(\frac{\delta}{\delta x} (k_x \frac{\delta T}{\delta x}) + \frac{\delta}{\delta y} (k_y \frac{\delta T}{\delta y}) + \frac{\delta}{\delta z} (k_z \frac{\delta T}{\delta z}) \right) - \dot{q} = 0, \quad (3.7)$$

where

ρ – the density of the studied solid material, kg/m³;

c – the specific heat, $J \cdot K^{-1} \cdot kg^{-1}$;

k – the coefficient of thermal conductivity;

\dot{q} – the internal heat generation rate, per unit volume, per unit time, W/m³/h;

x, y, z – coordinates;

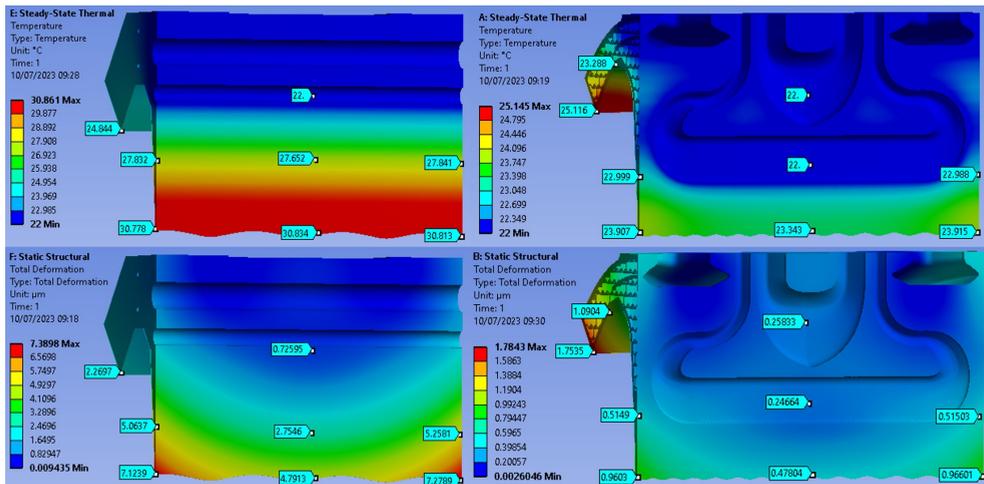


Fig. 3.8. ANSYS FEM Steady-State Thermal temperature distribution in RFQ body and structural distortion due to temperature distribution by Static Structural analysis.

t – time;

T – the variable temperature for the coordinates x, y, z and time t .

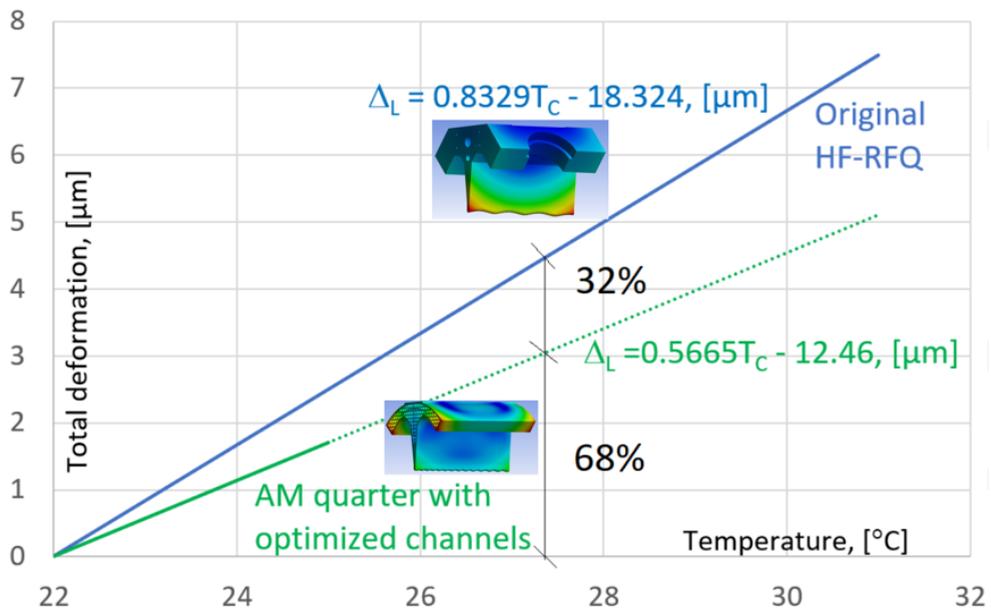


Fig. 3.9. A comparison of the temperature/deformation relations in the CAD models of the HF-RFQ and AM RFQ.

Finite element equations for solid problems can be obtained by applying the weighted

residue method to the differential equation that governs this problem [23]. Matrix form of the finite element equation:

$$[k]\{\delta\} = \{F\} + \{F_0\} \quad (3.8.)$$

ANSYS Steady-State Thermal and Static Structural finite element method (FEM) application, which is based on Equation (3.8.) and applied to original HF-RFQ and AM RFQ models is showing indisputable advantages of AM RFQ cooling channel design. The main advantage is the significant decrease of temperature difference in RFQ body, which further impress to decreasing of deformation level due to uneven temperature field distribution. Colour maps of temperatures and distortion are shown in Fig. 3.8.. Further, temperature and deformation values were compared and are given in Fig. 3.9., which is showing an impressive 32 % advantage of AM manufactured sample. The report on ANSYS simulation input parameters and constraints is given in Annex G of the full text version. Thermal simulation inputs are taken from previously generated SUPERFISH calculation Annex F.

3.5. Conclusions

In general, all of CERN's 750MHz RFQ designs are highly tuned and do not have a significant gaps for considerable improvements using traditional manufacturing. **However, application of AM advantages allows several meaningful advances.** The mathematical model of the cavity profile was created on basic geometrical Equations 3.4., 3.5., 3.6., including physical form restrictions such as minimum vane, wall thickness, cooling channel implementation in vane volume and ideal cavity shape concept. The further developed mathematical model could be used for another size RFQs' design improvement and adaptation for AM, particularly for cavity quality factor improvement.

Thermal simulations of original HF-RFQ and AM prototype designs Fig. 3.9. are showing around 32 % improvement in thermal deformation over traditionally manufactured HF-RFQ. Thermal distortion simulation and the obtained temperature/deformation equation are valid only for the current CAD model, and simulation values are strongly affected by cooling channel shape, routing and concept design. The thermal management possibilities of AM RFQ prototype have significant advantages over conventionally manufactured RFQ. The key benefits are improved cooling channel shape, routing and increased surface areas. One of the main goals of cooling channel development is to minimize temperature differences in the RFQ body, reducing structural distortion and significantly impacting beam stability and quality. Improvements can be achieved by AM technology, as demonstrated in this research.

