JÜLICH Forschungszentrum | CENTRAL INSTITUTE OF ENGINEERING, ELECTRONICS AND ANALYTICS

Document	**298-DOC-20230131-STS-SNS-Moderator-Final-Report-V03**

Title:

Second Target Station (STS) Tube Moderator Manufacturing Development – Final Development Report

Distributed to:

Oak Ridge National Laboratory

Author / Organizational Unit	Phone	Fax	E-mail	Date
Christoph Happe / ZEA-1	-4275	6816	c.happe@fz-juelich.de	2023-01-31 Christoph Happe Digital unterschrieben von Christoph Happe Datum: 2023.02.09 10:04:35 +01'00'
Eberhard Rosenthal / ZEA-1	-3460	6816	e.rosenthal@fz-juelich.de	2023-01-31 Eberhard Rosenthal Digital unterschrieben von Eberhard Rosenthal Datum: 2023.02.09 16:11:32 +01'00'
Wilfried Behr / ZEA-1	-2156	6816	w.behr@fz-juelich.de	2022-09-29 Dr. Wilfried Behr Digital unterschrieben von Dr. Wilfried Behr Datum: 2023.02.09 11:09:04 +01'00'

Reviewer / Organizational Unit	Phone	Fax	E-mail	Date
Yannick Beßler / ZEA-1	-6808	6816	y.bessler@fz-juelich.de	2023-01-31 Yannick Bessler Digital unterschrieben von Yannick Bessler DN: c=DE, o=Forschungszentrum Juelich GmbH, ou=ZEA-1, cn=Yannick Bessler Datum: 2023.02.09 16:17:00 +01'00'

Approver / Organizational Unit	Phone	Fax	E-mail	Date
Ghaleb Natour / ZEA-1	-5045	6816	g.natour@fz-juelich.de	2023-01-31 Natour Digital unterschrieben von Ghaleb Natour Datum: 2023.02.13 09:22:27 +01'00'

This document describes the design solution for the tube moderator development project.

Address of manufacturer:

Forschungszentrum Jülich GmbH
Central Institute of Engineering, Electronics and Analytics (ZEA)
Engineering and Technology (ZEA-1)

52425 Jülich

Phone / Email:

Director of Central Institute of Engineering, Electronics and Analytics (ZEA)
Engineering and Technology (ZEA-1)

Prof. Dr. Ghaleb Natour
Phone: +49 2461 61-5045
Email: g.natour@fz-juelich.de

Project manager

Dr. Yannick Beßler
Phone: +49 2461 61-6808
Email: y.bessler@fz-juelich.de

Table of contents

1 INTRODUCTION

1.1 Objective of this document

The main objective of this document is to describe the design solutions for the tube moderator manufacturing feasibility study.

The scope of the tube moderator manufacturing feasibility studyis to develop all processes, including, but not limited to machining, assembling and welding, necessary to produce a Second Target Station (STS) tube moderator unit, ultimately resulting in the production of an STS tube moderator development assembly and an additional STS tube hydrogen vessel development assembly for cryogenic burst testing. The resulting vessel shall be delivered to the Oak Ridge National Laboratory.

<u>This tube moderator unit is not intended and furthermore shall not be used for installation in the STS</u>.

The goal for this development work is to prove out all processes for building a tube moderator unit with necessary robustness and dimensional tolerance adequate for service in the STS. Therefore, all testing shall be performed to the intent of the Pressure Equipment Directive 2014/68/EU, although no independent inspections are required. All leak tests shall be performed with a sensitivity of less than $1x10^{-9}$ mbar*l/s and show no detectable leak. All machined parts shall have a profile tolerance of 0.25mm on all surfaces and all final welded vessels shall have a profile tolerance of 0.50mm. [1]

2 TECHNICAL SOLUTION

2.1 Scope of Work

The following tasks were performed:

- Detail design and drawing creation from supplied STS models in the units of mm
- Detail design and drawing creation for any required weld development samples
- Design of fixtures and tooling required for machining, welding, and testing
- Fabrication of fixtures and tooling required for machining, welding, and testing, including required material
- Machining of all weld development samples including weld filler material, including required material
- Machining of all tube moderator parts including weld filler material and spacers.
- Dimensional inspection of tube moderator piece parts prior to welding with CMM
- Welding development samples and subsequent non-destructive testing and mechanical testing in support of creation of WPS's for all welds required for tube moderator fabrication
- Welding tube moderator based on previously created WPS's
- Non-destructive testing of tube moderator welds including visual inspection, dye penetrant inspection, computer-tomographic (CT) inspection of the hydrogen moderator and helium leak tests.
- Full dimensional inspection of welded hydrogen vessel and vacuum jacket with CMM
- Functional testing of tube moderator vessels including cold shock tests and pressure tests
- Burst testing of additional Hydrogen Vessel at liquid nitrogen temperatures
- Monthly reports detailing all progress made including as many photos as possible to be discussed during a monthly conference call.
- Final development report which documents all machining, welding, and testing, including clear photographs of every set up and process. Final report shall also include discussion of any non-conforming dimensions or tests and strategies for improvement of non-conforming conditions.
- Delivery of the tube moderator assembly at the conclusion of the project

2.2 Delivered design by SNS

2.2.1 Hydrogen moderator vessel

The following pictures show the preliminary design of the hydrogen vessel, provided by SNS, that represents the initial design for the manufacturing development. [1]

The weld seam is designed perpendicular to each tube's rotation axis. This leads to a constant thickness of the filler material, respectively the resulting wall thickness in the cut sections is constantly 2mm. The two end caps have a backer lip for the filler material to ensure full weld seam penetration by the electron beam during welding and to prevent, that the beam is hitting the opposite wall during welding.

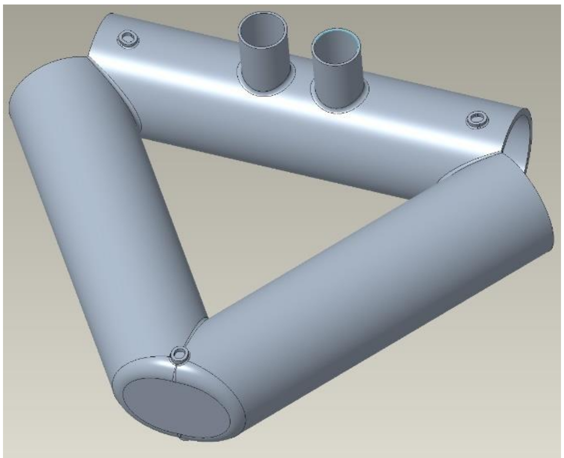


Figure 2.1: Hydrogen vessel

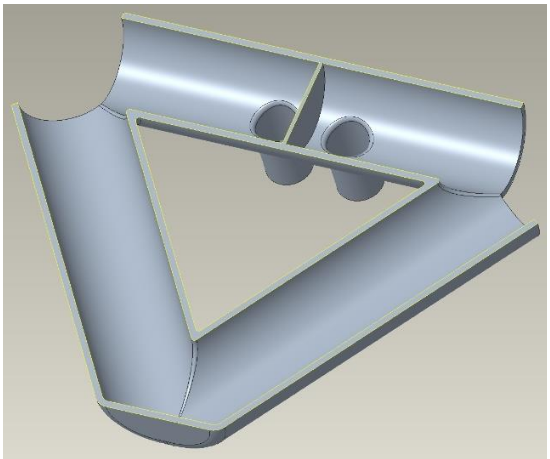


Figure 2.2: Hydrogen vessel cut section

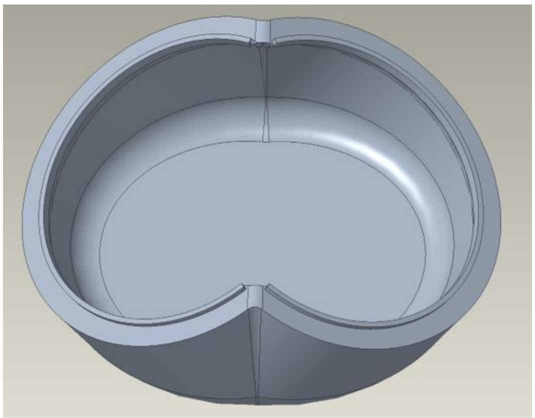


Figure 2.3: Hydrogen vessel end cap

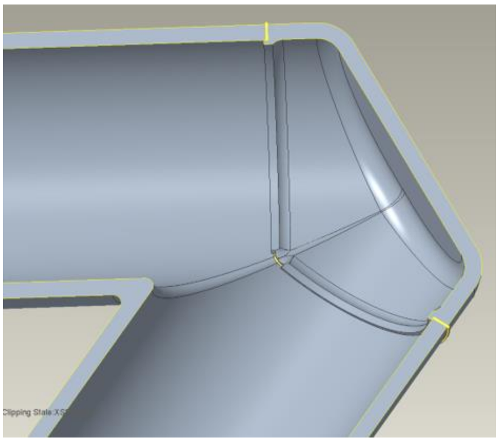


Figure 2.4: Cut section of welded area

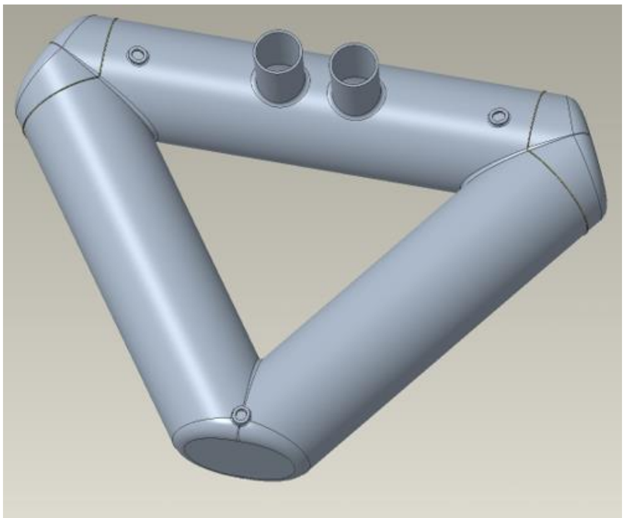


Figure 2.5: Welded hydrogen vessel assembly

2.2.2 Vacuum vessel

The following pictures show the preliminary design of the vacuum vessel, provided by SNS, that represents the initial design for the manufacturing development. [1]

The weld seam is designed perpendicular to each tube's rotation axis. This leads to a constant thickness of the filler material, respectively the resulting wall thickness in the cut sections is constantly 2mm. The main body (lower part) has a backer lip for the filler material on the outside and the inside track to ensure full weld seam penetration by the electron beam during welding and to prevent, that the beam is hitting the opposite wall, or the installed hydrogen vessel during welding.

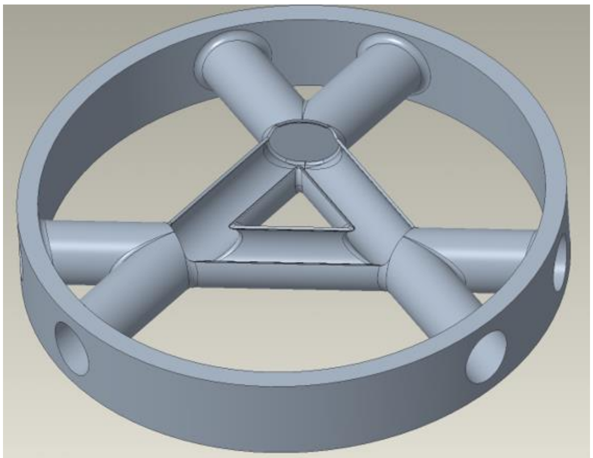


Figure 2.6: Vacuum vessel

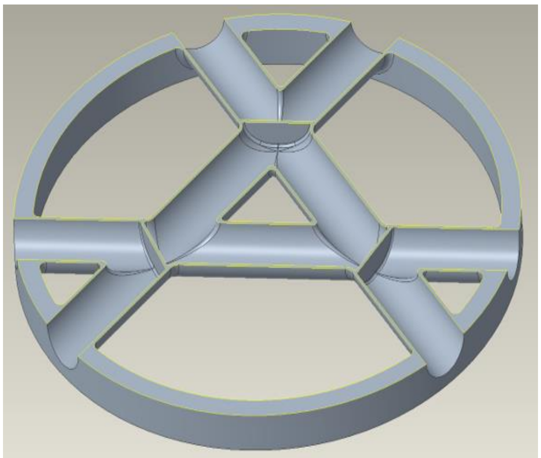


Figure 2.7: Vacuum vessel cut section

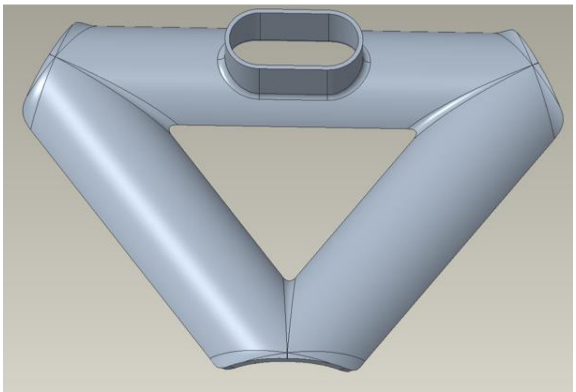


Figure 2.8: Vacuum vessel lid

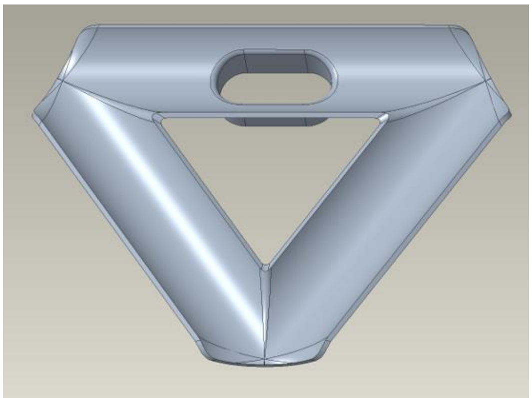


Figure 2.9: Vacuum vessel lid

2.2.3 Assembly of hydrogen vessel & vacuum vessel

The following pictures show the preliminary design of the vessel assembly, provided by SNS, that represents the initial design for the manufacturing development. In this design, the hydrogen vessel is located inside the surrounding vacuum vessel and is aligned by a total of six titanium pins, three on the top side and three on the bottom side. [1]

The structure of this assembly and the alignment of the moderator inside the vacuum vessel were not modified and completely carried over by FZ Jülich.

