



DESIGN OPTIMIZATION OF THE WATER-COOLED COIL FOR THE PULSED ELECTROMAGNETIC EXTRACTION SEPTUM, SMH40.

Bachelor Thesis

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by

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ABSTRACT

The septum blade is a 900 mm long, water cooled OFE Cu conductor (operation at 28 kA). It is a critical component of a pulsed magnet (SMH40) used for heavy ion extraction out of the Low Energy Ion Ring (LEIR) in the accelerator complex at CERN. A failure analysis of the currently operational design has shown issues with fatigue due to operational loads, and a brazing defect on the sequential reinforced design. The objective of this bachelor thesis is **to analyze and redesign the septum blade, allowing an increased lifetime, optimized manufacturing procedure, and reduced non-conformities**. The following list of sub-tasks have been completed to achieve the main objective:

- Failure analysis including numerical computation (structural mechanics and computational fluid dynamics), non-destructive testing (leak testing and ultrasonic inspection) as well as destructive testing (optical microscopy of a metallurgical cross section).
- Develop a list of requirements for a new design, based on the functional- and failure analysis. The compliance with this set of requirements is tested on the new design.
- Production of three vacuum furnace brazed samples to prove a successful leak tight connection with the optimized joint configuration, changed type of brazing filler metal and brazing procedure.
- A physical prototype to analyse the feasibility of the design.

SAMENVATTING

De Septum blade is een 900 mm lange, watergekoelde OFE koperen geleider (operationeel bij 28 kA). Het is een kritisch onderdeel van een pulserende magneet voor de extractie van zware ionen uit de Low Energy Ion Ring (LEIR) versneller in het versneller complex van CERN. Een faal analyse van het huidige operationele ontwerp heeft problemen aangetoond betreft vermoeiing door de operationele belastingen, en een foutieve hard gesoldeerde verbinding in het opeenvolgende versterkte ontwerp. Het hoofddoel van dit proefschrift is **het analyseren en herontwerpen van de septum blade, voor een langere operationele levensduur, geoptimaliseerde productie procedure, en gereduceerde non-conformiteiten**. De volgende lijst met deeltaken zijn uitgevoerd om het hoofddoel te behalen:

- Een faal analyse met numerieke berekeningen (statische mechanica en stromingsleer simulaties), niet-destructieve testmethodes (lek-testen onder druk en ultrasoon inspectie), en destructieve testmethodes (optische microscopie van een metallurgische dwarsdoorsnede).
- Een programma van eisen met daarin de meest belangrijke eisen en wensen voor een nieuw ontwerp, gebaseerd op de functionele- en faal analyse. Validatie van het nieuwe ontwerp is getoetst met het programma van eisen.
- Productie van drie vacuüm oven hard gesoldeerde proefstukken heeft een lekdichte verbinding aangetoond, door middel van een geoptimaliseerde verbinding, type soldeerlegering en hardsoldeer procedure.
- Een fysiek prototype om de werkzaamheid van het ontwerp te kunnen valideren.

PREFACE

This thesis is written for a 6-month graduation internship for the bachelor mechanical engineering at the University of applied sciences Utrecht¹. The assignment is commissioned by the Accelerator Beam Transfer - Septa section (SY-ABT-SE) at European Organization for Nuclear Research (CERN) in Switzerland and was carried out from February 2022 until August 2022. Three reports were written during the internship period:

- A project initiation document (PID) submitted in March 2022, containing the plan of approach.
- The bachelor thesis
- A reflection report for the progress of two personal learning goals and various professional soft skills.

Readers mostly interested in the detailed design of the new generation septum blade and the manufacturing and inspection plan (MIP), can find this information in chapter 6 and 7.

I wish to show my appreciation for the guidance from my supervisors, F. Lackner (CERN) and G. Kloosterman (HU). Their attentiveness and help was indispensable for the success of the thesis. I am grateful for the vote of confidence from the SE section leader J. Borburgh, for offering me the opportunity to work on this project. In addition I am grateful for the support and patience I have received from all colleagues within the SY-ABT-SE section, M. Atanasov, L. Jorat, C. Baud, M. Rouchouse, F. Pirozzi, R. Bonthond, T. Masson, P. Blaise, A. Prost and B. Balhan.

Furthermore, I am thankful for the Engineering department, Materials & Mechanical Engineering department (EN-MME) at CERN for the various inspections and manufacturing of samples and the prototype. In particular to F. Motschmann and A. Gerardin, whose experience and knowledge on vacuum brazing was essential to the project. Without them the production of the brazing samples and the prototype would not have been possible.

Finally, I would like to thank my friends and family, for all the support and loving encouragements while living far from home during this time.

Prévessin-Moëns, August 2022
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ACRONYMS

ABT	Accelerator Beam Transfer
ALICE	A Large Ion Collider Experiment
BFM	Brazing Filler Metal
BWE	Back Wall Echo
CAD	Computer Aided Design
CERN	European Organization for Nuclear Research
CFD	Computational Fluid Dynamics
DT	Destructive Testing
DFM	Design For Manufacturing
EB	Electron Beam Welding
EDMS	Engineering & Equipment Data Management Service
EN	Engineering department
FD	Functional Decomposition
FEM	Finite Element Method
FW	Forming & Welding section
LEIR	Low Energy Ion Ring
LHC	Large Hadron Collider
LINAC-3	Linear Accelerator 3
LS2	Long Shutdown 2
MIP	Manufacturing and Inspection Plan
MMA	Manual Metal Arc Welding
MM	Materials & Materials, Metrology and Non-Destructive Testing Section
MME	Mechanical & Materials Engineering group
MTTF	Mean Time To Failure
NDT	Non-Destructive Testing
OFE	Oxygen-Free Electronic
PID	Project Initiation Document
PPE	Personal Protective Equipment
PS	Proton Syncotron
QC	Quality Control
SCC	The Surface Coatings & Chemistry section
SE	Septa
SF	Shrink Fitting
SMH40	Septum Magnet Horizontal 40
SPS	Super Proton Syncotron
SS	Stainless Steel
SY	Accelerator Systems
TIG	Tungsten Inert Gas Welding
UT	Ultrasonic Testing

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1

INTRODUCTION

The *Low energy Ion Ring* (LEIR) is an important part in the chain of CERN's accelerators facilities, that injects heavy ions into LHC to be analyzed by collisions in the ALICE detector and fixed target experiments in the North area [14]. The main goal of ALICE is to characterize the physical properties of quark-gluon plasma. Quark-gluon plasma is studied to recreate and understand the conditions of the universe in the first microseconds after the Big Bang [15].

The chain of particle accelerators is needed for the particles to reach the required energy. Every accelerator in the complex, linear or circular, has its own dynamic range [16]. These ranges of each individual accelerator are comparable to the gears in a gearbox. The lead ion beam is extracted out of, or injected into accelerators and colliders. The ion chain starts in the LINAC-3 to LHC via LEIR, PS and SPS [14]. The Accelerator beam transfer group (ABT) is responsible for all injection- and extraction related equipment [13]. Figure 1.1 shows the CERN accelerator complex with the ion chain indicated with dark grey arrows.

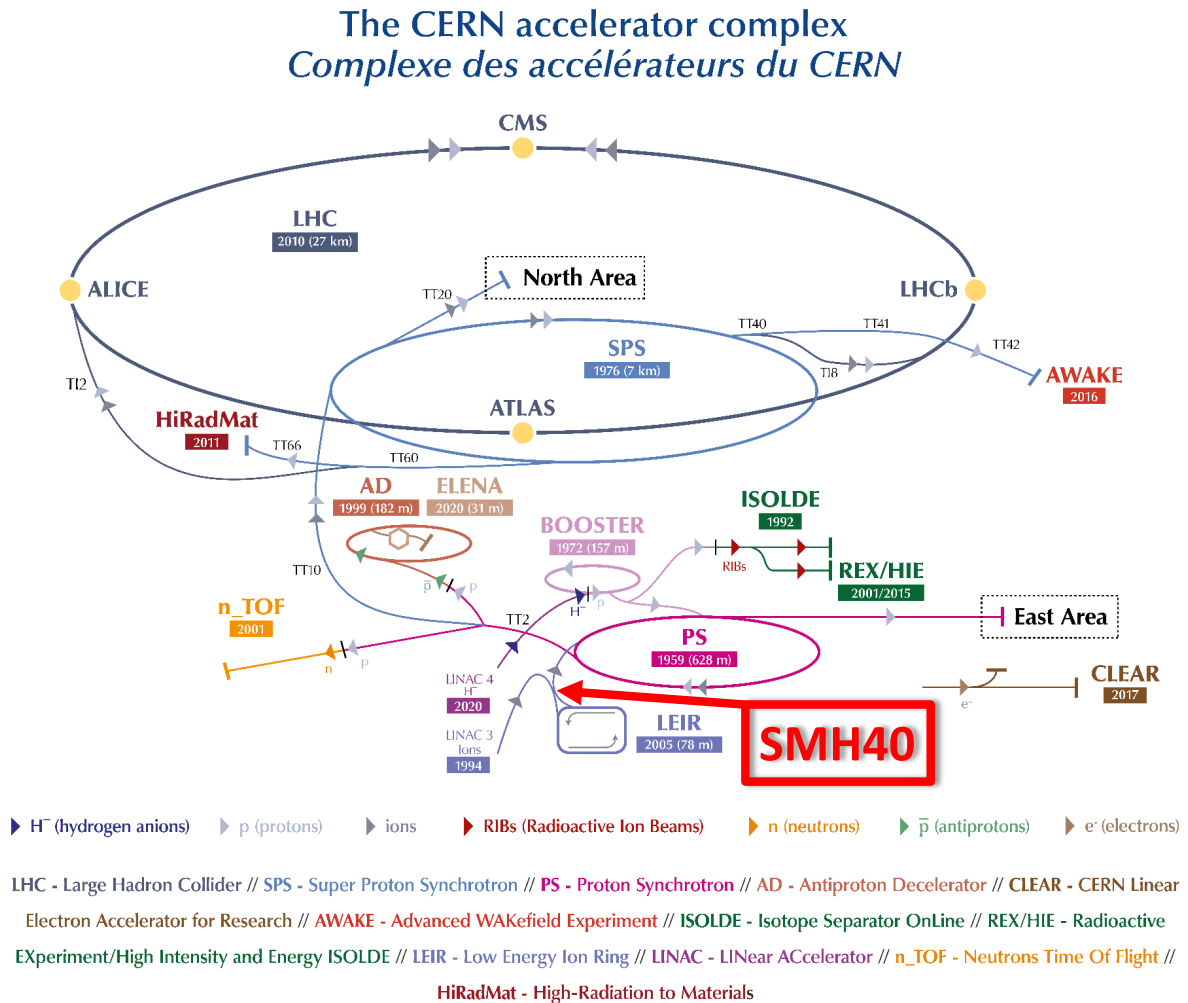


Figure 1.1: Schematic overview of CERN's accelerator complex [12].

A combination of a kicker magnet and a pulsed electromagnetic septum magnet (SMH40) is used to extract the ion beam out of LEIR into a transfer line towards PS (Figure 1.1). A kicker magnet diverts the beam by providing an initial deflection. The pulsed electromagnetic septum provides the final deflection of 130 mrad (Figure 1.2) [6]. The amount of deflection depends on the intensity of the magnetic field. A stable and homogeneous magnetic field is important for the consistency and repeatability of the ion beam extraction.

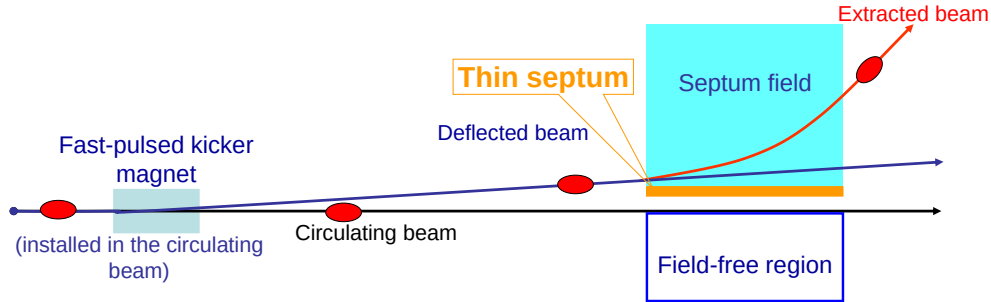


Figure 1.2: Schematic visualizing the deflection/extraction of the ion beam using a combination of a kicker magnet and a pulsed electromagnetic magnet [4].

In the SMH40, the beam passes through the homogeneous septum field region only once every 3,6 s during beam extraction. However, the circulating beam passes through the "field-free region" many times during the entire machine cycle (Figure 1.2). Achieving a very low level of stray field in this region is important to keep the circulating beam on the same trajectory [6].

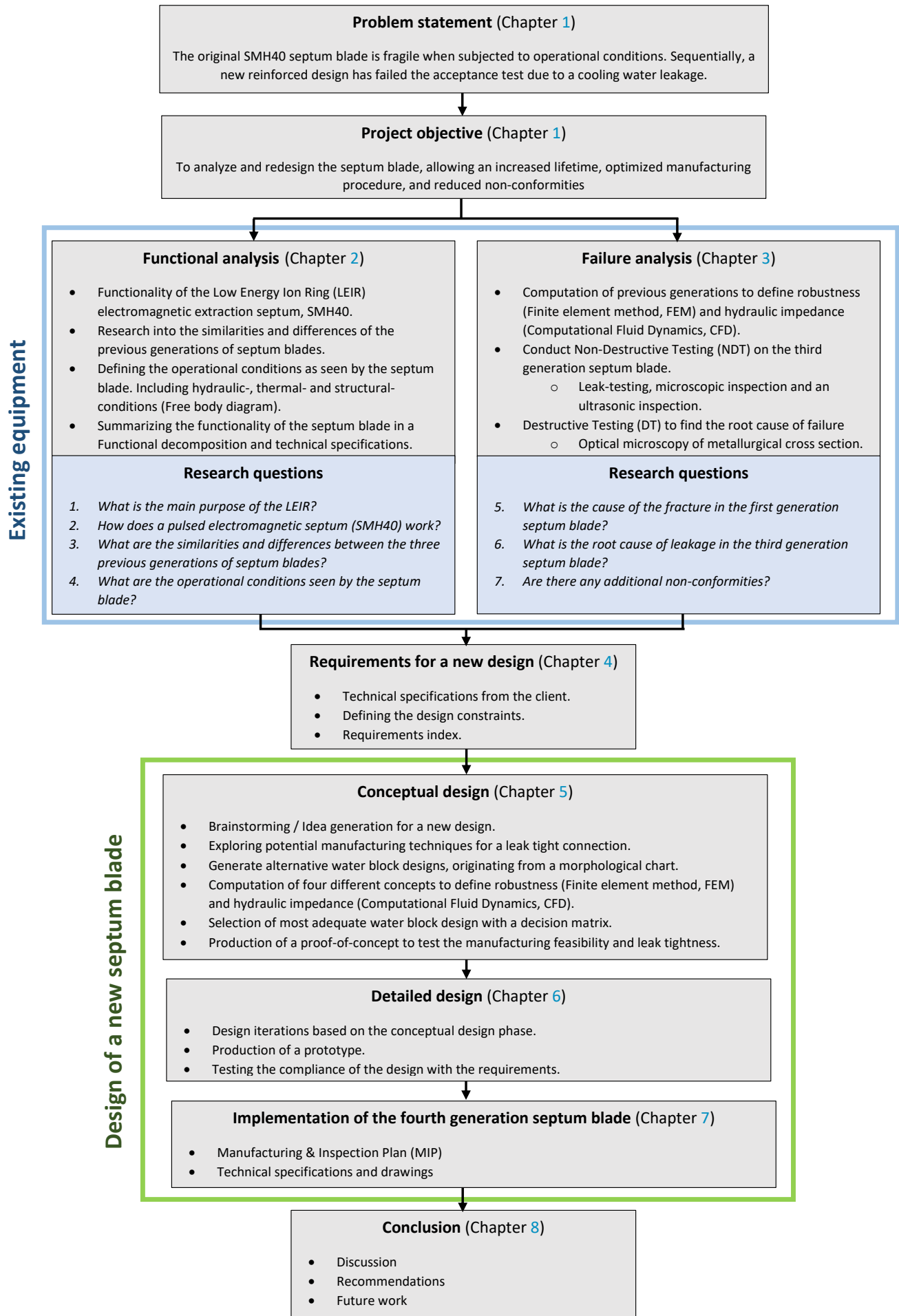
A solution to minimize the stray field in the field-free region is a physical boundary called the "*septum*" (Latin for "*something that encloses*" or "*wall*"). The septum blade is a water cooled 900 mm long Cu conductor with a high current density, installed in the gap of a laminated iron yoke (Figure 1.2). The main function of the septum blade is to generate a homogeneous and stable magnetic field in the gap of the yoke, while preventing a leak field in the region of the circulating beam, in a repeatable and reliable manner.

1.1 PROBLEM STATEMENT & MAIN OBJECTIVE

A failure of the septum blade, due to a hydraulic, fatigue or thermal issue, would result in the shut-down of the SMH40, since the septum blade will need to be replaced with a spare [8]. Ion experiments will be put on hold if the beam cannot be extracted out of LEIR. Currently there is a 20 year old version of the septum blade installed in the SMH40. This design has had fatigue issues in the past due to the fragile geometry of the exposed cooling water channels. Sequentially, a new generation was designed in 2017, in which the OFE Cu conductor was reinforced, but the prototype has failed the acceptance test due to a cooling water leakage and was never installed on the SMH40. Therefore, a new reinforced leak-tight design is required. **The objective of this thesis is to analyze and redesign the septum blade, allowing an increased lifetime, optimized manufacturing procedure, and reduced non-conformities.**

1.2 METHODOLOGY & RESEARCH PLAN

A combination of the V-model [11] and "*Ontwerpen van technische innovaties*" [23] is used during this project to provide a methodical and structured approach. These design methodologies will be particularly suitable for this project because this model allows for defined checks and design iterations. A flowchart of the research plan is shown in Table 1.1. Substantiation for each research question (the goal, research type, methods and sources to be used) can be found in Appendix A.1. The flowchart defines the scope of this project and thesis structure, in addition to the research plan and research questions.

Table 1.1: Research plan containing the topics of this thesis per phase, corresponding to the thesis structure.

2 | FUNCTIONAL ANALYSIS

This functional analysis will answer the following research questions, originating from the research plan in Table 1.1:

- *What is the main purpose of LEIR?* ⇒ Section 2.1
- *How does a pulsed electromagnetic septum (SMH40) work?* ⇒ Section 2.2
- *What are the similarities and differences between the three previous generations of septum blades?* ⇒ Section 2.3
- *What are the operational conditions seen by the septum blade?* ⇒ Section 2.4

2.1 THE LOW ENERGY ION RING

LEIR provides ions for the LHC Ion Physics runs as well as the North Area fixed target experiments during November each year. The remainder of the year is used for setup and development [14].

LEIR collects the small bunches of ions coming from LINAC-3. LEIR densifies and accelerates them from 4.2 MeV per nucleon to 72 MeV per nucleon to be extracted towards PS. A cycle occurs every 3,6 seconds [16]. The injection- and extraction site are located on the top left of Figure 2.1a and Figure 2.1b.

The position and the basic shape of LEIR is fixed by the fact that LEIR recycles the LEAR (Low Energy Accumulating Ring) bending blocks at their original position. It has an almost “square” geometry, 80 m in circumference, with four bending sections, each one deflecting the beam by 90° and four straight sections, each one with a total length of about 12.8 m [14].

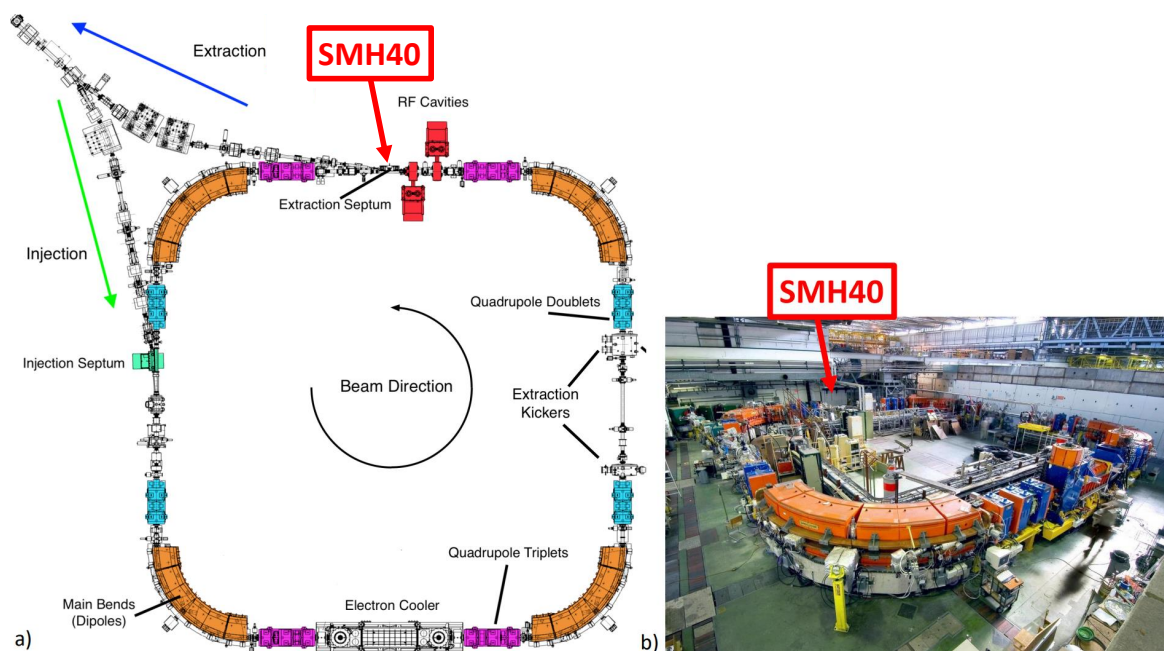


Figure 2.1: a) Schematic drawing of the LEIR as seen from above [14] b) Photograph of the 78m long accelerator, LEIR located at the CERN Meyrin site. [15]

2.2 THE LEIR EXTRACTION SEPTUM (SMH40)

There exist two families of septa: electrostatic and electromagnetic septa. In both families there are multiple configurations and variations. This thesis will only focus on the SMH40 (Figure 2.2), as this is in the scope of this thesis. More information on different types of septa can be found in [35].

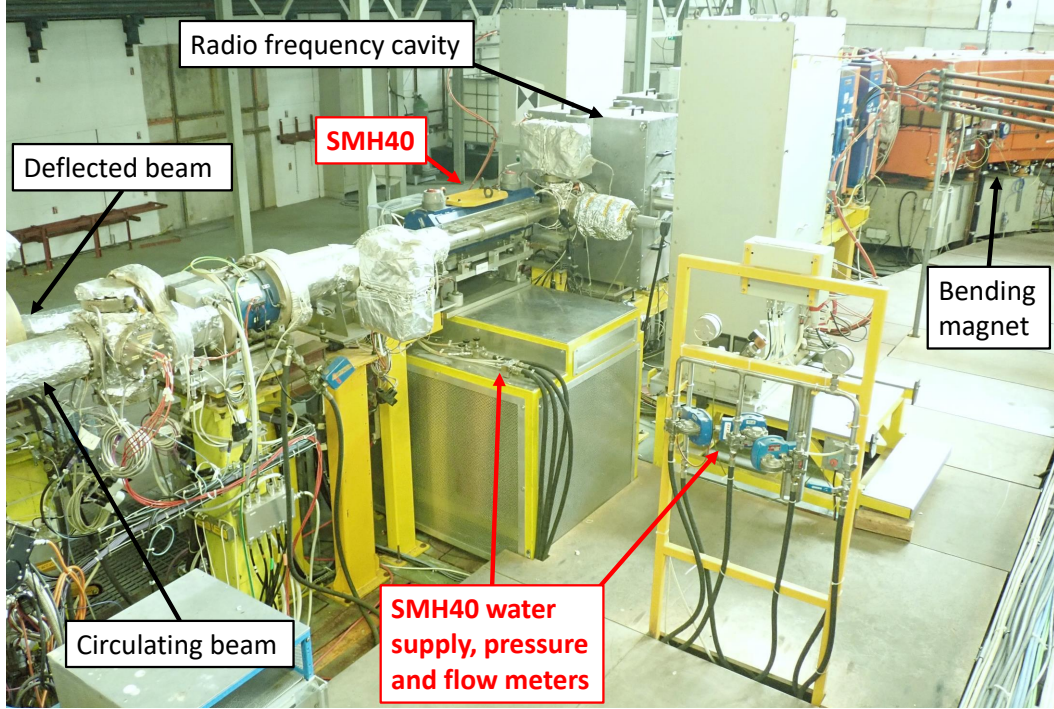


Figure 2.2: Overview photo of the SMH40 located in LEIR.

2.2.1 Functionality of a pulsed electromagnetic septum

The SMH40 is a pulsed electromagnetic septum. It consists of a conducting coil embedded into the gap of a C-shaped ferromagnetic yoke. The yoke amplifies and channels the magnetic flux, which is induced by the flow of current in the coil. This coil consists of one turn to decrease self inductance. Figure 2.3 shows schematically a cross section of the magnet, showing the yoke in blue and the coil in orange. Figure 2.3 also shows the deflected beam line in the high field region of the gap of the C-shaped yoke and the circulating beam line next to the magnet in the field free region. These regions are separated by the septum conductor, or septum blade. It is named a septum "blade" because it slices the circulating particle beam to be extracted in electrostatic septa. One can see that the magnetic field in the gap is homogeneous and drops close to 0 due to the septum blade and vacuum chamber [3] [6] [10].

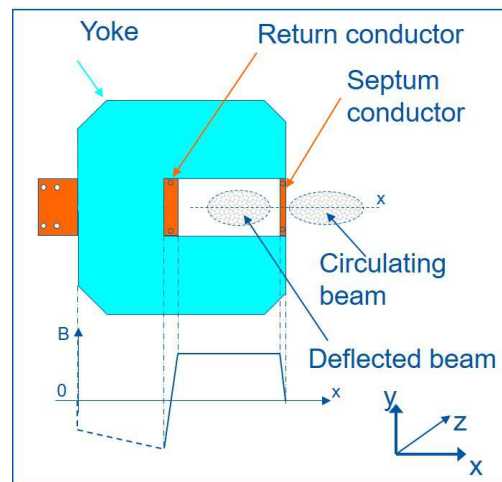


Figure 2.3: Schematic cross section of the principle of an electromagnetic septum [4].

2.2.2 The coil

The single turn coil, as previously schematically shown in Figure 2.3, consists of two return conductors, a septum blade and four electrical connectors between them. A CAD model of the coil is shown in Figure 2.4 and the SMH40 is shown in Figure 2.5 and 2.6. The coil is clamped around the vacuum chamber for removal of the magnet from the vacuum chamber during bake-out. The coil is outside vacuum due to the stringent vacuum requirements of LEIR (dynamic pressure $\approx 10^{-12}$ mbar) [10].

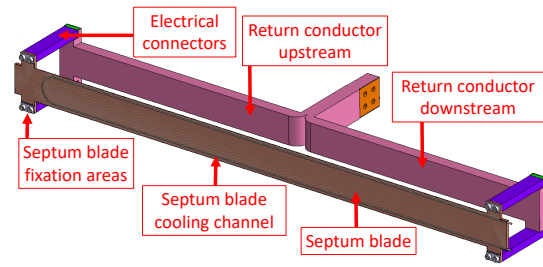


Figure 2.4: CAD drawing of the 900 mm long coil.

Stabilizing the coil temperature is an important parameter to achieve the required precision for beam extraction out of LEIR. A stable coil temperature means a stable electrical resistance, as seen by the power supply ($0,2 \Omega$) [9]. Therefore the temperature of the septum blade is stabilized with demineralized water. The embedded water channel in the septum blade is connected to the water supply via a hydraulic connector and a flexible hose. Figure 2.6 shows the hydraulic connectors of the septum blade and of the return conductors. The four mounting areas of the septum blade are located on either side of the yoke, above and below the circulating beam line.

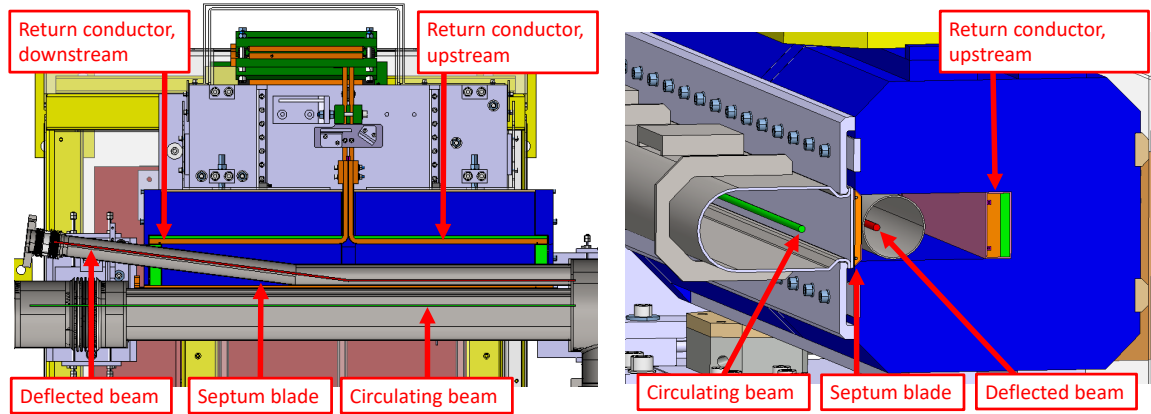


Figure 2.5: CAD model of the SMH40 showing the location of the septum blade (orange) in between the circulating beam line (green) and the deflected beam line (red). Left is a cross section of the SMH40 assembly seen from the top view. On the right a cross section seen from a side view.

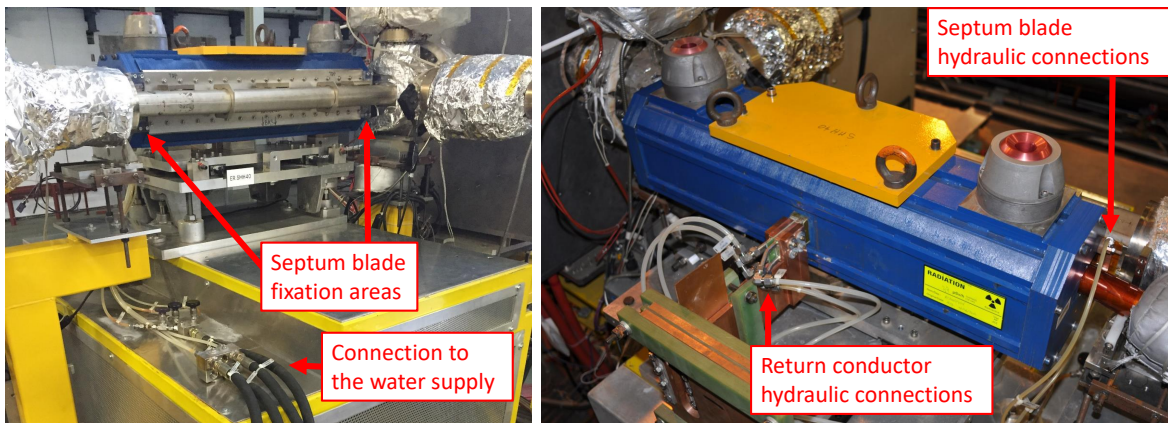


Figure 2.6: Photographs of the SMH40 [32].

2.3 THE SEPTUM BLADE

2.3.1 Key components

The septum blade of the SMH40 consists of seven key components:

1. **Conductor**

The conducting part of the septum blade is made from a OFE C10100 Cu plate. *C10100 Oxygen-Free Electronic CU, also known as OFE, is a 99.99% pure Cu with 0.0005% oxygen content. C101 achieves a minimum 101% IACS conductivity rating (low resistance of $1,72 \cdot 10^{-8} \Omega \text{m}$). [33]* More material properties of OFE Cu can be found in Appendix A.4. The plate is 900 mm long and 4,5 mm thick. The long edges of the conductor are tapered to reduce the amount of leak field in the field free region and to properly constrain it in between the yoke and the vacuum chamber. Together with the placement of the cooling channels, tapering of the edges of the conductor allows for good current uniformity in the septum blade [10].

2. **Cooling channel**

The U-shaped cooling channel is a 1734 mm long and $\varnothing$ 2mm 316L SS cooling channel embedded into a groove that is milled out of the OFE Cu conductor. The 316L SS cooling channel is assembled to the conductor via vacuum furnace brazing. The flow in the cooling channel is approximately 1 L min^{-1} with a SMH40 water supply inlet pressure of 25 bar. More information about fluid flow can be found in section 2.4.3.

3. **Reinforcement plate**

An additional 0,5 mm thick 316L SS plate, vacuum furnace brazed on the back of the OFE Cu conductor, reinforces the conductor during operational conditions. Reinforcement is required to prevent fracture due to fatigue during pulsing with approximately 8728 N Lorentz force every 3,6 s. More information about the excitation Lorentz force can be found in section 2.4.1.

4. **Water block**

The OFE Cu water block provides the connection between the water supply and the cooling channel. The design of this water block varies in the generations of septum blade. It is a critical component to ensure a leak tight septum blade. The water block is located on one end of the septum blade and holds both the hydraulic connectors for the inlet and the outlet of the cooling channel.

5. **Hydraulic connectors**

All generations contain SAGANA hydraulic connectors, vacuum furnace brazed into the water block. The hydraulic connectors allow for repeated (de-)coupling of the water supply to the septum blade allowing the cooling channel to be dried with compressed air during maintenance operations.

6. **Electrical insulation**

Electrical insulation between the grounded yoke and the conducting septum blade is needed to prevent short circuit. The thickness of the insulation has an effect on the amount of leak field in the field free region since the insulation is "invisible" to the magnetic field. The insulation should be as thin as possible to minimize this effect, but it should still be able to have a sufficient amount of hold-off voltage. The amount of hold-off voltage is $2 \times$ the magnet voltage + a safety margin, according to CERN standard [8]. The amount of hold-off voltage depends on the peak current, the resistance, and the electrical impedance. The hold-off voltage for the insulation is approximately 1 kV.

7. **Mounting assembly**

The septum blade is mounted on the return conductor with four integrated mounts. Each mount contains two holes and a 316L SS pressure plate ($24 \times 10 \text{ mm}$), to properly connect the two conductors together. The septum blade is mounted to the return conductors with helicoil bolts including safety spring washers. See Section 3.1.3 for damage on the mounting assemblies due to insufficiently tightened bolts.

2.3.2 Three generations of blades

The septum blade design has seen several iterations due to repairs and component replacements over the last 20 years. A clear distinction between three generations can be made; The first (SMH40.1), the second (SMH40.2) and the third (SMH40.3) generation. The improved variant of the septum blade will therefore be referred to as the fourth generation (SMH40.4).

First generation (currently in operation)

The first generation was designed 20 years ago (Figure 2.7) [8]. The currently operational septum blade was manufactured in 2011. The hydraulic connectors are brazed into the OFE Cu water block, and the water block is connected to the conductor via the cooling channels. A fracture of the cooling channel occurred after six years in operation (Figure 2.7a & 2.7b) [8]. An identical spare septum blade was installed after the fracture in 2016. The negligible dose rate of the old removed septum blade at contact, is $< 0.1 \mu\text{Sv/h}$, measured on 23-02-2022 (CERN TREC ref. no. PXMSCST10A-CR000001). The water block of the first generation septum blade is also constrained on the side of the yoke with a bolted connection (Figure 2.7c), in addition to the four designated fixation areas as explained in the previous section. The tapered edges on both sides are covered with a 0,2 mm thick layer of aluminium oxide coating (Al_2O_3), including an extra protection of 0,1 mm thick Kapton® sheet to electrically insulate the conductor. Manufacturing costs are included in Appendix A.6.

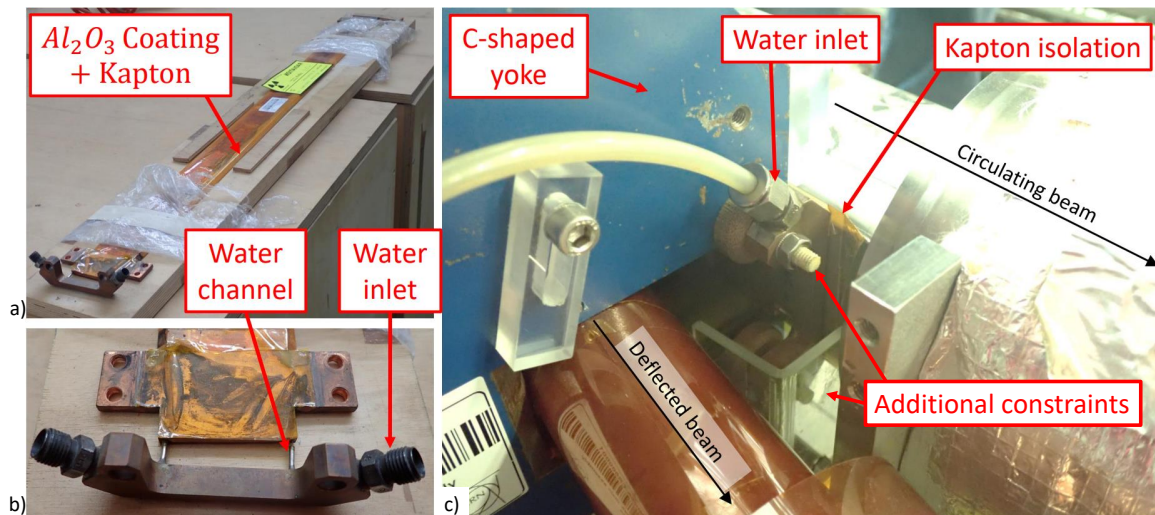


Figure 2.7: a) Photograph of the removed septum blade. b) close-up of the water block. c) Photograph of the replaced septum blade installed on the SMH40. The septum blade is approximately 920mm x 27mm x 94mm and weighs approximately 2,1 kg.

Second generation (spare)

The second generation is used as a spare. This generation is structurally the same as the first generation. The only difference between the first and the second generation is the type and thickness of the electrical insulation. This design version uses a polymerized polyimide insulation known as Pyralin [2]. The pyralin is slightly thicker (0,5 mm) instead of the Al_2O_3 coating (0,2 mm). The currently installed yoke is also coated with Al_2O_3 coating to match the first generation septum blade. Installing the second generation would require a replacement of a non-coated yoke. Another unmodified spare yoke exists, but replacing the yoke is a time consuming and therefore costly solution, especially, because this design is expected to have the same structural issues as the first generation.

Third generation (failed acceptance test)

The third generation was designed in 2016 and two blades were produced in March 2017 (Figure 2.8) . The water block design is reinforced by machining the water block and conductor from one part and embedding the cooling channel completely into the conductor. However, machining the water block and conductor from one piece resulted in a large amount of wasted material because machining removed approximately 80 - 85%. The septum blade was leaking significantly during the acceptance testing. This version was never installed, therefore no conclusion can be made regarding the robustness of the design.

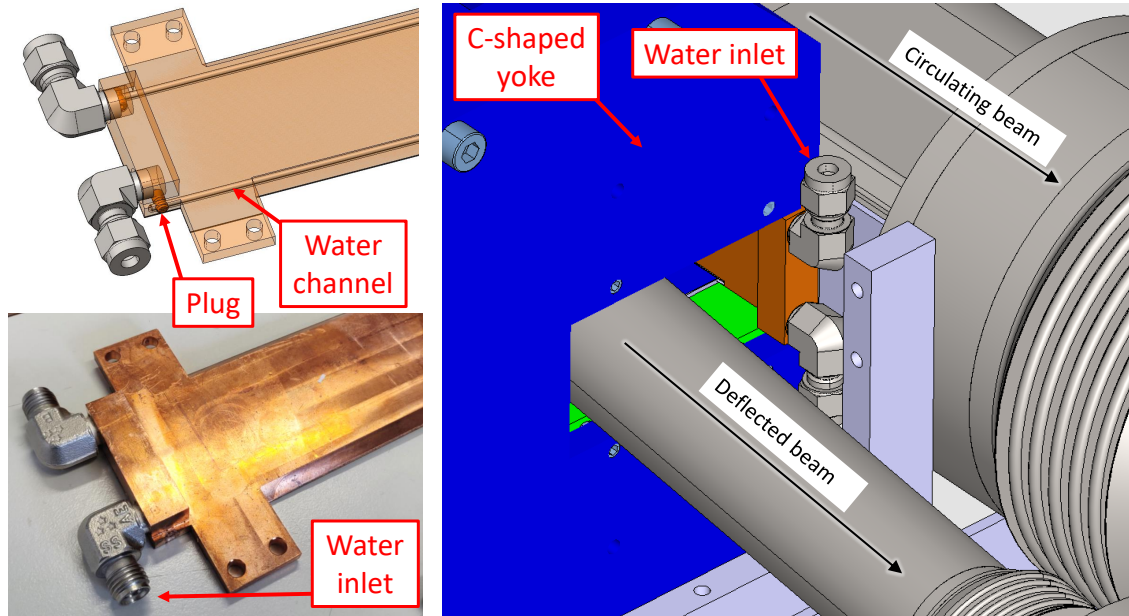


Figure 2.8: One photograph and two CAD models showing the third generation septum blade, On the right a CAD model of how the septum blade would have been installed on the SMH40. The septum blade is approximately 915mm x 13.5mm x 94mm and weighs approximately 2,1 kg.

The third generation septum blade was assembled via vacuum furnace brazing by the CERN EN-MME group in February 2017 [28]. Three individual cycles were required to fully assemble the septum blade. Before brazing, all 316L SS components were coated with nickel to enhance the wetting process during brazing. Photographs and specifications of these cycles are shown in Figure 2.9 and Table 2.1. Manufacturing costs of this septum blade were considerably higher compared to the first generation. More information about manufacturing costs are included in Appendix A.6.

