Riga Technical University

Research on design improvement of accelerator components by additive manufacturing

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Contents

1 Introduction

1.1 Particle accelerators, critical components and engineering challenges

A particle accelerator is a device that accelerates electrically charged subatomic and atomic particles, such as protons, electrons and ions. Acceleration requires the input of energy, which, for charged particles, is achieved by applying an electric field. Magnetic fields are deployed, which cause the paths of charged particles to be deflected, thus offering a means to focus and steer the particle beam which is essential for the practical application of an accelerator device [1]. Particle accelerators today are used in large variety of industries and future concepts includes also greener energy concepts described by Torims[2]

In general accelerators consists of large number assemblies, sub-assemblies and separate parts, furthermore there is difficult to point out which part of it is more important. But one of most critical components of accelerator assembly is part which creates initial particle acceleration, focusing and bunching. For many of accelerator laboratories this task is carried by radio frequency quadrupole (RFQ). The RFQ is a low-velocity, high-current linear accelerator with high capture efficiency that can accelerate ion species from protons through uranium. Ion sources need only to operate at relatively low extraction voltage and pre-acceleration voltages to inject the RFQ[3]. The RFQ output energy is well matched to the input energy requirement of linear accelerators such as drift-tube linacs. Many of laboratories have adopted the RFQ as a front end accelerator for injectors synchrotrons[4].

1.2 Technological challenges and design options

Accelerators are significant part from High Energy Physics field. Thereby as one of more specific requirements which is not common for other fields of industry are high and ultra-high vacuum compatibility as well as good outgasing behavior. Typically by default AM technology is way how to make final product more efficient and with higher cost efficiency than traditionally manufactured ones. At current stage AM technology already is reached level, where it can "push out" traditional conservative methods of manufacturing. The part of most known specific requirements for AM application prepared by CERN's AM expert R.Gerard are shown in figure 1. Currently

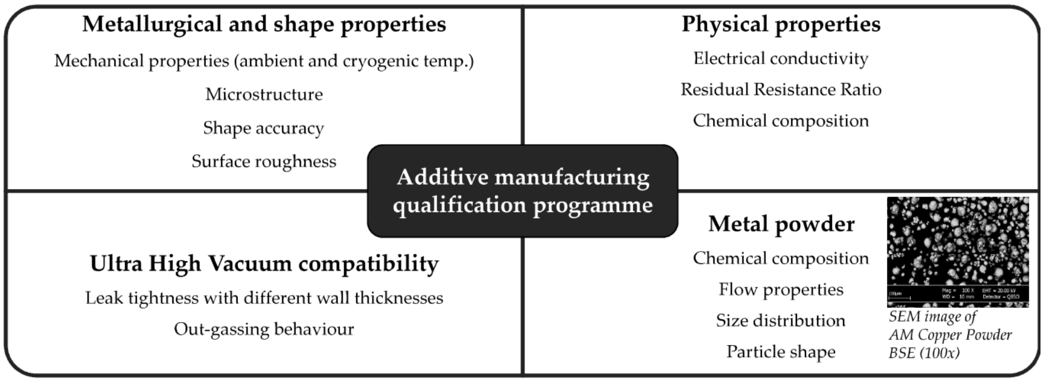

Figure 1: Qualification programme for Additive Manufacturing at CERN.[5]

most of requirements are reachable by combination of fine tuned additive manufacturing and post-processing involvement.

The additive manufacturing technology is relatively new and promising game changer for many of industries, but despite to that there is still many opinions on first historical event. Many of publishers are giving different cases on the first AM launch. In opinions of AMPower analytics the metal AM history started in 1983 with invention of stereolitography by Charles Hull, see figure 3. However in other articles AM history starts even later, as sample Jemghili et al. [6] started history timeline from year 1987.

Wohlers Associates annually preparing updated reports on AM industry trends and impact on whole tendencies of economics. However the Wohlers reports and access to them it is not for free, most of AM community players relies on them for business planning and being granted access to updated trends in field. Wohlers Associates is a more than 35 year old consulting company, which is based in Washington, DC and Fort Collins, Colorado. The company is targeting on technical and strategic consulting on the new developments and trends in rapid prototyping and additive manufacturing technologies. The company is helping to recognize opportunities in mergers and acquisitions, provides advices on product positioning and competitive issues, as well as offers expert testimony in litigation. Wohlers Associates' past work has involved 280 client organizations in 27 countries around the world. The company has provided advice to nearly 200 additional companies in the investment community, most being institutional investors and private

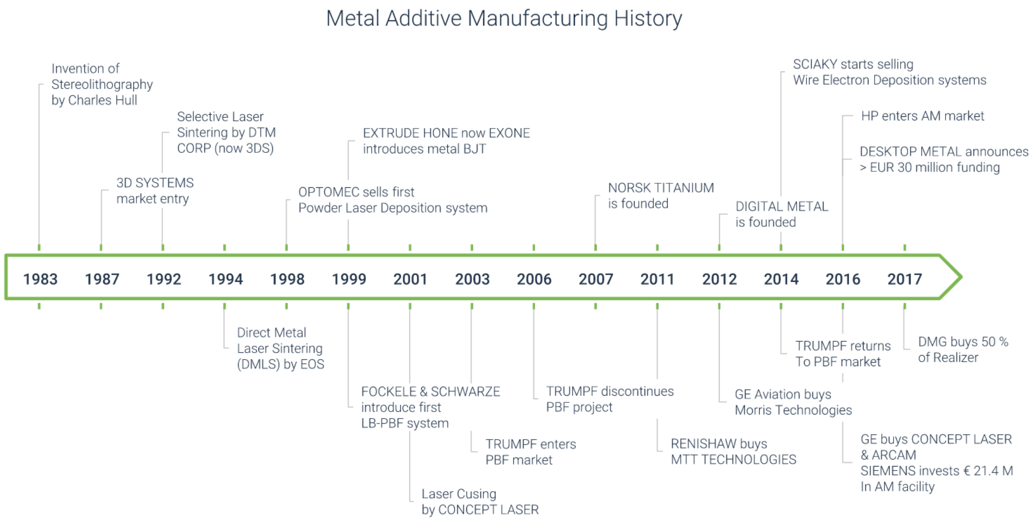

Figure 2: AM history timeline.[7]

equity valued at billions of dollars. For 26 consecutive years, the company has published the Wohlers Report, a publication that provides a worldwide review and analysis of additive manufacturing and 3D printing. The report has served as the undisputed industry-leading report on the subject for more than two decades. Many participants of sector have graciously referred to it as the "bible" of 3D printing.

Most beneficial AM results could be reached by new non-traditional designs for ultimate level of efficiency and performance. AM could also allow manufacturing of spare parts locally, which could give transportation and time savings to business owners and contributes to more efficient machine and plant operations. In same manner additive manufacturing is a technology that can be used for the manufacturing of prototypes and end-use parts. This technology can be used at any stage of the development process of a product[8]. The manufacturing capability and classification of the technology is devided in seven groups. It is shown in Fig.1., is the standardized classification of the European Committee of Standardization (CEN) [2] and the American Society for Testing and Materials (ASTM) [3]. Both organizations agreed to classify AM technologies according to their functional principle, and in general terms, the technology can be used at any stage of the development process of a product. Other classification methods are according to the working material and shape building technique; the equipment employed here, the physic state of the raw material, and the characteristics of embodiment. Lastly, the AM methods have also been classified according to the physic of material transformation [9]. These methods are often seen in several publications, and the selection criteria are often related to the preferences or approach of each author.

Further this work will be specifically focused on AM techniques used in the manufacturing of metal parts. Therefore, only four AM methods could be considered:

1. Powder bath fusion (PBF) process such as selective laser sintering/ melting (SLS, SLM) or electron beam melting (EBM);
2. Direct energy deposition(DED) such as direct metal deposition (DMD);
3. Material jetting such as drop on demand (DOD), and
4. Binder jetting (BJ),

known by the same name or also referred to as 3D printing (3DP) which currently is a registered name. Among these four technologies, the first two, powder bath and direct energy deposition, are the most commonly used in the industry and some reports giving high 80% of overall metal AM turnover. However only one of AM technologies can give more optimistic view in near future to fulfill specific demands for high energy physics field.