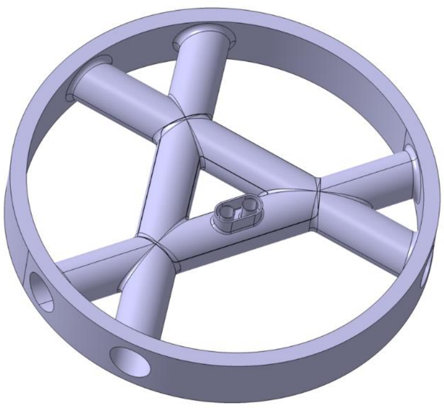


Figure 2.10: Final assembly

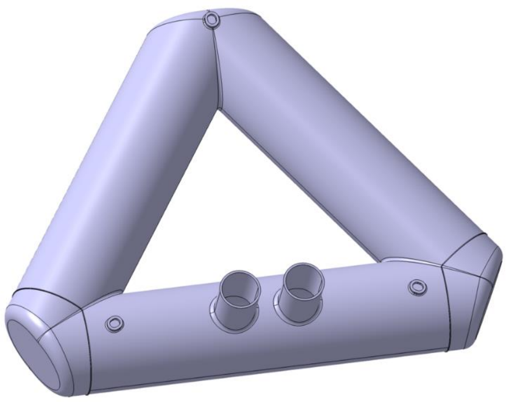


Figure 2.11: Final welded hydrogen vessel

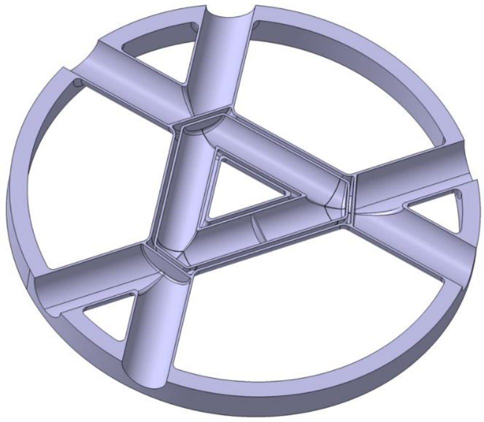


Figure 2.12: Final assembly cut section

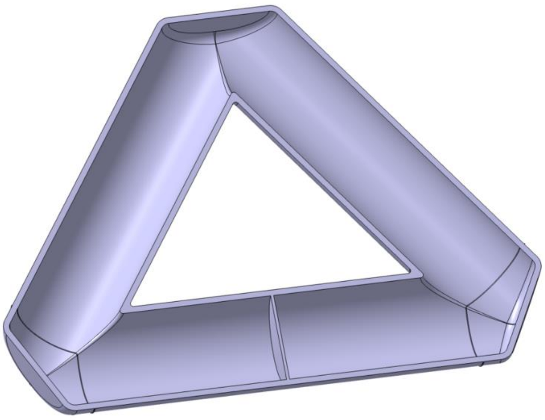


Figure 2.13: Final welded hydrogen vessel cut section

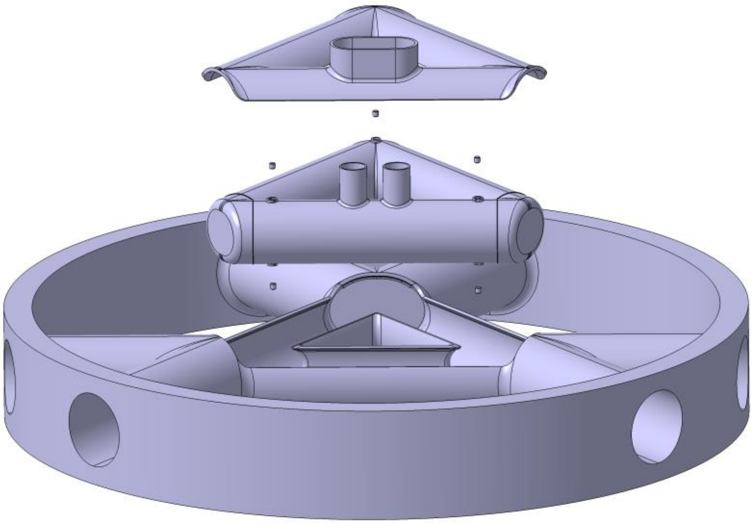


Figure 2.14: Exploded view of the final assembly

2.3 Design changes

2.3.1 Hydrogen vessel

For EBW (electron beam welding) a non-disrupted weld track is very beneficial and, in this case, substantial for a welding result according to the requirements. Therefore, the welding geometry on the hydrogen vessel end cap was changed, so that the welding can be performed continuously by turning the moderator vessel around the middle axis of the two tube meeting areas. [Figure 2.15 - Figure 2.17]

In the original design, the weld seam was perpendicular to the rotation axis of each individual tube, aiming straight to the center axis. [Figure 2.4]

A FEA stress analysis shown in Figure 2.18 performed by SNS shows, that the maximum stress location is in the center of where the neutron beam window meets the junction of the two tubes. At an internal pressure of 19bar, stresses are over the allowable for welded aluminum EN AW-6061 T6 but this is very localized [2]. Therefore, the weld location had to be at least 10mm from where the radii meet the tubes in order to keep this high stress area out of the heat affected zone, which results in 13mm distance from the flat inside face of the window. This result was implemented in the new design. [Figure 2.16]

As the filler material is cut out from a 0.04" sheet of aluminum EN AW-4047, its cross-section results in a rectangular shape. Because of this and the necessity to mill the end caps' filler backer lip, the step that holds the filler material will not follow the angle of the tubes in the different cross sections shown in Figure 2.15 & Figure 2.16.

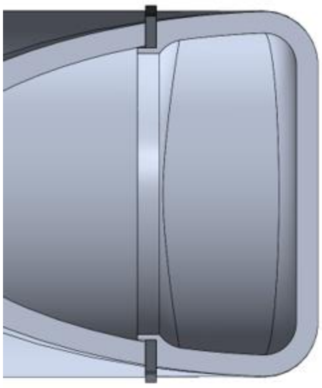


Figure 2.15: Welded end cap side view

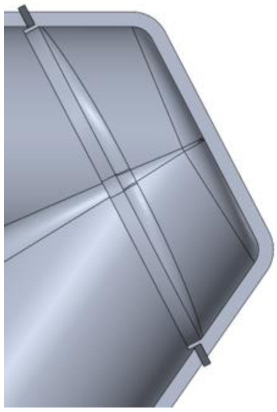


Figure 2.16: Welded end cap top view

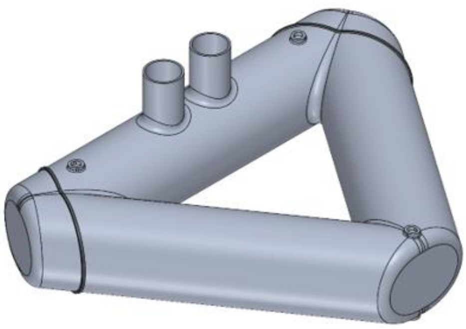


Figure 2.17: Hydrogen vessel

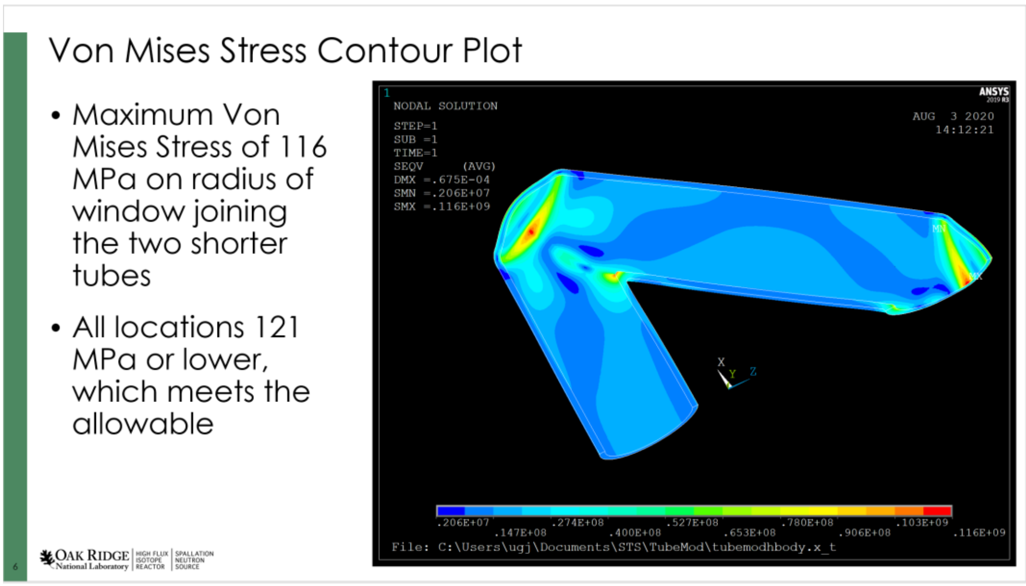


Figure 2.18: FEA stress simulation [2]

2.3.2 Vacuum vessel

To allow EBW (electron beam welding) for the vacuum vessel, the weld seam has to be continuously carried out from the top side.

In the original design, the weld seam was perpendicular to the rotation axis of each tube, aiming straight to the center axis [Figure 2.19]. This is not possible to implement, because the beam head of the EB welding machine cannot be tilted/angled, while the welding path is being traversed.

Therefore, the design was changed to enable a full and non-disrupted welding path from the top [Figure 2.20 & Figure 2.21].

With this new design, it was crucial to ensure a full penetration of the filler material all through the original wall thickness, to prevent weakening the vessels outside wall. To reach this goal, a backer lip was implemented, to ensure full weld seam penetration by the electron beam during welding and to prevent, that the beam is hitting the opposite wall, or the installed hydrogen moderator during welding. [Figure 2.20 & Figure 2.22]

The design in the corner of the main body was challenging, because the weld track does change in the planar and the height direction at the same time, to match the top lid outer shape [Figure 2.22]. The resulting shape of the backer material in this area will be manufactured with EDM machining.

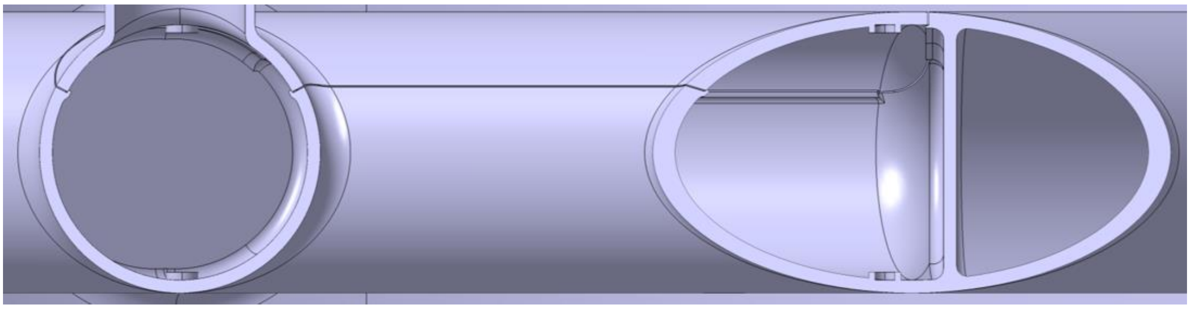


Figure 2.19: Vacuum vessel original weld track

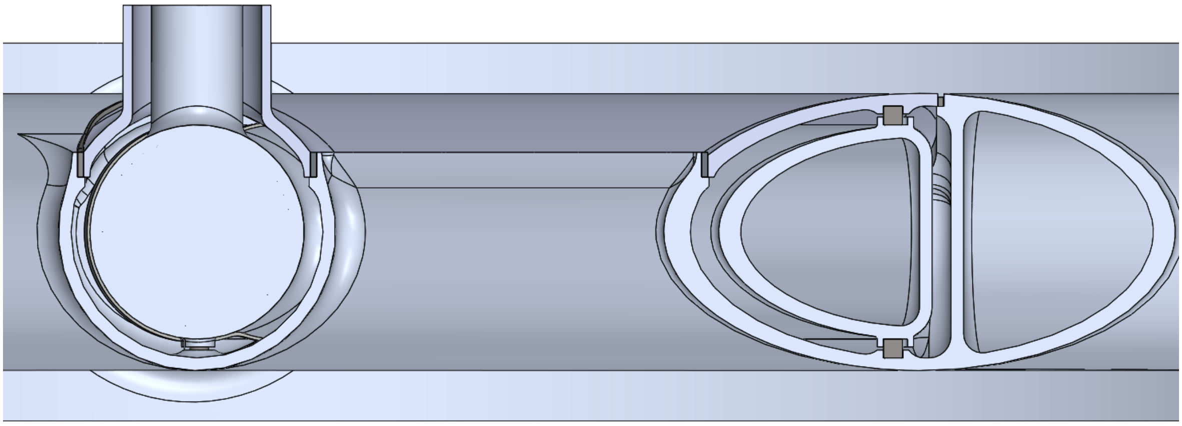


Figure 2.20: Vacuum vessel new weld track

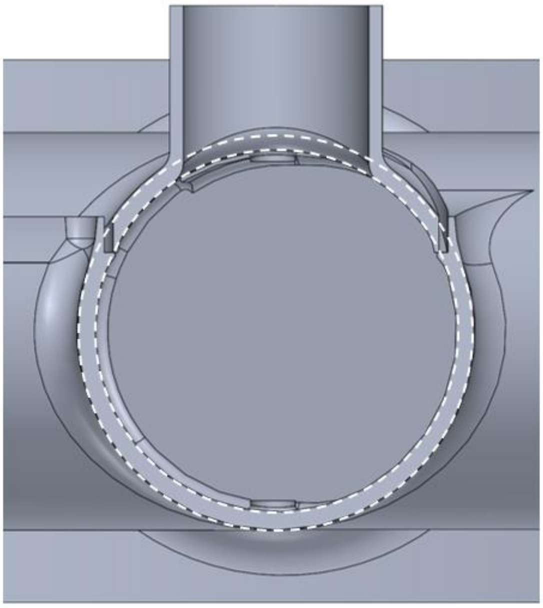


Figure 2.21: Vacuum vessel cross section

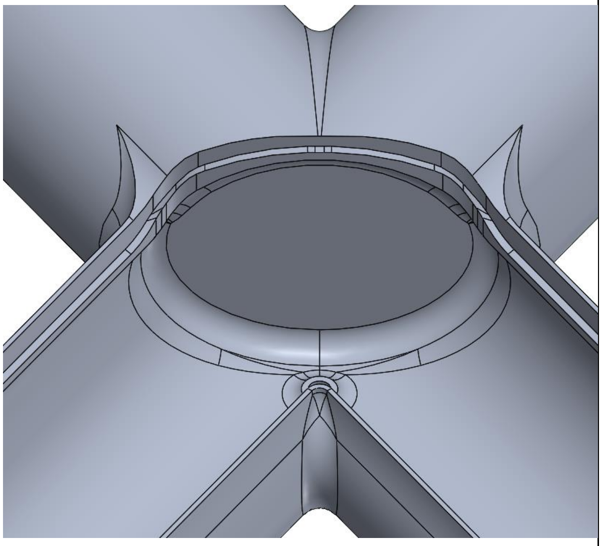


Figure 2.22: Vacuum vessel backer shape

Because of significant heat input from the electron beam into the welding areas with corners and change of direction of the welding filler, it was decided to weld the vacuum vessel before final manufacturing is processed. More material during the welding process will improve the heat removal from the vulnerable locations [Figure 2.23 & Figure 2.24]. In addition, defined reference points for the fixing on the various machining steps (milling, EDM, welding) were required.

After the welding process is finished, the outer shape of the vessel assembly will be manufactured to its final form.