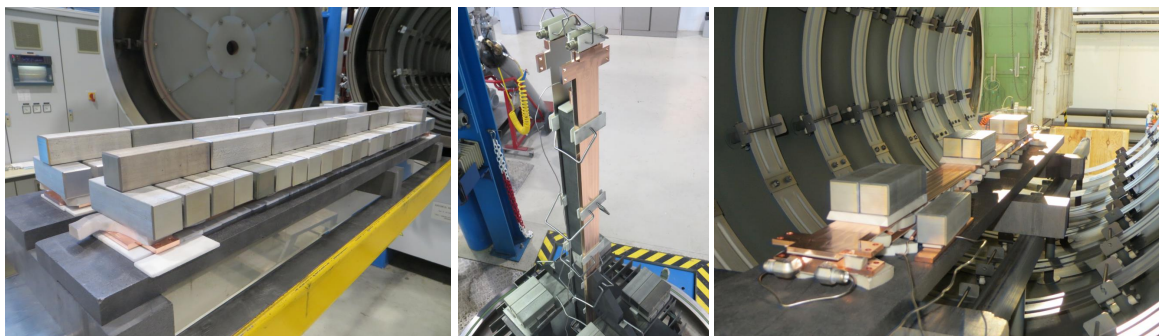


Figure 2.9: Photographs of the three brazing cycles needed to fully assemble the third generation septum blade, with the first step on the left and the third and last step on the right. [28]

Table 2.1: Procedure to braze the third generation septum blade [28].

Cycle	Configuration	Parts	BFM	Brazing temperature
1st brazing	Horizontal	Cooling channel, the 316L S.S. plate and the OFE Cu plate	Ag58.5Cu31.5Pd10 (Pd 387 V1)	860°C $\pm$ 5°C
2nd brazing	Vertical	Hydraulic connectors to the septum blade	Ag68.5Cu26.5Pd5 (Pd 287 V1)	813 - 825°C
3rd brazing	Horizontal	Cu-plugs	Ag72Cu (Ag 272 V1)	785 $\pm$ 5°C

A hole was drilled into the side of the water block, in-between the second and the third brazing cycle (Figure 2.10b). The hole connects the cooling channel to the hollow area behind the hydraulic connector. Threads are added to the hole, and it is closed-off with a separate part called the "plug". The plug is screwed in and then brazed in the third brazing cycle [21].

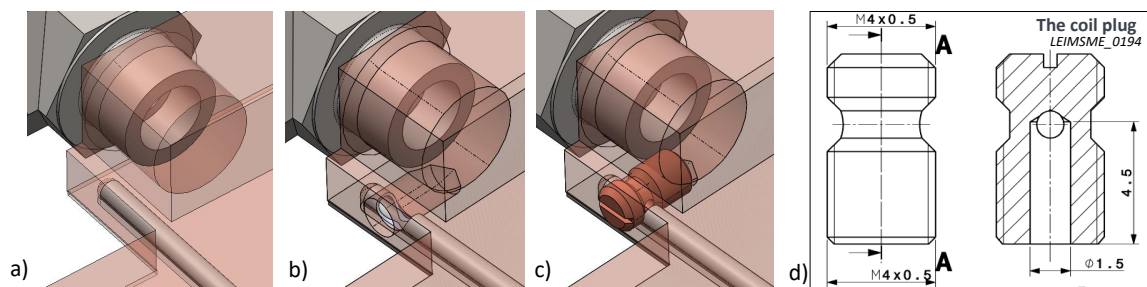


Figure 2.10: a) Result after the second brazing cycle. b) A hole was drilled and threaded into the side of the conductor through the cooling channel into the hollow area behind the hydraulic connector. c) The plug was screwed into the hole and brazed in the third brazing cycle. d) Section from the technical drawing of the coil plug.

2.3.3 Electrical safety covers

There are electrical safety covers installed to cover the water block (Figure 2.11a) and the four mounting areas (Figure 2.11b). They are fastened with socket head bolts and are easy to remove for maintenance operations. The covers are made from 4 mm thick transparent Makrolon® Polycarbonate sheet [7]. A new septum blade design is required to allow for enough clearance for electrical safety covers. However, re-using the existing covers is not mandatory.



Figure 2.11: a) Photograph of the safety cover on the water block. Photograph of the removed cover is shown in Figure 2.7 b) One out of four covers for the mounting areas.

2.4 OPERATIONAL CONDITIONS AS SEEN BY THE SEPTUM BLADE

Operational conditions as seen by the septum blade are:

- Mechanical forces due to the excitation magnetic field,
- Thermal loads as a function of the electrical resistance and the current density,
- Internal pressure because of the cooling water to stabilize the conductor temperature.

2.4.1 Mechanical forces

The septum blade is subjected to a pulsed Lorentz force, $F_{Lorentz}$, every 3,6 seconds. This paragraph is dedicated to calculating the amount of Lorentz force that acts on the septum blade during operation and to create a free body diagram (FBD). The information from the FBD is used to calculate the maximal stresses and deflection in the septum blade, both in previous generations and in the future generation.

Strength of the magnetic field

The velocity and trajectory of a charged particle can be guided in a different direction using a magnetic field. A magnetic field is represented using magnetic field lines. The vector of these field lines is always from the magnetic north pole to the magnetic south pole. The charged particle will be deflected, if the magnetic field lines are perpendicular to its trajectory. The direction of the deflection depends on the positive or negative charge of the particle and its direction of propagation [3].

The configuration and design of an electromagnet for beam guidance, is primarily based on three parameters. The amount of required deflection (θ in mrad), the energy (72 MeV/nucleon for lead ions [14]) and, the magnetic rigidity of the beam ($B\rho$ in T m). These parameters determine the required magnetic field strength (B_{field} in T) and effective magnetic field length (l in m). Magnetic rigidity is a term to describe the reluctance of a particle to change its trajectory within a magnetic field with perpendicular field lines. The value of the magnetic rigidity of a particle increases, if the particle momentum increases. Therefore, in a circular accelerator the magnetic rigidity can be derived from the Lorentz force (Equation 2.1 [3]).

$$F_{Lorentz} = e \cdot v \cdot B_{field} = \frac{m \cdot v^2}{\rho} \quad (2.1)$$

In equation 2.1, e is the particle charge in C, v the velocity in m s^{-1} , B_{field} in T, m is the particle mass in kg and ρ is the radius of the circular path. Therefore, the magnetic rigidity is defined as the left term of equation 2.2 with $p = mv$ [3].

$$B\rho = \frac{p}{e} \quad (2.2)$$

When p is written in N s and e in C, the unit of magnetic rigidity is in T m. The magnetic rigidity of the ion beam during injection into LEIR is 0,6 T m and during extraction out of LEIR, 4,8 T m [14].

The SMH40 needs to deflect the lead ion particles by 130 mrad to be extracted. The effective magnetic field length of the SMH40 is 0,852 m [9]. For a small deflection, $\theta \ll \frac{\pi}{2}$, equation 2.3 [8] is used to calculate the required magnetic field strength.

$$B_{field} = \frac{\theta \cdot B\rho}{l} = \frac{0,13 \cdot 4,8}{0,852} = 0.7324 \text{ T} \quad (2.3)$$

Lorentz force on the septum blade

In February 2006, magnetic field measurements were performed on a SMH40 test setup [9]. The magnet resistance ($0,2 \Omega$) and magnet inductance ($2,3 \mu\text{H}$) were measured, prior to operation. A nominal current of 27956 A was measured, for a B_{field} in the gap of the yoke of $0,732 \text{ T}$, with the effective magnetic length of $0,852 \text{ m}$. The septum blades thickness is 5 mm (conductor + reinforcement plate). However the effective septum blade thickness as seen by the beam is 10 mm , since the vacuum chamber including μ -metal plate contribute to preventing a leak field. The current density in the conductor is 128 A mm^{-2} , as shown in equation 2.4.

$$J_{septum} = \frac{I_{peak}}{A_{Cu}} = \frac{27956}{218} = 128 \text{ A mm}^{-2} \quad (2.4)$$

The direction of the force, $F_{magnetic}$, that acts on the septum blade can be derived from the "Right hand rule", as shown in Figure 2.12.

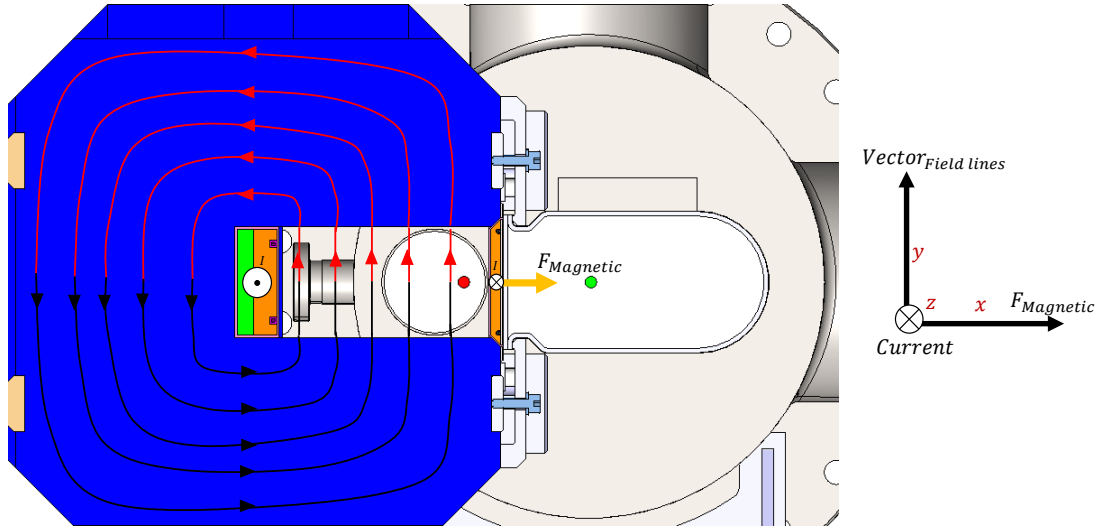


Figure 2.12: Schematic representation of the magnetic field lines drawn on a cross section of a CAD model of the SMH40. The direction of $F_{magnetic}$ is derived from the right hand rule on the right side of the figure. The red dot is the deflected beam line in the gap of the blue yoke. The green dot is the circulating beam in the field free region.

Equation 2.5 [8] is used to calculate the magnitude of $F_{magnetic}$. Based on the measured nominal current (I_{peak} in A), the magnetic field length (l_m in m) and the magnetic field strength (B_{field} in T).

$$F_{magnetic} = I_{peak} \cdot l_m \cdot \frac{B_{field}}{2} = 27974 \cdot 0,852 \cdot \frac{0,7324}{2} = 8728 \text{ N} \quad (2.5)$$

Septum blade deflection and free body diagram

Coil fatigue and deflection must be taken into consideration during the design process of a pulsed electro-magnetic septum. The septum blade is compressed between the yoke and the vacuum chamber, to reduce the probability of a failure due to fatigue. It is held in place between the tapered edges on the yoke, by the four mounting areas to the return conductor, a 2 mm thick μ -metal plate (50 - 50% Ferro-Nickel alloy), and two clamps [10]. The mounting equipment accounts for the non-operational forces in the FBD in Figure 2.13. The operational forces, $F_{magnetic}$ and F_{vacuum} , are represented with green arrows in Figure 2.13. The internal hydraulic force due to water pressure shall be addressed in paragraph 2.4.3 and is therefore not included in the FBD.

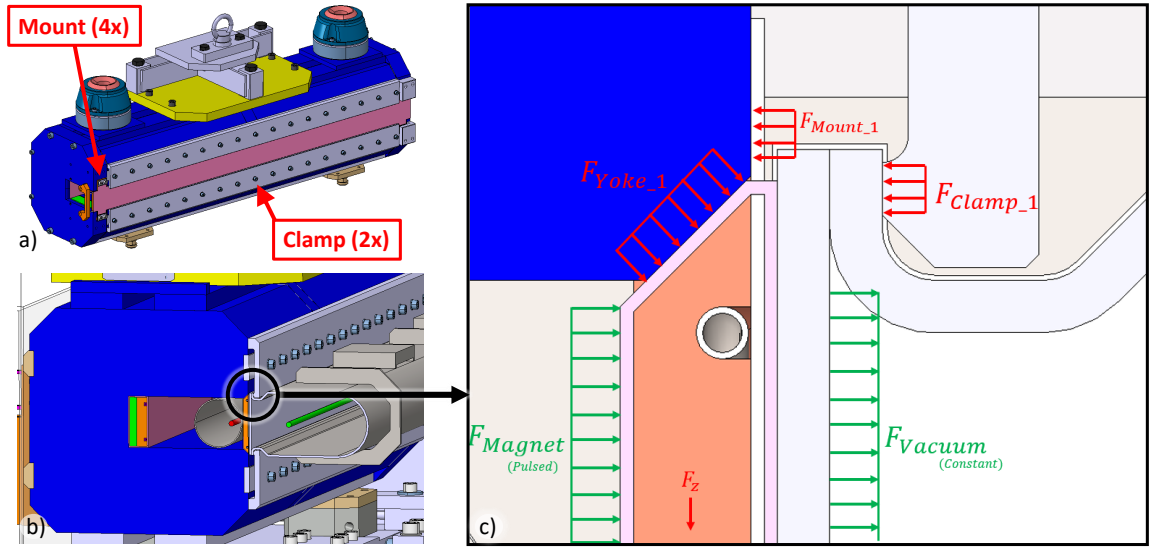


Figure 2.13: a) 3D CAD model of the magnet assembly b) Cross section of a 3D CAD model of the magnet assembly. c) 2D schematic image of a cross section showing a detail of the septum blade (orange), the yoke (blue), the electrical insulation (pink) and the vacuum chamber (light grey).

For the initial calculation, the conductor shall be considered as a rectangle Cu beam constrained at both ends with the four mounting areas. The operational Lorenz force is considered as a static uniformly distributed load. Beam theory shows that the nominal stress in the septum blade would exceed the tensile stress of the conductor, if the μ -metal plate was not supporting the septum blade.

The "V-line" showing the load distribution, and the "M-line" showing the moment of the beam, are drawn underneath FBD in Figure 2.14. The distributed load (q in N mm^{-1}) is calculated in equation 2.6 [20].

$$q = \frac{F_{magnetic}}{L} = \frac{8728}{828} = 10,5 \text{ N mm}^{-1} \quad (2.6)$$

The following equations are applicable, because the beam is considered to be symmetrical and made from a homogeneous material. The maximum moment (M_{max}) is calculated with equation 2.7 [20]

$$M_{max} = \frac{q \cdot L^2}{8} = \frac{10,5 \cdot 828^2}{8} \approx 900 \text{ N m} \quad (2.7)$$

When the beam is considered as a rectangle without the tapered edges, the moment of inertia is calculated with equation 2.8 [20].

$$I = \frac{b \cdot h^3}{12} = \frac{45,59 \cdot 4,5^3}{12} = 346 \text{ mm}^4 \quad (2.8)$$

This reveals a significant and unrealistic amount of nominal stress and strain as shown in equation 2.9 [19], equation 2.10 [19] and equation 2.11 [19], indicating a fracture of the conductor in this scenario.

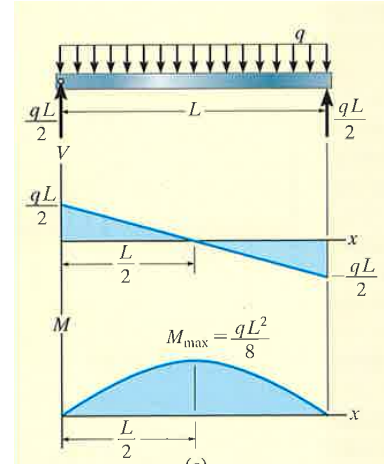


Figure 2.14: Free body diagram (top) with "V-line" (middle) and "M-line" (bottom) of a beam [19]

$$\sigma_{Max} = \frac{M \cdot c}{I} = \frac{899829 \cdot 2.25}{346} = 5851,5 \text{ MPa} \quad (2.9)$$

$$v_{Max} = \frac{-5 \cdot q \cdot L^4}{384 \cdot E \cdot I} = \frac{-5 \cdot 10,5 \cdot 828^4}{384 \cdot 1,266 \cdot 10^5 \cdot 346} = -1467 \text{ mm} \quad (2.10)$$

$$\theta_{Max} = \frac{-q \cdot L^3}{24 \cdot E \cdot I} = \frac{-10,5 \cdot 828^3}{24 \cdot 1,266 \cdot 10^5 \cdot 346} = -5,7 \text{ rad} \quad (2.11)$$

Beam theory (Euler-Bernoulli) assumes that the beam can rotate freely around the mounting areas on both ends. In reality the septum blade is fastened with four fixed mounting areas prohibiting angular deflection ($\theta_{max} = 0$), as shown with the red dotted line in Figure 2.15.

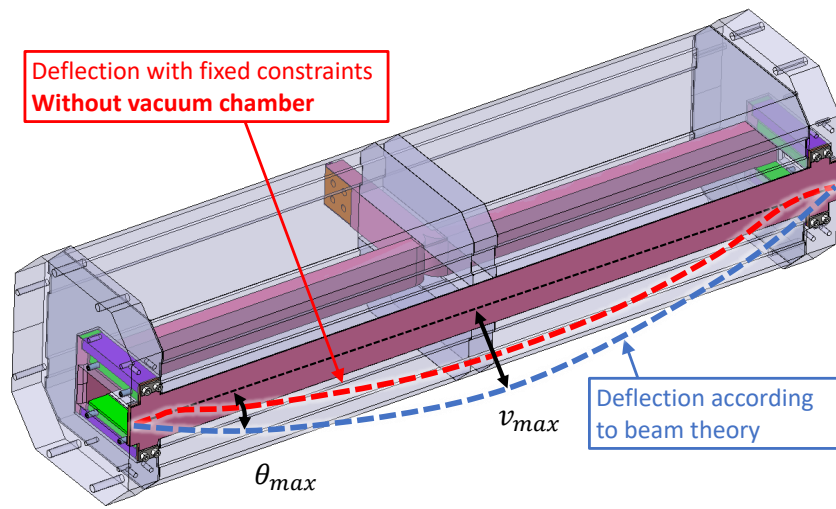


Figure 2.15: 3D CAD model showing schematically the deflection based on beam theory (blue dotted line) and the expected realistic deflection (red dotted line)

Static structural simulations were performed to calculate the amount of displacement and maximum stress (Figure 2.16). Three different scenarios are calculated: The septum blade without vacuum chamber; the septum blade with vacuum chamber in atmospheric pressure ; and the septum blade with vacuum chamber under vacuum. The model is constrained with fixed constraints at the mounting areas, and rollers/sliders at the tapered edges and location of the clamps on the μ -metal plate. A static force ($F_{magnetic}$) of 8728 N and the atmospheric pressure ($F_{vacuum} = 1 \text{ bar} = 0,1 \text{ N mm}^{-2}$) is applied. Results shown in Table 2.2. See Appendix A.7.1 additional information of the boundary conditions. In the initial analytical computation peak stresses were computed based on static determined beam theory. Subsequently, a FEA computation has been carried out. The observed mis-match can be explained by the static over constraining given by the supporting system, which is not covered in the initial analytical computation.

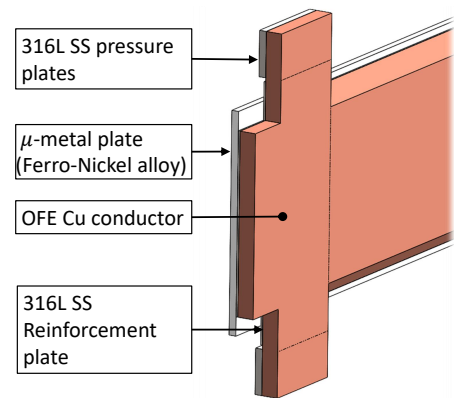


Figure 2.16: Model of simplified septum blade with μ -metal plate for structural analysis.

Table 2.2: FEA results of three scenarios

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3
Max stress	MPa	$1,1 \cdot 10^3$	7,8	14
Displacement	μm	$2 \cdot 10^4$	2,4	11

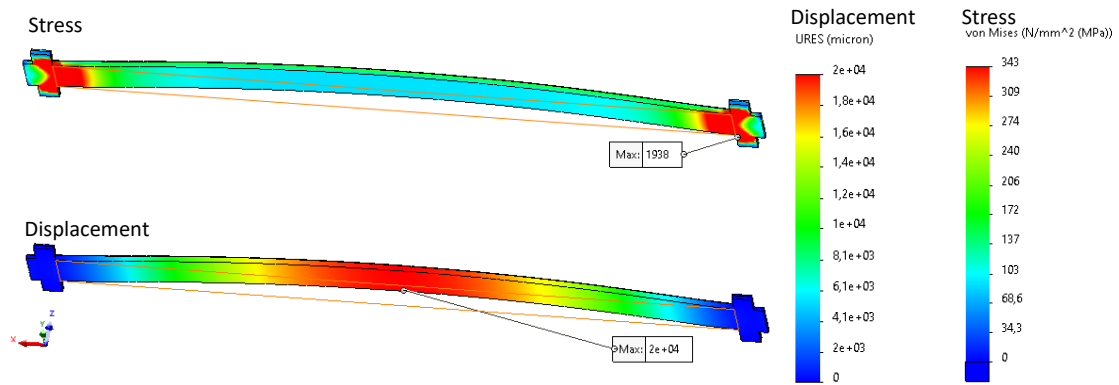


Figure 2.17: Scenario 1: Without vacuum chamber. Severe stress and displacement (Deformation scale 1). The red colored areas in the stress model exceed the ultimate tensile strength from OFE Cu. (Appendix A.4)

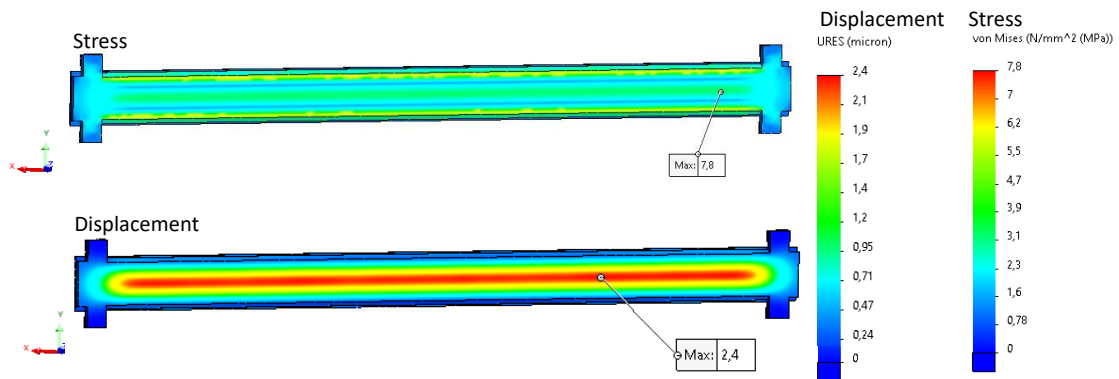


Figure 2.18: Scenario 2: With vacuum chamber in atmosphere. Minor stress and displacement (Deformation scale 1).

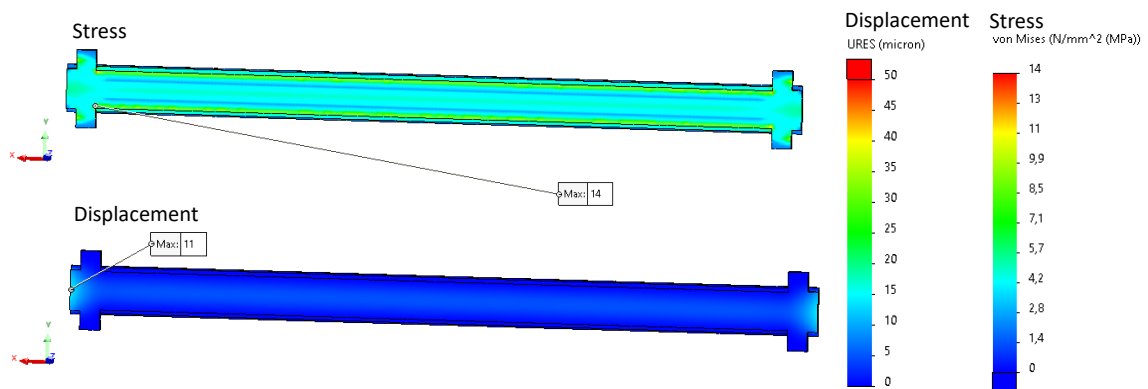


Figure 2.19: Scenario 3: With vacuum chamber under vacuum. Minor stress and displacement (Deformation scale 1).

2.4.2 Thermal loads

The SMH40 is pulsed with a half sine waveform to reduce the amount of generated heat in the septum blade. The pulse-width is 5 ms with a period of 3,6 s (Figure 2.20), powered by a 12:1 pulse transformer [10]. The first generation septum blade has been subjected to approximately 6 million pulses per year (See Appendix A.3)

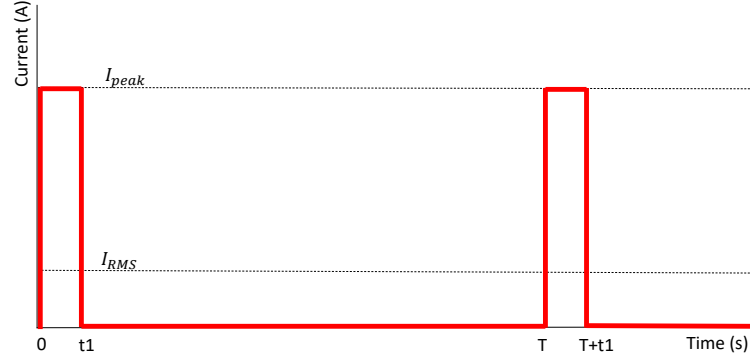


Figure 2.20: Schematic graph showing the timeline of the half sine pulsed electromagnetic septum. One cycle (T) is 3,6 seconds and the pulse-width is 5 ms ($t1$). I_{peak} represents the measured peak current in the septum blade. [30]

The peak current was used to calculate the amount of force on the septum blade due to the magnetic field. But the Root mean square (RMS) value is required to calculate the amount of heat. In reality the pulses are not completely square as shown in Figure 2.20, but have a slope on both sides with a flat top of 400 μ s [2]. The RMS value of the current in the septum blade is calculated using Equation 2.12 [30].

$$I_{RMS} = I_{peak} \cdot \sqrt{\frac{t1}{2 \cdot T}} = 27974 \cdot \sqrt{\frac{0,005}{2 \cdot 3,6}} = 737 \text{ A} \quad (2.12)$$

The resistance of the septum blade is calculated, in order to calculate the amount of heat energy An assumption is made to simplify the geometry of the septum blade, shown in Figure 2.21.



Figure 2.21: Schematic representation of the septum's blade resistance.

The resistance is based on the isotropic resistivity in Ω m (Appendix A.4), the length of the septum blade and the cross-sectional area of the geometry. The resistance for the septum blades OFE Cu part and for the 316L S.S. part is shown in equation 2.13 and 2.14.

$$R_{Cu} = \frac{\rho \cdot l_s}{A_{septum,cu}} = \frac{1,72 \cdot 10^{-8} \cdot 0,935}{2,18 \cdot 10^{-4}} = 7,38 \cdot 10^{-5} \Omega \quad (2.13)$$

$$R_{SS} = \frac{\rho \cdot l_s}{A_{septum,SS}} = \frac{7,472 \cdot 10^{-7} \cdot 0,935}{2,72 \cdot 10^{-5}} = 2,56 \cdot 10^{-2} \Omega \quad (2.14)$$

Equation 2.15 is used to calculate the total resistance of the septum blade.

$$\frac{1}{R_{septum}} = \frac{1}{R_{Cu}} + \frac{1}{R_{SS}} \Rightarrow R_{septum} = 7,36 \cdot 10^{-5} \Omega \quad (2.15)$$

The amount of heat energy produced due to the current and the resistance is shown in 2.16. The heat energy is calculated to find the amount of volume flow of cooling water.

$$P = I_{RMS}^2 \cdot R_{septum} = 737^2 \cdot 7,36 \cdot 10^{-5} = 40 \text{ W} \quad (2.16)$$

2.4.3 Internal hydraulic pressure

The amount of heat energy that is produced should be equal to the amount of energy that the cooling water removes from the system. This equilibrium is shown in equation 2.17. With a specific heat capacity of water, ($\dot{Q}$) in J/kg·K. A mass flow ($\dot{m}$) in kg/s. And a temperature difference (ΔT) in K.

$$\dot{Q} = P = \dot{m} \cdot c_{water} \cdot \Delta T = I_{septum}^2 \cdot R_{septum} \quad (2.17)$$

The temperature of the septum blade is stabilized with demineralized cooling water. The flow diagram of the water through the return conductor and the septum blade is given in Appendix A.5. The cooling water is approximately 26 °C (299 K) . The temperature difference between the inlet and the outlet is 0,6 K [8]. The required mass flow of the cooling water can be calculated as shown in equation 2.18.

$$\dot{m} = \frac{P}{c_{water} \cdot \Delta T} = \frac{40}{4182 \cdot 0,6} = 1,59 \cdot 10^{-2} \text{ kg s}^{-1} \Rightarrow 0,958 \text{ L min}^{-1} \quad (2.18)$$

The calculated mass flow is compared to the measured mass flow from a pressure test performed on the septum blade in 2016 [32]. During this test the volume flow of the first generation septum blade was measured for a certain water pressure. Water at pressures of 5, 10 and 15 bar is used in this test. The mass flow was calculated based on a water density of 1000 kg/m³. The heat energy was calculated using equation 2.17. The results are shown in Table 2.3.

Table 2.3: Pressure and flow measurements [32].

Pressure bar	Volume flow l/min	Mass flow kg/s	Heat energy Watt
5	0,56	$9,33 \cdot 10^{-3}$	23,41
10	0,72	$1,20 \cdot 10^{-2}$	30,11
15	0,86	$1,43 \cdot 10^{-2}$	35,96

Water pressure in the septum blade $\approx$ 25 bar with a volume flow of $\approx$ 1 l/min. The cooling channel is able to withstand this pressure because the hoop stress (7,5 MPa as shown in equation 2.19), is significantly lower than the tensile strength of 316L SS (521 MPa).

$$\sigma_h = \frac{P_{water} \cdot d_{inner}}{2 \cdot t} = \frac{2,5 \cdot 1,5}{2 \cdot 0,25} = 7,5 \text{ MPa} \quad (2.19)$$

2.5 SMH40 SEPTUM BLADE PARAMETERS

Table 2.4 states the parameters obtained during the research of the SMH40, relevant for the redesign of the septum blade.

Table 2.4: Technical specifications of the SMH40 and septum blade

Parameter	Symbol	value	Unit	Reference
Repetition time (Total cycle)	t	3,6	s	2.1
Deflection angle	θ	130	mrاد	2.4.1
Magnetic rigidity	$B\rho$	4.8	T m	2.4.1
Peak current SMH40	I_{Peak}	27974	A	2.4.1
Peak Current density Septum	J_{Peak}	128	A/mm ²	2.4.1
RMS Current Septum	I_{RMS}	737	A	2.4.1
RMS Current density Septum	J_{RMS}	3,54	A/mm ²	2.4.1
Magnetic field in the gap	B_{field}	0,779	T	2.4.1
Magnetic inductance	L	2,3	μH	2.4.1
Effective septum thickness	d_{sbeam}	10	mm	2.4.1
Lorentz force	$F_{Lorentz}$	8728	N	2.4.1
Effective magnetic field length	l_m	852	mm	2.4.1
Half sine pulse width	-	≈ 5	ms	2.4.2
Flat top duration	-	400	μs	2.4.2
Magnet resistance	R_{SMH40}	0,2	Ω	2.4.2
Septum blade resistance	R_s	$7,36 \cdot 10^{-5}$	Ω	2.4.2
Heat energy conductor	P	40	W	2.4.2
Required volume flow rate	$\dot{V}$	0,958	L min ⁻¹	2.4.3
Required mass flow rate	$\dot{m}$	0,0157	kg s ⁻¹	2.4.3
Temperature demineralized water	T	299	K	2.4.3
Temperature, inlet and outlet	ΔT	0,6	K	2.4.3
Yoke gap height	h_{gap}	48	mm	A.10
Septum blade length	l_s	900	mm	A.10
Septum blade thickness	d_s	5	mm	A.10
Septum blade conducting length	l_c	935	mm	A.10

2.6 FUNCTIONAL DECOMPOSITION

Figure 2.22 shows a functional decomposition of the septum blade. The objective of this model is to produce an overview of the functions and sub functions of a device. This overview is used again in the design phase. The decomposition starts with the main function of the septum blade and breaks down the functions in a "tree-like" model. The tree forms by asking the question "How?". This allows a function to be broken down into sub-functions. Therefore, the model is more detailed on the right side. **The main function of the septum blade is to contribute to a homogeneous and stable magnetic field in the yoke, while preventing a leak field in the region of the circulating beam, in a repeatable and reliable manner.**

The model is broken-down in five categories to divide the main function into sub-functions. The sub-functions with a **red** border are design constraints, the solution for these functions will remain the same (Section 4.2. Functional requirements with a **blue** border shall be solved with the chosen material and manufacturing technique in section 5.1. The functional requirements on the far right with a **green** border, shall be solved with the water block design in the morphological chart in section 5.3.

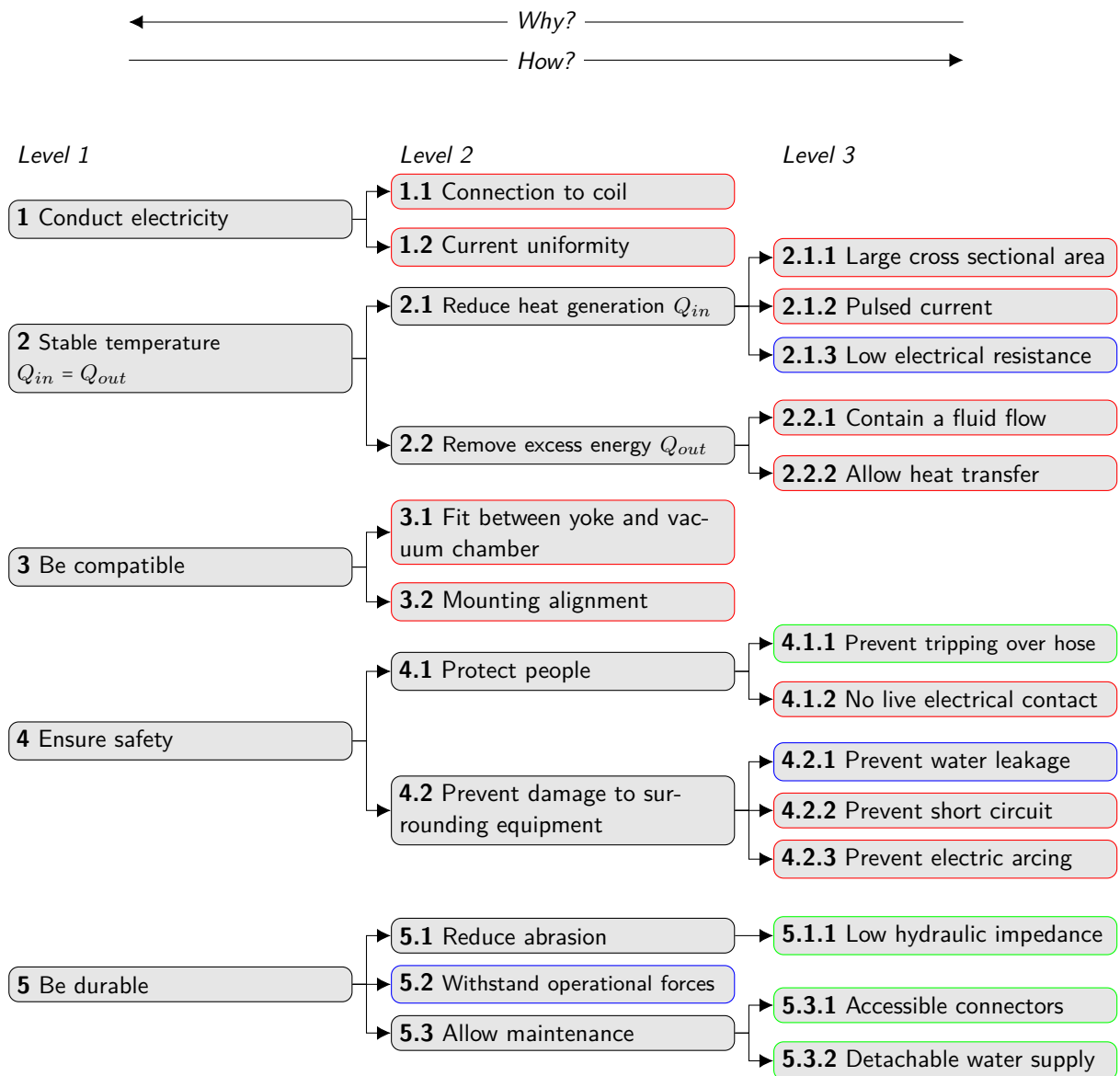


Figure 2.22: Functional decomposition of the septum blade for the SMH40 .

3 | FAILURE ANALYSIS

This failure analysis will answer the following research questions, originating from the research plan in Table 1.1:

- *What is the cause of the fracture in the first generation septum blade?* ⇒ Section 3.1
- *Are there any other failures of the first generation septum blade?* ⇒ Section 3.1.2 and Section 3.1.3.
- *What is the root cause of leakage in the third generation septum blade?* ⇒ Section 3.2

3.1 FIRST AND SECOND GENERATION SEPTUM BLADE

A structural simulation and a computational fluid dynamics study are performed to research the cause of failure of these two generations of septum blades. Additional non conformities are stated at the end of this section.

3.1.1 Fracture due to fatigue

A fracture of the cooling channel occurred after approximately six years in operation (Figure 3.1). The hypothesis is that the cooling channel experiences peak stresses during operation, due to the hyperstatic constraint of the water block.

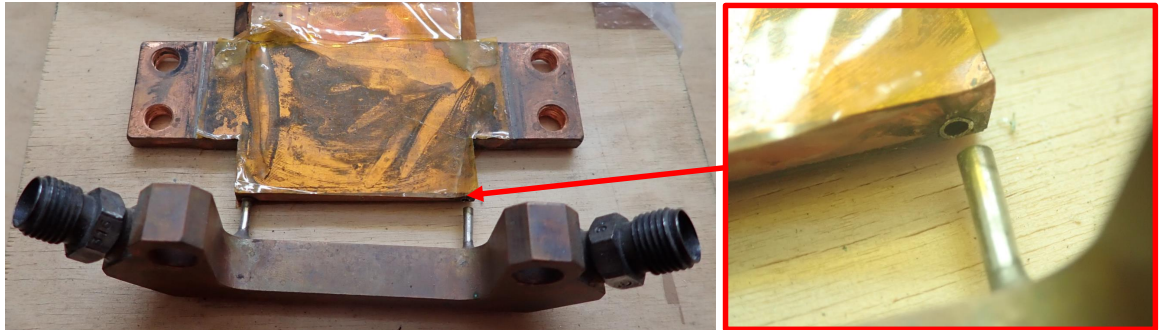


Figure 3.1: A photograph of the first generation septum blade, with a close-up of the fracture that occurred after six years in operation.

The Finite Element Method (FEM) contains bonded contacts and a static load of 8728 kN, representing the Lorentz force. The model contains fixed supports at the mounting areas and two rollers/sliders at the tapered edges, similar to the simulation in Section 2.4.1. A scenario with (scenario 1) and a scenario without (scenario 2) the additional constraint will be simulated, to compare the effect of the additional constraint on the cooling channels.

The maximal amount of displacement in scenario 1 is 17 μm . It is 30 μm in scenario 2 (Figure 3.2).

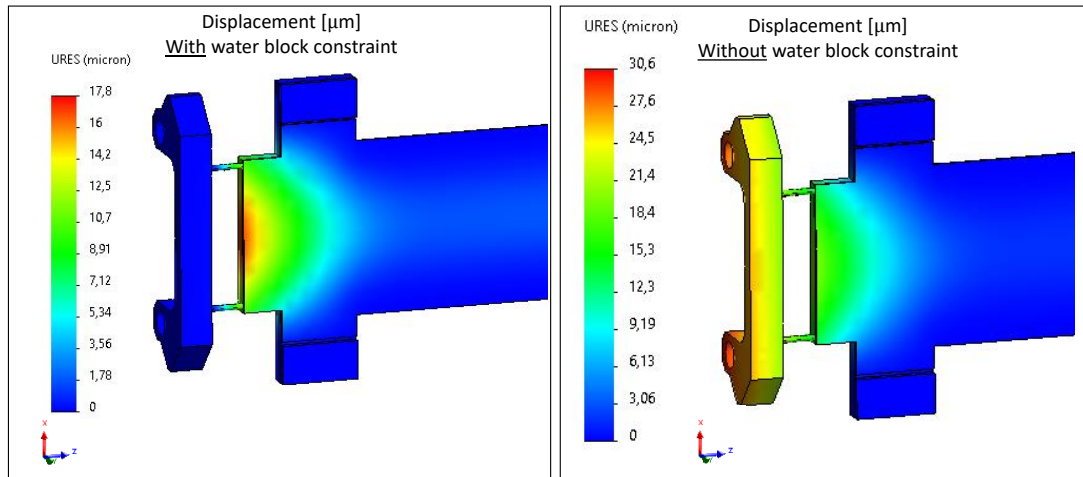


Figure 3.2: Simulation results of a static structural study performed in SOLIDWORKS®, showing the amount of residual displacement in mm. On the left scenario 1 and on the right scenario 2.

In scenario 1, the highest amount of stress in the geometry is located in the same area where the fracture occurred. The amount of stress is 95 MPa (Figure 3.3). The value is below the threshold of the tensile strengths of 316L SS (521 MPa). The fracture most likely occurred because of material fatigue over this long period (6 years with approximately 6 million pulses/year). The amount of stress in scenario 2, in the area where the fracture occurred, is considerably lower than scenario 1 (3.1 MPa). However, this simulation cannot guarantee that removing this constraint is the solution to the problem due to vibration being outside of the scope of this study.