4. COMPARISON OF THE MANUFACTURING TIME: AM VERSUS CONVENTIONAL MACHINING

The quarter sector of the AM RFQ was printed at Fraunhofer IWS on TRUMPF Truprint 1000 Green Edition machine in a 16 hours and 29 minutes with 3267 layers of 30 μm layer thickness. Therefore, it is possible to calculate the average time for one layer manufacturing cycle, which includes exposure and coating operations. Therefore, for the quarter RFQ prototype, 18.16 seconds were spent for one layer cycle. Moreover, the average build speed was calculated, as the prototype model's volume can be easily extracted from CAD software. Therefore, average volume build speed was obtained, which is 4.82 cm^3/min . However, this is an indicative value and build speed can vary depending on layer thickness, scanning speed, and percentage of exposed surface. TRUMPF Truprint 1000 Green Edition machine can build up to 25 cm^3/h [25], which is roughly five times faster than it was done for the RFQ sample built. It is necessary to mention that the actual build rate includes exposure and coating steps and depends on system configuration, process parameters, material and filling percentage of the build chamber. Then theoretical time to build a full-size AM RFQ section with a single laser source machine can be obtained by multiplying the quarter sector by four to get the entire section, and further by 5.3 to obtain a whole-length volume. Finally, the full section and length RFQ build time is 349.8 hours or 14 days and 13.8 hours. Here is necessary to add time for de-powdering, removing from the machine, build-plate, support removal, and transfer to the post-processing facility, which can take up to one working day. The further part should travel to the surface improvement facility, where a single well-organized and developed post-processing cycle in the optimistic scenario can take up to 24 hours. After surface roughness treatment and cleaning operations, metrology inspection is critical for final flange and port machining.

The conventional manufacturing procedure is far more complicated and time-consuming than AM technology, it consists of 11 major steps and 58 sub-steps in total [15]. Furthermore, even most sub-steps often contain multi-step procedures, covering various processing and preparation techniques. The complete machining cycle length for two modules of PIXE RFQ for the ELISA project took 16 months [26]. Overall machining time is extended because of several cleaning, metrology and stress relief treatments, which must be included between major manufacturing steps. Conventional manufacturing technology at CERN was developed and described by S. Mathot [15]. In fact, the novel technology also includes cleaning and metrology steps as they are critical for both technologies, but in the case of the novel technology the final product is monolith object.

Conclusions. One of the most significant advantages of AM over conventional manufacturing is a low number of transportation operations between different types of machines,

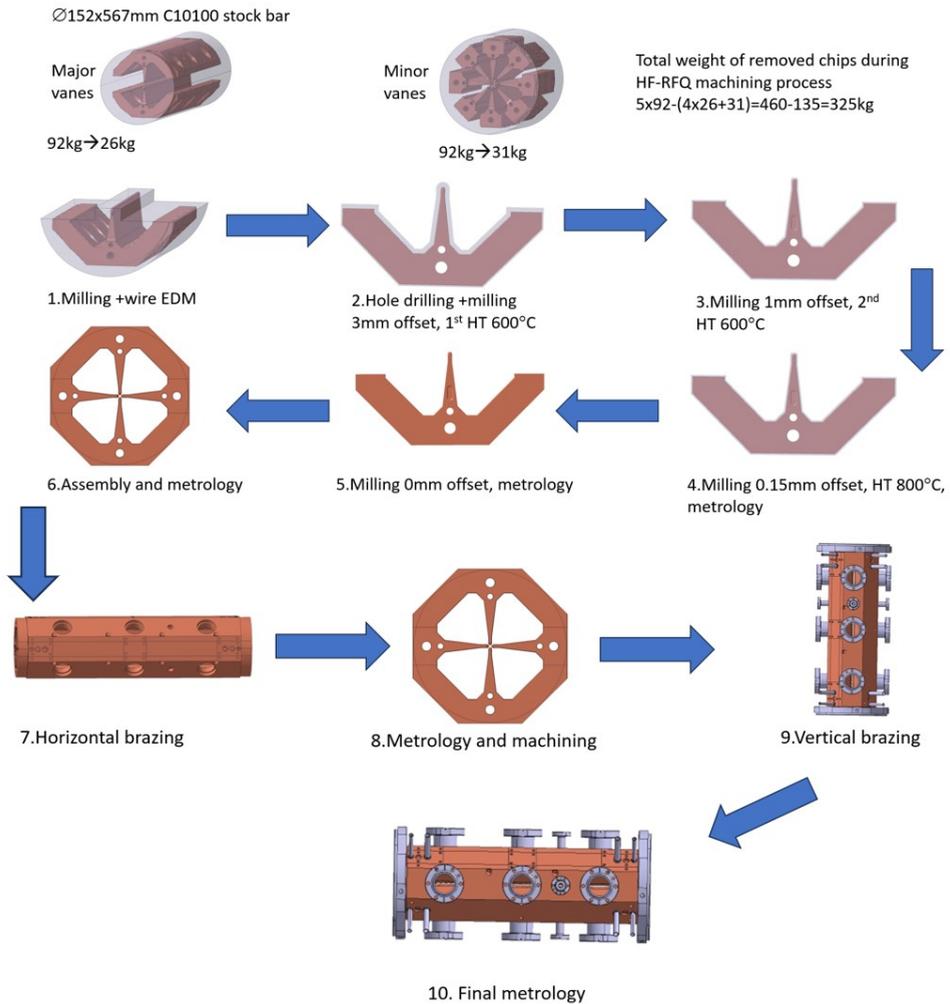


Fig. 4.1. The major steps in conventional manufacturing technology of RFQ.

facilities and sites during the entire manufacturing process. Technically, AM replaces most of the first nine major manufacturing steps of conventional machining with its first three steps, with a much lower potential for occasional failures. Therefore, AM monolithic build has over 75 % shorter machining – manufacturing time than conventionally built brazed versions.

Machining time calculation is partly estimated and based on CERN's and I.FAST project WP10 activities.

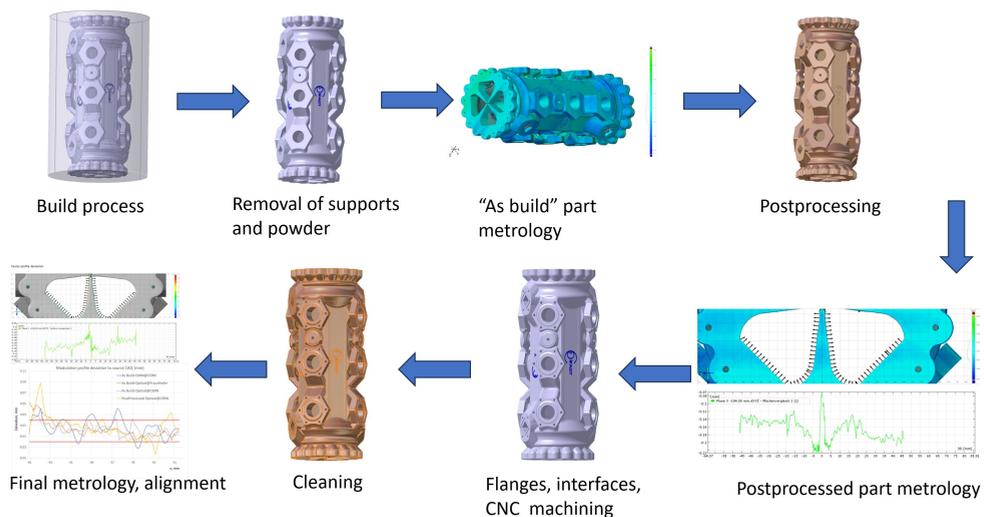


Fig. 4.2. The steps for novel manufacturing technology of RFQ.