Meanwhile, the industry is already using this relatively new technology with good results. However, the standardization process and implementation of even more precise monitoring techniques to ensure consistent results are continuously evolving. Presently, the consistency and outcome quality repeatability are still challenging for some areas of the industry, where is problematic to aford the failure of manufactured part, either due to production costs or safety reasons. Some of the issues related to these two areas are listed in Table 1 and all the scientific and industrial community is working on solving these issues within help of different approaches. The strategies that are mainly process parameter controlling oriented to laser power, scanning speed, and layer thickness; or material science-oriented. In European AM community are several initiatives and AM developing groups which are focused to new projects to advance in accelerator technology. Among leaders are Fraunhofer IWS(Dresden), PoliMi(Milano), INFN DIAM(Padova). secinaajums ka additiivajai razosanai ir liels potencial pielietojums paaatrinaataakju kopienaa

2 Literature rewiev and state of art analysis

Kuras datubaazes izmanto?
Databases: Google Scholar; JACoW Publishing; Science Direct; Elsevier; Springer; MDPI; IEEEXplore; arXiv.org; ResearchGate; indico.cern.ch; CORDIS;
Keywords used for search: Accelerator,Linear accelerator, LINAC, Design, Additive manufacturing, Powder Bed Fusion, Radio Frequency Quadrupole, Pure Copper,
Patents database: espacenet.com, wipo, [https://worldwide.espacenet.com/patent/search]
Highest density of articles in the field of additive manufacturing and the application to accelerators including high energy physics are published by JACoW Publishing. The number of articles where are mentioned accelerators and additive manufacturing started to grow especially in last 5 years. Geographical distribution of researches in field of accelerators still are more concentrated in Europe and USA, however some separate activities on the high technologies are recognized in Asia region. Currenly in China is difficult to identify any official activities which are focused on build of RFQ or accelerator parts, components by AM technologies. Even search on Chinese traditional and Chinese search engines not giving any obvious results. Books:

2.1 Advances of additive manufacturing

Additive manufacturing is growing at fascinating speed in last years. This technology is able for automatic manufacturing of ready to use components from various materials such as plastics, metals and alloys, biomaterials, and ceramics. Over the last three decades, the technology has served many sectors of industry such as automotive, aerospace, manufacturing, and medical. Starting from printing parts in plastic and metals to bioprinting of transplantable organs, the technology is making a progress, which is a breakthrough innovation, garnered by the rapid growth in the core technology.[10]
The idea of producing a 3 dimensional object layer by layer came out already long before the development of ideas around AM. The first similarities to AM can perhaps be traced back to Peacock for his patented laminated horse shoes in 1902. Exactly 50 years later in 1952, Kojima demonstrated the benefits of layer manufacturing processes. A number of additional patents and demonstrations took placed in the time period of 60–80 s that further solidified the idea of producing a 3 dimensional object using a layer wide approach and in the meantime set the stage for introduction and development of processes

based on this principle to produce physical prototypes.[11]
Industry reports such as the Wohlers Report considered by many to be the "bible" of 3D printing, present a yearly update to the latest developments within the technology but do not provide the technical detail of how these processes work.[12]
The AM technology is relatively new and promising game changer for most of industries. And there is still many opinions on first historical event. Many of publishers are mentioning different cases on the first AM launch event. By opinions of AMPower analytics the metal AM history started in 1983 with invention of stereolitography by Charles Hull, see figure 3. However in other articles AM history starts even later, as sample Jemghili et al. [6] started history timeline from year 1987.

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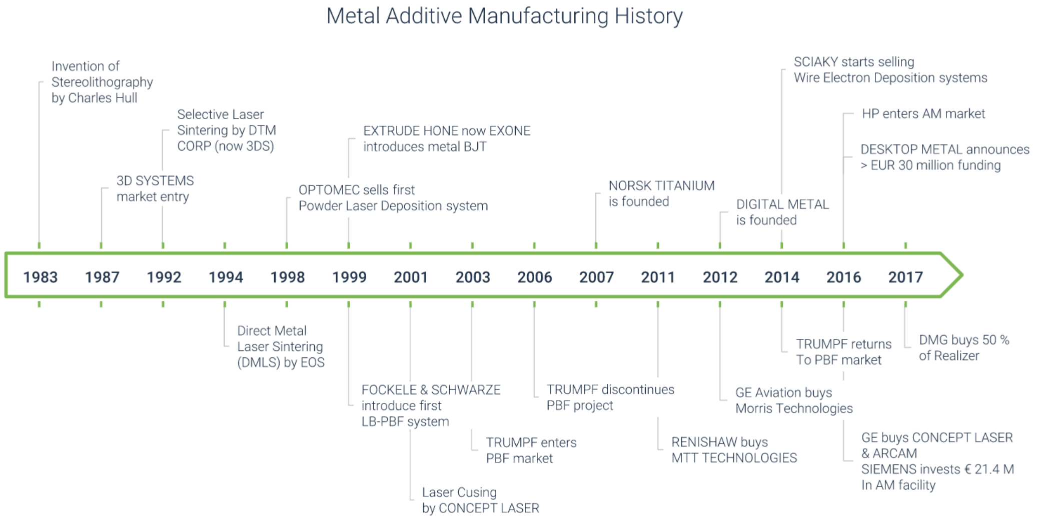

Figure 3: AM history timeline.[7]

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2.2 Applications of metal additive manufacturing within accelerator community

ievads no raksta The first known proposal on application of metal additive manufacturing in physics field appeared in 2003, then L.Waganer from Boeing Company presented metal deposition proposal for ARIES Compact Stellator coil structure(see figure 4.) [13]. The initial aim was to build cost effective shell for magnet coil winding which can make structure much cheaper and improve most of parameters in such way decreasing large capital investments. The proposal how to reach this aim was based on DED AM process which in general is predecessor of welding - cladding technique. During next two years ARIES-CS team developed concept and published results in article

[14]. Final calculations showed that cost is less than one-third the cost of conventional approach and is only 50% above the raw material cost.

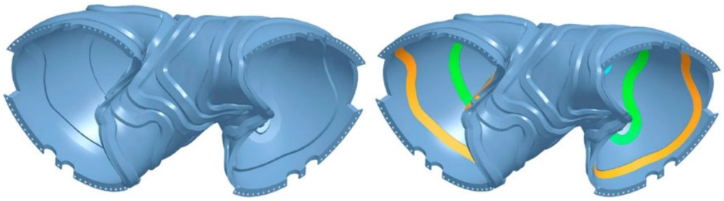


Figure 4: ARIES-CS Stellator coil structure without and with coils in the internal grooves.[14]

Soon after ARIES-CS Stellator appearance US SBIR funds started financial grants for metal additive manufacturing developments in field of accelerators, thereby already in 2006 appeared targeted collaborations among leading accelerator and AM technology developers like SLAC, NCSU, RadiaBeam, UTEP and LLNL. On 6th November of 2006. Ronald B. Agustsson and team from RadiaBeam Technologies LLC filled registration for first patent in additive manufacturing and accelerator field US2008129203A1, where they claimed method and apparatus how to build RF cavity. In general they claimed accelerator building by layers and further approach to more complex and advanced shapes of cooling channels. Practically in same year then patent was accepted, P.Frigola presented this idea on EPAC'08 poster session further article in conference proceedings. This became first officially known AM proposal for accelerator devices which was developed in RadiaBeam/UCLA/INFN collaboration[15]. Initial proposal of 100Hz photo injector model with integrated cooling channels and improved geometry can be seen in figure 5. Next year collaboration presented updated version of previous model at PAC'09, they tuned their 100Hz model to 500Hz, improved version.[16]

Couple years later in 2012 at IBIC2012 CERN's scientists reported about ongoing studies on new design concept their of fast beam scanner. The new proposal included application of additive manufacturing for beam scanning fork, aim was to create more advanced and faster beam scanner. Design concept was based on topology development for wire fork. Weight reduction and stiffness improvement was key factors for design proposal [18]. However model of scanner fork wasn't presented at Tsubukas conference in 2012, first official pictures of model appeared only at IBIC2015, where design analysis

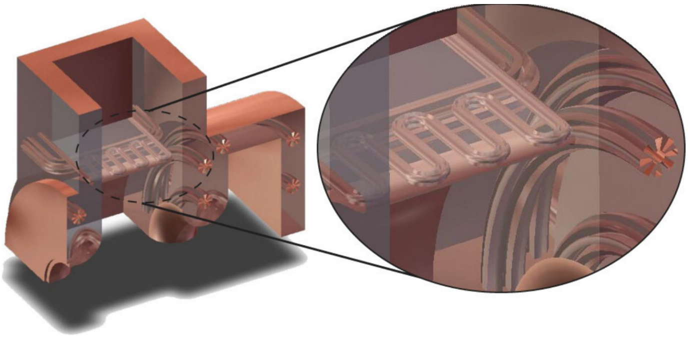


Figure 5: Quarter section of the RF Gun with star-shaped, conformal cooling channels. Detailed image shows the snake-like channels at the coupling window. [17]

and tests was reported. Beam scanner fork design, stiffness and stability calculations were done by Master's student S.Samuelsson under supervision of his thesis supervisor R. Veness [19].

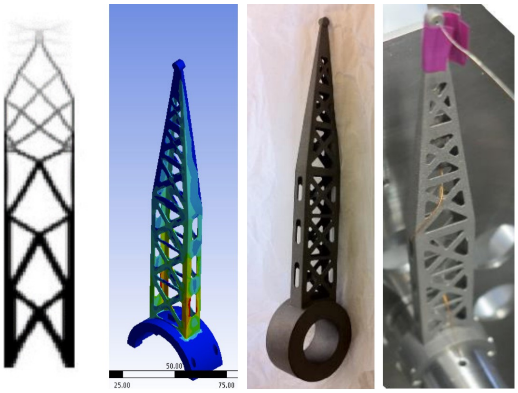


Figure 6: Designed and manufactured fast beam scanning forks. [20]

In general looks that year 2012 is the first official start of additive manufacturing projects at CERN. At that time appeared first contributions, and public documents in CERN's Indico, EDMS and CDS servers. CERN's engineers started to promote first application ideas, and it looks that beam instrumentation group's idea about fast beam scanner is the first official AM project in field of accelerators from CERN. However in 2012 AM was mentioned as potential technology. Year 2012. is time then invited lecturers from additive manufacturing industry started giving lectures on AM topics in dedicated seminars. By analyzing CERN's Indico server seems that first lecturer who started to promote additive manufacturing for CERN's audience is P.Kilburn from 3T RPD Ltd [21]. However in P.Kilburn's presentation already was presented parts which are produced for accelerators, these cases was like inspiration for those who didn't know anything about AM. The part, which already was made by additive manufacturing in that time was spacers for MQXC coils, see figure 7. In that time AM technology was proposed as an integral part of the next LHC high luminosity upgrade. AM then was used in the development of several magnet types: starting from the LHC standard Nb-Ti till the high field Nb3Sn, and high temperature superconductors HTS. AM parts was targeted to resist Nb3Sn processing reaction at temperature of 650°C. Metallic end spacers were designed to replace the old fiber glass parts [22].