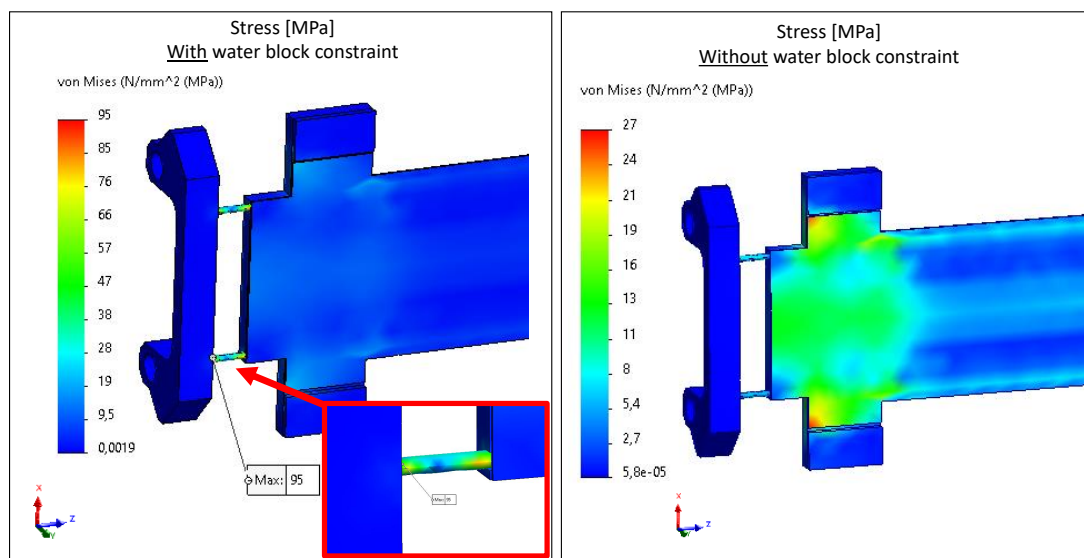


Figure 3.3: Simulation results of a static structural study performed in SOLIDWORKS®, showing the amount of stress in MPa for both scenarios

It is to be noted that the load applied in the simulation is constant, while in reality it is pulsed. The amount of displacement and stress might be higher with impact. This simulation is intended to give insight into the location of the weak areas of the geometry. A comprehensive non-linear study is required to derive more realistic values for the amount of displacement and stress. However, this simulation indicates that the extending cooling channels are a clear weak area of the design, especially because of the hyperstatic constraint on the side of the yoke. A new design of the septum blade must avoid the use of extending cooling channels.

3.1.2 Water damage to surrounding equipment

A cooling water leakage in the septum blade reduces its performance, but also damages other (electrical) components and materials. Wet surfaces have an increased chance of corroding. Figure 3.4 shows the consequences of a leak that occurred on the septum blade in 2016, and on the return conductor in 2015 [32].

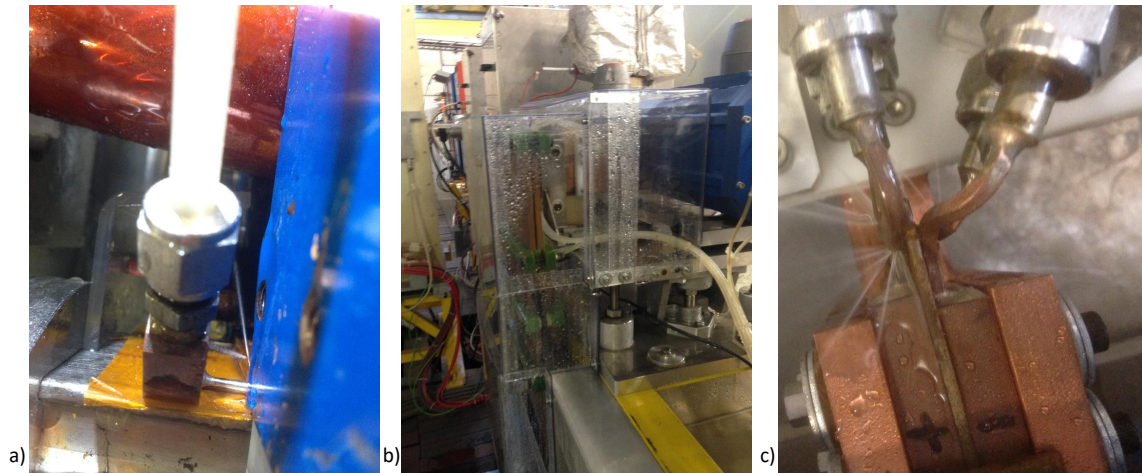


Figure 3.4: a) Close-up photograph of the septum blade water block showing a leak that occurred on 09-10-2016 [32]. b) The consequence of a leak to the surrounding equipment [32]. c) Close-up photograph of the return conductor showing a leak that occurred on 10-11-2015 [32].

3.1.3 Electrical arcing

On 11-01-2022 the septum blade was removed from the assembly for maintenance. Removal of the septum blade showed damage on the contact surfaces between the septum blade and the return conductor (Figure 3.5). The damage was caused by electric arcing because of insufficiently tightened bolts, and failure to replace the single use spring washers [2].



Figure 3.5: Two photographs of a failure that occurred in 2012 as a result of not sufficiently tightening the coil fasteners [32].

- | | |
|--|---|
| 1. 0,2 mm thick Al_2O_3 coating. | 6. Shim/sheet of Kapton® electrical insulation. |
| 2. Mounting holes to connect the septum blade to the return conductor. | 7. Gap in the yoke designated for the deflected beam vacuum chamber. |
| 3. Damaged OFE Cu contact areas because of electric arcing. | 8. Spacers. |
| 4. Septum blade. | 9. Helicoil threaded holes to mount the return conductor to the septum blade. |
| 5. 0,1 mm thick Kapton® for extra electrical insulation. | 10. Yoke. |

3.1.4 Hydraulic impedance of the first generation

The objective of a CFD study is to research the fluid velocity, dynamic pressure, static pressure, and Reynolds number of the cooling water in the septum blade. This will allow future comparison of previous generations and future design. An ANSYS Fluent manual shall be included in the thesis. This manual in appendix A.11 is also intended to be used as a tutorial to setup future simulations within the SY-ABT-SE section at CERN for similar situations, as CFD is not commonly performed in within the section. Figure 3.6 shows the first generation septum blade in orange and the Fluent model in blue. Methods of extracting the hollow area as a solid structure are described in the manual.

The geometry contains a "mass flow inlet" ($0,0017 \text{ kg s}^{-1}$) and a "outflow" outlet. This results in a overall static pressure of 4 bar to achieve the required fluid flow as calculated in Section 2.4.3. The average velocity is approximately 3 m s^{-1} and the maximum velocity calculated in the transition of the inlet into the cooling channel is 17 m s^{-1} (Figure 3.7).

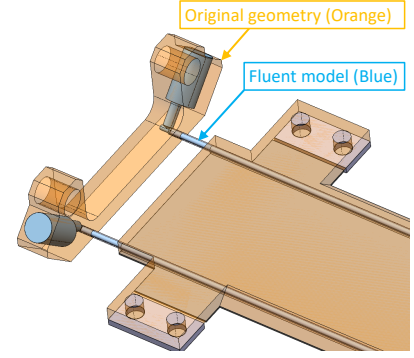


Figure 3.6: CAD model of first generation blade and fluent model.

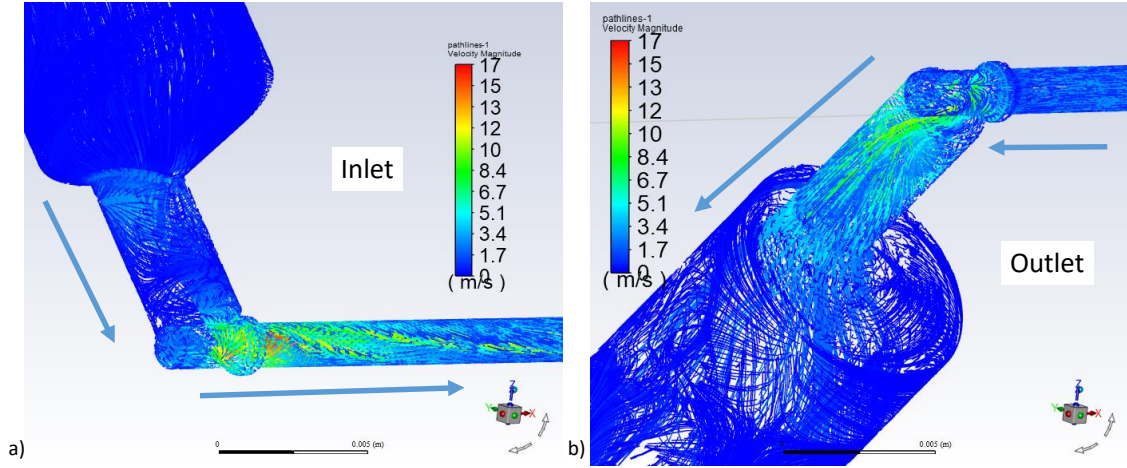


Figure 3.7: a) fluid velocity at the inlet b) fluid velocity at the outlet

ANSYS Fluent calculates the total pressure of the model as a sum of the dynamic pressure and the static pressure. The dynamic pressure is defined by the fluid viscosity and velocity, as $q = \frac{1}{2} \cdot \rho \cdot v^2$. The maximum dynamic pressure is 0,4 bar, located on the outlet in the water block (Figure 3.8).

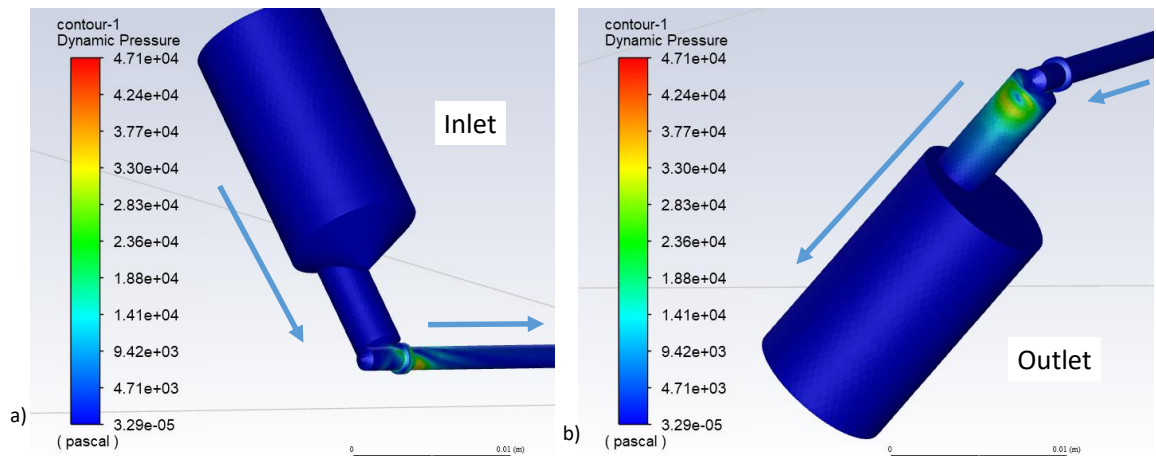


Figure 3.8: a) Dynamic pressure at the inlet b) Dynamic pressure at the outlet

No significant turbulent areas were found in the inlet and outlet of the septum blade. The turbulent areas are quantified with the dimensionless Reynolds number (Equation 3.1).

$$Re = \frac{\text{Inertia forces}}{\text{Viscous forces}} = \frac{\rho \cdot v \cdot d}{\mu} \quad (3.1)$$

An Ra value below 2000 represents laminar flow, Re between 2000 and 4000 is considered unstable flow. Values above 4000 are considered turbulent flow. The maximum Reynolds number is 3359, and is located in the outlet, as can be seen in Figure 3.9.

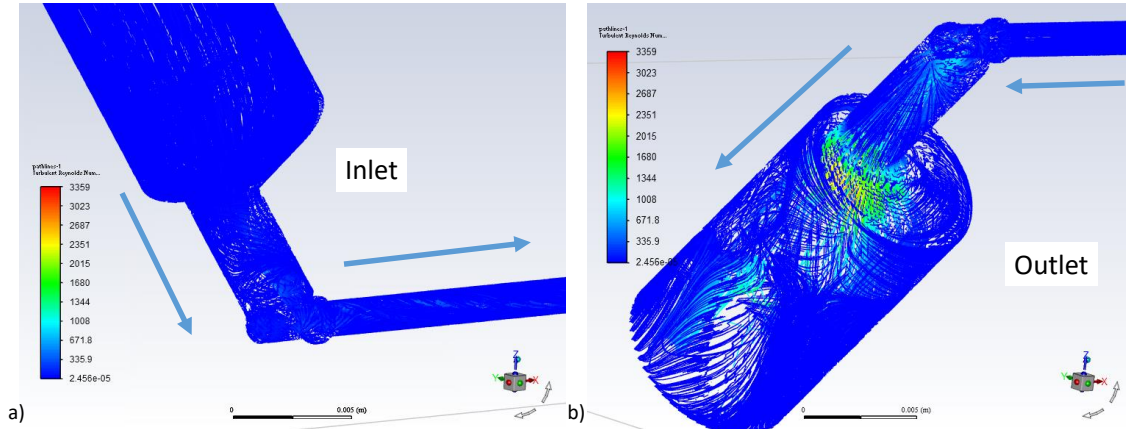


Figure 3.9: a) Turbulent flow at the inlet b) Turbulent flow at the outlet

No excessively large amount of dynamic pressure and turbulent flow were found in the first generation based on the information of the CFD analysis. Therefore, it is expected that abrasion of the material inside is minimal. However a Fluid structure interface (FSI) study is required to determine if this hypothesis is true. A FSI study is not included in the scope of this project.

3.2 THIRD GENERATION SEPTUM BLADE

The failure analysis for the third generation septum blade consists of a CFD analysis, NDT (leak testing and Ultrasonic inspection), and DT (Removal of the 316L SS plate and optical microscopy of a cross section).

3.2.1 Hydraulic impedance

The fluent model is extracted from the original 3D model with the same method as the first generation (Figure 3.10).

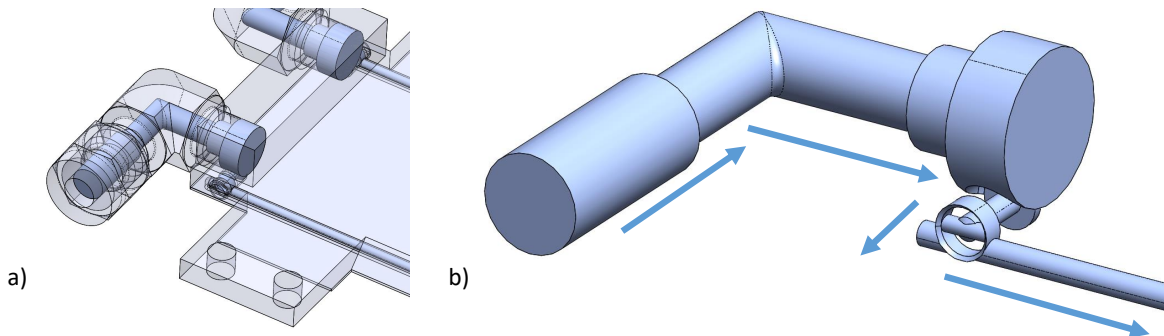


Figure 3.10: a) The original geometry of the third generation septum blade (transparent) and the fluent model in blue b) The isolated fluent model of the inlet, the blue arrows indicate the direction of flow.

The volume mesh is built from three different local sizings on the surface mesh, because the geometry is built from a large range of thicknesses. The volumetric mesh is a Poly-hexcore mesh with a maximum cell size of $0,5\ \mu\text{m}$ (Figure 3.11). On every wall there are ten gradually increasing (growth factor 1.1) boundary layers with a thickness of the first layer of $0,01\ \mu\text{m}$. More information on the parameters and boundary conditions are included in the ANSYS Fluent Manual in Appendix A.11.

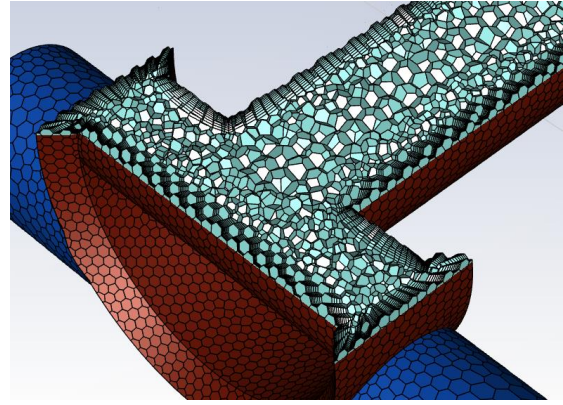


Figure 3.11: Clipping of the volumetric mesh.

The hydraulic impedance of the third generation is significantly higher, compared to the first generation. The maximum static pressure to achieve the required fluid flow ($1\ \text{L s}^{-1}$) is 28 bar. The dynamic pressure is 10x higher than the first generation (4 bar), as shown in Figure 3.12. The maximum dynamic pressure is located around the coil plug because the fluid has to flow through a narrow area (more information about the plug in section 2.3.2).

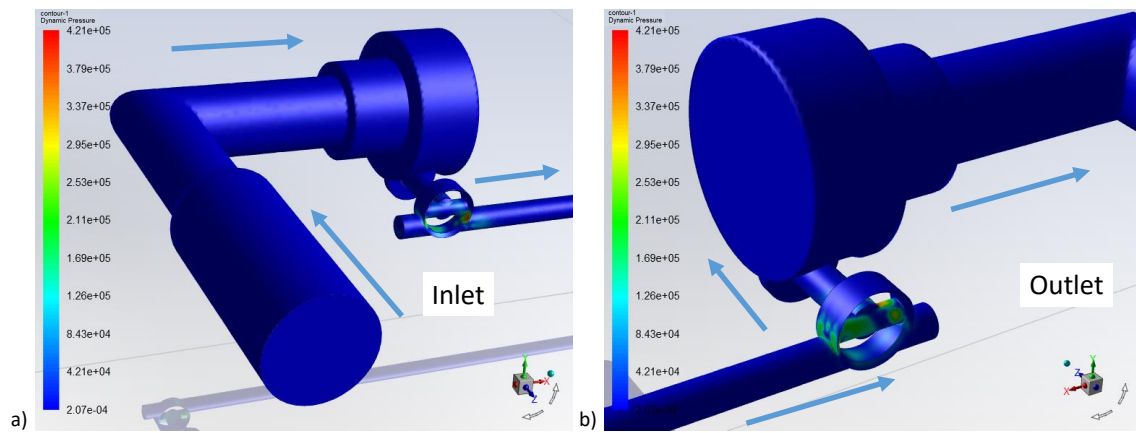


Figure 3.12: a) Dynamic pressure at the inlet b) Dynamic pressure at the outlet

Figure 3.13 shows a close-up of the flow around the plug with the velocity vectors. Red arrows represent very high velocities of $\approx 30\ \text{m s}^{-1}$, blue arrows represent a much lower velocity of $\approx 3\ \text{m s}^{-1}$. The conclusion of this analysis is that the total pressure required for the third generation design is too high for the SMH40 water supply. The septum blade would not be able to reach the required fluid flow, if the maximum pressure is 25 bar.

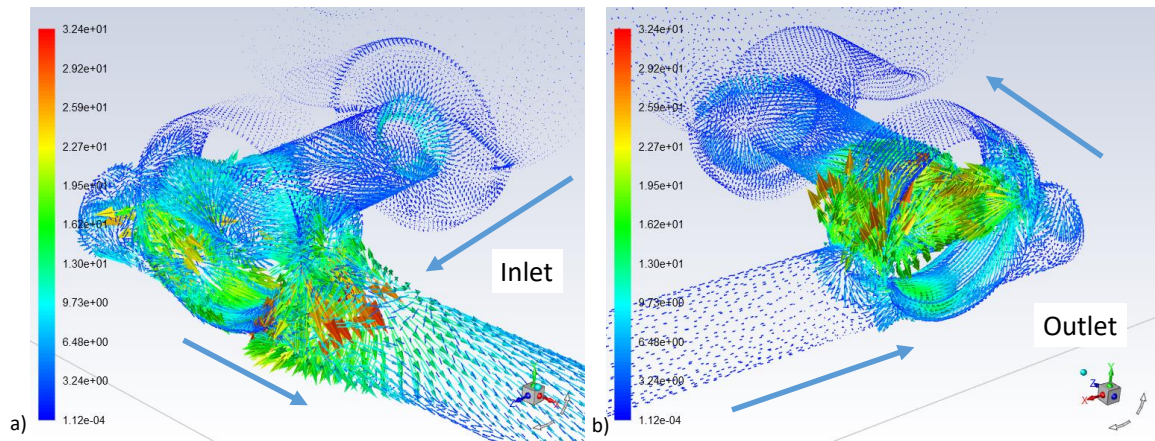


Figure 3.13: a) Fluid velocity at the Inlet b) Fluid velocity at the outlet

3.2.2 Non destructive inspection

The failure analysis of the physical septum blade starts with Non-Destructive Testing (NDT). Significant leaks out of the septum blade were observed during the pressure test at 50 bar. All leaks come from cavities in-between the OFE Cu and the 316L S.S. reinforcement plate. Figure 3.14 shows the results from the leak test.

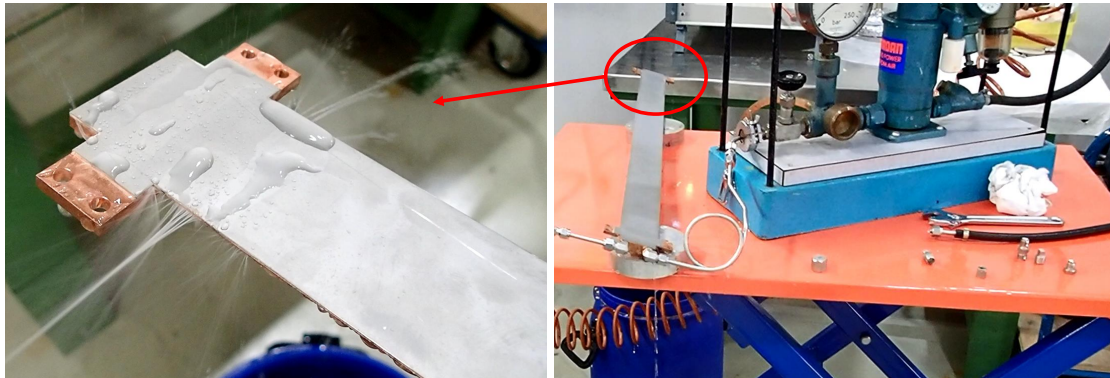


Figure 3.14: On the right side a photograph of the test setup. On the left a close-up of an extremity of the septum blade clearly showing significant leaks.

Sequentially, a microscopic inspection of the edge of the septum blade on the areas with and without observed leakages has shown dark areas in the brazing layer (Figure 3.15).

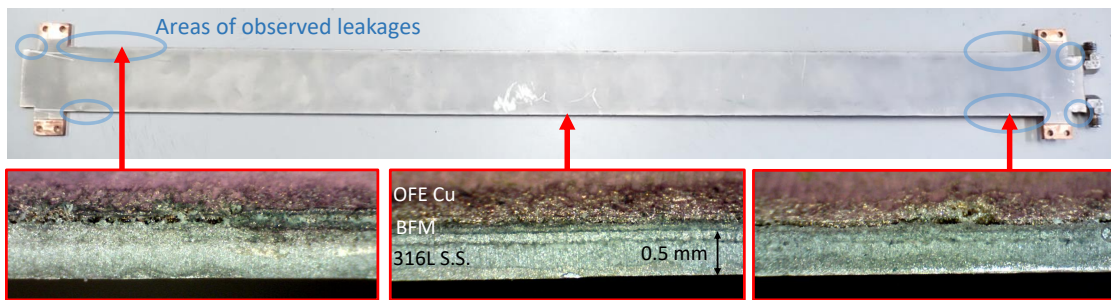


Figure 3.15: On the top, a photograph of the complete septum blade showing the areas of observed leakages and on the bottom three microscopic images.

Ultrasonic Testing (UT) has shown that there are cavities between the OFE Cu and the 316L SS plate. The white areas in Figure 3.16 correspond with superposed repetitions of the defect echo, meaning a hollow area between the entry echo and the Back Wall Echo (BWE). This causes the echo to "bounce" back and forth in this hollow area. The dark/black areas in the septum blade correspond to solid areas, showing a clear distinction between the entry echo and the BWE [24].

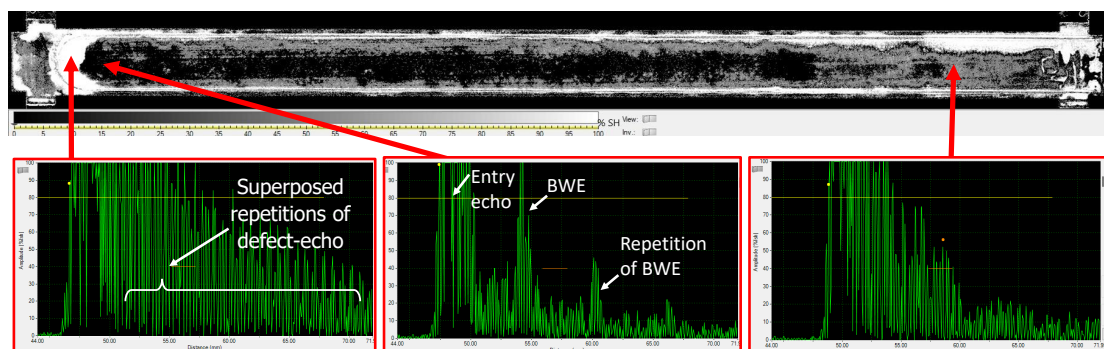


Figure 3.16: On the top an image generated by ultrasonic inspection and on the bottom three images of the corresponding echo wave defining the light or dark color in the image.

After analysing the results from the NDT and consulting with experts, two possible causes for the insufficient amount of BFM are plausible:

1. The solidus and the liquidus temperature of the BFM are far apart. This means that the BFM might diffuse into the Cu base metal before evenly spreading between the two base metals via the capillary effect.
2. The clearance between the two base metals is too large, causing the BFM not to fully spread out because of the capillary effect. A clearance of 0 - 50 μm is preferred for a Cu base metal joint.

3.2.3 Destructive testing

Destructive Testing (DT) consists of the removal of the 316L SS reinforcement plate and a metallurgical section cut inspected with an optical microscopy.

Removal of the reinforcement plate

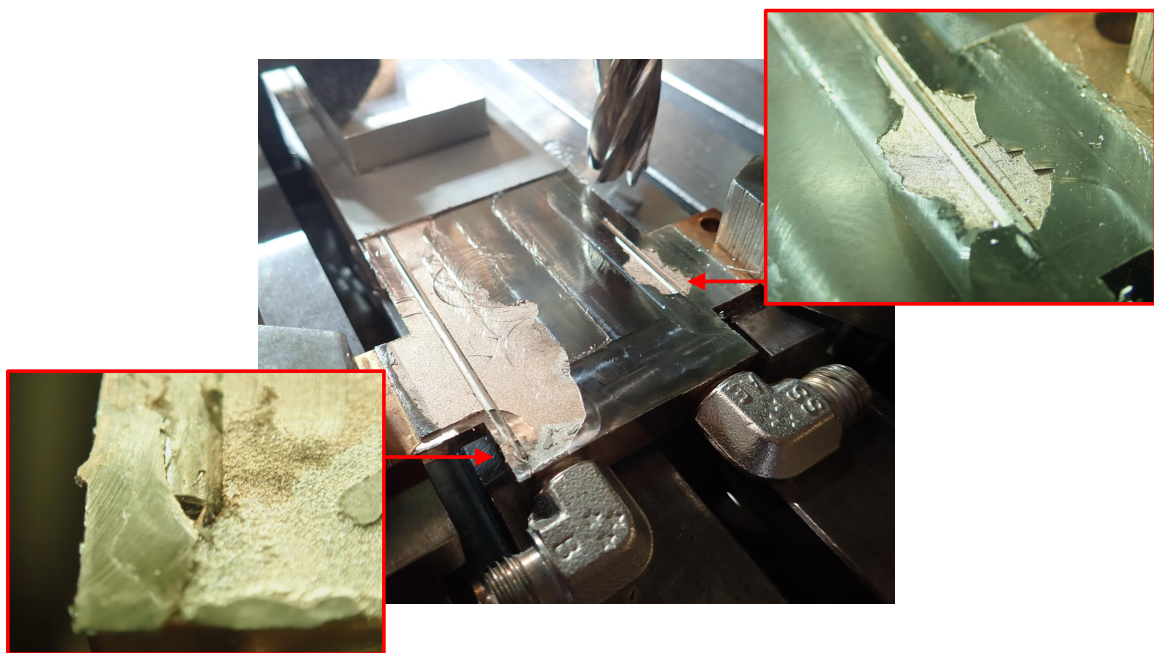


Figure 3.17: Three photographs of DT of the third generation septum blade.

Conclusion of observations:

1. Inefficient bonding of the brazing indicated by little to no adhesion between the base metals allowing water to flow freely in the cavities of the brazing layer.
2. A lack of BFM surrounding and above the cooling channel causing a hollow space (top right of Figure 3.17).
3. Water box design allows the water to flow outside the open end of the cooling channel (photograph on the left of Figure 3.17). In order to be leak tight, the design requires excellent uniform brazing with high quality covering the entire surface of the septum blade.
4. The colour of the surface area indicates that the BFM (Ag58,5 Cu31,5 Pd10) has diffused into the OFE Cu conductor. However, it is not clear at what depth the BFM has diffused into the base metal.

Metallurgical inspection

The main objective of an optical microscopy of a metallurgical section cut is to inspect the severity and depth of the diffused brazing layer. The complete inspection is located in EMDS report No. 2736197. The report states: A transverse cross section has been prepared following a general grinding and polishing procedure (Figure 3.18). No etchant has been used. Inspection has been carried out with a Carl Zeiss AXIO Imager optical microscope under bright field illumination. The equipment was judged by level of quality against ISO 18279.

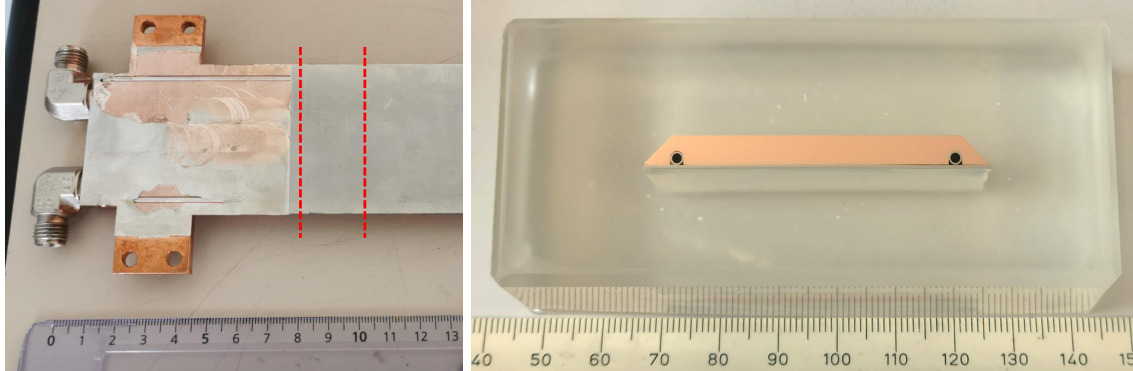


Figure 3.18: left a photograph of the septum blade showing the location of the two section cuts. On the right a photograph of the sample.

Figure 3.19 shows microscopic images from the inspection. The light-grey color in the OFE Cu blade shows the Ag component of the BFM which has diffused into the OFE Cu with a depth of 500 μm . The diffused layer is depleted from the brazed joint, leaving cavities behind. The grey layer in- between the cavities and the 316L SS plate is a mix between the brazing BFM and the Ni-coating. The conclusion from the report states that the present **metallographic inspection showed unequivocally that excessive alloying associated to gap clearance are linked to the leak on this septum blade.**

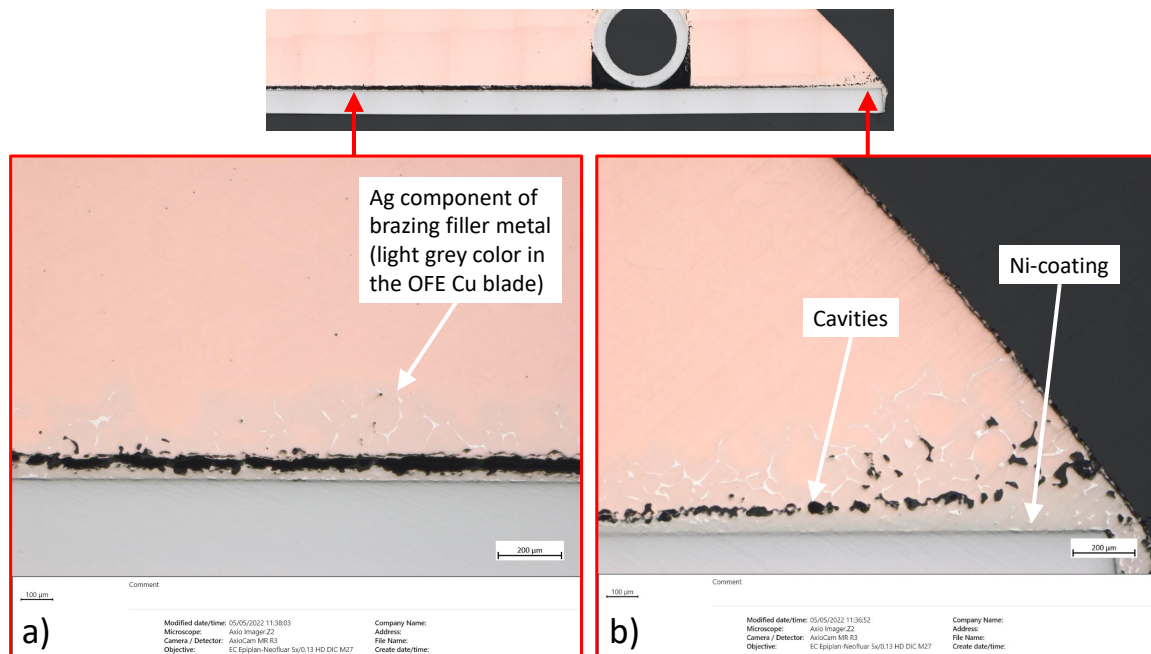


Figure 3.19: Three microscopic images of the metallurgical examination. Magnification 50x

3.3 ROOT CAUSE OF FAILURE

To summarize the failure analysis, the root cause of failure is stated in this section for the first, second and third generation septum blade.

3.3.1 First- and second generation septum blade

The extending cooling channels experience peak stresses, because of the hyperstatic constraint on the water block to the side of the yoke. This is an addition to the already hyperstatic mounting assembly of the septum blade. The observed fracture occurred because of material fatigue during the 6 years of operation (6 million pulses/year).

It is unlikely that the hydraulic impedance of the first generation contributed to the fracture, since the dynamic pressure (maximum of 0,4 bar in the transition between water block and cooling channel) is minor compared to the overall static inlet pressure of 4 bar. The CFD analysis measures the static inlet pressure as if it were measured from the opening of the septum blade inlet. The manometer of the SMH40 water supply measures 20 bar since the measurement represents the sum of all hydraulic losses in the SMH40 water supply line. For example, the filters, flexible hose, multiple bends ect. See Appendix [A.5](#) for a schematic of the complete SMH40 water supply.

3.3.2 Third generation septum blade

The root cause of the leakage is given by the inefficient bonding of the brazing layer, due to alloying of BFM (Ag58,5 Cu31,5 Pd10) into the OFE Cu conductor, causing severe cavities. The design of the cooling channel in the water block area allows water to flow freely outside of the cooling channel in between the OFE Cu conductor and the 316L SS reinforcement plate.

In addition to the manufacturing failure, CFD analysis has indicated that achieving the required volume flow (1 L s^{-1}) results in a high static pressure (28 bar), high local velocities and high dynamic pressure (4 bar). This indicates an increased chance of internal abrasion in the water block. The CFD fluid model calculates the static pressure from the septum blade inlet up until the outlet. It is expected that the required volume flow to stabilize the temperature of the OFE Cu conductor (40 W) will not be achieved, since the SMH40 water supply supplies 20 bar.

4

REQUIREMENTS FOR A NEW DESIGN

This chapter combines all the information from the functional analysis, the failure analysis and the stakeholder analysis into a list of technical specifications and requirements.

4.1 TECHNICAL SPECIFICATIONS FROM STAKEHOLDERS

A new generation septum blade will satisfy the following technical specifications from the stakeholders (Stakeholder analysis in Appendix [A.2](#)):

- Low production costs (< 5000 CHF)
 - ⇒ Production within CERN, CERN member states and CERN associate member states.
 - ⇒ Reduced production time.
 - ⇒ Reduced material waste.
 - ⇒ Low material costs.
- Robust & durable design
 - ⇒ Increased product life time (> 10 years)
 - ⇒ Low hydraulic impedance
 - ⇒ Withstand operational conditions
- Leak-tight design
- Accessible for maintenance
 - ⇒ Detachable water supply.
 - ⇒ Easily accessible hydraulic connectors.
 - ⇒ Removal of septum blade from the SMH40.
- Structural compatibility with existing equipment (Design constraints)
- Design for manufacturing (DFM)
 - ⇒ Manufacturing & Inspection Plan (MIP)
 - ⇒ ISO-quotation technical drawings

The technical specifications are combined with the design constraints and improvements based on the failure analysis, into a list of verifiable design requirements in Table [4.4](#).

4.2 DESIGN CONSTRAINTS

Some of the functions shall remain the same as the previous septum blades. The following design constraints apply for a new design:

(1.1) Connection to coil: The septum blade shall be connected to both return conductors via the four mounting assemblies. This includes the two helicoil bolts and pressure plate per mounting area.

(1.2) Current uniformity: The current uniformity in the septum blade will remain the same in a new design. This means that the location, cylindrical shape and size of the cooling channels. A 316L SS cooling

channel with a $\varnothing$ 2 mm outer diameter and $\varnothing$ 1.5 mm inner diameter will be used in a new design.

(2.1.1) Large cross-sectional area: Dissipated heat energy decreases if the cross sectional area increases and the current and material resistance remains the same. However, the thickness of the septum blade is defined by the surrounding equipment.

(2.1.2) Pulsed current: The current in the septum blade shall be pulsed. A new design must be able to withstand excitation due to the Lorentz force, without showing defects of fatigue within ten years.

(2.2.1) Contain a fluid flow and (2.2.2) allow heat transfer: The fluid, demineralised water at approximately 26 °C, used to stabilize the conductor temperature will remain the same. Due to the cooling channel having a second function to assure the current density in the conductor.

(3.1) Fit between the yoke and vacuum chamber: Compatibility of a new design with existing components, is important to for interchangeability and operational reasons. The dimensions and cross-sectional shape of the septum blade will be identical to previous generations.

(3.2) Mounting alignment: *The length of the septum blade, from mounting area to mounting area, will remain the same (828 mm).*

(4.2.2) Prevent short circuit: Short circuit will be prevented with the electrical insulation. The insulation that will be used is a 0,2 mm thick layer of Al_2O_3 coating. An additional layer of a 0,1 mm Kapton® sheet shall be added between the coil and the yoke to further improve the insulation properties. The voltage hold-off for the insulation shall be approximately 1 kV.

(4.2.3) Prevent electric arcing: An electric arc between the septum blade and the yoke shall be prevented with a proper surface contact. An identical mounting Assembly shall be implemented in the design.

4.3 IMPROVEMENTS BASED ON FAILURE ANALYSIS

A new design shall resolve known issues with previous generations, identified by the failure analysis in Chapter 3. The following improvements for the design are suggested:

- A 316L SS cooling channel completely embedded into the OFE Cu conductor is preferred over a design where the cooling channels are exposed in the transition region from the water block to the coil (Section 3.1).
- Avoid the use of an additional constraint on the water block to the yoke (Section 3.1).
- Sample study and a prototype to test the leak tight properties of the selected production technique.
- Provide leak-tightness in the transition region from the water block to the cooling channel (Section 3.2.3).

4.4 THE REQUIREMENTS INDEX

All technical specifications and requirements, which have been collected from of the functional analysis, failure analysis and PID are listed in the requirements index (Table 4.1). This Table is used to verify the compliance to the requirements during the concept design phase and detailed design phase. The requirements are divided in similar topics as the functional decomposition in section 2.6: Conduct electricity; Stable temperature; Compatibility; Safety; and Durability. A sixth topic, "0.0 Design or manufacturing" is added to include requirements about costs for materials & manufacturing.