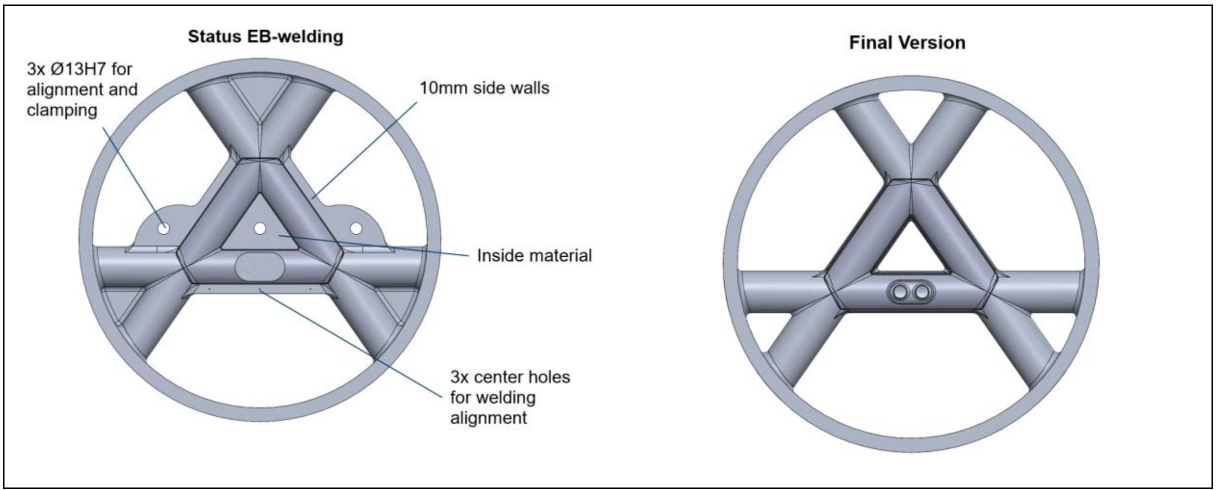


Figure 2.23: Manufacturing stages of the vacuum vessel

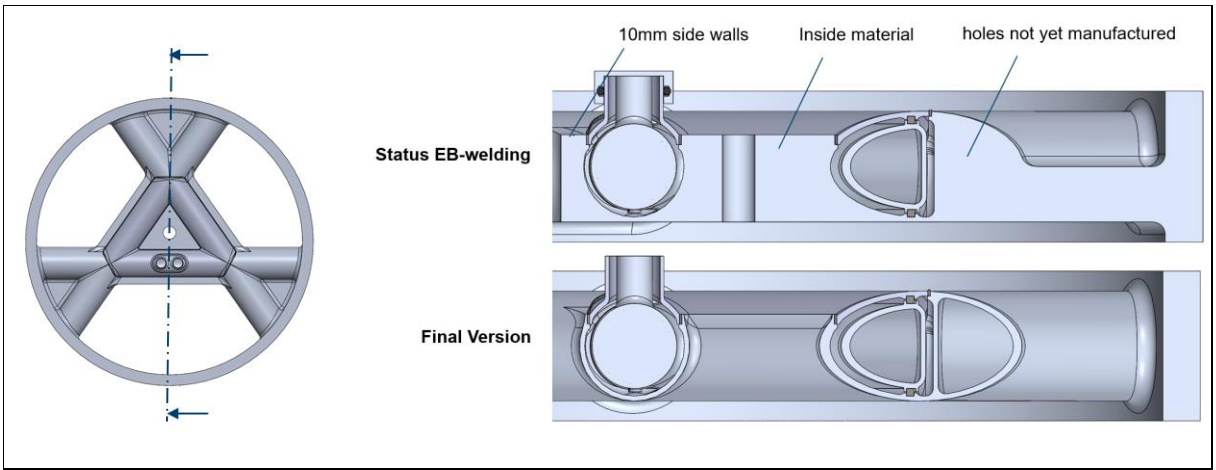


Figure 2.24: Cut section of the vacuum vessel

2.4 Design of welding samples

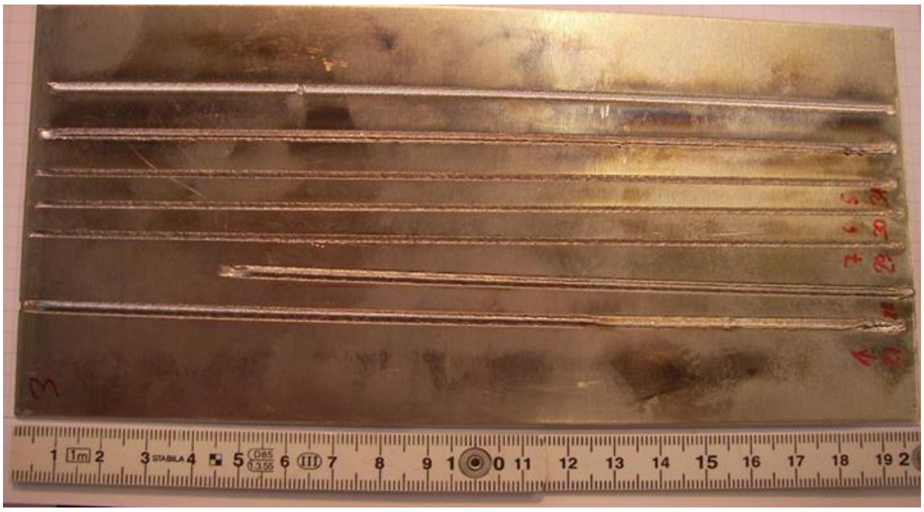
To determine the parameters of the welding process and the creation of the WPS for the final EB-welding, various pre-tests on several welding samples were performed.

2.4.1 Hydrogen vessel welding samples

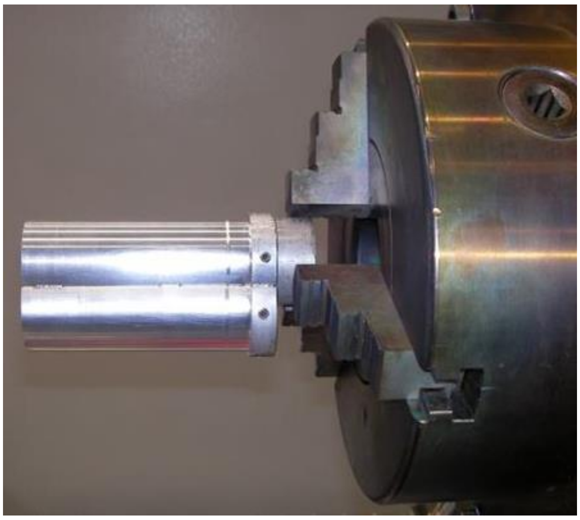
For the hydrogen vessel, these test pieces were successively increased in their level of detail to exactly match the final design in the last step.

1) Pre-setting of parameters on aluminum sheet-metal
2) Parameter transfer to tube material and eccentric tube sample
3) Welding test at a sample with the outer shape of the filler geometry and adjustment of parameters until proper results were achieved
4) Welding test at test samples with the original shape of the hydrogen vessel cap and the original filler geometry

1)



2)



3)

4)

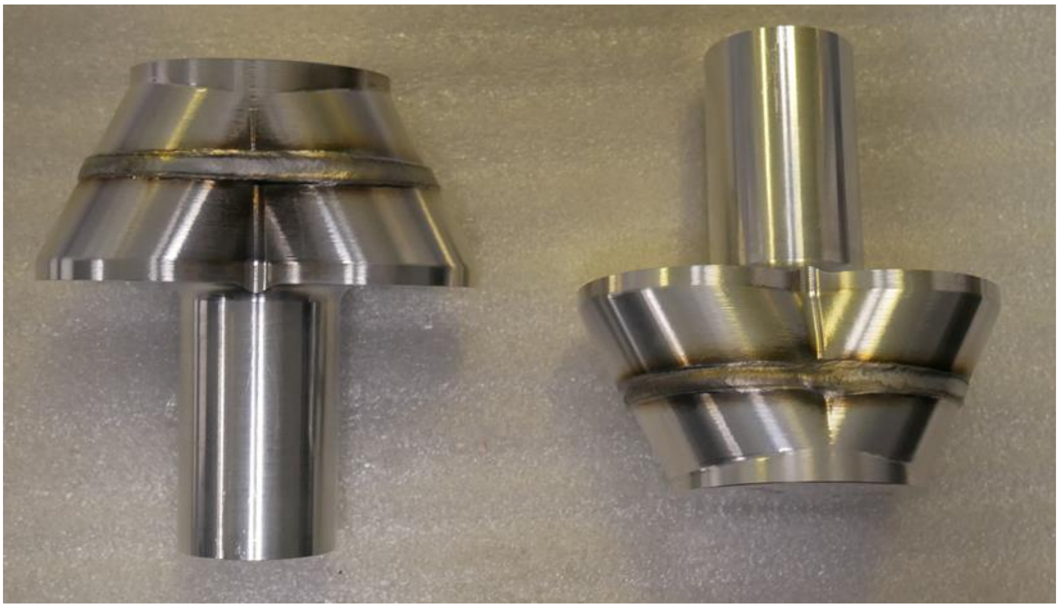


Figure 2.25: Welding samples for the hydrogen vessel

2.4.2 Vacuum vessel welding sample

As a welding sample for the vacuum vessel an exact copy of one of the corners was designed. Also, the simple outline weld track was engraved into a blank aluminum sheet for the simple outline track programming.

This is necessary to evaluate the parameters for the weld track, especially at areas where the filler material is not consistent in thickness.

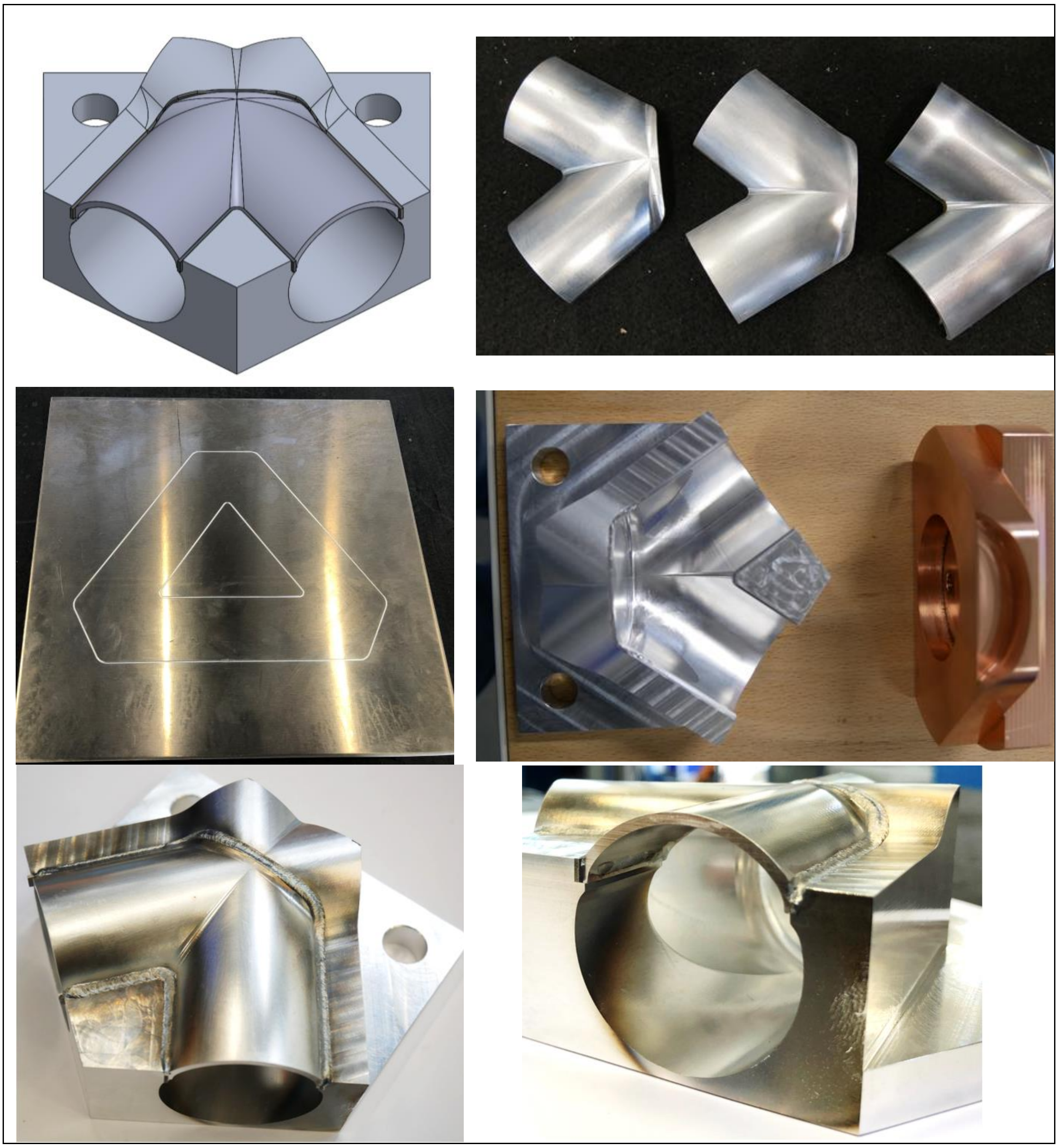


Figure 2.26: Pictures of manufactured sample parts

3 MACHINING

3.1 Hydrogen vessel

After milling the top side of the moderator, also the inside holes were completely milled for the separated tube, that is accessible from both sides. The other two inside surfaces of the tubes that meet at the top end were first pre-milled and then finally EDM-machined with a special copper electrode [Figure 3.1].

The caps, that are going to be welded to the main body, are completely milled and in a final step cut off from the raw material by wire-EDM [Figure 3.2].

The filler material was completely cut out via micro-water-cutting from a 0.04” thick sheet of EN AW-4047 aluminum, so there was no machining in regards of thickness necessary [Figure 3.3].

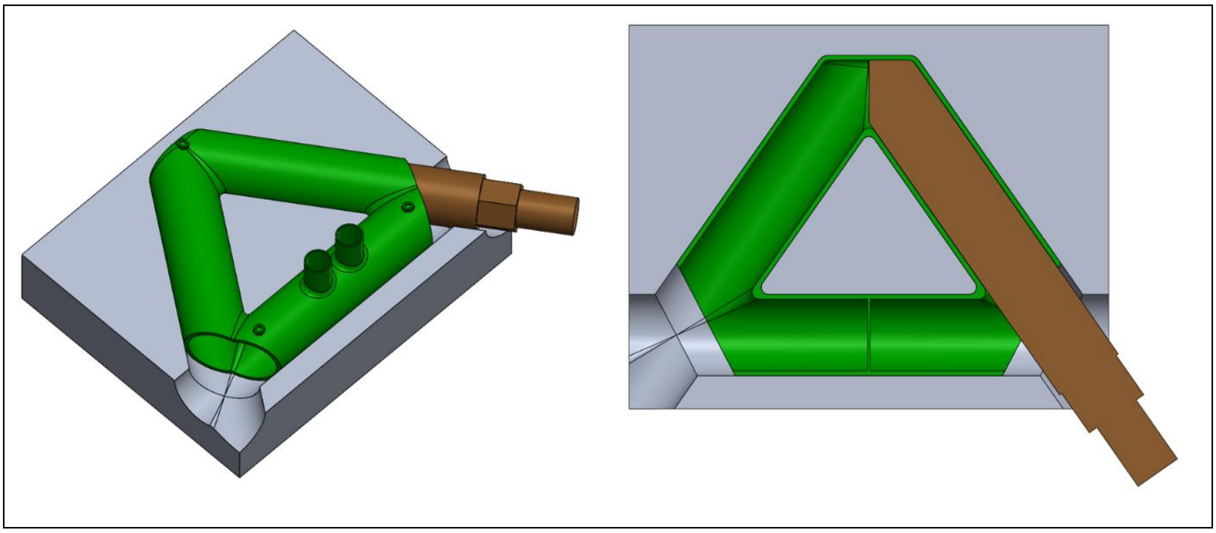


Figure 3.1: EDM electrode for the hydrogen vessel

Figure 3.2: Machined parts of the hydrogen vessel and end caps

Figure 3.3: Welding filler

For the machining of the bottom side of the hydrogen vessel, the pre-milled piece is glued into a negative form with a special wax that can be removed by heat after the machining. The duration of heating the moderator for melting the wax at a temperature of around 80°C is well below the time period of 1000 hours before thermal ageing of EN AW-6061 T6 will set in at a temperature of 150°C [3].

Figure 3.4 shows the pre-milled moderator and the negative form before they are put together.

Figure 3.5 & Figure 3.6 show the machining of the back side and the final milled hydrogen vessel.

Figure 3.4: Pre-milled moderator (left) & negative form (right)

Figure 3.5: Final machining of the hydrogen vessel

Figure 3.6: Final machined hydrogen vessel

3.2 Vacuum vessel

3.2.1 Pre-welding stage

After milling the outer shape of the vacuum vessel in the pre-welding stage, only the corner areas of the filler backer that are undergoing a change of height have to be machined with EDM [Figure 3.8].

The filler material is milled from a solid plate of EN AW-4047 aluminum and after the final shape is manufactured, the 1mm stripes are cut out by wire-EDM [Figure 3.9].

When machining of the pre-welding stage is finalized, the hydrogen vessel is inserted into the vacuum vessel and aligned with each three titanium pins on the bottom and on the top [Figure 3.11].

After that procedure, the vacuum vessel is closed with the lid and the welding fillers are inserted. Subsequent to the EB-welding-process, the outer shape of the vacuum vessel assembly is finally milled and the manufacturing process is completed.