Figure 7: Additive manufactured Ti end spacers for MQXC. [21]

Practically this was time then number of additive manufacturing projects in European accelerator community started arising. There is difficult to recognize which of European accelerator center was first, but looks that INFN already on that time participated in AM developments with Radiabeam, as they were in coauthor list[15]–[17], [23].

2013 was year then UK additive manufacturing company Croft Additive joined to STFC CERN BIC based in Sci-Tech Daresbury [24]. The aim of project was to accelerate additive manufacturing development and en-

gineering knowledge transfer to industry. Croft was interested in CERN's expertise of metal alloys and materials science to improve their competitiveness in rapidly growing metal AM market.
Practically after couple months, in the beginning of next year arrived new proposal from CERN's CLIC experiment, during CLIC14 workshop Alexej Grudiev presented results of additively manufactured Ti6Al4V WR90 wave guide prototype demonstrator, see figure 8. There should be mentioned that CLIC RF team is one of first who did most needed tests of AM samples: DC conductivity, RF loss, leak tightness, outgassing, shape accuracy, surface roughness, mechanical strength and material micro structure analysis. For next developments RF group proposed to manufacture samples with integrated cooling for high power tests [25].

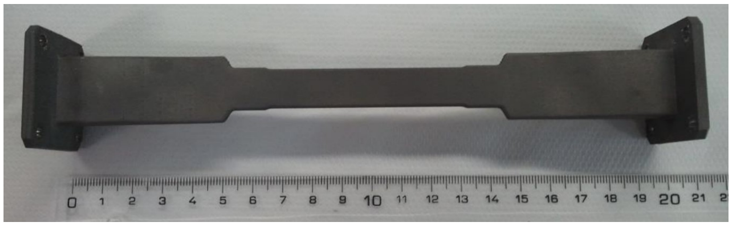


Figure 8: Additively manufactured Ti6Al4V WR90 waveguide prototype. [25]

At that time CERN hadn't metal additive manufacturing machines, and five samples were ordered from three different AM companies. It was like acceptance test to see and compare quality and recognize gray areas of newly arrived technology. In addition two of companies did manufacturing by PBF-LB technology, but one by PBF-EB. CERN's experts did metrology, vacuum and conductivity tests. Final conclusions from first tests were that PBF-LB technology was more successful than PBF-EB. Final conclusions was, that electron beam process need more focused improvements, as second major issue was recognized surface roughness and geometrical accuracy which became more challenging part for validating of AM technology [25]. Further development for next stage were applied, and already after couple months appeared updated report from M.Colling [26]. In new design was increased wall thickness, added vacuum flanges and water cooling jacket, see figure 9.
As next development after simplest versions, in IPAC'2018 appeared version of High power conditioning of X-band load with implemented complex shape geometry and tuned cooling configuration [27].

Figure 9: Upgraded version of AM Ti6Al4V X-band load. [26]

In middle of 2014 joint author team from Radiabeam, NCSU and UTEP published article in Advanced materials & processes journal about their experience on pure copper additive manufacturing. Article was mainly focused to give reader information about current status of PBF-EB technology, and in same time to show already reached goals. As sample piece there was given case of pure copper cathode for UCLA Pegasus 1.6 cell Photoinjector, see figure 10.

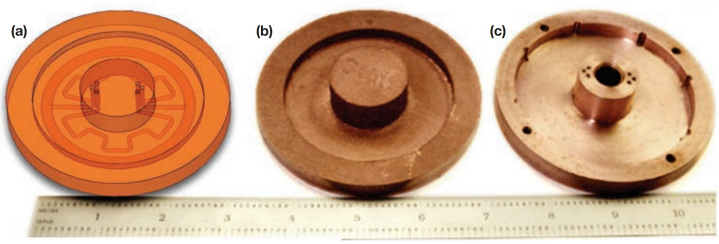


Figure 10: Additively manufactured cathode with internal cooling channels for UCLA Pegasus 1.6 cell Photoinjector: a) 3D model; b) as build part; c) postmachined part. [28]

In 2014 at Annual Solid Free Form Manufacturing Symposium in Austin, Texas, C.A. Terrazas, team from UTEP and P. Frigola from Radiabeam presented their work on PBF-EB for high purity niobium supercondusting applications, as sample for case study was chosen SRF cavity. He presented AM technology as promising alternative replacement to conventional forming with significant advantages for uniform wall thicknesses, improved structure rigidity and material purity, however article was mainly focused on PBF-EB process parameter optimization [29]. At that time author team didn't mentioned that several months ago patent application has been filled, and in 5th of May in 2015 US9023765B1 patent "Additive manufacturing method for SRF components of various geometries" was published [30]. Soon after receiving of patent RadiaBeam, JLab and UTEP prepared presentation for SRF2015, where they reported their results on PBF-EB application for single cavity, design was based on Fermilab's 3.9 GHz 3rd Harmonic Cavity. Furthermore it was manufactured as completely functioning single SRF cavity, however it still was made from two parts and included additional steps of internal surface machining, polishing and final EB welding, see figure 11. In 2015 at Locheed Martin was workshop on advanced methods of manufacturing where P.Frigola presented all latest achievements of Radiabeam and partners[31].

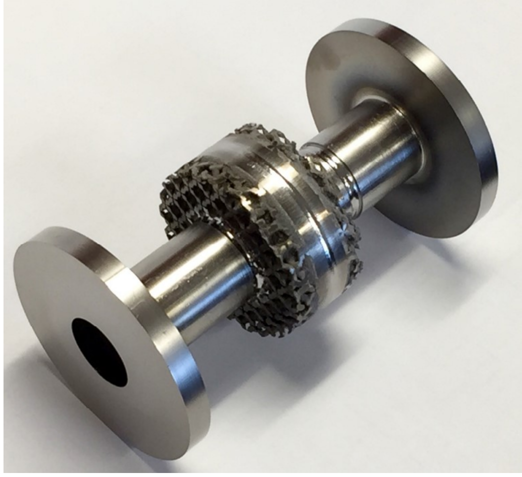


Figure 11: Photograph of the PBF-EB/M/Ni single-cell cavity.[32]

Starting from 2012 AM number of cases and overall interest about technology started to rise more rapidly. Already at that time RF group had their first development of additive manufactured RF load, which already has been presented in CLIC14 Workshop by A.Grudiev [25]. Soon under hostage of several more interested and progressive minded groups in November of 2014 at CERN was organized AM Workshop [33]. This was first event at CERN which was dedicated exclusively to AM topics, there was 115 registered participants, mostly they were from different CERN's groups, others were already in CERN projects involved AM industry and institutional representatives. Workshop was split in two parts, metal and plastic AM.
End of 2015 came with new report from CERN's CLIC's RF group. Bachelor student Gian Luigi D'Alessandro under supervision of experts A.Grudiev and

W. Wuensch prepared development of X-band High-Power RF load application study for additive manufacturing [34]. In general thesis was focused on spiral load 3D model development, including mathematics and physics phenomena analysis. Technically D'Alessandro's thesis was preparation of physics model for further real part 3D model and application of additive manufacturing, spiral load model can be seen in figure 12.

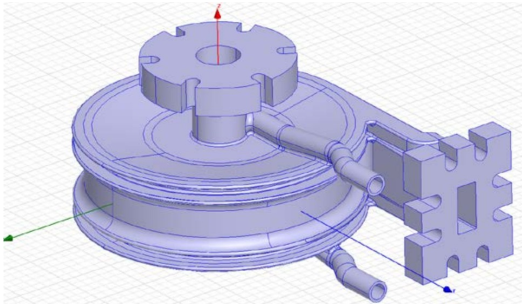


Figure 12: Developed 3D spiral load model for AM 3D model. [34]

After preparatory work CERN's RF group did next step toward, and already at CLIC 2017 workshop, team presented additively manufactured X-band spiral load and various tests which proved concept. [35]. However RF groups team already had plans about design improvements group still continuing work on developments and already at IPAC2018 N. Catalan-Lashera was giving overwiev about high power conditioning for RF loads [27]. when main geometry studies was tuned RF group team arrived with proposal for concept of mass production of RF spiral loads, complete concept was presented in IPAC2021 by Bursali [36]. Latest model wich was approved for mass production can be seen in figure 13.

One of most typical applications where AM can prove their advantages over standard manufacturing systems are heat exchangers. AM allows to build highly specific heat exchange structures by heat transfer ratio and shape of structure itself. Already at the beginning of 2015 CERN's LIEBE WP3 team started looking on advantages of AM [37] Finally after several steps of development studies they build lead-bismuth/water heat exchanger, see figure 14.