Table 4.1: Requirements index for a fourth generation septum blade for the SMH40 . Last updated on 03-06-2022

No.	Technical specification	Requirement	Verification	Stakeholder, date
0.0 Design for manufacturing (DFM)				
0.1	Production of the septum blade within CERN is preferred over subcontracting.	All parts of the septum blade can be manufactured and assembled in CERN, 23 CERN member states or CERN associate states (Section 4.1).	Verify in the QC and MIP if all production is done in CERN, CERN member states or CERN associate states.	SE Section leader 02-03-2022
0.2	The manufacturing costs per blade are as low as possible.	The manufacturing costs for a single blade do not exceed 5000 CHF (Section 4.1).	Evaluate the costs of manufacturing the prototype.	SE Section leader 02-03-22
0.3	The manufacturing time per blade is as low as possible.	The manufacturing time for a single blade does not exceed 6-months (See PID).	Evaluate the time of manufacturing the prototype.	SE Section leader 03-06-2022
0.4	The design avoids material waste as much as possible during manufacturing.	The amount of material waste does not exceed 80% , as seen in previous generations (See 2.3.2).	Estimate the amount of material waste during manufacturing.	SE Section leader 03-06-2022
0.5	The design can be manufactured with the selected manufacturing technique.	DFM is included throughout the concept design and the detailed design phase. The fourth generation blade complies with DFM	Production of a prototype, BOM, MIP and technical drawings	EN-MME 10-03-2022
1.0 Conduct electricity				
1.1	The cross sectional thickness is the same as the first generation septum blade.	The thickness of the septum blade is Cu 4,5 mm $\pm$ 0,05 mm + reinforcement plate 0,5 mm. (Appendix A.10).	See technical specifications, QC and MIP if the dimension is defined and adequately executed.	Equipment owner 02-03-2022
1.2	The septum blade can be mounted on the return conductors.	The length of the septum blade, from mounting area to mounting area, will be 828 mm (Appendix A.10).	Verify the length on the technical drawings and measure the prototype.	Equipment owner 02-03-2022
2.0 Stable temperature				

Continues on next page

Table 4.1: Requirements index for a fourth generation septum blade for the SMH40 . Last updated on 03-06-2022

No.	Technical specification	Requirement	Verification	Stakeholder, date
2.1	The current uniformity in the conductor is the same as in previous generations.	A 316L SS cooling channel with a $\varnothing$ 2 mm outer diameter and $\varnothing$ 1,5 mm inner diameter is used (Appendix A.10).	Technical specifications and QC.	SE Section leader 02-03-2022
2.2	The current uniformity in the conductor is the same for previous generations.	The length and location of the straight section of the cooling channel is 837 mm, located at the beginning of the tapered edges (Appendix A.10).	Compare technical drawings of a new design to the drawings of the first generation blade.	SE Section leader 02-03-2022
2.3	The fluid flow is able to remove all excess energy from the system.	An energy of 40 W can be removed from the conductor by the fluid flow (Section 2.4.3).	Hand calculation and numerical computation.	Equipment owner 02-03-2022
2.4	The septum blade has the lowest possible electrical resistance, measured from mount to mount.	Electrical resistance of the septum blade, measured from mount to mount, does not exceed $7,36 \cdot 10^{-5} \Omega$ (Section 2.4.2).	Measure the prototype after manufacturing (QC-MIP). Calculate the expected resistance during the design process.	Equipment owner 02-03-2022
2.5	Orientation of the hydraulic connectors prevents the flexible hose from buckling.	Buckling of the flexible hose, causing an obstruction of the water flow during operation, is prevented.	Physical testing with the flexible hose.	Equipment owner 02-03-2022
3.0 Compatibility				
3.1	Assure structural compatibility of a new design with existing components.	No other equipment needs to be altered to mount the septum blade on the SMH40 (Appendix A.10 and Section 4.1).	Recreate the assembly of the septum blade in CAD (Mount the Septum blade on the SMH40 if a prototype is available).	SE Section leader 02-03-2022
3.2	The electrical insulation's total thickness (Kapton [®] + Al_2O_3 coating) is the same as for the first generation blade.	The thickness of the electrical insulation is $2 \times 0,2$ mm Coating on the yoke and the septum blade + 0,1 mm Kapton [®] = 0,5 mm (Section 2.3.2).	QC and MIP if the insulation is defined and adequately executed.	SE Section leader 02-03-2022
4.0 Safety				

Continues on next page

Table 4.1: Requirements index for a fourth generation septum blade for the SMH40 . Last updated on 03-06-2022

No.	Technical specification	Requirement	Verification	Stakeholder, date
4.1	There is no risk of live electrical contact with the septum blade.	There are designated covers around any accessible components of the septum blade (Section 2.3.3).	Measurements by electrical safety expert within ABT-SE.	SE Section leader 01-03-2022
4.2	The septum blade must be safe for technicians to hold when handling it.	The edges of the septum blade must be deburred to prevent injuries when carrying the component (Stakeholder analysis in the PID).	Verify of a prototype and check if this is included in the MIP and technical specifications.	SE Section leader 28-03-2022
4.3	The chance of a leak in the septum blade during operation is as low as possible.	No water is leaking out of the septum blade while pressurized at 25 bar (See section 2.4.3 and 4.1).	Pressure test the prototype at a minimum of 1, 43 · 25 = 35, 75 bar No water pressure drop of more than 2% within 24 hours in the entire test setup.	SE Section leader 02-03-2022
4.4	Short circuit between the OFE Cu and the yoke shall be prevented	The electrical insulation must be able to contain a voltage hold off for 1 kV (Section 2.3.1).	See technical specifications, QC and MIP if the insulation is defined and adequately executed.	SE Section leader 02-03-2022
4.5	Electric arcing between the septum blade and the return conductor shall be prevented.	The design includes the four mounting assemblies as stated in section 2.3.1 and section 4.2 combined with adequate QC.	See technical specifications, QC and MIP if the mounting assemblies are included in the design.	SE Section leader 02-03-2022
5.0 Durability				
5.1	The MTTF of the septum blade assembly is as long as possible.	The MTTF of the septum blade assembly is at least 10 years, based on an average of 6 million pulses/year (See section 2.4.1 and 4.1)	Estimate based on numerical computation and manual calculations compared to the material specifications.	SE Section leader 02-03-2022

Continues on next page

Table 4.1: Requirements index for a fourth generation septum blade for the SMH40 . Last updated on 03-06-2022

No.	Technical specification	Requirement	Verification	Stakeholder, date
5.2	The septum blade must be able to withstand the pulsed force, due to the magnetic field.	No non-reversible deformations, meaning micro- and macro fractures or plastic deformation in the septum blade during operation, when subjected to 8621 N every 3,6 s (See section 2.4.1).	Combination of numerical computation and tests on physical samples.	SE Section leader 02-03-2022
5.3	The hydraulic connectors are easy accessible to connect the water supply after the septum blade is installed. Also to be able to dry the inside of the septum blade during maintenance of SMH40	The water supply can be assembled and disassembled by hand, or with hand tools, without the need to relocate surrounding parts (Section 2.5).	Recreate the assembly of the septum blade in CAD (Mount the Septum blade on the SMH40 if a prototype is available).	SE Section leader 02-03-2022
5.4	The flexible hose is easy to (de-) couple to the hydraulic connectors for maintenance.	The flexible hose must be able to be (de-) coupled within 1 minute with basic hand tools (Section 2.5).	Recreate the assembly of the septum blade in CAD (Mount the Septum blade on the SMH40 if a prototype is available).	SE Section leader 02-03-2022
5.5	Repeated (Dis-) connecting of the water supply has the least negative effect on the leak tightness.	The water supply can be disconnected and reconnected at least 10 times without meeting the leak tightness requirement (Section 2.5).	Test connecting and reconnecting of the flexible hose on a test piece.	SE Section leader 02-03-2022
5.6	The hydraulic impedance, therefore the risk of internal abrasions, is as low as possible.	Avoid non-optimized bends, a large amount of bends and rapid volume changes in the fluid flow (See section 2.4.3).	verify hydraulic impedance with CFD.	SE Section leader 02-03-2022

5 | CONCEPTUAL DESIGN PHASE

This chapter is structured according to the flowchart in Figure 5.1. The input from the functional analysis, failure analysis and requirements is used to design a new concept. The conceptual design phase is divided into the same three topics (red, blue and green) as the functional decomposition in section 2.6.

The red node represents the design constraints as shown in section 4.2

The blue node explore a range of possible manufacturing techniques to assemble the septum blade. The manufacturing technique is chosen based on the achievable leak-tightness of the connection (**FD 4.2.1 Prevent water leakage**), good structural stability (**FD 5.2 Withstand operational forces**) and the excellent electrical conductivity (**2.1.3 Low material resistance**) of the assembled parts. The chosen manufacturing type, vacuum furnace brazing, is tested with a physical "Proof-of-concept". The Proof-of-concept is thoroughly inspected with NDT and DT before designing a water block.

The green nodes are focused on the water block design, solving the four green functions from the functional decomposition (**FD 4.1.1 Prevent tripping over hose**; **FD 5.1.1 Low hydraulic impedance**; **FD 5.3.1 Accessible connectors and**; **FD 5.3.2 Detachable water supply**). Four water block concepts are researched during this phase, and one is chosen at the end of this chapter. It is chosen based on the best compliance with technical specifications from the client as stated in the requirements index in Section 4.4. The chosen concept will be further detailed, and tested in the next chapter.

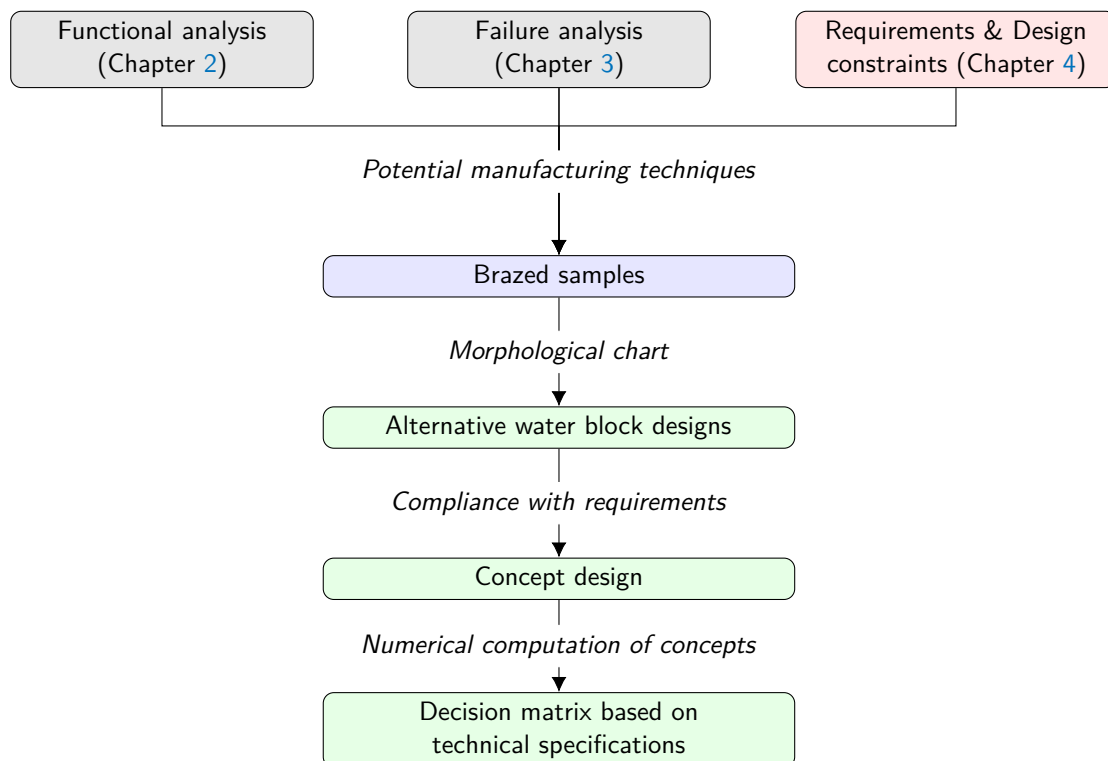


Figure 5.1: Flowchart for the methodical approach of the conceptual design phase. Inspired by the design methodology from I. Oskam [23]

5.1 POTENTIAL PRODUCTION TECHNIQUES TO ENSURE A LEAK-TIGHT COUPLING

This section is divided into three sub-sections: 5.1.1 Material research, 5.1.2 Manufacturing for individual parts (3D-printing and machining) and 5.1.3 Assembly techniques (O-rings, welding, glue, flame brazing, vacuum furnace brazing and shrink fitting). The objective is to select a suitable production technique based on the technical specifications (Section 2.5) to ensure a leak tight coupling between the cooling channel and a water block. The selected manufacturing and assembly technique is tested with physical samples.

5.1.1 Material

The materials to be selected for the septum blade must fulfill the following two functional requirements from section 2.6: **2.1.3 Low electrical resistance** and **5.2 Withstand operational conditions**. Additionally, the material must be affordable to prevent exceeding a total production cost of 5000 CHF (Section 2.5).

OFE C10100 grade Cu is the most suitable choice for the septum blade. The only other type of metal with better conductive properties is silver. Silver is not a feasible option because the ultimate tensile strength is approximately half of the tensile strength of OFE Cu and the material price/kg approximately 20 times as high. Other metals such as aluminium, stainless steel grades or molybdenum are disregarded as feasible options because of low conductive properties.

5.1.2 Manufacturing techniques for individual parts

Metal 3D printing

The first manufacturing possibility is additive manufacturing. CERN has a facility for direct **selective laser melting (SLM)**, this method melts metallic power per layer with a laser beam. Significant advantage of metal 3D printing is the ability to manufacture embedded cavities into a solid structure as shown in Figure 5.2. The conductor and water block, with an embedded cooling channel, could be manufactured from one piece, with minimal to no material waste. However, pure Cu is challenging to melt with a laser because of its high conductivity and high reflective properties [34].

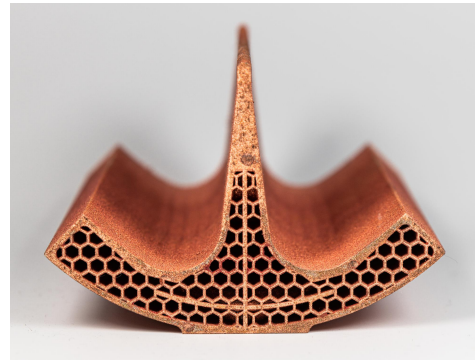


Figure 5.2: A quadrupole quarter segment with material-saving hollow structures and cooling channels [17].

In addition to SLM, another additive manufacturing method available at CERN, is called **electron beam melting (EBM)**. EBM operates under vacuum and generally with a hot powder bed, as compared to SLM which operates in air on a cold powder bed. Cu parts manufactured with EBM had a relative density of 98,6% and an electrical conductivity of 97% IACS, and a tensile strength of 177 MPa. *"Because of the high thermal conductivity of Cu, the dissipation of thermal energy during the melting process was severe, resulting in large variations in the dimensions and mechanical performance of the printed Cu parts."* [18]

Metal 3D printing is disregarded as an option to manufacture the septum blade at this time. This is due to the unreliable mechanical properties of the currently available printing techniques, porosity of the 3D printed parts, and the high current density and need for structural reliability in the septum blade. However, this manufacturing technique is rapidly advancing, and the use of metal 3D printing for accelerator components is being actively researched at CERN.

Machining (Milling and lathe)

Machining the parts from a solid block of OFE C10100 Cu guarantees excellent conductive and thermal properties, compared to metal 3D printing. The following checklist of design suggestions based on DFM shall reduce the production costs, time and machining difficulty [29] :

1. Tapered edges are preferred to radii on outer corners.
2. Avoid deep pockets/holes.
3. Avoid sharp internal corners.
4. Assure that all machine operations are accessible.
5. Avoid thin walls (< 1 mm)
6. Cone shaped hole bottoms are preferred to flat bottom holes.
7. Holes perpendicular to the surface.

5.1.3 Assembly techniques

Table 5.1 shows a chart comparing assembly techniques to various parameters to ensure a leak tight coupling. The parameters in the left column are based on the technical specifications of the client.

Table 5.1: Possible assembly techniques for a new leak tight design based on assembling machined parts.

Parameter	O-Rings	Welding			Glue	Brazing		SF
		MMA	TIG	EBW		Flame	Furnace	
Production costs	–	+	+	--	++	+	--	+
Production time	+	+	–	–	–	--	–	+
Available within CERN	+	++	++	++	+	++	++	++
Mechanical robustness	–	+	+	++	+	++	++	–
Durable	–	+	++	++	--	+	++	–
Leak tightness (Between Cu-SS joints)	+	++	++	++	--	+	++	–
Deformation of parts	++	--	--	+	+	–	+	–
Consistency/repeatability	+	--	–	++	–	–	++	+
Capable of large thickness differences	+	--	–	+	–	+	++	+

Electron Beam welding (EBW) and vacuum furnace brazing are compliant with the most parameters. It is expected that both manufacturing techniques will be suitable for a fourth generation septum blade. Vacuum furnace brazing is chosen, compared to EBW, because its functionality is verified with the first generation septum blade and with many other septa coils. The chosen manufacturing technique is tested with physical samples in the next section.

5.2 BRAZED SAMPLES

The objective of producing samples is to verify the leak-tightness of the brazed joints, therefore assuring functional requirement, **4.2.1 Prevent water leakage**. Three samples were produced with machining and vacuum furnace brazing. The three samples were inspected similarly to the third generation septum blade, with NDT (leak testing, X-ray tomography and ultrasonic testing) and DT (optical microscopy of a metallurgical cross section). This section concludes with a summarized list of observations and recommendations in subsection 5.2.6.

5.2.1 Manufacturing the samples

The process has started with a CATIA CAD model (Figure 5.3a). All parts in the sample are circular because manufacturing on a conventional lathe in the SY-ABT workshop is the fastest method of producing the samples (Figure 5.3c).

Subsequently, technical drawings were made. A detail of the assembly drawing is shown in Figure 5.3b. All technical drawing numbers can be found in Appendix A.10. The hydraulic connector is a SAGANA® 1/2" NPT thread $\varnothing 6$ mm compression tube fitting. The threads will be removed and machined to $\varnothing 12$ mm with a lathe. The body consists of two parts: a $\varnothing 20$ mm water block and a $\varnothing 30$ mm disk (the blade). Manufacturing the water block and the blade separately allows for testing of both Cu-Cu brazed lap joints as well as SS-Cu socket joints. The last part is the cooling channel with a 50 mm long, $\varnothing_{inner}$ 1,5 mm, $\varnothing_{outer}$ 2 mm 316L SS cooling channel. Important dimensions and tolerances on this part are:

- The hole in the blade and the water block for the cooling channel. The tube must have enough play for the Ni-coating, but be tight enough for the capillary action of the BFM. The authorized play between the tube and the hole is $+0,01/+0,05$ mm.
- A *rule of thumb* for the design a brazed socket joint is, that the inner cylindrical part be must at least three times the wall thickness deep inside the other part ($3 \cdot 0,25 = 0,75$ mm). The tube and Cu blocks overlap by a sufficient value of 13,5 mm.
- The outer diameter of the hydraulic connector ($\varnothing 12$ mm $0/-0,02$) and the hole in the water block ($\varnothing 12$ mm $+0,03/+0,01$).
- Contact surfaces between the water block and the blade need to have a proper contact. A relative specification of perpendicularity measured from the hole's axis is required on these surfaces ($\pm 0,05$ mm).

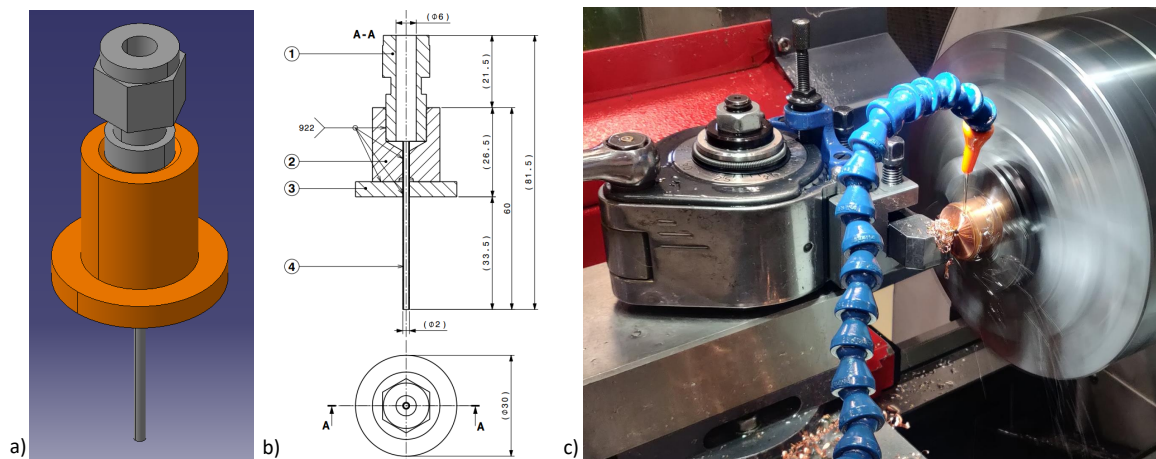


Figure 5.3: a) CATIA CAD model of the sample. b) CATIA technical assembly drawing of the sample. c) Machining of the upper Cu part on a lathe. Machining was done by R.Bondthond (SY-ABT-SE).

Figure 5.4a shows the finished machined parts for two samples. The Ni-coating of all 316L SS parts was done in the surface treatment workshop at CERN (TE-VSC-SCC). The parts are sent to the brazing workshop after the coating is finished. Figure 5.4b shows the coated parts with BFM. A sheet of BFM is used for the Cu-Cu lap joint. A wire around the tube is placed to braze the tube in both the water block and the blade. A second wire of BFM is placed around the hydraulic connector. All Cu-SS joints were brazed with Pd287 (Ag86 Cu27 Pd5) at 850 °C. All Cu-Cu joints with Ag272 (Ag72 Cu28) at 780°C under a vacuum of approximately 10^{-6} mbar. See Table 5.2 for the four contact surfaces and the brazing sequence for three samples (A,B & C). The last step was to weld the ends of the tube (EN-MME-FW), allowing for leak testing the samples at high pressure.

Table 5.2: Brazing sequence

Sample	A & C	B
First brazing	2+3+4	1 & 4
Second brazing	1	3+2

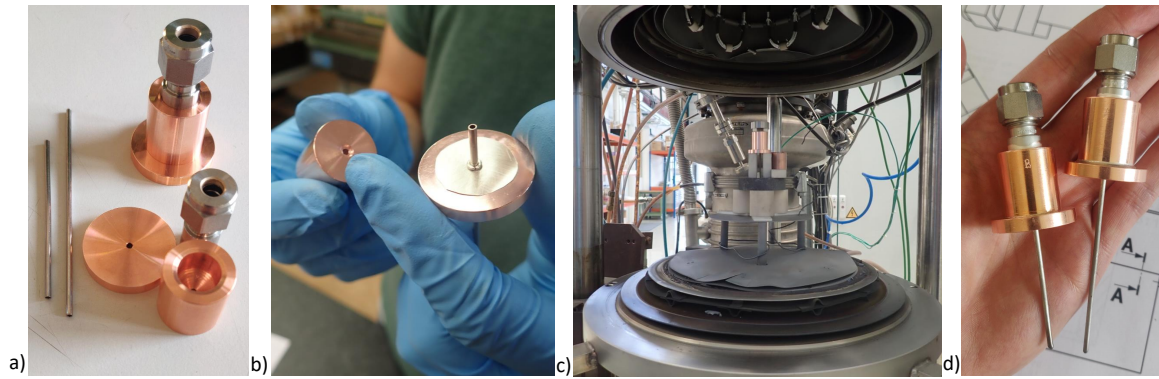
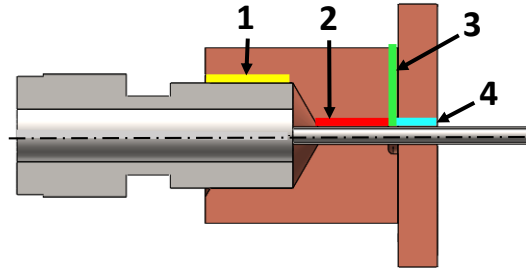


Figure 5.4: a) All machined parts for two samples, b) 316L SS parts have been Ni-coated in the surface treatment workshop, and the sheet and wire of BFM are placed. c) The assembled parts in the vacuum furnace prior to brazing. d) The finished samples.

A brazing defect occurred during the brazing procedure of sample A. A misalignment of the parts resulted in an insufficient spread of BFM between the Cu parts (Figure 5.5). The misalignment happened because of the thickness (0,5 mm) of the BFM wire located in the groove between the parts. This pushed the water block upwards creating the gap. Therefore, the sample has been re-brazed with additional BFM surrounding the tube (surface A2) and an additional wire surrounding the water block (surface A3). A third sample, labeled sample C, was manufactured with the same production procedure as Sample A. It is recommended to change the placement of BFM to the top of the cooling channel, instead of in a groove. To prevent a misalignment from happening during the brazing procedure of the new design.

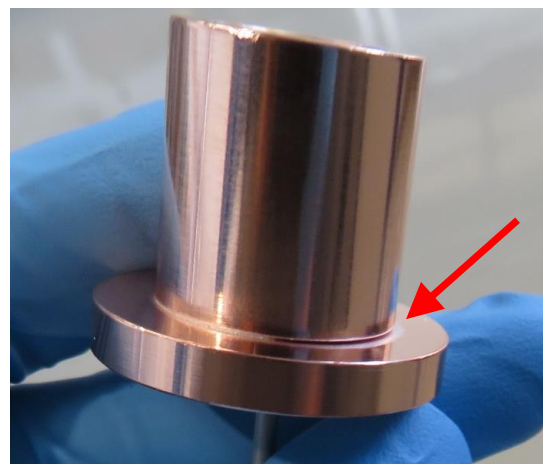


Figure 5.5: Sample A with brazing defect.

5.2.2 Leak testing

The leak tightness of all three samples was tested based on a pressure test. The samples were connected to a test setup that allows for pressurizing water with compressed air (Figure 5.6). All samples have proven to be leak tight at 50 bar for at least 30 minutes during this test.

5.2.3 X-ray tomography

The scan was performed by EN-MME-MM on a Zeiss METROTOM 1500 CT scanner, according to a quality standard EN ISO 9712 level 2. Results of the inspection are: *"Sample A was scanned twice: with max flux (voxel of 35 μm) and without full penetration energy (voxel of 25 μm). Samples B and C were scanned only with voxel of 25 μm . Discovered voids in each flat brazing. For the cylindrical brazing the resolutions was not good enough to clearly see the brazing."* See CERN EMDS document 2747841 for the full inspection report.

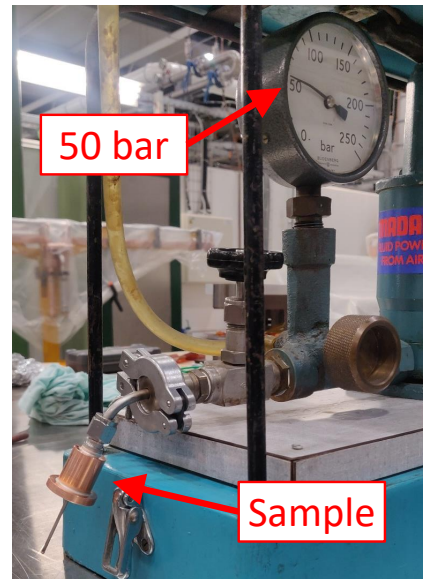


Figure 5.6: Leak testing the samples at 50 bar for 30 minutes.

The outer diameter of all three samples were reduced prior to the X-ray scan, to improve the resolution of the images (left side of Figure 5.7a, Figure 5.7b and Figure 5.7c). However, the thickness of the samples was too thick to inspect the circular brazing surfaces 1,2 & 4. These surfaces were inspected with Ultrasonic inspection by immersion.

Figure 5.7 shows the X-ray images of contact surface 3 for samples A,B and C. Dark grey indicates a cavity in the BFM. The inner light grey ring is the cross section of the tube, and the large circular cavity surrounding the tube is the groove where the BFM was placed. In Sample C this groove is light grey, indicating that not all BFM has migrated out of the groove. Sample B has more cavities than sample A and C.

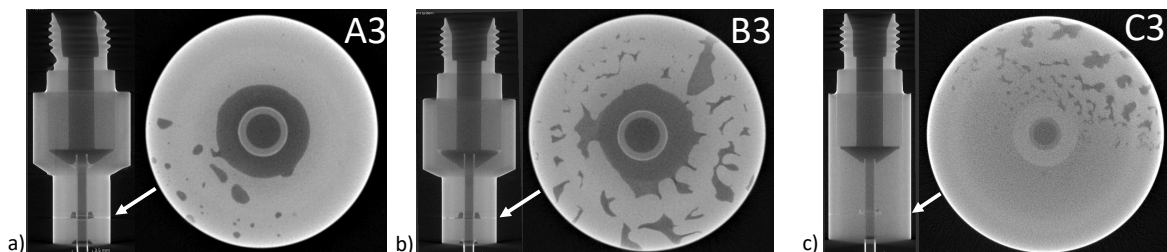


Figure 5.7: Results of the X-Ray tomography of contact surface 3, for samples A,B & C.

5.2.4 Ultrasonic inspection by immersion

The ultrasonic inspection was carried out by EN-MME-MA following a quality standard EN 12799 and acceptance quality standard EN ISO 18279. The inspection was performed on a Triton 1000 with the following probe specifications: TECHNISONIC IPU-0502-HR: SN-19452 Single crystal-5 MHz- $\varnothing$ 0,25 inch – 0.5 inch focalized. Two cavities were observed on surface 1 of Sample A. The cavities can be seen in Figure 5.8a with green, yellow and red colors, compared to no cavities as indicated with a blue color. Sample A is not representative for a successful brazing procedure because of the repair. Even though it has still proven to be leak tight in the pressure test, it is considered to be the worst case scenario. Sample C has excellent brazing as no cavities or irregularities were observed. The brazing sequence of Sample A and C is recommended for a new design because of the excellent brazing on Sample C. The complete inspection can be found in CERN EMDS document 2748744.

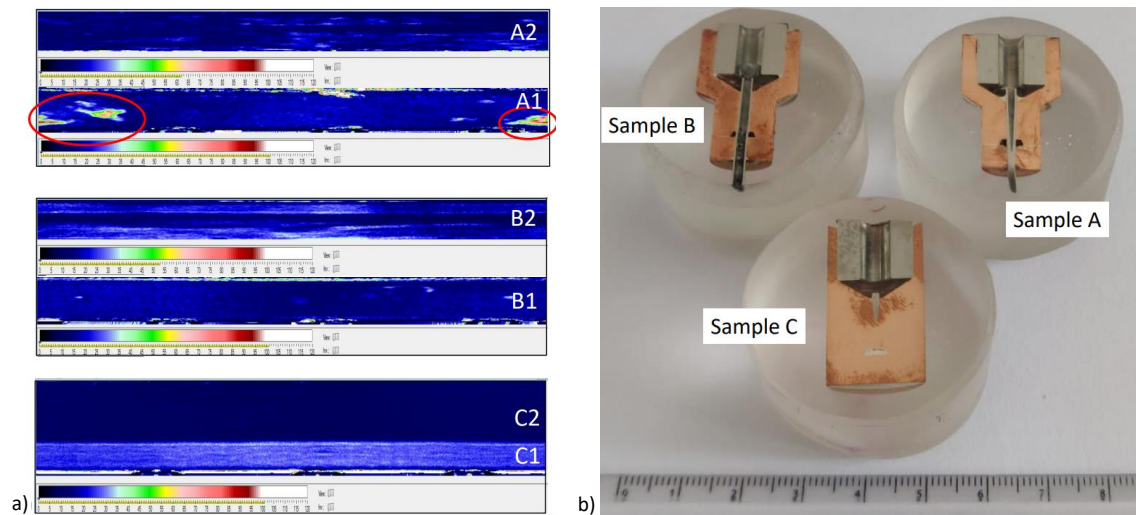


Figure 5.8: a) Results of the Ultrasonic inspection of Sample A,B & C. showing two cavities on surface 1 of Sample A and excellent brazing on sample C. b) Metallurgical section cut of Sample A and B and C for an optical microscopy.

5.2.5 Optical microscopy

The prepared samples for the optical microscopic inspection of a metallurgical cross section are shown in Figure 5.8b. The EMDS report 2756100 states: Examinations were carried out using a Keyence VHX7000 digital microscope. Transverse cross sections were prepared following a general grinding and polishing procedure. No etchant was used. The specimens were judged by level of quality against ISO 18279.

Extensive alloying is observed by the brazing layer with the Cu base metal in Sample A. Although less severe, the cavities (two cavities as seen in ultrasonic testing) that formed due to diffusion of the BFM into the Cu base metal, are comparable to the cavities observed in the third generation septum blade (Figure 5.9). Alloying of the BFM occurred during re-brazing of sample A after the brazing defect. It did not occur in Sample C with the same brazing procedure.

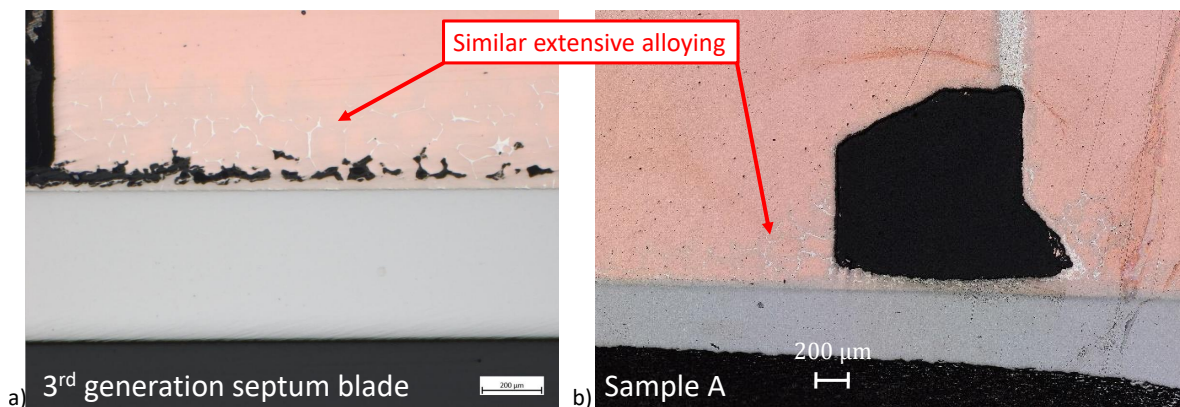


Figure 5.9: a) Image from the failure analysis of the third generation septum blade showing extensive alloying of BFM with the base metal causing severe cavities. b) microscopic image of sample A showing extensive alloying (surface 2,3 and 4). The two cavities observed with ultrasonic testing were caused by the diffusion of BFM into the Cu base metal.

Brazing surface 1 for sample A, B and C is shown in Figure 5.10. A clear distinction of the brazing layer with the base metals is observed in sample C, as opposed to sample A and B. However, alloying of the BFM in sample B is not as deep as sample A and did not cause any notable cavities in the brazing layer.

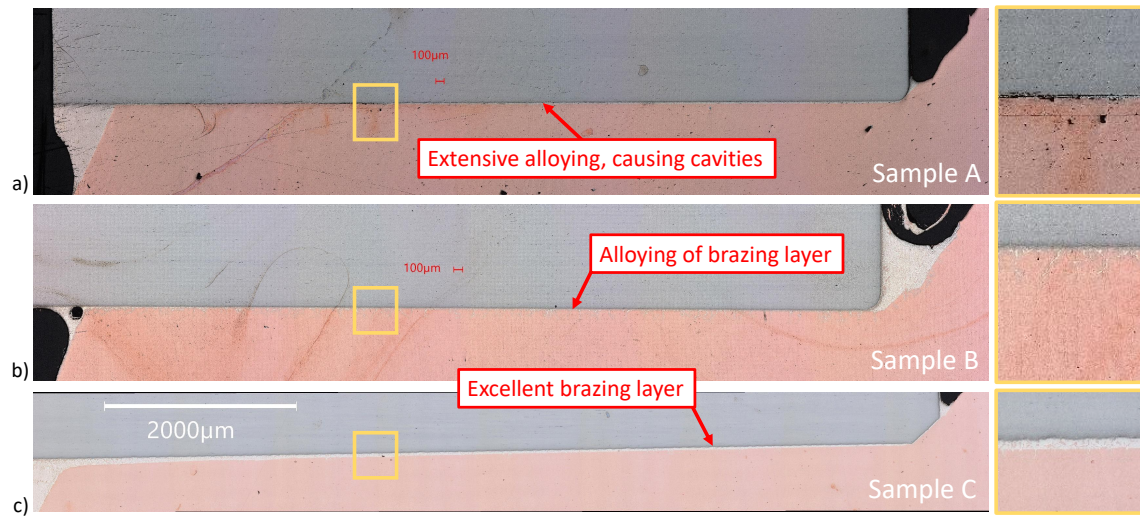


Figure 5.10: a) Brazing surface 1 on sample A showing extensive alloying causing cavities. b) Brazing surface 1 on sample B showing slight alloying. c) Brazing surface 1 on sample C showing excellent brazing.

Adding the extra wire of BFM surrounding the tube after the brazing defect caused an excess of BFM, forming a radius between the 316L SS cooling channel and the Cu. An excess of BFM, as observed in sample A, is improving the leak tightness of the assembly, as opposed to the lack of brazing observed in sample B. The BFM is placed in the groove on the far right of the image. Note that brazing surface 1 could not be inspected in sample C due to insufficient sample preparation regarding the section cut (Figure 5.8).

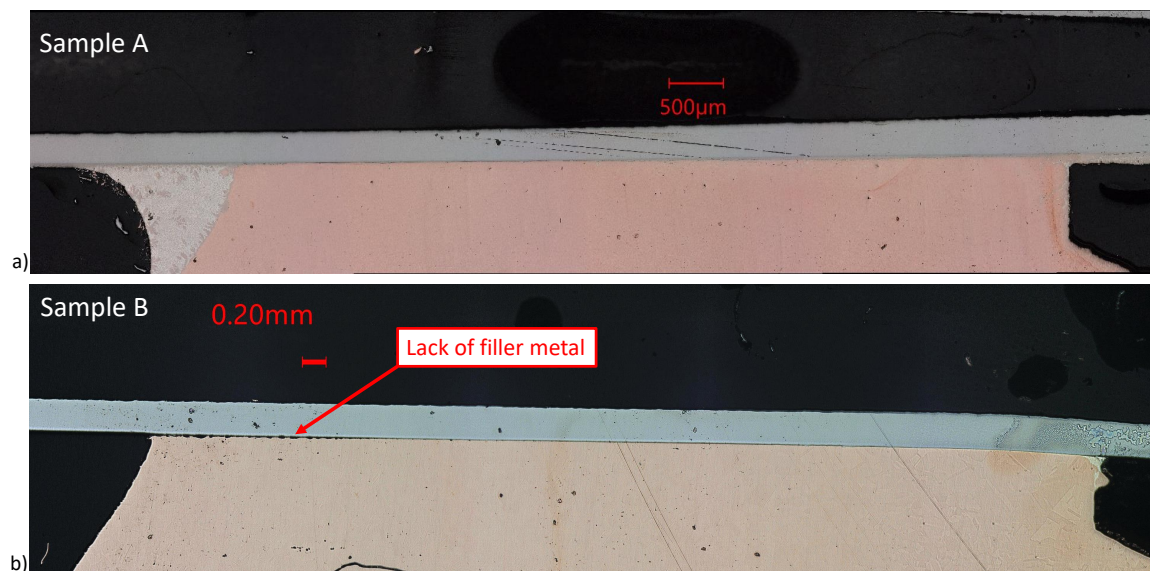


Figure 5.11: a) Brazing surface 2 on sample A. b) Brazing surface 2 on sample B, showing a lack of BFM.

5.2.6 Summary of observations for brazed samples

The following list summarizes observations including design recommendations based on the brazed samples:

1. An alignment defect occurred between the Cu parts of sample A. Placing the BFM resulted in a high gap clearance, which caused an insufficient spread of the BFM. BFM placement in a groove between two base metals is discouraged.
2. Brazed socket joints contain less cavities in the brazing layer than brazed lap joints. A socket joint is recommended for manufacturing leak tight connections.
3. Re-brazing of a joint is a probable cause for alloying of the BFM into the OFE Cu base metal. As seen after re-brazing sample A (to repair a alignment defect) and in the third generation septum blade. Brazing the third generation septum blade conductor to the reinforcement plate was the first brazing cycle of three cycles. It was re-brazed two times to connect the hydraulic connector and the coil plug causing the initial braze to alloy with the base metal. Alloying of the BFM into the OFE Cu base metal occurred even though the consecutive brazing cycles reduced in temperature (See section 2.3.2 for brazing sequence)
4. The brazing sequence for sample B combined with the BFM placement results in a lack of brazing surrounding the cooling channel. The brazing sequence of sample A and C is recommended for the assembly of the septum blade (See section 5.2.1 for the brazing sequence).

5.3 MORPHOLOGICAL CHART FOR WATER BLOCK DESIGN

The functional requirements, applicable to the water block design, are in the left column of Table 5.3. Different solutions are shown in column 1,2,3 and 4 for each functional requirement. Four alternative water block designs, as indicated with symbols (•, ▲, ■, ★), are generated by combining the solutions. The designs are based on a brazed joint configuration as shown in the previous section.

Table 5.3: Morphological chart for a fourth generation septum blade for the SMH40

No. Function	1	2	3	4
4.1.1 Prevent tripping over the flexible hose	Connectors orientated downwards	Inlet vertical orientation ★	Hose parallel to the side of the yoke ■	45° angle ●▲
5.1.1 Low hydraulic impedance	Least amount of bends ■★	smooth volume changes ●	Avoid buckling of flexible hose ●■▲	Biggest bend radii ★
5.3.1 Accessible connectors	Straight connectors ■▲★	90° angle connectors	45° angle connectors ●	Away from narrow space ★
5.3.2 Detachable water supply	Compression tube connectors ●▲★	Pipe fitting ■	Quick-coupling	Hose clamps ■

Figure 5.12 shows a sketch of water block design alternative 1. This alternative combines 45° angles in the hydraulic connector and the cooling channel with a compression tube fitting. An advantage of a 45° elbow hydraulic connector is that the shape of the water block remains simple, while still allowing for smooth volume changes in the cooling circuit.

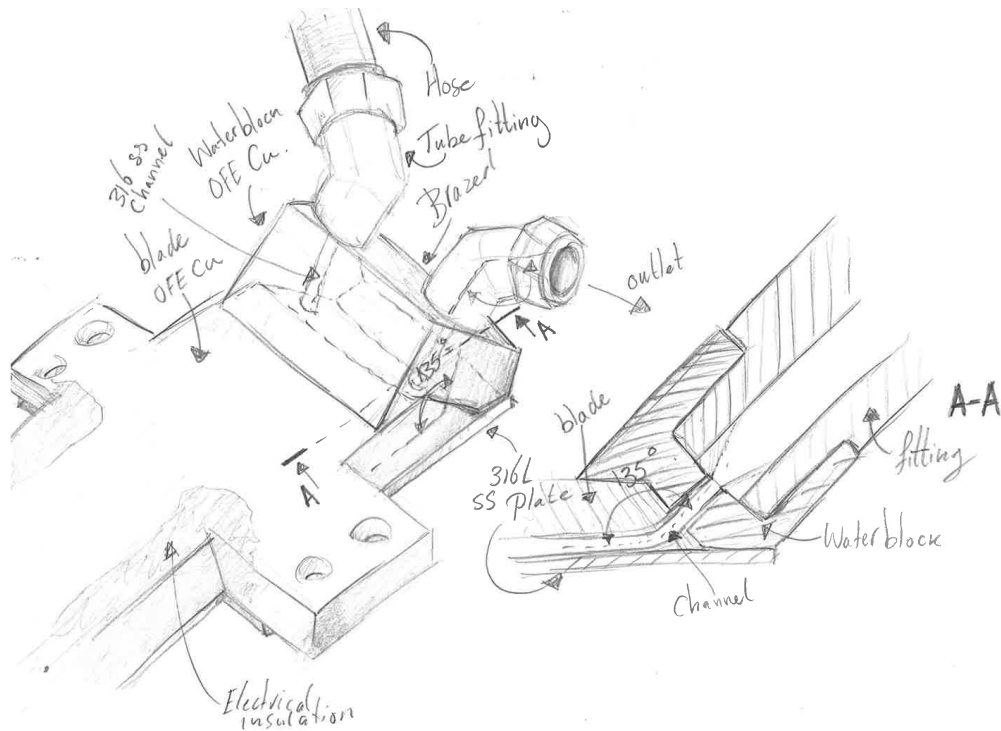


Figure 5.12: Sketch of water block design alternative 1 •

Water block design alternative 2 (Figure 5.13) aims for the least amount of bends combined with a flexible hose parallel to the yoke end-plate. The hose is connected to the rectangle water block via machined hydraulic nipple connectors and hose clamps.