Figure 3.7: Pre-welding stage of the vacuum vessel

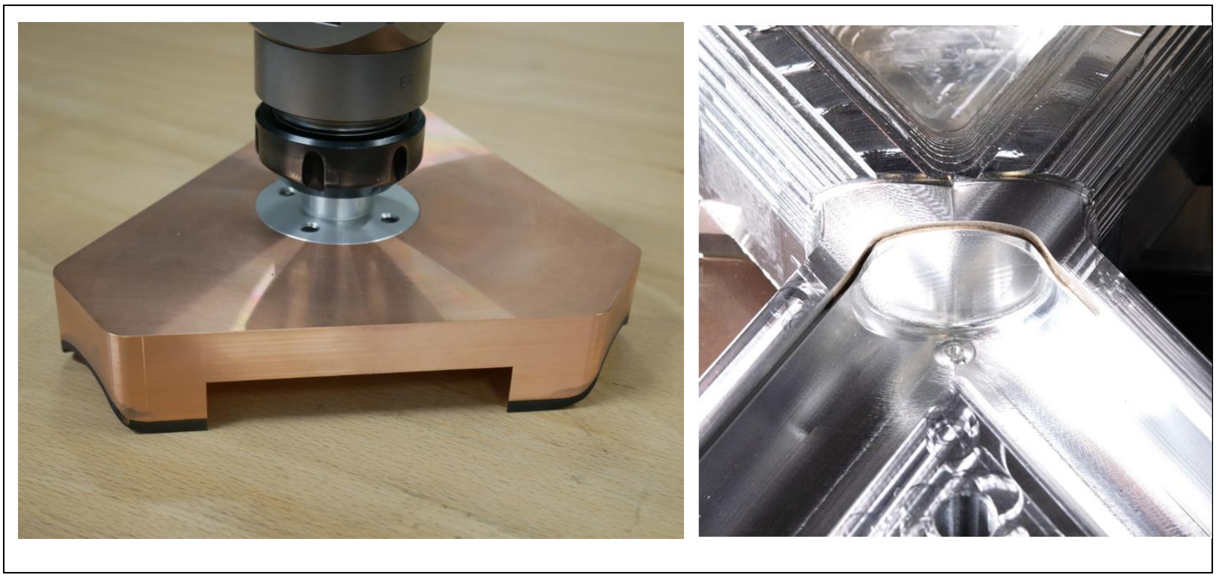


Figure 3.8: Manufacturing of the vacuum vessel

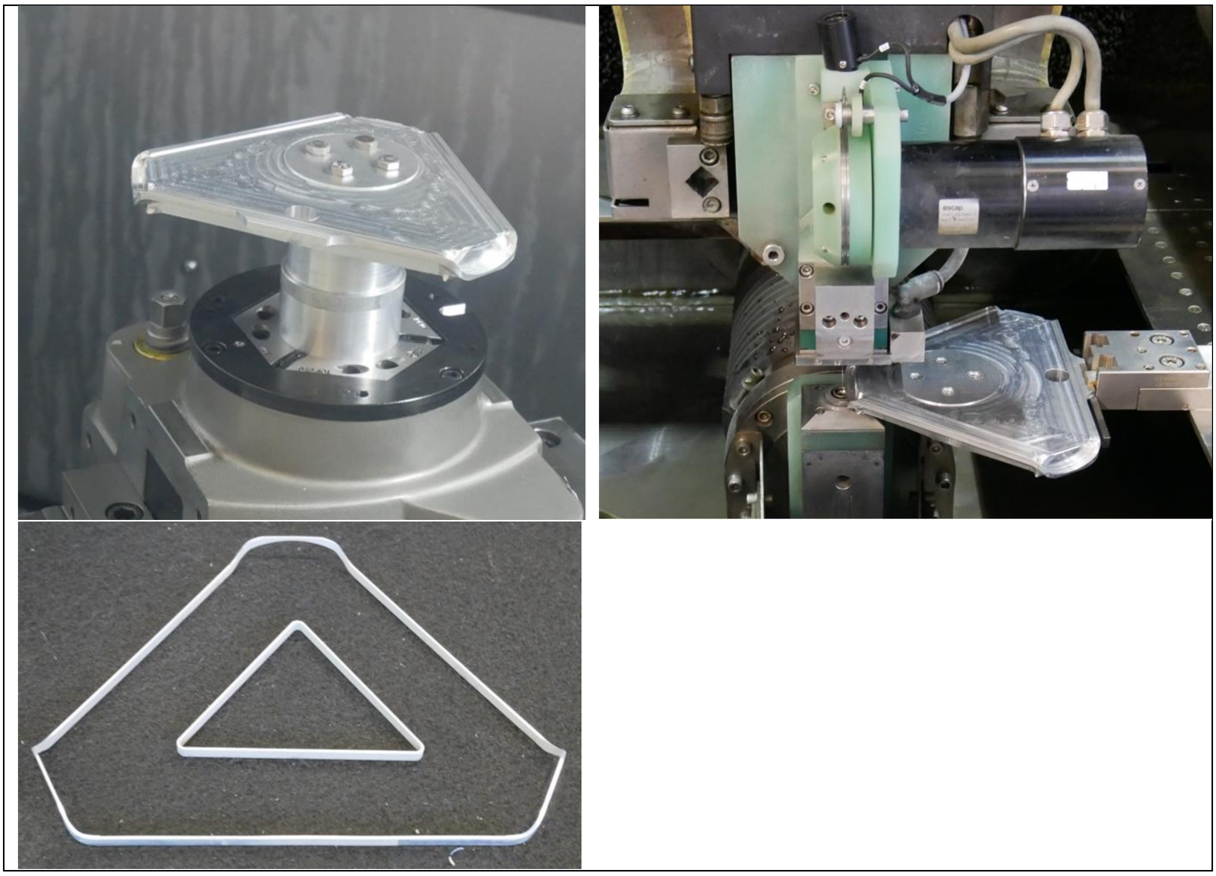


Figure 3.9: Milling and EDM of the outer filler material for the final vacuum vessel

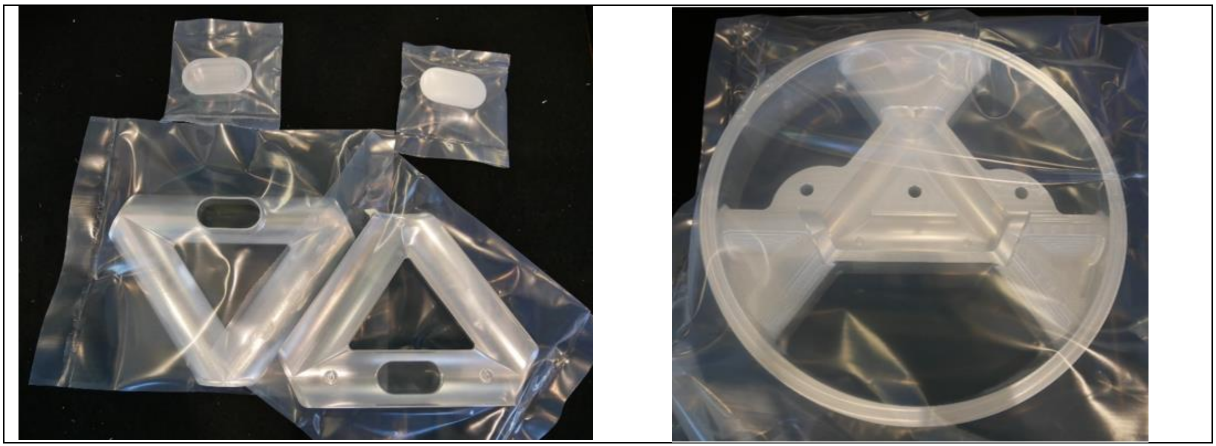


Figure 3.10: Cleaned and packed parts

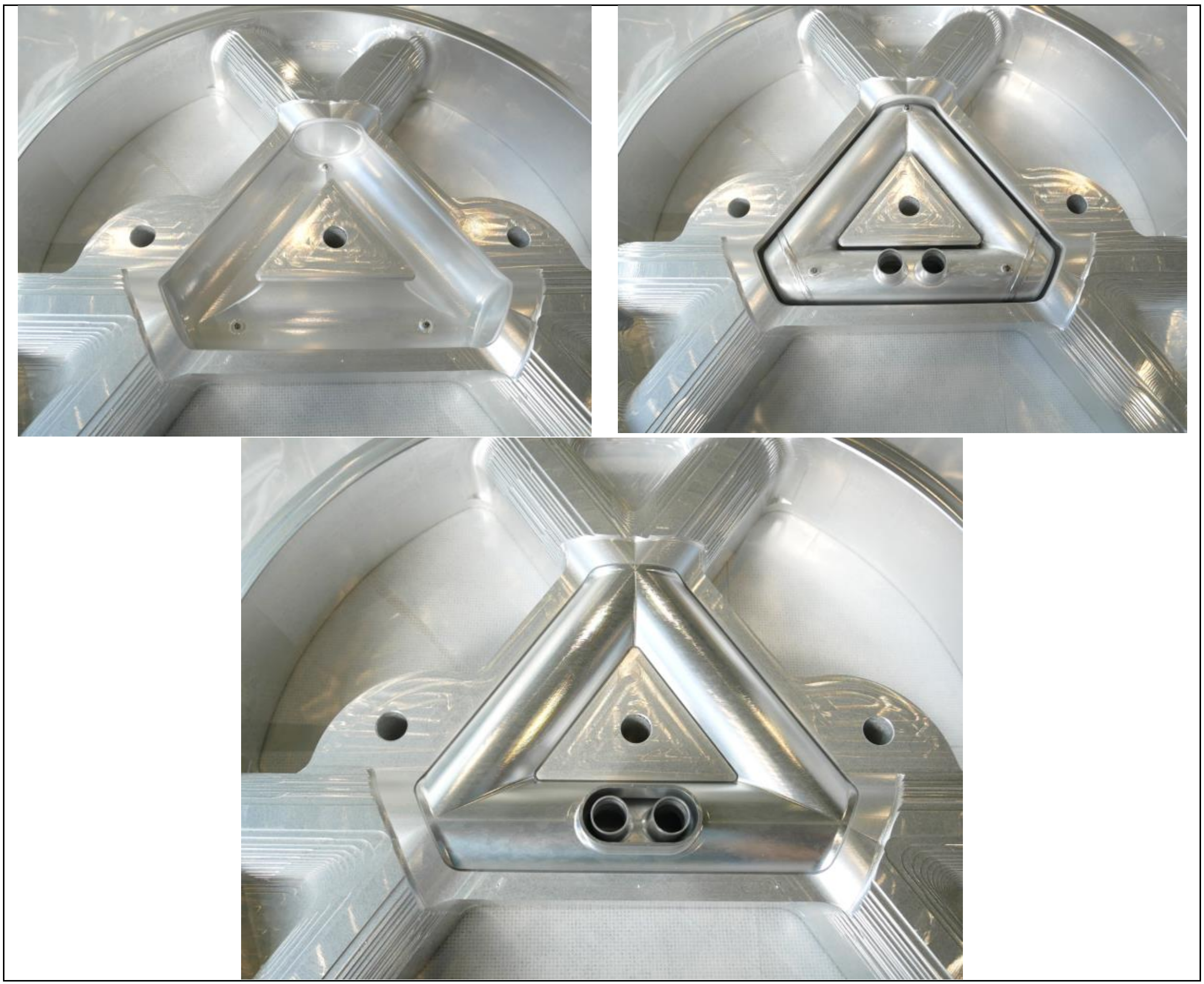


Figure 3.11: Assembly of the vacuum vessel with the hydrogen vessel inside

3.2.2 Final machining

After the welding of the vacuum vessel and the first non-destructive testing, the final outer shape has to be manufactured.

At first the beam tubes are pre-milled. After the milling is completed, the six beam port tubes are EDM-machined, as shown in Figure 3.12 & Figure 3.13. Then all additional material around the three tubes and in the inside triangle of the main body is milled away [Figure 3.14 & Figure 3.15].

As final steps, the whole assembly is again leak tested and then finally cleaned according to the regulations of Forschungszentrum Jülich [4] and packed for shipping.

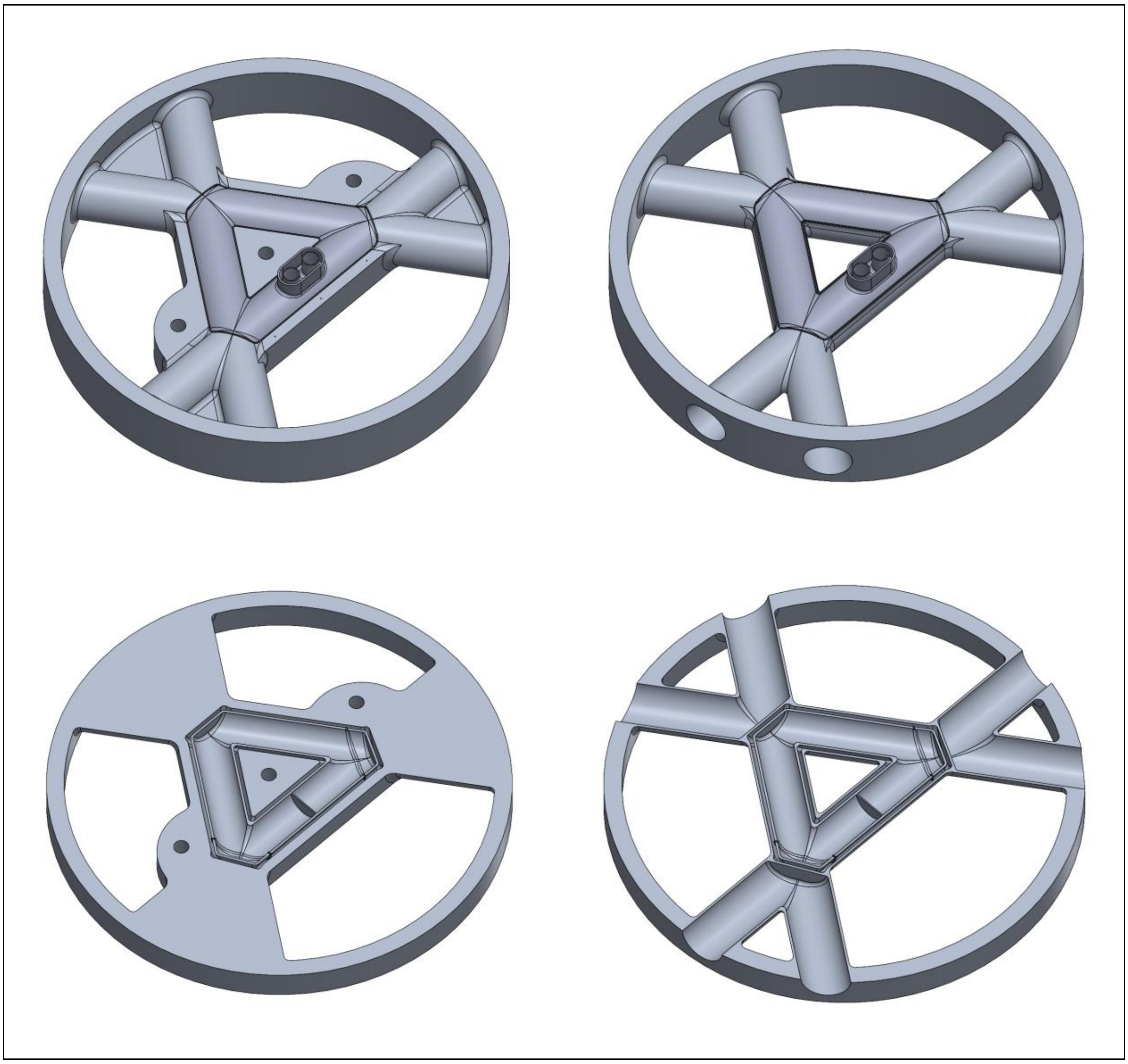


Figure 3.12: Manufacturing stages of the vacuum vessel, welding stage (left) and final machining (right)