At the beginning of 2017 scientists from french institutions LAL and CNRS/IN2P3 from Orsay joint to race for AM applications at high energy physics field. The first approach was to prove vacuum tightness of AM technology. They

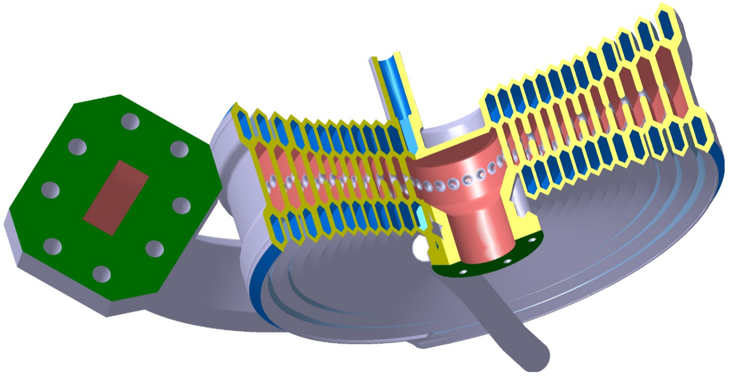


Figure 13: RF spiral load development for AM mass production 3D model with section cutout. Model from CERN's Smarteam database.

Figure 14: Additive manufactured lead-bismuth eutectic/water heat exchanger for LIEBE experiment. [38]

ordered 130 mm long DN40KF tubes to study vacuum tightness of 316L AM products. Manufacturing was done by PBF-LB technology at two different companies: BV Proto and AGS Fusion [39]. In general results of vacuum tests was promising for further investigation and development of AM projects. Then as next step came design proposal for slightly more complex structure - beam pipe monitor (BPM). In classic design BPM consists from several parts with high alignment tolerances. Already at the beginning it was clear that AM could good alternative for tolerances, cost effectiveness and manufacturing speed. The first test results of AM BPM was presented in IPAC2018 [40].

Since CERN started dealing with additive manufactured parts, the engineering department became involved in testing of AM samples more often. Mostly

Figure 15: Additive manufactured DN40KF tubes for vacuum tests. [39]

mechanical, geometrical accuracy and surface roughness tests are their specialty. The first registered EDMS report on additive manufactured parts is dated by January of 2014, it was made by Santillana[41]. But one of most crucial parameter for AM applicability in high energy field is vacuum tightness and outgassing. For proving AM applicability of different materials and AM proceses from point of vacuum tightness care was on TE-VSC team and L. Mourier. First review of applicability was reported at the end of 2016 [42]. The easiest way to test vacuum tightness and not to fail on expenses of inappropriate quality are manufacturing of ISO KF or CF type membranes for vacuum tests, before manufacturing of more complex and expensive shapes. Typical ISO-KF type membranes can be seen in figure 16.

One year later in FFC conference J.Gargiulo gave presentation on investigating of the vacuum tightness for AM parts [43]. In summary of presentation has been concluded that stainless steel 316L is helium leak tight with thicknesses from 0.25mm, but Ti and Al by HIP is helium tight starting from 0.5mm. However the presenter mentioned that these limits are strongly influenced from manufacturers experience.
As one of relatively simple and often developed pieces for AM technology are various types of beam dumps. Parts have been developed by different in-

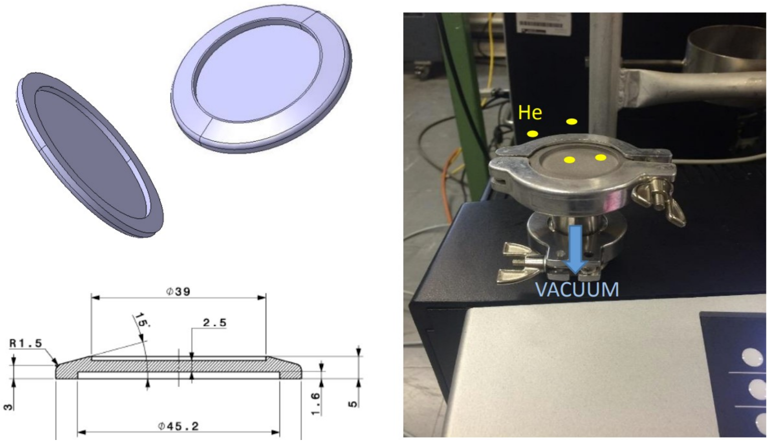


Figure 16: AM ISO-KF type vacuum test membrane 3D model, drawing and test assembly. [42]

stitutions and from various materials. In 2018 INFN DIAM developed pure copper beam dump prototype (figure 17) with internal cooling channels it has been designed for SPES LNL INFN. Specific design feature is that AM part has been built directly on pure copper substrate plate, which is half of whole structure [44].

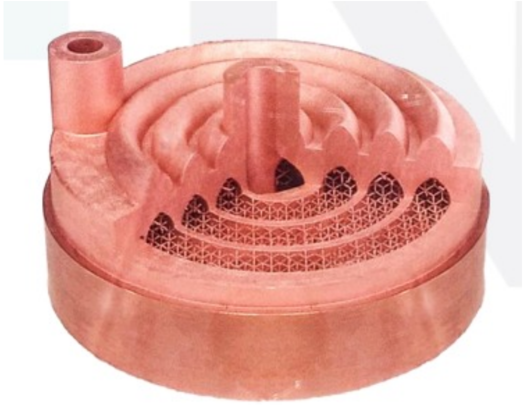


Figure 17: AM pure copper beam dump prototype. [45]

In 2018 CERN's RADIATE collaboration team introduced new design of AD target, which was named PROTAD Target (PROTotype AD Target). The new design version has several advantages over old one, it has larger core diameter, multi material configuration (Ta, Ir) and expanded graphite as matrix material. In addition new design target has double wall Ti-6Al-4V assembly with an internal spiral channel for pressurized (5-6bar) compressed air cooling. [46]. Part of new targets was made by PBF-LB technology at CERN's AM workshop, additive manufactured parts in figure 18.

Figure 18: AM Ti-6Al-4V PROTAD target housings. [47]

Since 2014 when first AM workshop dedicated to HEP was held at CERN, three of European particle physics centers started to develop applications of AM parts for their core projects. CERN and INFN even managed to open their own AM laboratories. In spring of 2015 T.Sanher from EN-MME team gave presentation in TE-MSC MDT technical seminar, where he mentioned about plans to have metal AM machine by the end of year [48]. Technically this was starting point of metal additive manufacturing workshop at CERN. Administratively it was developed under CERN's EN-MME department and still continue successful work. Practically several months later INFN's DIAM workgroup was created in Padova. It still is multi-disciplinary team including engineers, researchers, technicians, etc. with a background in mechanical design and material sciences [49].

Relatively recent development of an ultra high vacuum chamber build by PBF-LB process was developed in 2018 by UK young scientists and experts. The production of additive manufactured systems for ultra-high vacuum applications has so far proved as highly challenging and even been considered as impossible. At that time UK team demonstrated the first additively manufactured vacuum chamber operating at a pressure below 10^{-10}mbar. In addition to that they included exclusive design features which are not available by standard manufacturing. For part rigidity, weight and cooling improvement they implemented gyroid lattice structures. See picture 19

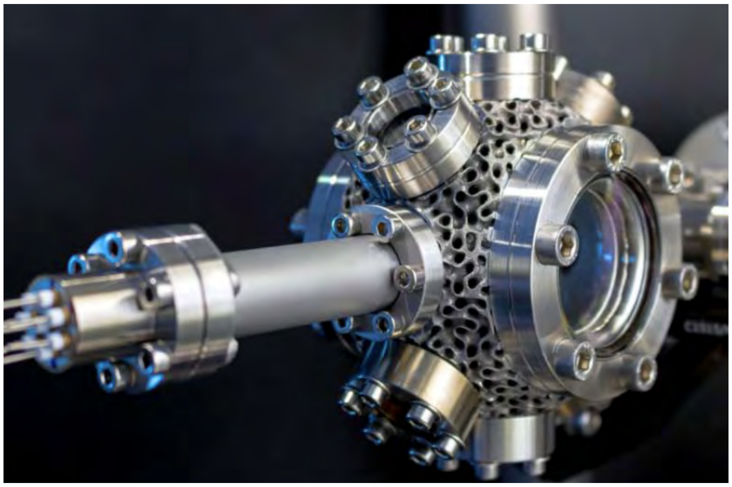


Figure 19: 3D printed UHV chamber.
[50]

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

History of additive manufacturing patents starts with Sandia Corp(US) and its inventors Greene Donald L (US); Griffith Michelle L (US); Harwell Lane D (US); Pressly Gary A (US) with US patent number US6143378A, the title of the patent was “Energetic additive manufacturing process with feed wire” with earliest priority 1998-05-12 and official publication date in 2000-11-07. During the last 20 years, a patent number where are words “additive manufacturing” in patent title rises to an amazing 5’328. But patents with the phrase “ additive manufacturing” somewhere in patents text are huge 39’252. This tendency shows that additive manufacturing technology expands very rapidly in the last 20 years. Today the main players in the additive manufacturing business are big companies and research institutes. They feel the business perspectives there in the future. As it is seen from the patent application US company General Electric is the leader in the number of patents on additive manufacturing. “Additive manufacturing + copper” in title 22 patents. But none of them on pure copper.

2.3 International research projects on additive manufacturing

EU H2020 projects for development of additive manufacturing technologies: H2020-EU FP7-2012-NMP-ICT-FoF AMAZE (Additive Manufacturing Aiming Towards Zero Waste and Efficient Production of High-Tech Metal Products) Coordinated by The Manufacturing Technology Centre Limited, (UK), overall budget € 18 088 574,46 . The team of project comprises 31 partners: 21 from industry, eight from academia and two from intergovernmental agencies. AMAZE project represented the largest and most ambitious team ever builded on additive manufacturing topic. Names of consortium participants here are well known in industry as European Space Agency (FR), Concept Laser GmbH (DE), Airbus Defence and Space GmbH (DE), Volvo Technology AB (SE), Renishaw PLC (UK), TRUMPF Laser- und Systemtechnik GmbH (DE), Thales Alenia Space France SAS (FR), etc.