Table 4.1.

Comparison of Conventional and AM Manufactured RFQ

Parameter	Conventional	Novel	Improvement, %
Manufacturing time, months	16*	4**	400
Material waste, %	41.2	2.5	1648
Number of manufacturing sub-steps	52***	15	346
Weight****, kg/m	175	55	318
Geometric accuracy	100 %	90 %	-10
Cooling performance by Δ_L , μm	0.8329T _C -18.324	0.5665T _C -12.46	32
Quality factor Q_{2D}	8028.51	8254.51	2.6

* – the value from the ELISA project for PIXE RFQ;

** – empirical values based on IFAST WP10 activities;

*** – PIXE technology;

**** – weight calculation for full RFQ sector/brazed unit.

5. PROOF-OF-CONCEPT PROTOTYPE OF AN ADDITIVE MANUFACTURED RFQ

5.1. Experimental setup and planning

The idea about development of the first AM prototype came after the analysis of situation and needs of accelerator community. Inside of H2020 I.FAST project task WP10.2, was found technical and knowledge support to realize the first trial of manufacturing such size an oxygen free, pure copper structure. Choosing the right laboratories and equipment to prove the technology's performance was a critical part of the experiment. It was clear from the outset that the AM component would require post-processing, which would require the involvement of an industrial partner. Rösler Italiana SRL was therefore invited to collaborate, and further exploration of technologies was undertaken with input from surface engineering experts at BINC Industries.

Print job realization was planned at Fraunhofer IWS, as the institution is well known among experts of pure copper AM technology and has vast knowledge and machine tools tuned for pure copper AM technology developments. Collaboration was possible thanks to long-standing cooperation between RTU and Fraunhofer IWS.

5.2. Development of the AM process of pure copper RFQ

In order to achieve the best possible results, the latest developments of AM technology and manufacturing equipment were deployed for the production of the first pure copper RFQ prototypes. A TruPrint1000 Green Edition AM machine in combination with a green TruDisk1020 disc laser providing the laser beam wavelength of 515 nm and maximum laser power of 500 W was used for sample manufacturing at Fraunhofer IWS in Dresden. Dedicated machine allows a cylindrical build volume of 97 mm in diameter and 100 mm in height [27]. The TRUMPF SE+Co.KG preset pure copper processing parameters with layer thickness of 30 μm , hatch distance 120 μm , line energy input 0.808 J/mm and scanning strategy were used throughout carefully monitored manufacturing process.

As a production material, m4pTM PureCu gas-atomised spherical shaped powder was used, which was confirmed with the Camsizer X2 and dynamic imaging analysis (see Table 5.1.). The sphericity was 0.923 according to scanning electron microscope imaging. The particle size distribution was confirmed to be between 19.5 μm and 34.9 μm , which is common for a PBF-LB process.

The choice between powder types, which fits better for RFQ requirements, and reliable AM process was clarified in previous research of S. Gruber, where she proved Cu-ETP advantages over Cu-OFHC [28]. Therefore, the decision fell on 30 μm grain size Cu-ETP powder [17].

Experimental part of Thesis is based on design development and modification of actual CERN's HF-RFQ. Decision to take HF-RFQ as a model for development was taken

Table 5.1.

Main Characteristics of Particle Size Distribution of Cu-ETP [17]

Powder	D10 in μm	D50 in μm	D90 in μm	Sphericity
Cu-ETP (Electrolytic Tough-Pitch: pure copper)	19.5	26.2	34.9	0.923

because of the size, complexity and potential manufacturing cost reductions.

Initial design development was started from HF-RFQ, which already is a novel development in accelerator community. HF-RFQ was introduced to accelerator community in the end of 2016. The HF-RFQ project development was taking over 2 years [29].

5.3. Post-processing

In the context of AM, post-processing refers to a set of actions or procedures carried out on a 3D-printed object after it has been removed from the AM machine built chamber. These extra actions are required to enhance the printed part's final look, usability, and performance. The output of AM may not always fulfill the specified specifications or quality requirements without extra treatment, hence post-processing is often necessary. For real cases, often specific post-processing steps are required and can vary depending on the AM technology, the material used, and the intended application of the part.

For initial development stage prototype surface quality and geometry were set as most critical elements in post-processing hierarchy. Post-treatment itself plays a vital role for achieving the desired quality, functionality, and aesthetics. For complete technology development, three industry well known post-processing techniques were applied to achieve initially set roughness and geometrical accuracy aims.

Traditional mass finishing. The process was performed in Rösler Italiana SLR 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 quarter RFQ, a three-step process was designed:

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

Chemically assisted finishing. Similarly to traditional mass finishing processes, the surface post-processing was obtained through the combination of the mechanical abrasion on the surface and the chemical reactions mediated by the CMP 03/21L compound. The number of treatment steps to reach targeted roughness value $Ra = 0.4 \mu\text{m}$ were the same as in mass finishing method however, the first step, which is a chemically assisted process,



Fig. 5.1. Quarter sector RFQ sample – chemically assisted finishing [30].

is significantly shorter.

Step 1. – Grinding: 1h with Rösler media RXX 07/14 ZS and compound CMP 03/21 L. Step 2 and 3 – same as in the mass finishing. Visual result is presented in the Fig. 5.1..

MMP TECHNOLOGY®. In order to be able to find most suitable and applicable technology for AM pure copper sample part finishing, the decision for trial application of MMP TECHNOLOGY® was taken. In general, MMP TECHNOLOGY® (Micro Machining Process), invented by BinC Industries, is focusing on high quality part super-finishing, where during processing surfaces are treated by selective removal of specific range of roughness. Unlike traditional polishing, MMP TECHNOLOGY® differentiates itself by its ability to finely control the material removal process. MMP TECHNOLOGY® can deliver finely controlled surfaces ranging from matte to brilliant mirror-like finishes. MMP TECHNOLOGY®'s advantages include reproducibility, homogeneity, precise preservation of the exact form of the part, and predictable costs [31].

MMP TECHNOLOGY® consists of a combination of a proprietary mechanical and physical process aided by a catalyst that activates the engineered microtool technology. The mechanical part of the process is provided by a machine whose very high energy movement creates a flux.

Conclusions. Required Ra values $< 0.4 \mu\text{m}$ were successfully accomplished by the three different post-processing methods, see Table 6.5.. For the conventional surface mass finishing, processing time was longer, however, material removal was smaller, in comparison to chemically assisted process, where processing time was smaller and material removal significantly higher. 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 finishing (see Fig. 5.1.) 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.