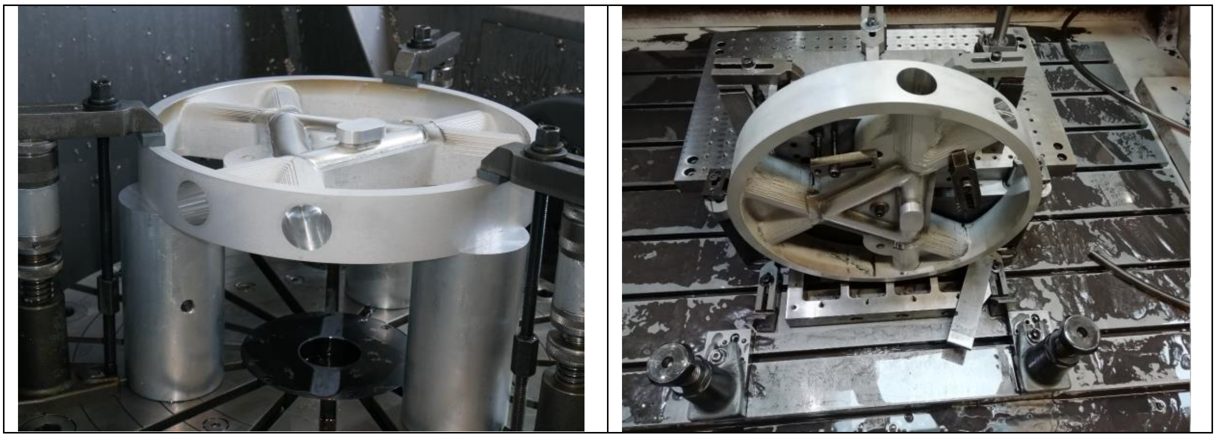


Figure 3.13: Milling (left) & EDM (right) of the beam port tubes

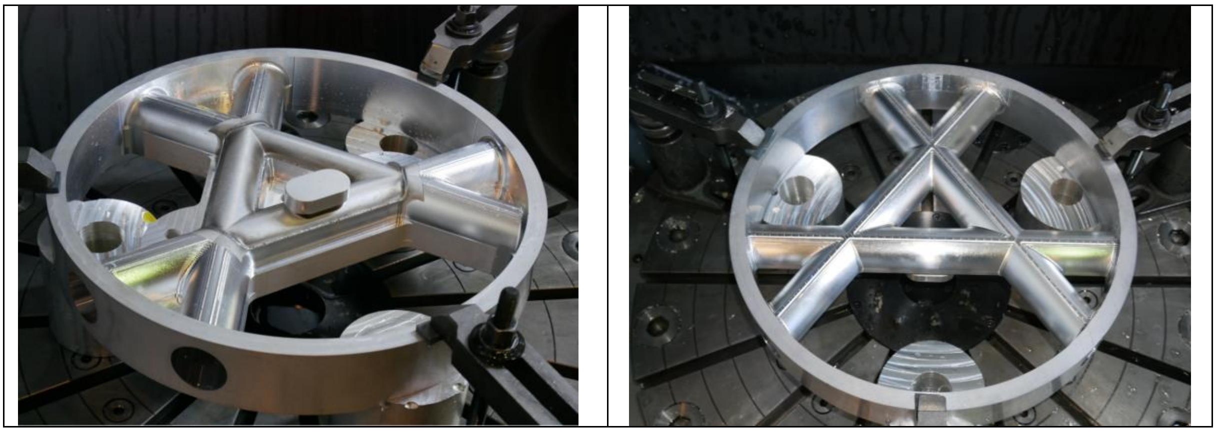


Figure 3.14: Final machining of the vacuum vessel assembly

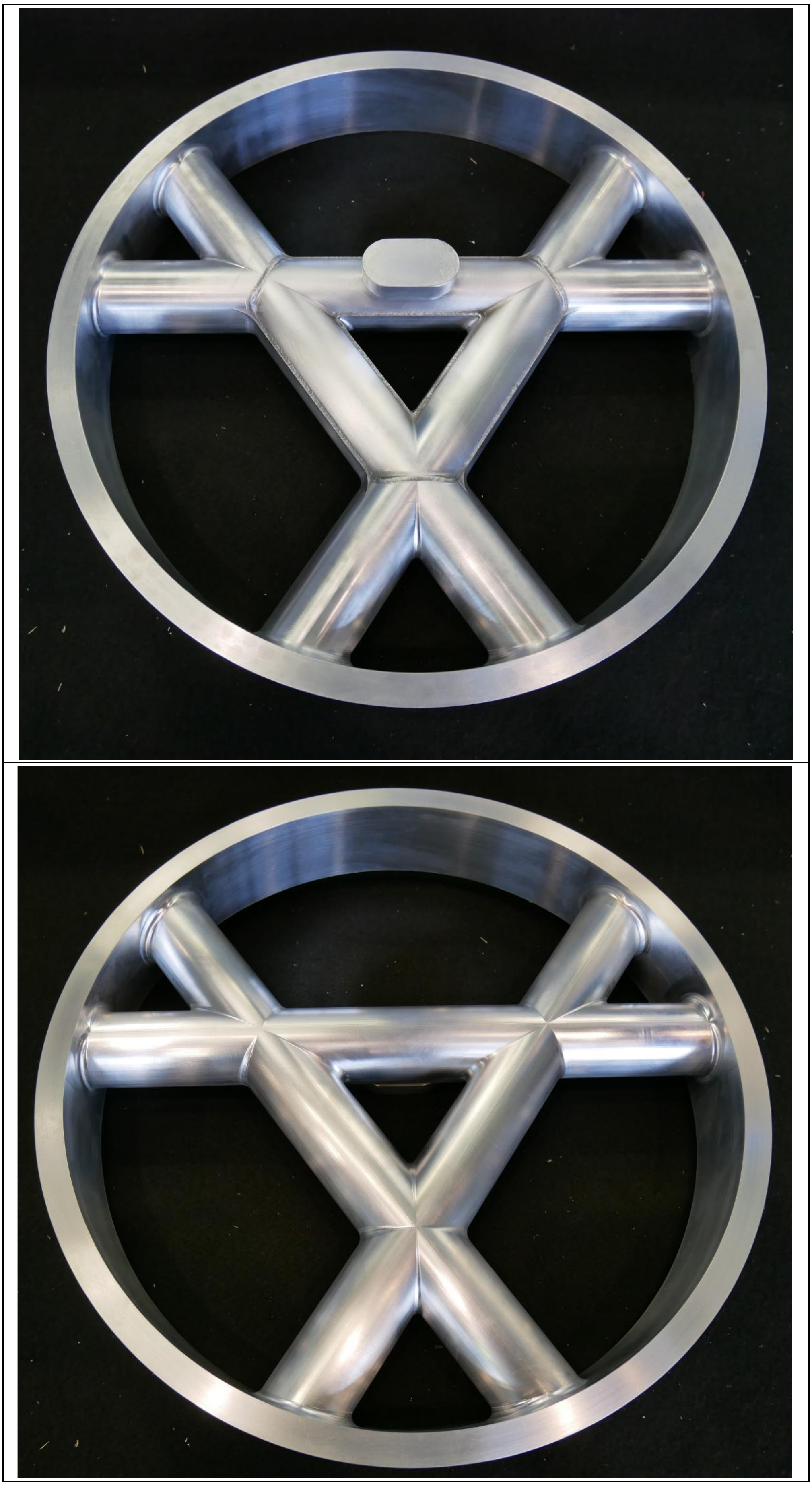


Figure 3.15: Final STS SNS Tube Moderator Unit, top view (top) and back view (bottom)

4 FINAL WELDING PROCEDURE

After the evaluation of the welding samples for each, the hydrogen vessel and the vacuum vessel, the final welding was performed. This evaluation process in described in detail in chapter *5 DESTRUCTIVE & NON-DESTRUCTIVE TESTING*.

Before the welding can be performed, all aluminum components of each assembly are pickled and cleaned according to the regulations of Forschungszentrum Jülich [4].

4.1 Welding of the hydrogen vessel

4.1.1 Design of the welding fixture

For the rotational welding of the hydrogen vessel, a fixture was needed that enables the rotation of the two vessel welding areas at the end caps [Figure 4.1].

The vessel can be inserted in two different orientations, so both end caps can be welded.

The orientation and alignment of the vessel is crucial for good welding results. Therefore, the vessel is located in the same way it will be in the final assembly inside the vacuum vessel via 6 pins in the original alignment positions. Other than the pins in the vacuum vessel, not thermal-isolating titanium pins are used, but ones made of the same EN AW-6061 aluminum as the vessel. Also, the contact surface at the alignment points was designed as big as possible, to ensure sufficient heat transfer from the vessel into the fixture. This will keep the overall heat input at a low level.

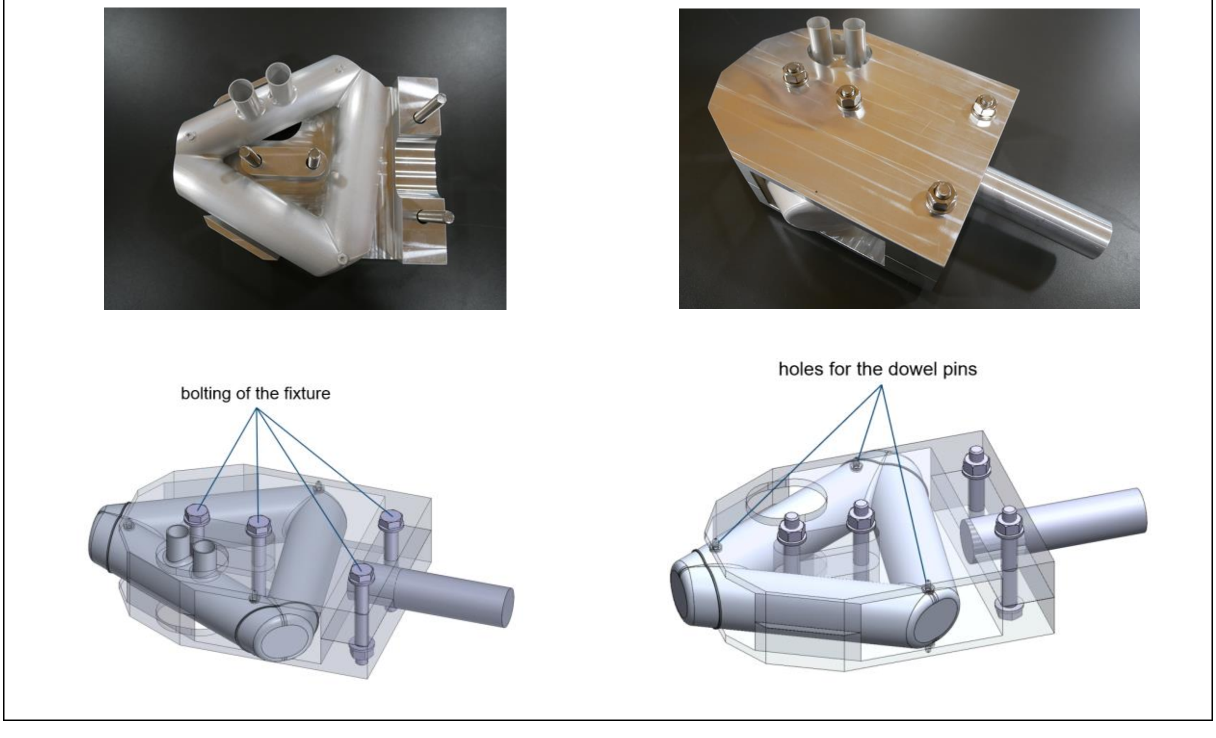


Figure 4.1: Fixture for welding of the hydrogen vessel

4.1.2 Welding of the hydrogen vessel

With the evaluated parameters of the welding samples, the final welding of the hydrogen vessel was performed. Figure 4.2 shows the moderator vessel clamped into the rotation device of the EB-welding machine and Figure 4.3 shows the hydrogen vessel after the final welding. The dark spots are magnesium that evaporated during welding and deposited on the vessel surface. This will be removed by the following cleaning step according to the regulations of Forschungszentrum Jülich [4].

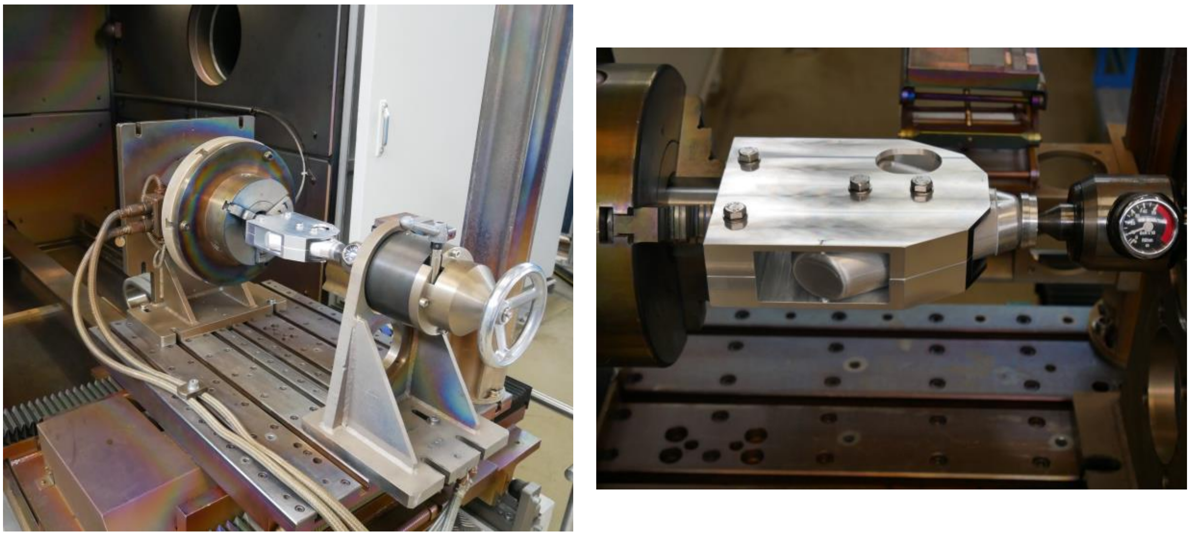


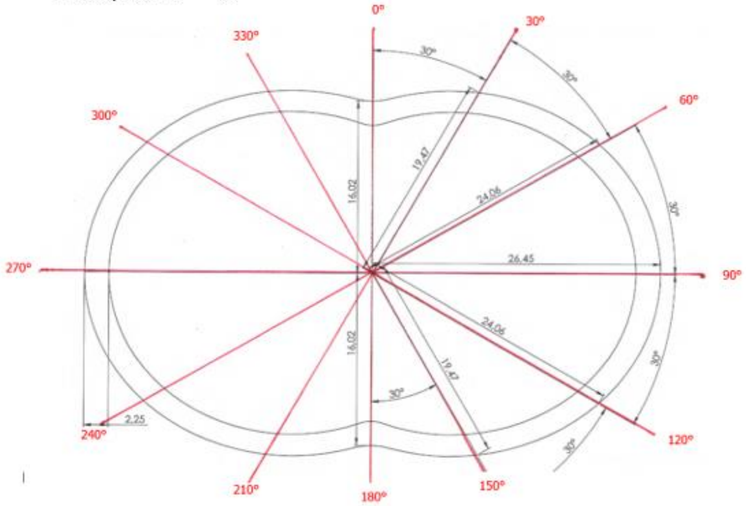
Figure 4.2: Hydrogen vessel on the EB welding machine

Figure 4.3: Hydrogen vessel after the final welding

4.1.3 WPS of the hydrogen vessel

Overview of the degree division in the program. The A value quantifies the degree number in the welding program!

Example A90 = 90°




```
DATEI:    SNS_MIT2.EBC

N0001     (Pistel 11.01.2022)
N0002     (Drehvorrichtung SNS Moderator)
N0003     G04  SL1888  SH1400  SW414  F1000
N0004     G29  X2.5  X1.  SF150  E1  F100
N0005
N0006
N0007     G00  G90  X-79.55  Y55.19  D45.
N0008     G01  G90  A90.  D45.  F100
N0009     G01  G90  A180.  D45.
N0010     G01  G90  A270.  D45.
N0011
N0012     G01  G90  A0.  D45 .  SQ50  F200
N0013     G01  G90  A30.  D45.
N0014     G01  G90  A60.  D45.
N0015     G01  G90  A90.  D45.
N0016
N0017     G01  G90  A120.  D45.
N0018     G01  G90  A150.  D45.
N0019     G01  G90  A180.  D45.
N0020
N0021     G01  G90  A210.  D45.
N0022     G01  G90  A240.  D45.
N0023     G01  G90  A270.  D45.
N0024
N0025     G01  G90  A300.  D45.
N0026     G01  G90  A330.  D45.
N0027     G01  G90  A60.  D45.  SL2400  SQ0
N0028
N0029     G01  G90  A90.  D45.
N0030
N0031     M02
```

Figure 4.4: Program of the hydrogen vessel welding geometry

Schweissprotokoll

Elektronenstrahl-Schweißen SG Tube Moderator

JÜLICH Forschungszentrum

Maschinentyp:	**EBM - K40**		
Masch.-Operateur:	**Hans-Josef Pistel**		
Datum:	**12. Mai 2022**		
Auftrags-Nr.:	**D.Z.004191**	Werkstoff:	**EN AW-6061 T6 + EN AW-4047**
Zeichnungs-Nummer:	**S298-000025**	Schweißtiefe:	**2,0 - 2,6 plus Filler**
Kunde:	**Beßler**	Abmessung:	**siehe Zeichnung**
Bezeichnung:	**SG Tube Moderator**	Reinigung:	**gebeizt**
Vorrichtung:	**Drehvorrichtung**		
Programm:	**SNS_MIT2.EBC**		
Kathodentyp:	**Bandkathode 1.4**		
Dateien:	**Hydrogen Vessel WT02**		

Nr.	U	I	V	Korrektur-wert	Fokus 1	Fokus 2	Ablenkung Amplitude		Ablenkung Frequenz	Figur	Slope Auf	Slope Ab	Arbeits-abstand	Fokus	Bemerkung
	SH (kV)	SQ (mA)	F (mm/s)	Isk sw	SL (mA)	SL (mA)	x (mm)	y (mm)	(Hz)	(neu)	(mm)	(mm)	(vom Tisch) mm	(mm)	2 Bauteile mit je 2x Schweißnaht
22_20A	**1400**	**50**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Heftnaht
Heftnaht	140 kV	5 mA	20 mm/s												
	1400	**85**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Schweißnaht
Schweißnaht	140 kV	8 mA	20 mm/s												
22_22B	**1400**	**50**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Heftnaht
Heftnaht	140 kV	5 mA	20 mm/s												
	1400	**85**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Schweißnaht
Schweißnaht	140 kV	8,5 mA	20 mm/s												
22_23A	**1400**	**50**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Heftnaht
Heftnaht	140 kV	5 mA	20 mm/s												
	1400	**85**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Schweißnaht
Schweißnaht	140 kV	8,5 mA	20 mm/s												
22_23B	**1400**	**50**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Heftnaht
Heftnaht	140 kV	5 mA	20 mm/s												
	1400	**85**	**200**	**414**	**1888**		**2.0**	**1.0**	**1000**	**E1**				**0**	Schweißnaht
Schweißnaht	140 kV	8,5 mA	20 mm/s												

Figure 4.5: Welding parameter overview of the hydrogen vessel [5]

4.2 Welding of the vacuum vessel

Before the final welding of the vacuum vessel can be performed, the welding track of especially the outer filler has to be programmed. Figure 4.7 & Figure 4.8 show the offline programming of the basic path from CAD data with interpolation points for parameterization of the weld seam depending on geometry, filler material and seam depth.