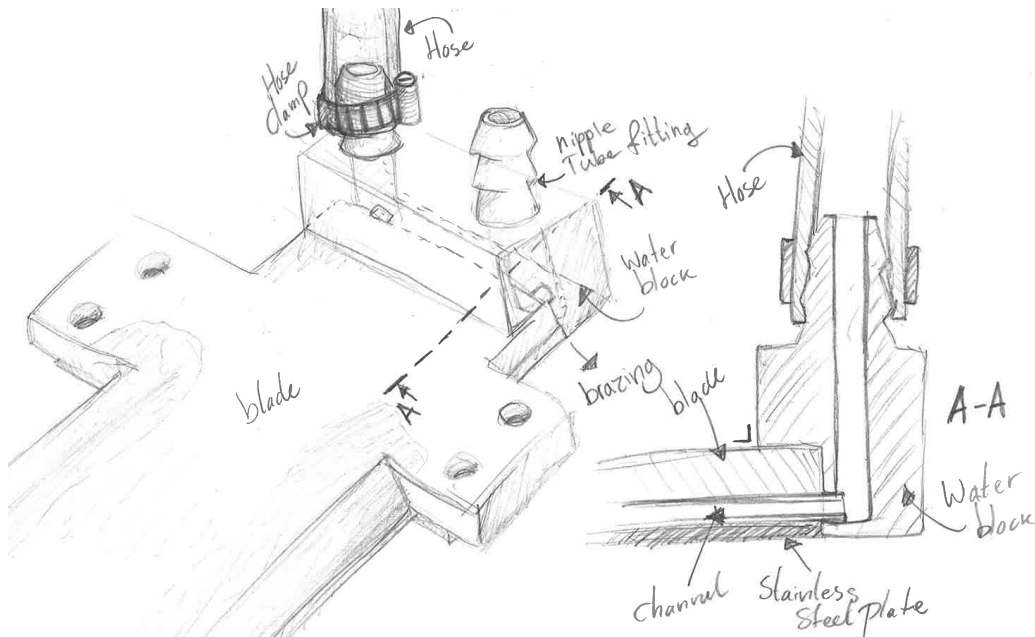


Figure 5.13: Sketch of water block design alternative 2 ■

Alternative 3 (Figure 5.14) is similar to alternative 1. The only difference is that the machining difficulty of the water block increases because it integrates the second 45° angle of the cooling circuit. Thereby allowing the use for straight hydraulic connectors.

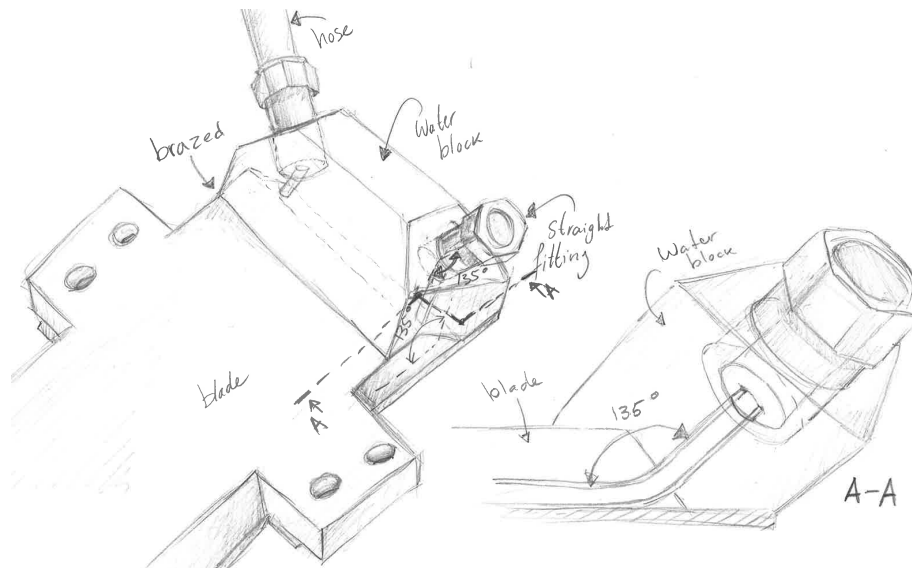


Figure 5.14: Sketch of water block design alternative 3 ▲

The fourth water block design alternative (Figure 5.15) allows the straight hydraulic connectors away from the narrow area, because of a large radius in both ends of the cooling channel. The water block is rectangle shaped and supported by the extended reinforcement plate.

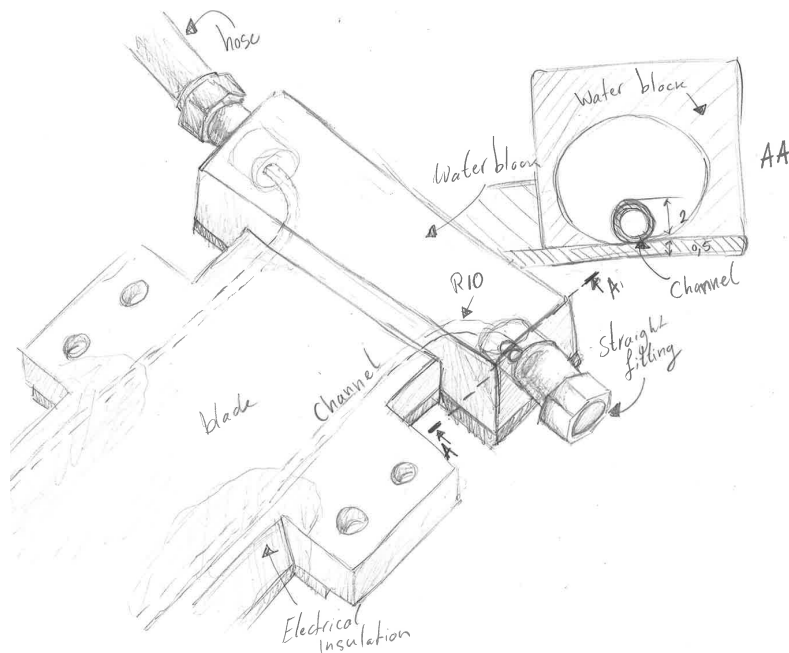


Figure 5.15: Sketch of water block design alternative 4 ★

5.3.1 Compliance of alternatives with the requirements

All alternatives seem to have potential to fulfill the requirements. The complete table for the expected compliance of these alternatives with the requirements index is listed in Appendix A.8. The conclusion from this chart is that all alternatives need to be further detailed, before disregarding one or more of the designs.

5.4 CONCEPT DESIGN

The four alternatives are further detailed into concepts. This section shows the CAD models of these concepts with each a description of its most distinctive features. The structural robustness and hydraulic properties of each concept are calculated at the end of this section.

5.4.1 Concept 1

The first concept is shown in Figure 5.16. The water block is connected to the conductor with a 45° angle, which allows for good accessibility of the hydraulic connectors. Bending the ends of the cooling channel away from the vacuum chamber allows for enough space for OFE Cu to braze the 316L SS cooling channel into the water block. The hydraulic connectors are SAGANA[®] 45° male elbow connectors (EQM45S) to further improve the accessibility. The reinforcement plate extends underneath the water block for additional support. The triangular shape of the water block allows for an increased surface area for brazing the Cu-Cu joint. The sides of the water block have been optimized compared to alternative 1 to: align with the cooling channel; to provide enough space for the 0,5 mm thick electrical insulation; and avoid surface-to-surface contact with the yoke. A challenge of this design are the stringent tolerances of the brazed surfaces between the conductor and the water block.

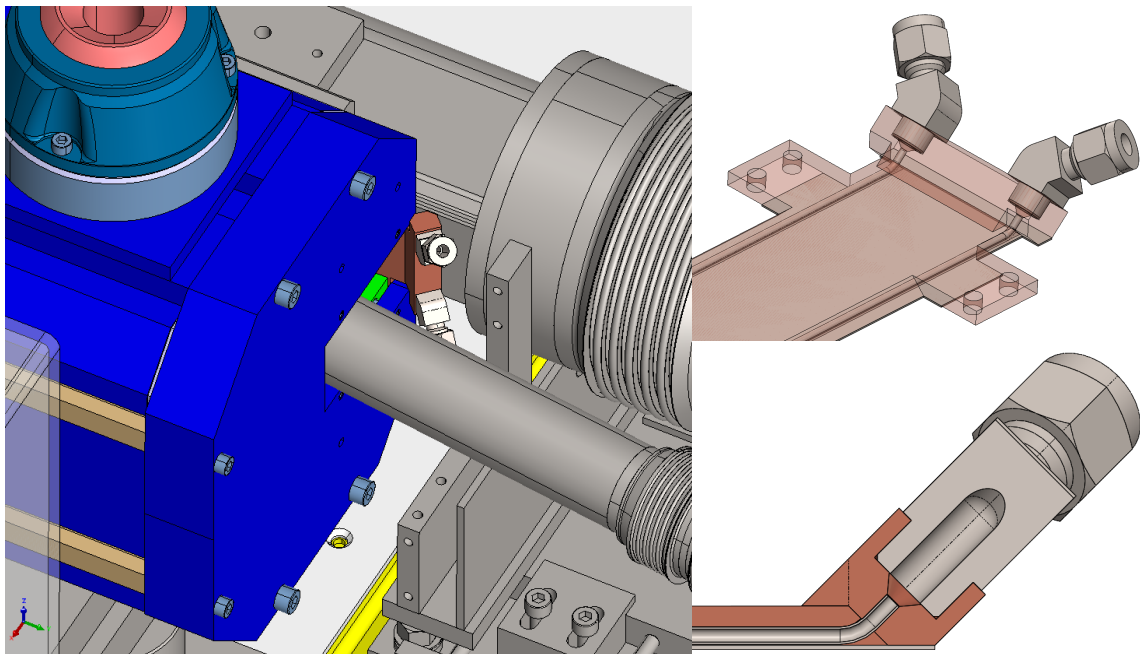


Figure 5.16: A CAD-model of concept 1, originating from alternative 1. On the Left a CAD model of the design as it would be installed on the SMH40. On the right a transparent view and a cross sectional view of the water block area showing the cooling channel.

5.4.2 Concept 2

Concept 2 differs the most from the other concepts (Figure 5.17). It uses a hydraulic nipple connection with a tube clamp, instead of compression tube connector. This allows for less parts to be machined because the hydraulic connectors and water block can be manufactured from the same piece. The tolerances of bending of the cooling channel are less stringent than on the other concepts. Challenges for this design are as follows: 1) Thin material thickness (0,5 mm) because of the brazed socket joint between the cooling channel and the water block. 2) The flexible hose from the water supply is laying on top of the vacuum chamber for the deflected beam line. 3) The OFE Cu hydraulic nipple connectors can get damaged, risking a leak.

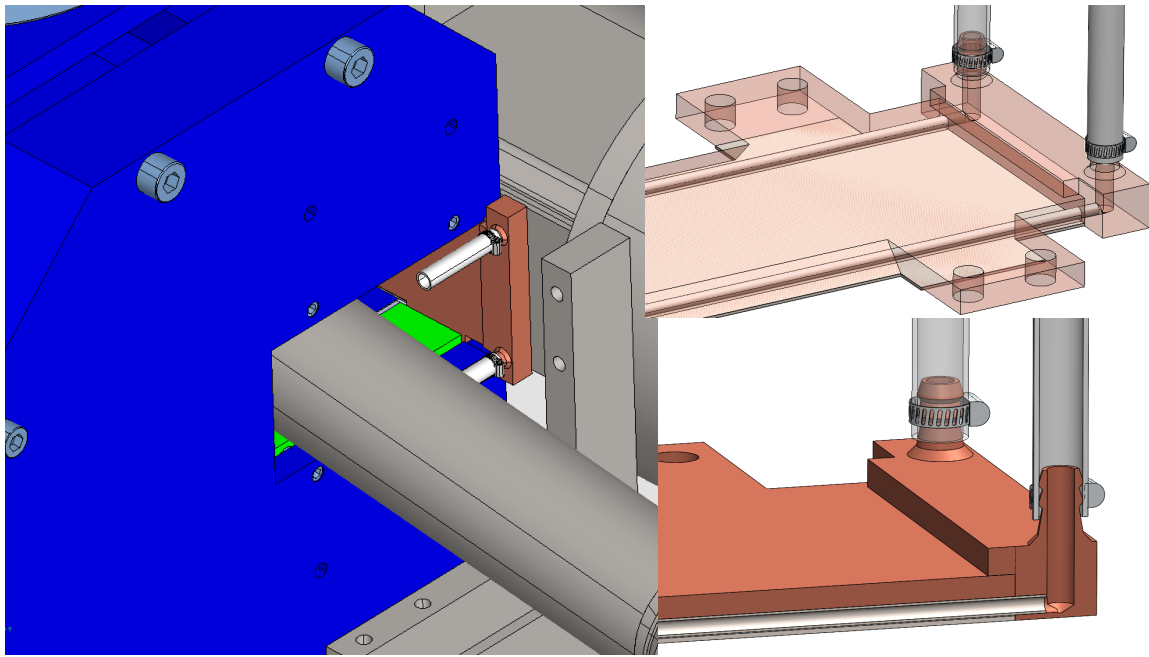


Figure 5.17: A CAD-model of concept 2, originating from alternative 2. On the Left a CAD model of the design as it would be installed on the SMH40. On the right a transparent view and a cross sectional view of the water block area showing the cooling channel.

5.4.3 Concept 3

Concept 3 (Figure 5.18) is similar to concept 1. However, concept 3 requires SAGANA[®] straight hydraulic compression tube connectors instead of using 45 ° elbow connectors, seen in concept 1. The surfaces of the water block are machined in a 45 ° angle, allowing for accessibility of the straight hydraulic connectors.

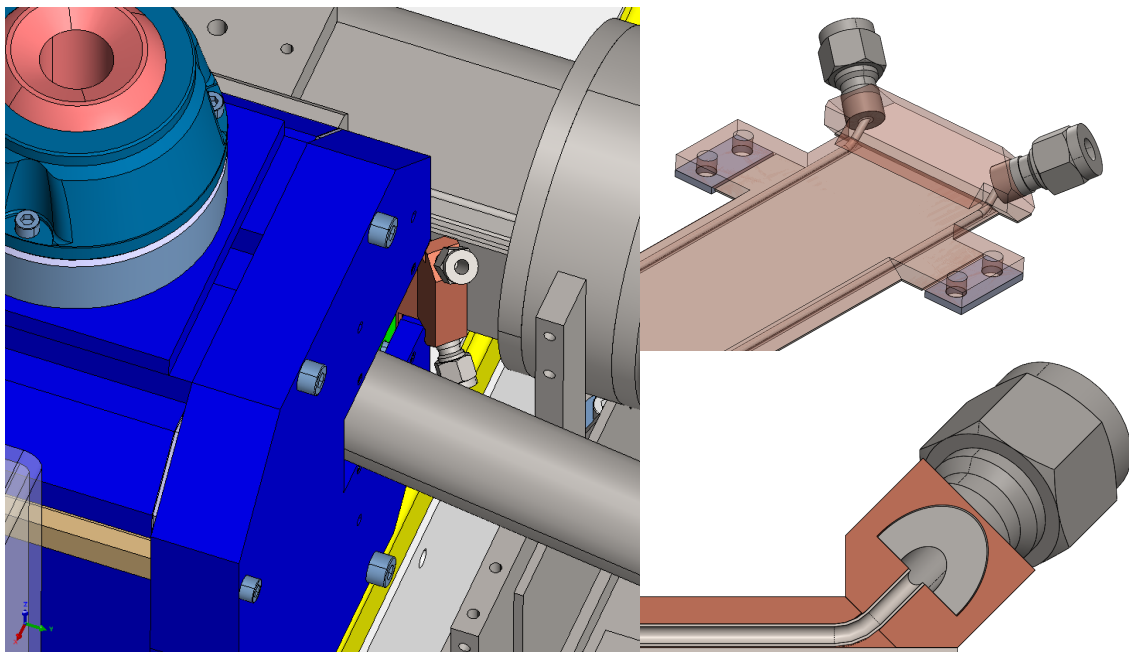


Figure 5.18: A CAD-model of concept 3, originating from alternative 3. On the Left a CAD model of the design as it would be installed on the SMH40. On the right a transparent view and a cross sectional view of the water block area showing the cooling channel.

5.4.4 Concept 4

Concept 4 has two separate water blocks on the connection sides of the blade (Figure 5.19). The advantage of this design is the simple shape of the water blocks and straight connectors, resulting in fast machining and less stringent tolerances. Challenges of this design are: 1) The possibility of buckling the flexible hose, since the inlet hose is orientated vertically to the septum blade. 2) Tolerances on the cooling channel and groove in the conductor, because of the two bends of the cooling channel (Bending radius = 5 mm). 3) Mounting of the septum blade on the SMH40 magnet assembly, since the water blocks overlap with the vacuum chamber of the circulating beam.

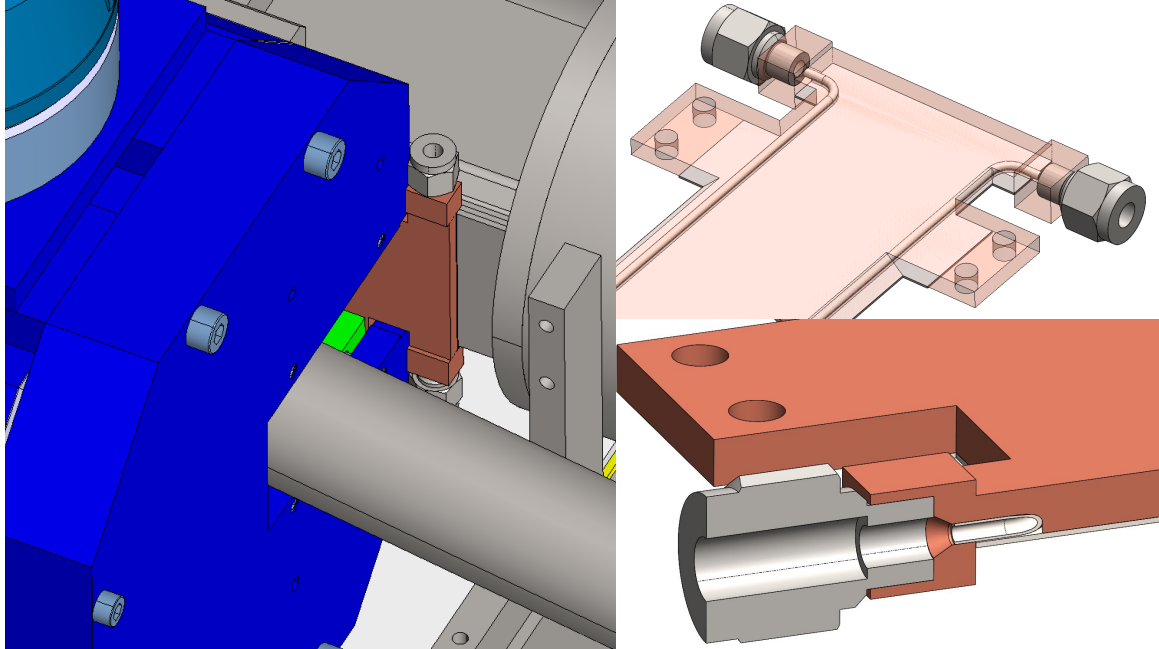


Figure 5.19: A CAD-model of concept 4, originating from alternative 4. On the Left a CAD model of the design as it would be installed on the SMH40. On the right a transparent view and a cross sectional view of the water block area showing the cooling channel.

5.4.5 Numerical computation

The structural robustness (FEA) and hydraulic properties (CFD) of each concept are shown in Table 5.4. See appendix A.9 for screenshots and more information about the simulations. Results from the analysis are used in the decision matrix.

Table 5.4: Results from numerical computation. Static structural in Solid Works and CFD in ANSYS Fluent

Parameter	Unit	C1	C2	C3	C4
Maximum deformation	μm	35	33	37	85
Maximum Stress	MPa	33	57	35	56
Static pressure	bar	2,4	12,7	4	3,9
Maximum dynamic pressure	bar	0,5	0,7	0,3	0,4
Maximum velocity	m s^{-1}	14	15,7	15	12
Turbulence Reynolds number	-	5706	1948	2286	3918

5.5 DECISION MATRIX

The objective of the decision matrix is to choose the concept which merges the solutions to the technical specifications in the best possible way. In the decision matrix, every technical specification is valued with a "Factor of significance" (1 - 5), since some technical specifications are more important than others. A score of 1 - 5 is assigned to each concept indicating the compliance with each technical specification. The sum of all scores are compared to each other.

Concept 1 is the concept with the highest score (195), compared to concept 2 (103), concept 3 (166), and concept 4 (169). The complete decision matrix, including substantiation of the assigned factors of significance and assigned scores, is in Appendix 5.5.

5.6 DISCUSSION CONCEPTUAL DESIGN PHASE

The DFM-orientated approach of the conceptual design phase has resulted in a feasible concept that potentially fulfills all requirements in the best possible way. Selecting a production technique compliant with the technical specifications from the client, prior to the water block design, has resulted in a physically verified leak-tight connection. By doing so, the water block design phase was mainly focused on different concept ideas to access the hydraulic connectors without increasing the risk of a leak during operational conditions. The chosen concept might not be the most innovative or "out-of-the-box" idea, due to this approach. However, the goal of the conceptual design phase was to create a design that is durable, robust and leak tight.

The chosen concept, *concept 1*, will be vacuum furnace brazed with a socket joint between the water block and the cooling channel, assuring leak-tightness. A potential procedure for vacuum furnace brazing the assembly is shown in Table 5.5. This brazing procedure is based on the observations of the brazed samples, discussions with EM-MME and the water block design. The placement of the BFM is shown in section 6.1.

Table 5.5: Potential brazing procedure for a fourth generation septum blade.

Cycle	Configuration	Parts	BFM	Brazing temperature
1st brazing	Horizontal	316L SS Cooling channel, 316L SS plate, OFE Cu conductor OFE Cu Water block	Ag68.5 Cu26.5 Pd5 (Pd 287 V1)	813 - 825°C
2nd brazing	Horizontal	Hydraulic connectors	Ag 72Cu (Ag 272 V1)	785 ± 5°C

Concept 1 will be further detailed and analyzed with numerical computation and with a physical prototype in the next chapter.

6

DETAILED DESIGN

The detailed design phase consists of two main topics. Firstly, the design will be further detailed and improved in section 6.1. The second topic is to verify the detailed design. Design verification consists of numerical computation (CFD and structural FEA), compatibility with existing equipment, accessibility of the hydraulic connectors, leak-testing of a physical prototype and a design review by checking the design's compliance with the technical specifications and requirements. The chapter concludes with a discussion.

6.1 DESIGN ITERATIONS AND IMPROVEMENTS

Concept 1 has been optimized into a detailed design to further improve the manufacturing feasibility. The substantiation of the eight design changes, (listed (A) to (I) in Figure 6.1 and Figure 6.3) are described in this section.

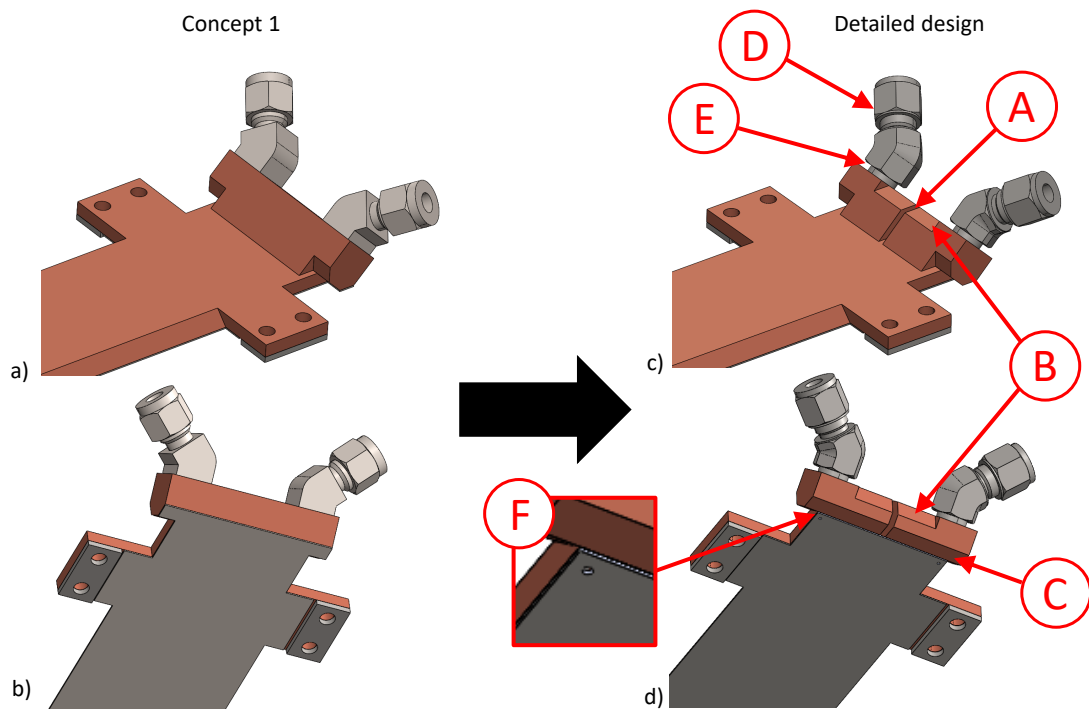


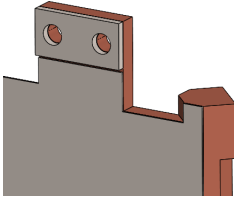
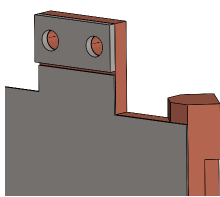
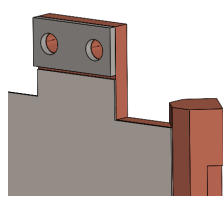
Figure 6.1: a) CAD model of Concept 1 (top). b) CAD model of concept 1 (bottom). c) CAD model of the detailed design (top) d) CAD model of the detailed design (bottom)

(A) The water block shall be manufactured out of two separate symmetrical blocks. Geometrical constraints and tolerances of the contact surfaces between the water block, the cooling channel, and the conductor will be less stringent. In addition, two water blocks allow for a less rigid assembly in case of deflection due to operational forces.

(B) Two flat surfaces are included on each water block to constrain the part with clamps and weights in the vacuum furnace for brazing. These flat surfaces are located parallel and perpendicular to the length of the conductor as shown in Figure 6.1.

© The next design improvement is the coverage of the reinforcement plate underneath the water block. In concept 1 the reinforcement plate is completely supporting the water block. But this results in very stringent tolerances on the contact surfaces between the water block and the reinforcement plate and the conducting blade (Table 6.1). Three static structural simulations in SolidWorks have been done to research the effect of the coverage of the reinforcement plate. Boundary condition of the simulations are identical to the initial calculation calculation in 2.4.1. Comparing three situations (full-, partial-, and no coverage) has shown that the added value of extending the reinforcement plate is not worth the increased difficulty during manufacturing and brazing. Therefore, the reinforcement plate shall not cover the water block.

Table 6.1: Differences of reinforcement plate coverage supporting the water block, substantiating the design choice.

Parameter	Full coverage	Partial coverage	No coverage
CAD model			
Max displacement [μm]	38	38	32
Max stress [MPa]	36	36	33
Manufacturing plate	-	+	+
Manufacturing water block	-	-	+
Difficulty brazing procedure	-	-	+

© Hydraulic connectors in both return conductors, the previous generations of septum blades and the brazed samples were Rotatex SAGANA®. However, Rotarex has stopped manufacturing compression tube connectors since June 2019. An inquiry of similar 45 ° compression tube connectors from Parker® and from Swagelok® were requested. The Parker® connector (EV06LMEDOMD71) was 125,58 CHF/connector with a minimal order of 10 pieces and a lead time of 4 weeks. The Swagelok® connector (SS-6M0-5-4PR) is 33,72 CHF/connector with no minimal order quantity and a lead time of 7 weeks. The Swagelok® connectors were chosen for the septum blade due to the possibility of ordering small quantities and lower price. 8 pieces were ordered in total, for two septum blades and spares (Figure 6.2).



Figure 6.2: Swagelok®

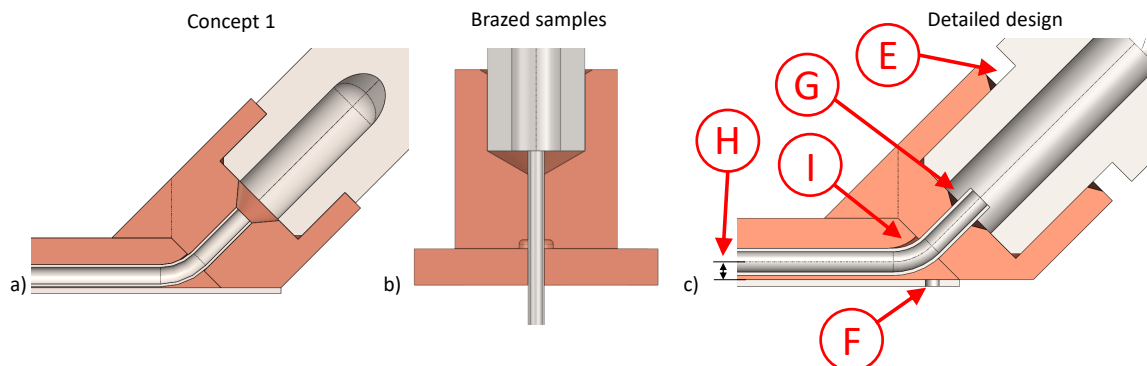


Figure 6.3: a) Section view of Concept 1. b) Section view of the brazed samples the proof-of-principle (middle). c) Section view of the detailed design.

© There is a 2 mm gap between the water block and the hydraulic connector for enough clearance to place the $\varnothing 1$ mm wire of BFM. The BFM is placed in a 0,6 mm $\times$ 60° chamfer surrounding the hydraulic

connector, similar to the brazed samples.

Ⓕ The pressure of the vacuum furnace during brazing is approximately $1e-6$ mbar. Outgassing of the hollow areas underneath the cooling channel will prevent the furnace from reaching this pressure within a reasonable time. A solution is to drill a $\varnothing 1$ mm hole in the reinforcement plate, opening the enclosed area. The outgassing holes will not increase the risk of a leak, because leak tightness is assured by the brazed socket joint (cooling channel - water block) prior to the outgassing holes.

Ⓖ The $\varnothing 2$ mm cooling channel will extend out of brazed socket joint on the inside of the water block. There is a risk that the BFM will migrate into the cooling channel during the brazing procedure, closing it off. The BFM shall also be placed in a $0,6$ mm $\times$ 60° chamfer, instead of the groove as seen in the brazed samples (Section 5.2). The effect of extending the cooling channel is analyzed with CFD in Section 6.3.1.

Ⓕ The machined groove in the conductor is $0,15$ mm deeper, increasing the clearance between the reinforcement plate and the cooling channel from $1,1$ mm to $1,25$ mm (Figure 6.4). This allows for the placement of two $\varnothing 0,5$ mm wires of BFM.

Ⓕ The clearance between the 4 mm radii bends of the cooling channel and the conductor was increased, by reducing the radius in the conductor, to prevent interference of these two parts.

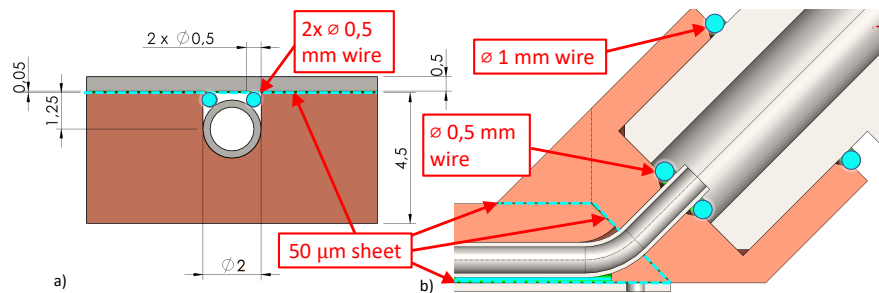


Figure 6.4: a) section view of the cooling channel placed in the groove of the conductor with dimensions and BFM placement. b) Section view of the detailed design showing the placement of the BFM.

6.2 ELECTRICAL SAFETY COVER

Figure 6.5 shows a design for the electrical safety top cover guaranteeing to IP2X. The top cover consists of three parts glued together. The individual parts can be manufactured with water jet cutting and bending. Both symmetrical covers can be mounted on the yoke with bolts, in the same manner as the currently operational (section 2.3.3). The electrical safety cover verifies functional requirement: **4.1.2. No live electrical contact.**

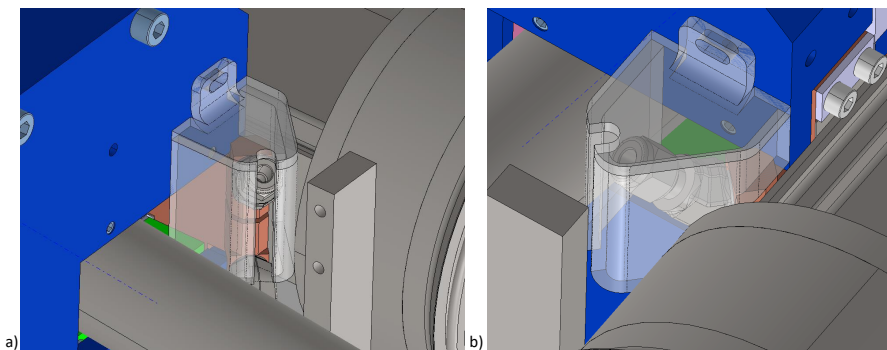


Figure 6.5: CAD model of a possible transparent safety cover for the fourth generation design.

6.3 NUMERICAL COMPUTATION

The hydraulic impedance and structural FEA was re-calculated because of the design iterations made in section 6.1.

6.3.1 Computational fluid dynamics

Hydraulic impedance of the detailed design is similar to the first generation septum blade. The maximum velocity is lower, $13,8 \text{ m s}^{-1}$ instead of 17 m s^{-1} . With an average velocity of 6 m s^{-1} . The total pressure (dynamic + static) is similar to the first generation septum blade, as shown in Table 6.2. An improvement of the fourth generation compared to the first generation is that all higher velocity & higher dynamic pressure areas are in 316L SS cooling channels instead of the OFE Cu, reducing the risk of internal abrasion.

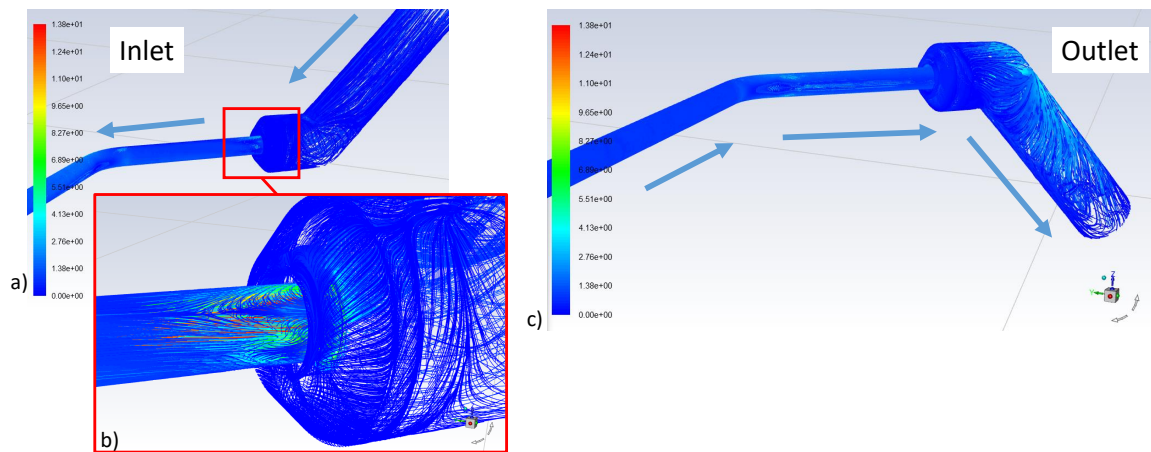


Figure 6.6: CFD results of the fourth generation septum blade. Mesh quality is verified with a maximum Y^+ value of 4,56 (See Appendix A.11 for more information on Y^+). a) Fluid velocity [m s^{-1}] in the inlet of the water block area. b) Close-up of the transition from the water block into the cooling channel showing the maximum velocity in the cooling circuit. c) Fluid velocity [m s^{-1}] in the outlet of the water block area.

In the detailed design the $\varnothing 2 \text{ mm}$ cooling channel extends 2 mm out of brazed socket joint on the inside of the water block to improve DFM (Section 6.1). Based on the results of this CFD analysis, the extending cooling channel has little to no effect on the hydraulic impedance of the septum blade as indicated by the results in Table 6.2 and Figure 6.6. Machining the protruding ends of the cooling channels within the water block prior to brazing the hydraulic connectors, shall not improve the fluid flow of the cooling circuit. Instead, it would increase the production costs and increase the risk of a leak during operation.

Table 6.2: Results from a CFD analysis for the fourth generation septum blade.

Parameter	Unit	1st & 2nd gen	3rd gen	Concept 1	Detailed design
Maximum velocity	m s^{-1}	17	32	12	13,8
Static inlet pressure	bar	4	28	3,9	4
Maximum dynamic pressure	bar	0,4	4	0,4	0,5
Maximum Reynolds number	–	3359	2426	3918	3742

6.3.2 Structural mechanics

Three static structural simulations were performed to locate peak stresses and deflection in the detailed design of the septum blade (Figure 6.7 and Table 6.3). The boundary conditions of the simulations are identical to the initial calculation in section 2.4.1. The hydraulic connector and cooling channel are excluded from the analysis. The conclusion of this analysis is that peak stresses of the septum blade are located near the mounting assemblies (maximum 33 MPa), not on the water blocks. The water blocks have a stress of < 10 MPa. The negligible displacement of $< 18 \mu\text{m}$ on the water blocks, when subjected to F_{vacuum} and F_{Lorentz} indicates no risk of a fracture. The maximum deflection of 32 MPa is located on the end of the septum blade opposite from the water block. However, this FEA is based on a static F_{Lorentz} . No conclusion can be made regarding the effect of a pulsed F_{Lorentz} .

Table 6.3: Stress and deflection of the previous generations of septum blades, concept 1 and the detailed design

Parameter	Unit	1st & 2nd gen	3rd gen	Concept 1	Detailed design
Maximum displacement	μm	17	12	35	33
Maximum stress	MPa	95	18	33	32

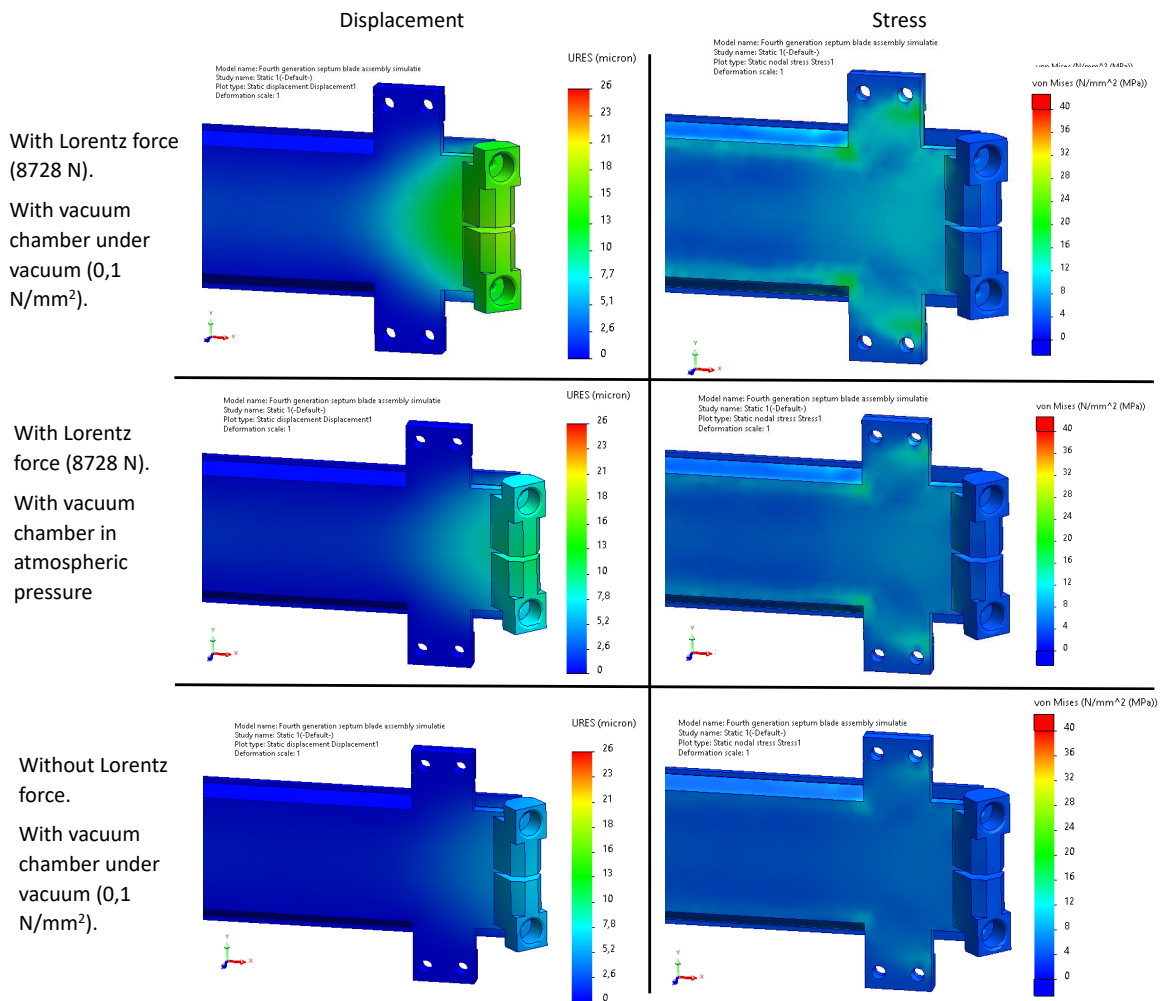


Figure 6.7: FEA results of three different scenarios for the fourth generation septum blade. The displacement is shown in the left and the stress plot on the right side of the image.

6.4 CLEARANCE FOR ELECTRICAL INSULATION

The total thickness of electrical insulation between the septum blade and the yoke is 0,5 mm ($2 \times 0,2 \text{ mm} \pm 0,05 \text{ Al}_2\text{O}_3 \text{ Coating} + 0,1 \text{ mm Kapton}^{\text{®}} \approx 0,5 \text{ mm}$). A review of the CAD model assembly was conducted to inspect if there is enough clearance ($> 0,5 \text{ mm}$) for the electrical insulation (Figure 6.8). The septum blade is purple colored for distinction of the model with surrounding equipment. Additionally, the functional requirements, **3.1 Fit between yoke and vacuum chamber** and **3.2 Mounting alignment** are verified.