H2020-EU.1.3. PAM2 (Precision Additive Metal Manufacturing) Coordinated by Katholieke Universiteit Leuven, EU contribution € 3 896 180,44 Participants from six universities and seven countries. In list of participants and partners here is Danmarks Tekniske Universitet (DK), Universita Degli Studi di Padova (IT), Karlsruher Institut fuer Technologie (DE), Technische Universiteit Delft (NL), The University of Nottingham (UK), LayerWise(B), Alicona Imaging GmbH (A), LEGO System AS (DK), Nuovo Pignone Tecnologie Srl (IT) and partners ASML Netherlands B.V.(NL), Magma Giessereitechnologie GmbH (DE). All of involved participants and partners are high class experts in AM related fields. For introduction MAGMA is one of the world's leading developers and providers of software for casting process simulation and virtual optimization, Alicona is global supplier of optical, industrial metrology for quality assurance of complex components of different shapes, sizes and materials, and their non-contact measuring systems are used in all areas of precision manufacturing. ASML is global manufacturer of complex lithography systems for production of microcrochips, LayerWise currently already is part of 3D Systems, initially grown from KU Leuven and at begining only experts of additive manufacturing in Benelux countries. Under the project was developed submicron optical measurement system prototype for surface and geometry measurements[xx], written 30 journal papers, 41 conference papers and 4 chapters for book "Precision Metal Additive Manufacturing"

H2020-EU.2.1.5.1.-Technologies for Factories of the Future OpenHybrid

(Developing a novel hybrid AM approach which will offer unrivalled flexibility, part quality and productivity), Coordinated by The Manufacturing Technology Centre Limited, (UK), EU contribution € 5 133 381,25 (01/10/2016 – 30/09/2019) The OpenHybrid project aimed for breakthrough thru the technical and commercial barriers of past hybrid manufacturing systems to deliver a single manufacturing system capable of undertaking a wider range of processes in a seamless automated operation. Project comprises well known and ambitious players, similar like two above mentioned projects. Some of them was Siemens Aktiengesellschaft (DE), GF Machining Solutions AG (CH), Gudel AG (CH), ESI Group (FR), Centro Ricerche FIAT SCPA (IT), European Federation for Welding Joining and Cutting (B). The project in general was focused mainly on direct energy deposition techniques, and as result here was four counference articles and practical development of manufacturing equipment.

H2020 projects at CERN, which have workpakages related to AM technologies: H2020 AIDA (Advanced European Infrastructures for Detectors at Accelerators) WP HM(Horizontal Mechanics) Microchannel cooling for detectors (Paulo Petagna EP-DT) H2020 I.FAST (Innovation Fostering in Accelerator Science and Technology) (WP10 (Toms Torims ATS-DO) Whole workpakage is related for promotion of advanced additive manufacturing solutions for high energy physics community and especially for acclerator and detector components.

In the UK in 90-ties of twenty century was established National Centre for Additive Manufacturing. NCAM is here to accelerate the uptake of Additive Manufacturing (AM) by developing the technology and systems required to address the key challenges within the Additive Manufacturing value chain. The National Centre for Additive Manufacturing is based at the Manufacturing Technology Centre (MTC), part of the High Value Manufacturing Catapult. We are also home to The European Space Agency (ESA) AM Benchmarking Centre and a founding partner of the ASTM AM Center of Excellence IUK projectNo.133086 and the EPSRC grants EP/R024111/1 andEP/M013294/1 and by the European Commission grantErBeStA (no. 800942)

3 Focus and scope of research

3.1 Statement of research gaps and identification of the case study

Modern particle accelerators are composed of a great variety of components and require state of art technological solutions. Most of the accelerator components are manufactured by conventional high-end precision machining. Firstly, conventional machining process requires high removal rates of the material and have a significant amount transferred to chips. Secondly, the standard machining process and technology are highly time-consuming, machine-time and human labor adding significant part to final cost. RFQ is made from oxygen-free pure copper (OFE-CU, C10100), the purity of material is higher than 99.98%. This is one of main obstacles for traditional machining process, because of material physical properties.

Most variety of advanced and complex accelerator components can not be manufactured from single-piece material and requires technological solutions like bridges, supports or channels, as well sometimes targets includes application of multi-material or multi-layer solutions. Thereby complex components often are limited by unattainable technological challenges. Despite to that additive manufacturing is one of the most promising technologies which is capable to solve prodigious ideas of new generation designers. Additive manufacturing could be the key technologie for the accelerator industry if additively manufactured parts could reach ultra high standards of quality, which even are higher challenging for conventional manufacturing methods. Despite to that AM has advantages over traditional methods because of infinite design possibilities to create the complex structures which have not been reached before. As one of minor problems, which also exists on this way is lack of trust to new technologies from accelerator community autorities.

However major part of the accelerator community is looking with distrust to the capabilities of additive manufacturing, the main reason is that there still are too weak activities, researches and pubications on high performance, exotic materials and technologies. The current research is first official trial to manufacture a realistic RFQ prototype, afterward including tests, analysis and technology mapping for successful results. Hovever technically, it is possible that someone already did some trials under military or any top-secret projects.

whyrfq? The RFQ itself is an RF cavity that contains a vane profile specifically designed for acceleration of one type of particle, at a given current and for a given energy range (input and output energy).[51]

The RFQ is unique by its complexity and high precision geometry and it is also one of most crucial element in accelerator complex. In addition to that cost of the RFQ section asks considerable amount from overall accelerator machine price. Furthermore materials and requirements for RFQ body is specific. Obviously, quadrupole is one of most expensive and liable things in assembly. Moreover RFQ's are relatively new development for accelerating structures, in fact they are lite older than additive manufacturing technology. Despite to that during last decades design and size of RFQ's are developing quite rapidly.[52]

3.2 Overall objective and tasks

The objective of thesis is to proof scientifically that the additive manufacturing technology is viable solution for the production of complex particle accelerator components and that AM technology is able to reach the stringent requirements which are set to accelerator components.

To reach this objective the following tasks are identified for this PhD research:

1. Based on the state of art analysis to identify the case study object in order to prove additive manufacturing performance to accelerator community;
2. To describe methodological approach of research;
3. To carry out analysis of survey
4. To calculate 2 dimensional RFQ geometry for RF parameter improvement;
5. To design HF-RFQ prototype model for additive manufacturing PBF-LB technology;
6. Simulate mechanical and thermal properties of the proposed design;
7. Build the prototype by previously mentioned AM technique, inspect geometrical and physical results;
8. Apply meteorology tests for "as build" part;
9. Compare designed CAD model with "as built" point cloud, compare results to the initial target values;
10. Apply post processing for surface roughness improvement;
11. Apply meteorology tests for post processed part;
12. Model and experiment comparison, draw conclusions and practical recommendations for further developments.

3.3 Scientific novelty

In the field of mechanical engineering, accelerator manufacturing and particle accelerating technology is quite new development. Contribution to: new models, technological approaches which will be demonstrated and validated through in-deph the case study. This is attempt to open doors for AM technology to highest performance of production technology.

Current research is first scientific and methodological approach targeted to AM application for accelerator components. In timescale of accelerator and additive manufacturing development history are only few minor researches on complete technology development for AM, avoiding deep insight on physical and technical challenges which opens doors to more detailed technology development. Furthemore current research is the first known additive manufacturing trial for pure copper RFQ. Additionally this is the first advanced design development, which is bassed on RFQ multiphysics analysis and is adapted and tuned for reliable high performance additive manufacturing process, to be able improve the design performance including RFQ physical and thermal management.

4 Research methodology

Literature and state of art analysis implies, by using mixed structure by time and project topic. This includes in-depth analysis of literature, data bases, conference proceedings, standards, patents and EU coo-financed projects as well as prior researches of AM applications within accelerator community; Overall approach; comparative study; survey as qualitative analysis tool.

4.1 Experiment planning

4.2 Quantitative analysis tools

4.3 Qualitative analysis tools

Survey- qualitative

other tools:

CERN EDMS,

CERN SmarTeam

INDICO,

JACoW,
ResearchGate
Espacenet
Google
LANL Superfish
DassaultSystems CATIA V5
ANSYS 2019 R1
Autodesk Netfabb Premium 2023
ZEISS GOM 2019

quantitive analysis tools qualitative analysis toools 4.2. jaapraksta problēma, raupjums, precizitāte.

ar kaadaam metodeem, man buus comparitive analysis

4.4 Validation of results

5 Survey of demands for accelerator and parts development

6 Development of additive manufactured RFQ prototype

6.1 Technological challenges for RFQ

An RFQ is a component of particle accelerators featuring strict technical requirements for its successful field service. At first glance, it appears that its stringent requirements (see Table 1) are almost 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 on commercially available, state-of-the-art laser-based AM technology, which is suitable for pure copper manufacturing. Table 1 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 of Table 1. 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 20µm for the vane tip and 100µm for all other 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. Clearly, if one cannot provide enough precision for the modulation geometry, beam transport and acceleration cannot be ensured. Furthermore, the surface arithmetical mean roughness value Ra has to be kept at a level of about 0.4µm. 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-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 Ra 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 as a minimum required value for the RFQ—circular accelerators often require lower pressures. 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 40MV/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.