This parametrization is mandatory, because the changes in direction, height of the weld seam and thickness of the filler material. These parameters, such as current and welding speed, were evaluated during the processing of the welding samples.

Due to the inserted filler material, a complex tacking procedure was required. All parts were first tacked manually with a pulsed Nd:YAG laser, as shown in Figure 4.6. This was followed by sectional tacking and continuous tacking using reduced electron beam power. The whole seam was tacked with step-tacking (10mm tacking / 20mm space) and continuous tacking. The reduced power for tacking was 490W.

Figure 4.13 shows the vacuum vessel assembly after the final EB welding process.

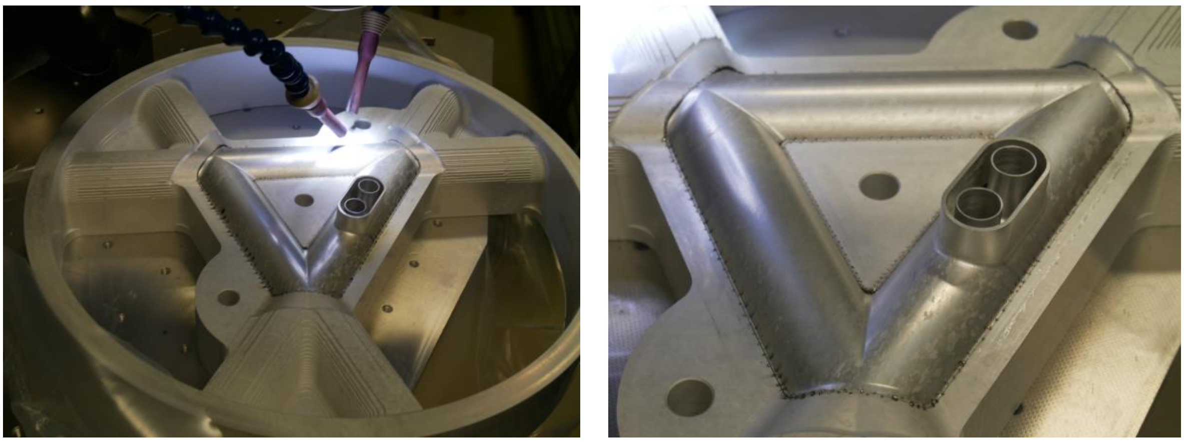


Figure 4.6: Laser tack welding of the filler

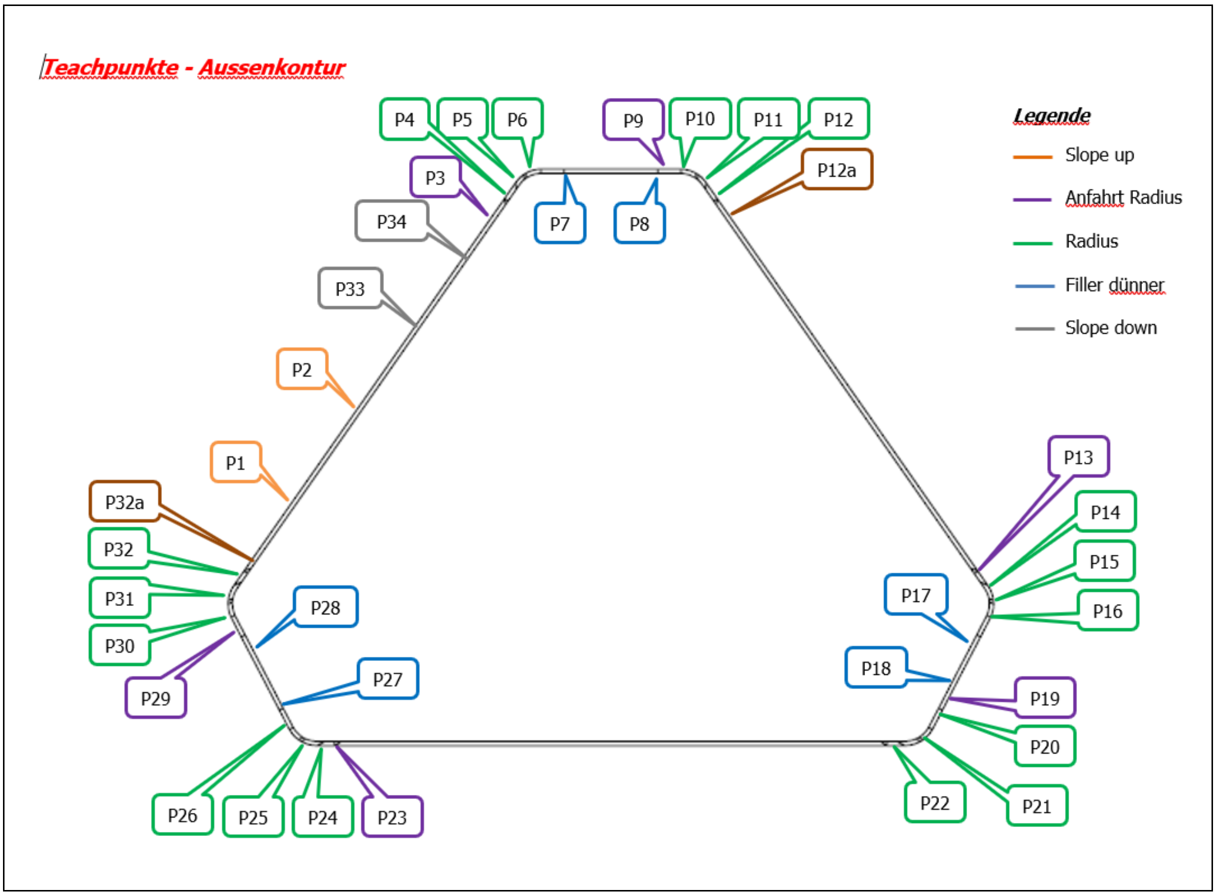


Figure 4.7: Parameter programming for the outer filler contour

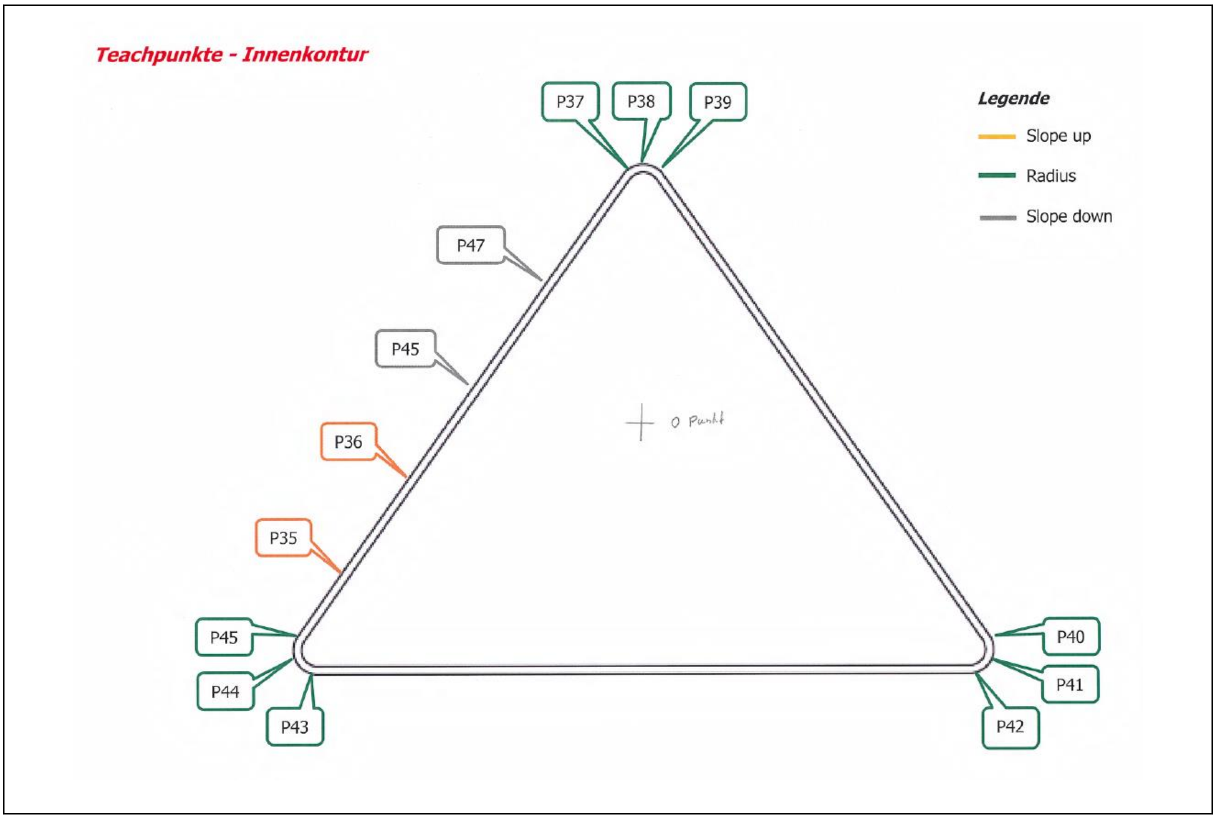


Figure 4.8: Parameter programming for the inner filler contour

4.2.1 Elaboration preparations for the welding work on the vacuum vessel

The moderator was clamped on a universal table with a height of 200 mm with several clamping screws and clamps.

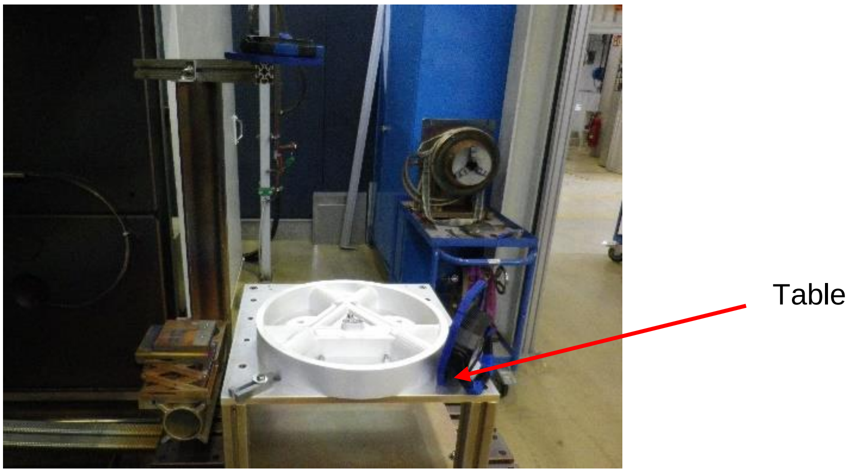


Figure 4.9: Vacuum vessel assembly on table

For better adjustment, stops were used.

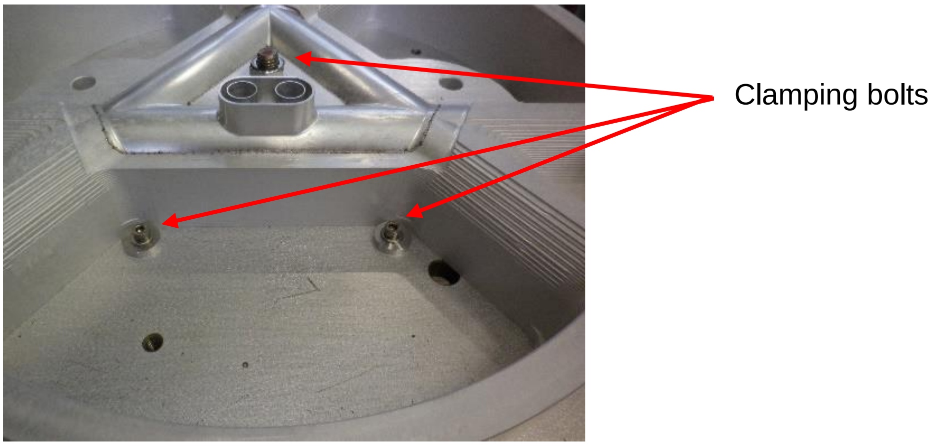


Figure 4.10: Clamped assembly

Before the welding was performed, a new cathode was installed into the welding machine and adjusted with the intended accelerating voltage of 140kV. Work lights were installed in the vacuum chamber in addition to the internal chamber lighting to provide sufficient image capture on the highly reflective surfaces [Figure 4.11]. This is required for teach-in programming of the welding track.

Figure 4.11: Position of the work lights

For programming, the teach position was partially marked with auxiliary tools.