6. EVALUATION OF GEOMETRICAL PRECISION AND SURFACE ROUGHNESS QUALITY FOR THE ADDITIVELY MANUFACTURED RFQ PROTOTYPE

In order to trace and evaluate the results of each technological stage, multi-step control techniques were applied during prototype manufacturing. One of the first controls is the built-in scanning camera of the TruPrint machine, which records each build layer and helps recognize unexpected machining issues. This helps to trace machine faults or technological glitches if any occurs during the long build job. Further, follow geometry and surface roughness tests in metrology labs. For the current case, first-initial geometry and surface roughness measurements for the “as-built” part were measured in Fraunhofer IWS by optical scanning techniques and ISO standardized surface roughness profile measurements. Further in-depth measurements for geometry and roughness for the same sample were repeated at the CERN’s EN-MME metrology lab, in addition to the geometrical measurements on the coordinate measurement machine (CMM). For further samples, tests were executed only at the CERN’s EN-MME metrology lab, and official test results were documented in the CERN’s EDMS system [32], [33].

Geometry measurements on CMM. Contact type coordinate measurements were

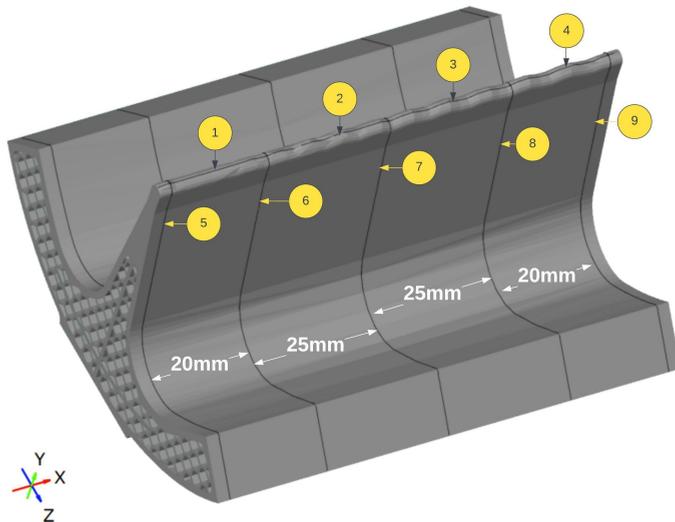


Fig. 6.1. CMM measurement track section numbering.

executed on ZEISS Prismo Ultra 12-18-10 bridge-type CMM with a moveable bridge. The

inspection of cavity shape was done in five crosssections, perpendicular to beam axis line (tracing lines 2 to 6 in Fig. 6.1.) of RFQ. One of most crucial measurements is the vane tip modulation inspection, which was done by a plane which goes through beam axis and intersects the modulation surface in two symmetrical parts (geometry tracing line 1 in Fig. 6.1.). To understand the manufactured part’s geometrical accuracy, the measured coordinates were compared with STL mesh model, from which the part was build.

Optical scanning of geometry. The first “as-built” part optical scan was performed in Fraunhofer IWS, but further prototype exploration was done at the CERN EN-MME metrology lab by Creaform MetraSCAN BLACK™ – Elite scanner with 0.025 mm measurement accuracy and volumetric precision of 0.064 mm at 9.1 m³[9], first applied inspection software Polyworks MS2020, for further more deep analysis, ZEISS GOM 2018 software was used. Several series of measurements were executed in the CERN’s EN-MME metrology laboratory by ZEISS Prismo Ultra 12-18-10, which is bridge-type CMM with a movable bridge.

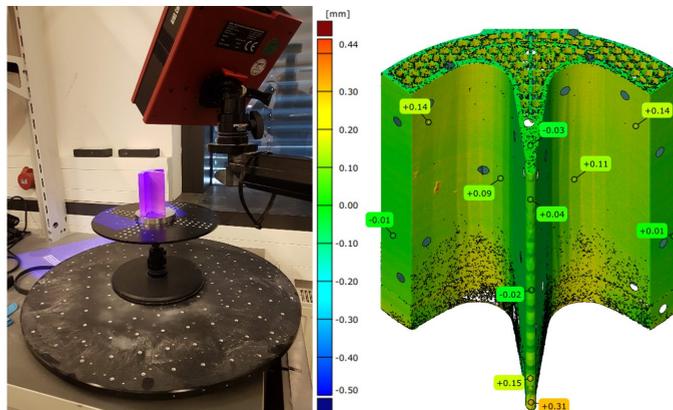


Fig. 6.2. Optical scanning and Point Cloud data comparison with as-designed CAD model at Fraunhofer IWS.

Table 6.1.
“As-Built” Part Vane Tip, Surface Deviation for Sections, Deviation Range Values, μm

Measurement	Tracks/Sections #				
	1	2	3	4	
Modulation sections					
Profile cross sections	5	6	7	8	9
Optical XY plane (modulation)	140	130	80	200	
Optical YZ plane (normalsection)	140	130	40	30	200
CMM XY plane (modulation)	200	160	70	200	
CMM YZ plane (normalsection)	140	140	40	30	200

Table 6.2.

“As-Built” Cavity Geometry Measurements, Deviation Range Values, μm

Measurement	Tracks/Sections #				
Modulation sections	1	2	3	4	
Profile cross sections	5	6	7	8	9
Optical XY plane (variation)	50	150	150	130	
Optical YZ plane (normalsection)	150	150	150	150	150
CMM XY plane (variation)	50	50	50	50	
CMM YZ plane (normalsection)	100	100	100	100	100

Table 6.3.

Post-Processed Sample, Surface Deviation for Sections, Deviation Range Values, μm

Measurement	Tracks/Sections #				
Modulation sections	1	2	3	4	
Profile cross sections	5	6	7	8	9
Vane tip XY plane (modulation)	140	130	80	200	
Vane tip YZ plane (normalsection)	140	130	40	30	200
Cavity XY plane (axial section)	200	160	70	200	
Cavity YZ plane (normalsection)	140	140	40	30	200

Surface roughness measurements. The surface roughness measurements described in the Thesis were carried out in several laboratories in order to facilitate comparison of the results and to ensure the reliability of the values obtained. The initial surface roughness profile of the first prototype sample was measured at Fraunhofer IWS by a perthometer Surfcom Touch 50 [34], which is a contact profilometer from Accretech, for surfaces where $Ra = 0.4 \mu\text{m}$ is required – on both sides of the vane (see Fig. 6.3. measurement numbers 9 and 10) and cavity internal surfaces (see Fig. 6.3. measurement numbers 6 and 8). Measurements have been repeated three times at each area.

The surface arithmetic mean roughness (Ra), on average, was $14.32 \mu\text{m}$, and the maximum height of the profile (Rz) was $116.7 \mu\text{m}$. Further additional measurements were executed to obtain a more comprehensive understanding of the surface quality of the prototype. The summarized indicative roughness measurement results are provided in Table 6.4..

Although these first roughness measurements of the proof-of-concept RFQ show that the obtained roughness values were still far from the required $Ra = 0.4 \mu\text{m}$, it is important to keep in mind that these results were obtained without any specific adaptations of the AM technological process to achieve better surface roughness outputs.