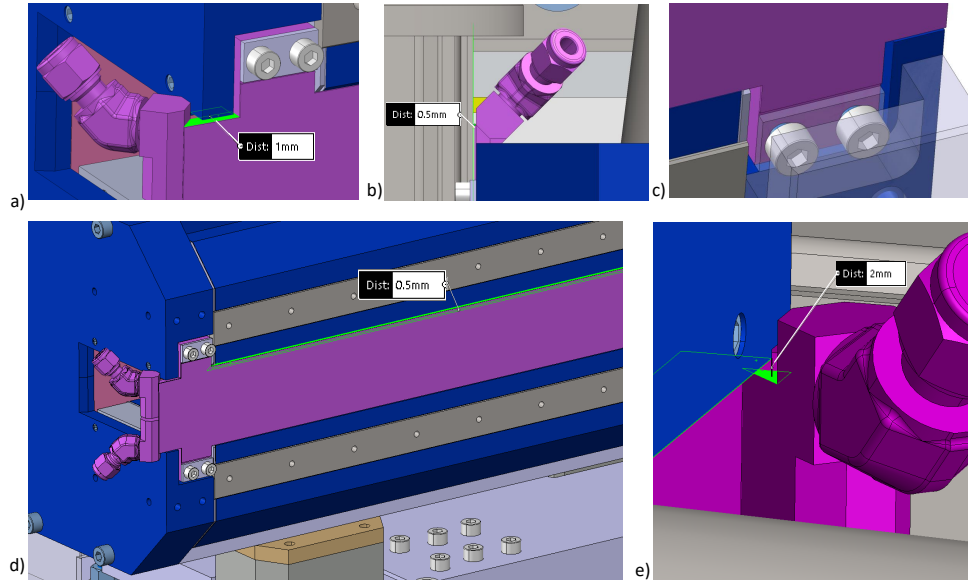


Figure 6.8: a) 1 mm clearance between the water block transition and the yoke endplate. b) 0,5 mm clearance between the water block and the vacuum chamber. c) Alignment of the mounting assemblies with the return conductor. d) 0,5 mm clearance between the tapered edge of the septum blade and the yoke laminations. e) 2 mm clearance between the water block the narrow area of the yoke endplate.

6.5 ACCESSIBILITY OF HYDRAULIC CONNECTORS

Figure 6.9 shows that both hydraulic connectors are accessible with two 14 mm spanners. Therefore, verifying functional requirement **5.3.1 Accessible connectors**. The shape of the hydraulic connector allows for the placement of a spanner on the body of the connector and the nut, without the need to place a spanner on the OFE Cu water block. By doing so, torque applied does not act on the brazed joint, but on the connector its self.

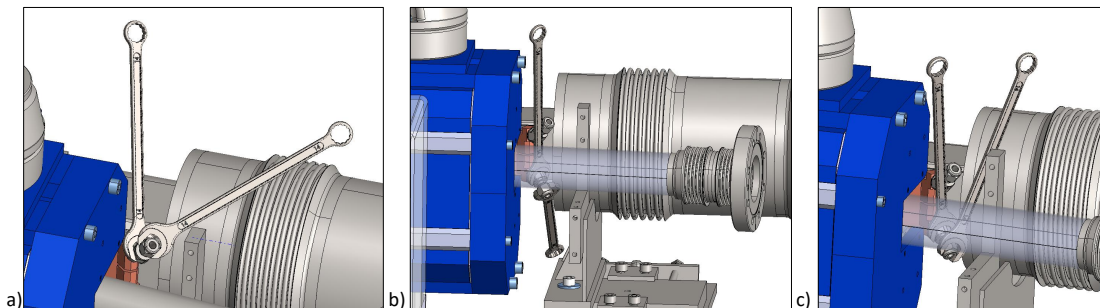


Figure 6.9: a) Two 4 mm spanners placed on the upper hydraulic connector (inlet) Verifying the presence of enough clearance to rotate the nut. b) One spanner placed on the lower hydraulic connector (outlet) and one spanner placed on the nut from below the vacuum chamber. c) Both spanners placed on the lower hydraulic connector (outlet) from above.

6.6 THE PROTOTYPE

The objective of manufacturing a physical prototype is to analyse the manufacturing feasibility and the leak tightness of the design. This section contains the manufacturing of individual parts, vacuum furnace brazing and NDT of the prototype. The section concludes with a list of design iterations based on the observations.

The prototype is a shorter representative version of the full length septum blade, as shown in Figure 6.10, to reduce material, manufacturing time and costs. See Appendix A.10 for all technical drawings.

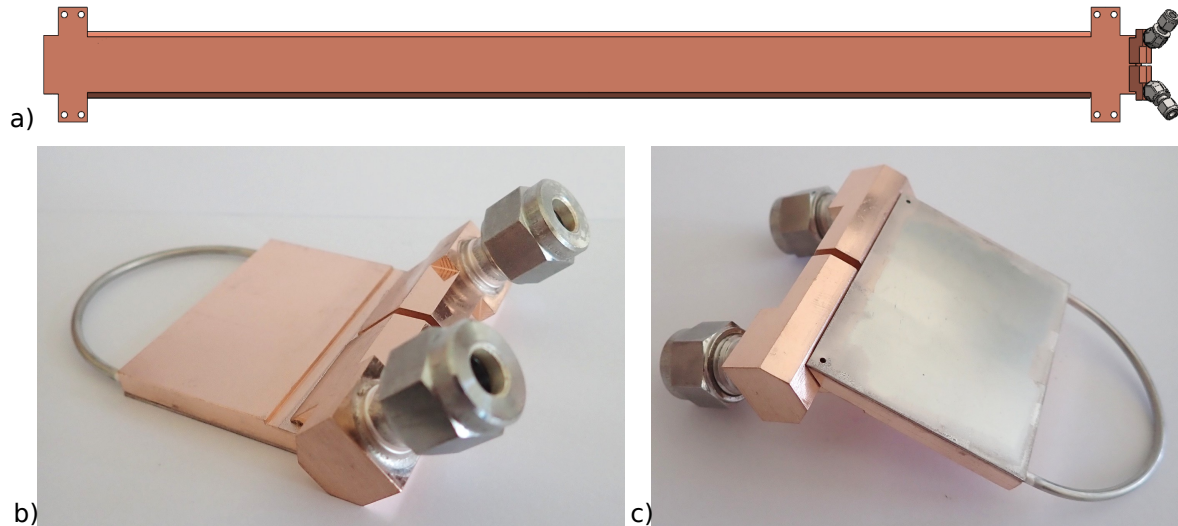


Figure 6.10: a) CAD model of the complete septum blade (906 mm long) b) Photograph of the prototype (80 mm long). c) Photograph of the bottom of the prototype.

6.6.1 Production of the prototype

Both water blocks and the conductor were CNC machined out of OFE Cu (Figure 6.11a). Two separate aluminium bending tools were manufactured to produce the 22 mm radius and both 4 mm radii in the cooling channel (Figure 6.11b and Figure 6.11c). Both hydraulic connectors were machined with a lathe, identical to the brazed samples (Figure 6.11d). The reinforcement plate required a heat treatment after cutting to improve the flatness. All 316L SS parts were de-greased prior to a sulfuric acid bath to create an oxide layer on the 316L SS. The Ni-coating is applied on the parts with a hydrochloric acid bath with nickel salts.

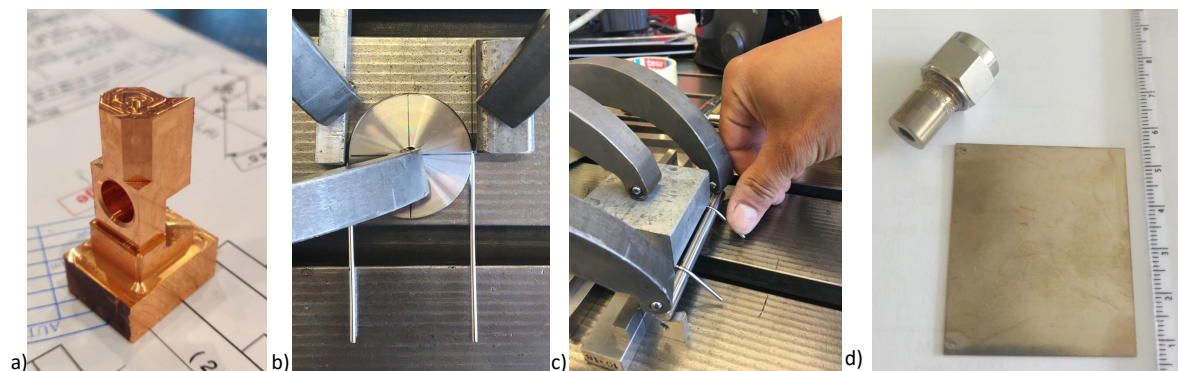


Figure 6.11: a) Water block during machining. b) Bending of the 22 mm radius on the cooling channel with a bending tool. c) Bending on the two 4 mm radii on the cooling channel with a bending tool. d) finished hydraulic connector machined on a lathe and the reinforcement plate after heat treatment to improve the flatness.

The prototype was brazed with three brazing cycles (Figure 6.12 and Table 6.4). It was intended to braze the prototype with two brazing cycles, based on the results of the samples. However, constraining the loose sub-assembly with the clamps is impractical.

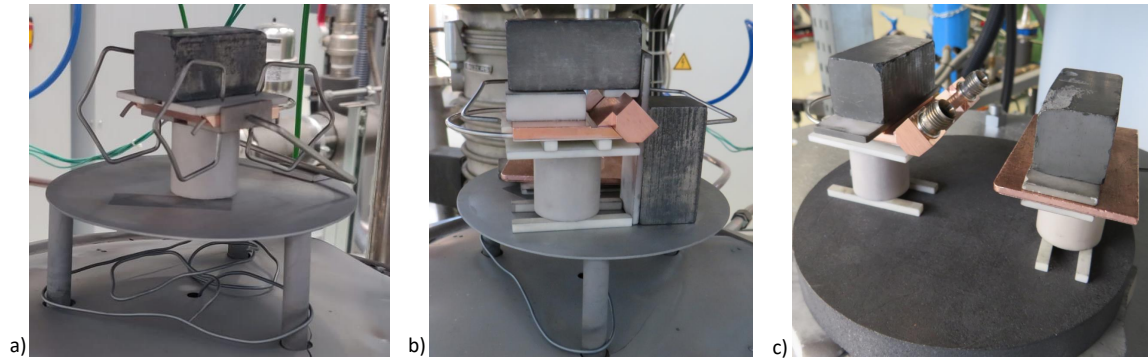


Figure 6.12: a) First brazing cycle. b) Second brazing cycle. c) Third brazing cycle.

Table 6.4: Procedure to braze the prototype

Cycle	Configuration	Parts	BFM	Brazing temperature
1st brazing	Horizontal (upside down)	316L SS Cooling channel, 316L SS plate, OFE Cu conductor	Ag58.5Cu31.5Pd10 (Pd 387 V1)	860°C $\pm$ 5°C
2nd brazing	Horizontal	OFE Cu Water blocks	Ag68.5 Cu26.5 Pd5 (Pd 287 V1)	813 - 825°C
3rd brazing	Horizontal	Hydraulic connectors	Ag 72Cu (Ag 272 V1)	785 $\pm$ 5°C

An adjustment was made after the first brazed sub assembly, because the cooling channel did not exit the groove on the tapered edge at the specified location (Figure 6.13). This issue was solved by machining 0,7 mm off the top of the conductor, re-aligning the cooling channel with the hole in the water block. The 0,1 mm $\times$ 45 ° chamfer was The misalignment was caused by the undefined positioning of the 22 mm radius in the conductor. This issue is not possible in the septum blade because the position is defined with the shape of the groove.

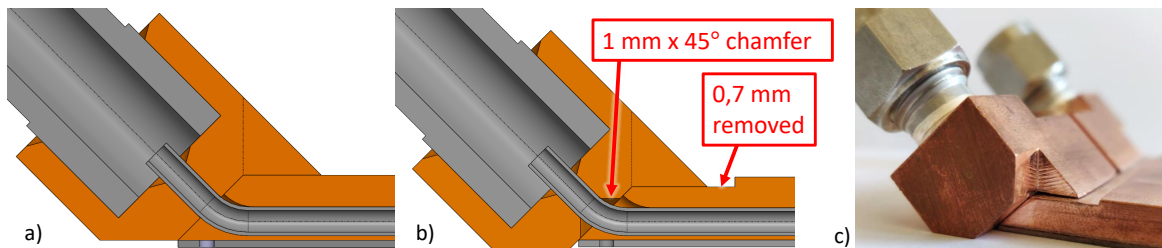


Figure 6.13: a) Indented alignment as specified. b) CAD model showing the Misalignment of the cooling channel and two adjustments for re-alignment (increasing the size of a chamfer and machining 0,7 mm of the flat face on top of the conductor.c) Close-up photograph of the prototype showing the adjusted alignment.)

6.6.2 Leak-testing

The prototype has proven to be leak tight with a pressure test at 50 bar for one hour (Figure 6.14). The minimal test pressure (P_t) for a pressure vessel is $1,43 \cdot 25 = 35,75$ bar. With an operational pressure 25 bar.

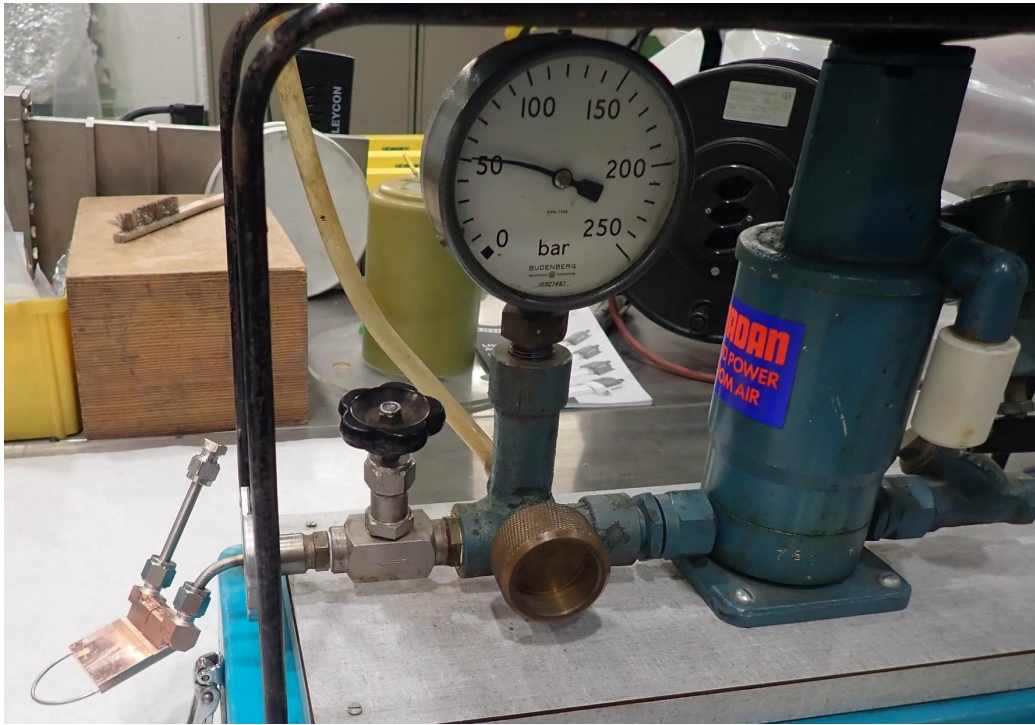


Figure 6.14: A leak test of the prototype using a water pressure test setup.

6.6.3 Design iterations based on prototype production and inspection

The following design changes are based on what was learned during the manufacturing and testing of the prototype:

- The assembly shall be brazed in three brazing cycles instead of two. Because constraining the part in the vacuum furnace is not possible for two cycles.
- The functionality of the outgassing holes has become obsolete due to the changed brazing procedure.
- The chamfers on the bottom of the water blocks will increase from 0,1 mm × 45 ° to 1 mm × 45 °). This allows for more clearance surrounding the 4 mm bending radius of the cooling channel.

6.7 DESIGN REVIEW

Compliance of the fourth generation design with the technical specifications and requirements will be verified with the requirements index in Table 6.6. Definitions of the colors used in Table 6.6 are described in the legend in Table 6.5

Table 6.5: Legend explaining the meaning of the colors used in the requirements review in Table 6.6

Legend	Color
Verified compliance with requirement and approved	
Expected compliance with requirement. Not verified.	
Uncertain compliance with requirement	
Does not comply	

Table 6.6: Verification of the compliance of the new design with the requirements index

No.	Technical specification	Requirement	Substantiation	Reference
0.0 Design for manufacturing (DFM)				
0.1	Production of the septum blade within CERN is preferred over subcontracting	All parts of the septum blade can be manufactured and assembled in CERN, 23 CERN member states or CERN associate states.	Machining in the main workshop, EN-MME-ME section. Brazing in the CERN EN-MME-FW section. The electrical insulation and electrical safety covers is outsourced within a CERN member states.	Section 7.3
0.2	Manufacturing costs per blade is as low as possible.	The manufacturing cost for a single septum blade does not exceed 5000 CHF.	Expected manufacturing cost including material procurement is 4041 CHF / septum blade (Excl. The electrical safety cover and the electrical insulation).	Section 7.2
0.3	Manufacturing time per blade is as low as possible.	The manufacturing time for a single blade does not exceed 6-months.	Expected manufacturing time for two septum blades is 3 months $\pm$ 1 month (Excl. the electrical safety cover and the electrical insulation). Production is launched in august 2022 and expected to be finished in November 2022.	Chapter 7
0.4	The design prevents material waste as much as possible during manufacturing.	The amount of material waste does not exceed 80% , as seen in previous generations.	Material waste is prevented by machining the water blocks and the conductor separately.	Section 7.3
0.5	The design can be manufactured with the selected manufacturing technique.	DFM is included throughout the concept design and the detailed design phase. The fourth generation blade complies with DFM	The fourth generation septum blade can be manufactured with the selected production technique (machining + vacuum furnace brazing), as shown with a physical prototype.	Section 6.11
1.0 Conduct electricity				
1.1	The cross sectional thickness is the same as the first generation septum blade.	The thickness of the septum blade is Cu 4,5 mm $\pm$ 0,05 mm + reinforcement plate 0,5 mm.	The thickness of the septum blade is the same as the previous generations. Tolerances are defined on the technical drawings.	Appendix A.10

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Table 6.6: Verification of the compliance of the new design with the requirements index

No.	Technical specification	Requirement	Substantiation	Reference
1.2	The septum blade can be mounted on the return conductors.	The length of the septum blade, from mounting area to mounting area, will be 828 mm.	The length of the septum blade is $828 \pm 0,2$ mm as defined in the technical drawings.	Appendix A.10
2.0 Stable temperature				
2.1	Current uniformity in the conductor is the same as previous generations.	A 316L SS cooling channel with a $\varnothing 2$ mm outer diameter and $\varnothing 1.5$ mm inner diameter is used.	The same cooling channel is implemented in the fourth generation design.	Appendix A.10
2.2	Current uniformity in the conductor is the same as previous generations.	The length and location of the straight section of the cooling channel is 837 mm and is located at the beginning of the tapered edges.	The groove is 0,15 mm deeper due to BFM placement. This results in a $17,18 \text{ kg m}^{-3}$ reduction in cross sectional area. Increasing the dissipated heat energy from 40 to 43 W and increasing mass flow from $0,017 \text{ kg m}^{-3}$ to 0,0174. The design change was discussed with the section leader and accepted.	Section 6.1
2.3	The fluid flow is able to remove all excess energy from the system.	An energy of 40 W can be removed from the conductor by the fluid flow.	CFD analysis has shown that the required volume flow of 1 L min^{-1} can be achieved with a total inlet pressure of 4,5 bar.	Section 6.3.1
2.4	The septum blade has the lowest possible electrical resistance, measured from mount to mount.	Electrical resistance of the septum blade, measured from mount to mount, does not exceed $7,36 \cdot 10^{-5} \Omega$.	The conductor of the fourth generation septum blade is manufactured from the same material, OFE Cu. C10100 grade. However the resistance has increased to $8,02 \cdot 10^{-5} \Omega$ because of the depth of the groove. The design change was discussed with the section leader and accepted.	Section 2.4.2
2.5	Orientation of the hydraulic connectors prevents buckling of the flexible hose as much as possible.	Buckling of the flexible hose, causing an obstruction of the water flow during operation, is prevented	No buckling of the flexible hose was observed with a similar 45° angle compared to the horizontal plane in the operational first generation design.	Section 2.3.2
3.0 Compatibility				

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Table 6.6: Verification of the compliance of the new design with the requirements index

No.	Technical specification	Requirement	Substantiation	Reference
3.1	Assure structural compatibility of a new design with existing components.	No other equipment needs to be altered to mount the septum blade on the SMH40.	The septum blade can be mounted on the SMH40 without the need to alter any other equipment in the CAD model.	Section 6.8
3.2	Electrical insulation's total thickness (Kapton [®] + Al_2O_3 coating) is the same as for the first generation blade.	The thickness of the electrical insulation is $2 \times 0,2$ mm Coating on the yoke and the septum blade + $0,1$ mm Kapton [®] = $0,5$ mm (Section 2.3.2).	Al_2O_3 coating will be outsourced to a company with a CERN member state. A coating thickness of $0,3$ mm to be grinded down to $0,2$ mm is defined on the technical drawings. The company can provide a sample of the Al_2O_3 coating on the tapered edges of the third generation septum blade that was used in DT. A Metrology inspection by EN-MME-EM of the thickness of the sample will verify this requirement.	Section 2.3.1
4.0 safety				
4.1	There is no risk of live electrical contact with the septum blade.	There are designated covers around any accessible components of the septum blade.	The fourth generation water block design can be covered with a electrical safety cover made from 4 mm thick transparent Makrolon [®] Polycarbonate sheet. Manufacturing of the electrical safety cover is outsourced within a CERN member state. The cover will be manufactured after acceptance testing of the septum blade.	Section 6.2
4.2	The septum blade must be safe to hold for technicians handling it.	The edges of the septum blade must be de-burred to prevent injuries when carrying the component.	All sharp edges ($\geq 90^\circ$) are to be de-burred as defined in the technical drawings.	Section A.10
4.3	The septum blade shall be leak tight.	No water is leaking out of the septum blade while pressurized at 25 bar.	A physical representative prototype has proven to be leak-tight at 50 bar for 1 hour.	Section 6.6.2

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Table 6.6: Verification of the compliance of the new design with the requirements index

No.	Technical specification	Requirement	Substantiation	Reference
4.4	Short circuit between the OFE Cu conductor and the yoke shall be prevented.	The electrical insulation must be able to contain a voltage hold off for 1 kV .	Electrical insulation will be the identical to the verified operational first generation septum blade. The thickness and location of the Al_2O_3 coating is defined on the technical drawings. See requirement 3.2 for more information.	Section 7.3
4.5	An electric arc between the septum blade and the return conductor shall be prevented.	The design includes four mounting assemblies as stated in section 4.2 combined with adequate QC.	The mounting assemblies are the identical to the first generation as defined on the technical drawings. QC is added for the SMH40 assembly procedure.	Section A.10
5.0 Durability				
5.1	The MTTF of the septum blade assembly is as long as possible.	The MTTF of the septum blade assembly is at least 10 years, based on an average of 6 million pulses/year.	The maximum stress in the septum blade does not exceed 35 MPa as shown by static structural FEA. The water block design is more robust than the first generations septum blade, which was operational for 6 years before failure. However, compliance with this requirement is uncertain, because no fatigue study was performed. Therefore, no conclusion can be drawn about the MTTF when subjected to pulsed operational conditions.	Section 6.3
5.2	The septum blade must be able to withstand the pulsed force, due to the magnetic field.	No non-reversible deformations, meaning micro- and macro fractures or plastic deformation in the septum blade during operation, when subjected to 8.73 kN every 3,6 s.	See description from requirement 5.1	Section 6.3
5.3	The hydraulic connectors are easy accessible to connect the water supply after the septum blade is installed and during maintenance of the SMH40.	The water supply can be assembled and disassembled by hand, or with hand tools, without the need to relocate surrounding parts.	The 45 ° angle of the water block and the hydraulic connectors allow for easy accessibility. Accessibility with a 14 mm spanner was verified with the CAD model.	Section 6.9

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Table 6.6: Verification of the compliance of the new design with the requirements index

No.	Technical specification	Requirement	Substantiation	Reference
5.4	The flexible hose is easy to (de-) couple to the hydraulic connectors for maintenance.	The flexible hose must be able to be (de-) coupled within 1 minute with basic hand tools	The standard issue hydraulic connector can be opened and closed with two 14 mm spanners by hand. The spanners are both placed on the hydraulic connector to prevent damage of the OFE Cu water block when applying torque to fasten the flexible hose. Accessibility with two 14 mm spanners was verified with the CAD model.	Section 6.9
5.5	Repeated (Dis-)connecting of the water supply has the least negative effect on the leak tightness.	The water supply can be dis-connected and reconnected at least 10 times without meeting the leak tightness requirement	The certified compression tube connectors allow for repeated (Dis-)connecting of the flexible hose without damage.	Section 6.1
5.6	The hydraulic impedance, therefore the risk of internal abrasions, is as low as possible.	Avoid non-optimized bends, a large amount of bends and rapid volume changes in the fluid flow.	The optimized internal cooling circuit contains two 45 ° bends. CFD analysis has shown that a static inlet pressure of 4 bar, maximum dynamic pressure of 0,5 bar and a maximum fluid velocity of 13,8 m s ⁻¹ is required for a volume flow of 1 L s ⁻¹ . The risk of abrasion is reduced because the high dynamic pressure regions are located within 316L SS parts of the cooling circuit, instead of OFE Cu.	Section 6.3.1

6.8 DISCUSSION DETAILED DESIGN PHASE

The feasibility of the new septum blade design is strongly underlined by the production and analysis of a physical representative prototype. The prototype was vacuum furnace brazed in three cycles and has proven to be leak tight with a water pressure test at 50 bar for one hour. Therefore, assuring the leak-tight properties of the optimized manufacturing procedure combined with the selected water block design. Numerical computation indicates the water block design's robust and durable features (stress in the OFE Cu water block < 10 MPa during static operational conditions), and low hydraulic impedance of the optimized cooling water circuit (maximum dynamic pressure of 0,5 bar), reducing the risk of abrasion. The fourth generation septum blade is compatible with the existing equipment and accessible with hand tools to fasten the hydraulic connectors to connect to the SMH40 water supply. A design review for compliance of the fourth generation septum blade with the technical specifications from the client, design constraints and requirements has verified the complete fulfillment of the required functionality. Therefore, concluding the design phase. The following phase is to realize the production of two fourth generation septum blades, as shown in chapter 7.

7 | IMPLEMENTATION

The final phase within the scope of the bachelors thesis, is to prepare for the production of two fourth generation septum blades. One septum blade to be installed in July 2022 during a LEIR shutdown and one spare septum blade. This chapters contains the BOM, expected costs, expected manufacturing time and a Quality Control (QC) system with Manufacturing & Inspection Plan (MIP).

7.1 BILL OF MATERIALS (BOM)

The Bill Of Materials (BOM) for two fourth generation septum blades is shown in Table A.10.

Table 7.1: BOM for two fourth generation septum blades

Part(s)	CDD	Material	Size [mm]	price [CHF]
Swagelok®	LEIMSME.0201	316L SS		33,72/piece
Water blocks	LEIMSME.0020.0199	OFE Cu	60 x 30	5,60
Conductor	LEIMSME.0196	OFE Cu	1000 x 200	107,10
Plate	LEIMSME.0198	316L SS	1000 x 200	28,4
Tube	LEIMSME.0197	316L SS	4000 x Ø2	128,00
Total for two septum blades				403,98

7.2 PRODUCTION COSTS

Table 7.2 shows the expected costs for the production of two fourth generation septum blades. The costs are based on the prototype and on discussions with EN-MME-MA and EN-MME-FW. The manufacturing time is estimated to be 3 months ± 1 month. The goal is to install the fourth generation septum blade on the SMH40 during a LEIR shutdown in July 2023. Procurement of the material is requested for two septum blades and production is expected to be finalized at the end of November 2022, allowing enough time for acceptance testing and electrical insulation. **The current estimated production cost including material procurement is 4041 CHF/ septum blade. Therefore complying with the objective of a maximum production costs of 5000 CHF/ septum blade.**

Table 7.2: Expected manufacturing costs for two fourth generation septum blades.

Description	Department	Time [hours]	Costs [CHF]
Sheet metal work	EN-MME-FW	2	120
CNC machining + CAM	EN-MME-MA	65 (8 days)	3900
Bending + bending tool	EN-MME-MA	16 (2 days)	960
Versatile	EN-MS-MA	1	60

Continues on next page

Table 7.2: Expected manufacturing costs for two fourth generation septum blades.

Description	Department	Time [hours]	Costs [CHF]
Machining lathe	EN-MME-MA	4	240
Vacuum brazing + heat treatment	EN-MME-FW	-	2400
Total for two septum blades			7680

7.3 ELECTRICAL INSULATION

The Al_2O_3 coating (Figure 7.1b) will be applied to both tapered edges of the septum blade with plasma spray as defined in the technical drawing (Figure 7.1a). It is recommended to apply the coating with a thickness of 0,3 mm and grind it to $0,2 \text{ mm} \pm 0,05 \text{ mm}$ to obtain the required tolerance. Procurement of the coating will be outsourced to a company within a CERN member state. It is important that the mounting areas of the septum blade are protected during the plasma spray to prevent unwanted coverage on these areas.

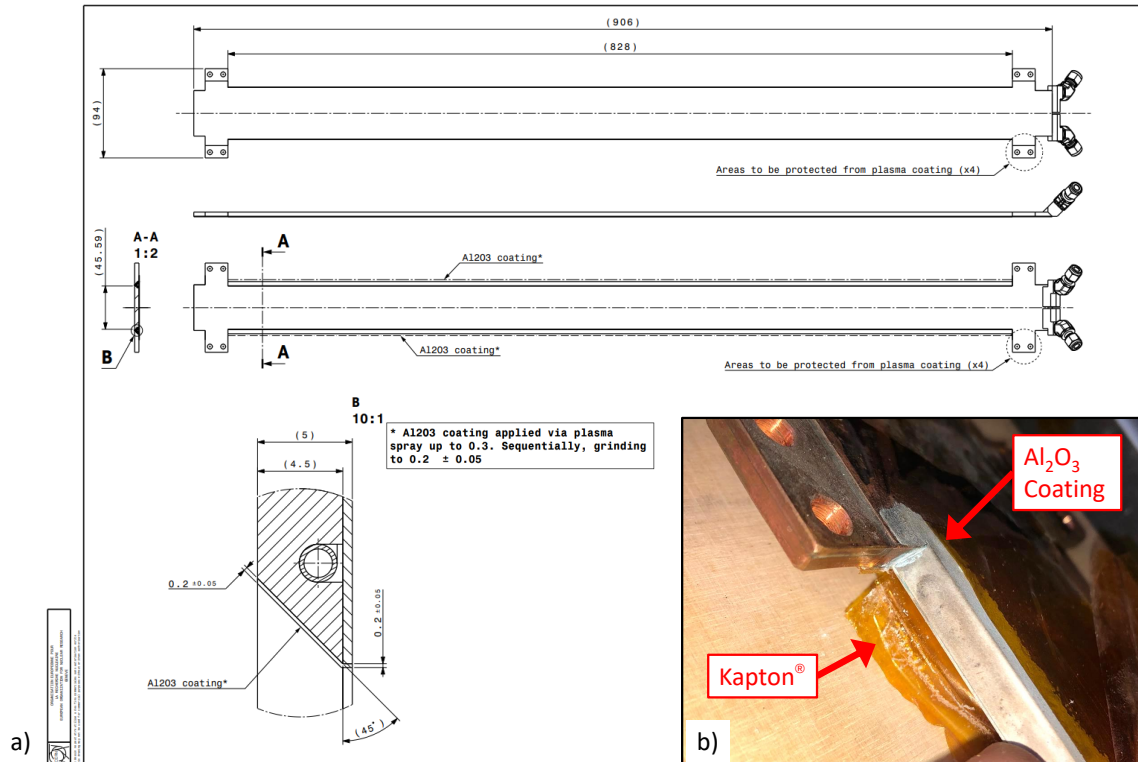


Figure 7.1: a) Detail from of the technical drawing for electrical insulation Appendix A.10. b) Photograph of the first generation septum blade showing the aluminium oxide coating and Kapton® layer.

7.4 MANUFACTURING & INSPECTION PLAN (MIP)

A Quality Control (QC) system is implemented with a Manufacturing & Inspection Plan (MIP), as shown in Table 7.3. The MIP contains the activities to be performed to manufacture the septum blade including the department and/or person responsible for this activity. The Quality control system includes the type of inspection, the department and/or person responsible for this inspection. Ideally the person performing the activity is not the same as the person inspecting the parts. The Hold Point (HP), marked with an "X", indicates a stop in the activities. This means that all activities prior to the HP must be completed before continuing the manufacturing process.

Table 7.3: Manufacturing & inspection plan (MIP) for septum blade for the SMH40 . Project Engineer (PE), ABT Design Office (DO), Equipment Owner (EO))

No.	Activity	Person/department	References	Quality control	Inspector	HP
3.3	Ni-coating of 316L SS in a hydrochloric acid bath with nickel salts	M. Thiebert	TE-VSC-SCC	Visual inspection	SCC & FW	
4.0 Brazing						
4.1	Heat treatment 316L SS plate for flatness	A. Gerardin	EN-MME-FW	Flatness measurement		PE & MM
4.2	First brazing cycle (blade, cooling channel, and plate)	F. Motschmann	EN-MME-FW	Brazing procedure	Visual inspection of brazed joints	
4.3	Second brazing cycle (water blocks)	F. Motschmann	EN-MME-FW	Brazing procedure	Visual inspection of brazed joints	
4.4	Third brazing cycle (hydraulic connector)	F. Motschmann	EN-MME-FW	Brazing procedure	Visual inspection of brazed joints	X
5.0 Unit testing						
5.1	pressure test at 30 - 40 bar for > 1 hour	PE				X
6.0 electrical insulation						
6.1	Apply Al_2O_3 insulation via plasma spray, thickness 0,3 mm	Outsourcing	ST1605585 & Section 7.3			
6.1	Grind Al_2O_3 insulation to a thickness of 0,2 mm $\pm$ 0.05	Outsourcing	ST1605585 & Section 7.3	Thickness and coverage inspection (Metrology report)	MM	X
6.2	Apply Kapton® insulation	SY-ABT-SE		Test fit septum blade on spare yoke	PE	
7.0 Electrical safety cover						

Continues on next page

Table 7.3: Manufacturing & inspection plan (MIP) for septum blade for the SMH40 . Project Engineer (PE), ABT Design Office (DO), Equipment Owner (EO))

No.	Activity	Person/department	References	Quality control	Inspector	HP
7.1	Water jet cutting, bending and assembly of transparent Polycarbonate sheet	Outsourcing	IP2X	Visual inspection and fit electrical safety covers on the SM40	PE	X
8.0 Acceptance testing						
8.1	Mount septum blade on SMH40 according to procedure	SY-ABT-SE	EDMS 1834531			
8.2	Pulse SMH40 (28 kA / 3,6 s)	SY-ABT-SE		Visual inspection for any water leakages and with thermal camera		

8 | CONCLUSION

The bachelor thesis concludes with a general discussion, recommendation for future studies and future work for the realization of the septum blade.

8.1 DISCUSSION

The objective of this bachelor thesis was **to analyze and redesign the septum blade, allowing an increased lifetime, optimized manufacturing procedure, and reduced non-conformities**. The result of this 6-month project is a both numerically and physically verified fourth generation design for the SMH40 septum blade (Figure 8.1). The improved version is based on the functional analysis of the equipment, a failure analysis of the previous generations and a concise list of requirements. The technical documentation includes technical drawings, expected costs & a MIP for the production of two septum blades. A summarized list of parameters for the fourth generation septum blade is shown in Table 8.1

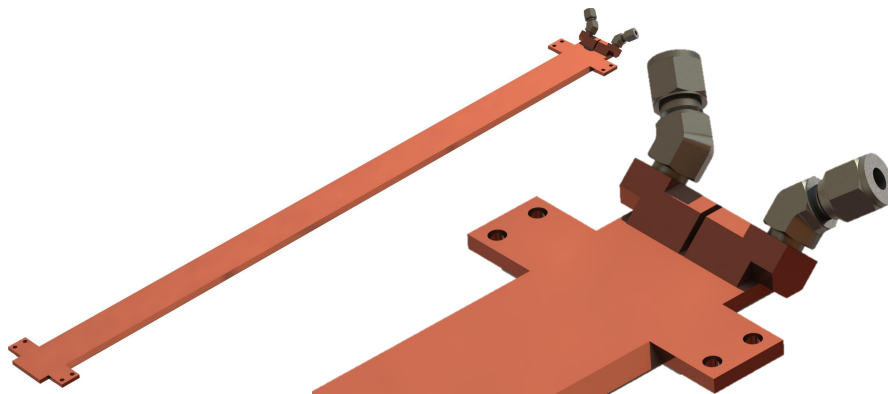


Figure 8.1: Rendered image of the fourth generation septum blade with a close-up of the water block.

Table 8.1: Summary of technical parameters of the fourth generation SMH40 septum blade

Parameter	Symbol	value	Unit	Reference
Peak current SMH40	I_{Peak}	27974	A	2.4.1
Current density	J_{Peak}	128	A/mm ²	2.4.1
Septum blade resistance	R_s	$7,36 \cdot 10^{-5}$	Ω	2.4.2
Lorentz force	$F_{Lorentz}$	8728	N	2.4.1
Maximum stress (mounting area)	σ_{max}	40	MPa	6.3.2
Stress water block	$\sigma_{waterblock}$	< 10	MPa	6.3.2
Maximum displacement	δ	< 18	μm	6.3.2
Heat energy conductor	P	40	W	2.4.2

Continues on next page

Table 8.1: Summary of technical parameters of the fourth generation SMH40 septum blade

Parameter	Symbol	value	Unit	Reference
Volume flow rate	$\dot{V}$	1	L min ⁻¹	6.3.1
Mass flow rate	$\dot{m}$	0,017	kg s ⁻¹	6.3.1
Maximum velocity	v_{max}	13,8	m s ⁻¹	6.3.1
Static inlet pressure	p_s	4	bar	6.3.1
Maximum dynamic pressure	p_d	0,5	bar	6.3.1
Maximum Reynolds number	Re	3742	–	6.3.1
Temperature demineralized water	T	299	K	2.4.3
Temperature, inlet and outlet	ΔT	0,6	K	2.4.3
Length	l_s	906	mm	A.10
Thickness	d_s	5	mm	A.10
Conducting length	l_c	935	mm	A.10
Weight	m	2,2	kg	A.10

8.2 RECOMMENDATIONS

The following recommendations for future studies are made, based on what was learned during this project:

1. ANSYS mechanical FEA fatigue studies of septum blades for pulsed electromagnetic septa, for an accurate computation of mechanical durability.
2. Physical tensile strength tests on brazed joints to measure the mechanical properties of a brazing layer, type of joint configuration and fatigue resistance.
3. Larger sample size for brazed samples to research diffusion and alloying of Ag-Cu-Pd BFM into the OFE Cu base metal.
4. CFD during the design phase of water cooled conductors. A CFD analysis prior to manufacturing the third generation septum blade could have prevented high manufacturing costs.

8.3 FUTURE WORK

The following list of future work is defined to be done after the end of the thesis in august 2022:

1. Production of two septum blades for acceptance testing (pressure test), prior to electrically insulation the conductor.
 - ⇒ Ordering material as specified in the BOM (Section [7.1](#)).
 - ⇒ Production of two blades is expected to be finished in November 2022.
 - ⇒ The target is to install the fourth generation septum blade during Long Shutdown 3 (LS3).
2. Contact with companies to procure the Al_3O_2 coating via plasma spray (thickness $0,2 \pm 0,05$ mm).
3. Technical specifications for electrical safety covers and procurement of the covers to an external company.

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A | APPENDICES

A.1 RESEARCH PLAN FOR RESEARCH SUB-QUESTIONS

This appendix includes the research plan to answer the seven research questions that have been defined in section 1.1. The answers to the research questions can be found in Chapter 2 and Chapter 3.

Table A.1: Research plan to answer the research questions.

No.	Research question	Goal	Quantitative or qualitative	Desk or field	Methods & tools
Functional analysis (Chapter 2)					
1	What is the main purpose of LEIR?	To gain insight in the accelerator that the septum blade is a part of. This will help to determine the relevance of the project as well as an understanding of the functionality and role of the septum blade.	Qualitative	Desk & field	Interviews with colleagues in SY-ABT-SE and literature research. Additionally, a guided visit to LEIR.
2	How does a pulsed electromagnetic septum (SMH40) work?	Understanding of the technical specifications and design constraints for a new design. This information shall be used in the failure analysis and requirements index.	Qualitative	Desk	Interviews with colleagues in SY-ABT-SE, SMH40 CAD-model, literature research (Scientific papers, master thesis, SE- section internal documents) and a guided tour to the SMH40.
3	What are the similarities and differences between the three previous generations of septum blades?	Critical research sub-question to understand the functionality of the septum blade. Information required to conduct a failure analysis of the previous generations.	Qualitative	Desk & Field	CAD models of all generations of septum blades and the SMH40 CAD model. There are two third generation septum blades available for testing. Interviews with colleagues in SY-ABT-SE. literature research (Scientific papers SE-section internal documents).

Continues on next page

Table A.1: Research plan to answer the research questions.

No.	Research question	Goal	Quantitative or qualitative	Desk or field	Methods & tools
4	<i>What are the operational conditions seen by the septum blade?</i>	Understanding the forces that act on the septum blade, represented in a free body diagram, is required to understand the input parameters for numerical computation.	Quantitative	Desk	Hand calculations and numerical computation (SolidWorks, CATIA & ANSYS) for structural, hydraulic- and electrical interfaces. Literature research and background knowledge in structural mechanics and fluid dynamics. CAD models suitable for simulation.
Failure analysis (Chapter 3)					
5	<i>What is the cause of the fracture in the first generation septum blade?</i>	Understanding why it fractured shall help to prevent similar issues in a new design.	Qualitative	Desk	A hydraulic issue of a structural issue is considered as a cause for the fracture. Numerical computation: Static structural in SolidWorks and CFD in ANSYS Fluent are used to find the cause of the fracture.
6	<i>What is the root cause of leakage in the third generation septum blade?</i>	Understanding why the septum blade is leaking shall help to prevent similar issues in a new design.	Qualitative	Desk & Field	Numerical computation: Static structural in SolidWorks and CFD in ANSYS Fluent are used to determine the cause of the leakage and hydraulic impedance. In addition to desk research, The 2 third generation septum blade shall be inspected with NDT (Leak test, Microscopy and Ultrasonic testing). DT shall be performed if the NDT is inconclusive. DT is a visual inspection of the brazing layer by removing the reinforcement plate and/or Microscopy of metallurgical cross section

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Table A.1: Research plan to answer the research questions.