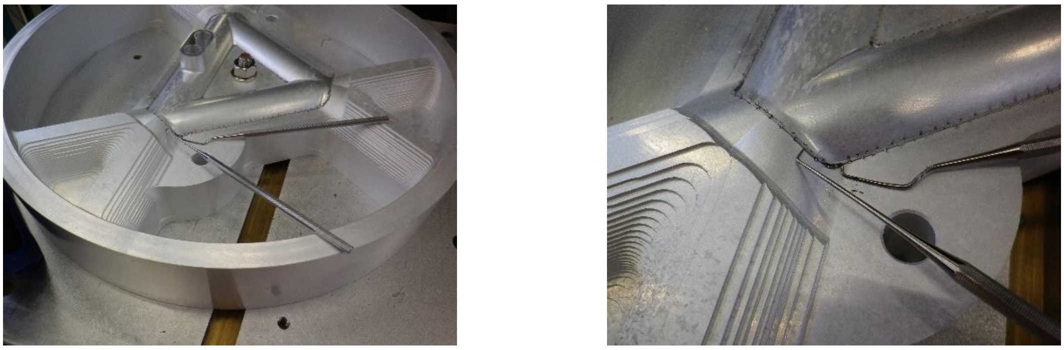


Figure 4.12: Teach point visualization with tear and hook needles on the laser-stitched component (dark points)

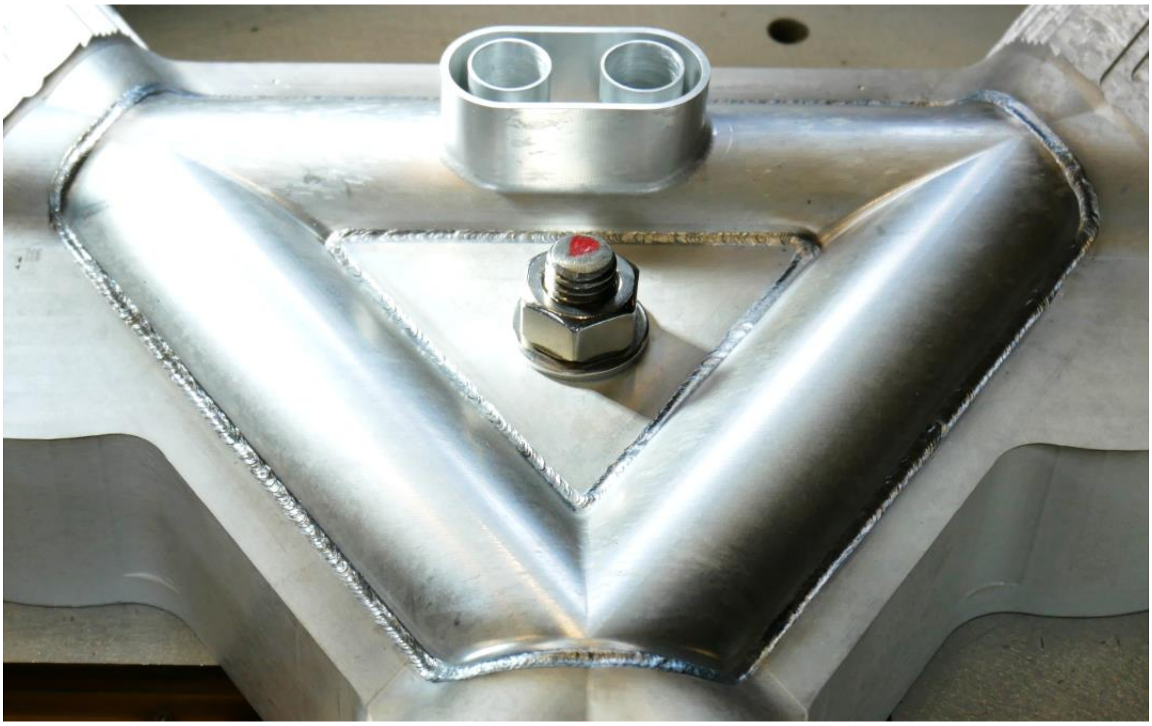


Figure 4.13: Vacuum vessel assembly after the final welding

4.2.2 WPS of the vacuum vessel

JÜLICH Forschungszentrum	Schweissprotokoll Elektronenstrahl-Schweißen SG Tube Moderator	Maschinentyp:	EBM - K40
		Masch.-Operateur:	Hans-Josef Pistel
		Datum:	21. Juli 2022

Auftrags-Nr.:	D.Z.004191	Werkstoff:	EN AW-6061 T6 + EN AW-4047	Vorrichtung:	Aufspanntisch
Zeichnungs-Nummer:	S298-000028 (Naht aussen)	Schweißtiefe:	1,96mm / 3,95mm + SZW	Programm:	SNS_HEFT.EBC / SNS_T_12.EBC
Kunde:	Beßler	Abmessung:	siehe Zeichnung	Kathodentyp:	Bandkathode 1.4
Bezeichnung:	SG Tube Moderator	Reinigung:	gebeizt	Dateien:	

Nr.	U SH (kV)	I SQ (mA)	V F (mm/s)	Korrektur-wert Isk sw	Fokus 1 SL (mA)	Fokus 2 SL (mA)	Ablenkung Amplitude x (mm)	Ablenkung Amplitude y (mm)	Ablenkung Frequenz (Hz)	Figur (neu)	Slope Auf (mm)	Slope Ab (mm)	Arbeits-abstand (vom Tisch) mm	Fokus (mm)	Bemerkung
26_01	1400	35	200	392	1883		1.0	2.0	1000	E1				0	Heftnaht, Manuell aus- und einschalten über Handrad
eftnaht, manu	140 kV	3,5 mA	20 mm/s												alle circa 20 mm, circa 10 mm lang
	1400	35	200	392	1883		1.0	2.0	1000	E1				0	Heftnaht
Heftnaht	140 kV	3,5 mA	20 mm/s												
	1400	80 / 120	200	392	1883		1.0	2.0	1000	E1				0	Schweißnaht
Schweißnaht	140 kV	8 / 12 mA	20 mm/s												Strahlparameter sind variabell, siehe Zusatzblatt

Figure 4.14: Welding parameter overview of the outer filler (due to single point programming and path interpolation only min. and max. values for beam current #I are given) [6]

Schweissprotokoll

Elektronenstrahl-Schweißen SG Tube Moderator

JÜLICH FORSCHUNGSZENTRUM

Maschinentyp:	**EBM - K40**				
Masch.-Operateur:	**Hans-Josef Pistel**				
Datum:	**21. Juli 2022**				
Auftrags-Nr.:	**D.Z.004191**	Werkstoff:	**EN AW-6061 T6 + EN AW-4047**	Vorrichtung:	**Aufspanntisch**
Zeichnungs-Nummer:	**S298-000028 (Naht innen)**	Schweißtiefe:	**3,95mm + SZW**	Programm:	**SNS_HEFT.EBC / SNS_T_12.EBC**
Kunde:	**Beßler**	Abmessung:	**siehe Zeichnung**	Kathodentyp:	**Bandkathode 1.4**
Bezeichnung:	**SG Tube Moderator**	Reinigung:	**gebeizt**	Dateien:	

Nr.	U SH (kV)	I SQ (mA)	V F (mm/s)	Korrektur-wert Isk sw	Fokus 1 SL (mA)	Fokus 2 SL (mA)	Ablenkung Amplitude x (mm)	Ablenkung Amplitude y (mm)	Ablenkung Frequenz (Hz)	Figur (neu)	Slope Auf (mm)	Slope Ab (mm)	Arbeits-abstand (vom Tisch) mm	Fokus (mm)	Bemerkung
26_01	**1400**	**35**	**200**	**392**	**1883**		**1.0**	**2.0**	**1000**	**E1**				**0**	Heftnaht, Manuell aus- und einschalten über Handrad
eftnaht, manu	140 kV	3,5 mA	20 mm/s												alle circa 20 mm, circa 10 mm lang
	1400	**35**	**200**	**392**	**1883**		**1.0**	**2.0**	**1000**	**E1**				**0**	Heftnaht
Heftnaht	140 kV	3,5 mA	20 mm/s												
	1400	**120**	**200**	**392**	**1883**		**1.0**	**2.0**	**1000**	**E1**				**0**	Schweißnaht
Schweißnaht	140 kV	12 mA	20 mm/s												Strahlparameter sind variabell, siehe Zusatzblatt

Figure 4.15: Welding parameter overview of the inner filler (due to single point programming and path interpolation only min. and max. values for beam current #I are given) [7]

5 DESTRUCTIVE & NON-DESTRUCTIVE TESTING

5.1 Grinding patterns of the hydrogen vessel welding sample

The grinding patterns were processed after the welding of the first of five samples with the final geometry. The following Figure 5.1 & Figure 5.2 show grinding patterns of the tack-weld of the first of five test samples. Air pockets and remaining filler material visible in the pictures will be fully melted after the evaluation of the final welding parameters and during the final weld step.

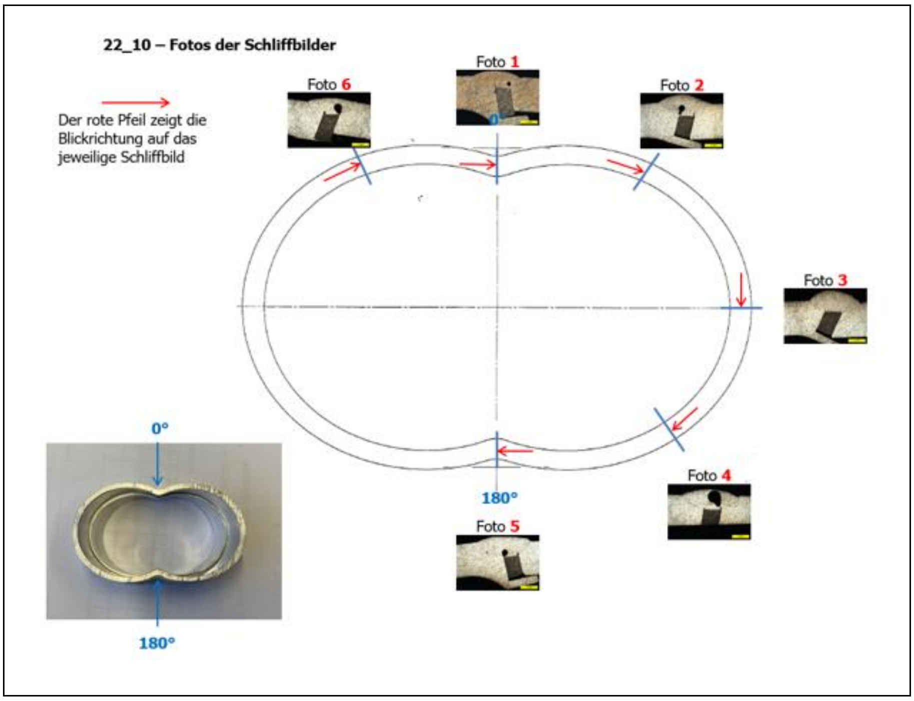


Figure 5.1: Destructive testing of sample #1

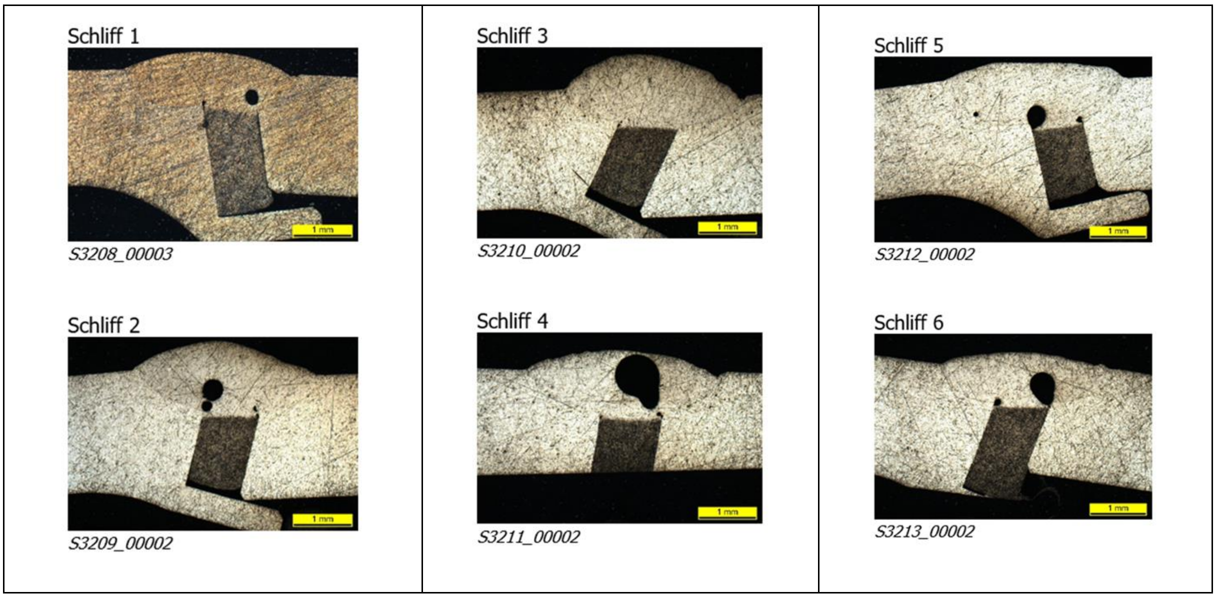


Figure 5.2: Destructive testing of sample #1: Grind patterns after first pass

5.1.1 Parameter Optimization

The grinding patterns in Figure 5.3 & Figure 5.4 were processed after the welding of sample #4 of 5 with the final geometry and further more developed welding parameters. For the final test piece, the welding parameters were adapted due to these results again.

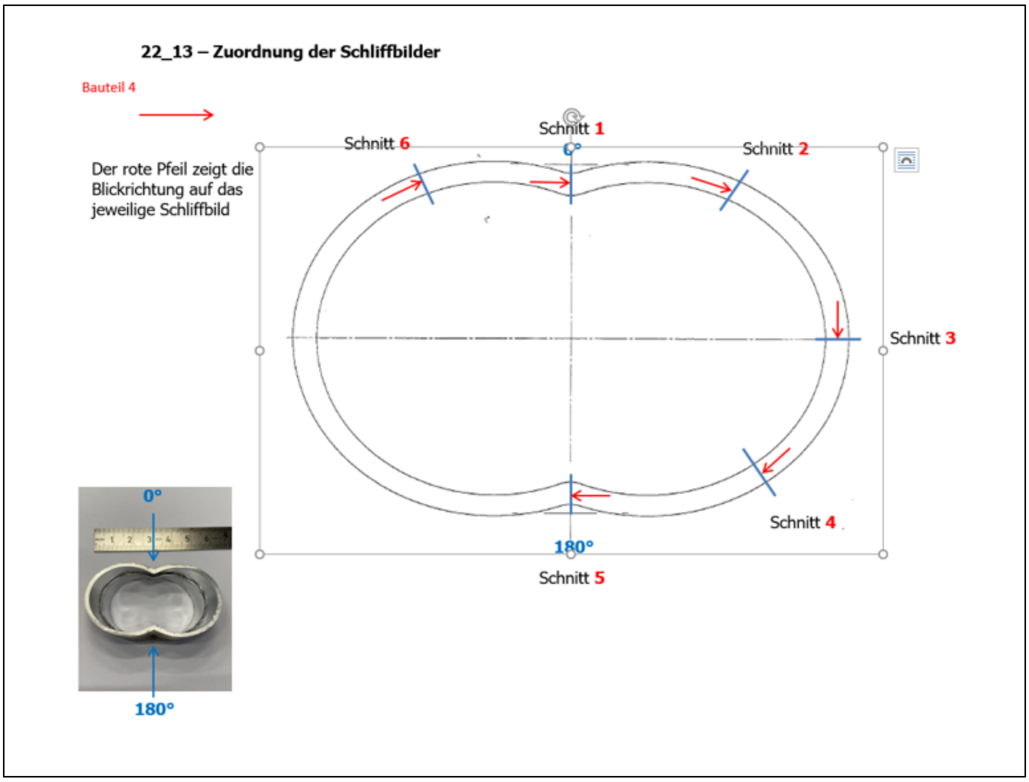


Figure 5.3: Destructive testing of sample #4

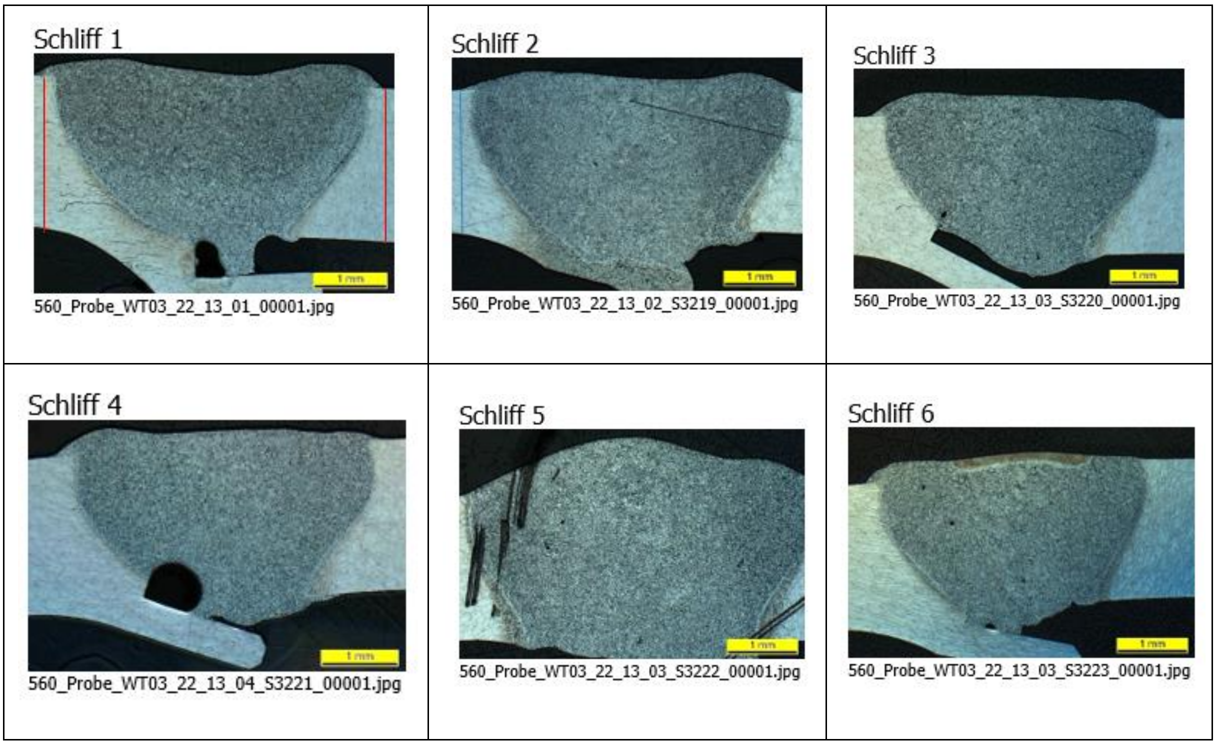


Figure 5.4: Destructive testing of sample #4: Grinding patterns

5.2 Grinding patterns of the vacuum vessel welding sample

The grinding patterns in Figure 5.5 were processed after the welding of the first sample with the final geometry. These were the basis for welding parameter optimization for the following samples and the final weld.