Post-processed part inspection. The current research covers two RFQ quarter section prototype manufacturing and post-processing by two different companies – Rösler

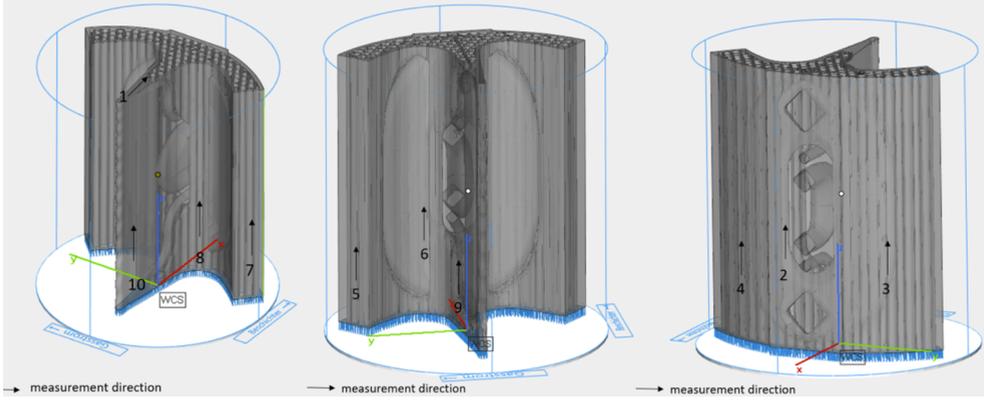


Fig. 6.3. Surface roughness profile measurement trails.

Table 6.4.
RFQ Proof-of-Concept Surface Roughness Profile Values for “As-Built” Part According to ISO 4288, Measured at Fraunhofer IWS metrology lab [17]

Location	Measurement No.				Measurement No.			
	Ra (μm)				Rz (μm)			
	1	2	3	Mean	1	2	3	Mean
6	10.4	12.4	12.8	11.9	84.2	89.5	85.6	86.5
8	15.1	15.0	15.3	15.1	148.8	138.7	143.0	143.5
9	13.8	14.9	13.5	14.1	117.2	123.6	104.7	115.1
10	13.9	14.9	14.9	14.6	117.5	134.2	103.3	118.3

Italiana Srl. (Italy) and BINC Industries (France). Each company were used different post-processing techniques. Rösler did mechanical and combined chemical-mechanical, but BINC proved their innovative MMP TECHNOLOGY®.

Geometry measurements on coordinate measurement machine. Similarly as for “as-built” part, post-processed part measurements were carried out at CERN’s EN-MME metrology laboratory on the same CMM machine and were compared with as-designed STL model geometry. The measurement procedure and track sections were the same as for “as-built” part. Geometry tracing lines and line numbering are shown on Fig. 6.1..

Optical scanning of geometry. Post-processed part optical measurements were executed at two metrology laboratories at Rösler Italiana Srl. and the CERN’s EN-MME laboratory. CAD and Point Cloud models were compared in Polyworks MS2020 and ZEISS GOM Inspect’2018 environment. Optical inspection results approved initial predictions on roughness and part geometry. Figure 6.4. is presenta a colour map of surface deviation between the as-designed CAD model and the MMP post-processed part Point Cloud model; on the right side of the model there is deviation distribution curve, which gives obvious result that post-processed surface has – 160 μm negative offset from

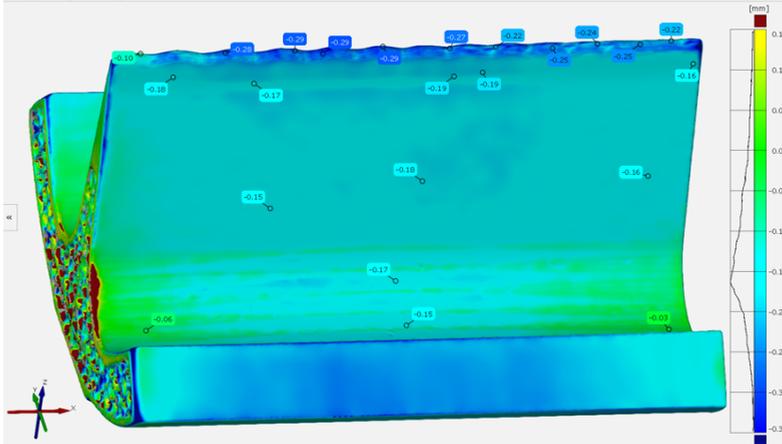


Fig. 6.4. As-designed and Point Cloud model surface deviation colour map for MMP post-processed sample generated by ZEISS GOM Inspect.

as-designed CAD model.

Surface roughness measurements. In general, surface roughness parameters were controlled already during the whole post-processing cycle. Both companies, for all three cases of post-processing, set roughness target to $Ra = 0.4 \mu\text{m}$, as it was required.

At the final stage, additional independent surface roughness measurements were executed at the CERN’s MME metrology laboratory. Surface profile roughness values for all post-processing cases were below $Ra = 0.4 \mu\text{m}$.

Table 6.5.
Surface Roughness Values of 1/4 RFQ Before and After Post-processing

Post processing method	Side	Ra (μm)	Rz (μm)
Before postprocessing		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

Conclusions. The measured average surface profile roughness value $Ra = 15 \mu\text{m}$ of “as-built” prototype is relatively far from initially set requirements, moreover Rz values in some regions are larger than $100 \mu\text{m}$. This could be the main obstacle to reach acceptable high voltage holding characteristics as well as geometric precision further. In order to improve cavity surface roughness values, several approaches of processing were applied and it was shown that initially set targets are reachable without significant difficulties. Average surface profile roughness target $Ra = 0.4 \mu\text{m}$ was reached by all three post-processing methods.

7. VALIDATION OF RESULTS

In order to prove the hypothesis on AM applicability for accelerator parts, validation of AM technology results on high precision geometry and surface roughness quality is critical. AM technology can be tuned to the same precision level as conventional machines, which is critical for the accelerator community. A list of target parameters for AM prototype Table 3.2. was set in the first steps of the Thesis. Further additional data, which are crucial to prove the advantages of AM technology, were found during research. The final list of validation parameters is based on general requirements and several specific ones added during research, and all output results and validation parameters were collected in Table 7.1. for main geometrical and surface roughness validation, and a secondary table for other crucial parameters, Table 7.2.