AM processes for metals can be divided into nozzle-based processes and powder bed-based processes. Nozzle-based processes feed the raw material, powder or wire, through a nozzle to the work zone into the focus of an energy source, which can be a laser, an electron beam, or an electric arc. Powder bed processes either use a laser (PBF-LB - powder bed fusion- Laser Beam) or an electron beam (electron beam melting—EBM) as an energy source or a binder (binder jetting—BJ) to fuse the powder together. PBF-LB is the most promising AM process for pure copper parts, thanks to the fact that high relative density and high electrical conductivity can be achieved, and build-up of complex-shaped parts is possible with a minimum wall thickness of $400\mu m$ and a layer of $30\mu m$. These challenging material properties can be attained by deploying a short wavelength laser, because the absorption level of the pure copper is very low within the commonly used infrared L-PBF systems and significantly increases in the green wavelengths. Thus, the energy coupling into the pure copper powder bed increases, and defect-free processing is possible by using a green laser source [9,10]. At the same time, the PBF-LB technology is well-placed for the required mechanical complexity and offers significant design and optimization freedom to meet the requirements for the RFQ (i.e., integrated cooling channels) that cannot be achieved by the mentioned nozzle technology [9–13]. Nonetheless, there are some design restraints for the PBF-LB process to consider, such as minimum wall thickness. To ensure material integrity, 0.6mm minimal wall thickness was used in this proof-of-concept, following material and machine requirements. Likewise, to prevent collapse of the build-up structure, the overhang angle without support technically cannot be smaller than 45°[14]. In addition, there are challenges to overcome related to the surface roughness, tolerances, and geometry of the RFQ. These are rather demanding issues and cannot be directly addressed by the standard PBF-LB process due to the staircase effect, adhesion of powder particles, and material distortion during the cooling of the part. Therefore, at the outset of making this proof-of-concept, it was evident that the whole process chain of RFQ manufacturing with L-PBF would require future improvements and the fine-tuning of the technological process itself, and eventually it may require subsequent post-processing stages. The removal of powder can also be critical when using internal cavities. In the case of the proof-of-concept, to ensure that all residual manufacturing powder was eliminated, the prototype was cleaned with pressurized air and in an ultrasonic bath.

6.2 Traditional manufacturing process of pure copper RFQ's

Normally the pure copper RFQ's are manufactured by multistep machining and brazing technology. Fourteen step development of pure copper RFQ's was introduced at CERN more than 10 years ago, however thru the time technology is developing accordingly to advances in machining and brazing tools.[53] These fourteen steps includes complete technology, starting from solid pure copper block machining to already tuned and ready for beam RFQ. The first step of technology is machining of forged and multi-way hammered OFE-Copper ingot. The first processing steps include milling to several cm allowance in length and one millimeter positive offset for all other external surfaces and final wire EDM for length allowing several centimeters. The second step starts with As RFQ's are relatively new devices, and accelerating structures still are not mass production, number of registered patents is low. Currently while accelerator community looks on AM is not approved from accelerator community One of most clear and solid patent is CERN's WO2016023597A1 which was published in February of 2016. It describes complete RFQ technology and especially high frequency RFQ design.[54]

6.3 Additive manufacturing process of pure copper RFQ prototype

In order to attain the best possible results, state-of-the-art AM technology and manufacturing equipment was chosen for the production of the first pure copper RFQ prototype. A TruPrint1000 Green Edition (see Figure20) in combination with a green TruDisk1020 laser providing the wavelength of 515nm and maximum laser power of 500W was used at Fraunhofer IWS in Dresden. Dedicated machine allows cylindrical build volume of 100mm in diameter and 100mm in height. The TRUMPF GmbH pre-set pure copper processing parameters and scanning algorithms were used throughout carefully monitored manufacturing process. As a production material, m4pTM PureCu gas-atomised spherical shaped powder was used, which was con-

Figure 20: Trumpf TruPrint 1000 Green Edition

firmed with the Camsizer X2 and dynamic imaging analysis (see Table 2 and figure 21). The sphericity was 0.923 according to scanning electron microscope imaging. The particle size distribution was confirmed to be between 19.5 and 34.9µm, which is common for PBF-LB process.

The choice between powder types which fits better for RFQ requirements and AM process is clarified in previous researches of S.Gruber, where she proved Cu-ETP advantages over Cu-OFC[55]. Therefore final decision fell on 30µm grain size Cu-ETP powder[56].

Experimental part of thesis is based on design development and modification of actual CERN's HF-RFQ. Decision to take HF-RFQ as model for development was taken because of size, complexity and potential manufacturing cost reductions. HF-RFQ size fits to current scale of commercial AM machines and our goal is to prove benefits of AM technology for accelerator community. In other hands HF-RFQ is smallest one from RFQ's product line and in that way it is perfect candidate for AM manufacturing, because large volume builds still are too challenging from point of view of . Currently in

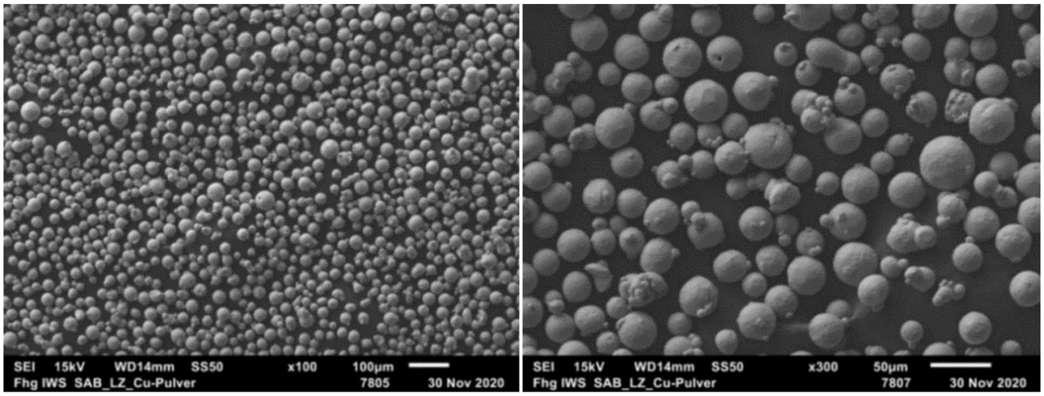


Figure 21: SEM images of Cu-ETP powder: left: magnification of ×100; right: magnification of ×300.[55]

a market are AM machines which can build micro and nano size parts with exceptionally high precision, but most of them are not acceptable for part manufacturing which are larger than 100mm in any dimension, because of build speed and build space. Even large size AM machines with build volume close to $0.25m^3$ and layer thickness 30 microns are comparatively slow at maximum build volume. Often for most of builds processing time varies from couple of hours to weeks. for parts which are in similar size of HF-RFQ. [57]

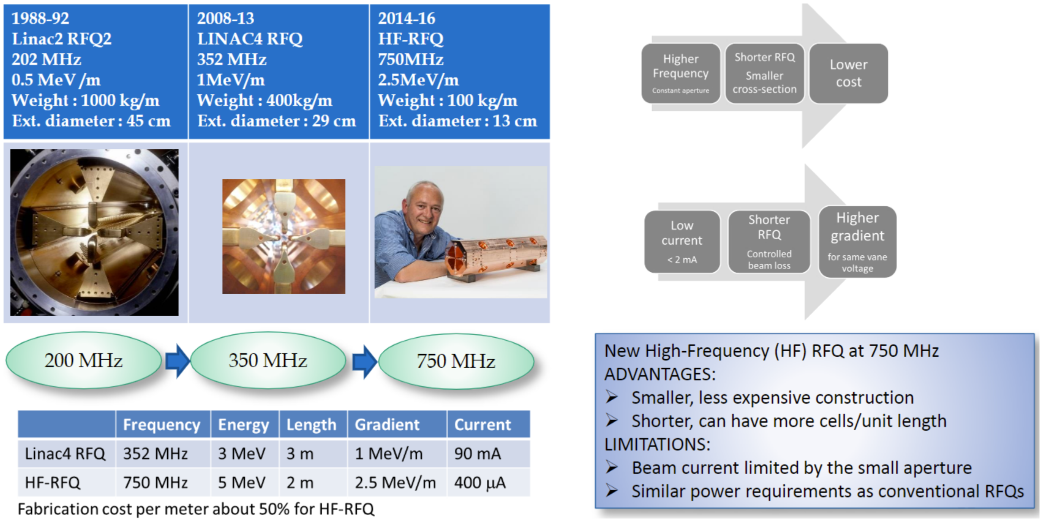
Initial design development was started from HF-RFQ, which already is relatively new development in accelerator community. HF-RFQ was introduced to accelerator community in the end of 2016. HF-RFQ project development was taking over 2 years.[4]

6.4 RFQ cavity 2D geometry development

As initial inputs

6.5 Thermal concept development

The basic concept of the thermal management for AM produced RFQ was tested 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 750MHz PIXE RFQ[58]. Crucial input data for the analysis were: 22°C cooling channel temperature, heat flux on vane tip $2 \times 10^{-3} W/mm^2$, flux on the vane and internal walls



	Frequency	Energy	Length	Gradient	Current
Linac4 RFQ	352 MHz	3 MeV	3 m	1 MeV/m	90 mA
HF-RFQ	750 MHz	5 MeV	2 m	2.5 MeV/m	400 µA

Fabrication cost per meter about 50% for HF-RFQ

New High-Frequency (HF) RFQ at 750 MHz
ADVANTAGES:
- Smaller, less expensive construction
- Shorter, can have more cells/unit length

LIMITATIONS:
- Beam current limited by the small aperture
- Similar power requirements as conventional RFQs

Figure 22: RFQ development history at CERN. [51]

$8 \times 10^{-3} W/mm^2$, and additional negligible values for heat loss through convection from outer surfaces. Thermal analysis results are provided in Figure 5. From the steady-state thermal analysis it is evident that the difference of 0.8°C see values on figure23 does not posing any risk for the RFQ functionality. Proposed design concept, especially the internal honeycomb structure and improved cooling channels, could be highly beneficial for the AM manufactured RFQs and other complex (in shape and structure) accelerator components.