No.	Research question	Goal	Quantitative or qualitative	Desk or field	Methods & tools
7	Are there any additional non-conformities?	Investigating other flaws with the design shall help to improve/reduce them in the future.	Qualitative	Desk & Field	Interviews with colleagues in SY-ABT-SE, the project engineer and/or technicians. Observation of operational conditions on the LEIR. Reading the eelogbook.

A.2 STAKEHOLDERS

This appendix states the project stakeholders. Table A.2 lists the Role, the technical specification, the influence on the detailed design and methods of communication of each stakeholder. The technical specifications,

Table A.2: Project Stakeholders listed by department, technical specification, and influence on a new design.

Section	Role	Technical specification	Influence	Communication
SY-ABT-SE	Group leader & Client	⇒ Robust & durable design, ⇒ Increased product life time (> 10 years), ⇒ Low production costs (< 5000 CHF), ⇒ Leak-tight design.	++	Frequent project status updates throughout the entire project.
SY-ABT-SE	SMH40 equipment owner	⇒ Accessible for maintenance, ⇒ Structural compatibility with existing equipment, ⇒ Electrical compatibility.	+++	Project status updates during conceptual and detailed design phase.
SY-ABT-SE	Supervising project engineer	⇒ Technical documentation ⇒ QC & MIP	++	Frequent project status updates throughout the entire project.
EN-MME-MA	Machining	⇒ ISO-quotation technical drawings, ⇒ DFM & MIP	+	Project status updates during conceptual and detailed design phase. Implement design recommendations based on machining constraints.
EN-MME-FW	Brazing Workshop	⇒ ISO-quotation technical drawings, ⇒ DFM & MIP	+	Project status updates during conceptual and detailed design phase. Implement design recommendations based on brazing constraints.
EN-MME-MA	Sheet metal technicians	⇒ ISO-quotation technical drawings, ⇒ DFM & MIP	+--	Implement production constraints in regard to sheet metal and tubes. Verify design choices during conceptual design phase in regard to DFM
EN-MME-MM	Materials & Metrology	⇒ Material thickness constraints for test samples	--	Stakeholder during failure analysis and conceptual design phase. Implement recommendations for inspection constants.

A.3 REGISTERED AMOUNT OF PULSES ON THE SMH40.

Table A.3: Registered amount of pulses on the SMH40 [32].

Year	Counter	No. pulses	No. weeks	Pulses/week	Pulses/year
2013	11302356	4006050	22	182093	
2014	12836298	1533942	6	255657	
2015	15168885	2332587	6	388764	
2015	15953681	784796	13	60368	
2015	17242366	1288685	12	107390	
2015	19847053	2604687	14	186049	7010755
2016	19847451	398	1	398	
2016	20026240	178789	8	22348	
2016	22339936	2313696	14	165264	
2016	23511874	1171938	7	167419	
2016	24652411	1140537	6	190089	4805358
2017	25045825	393414	3	131138	
2017	26126679	1080854	5	216170	
2017	27968354	1841675	10	184167	
2017	30753078	2784724	12	232060	6100667
2018	32735511	1982433	9	220270	
2018	39857425	7121914	13	547839	

A.4 MATERIAL PARAMETERS

The septum blade is made from C10100 grade oxygen-free electronic CU (OFE). This material is well suited because of its excellent electrical and thermal conductivity, outstanding resistance to corrosion, and ease of fabrication, together with good strength and fatigue resistance.

Oxygen-free Cu C10100 are made by induction melting prime-quality cathode Cu under non-oxidizing conditions, produced by a granulated graphite bath covering and a protective reducing atmosphere that is low in hydrogen. [33]

The Cu needs to be cold worked to increase both, the tensile strength and the yield strength. The tensile strength of the hardest cold-worked Cu is approximately twice the tensile strength of the annealed Cu. See Table A.4 for the material properties of cold worked C10100 grade OFE Cu. [33]

The cooling channel and the reinforcement plate are both made from 316L S.S. Type 316 stainless steel is austenitic steel that differs from grade 304 through the addition of molybdenum, which increases its resistance to chemical corrosion. 316" L" stainless steel is an extra-low carbon version of 316 S.S. See Table A.4 for the material properties of 316L S.S [33].

Table A.4: Material properties. Data compiled by the Granta Design team at ANSYS

Material property	Unit	OFE Cu	S.S. 136L
Density	kg m ⁻³	8942	7969
Yield strength	Pa	$2,508 \cdot 10^8$	$2,296 \cdot 10^8$
Tensile Ultimate Strength	Pa	$3,432 \cdot 10^8$	$5,212 \cdot 10^8$
Young's modulus at 20 °C	Pa	$1,266 \cdot 10^{11}$	$1,951 \cdot 10^{11}$
Shear modulus at 20 °C	Pa	$4,7063 \cdot 10^{10}$	$7,6811 \cdot 10^{10}$
Bulk modulus at 20 °C	Pa	$1,3613 \cdot 10^{11}$	$1,4138 \cdot 10^{11}$
Poisson ratio	-	0,345	0,27
Liquidus temperature	°C	1083	1440
Specific heat capacity	J/Kq·°C	382,5	484,49
Coefficient of thermal expansion at 20 °C	/K	$1,672 \cdot 10^{-5}$	$1,609 \cdot 10^{-5}$
Thermal conductivity at 20 °C	W/m·°C	397,3	14,19
Isotropic Resistivity	Ω m	$1,72 \cdot 10^{-8}$	$7,472 \cdot 10^{-7}$

A.5 HYDRAULICS

LEIR - Synoptique pour page de contrôle - ER.SMH40

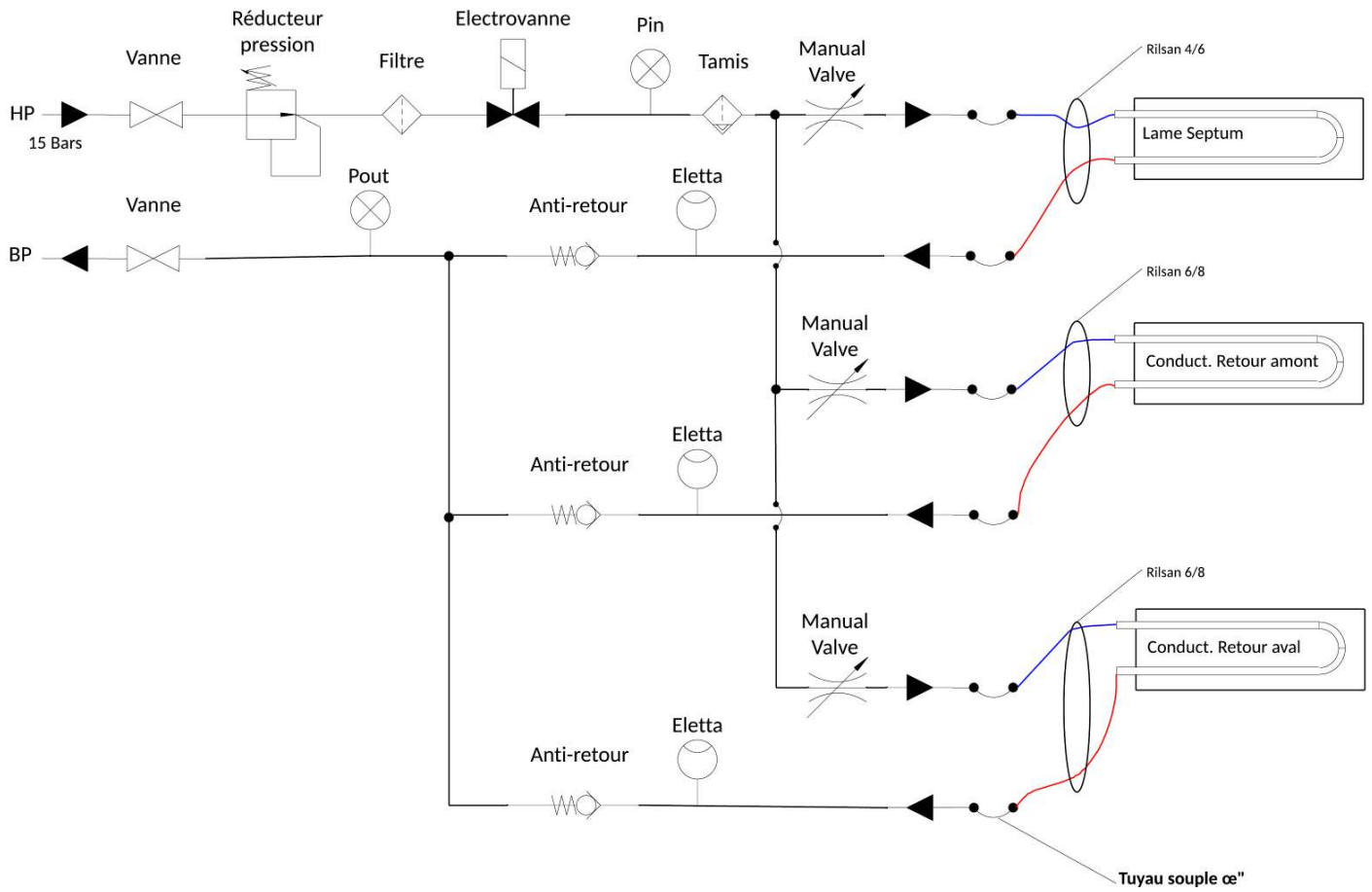


Figure A.1: Schematic flowchart of the SMH40 hydraulics system [32].

A.6 MANUFACTURING COSTS

a.6.1 First generation septum blade

Job reference number	J3000636
Description	SEPTUM BLADE. Manufacture of 1 equipped septum blade according to LEIMSME_0048 plan.
End date	28-02-2011

Table A.6: Known manufacturing costs of the first generation septum blade. This list does not include the time spend by the engineer to design the part. Costs of raw materials are included [32].

Description	Department	Time [hours]	Costs [CHF]
Milling	EN-MME-MS	32	2080
Sheet metal work	EN-MME-FW	-	300
Small supplies	EN-MME-MA	-	104
Vacuum brazing	EN-MME-FW	-	500
Al_2O_3 Coating	Radiance	-	3100
Total costs			6086

a.6.2 Third generation septum blade

Job reference number	J3037807
Description	SMH40 SEPTUM PLATE. Manufacture of 2 sets LEIMSME_0190 according to unsigned plans. The customer has already discussed the details with the brazing.
End date	24-03-2017

Table A.8: Known manufacturing costs of 2 x third generation septum blades. This list does not include the time spend by the engineer to design the part. Costs of raw materials are included [32].

Description	Department	Time [hours]	Costs [CHF]
Sheet metal work	EN-MME-FW	16	1040
Milling	EN-MME-MA	120	7800
Turning	EN-MME-MA	12	780
FAO/Delcam	EN-MME-MA	4	260
Versatile/Grinding	EN-MME-MA	4	260
Costs incurred	EN-MME-FW	-	212
Small Supplies	EN-MME-MA	-	455
Vacuum brazing	EN-MME-FW	3 brazing cycles	3000
Laser	EN-MME-FW	-	200
Total costs			14007

Note that the septum blade was not insulated with Al_2O_3 coating due to the failed acceptance test. An additional 3100 CHF per blade would have been added if it passed the acceptance testing. Totalling the costs for 2 blades at 20207 CHF.

The septum blade has undergone a repair on 30-06-2017. The costs of the repair are shown in Table A.9. Adding the repair costs to the manufacturing costs results in a total cost of 15813 CHF.

Table A.9: Known costs of the repair of 2 x third generation septum blades. This list does not include the time spend by the engineer to design the part [32].

Description	Department	Time [hours]	Costs [CHF]
Versatile/Grinding	EN-MME-MA	8	520
Electron beams	EN-MME-FW	-	1200
Costs incurred	EN-MME-FW	-	60
Small Supplies	EN-MME-MA	-	26
Total costs			1806

a.6.3 The prototype

Table A.10: Bill Of Materials (BOM) for one fourth generation septum blade prototype.

Part(s)	CDD	Material	Size [mm]	SCEM /Product code	price [CHF]	Weight [kg]
3x SAGANA hydraulic connector	CRNMRD_0024	316L SS	6 X 1/2 NPT	41.40.07.068.0	39	-
2x Water block	CRNMRD_0020/0025	OFE Cu C10100	30x30 mm	44.09.56.215.6	2,8	0,24
1x Conductor	CRNMRD_0023	OFE CU C10100	60x50	44.09.56.208.5	2,45	0,21
1x Plate	CRNMRD_0022	316L SS	140x500	44.59.20.150.0	9,94	0,28
1x Tube	CRNMRD_0021	316L SS	Ø2x1000	39.36.05.350.5	32	-
Bending tools	CRNHZMW_9384	304L	Ø2x1000	44.57.10.445.5	7,45	1,25
Total					93,64	

Job reference number

J3078645

Description

Manufacture of a prototype according to plan CRNMRD_0019

End date

29-07-2022

Table A.12: Manufacturing costs of The prototype.

Description	Department	Time [hours]	Manufacturing costs [CHF]
Sheet metal work	EN-MME-FW	5	300
CNC machining	EN-MME-MA	8	480
Bending	EN-MME-MA	1	60
Versatile	EN-MS-MA	1	60
Machining lathe	EN-MME-MA	4	240
CAM/Delcam	EN-MS-MA	1	60
Vacuum brazing + heat treatment	EN-MME-FW	-	1200
Total costs			2400

A.7 BOUNDARY CONDITIONS FOR A STATIC STRUCTURAL STUDIES

a.7.1 Simplified blade for initial calculation

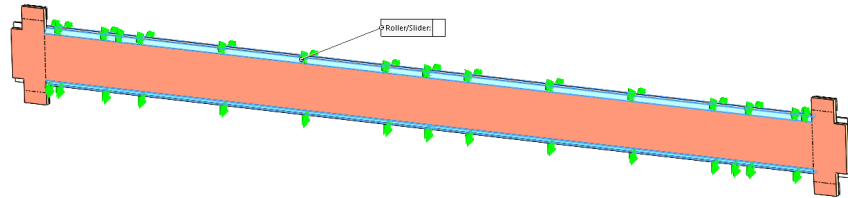
Figure A.2 shows the boundary conditions that have been applied to the septum blade with μ -metal plate for the initial calculation in section 2.4.1. Three scenarios were simulated:

Scenario 1: Constrained at the four return conductor mounting areas without vacuum chamber (μ -metal plate excluded from analysis). Lorentz force as static uniformly distributed load (8728 N).

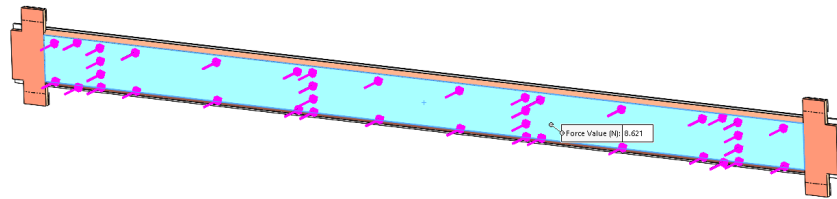
Scenario 2: Constrained at the four return conductor mounting areas. With a vacuum chamber in atmospheric pressure. Lorentz force as static uniformly distributed load (8728 N).

Scenario 3: Constrained at the four return conductor mounting areas. With a vacuum chamber in under vacuum ($0,1 \text{ N/mm}^2$). Lorentz force as static uniformly distributed load (8728 N).

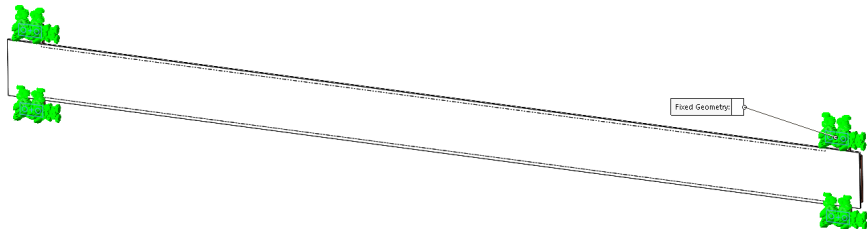
Roller/slider on the tapered edges of the OFE Cu conductor for contact area with the yoke.



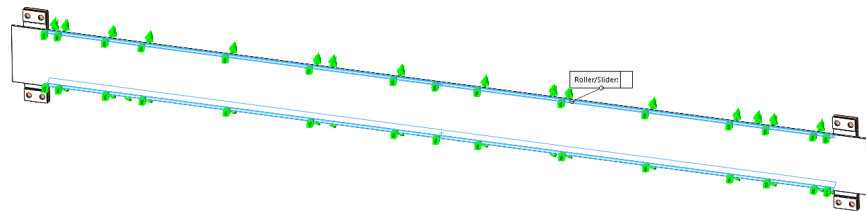
8728 N static force for the Lorentz force.



Four fixed constraints on the mounting pressure plates.



Roller/slider on the μ -metal plate for the contact area with the vacuum chamber clamp.



Atmospheric pressure (1 bar) pushing on the μ -metal plate because of vacuum Pressure of 0.1 N/mm^2 .

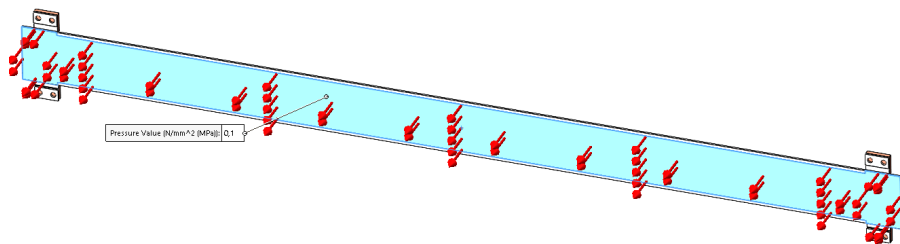


Figure A.2: Boundary conditions for the model to simulate stress and deflection in the septum blade .

a.7.2 First- and second generation septum blade

This appendix provides additional information for the boundary conditions, for the static structural study performed for failure analysis of the first- and second generation septum blade. The model contains all bonded contacts and a static load of 8728 N on the side of the septum blade. The septum blade is constrained with four fixtures at the mounting areas and two roller/sliders at the tapered edges, where the septum blade is in contact with the yoke (Figure A.3). Gravity is also added to the model.

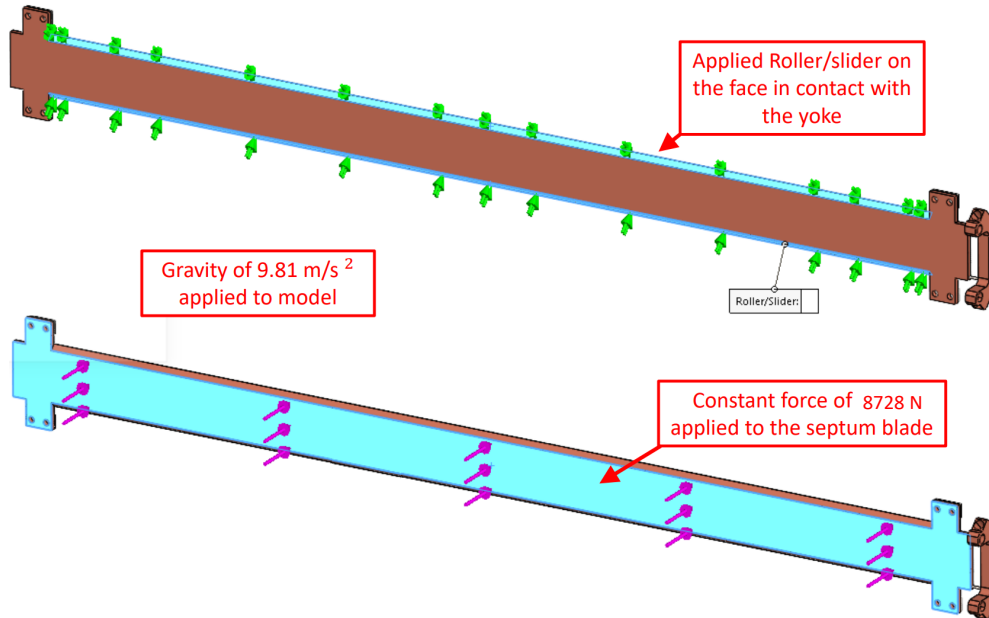


Figure A.3: Boundary conditions showing the roller/slider and the static load.

Two scenarios will be calculated: one with the water block constrained to the yoke and one without. Comparing the results of both simulations will provide insight in the effect of the constrained water block (Figure A.4).

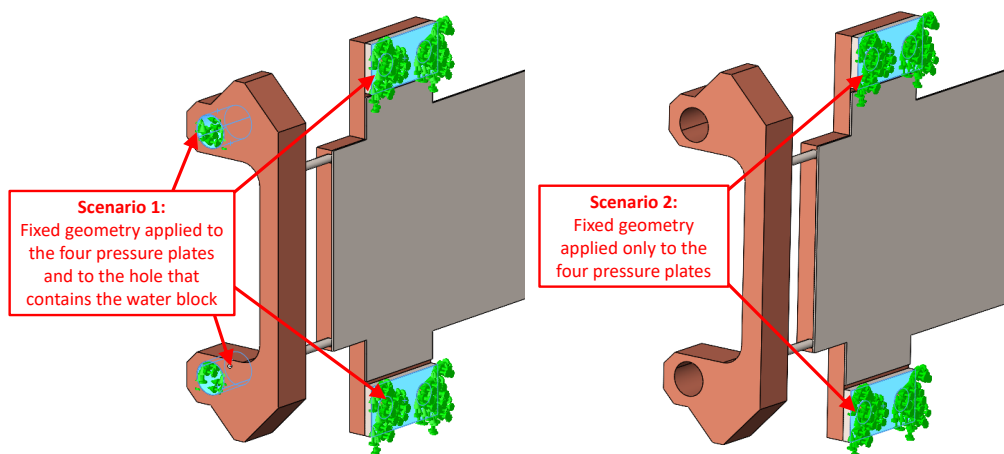


Figure A.4: Screenshots showing the difference between scenario 1 and 2.

The mesh, used during this calculation, is shown in Figure A.5. It has a maximum element size of 10 mm and a minimum of 2 mm. A refined mesh was added on the cooling channel to avoid a stress singularity due to the mesh. The area of the highest stress is covered by at least 3 elements and does not have a growth factor higher than 50%.

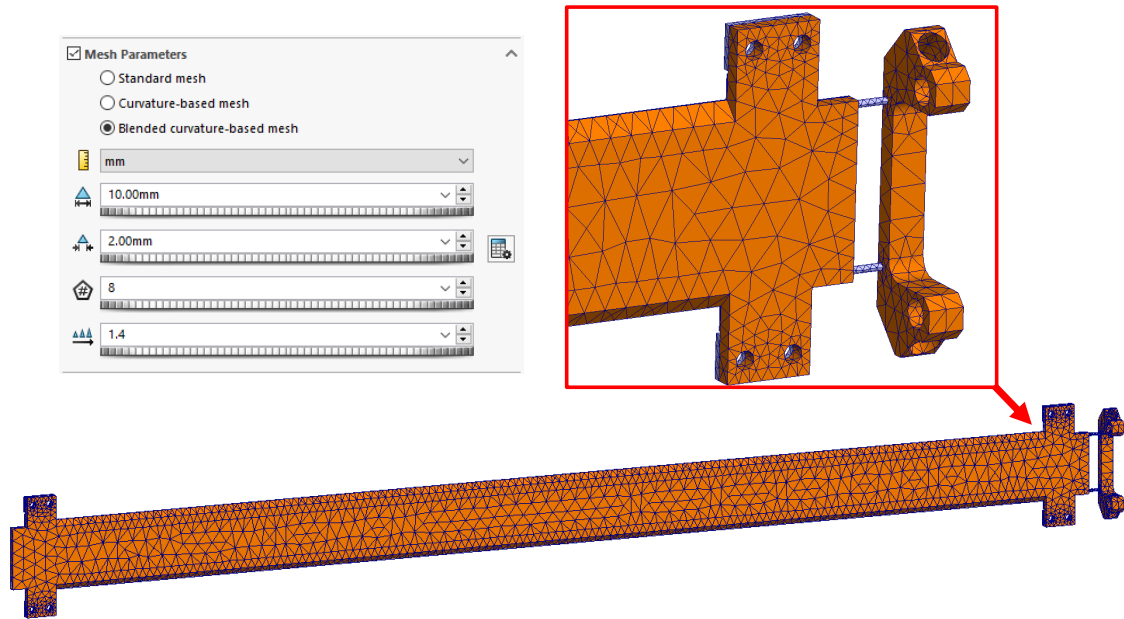


Figure A.5: Screenshot of the mesh that was used for this analysis.

A.8 COMPLIANCE OF FOUR DIFFERENT DESIGNS TO THE REQUIREMENTS INDEX

The four alternatives (Figure A.6), generated by combining the solutions in the morphological chart, are tested by evaluating their expected compliance with the requirements index (Table A.14). The design ideas are granted one of three possible colors. Definitions of these colors are shown in Table A.13. Conclusion of this evaluation is that all alternatives seem to have potential to fully fulfill all requirements. The conclusion from this chart is that all alternatives need to be further detailed into concepts, before disregarding a design.

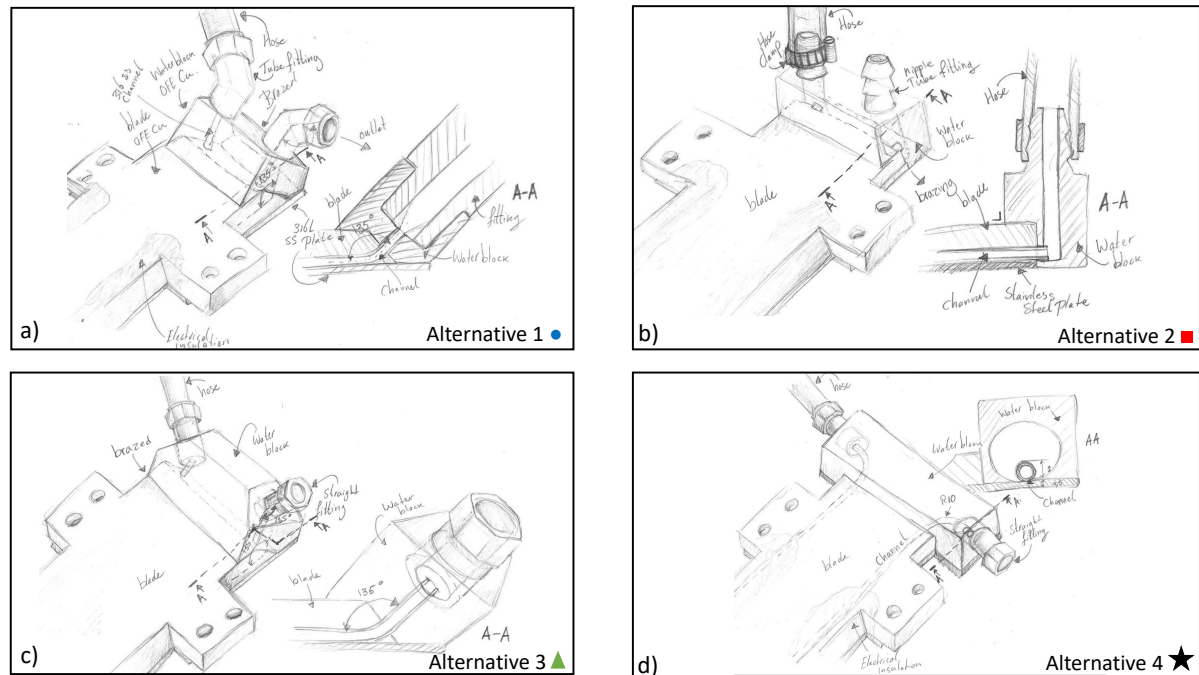


Figure A.6: Four sketches of possible alternatives for the water block design originating from the morphological chart.

Table A.13: Legend explaining the meaning of the colors used in the requirements index

Legend	Symbol
Likely to comply	
More information required	
Unlikely to comply	

Table A.14: Requirements index for a fourth generation septum blade for the SMH40 . Last updated on 03-06-2022

No.	Requirement	A1 •	A2 ■	A3 ▲	A4 ★
0.0 Design for manufacturing					
0.1	The septum blade is produced in one of 23 countries part of the CERN member states.				
0.2	Manufacturing cost for a single blade does not exceed 5000 CHF				
0.3	Manufacturing time for a single blade does not exceed 6-months.				
0.4	The amount of material waste does not exceed the previous generations				
0.5	DFM is included throughout the concept design and the detailed design phase. The fourth generation blade complies with DFM				
1.0 Conduct electricity					
1.1	Thickness of the septum blade is Cu 4,5 mm ± 0,05 mm + plate 0,5 mm + insulation 0,2 mm				
1.2	Length of the septum blade, from mounting area to mounting area, will be 828 mm.				
2.0 Stable temperature					
2.1	A 316L SS cooling channel with a Ø 2 mm outer diameter and Ø 1.5 mm inner diameter is used.				
2.2	Length and location of the straight section of the cooling channel is 837 mm and is located at the beginning of the tapered edges.				
2.3	An energy of 40 W can be removed from the conductor by the fluid flow				
2.4	Electrical resistance of the septum blade, measured from mount to mount, does not exceed $7,36 \cdot 10^{-5} \Omega$				
2.5	Orientation of the hydraulic connectors prevents buckling of the flexible hose as much as possible.				
3.0 Compatibility					
3.1	No other equipment needs to be altered to install the septum blade on the SMH40				
3.2	Thickness of the electrical insulation is 2 x 0,2 mm Coating on the yoke and the septum blade + 0,1 mm Kapton [®] = 0,5 mm				
4.0 safety					
4.1	There are designated safety covers around any accessible components of the septum blade.				

Continues on next page

Table A.14: Requirements index for a fourth generation septum blade for the SMH40 . Last updated on 03-06-2022

No.	Requirement	A1 ●	A2 ■	A3 ▲	A4 ★
4.2	The edges of the septum blade must be deburred to prevent injuries when carrying the component.				
4.3	No water is leaking out of the septum blade while pressurized at 25 bar.				
4.4	The electrical insulation must be able to contain a voltage hold off for 1 kV.				
4.5	The design includes the four mounting assemblies as stated in section 4.2 combined with adequate QC				
5.0 Durability					
5.1	The MTTF of the septum blade assembly is at least 10 years, based on an average of 6 million pulses/year.				
5.2	No non-reversible deformations, meaning micro- and macro fractures or plastic deformation in the septum blade during operation, when subjected to 8.73 kN every 3,6 seconds				
5.3	The water supply can be assembled and disassembled by hand, or with hand tools, without the need to relocate surrounding parts.				
5.4	The flexible hose must be able to be (de-) coupled within 1 minute with basic hand tools				
5.5	The water supply can be dis-connected and reconnected at least 10 times without a leak during operational conditions				
5.6	Avoid non-optimized bends, a large amount of bends and rapid volume changes in the fluid flow.				

A.9 NUMERICAL COMPUTATION FOR CONCEPT DESIGN.

This appendix contains screenshots from the structural FEA and CFD analysis for concept 1,2,3 and 4, as substantiation for the results in Table 5.4 in section 5.4.5.

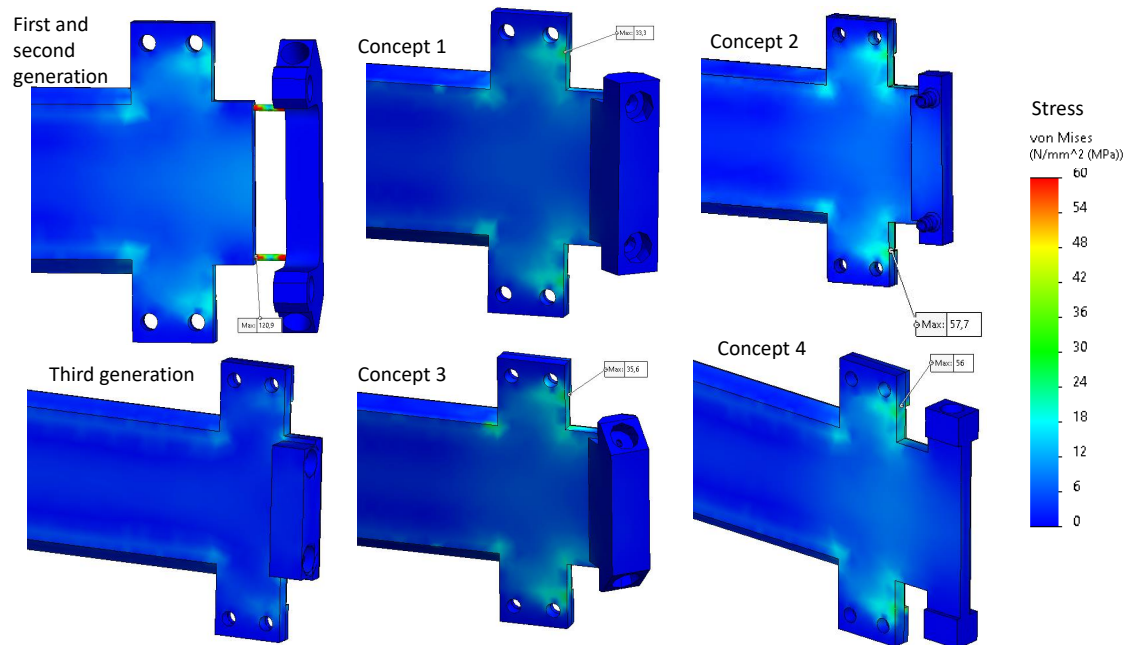


Figure A.7: Stress plots for the previous generations and for concept 1,2,3 and 4.

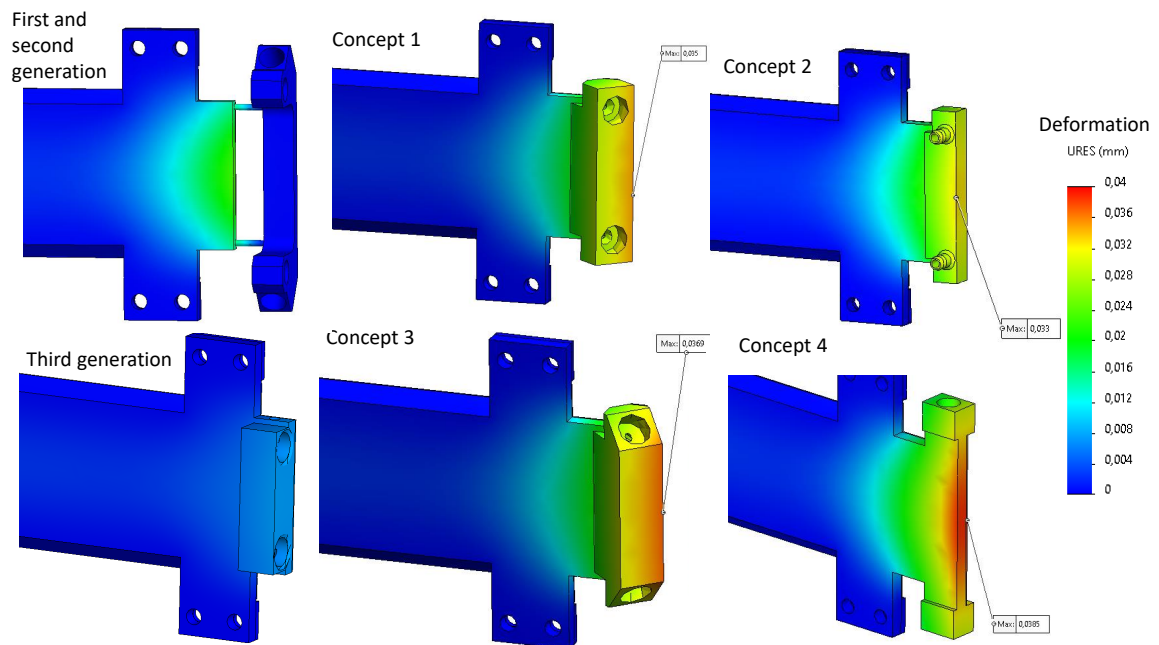


Figure A.8: deformation plots for the previous generations and for concept 1,2,3 and 4.