Table 7.1.
Requirements and Result Validation of HF- RFQ Prototype Geometry and Surface Roughness

Challenge	Target	Result	Compliance
Geometrical accuracy for “as-built” part:			
On vane tip,	$\leq 20 \mu\text{m}$	20 μm	with compensation
Elsewhere on cavity	$\leq 100 \mu\text{m}$	75 μm	with compensation
Vane shape	$\pm 5 \mu\text{m}$	$\pm 5 \mu\text{m}$	with compensation
Vane relative position	$\pm 15 \mu\text{m}$	$\pm 10 \mu\text{m}$	with compensation
Cavity shape	$\pm 20 \mu\text{m}$	–	with compensation
Displacement max (X-Y)	$\pm 50 \mu\text{m}$	–	with compensation
Surface roughness profile R_a for all inner surfaces	$\leq 0.4 \mu\text{m}$	15 μm	none
Geometrical accuracy for “post-processed” part:			
On vane tip,	$\leq 20 \mu\text{m}$	25 μm	with compensation
Elsewhere on cavity	$\leq 100 \mu\text{m}$	80 μm	with compensation
Vane shape	$\pm 5 \mu\text{m}$	$\pm 5 \mu\text{m}$	with compensation
Vane relative position	$\pm 15 \mu\text{m}$	$\pm 15 \mu\text{m}$	with compensation
Cavity shape	$\pm 20 \mu\text{m}$	–	with compensation
Displacement max (X-Y)	$\pm 50 \mu\text{m}$	–	with compensation
Surface roughness profile R_a for all inner surfaces	$\leq 0.4 \mu\text{m}$	0.4 μm	fully

Result values of geometrical accuracy and surface roughness were obtained from series of metrology measurements at Rösler Italiana Srl. and CERN EN-MME metrology labs. As well as from additional analysis by ZEISS GOM Inspect’2018 software.

Vane tip, vane, and cavity measurement analysis give a comprehensive view that on surface regions where STL file meshing does not have sharp triangulation edges, geometric

Table 7.2.

Requirements and Results of HF- RFQ Prototype Secondary Research Parameters

Challenge	Target	Result	Compliance
Measured parameter:			
Electrical conductivity % of pure copper IACS	$\geq 90 \%$	$\geq 99 \%$	fully
Simulated parameters:			
Max temperature difference	$\leq 8.9 \text{ }^\circ\text{C}$	$3.1 \text{ }^\circ\text{C}$	fully
Max temperature difference on tip	$\leq 8.9 \text{ }^\circ\text{C}$	$0.9 \text{ }^\circ\text{C}$	fully
Max total deformation	$\leq 7.3 \text{ } \mu\text{m}$	$1.8 \text{ } \mu\text{m}$	fully
Max total deformation on tip	$\leq 7.3 \text{ } \mu\text{m}$	$0.98 \text{ } \mu\text{m}$	fully
RFQ cavity shape Q-value	≥ 8028	8254	fully

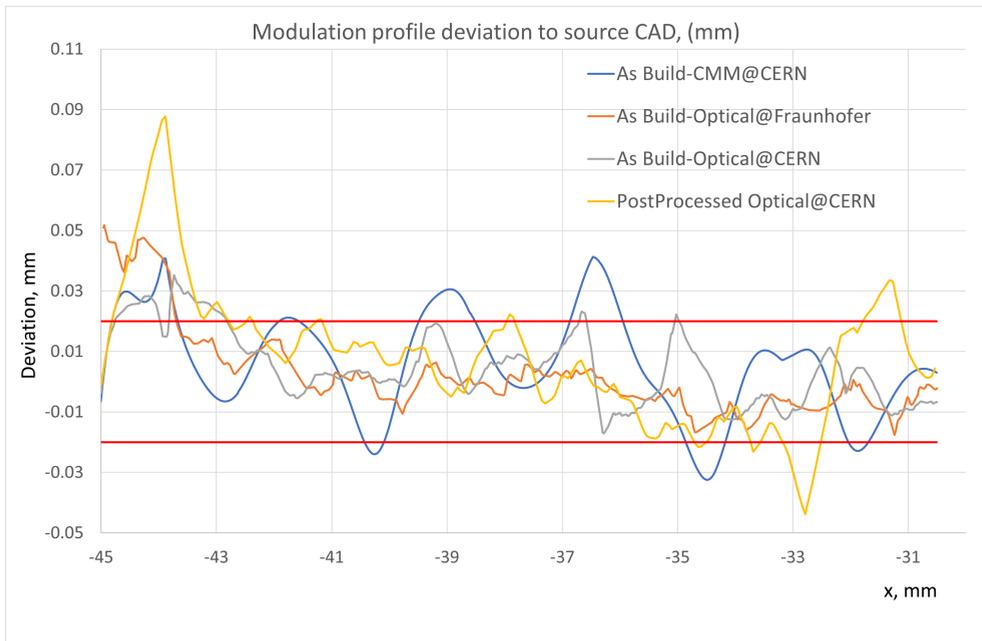


Fig. 7.1. Indicative metrology results for AM build RFQ vane tip modulation deviation.

accuracy measured by two different methods, CMM and optical, is remarkably close to the initially set requirements but for the regions where STL mesh triangulation has relatively narrow and sharp edges with angles smaller than 120° . In fact, “green laser” spot size $200 \text{ } \mu\text{m}$ physically cannot copy contours in the range of $20 \text{ } \mu\text{m}$ accuracy (Fig. 7.1.). PBF-LB technology, as well as further post-processing, is giving additional surface deviation error, which in some cases is higher than the initially set target for the vane tip area, which also is characterized by the yellow deviation line in Fig. 7.1. Technically, it means that

surface STL mesh triangulation in vane tip and cavity curved areas must be larger than the “green laser” melt pool radius. In addition, post-processing magnifies deviation values on sharp edges. This phenomenon has a simple and obvious explanation – if there are any narrow angled edges, they become smooth already in the first post-processing steps. Figure 7.1. proves that CMM and optical 3D scanning techniques give acceptable quality and repeatable results. It also shows the post-processing impact on surface deviation. Post-processing significantly improves roughness, but small radii’ inner and outer edges are still challenging due to the relatively large laser beam spot size.

Table 7.3.
Descriptive Statistics Parameters for Vane Tip Modulation Profile Deviation Values, mm

Parameter	“As-built” short section		Scan.vs.Scan.	Optical long section	
	Optical	CMM	“As-built”	“As-built”	Post-processed
Mean	-0.00025	0.03315	-0.00862	-0.02776	-0.014
Standard Error	0.000235	0.000208	0.000136	0.0003538	0.000757
Median	-0.00033	0.032655	-0.00879	-0.02770	-0.0108
Mode	0.000186	0.027824	-0.0287	-0.02838	0.00189
Standard Deviation	0.00969	0.014434	0.01080	0.01582	0.02045
Sample Variance	0.000094	0.0002083	0.0001168	0.0002503	0.000418
Kurtosis	0.9641	-0.59378	0.8337	-0.4778	0.1326
Skewness	0.2034	0.19665	-0.1776	0.1092	-0.3719
Range	0.05888	0.07511	0.07905	0.0807	0.1077
Minimum	-0.02526	0.004182	-0.04988	-0.065125	-0.0638
Maximum	0.03361	0.079292	0.029168	0.015658	0.0439
Sum	-0.4228	159.583	-54.0736	-55.503938	-10.225
Count	1691	4814	6268	1999	730
Largest	0.03361	0.079292	0.029168	0.015658	0.0439
Smallest	-0.02526	0.004182	-0.04988	-0.065125	-0.0638
Confidence Level (95.0 %)	0.0004624	0.0004078	0.000267	0.0006939	0.001486

Values of electrical conductivity were tested at Fraunhofer IWS (Dresden) and PoliMi (Milano)[35].