Temperature values of RFQ body strongly depending from duty cycle, and heat flux values in cavity.

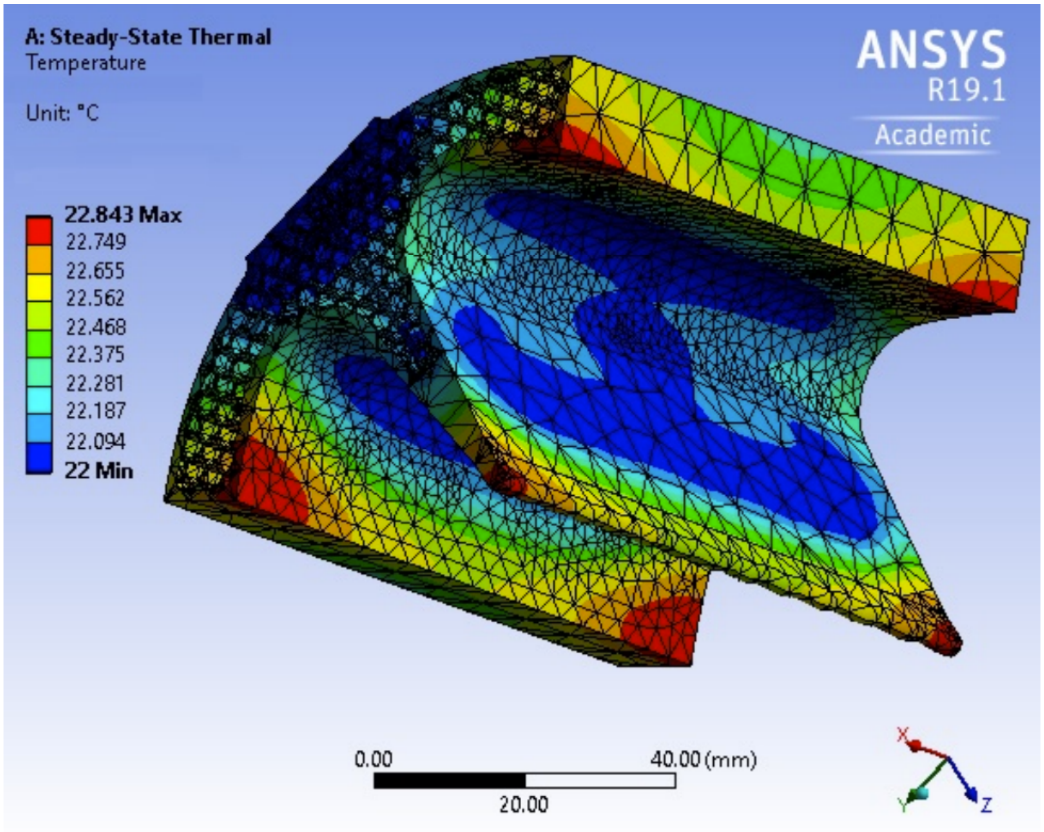


Figure 23: Steady-State Thermal analysis of RFQ sector

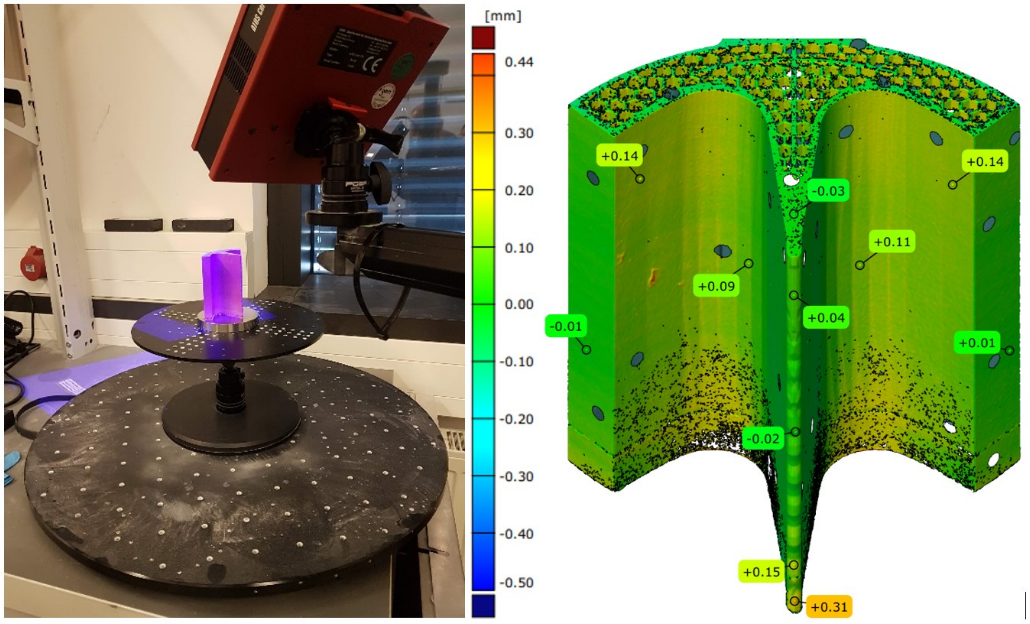


Figure 24: Optical scanning and Point cloud data comparison with original CAD model at Fraunhofer IWS.

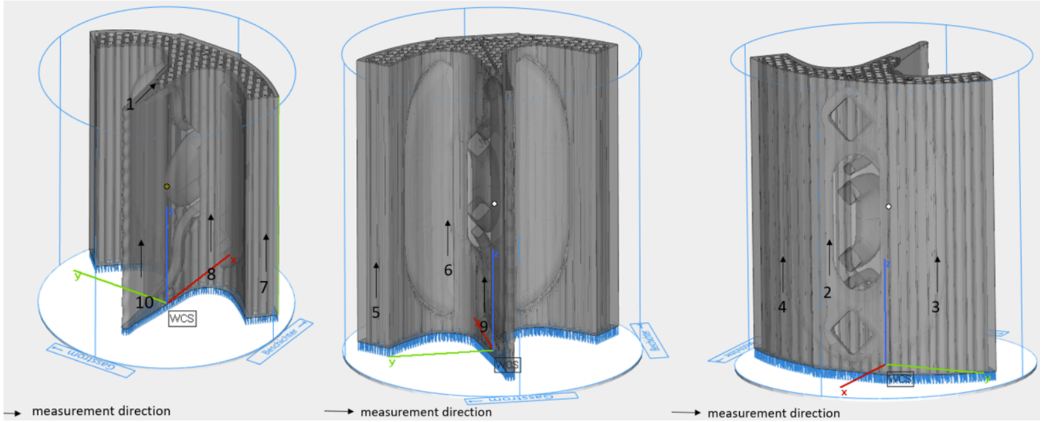


Figure 25: Surface roughness measurement locations

7 Manufacturing and measurements of quarter section HF-RFQ prototype

7.1 Quarter section manufacturing by PBF-LB green laser technology

7.2 ”As build” part meteorological inspection

7.2.1 Contact type geometry measurements

7.2.2 Optical inspection of geometry

7.2.3 Surface roughness measurements

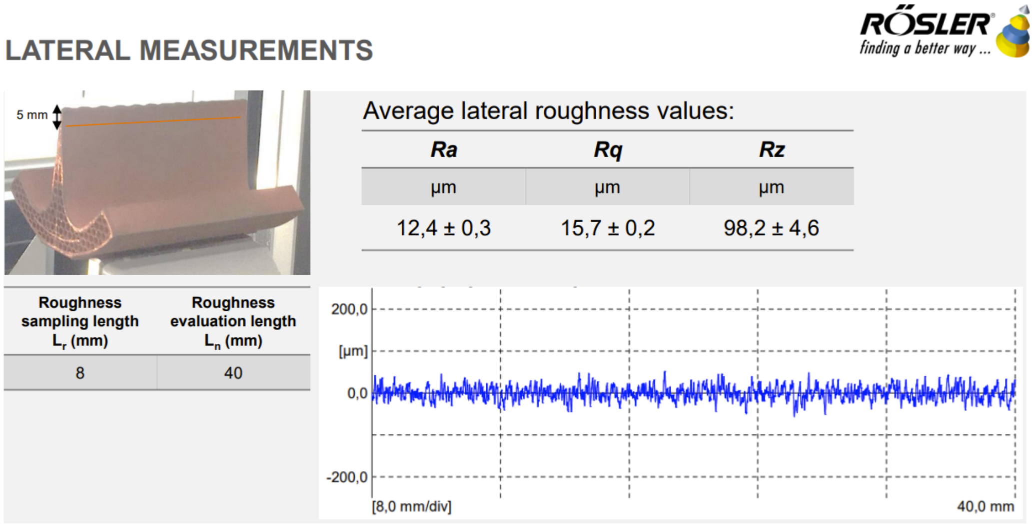
The surface roughness was measured at Fraunhofer IWS with the perthometer Surfcom Touch 50, which is a contact profilometer from Accretech, for surfaces where Ra = 0.4µm is required—on both sides of the vane (see Figure25. measurement numbers 9 and 10) and RFQ internal surfaces (see Figure25. measurement numbers 6 and 8). Measurements have been repeated three times at each area.