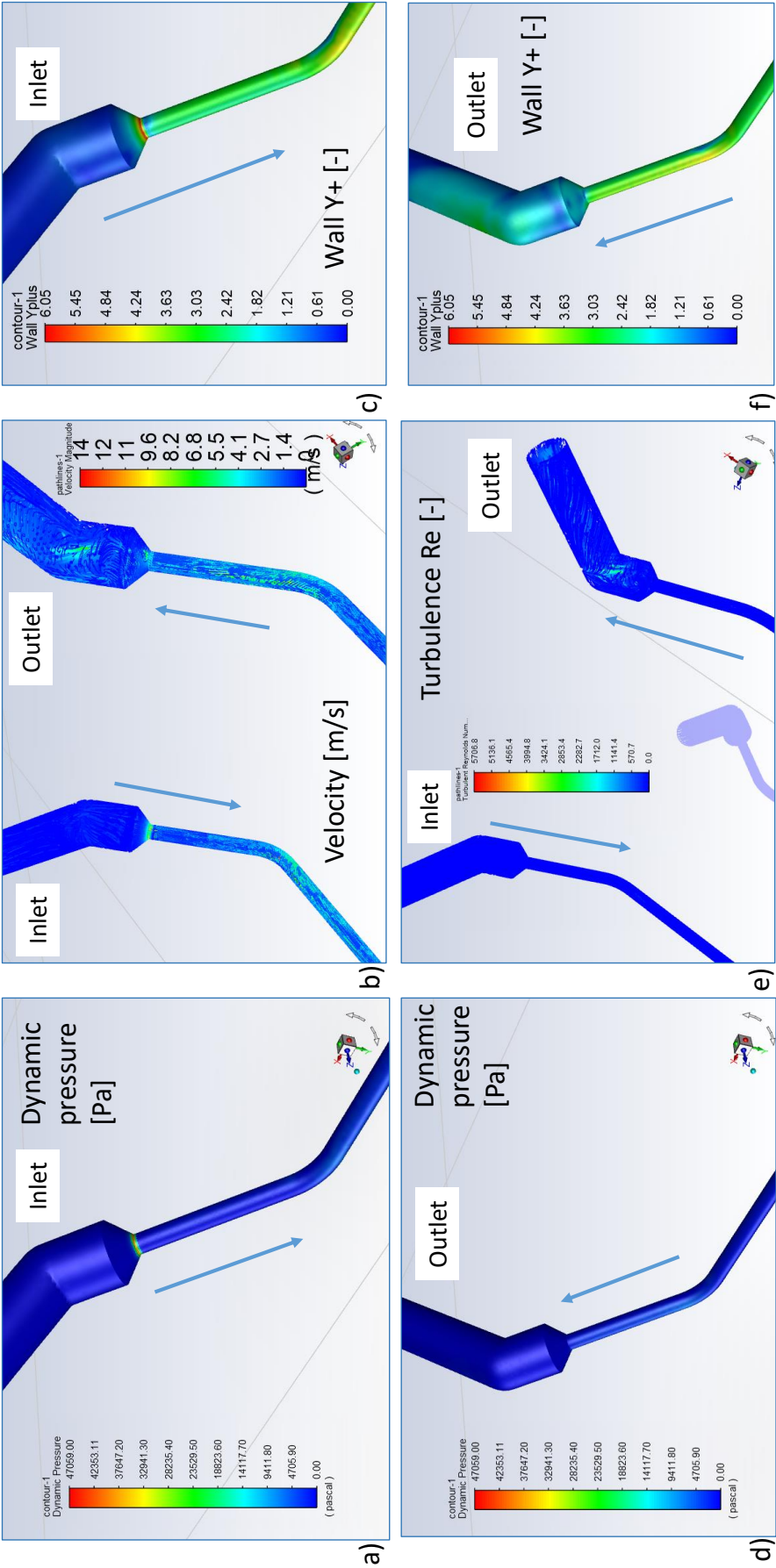


Figure A.9: CFD analysis results for concept 1

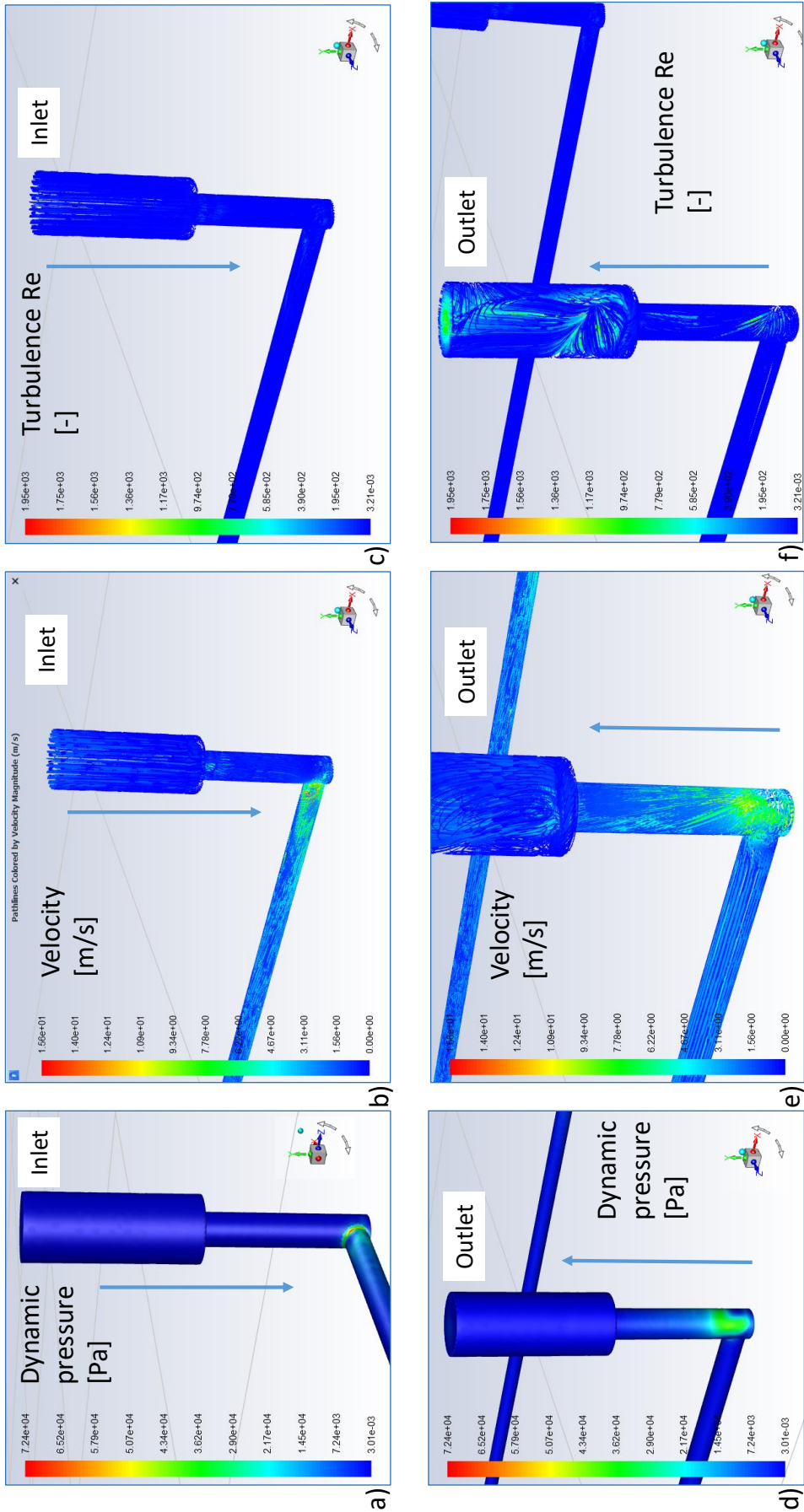


Figure A.10: CFD analysis results for concept 2

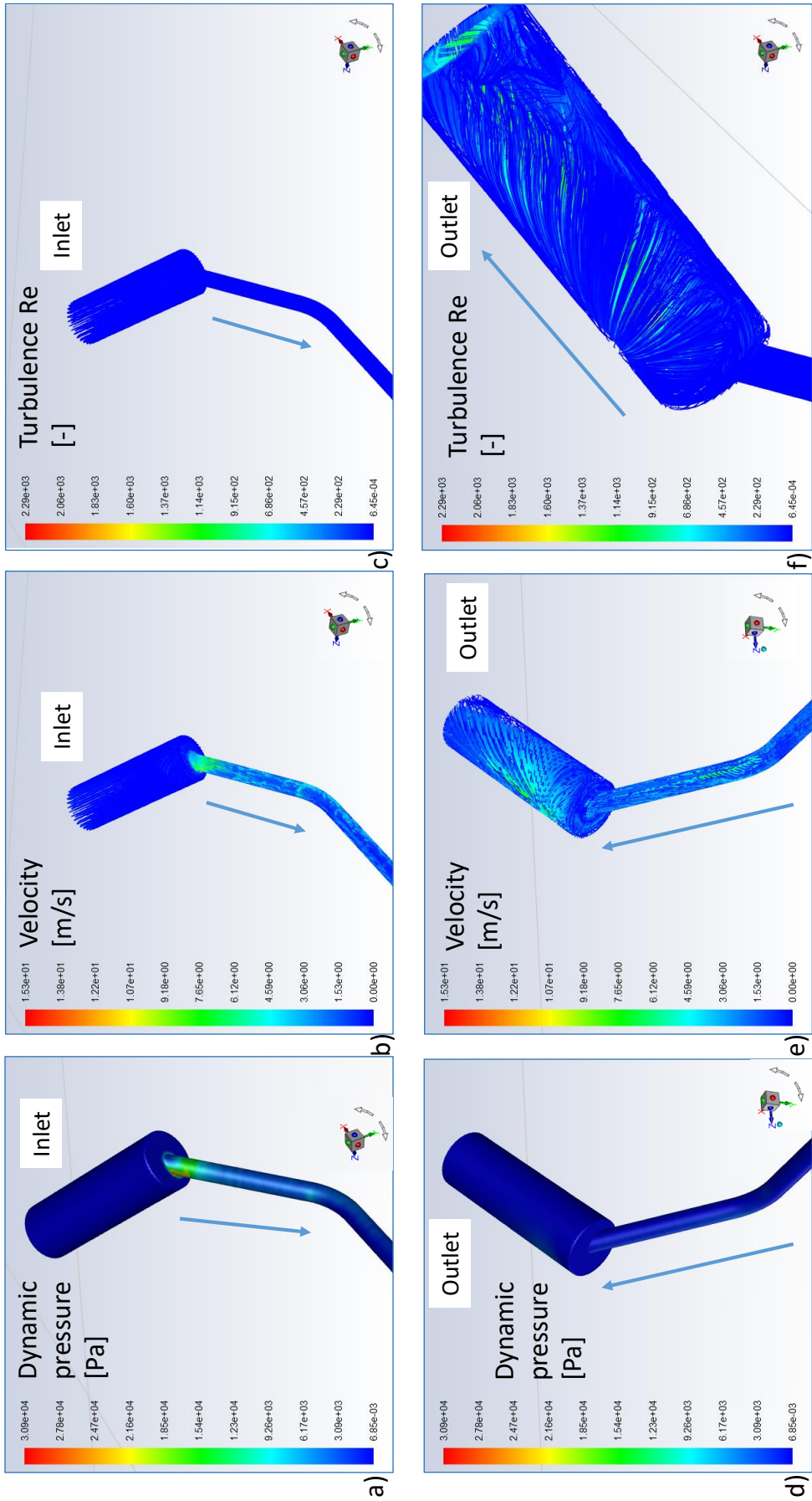


Figure A.11: CFD analysis results for concept 3

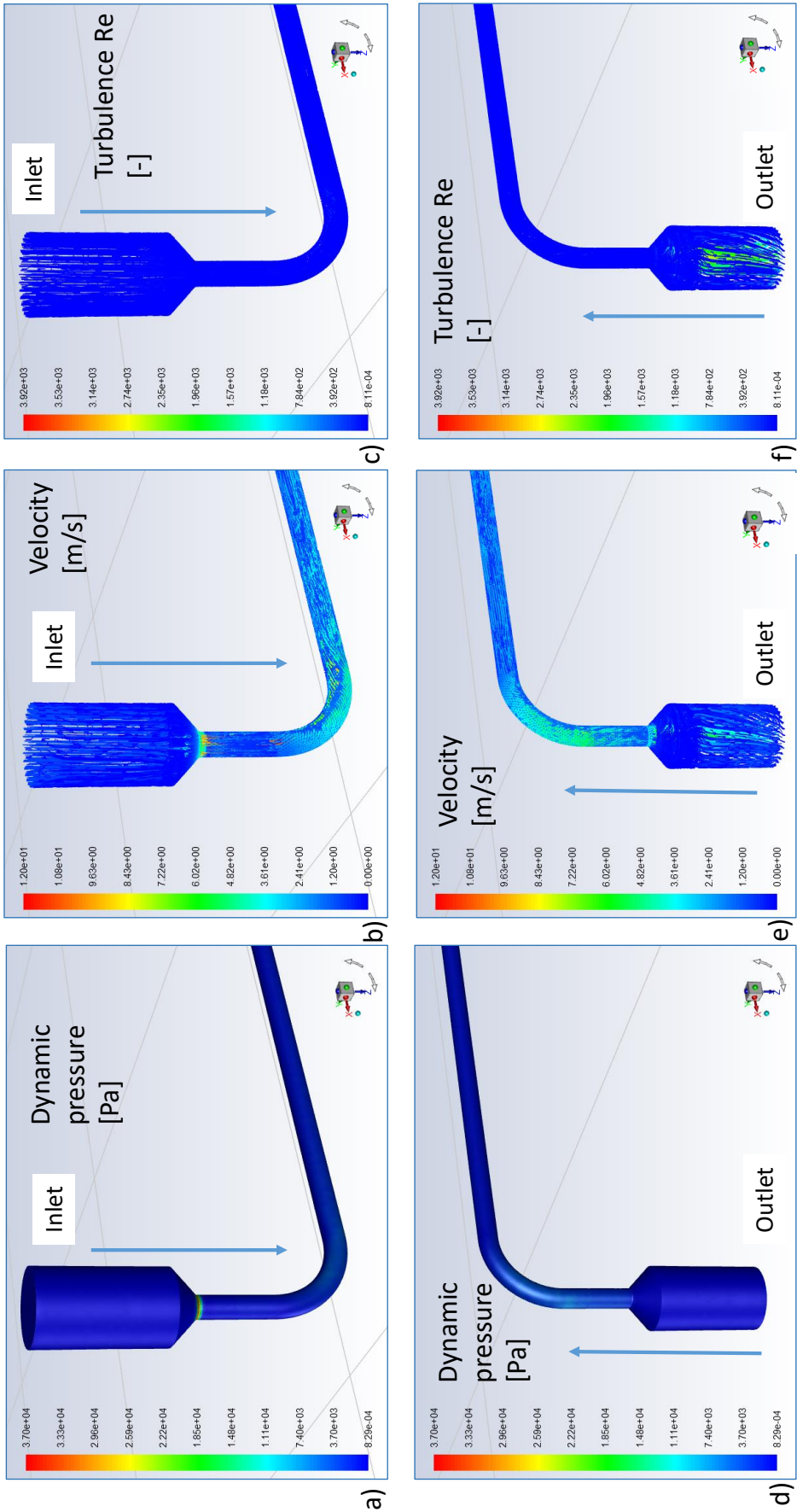


Figure A.12: CFD analysis results for concept 4

A.10 CAD-FILES AND DRAWING NUMBERS

Table A.15: List of references for parts CAD-models and Technical drawings

Name	SmarTeam CAD-model	CDD Drawing No.	Date*	SCEM CERN stores purchase code
SMH40				
Assembly	ST0441931	LEIMSME_0024		
Magnet assembly	ST0441503	LEIMSME_0001	06-04-2020	-
Coil assembly	ST0441504	LEIMSME_0010	28-01-2005	-
First- and second generation septum blade				
Assembly	ST0441504	LEIMSME_0048	09-02-2005	-
Reinforcement plate	ST0441507	LEIMSME_0188	31-01-2005	44.59.20.150.0
Water block	ST0441522	LEIMSME_0150	02-04-2020	44.09.48.176.3
Conductor	ST0441505	LEIMSME_0250	09-02-2005	44.09.56.205.8
Cooling channel	ST0441506	-	-	39.36.05.350.5
Third generation septum blade				
Assembly	ST0798366	LEIMSME_0190	-	-
Reinforcement plate	ST0441507	LEIMSME_0188	31-01-2005	44.59.20.150.0
Coil plug	ST0857617	LEIMSME_0194	31-05-2017	44.09.4.512
Hydraulic connector	ST0797825	-	-	
Conductor	ST0797819	LEIMSME_0188	27-09-2016	44.09.59.215.6
Cooling channel	ST0797825	LEIMSME_0189	17-09-2016	
Brazed samples				
Assembly	ST1574623	CRNMRD_0014	04-05-2022	
Hydraulic connector	ST1575732	CRNMRD_0015	04-05-2022	41.40.07.068
Water block	ST1571173	CRNMRD_0016	04-05-2022	44.09.47.520
Conductor	ST1574559	CRNMRD_0017	04-05-2022	44.09.47.530.9
Cooling channel	ST1574558	CRNMRD_0018	04-05-2022	39.36.05.350.5
Prototype				
Assembly	ST1589753	CRNMRD_0019	17-06-2022	-
Water block right	ST1589756	CRNMRD_0020	17-06-2022	-
Cooling channel	ST1589757	CRNMRD_0021	17-06-2022	39.36.05.350.5
Reinforcement plate	ST1589758	CRNMRD_0022	17-06-2022	44.59.20.150.0
Conductor	ST1589759	CRNMRD_0023	17-06-2022	44.09.47.530.9

Continues on next page

Table A.15: List of references for parts CAD-models and Technical drawings

Name	SmarTeam CAD-model	CDD Drawing No.	Date*	SCEM CERN stores purchase code
Hydraulic connector	ST1589767	CRNMRD_0024	17-06-2022	41.40.07.068
Water block left	ST1589788	CRNMRD_0025	17-06-2022	41.40.07.068
Hydraulic connector	ST1589767	CRNMRD_0026		41.40.07.068.0
Fourth generation				
Assembly	ST1577432	LEIMSME_0195	29-07-2022	-
Water block left	ST1590485	LEIMSME_0199	29-07-2022	44.09.56.215.6
Water block right	ST1577787	LEIMSME_0200	29-07-2022	44.09.56.215.6
Conductor	ST1577299	LEIMSME_0196	29-07-2022	44.09.47.530.9
Reinforcement plate	ST1577286	LEIMSME_0198	29-07-2022	44.59.20.150.0
Cooling channel	ST1577289	LEIMSME_0197	29-07-2022	39.36.05.350.5
Hydraulic connector	ST1602971	LEIMSME_0201	29-07-2022	Swagelok SS-6M0-5-4PR

**The date (DD-MM-YYYY) as shown on the technical drawings. This corresponds to the date the CAD model was assigned a CDD number or most recently updated. Not when the CAD model was first created.*

A.11 ANSYS FLUENT MANUAL FOR SY-ABT-SE INTERNAL

This appendix describes the steps that were taken to simulate the turbulent fluid flow (water), pressure and temperature in the first- and second generation septum blade using ANSYS Fluent. All other simulations (third generation, four concepts and the detailed design) were simulated using these steps. This appendix is also intended to be used as a tutorial to setup future similar CFD simulations within the SY-ABT-SE group at CERN for similar situations. As CFD is not commonly performed in within the section.

a.11.1 Objective

The objective of this analysis is to simulate the fluid velocity, total pressure (static- & dynamic pressure) and turbulent Reynolds number (Re) for the cooling circuit of the septum blade. These parameters indicate the hydraulic impedance of the system. Geometries with a high hydraulic impedance are expected to endure more internal damage because of abrasion, reducing its life time.

a.11.2 ANSYS Workbench

The STEP file is imported into ANSYS Workbench as “stand alone geometry”. Fluent (with fluent meshing) is connected to the imported geometry as shown in Figure A.13a. The simulation will not work with a mesh from ANSYS mechanical combined with “fluent” because a 3D-mesh is required, not a 2D mesh. Using Fluent via ANSYS workbench, instead of directly, allows the user to analyse different geometries within the same file. The output of a Fluent simulation can also be used as input of a mechanical simulation. This is called a Fluid–structure interaction (FSI). FSI is outside the scope of this thesis. However, it is an useful tool to be used in the future.

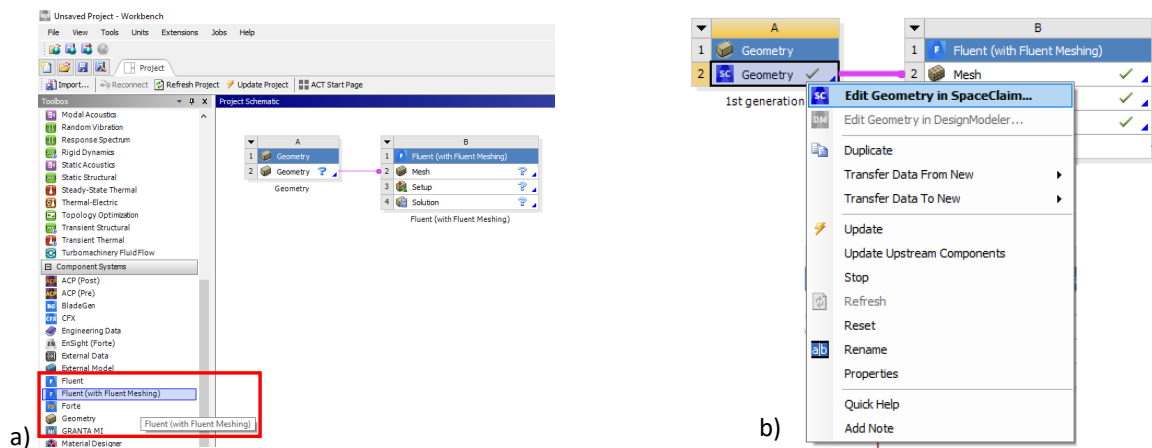


Figure A.13: a) Screenshot from ANSYS workbench showing a standalone geometry and fluent (with fluent meshing). b) Screenshot of the drop-down menu to open SpaceClaim via the standalone geometry..

a.11.3 The geometry

The original STEP file needs to be inversed to extract the Fluent model. Inverting the model can be done in a CAD program (SolidWorks, CATIA, Inventor, Siemens NX ect.) and importing it directly as a STEP file into ANSYS Workbench or in SpaceClaim within ANSYS Workbench.

Inverting the model in SpaceClaim

SpaceClaim can be opened via ANSYS Workbench after the geometry is uploaded as shown in Figure A.13b. The fluent model can be extracted using the “Volume extract” function (Figure A.14a). The user selects the faces that enclose the areas (orange selection in Figure A.14b) and a face that lies within the area that needs to be enclosed (blue selection in Figure A.14b). This automatically generates the enclosed volume. There is no need to select all faces in the enclosed area.

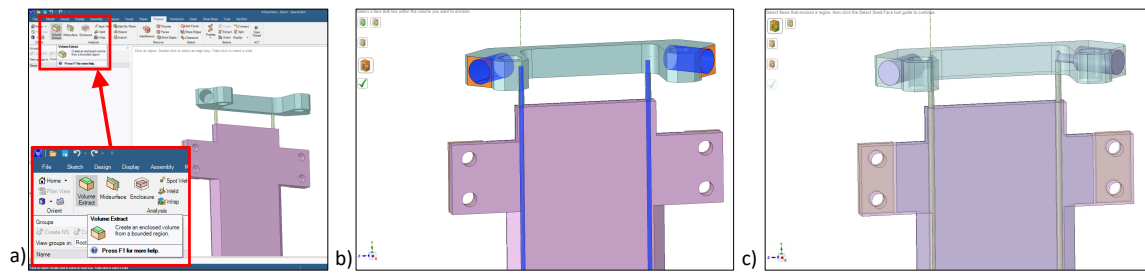


Figure A.14: a) close up of the "Volume extract" function in the Spaceclaim work environment. b) Face selection to extract the fluent model. c) The original geometry with fluent model.

Named selections

Named selections (NS) are defined on faces of the model within SpaceClaim (Figure A.15a). These NS are used to define boundary conditions. There are four named selections in this model: The outlet, inlet, channel wall (Figure A.15b) and water block wall (Figure A.15c). The water block wall and channel wall are separately defined to assign a finer mesh on smaller geometries and a coarser mesh on larger geometries.

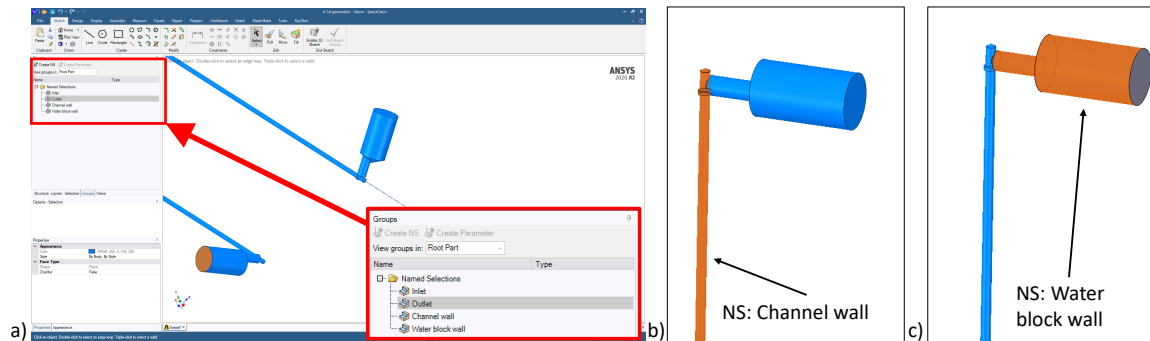


Figure A.15: a) Close up of defining the named selections in SpaceClaim. b) NS of the channel wall (orange) c) NS of the water block wall (orange)

a.11.4 Fluent meshing

The next step is to add a mesh to the model. The 3D mesh for turbulent CFD simulations contains the smallest element sizes at the boundaries/walls of the model. However, using a extremely small element size for the entire model will result in a unreasonably long computing time. This paragraph will show how to add a mesh using Local sizing and boundary layers based on the "Law of the wall" (Y^+).

Law of the wall (Y^+)

In the boundary layer, the velocity profile changes rapidly and can be broken up into three regions: viscous sublayer, log layer and outer layer. Resolving the boundary layer close to the wall provides an accurate representation of its profile, leading to accurate predictions of wall shear stress, surface pressure, the effect of adverse pressure gradients and forces. [26]

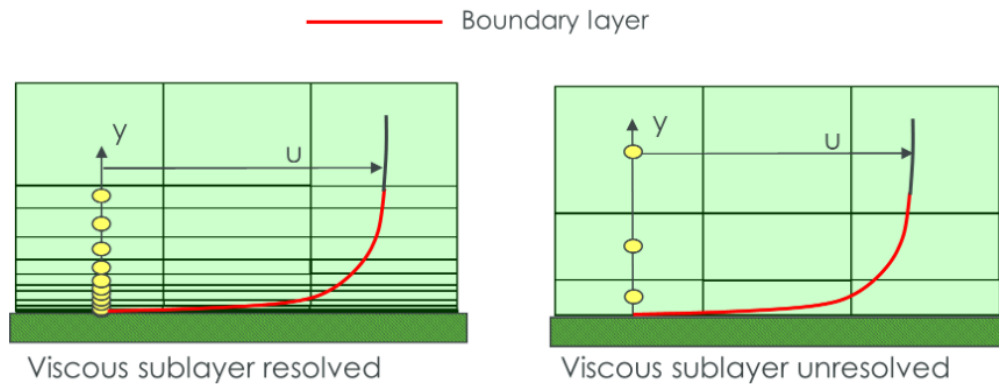


Figure A.16: Near wall mesh when resolving the viscous sublayer (left). Near wall mesh when using wall functions (right). [26]

In CFD software the boundary layer is modelled by extruding the surface mesh elements at the wall. The boundary layer resolution depends on the first cell height and the number of mesh layers. The solver calculates a value, Y^+ , which is computed from the first cell height, local flow speed and fluid properties. For the same fluid and flow conditions, reducing the first mesh height by a factor of 2 will reduce Y^+ by a factor of 2. Obtaining an initial value for Y^+ and then adjusting the prism heights in the meshing tool or via adaption is a common practice in CFD when tuning the mesh for best results. [26]

An iterative process is required to define the height of the first mesh layer, because the dimensionless value for Y^+ depends on the dimensionless value for the velocity. Figure A.17 shows the Y^+ contour results for the inlet of the cooling circuit. A Y^+ value < 5 is preferred to accurately calculate the viscous sub layer.

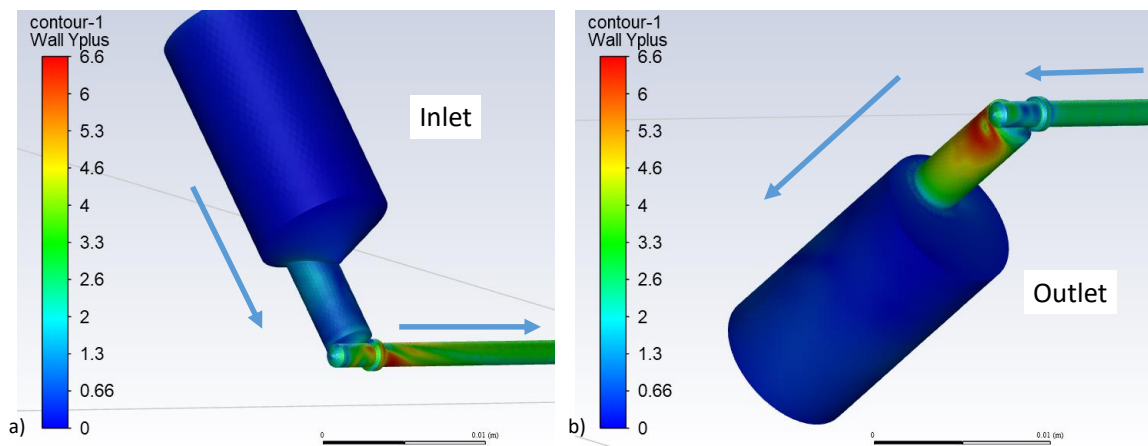


Figure A.17: a) contour plot showing the Y^+ value for the transition region in the water block between the inlet and the cooling channel. a) contour plot showing the Y^+ value for the transition region in the water block between the inlet and the cooling channel.

Different turbulence models are used to capture the boundary layer in different ways. The $k-\omega$ SST model, used in ANSYS Fluent, has been widely researched, tested and is accepted as a good choice for many industrial problems, and has the robustness to resolve the viscous sublayer or the log layer. If the first cell height is in the viscous layer, it will resolve the boundary layer by evaluating the velocity at each cell. If the first cell is in the log layer, the software will make an empirical assumption about the viscous sublayer, referred to as using a wall function. [26]

This section covers only an introduction into the law of the wall. Implementing a volume mesh into the fluent model, small enough to ensure a $Y^+ < 5$ calculate the viscous sub layer with no slip conditions, is sufficient for this analysis. The following sources for the "Law of the wall" are recommended for further study: [26], [1], [27]

The mesh Workflow

Open fluent meshing by right clicking on "Mesh" in ANSYS workbench and selecting "Edit..." (Figure A.18a). The Workflow (Figure A.18b) starts with importing the geometry.

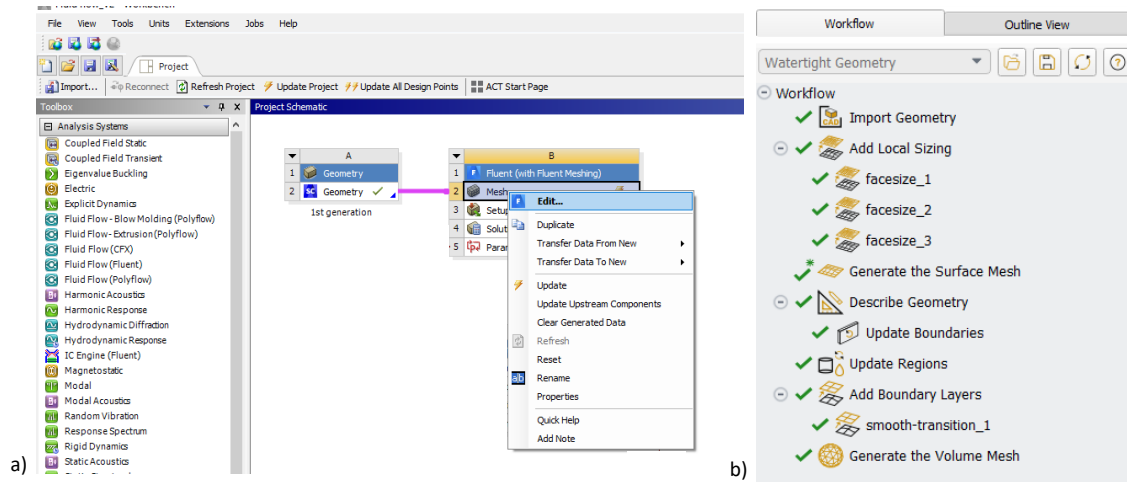


Figure A.18: a) Screenshot of ANSYS workbench with a drop-down menu to open Fluent meshing. b) Screenshot of a completed meshing workflow, as indicated by the green check marks.

The surface mesh must be created prior to a volume mesh. The user can define a global minimum and maximum mesh size and growth rate of the cells. Local sizing can be added in addition to the global mesh, for a more detailed mesh for certain edges/faces/bodies of the geometry. This model contains three different areas with a specific face local sizing (Figure A.19b).

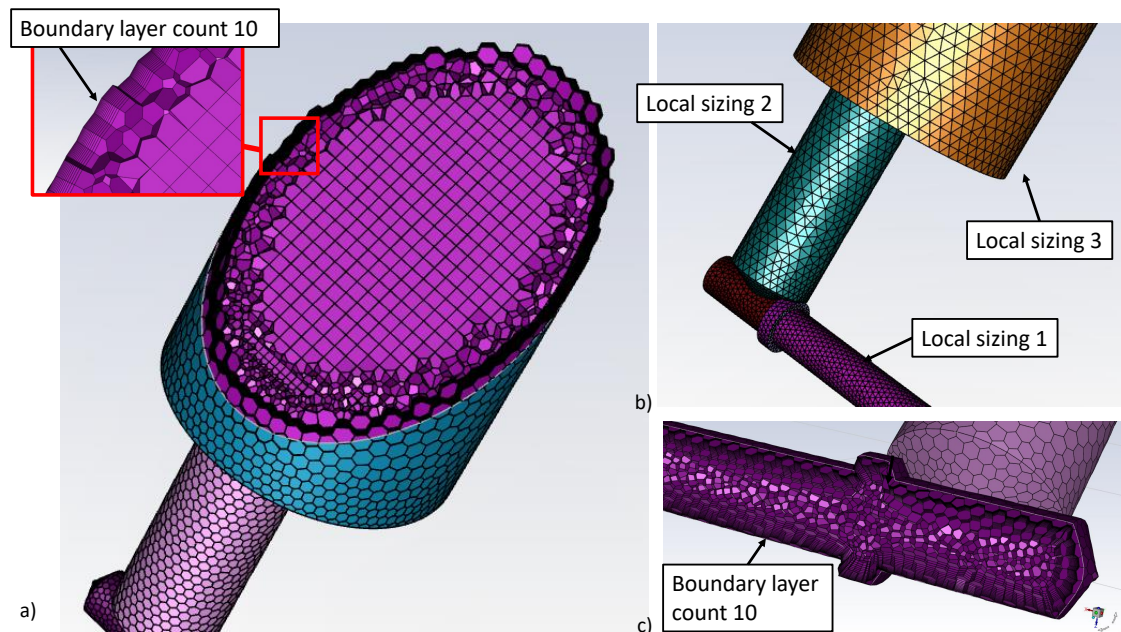


Figure A.19: a) Poly-hexcore volumetric mesh with 10 uniformly increasing boundary layers with a growth factor of 1,1. The height of the First layer is 0,001 μm . b) surface mesh showing three local sizings. c) Poly-hexcore volumetric mesh with the same boundary layer conditions.

Reducing the maximum cell size of the surface mesh with local sizing significantly increases the computing time. For example, a local sizing maximum cell size of 0,2 μm for the cooling channel, with a global mesh size of minimum 4 μm and max 5 μm , takes 1,8 minutes of computing time to create the surface mesh. While a local sizing maximum cell size of 0,1 μm for the cooling channel, with the same global

mesh takes 10 minutes of computing time to create the surface mesh. The values for the global surface mesh and for the local sizing of the cooling channel can be seen in Figure A.20a and Figure A.20b. The local sizing_2 has a maximum element size of $0,3 \mu\text{m}$ and local sizing_3 a maximum element size of $0,5 \mu\text{m}$. A growth rate of 1,1 is chosen for the model because of the small channel diameter ($\varnothing_{inner} = 1,5\text{mm}$), compared to a standard growth rate of 1,2.

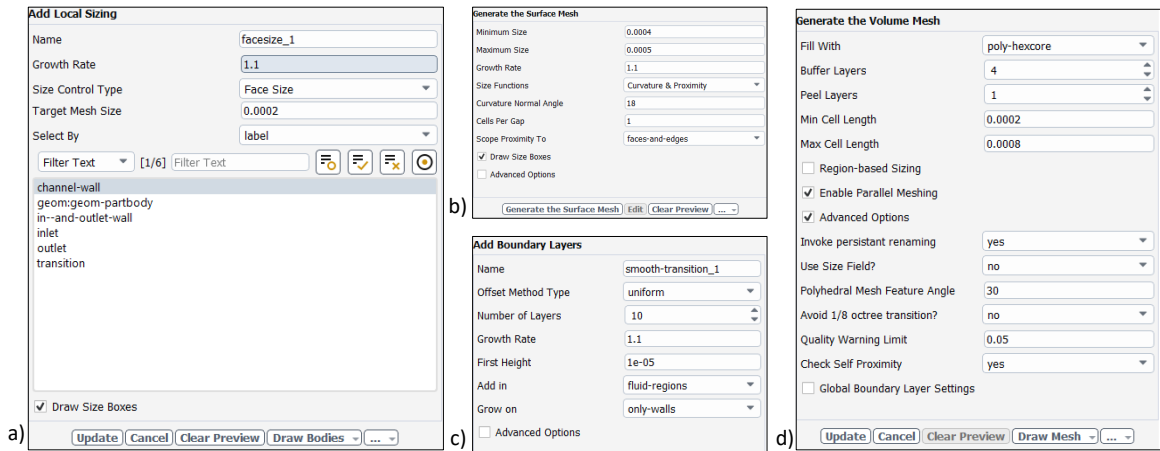


Figure A.20: a) Window to add local sizing to a NS. b) Window for the parameters of the surface mesh. c) Window for the parameters to add boundary layers to the model. d) Window for the parameters to generate the volume mesh.

The next step in the work flow in Figure A.18b is *"describe the geometry"* and *"Update regions"*. These steps are easy for this geometry because the model was already converted to a fluid model in SpaceClaim. These option can be used to invert the model If the geometry is the outer shell with a hollow fluid area. However, including the outer shell in the analysis shall increase the computing time and it is not necessary for a CFD analysis of the septum blade. Including the outer shell in the analysis is useful for a FSI analysis. For this analysis it will be sufficient to check the box: *"The geometry consist of only fluid region with no voids"*. Shared topology can be turned off because the geometry consists of one part only.

Then, the boundary layers are added to the mesh. As seen in section A.11.4, the size and amount of boundary layers have a big impact on the value for Y^+ . A uniform offset method type for the boundary layers is recommended compared to the other boundary layer types. Ten boundary layers are added to the model with a growth rate of 1,1 (Figure A.19a, Figure A.19c) and Figure A.20c.

the last step in the meshing workflow is to generate the volume mesh (Figure A.20d). A Poly-hexcore volumetric mesh type is recommended because ANSYS fluent calculates the values according to the nodes of the elements. Poly-hexcore allows for many nodes with fewer cells than a tetrahedral meshing type, decreasing computing time. A minimum element size of $0,4 \mu\text{m}$, and maximum element size of $0,5 \mu\text{m}$ has proven to be detailed enough for a good Y^+ value and coarse enough for a reasonable computing time.

a.11.5 Boundary conditions

For a CFD analysis it is important to avoid to over-constrain the system. Defining the inlet pressure will have no effect if the mass flow is also defined. Click on *"Switch to solution"* to define the boundary conditions if the meshing process is complete.

The outline of the Ansys fluent solver is divided into three topics: the setup, the solution and the results (Figure A.21b.) Figure A.21c shows the expanded workflow of the setup. The viscous solver should be changed to the $k-\omega$ SST model for this analysis. The energy model needs to be turned *"On"* if there is a different inlet and outlet temperature. However, the temperature is assumed to be continuous in this analysis to decrease computing time and simplifying the model. The materials (fluid and solid) can be

assigned in the next tab. Assigning the solid materials is not necessary in this analysis, because it only applies for thermal studies. The type of fluid is assigned to the model in the "Cell Zone Conditions tab". Gravity ($9,81 \text{ m s}^{-2}$) and the operational pressure is defined in the "operational conditions tab" (Figure A.21a). An atmospheric pressure of 101325 Pa is assigned because this is an incompressible flow analysis.

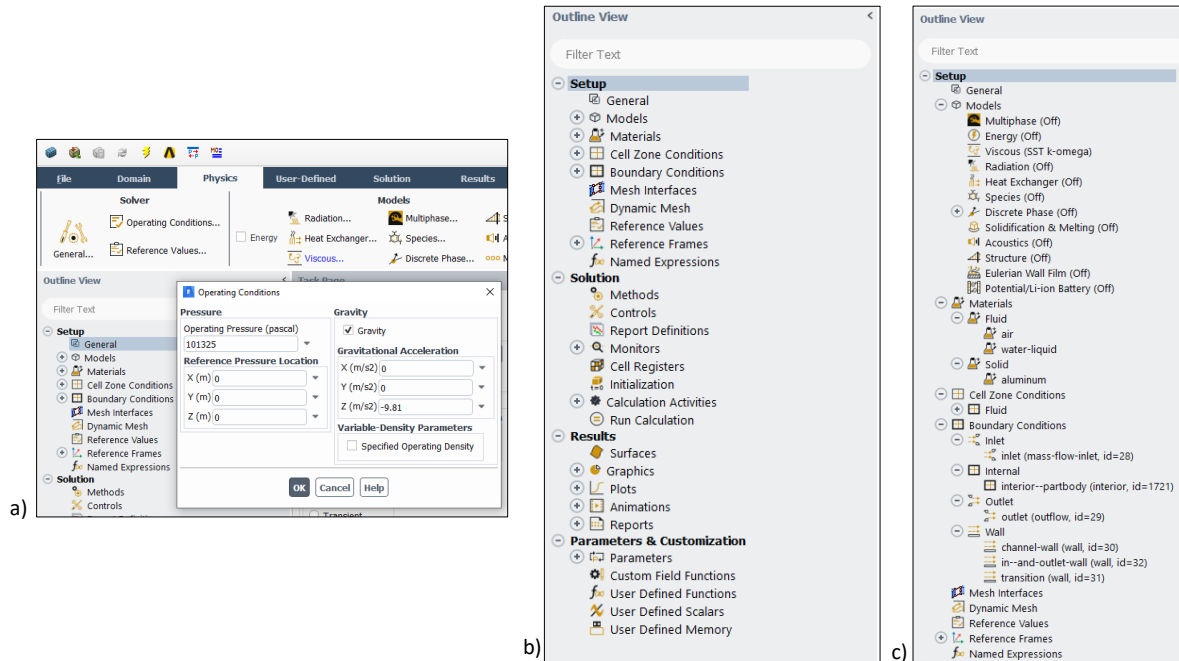


Figure A.21: a) Screenshot from the operational conditions window for defining gravity and operating pressure. b) Overview of the complete ANSYS Fluent workflow. c) Unfolded workflow of the setup.

The next step is defining the parameters to the named selections. The outlet was already defined as an "outflow outlet", no other parameters can be defined for this type of outlet. Parameters for the inlet (Figure A.22a) are the mass flow rate ($1 \text{ L/minute} \approx 0,017 \text{ kgs}^{-1}$) and turbulence model. The parameters for the wall (Figure A.22b) include the "no slip condition", "standard roughness model" and "stationary wall".

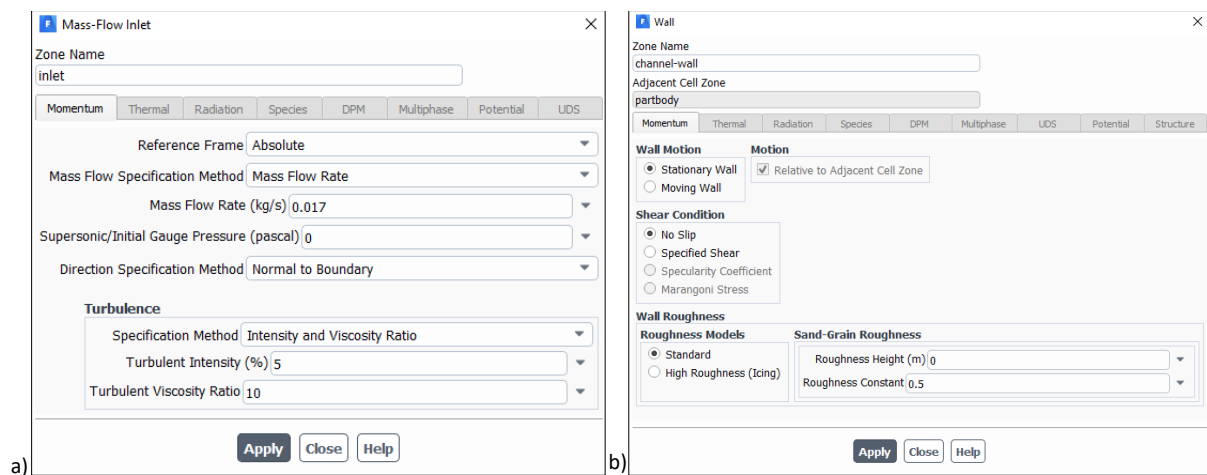


Figure A.22: a) Defining the boundary conditions for the inlet NS. a) Defining the boundary conditions for the wall NS.

a.11.6 Solver

The solver consists of two phases. The *"hybrid initialization"* (Figure A.23a) and the *"Run calculation"* (Figure A.23b). 50 iterations are defined for both phases, as this is common practice to ensure reliable results. The results from the analysis can be extracted with 3D contour plots, Path lines, vectors, 2D plots, documents ect. As shown in the thesis.

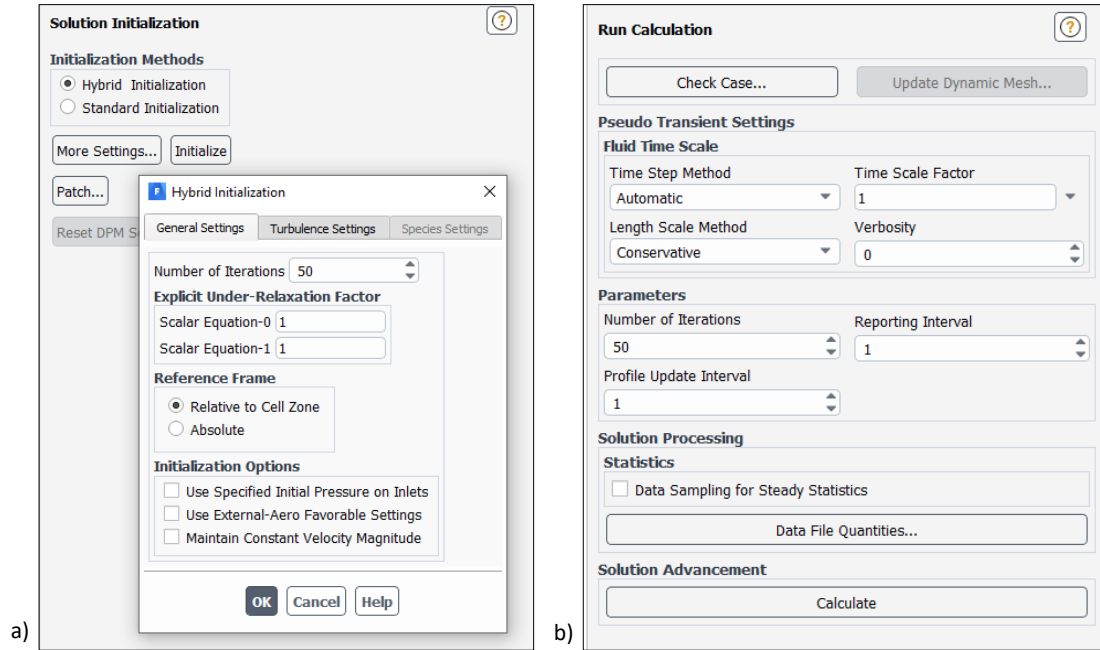


Figure A.23: a) Hybrid initialization. b) Run calculation

Vera Erends
Prévessin-Moëns, August 2022