Thermal and structural performance values were obtained from ANSYS Steady-State Thermal and Static Structural simulations. In the case of improved design model maximal temperature and deformation values of sample relocated from vane tip area to periphery of cavity, which gives less distortion on most critical region (vane tip) and less theoretical performance loss. See visualization of thermal and deformation map in Fig. 3.8..

The last value in result validation Table 7.1. is RFQ cavity shape statistic quality value Q, which normally is a starting point for new RFQ design. In the Thesis it is used as a quality evaluation value, which is 2.8 % higher than standard HF-RFQ’s quality value.

For analysis of vane, vane tip modulation and cavity surface profile deviations between measured Point Cloud and “as-designed” CAD models standard descriptive statistics were applied. General analysis formulas were used to calculate statistical parameters [36].

Descriptive statistics of profile deviation were calculated in MS Excel environment, the

results for “as-built” and “post-processed” parts were extracted from CMM and optical scan output files, and processed in CATIA and ZEISS GOM Inspect environments. The results of descriptive statistics were summarized in Table 7.3.

8. CONCLUSIONS

The study has substantiated that AM can provide a significant breakthrough for the fabrication of an RFQ by combining PBF-LB/M and adopted post-processing technologies. Recent advancements in powder bed fusion offer superior opportunities to enhance the manufacturing processes and design of the RFQ as well as minimize the machining duration and associated expenses. The Thesis research has yielded the following findings:

1. AM technology is particularly **well suited for the required mechanical complexity of accelerator components** and, in combination with the latest processing developments, offers significant design and optimization freedom that cannot be achieved by conventional manufacturing technology. At the same time, AM technology allows to **reduce manufacturing time from 16 to 4 months due to 4 times less machining operation number**.
2. The **pure copper HF-RFQ prototype** quarter-sector, with a length of 95 mm, was built using an PBF-LB/M system equipped with a green laser. **Manufacturing took 16 hours and 29 minutes with 3267 layers and 30 μm layer thickness settings**. Successful manufacturing of prototype confirmed the actual industrial manufacturing feasibility.
3. The **external and internal shapes of the RFQ were successfully optimized**. For instance, the lightened RFQ structure was developed by using lattice structures as honeycomb patterns by replacing the most massive sections in regions where full material density is not required. The minimum acceptable wall thickness of **0.5 mm for stable lattice structures and 1.5 mm for helium leak tightness were achieved**.
4. The shape and structure of the **RFQ cooling channels were significantly improved** according to the optimum thermal management and flow-dynamics simulations. The conventional manufacturing limitations no longer steer cooling channel configurations. The steady-state thermal and static structural simulations performed by SUPERFISH heat flux calculation showed that thermal distortions on AM prototype versus the original HF-RFQ have a **33 % advantage in average and over 100 % on beam axis area** for the same conditions.
5. In the case study, the honeycomb structure implementation and optimization of the cooling channels allow for **substantial weight reduction, $\approx 37\%$ ($\approx 21\%$ and $\approx 16\%$, respectively)**. Still, there are certain design limitations for wall overhangs, closed pockets and powder removal solutions.
6. The surface roughness measurements for the **“as-built”** model indicated that the prototype surface roughness quality is still far from the required $Ra = 0.4 \mu\text{m}$.

The surface arithmetical mean roughness average (Ra) was measured as **14.32 μm** , and the ten-point irregularities value (Rz) as **116.7 μm** . However, these results are encouraging since they were obtained without the unique adaptation of the AM technological process for improved surface roughness outputs.

7. The **geometrical accuracy measurements after post-processing revealed promising results** – with the standard AM PBF-LB method **approaching the required accuracy of 20 μm on the vane tip and fully reaching 100 μm on other surfaces**. The highest deviation of 0.31 mm on the vane tip can be attributed to a technological glitch – distortion of the support during the built process and STL file meshing quality. Moreover, there still is vast potential to reach a higher level of accuracy by distortion compensations and tuned laser beam scanning approaches.
8. Significant AM technology advantage is the **ease of free-form manufacturing and single set-up build for complex shape parts**. This allows to avoid assembly misalignment during the brazing stage. This advantage also gives the option for improvement of cavity Q factor as no more brazed seams are needed. In current research the static Q value of the RFQ, **cavity was improved by 2.6 %** by implementing smoother cavity shape transitions.
9. **The geometric model for static 2-dimensional RFQ cavity quality factor was developed** and tuned for 750 MHz cavities. For design line of 750 MHz, RFQ's **mathematical model works with ± 1.5 % accuracy**. The model concept can be used and adapted for different size AM RFQ designs.

8.1. Practical recommendations

The current research constitutes a significant step towards developing AM technology for the complex accelerator component, the high-frequency radio frequency quadrupole (HF-RFQ). Based on the findings of this study, the following recommendations are proposed to support further developments in this area:

1. While AM technology holds **high potential** to become a viable option **for the production of compact-size RFQs**, further research and developments are needed to reach complete “ready to go” technology.
2. Surface **post-processing techniques are critical** for achieving the desired **roughness values of $Ra = 0.4 \mu\text{m}$** for the RFQ internal surfaces like cavity and vane.
3. The **required level of geometrical precision** of 20 μm for the vane tip and 100 μm for the cavity is a challenging task, and it **can be accomplished by using compensation techniques**, which are applied either during the CAD modelling phase and/or the manufacturing cycle.

4. The current research shows that **additional 3-dimensional compensation**, in the range of 150 – 200 μm , **is necessary to compensate radial shrinkage** of the cavity surface and material removal during post-processing.

8.2. Future research challenges

The present study outlines the preliminary phase of utilizing AM PBF-LB/M in creating a complete and operational RFQ prototype. The subsequent stage of advancement entails creating and designing a complete RFQ prototype on a scale that represents the final product. The process will also include meticulous physical and metrological examinations to ensure the prototype meets the predetermined performance specifications. The required tests include a wide range of evaluations, such as creating a complete-sector and full-length RFQ, evaluations of vacuum integrity and outgassing, evaluations of voltage holding capacity, examinations of waterproofness, and evaluations of radio frequency performance and the final beam test. These assessments aim to evaluate the RFQ prototype's functionality and identify and resolve any potential challenges that may emerge throughout the development phase. Hence, it is imperative to engage in thorough planning and meticulous attention to detail during the entirety of the development process in order to guarantee that the RFQ prototype satisfies the essential performance specifications and is appropriate for practical implementation.