The surface arithmetical mean roughness (Ra) average was 14.32µm, and the maximum height of the profile (Rz) was 116.7µm. The latter was measured additionally to RFQ prototype requirements (Table 1) to obtain a more comprehensive understanding of the surface quality of the prototype. The most indicative surface roughness measurement results are provided in the

Table 3. Table 3. RFQ proof-of-concept surface roughness values according to ISO 4288.

Although these first roughness measurements of the proof-of-concept RFQ show that the obtained surface roughness quality was still far from the required Ra = 0.4 µm, 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. Therefore, even before considering potential post-processing needs and methods for the AM RFQ, there are a range of opportunities to optimize the technological process of the pure copper L-PBF manufacturing to attain better surface roughness quality. This shall be part of future experimental and research work, along with the consideration of the appropriate post-processing scenarios and experiment.

Additional surface roughness tests at Rosler Italiana see figures26, 27.



LATERAL MEASUREMENTS

RÖSLER finding a better way ...

Average lateral roughness values:

Ra	Rq	Rz
µm	µm	µm
12,4 ± 0,3	15,7 ± 0,2	98,2 ± 4,6

Roughness sampling length L_r (mm)	Roughness evaluation length L_n (mm)
8	40

Figure 26: Roughness profile measurement at Rosler Italiana Srl.

7.3 Post-processed part meteorological inspection

In this research two quarter prototype parts was manufactured and post processed by two different post processing companies Rosler Italiana(Italy) and BINC Industries(France). Each of companies are using diffenet approach for post processing. Rosler did mechanical and combined chemic-mechanical

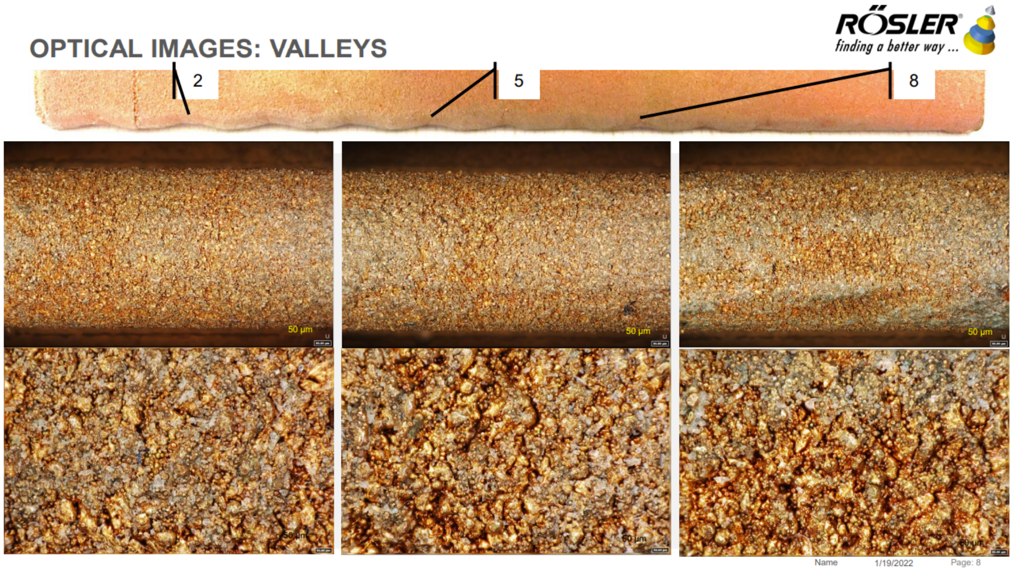


Figure 27: AM RFQ surface optical images Rosler Italiana.

7.3.1 Contact type geometry inspection

7.3.2 Optical inspection of geometry

7.3.3 Surface roughness measurements

7.4 Other physical tests to prove concept

In order to perform voltage holding tests, experiments are planned on sample electrodes, built from same material as RFQ sector. Experiment series of various tests are planned. First stage starts from non-postprocessed raw printed electrode pieces for investigation of voltage holding characteristics for raw printed geometry and final experiments with mirror smooth surface and perfect shape geometry. The design of electrodes is adapted for high voltage testing device, which mostly is used for beam electrode tests for CLIC experiment see figure 28.

Vacuum tightness is parameter, which mostly is applied to parts for high energy physics. However this parameter is quite close related to manufactured product density and porosity. Obviously part which is built for any HEP purpose rather will be with high or ultrahigh vacuum tightness and outgasing requirements. Sample vacuum membranes often are used for test-

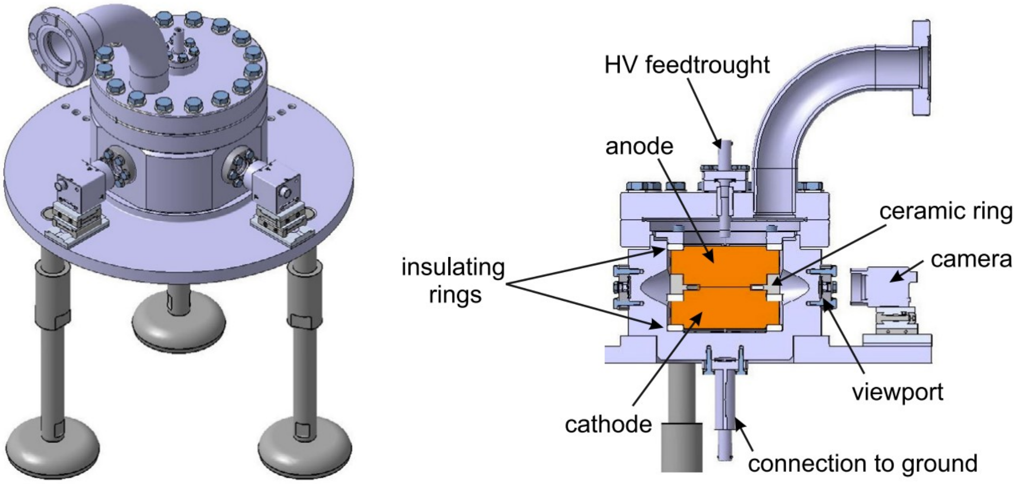


Figure 28: Voltage holding large electrode system(LES) model[59].

ing of additively manufactured material and technology. This step helps to avoid expenses due to fails of vacuum tightness level. Most often practice is manufacture samples with different wall thickness and build angle, and test them afterward.

8 Results and Analysis

9 Conclusions

9.1 Practical recommendations

Current multidisciplinary effort proved that a pure copper RFQ prototype can be successfully manufactured with AM technology, and it is, to the best of the authors' knowledge, the first AM manufactured RFQ in the world. Indeed, the latest developments of the AM technology are providing much-needed means to improve the manufacturing aspects of the RFQ and could considerably reduce machining time and overall costs. Therefore, thanks to dedicated teamwork, the concepts on how to improve RFQ design and manufacturing features offered by the state-of-the-art L-PBF technology were described in this paper. The pure copper RFQ proof-of-concept allowed the following conclusions to be derived:

1. AM technology is particularly well suited for the required mechanical complexity of RFQ, and offers significant design and optimisation freedom to meet the stringent manufacturing requirements that cannot be achieved by conventional technology. This also opens up a path to major RFQ improvements and eventually full-scale production, even using pure copper, which is a technologically demanding material.

2. The pure copper RFQ prototype, using an L-PBF system equipped with a green laser, can be manufactured in a reasonable time 16h29min with 3267layers of 30µm layer thickness.

3. Most of the external and internal shapes of the RFQ can be successfully optimized. The lightened RFQ structure is feasible by using a honeycomb pattern and by replacing the most massive sections.

4. The shape and structure of the RFQ cooling channels can be improved according to the optimum thermal management and flow-dynamics needs—and not dictated by technological restrictions of the conventional manufacturing.

5. The honeycomb structure implementation and optimization of the cooling channels allow for substantial weight reduction—in this case $\approx 37\%$ ($\approx 21\%$ and $\approx 16\%$ respectively).

6. The steady-state thermal analysis showed that for the operating conditions of the CERN PIXE RFQ, the temperature difference between different sectors remains in the order of ≈ 0.8C—thereby not posing any risk for the RFQ's functionality.

7. The surface roughness measurements indicated that the prototype surface roughness quality is still far from the required Ra = 0.4µm. The surface arithmetical mean roughness average (Ra) was registered as 14.32µm, and the maximum height of the profile (Rz) as 116.7µm. However, these results are encouraging, since they were obtained without any adaptation of the AM technological process for better surface roughness outputs.

8. The geometrical accuracy measurements revealed promising results—with the conventional AM methodology approaching the required precision of 20 µm on the vane tip and fully reaching 100µm on other surfaces. The largest deviation of 0.31mm on the vane tip can be attributed to a technological glitch—distortion of the support structures during the build process. However there is potential to reach higher level of accuracy by distortion compensations as it is described by Afazov [60].

9.2 Future research challenges

The current thesis is first development stage of AM application for full size RFQ prototype. Further stage will be needed to develop more detailed physical and technical aspects.

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