BIBLIOGRAPHY

- [1] S. A. Johansson, J. L. Campbell, and K. G. Malmqvist, *Particle-induced X-ray emission spectrometry (PIXE)*. Wiley New York, 1995, vol. 133.
- [2] M. Vretenar, “Applications of Particle Accelerators in Europe,” CERN, Report, 2017. [Online]. Available: http://apae.ific.uv.es/apae/wp-content/uploads/2015/04/EuCARD_Applications-of-Accelerators-2017.pdf.
- [3] “I.FAST WP10: Advanced accelerator technologies.” (May 1, 2021), [Online]. Available: <https://ifast-project.eu/wp10-advanced-accelerator-technologies>.
- [4] D. I. Wimpenny, P. M. Pandey, L. J. Kumar, *et al.*, *Advances in 3D printing & additive manufacturing technologies*. Springer, 2017.
- [5] G. Pikurs, “Additive manufacturing applied to particle accelerators,” IJCLab, report, Mar. 18, 2022. [Online]. Available: https://indico.cern.ch/event/1126958/contributions/4730216/attachments/2393754/4124387/I.FAST_Paris_G.pdf.
- [6] “Additive Manufacturing applied to Particle Accelerators.” (2022), [Online]. Available: https://indico.cern.ch/event/1133254/contributions/4853087/attachments/2438320/4176612/I.FAST_1st_Annual_WS_GP_ND.pdf.
- [7] J. Billen and L. Young, “Poisson Superfish Documentation,” *LA-UR*, pp. 96–1834, 1996.
- [8] “Materialise Magics 3D Print Suite.” (2022), [Online]. Available: <https://www.materialise.com/en/industrial/software>.
- [9] “Technical Specifications MetraSCAN BLACK™—Elite.” (Oct. 10, 2022), [Online]. Available: <https://www.creaform3d.com/en/optical-3d-scanner-metrascan/technical-specifications>.
- [10] “ZEISS PRISMO Specifications Version: November 2017.” (2017), [Online]. Available: https://www.msiviking.com/documents/ZEISS/CMMs/Specifications_ZEISS_PRISMO.pdf.
- [11] M. Dotcheva, J. Favrot, K. Dotchev, and J. Zekonyte, “Planning for metal additive manufacturing,” *Procedia Manufacturing*, vol. 51, pp. 710–716, 2020. [Online]. Available: <https://doi.org/10.1016/j.promfg.2020.10.100>.

- [12] T. P. Wangler, *RF Linear accelerators*. John Wiley & Sons, 2008.
- [13] H. W. Pommerenke, “Compact Radio-Frequency Quadrupoles for Industrial and Medical Applications,” Ph.D. dissertation, Universität Rostock, 2020. [Online]. Available: https://rosdok.uni-rostock.de/file/rosdok_disshab_0000002457/rosdok_derivate_0000099121/Pommerenke_Dissertation_2021.pdf.
- [14] S. Hanna, *RF linear accelerators for medical and industrial applications*. Artech House, 2012.
- [15] S. Mathot. “Manufacturing of the High Frequency RFQ.” (2018), [Online]. Available: https://indico.cern.ch/event/686876/contributions/2817925/attachments/1614272/2564777/Manufacturing_of_the_HF-RFQ_v1.pptx.
- [16] K. Scibor, “PIXE-RFQ modulation and cavity machining,,” [Online]. Available: <https://www.euspen.eu/knowledge-base/ICE20189.pdf>.
- [17] T. Torims, G. Pikurs, S. Gruber, *et al.*, “First Proof-of-Concept Prototype of an Additive Manufactured Radio Frequency Quadrupole,” *Instruments*, vol. 5, no. 4, p. 35, 2021. [Online]. Available: <https://doi.org/10.3390/instruments5040035>.
- [18] “Compact radio frequency quadrupoles for medical and industrial applications.” (Mar. 9, 2018), [Online]. Available: https://indico.cern.ch/event/686876/contributions/2817924/attachments/1614164/2564508/compact_RFQ_KT_03_18.pdf.
- [19] A. Lombardi, “High frequency compact low-energy linear accelerator design,” WO2016023597A1, Feb. 18, 2016. [Online]. Available: <https://worldwide.espacenet.com/patent/search/family/051429257/publication/WO2016023597A1?q=W02016023597A1>.
- [20] K. Halbach, “Superfish a computer program for evaluation of RF cavities with cylindrical symmetry,” 1976.
- [21] G. Pikurs, “Research on design improvement of accelerator components by additive manufacturing,” National Centre of Physical and Technological Sciences, report, Oct. 12, 2022. [Online]. Available: https://indico.cern.ch/event/1147717/contributions/5082259/attachments/2526799/4346280/CBC2022_GP.pdf.
- [22] H. W. Pommerenke and A. Grudiev, “RF Measurements and Tuning of the PIXE-RFQ,” 2020. [Online]. Available: <https://cds.cern.ch/record/2746335>.
- [23] S. S. Rao, *The finite element method in engineering*. Butterworth-heinemann, 2017.
- [24] H.-H. Lee, *Finite element simulations with ANSYS workbench 2019*. SDC publications, 2019.

- [25] “Whitepaper TruPrint 1000 Green Editio.” (Oct. 2020), [Online]. Available: https://www.apricon.fi/wp-content/uploads/trumpf_whitepaper_truprint-1000_green_3d-printing_copper.pdf.
- [26] *Private conversation with Serge Mathot(CERN EN-MME)*, 2023.
- [27] “TruPrint 1000 Green Edition.” (Nov. 2021), [Online]. Available: https://www.trumpf.com/filestorage/TRUMPF_Master/Products/Machines_and_Systems/02_Brochures/TRUMPF-TruPrint-1000-Green-Edition-flyer-EN.pdf.
- [28] S. Gruber, L. Stepien, E. López, F. Brueckner, and C. Leyens, “Physical and geometrical properties of additively manufactured pure copper samples using a green laser source,” *Materials*, vol. 14, no. 13, p. 3642, 2021. [Online]. Available: <https://www.mdpi.com/1996-1944/14/13/3642/pdf?version=1625103967>.
- [29] A. W. Chao, K. H. Mess, *et al.*, *Handbook of accelerator physics and engineering*. World scientific, 2013.
- [30] T. Torims, A. Ratkus, G. Pikurs, D. Krogere, A. Cherif, S. Gruber, *et al.*, “Evaluation of geometrical precision and surface roughness quality for the additively manufactured radio frequency quadrupole prototype,” *Proceedings of IPAC2022*, pp. 787–791, 2022. [Online]. Available: <https://cds.cern.ch/record/2845877/files/document.pdf>.
- [31] “BINC Industries.” (2022), [Online]. Available: <https://www.youtube.com/user/BestinClassch/videos>.
- [32] B. Bulat, “J3073560 – 3D printed AM-RFQ,” CERN EN-MME, Geneva, Measurement report, Feb. 13, 2023. [Online]. Available: <https://edms.cern.ch/document/2644691/1>.
- [33] R. J., “iFAST CERN,” CERN EN-MME, Geneva, Measurement report, May 19, 2022. [Online]. Available: <https://edms.cern.ch/document/2739166/1>.
- [34] “Surface Texture Measuring Instruments.” (2022), [Online]. Available: https://www.accretech.jp/english/product/measuring/surface/files/s-touch_e.pdf.
- [35] T. Romano, “18th I.FAST AM group meeting,” PoliMi, report, Nov. 17, 2022. [Online]. Available: <https://indico.cern.ch/event/1211623/contributions/5096591/attachments/2549403/4391027/task%2010.2%2013th%20IFAST%20meeting.pdf>.
- [36] D. C. Montgomery and G. C. Runger, *Applied statistics and probability for engineers*. John wiley & sons, 2020.



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