Figure 5.5: Destructive testing of sample #1: Grind patterns after first pass

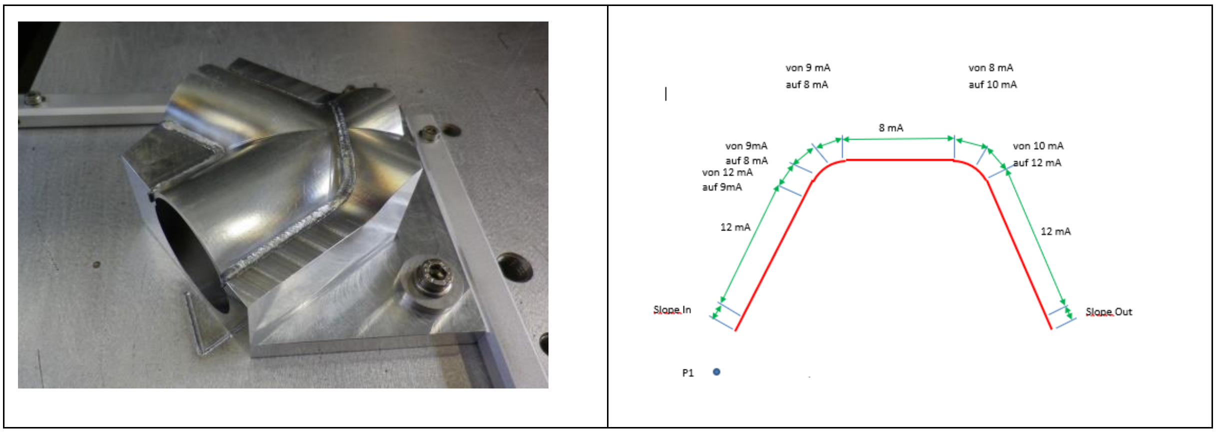


Figure 5.6: Programming of the WPS

5.2.1 Parameter Optimization

To define the parameters, the micrographs of the tube moderator vacuum vessel test part weld were evaluated and assigned to the respective path positions. Based on the detailed definition of the first teach points in the belonging sketches in Figure 4.7, Figure 4.8 & Figure 5.9, the adapted welding parameters could be inserted into the welding program and the beam power was specifically increased in the belonging teach points.

Figure 5.7 shows the third and final welding sample with optimized parameters; P4a – 6 were optimized in a second step by rising up the beam power about 6 %.

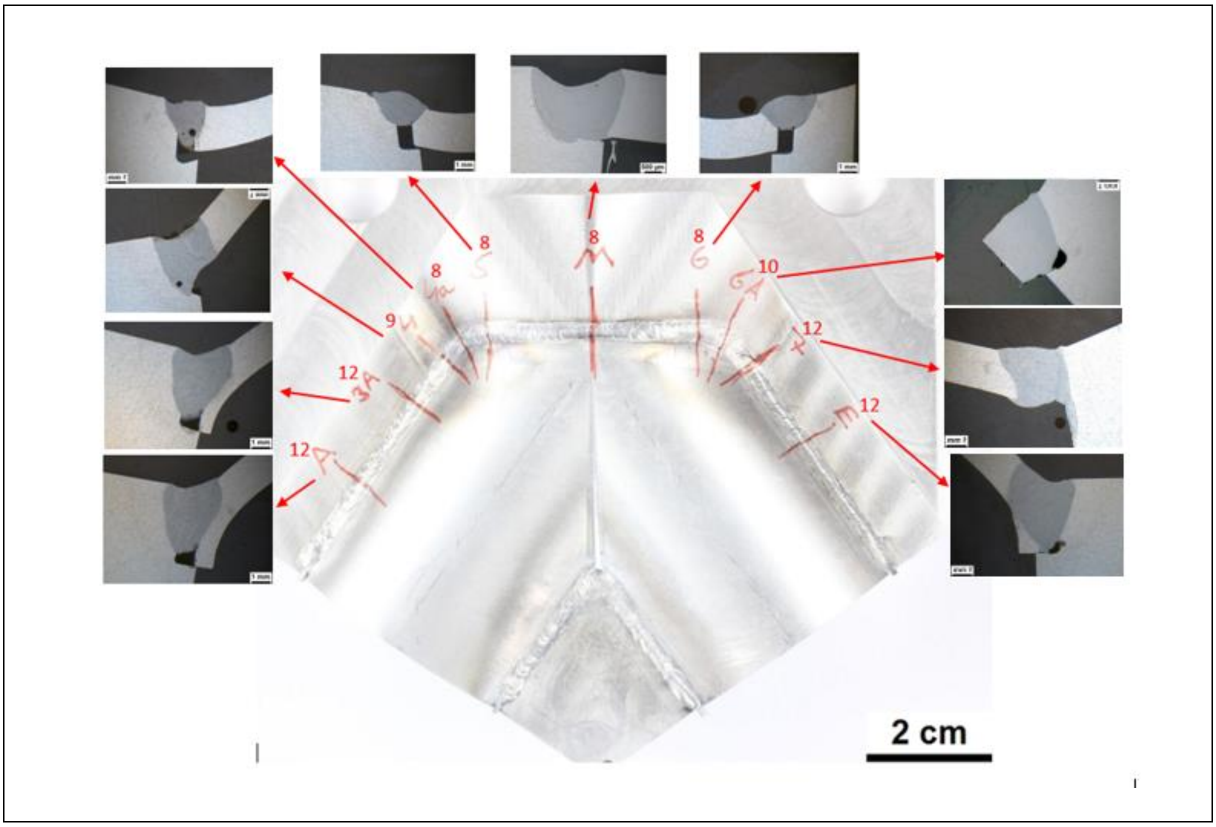


Figure 5.7: Test part with weld seam evaluation

Finally, the whole welding program was updated with the pre-evaluated parameters. The heat consumption at original geometry was considered and overlapping at slope-in area with full power welding parameters were adopted, as shown Figure 5.8.

```
Programm:  SNS_T_12.EBC

N0001  (Pistel 12.07.2022)
N0002  (Teachprogramm SNS Moderator)
N0003  G04  SL1883  SH1400  SW392  F1000
N0004  G29  X1  Y1.7  SF150  E1  F100  (Figur Ellipse)
N0005
N0006  G00  G90  X-34.67  Y14.64  (Werkstück-Nullpunkt anfahren)
N0007  G92  X0  Y0  (Nullpunkt setzen)
N0008  M32
N0009  G63  SQ1  (Strahl aufs Handrad legen)
N0010  G01  G90  X-85.61  Y-25.21  F100  (P1)  (Startpunkt anfahren)
N0011  G01  G90  X-78.12  Y-14.34  SQ120  (P2)  (Strahl hochfahren)
N0012  G01  G90  X-27.17  Y58.39  (P3)
N0013  G01  G90  X-23.22  Y64.43  SQ90  (P4)
N0014  G03  G17  G90  X-21.13  Y67.32  I-143.83  J153.85  SQ80  (P5)
N0015  G02  G17  G90  X-17.35  Y68.93  I-14.79  J57.68  SQ85  (P6)
N0016  G01  G90  X-14  Y68.93  SQ80  (P7)
N0017  G01  G90  X14  Y68.93  (P8)
N0018  G01  G90  X16.17  Y68.93  SQ85  (P10)
N0019  G02  G17  G90  X19.55  Y68.11  I16.6  J63.36  SQ100  (P11)
N0020  G03  G17  G90  X21.1  Y66.88  I36.02  J87.28  SQ110  (P12)
N0021  G01  G90  X23.52  Y63.73  SQ120  (P12a)
N0022  G01  G90  X89.69  Y-30.69  (P13)
N0023  G01  G90  X90.12  Y-31.62  SQ90  (P14)
N0024  G02  G17  G90  X90.86  Y-34.72  I85.94  J-34.25  SQ80  (P15)
N0025  G02  G17  G90  X90.46  Y-37.11  I83.34  J-34.69  SQ85  (P16)
N0026  G01  G90  X88.52  Y-41.02  SQ80  (P17)
N0027  G01  G90  X78.84  Y-59.93  (P18)
N0028  G01  G90  X77.13  Y-63.32  SQ85  (P19)
N0029  G02  G17  G90  X75.15  Y-66.28  I33.16  J36.05  SQ85  (P20)
N0030  G02  G17  G90  X71.84  y-67.93  I70.73  J61.55  SQ100  (P21)
N0031  G01  G90  X67.44  Y-67.93  SQ120  (P22)
N0032  G01  G90  X-64.13  Y-68.15  (P23)
N0033  G01  G90  X-68.34  Y-68.16  SQ90  (P24)
N0034  G02  G17  G90  X-73.23  Y-67.33  I-68.56  J-54.66  SQ80  (P25)
N0035  G02  G17  G90  X-76.44  Y-64.57  I-69.3  J-59.51  SQ85  (P26)
N0036  G01  G90  X-78.47  Y-60.95  SQ80  (P27)
N0037  G01  G90  X-89.18  Y-39.67  (P28)
N0038  G01  G90  X-90.11  Y-38.11  SQ85  (P29)
N0039  G02  G17  G90  X-90.77  Y-35.35  I-86.23  J-35.73  SQ100  (P31)
N0040  G02  G17  G90  X-89.83  Y-31.42  I-85.01  J-34.66  SQ110  (P32)
N0041  G01  G90  X-84.91  Y-24.09  SQ120  (P32a)
N0042  G01  G90  X-44.54  Y33.82  (P33)
N0043  G01  G90  X-25.93  Y60.32  SQ0  (P34)  (Strahl herunterfahren)
N0044
N0045  (Wechsel Innenkontur)
N0046  G01  G90  X-37.48  Y-20.37  (P35)
N0047  G01  G90  X-27.97  Y-7.05  SQ120  (P36)  (Strahl hochfahren)
```

Figure 5.8: Final welding program of the outer and inner weld-seam of the vacuum vessel

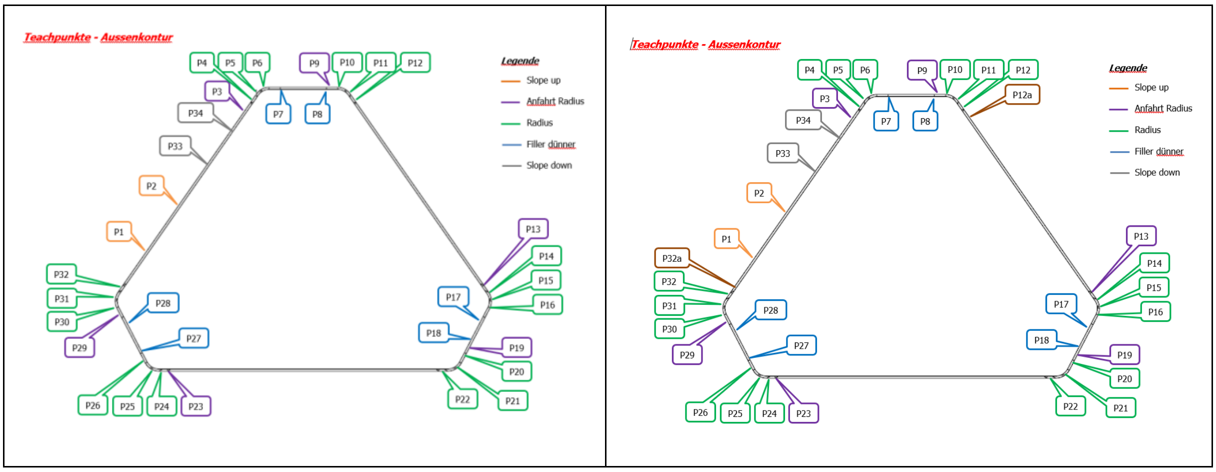


Figure 5.9: First (left) and corrected and supplemented (right) teach program points after ground joint evaluation

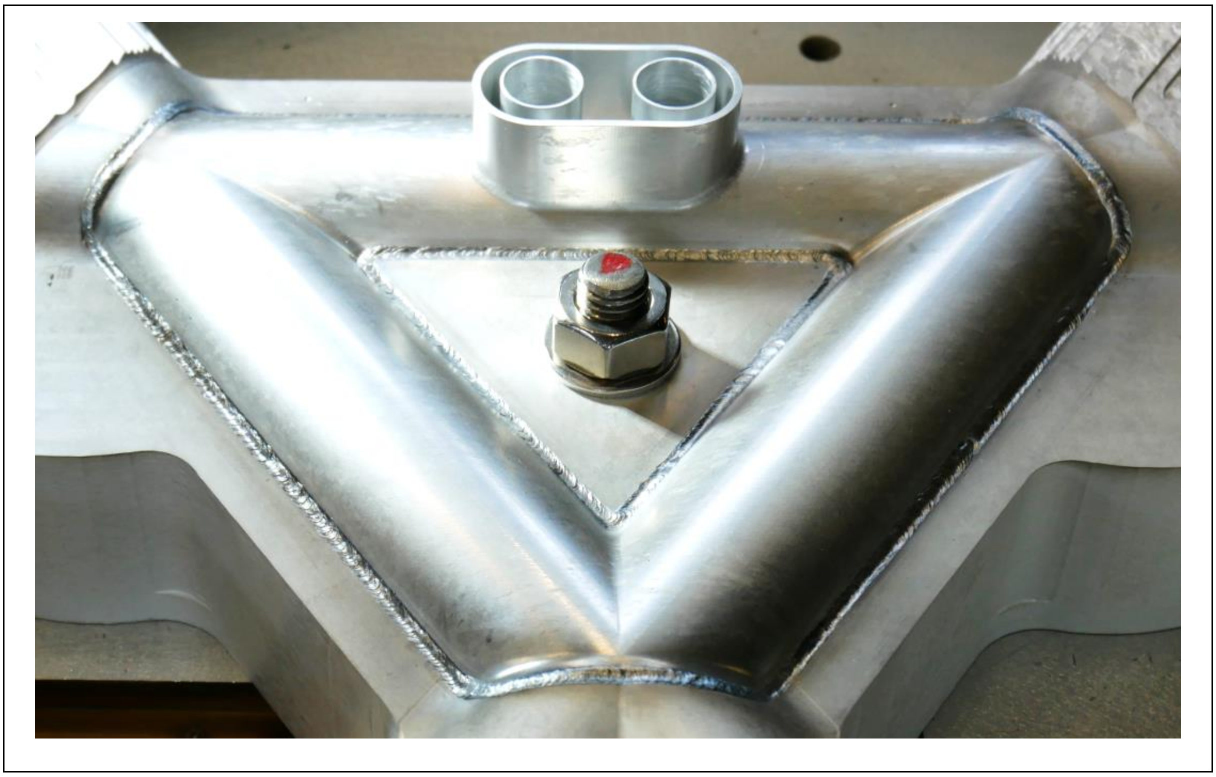


Figure 5.10: Vacuum vessel assembly after the final welding

5.3 NDT of the welding samples

Figure 5.11 shows the evaluation of hydrogen vessel welding tests of the final test samples with computed tomography scans (CT).

The CT pictures in Figure 5.12, Figure 5.13, Figure 5.14 & Figure 5.15 show the results of the final weld of sample #2 to #5 of 5, that represent good evaluation of the welding parameters in terms of weld seam penetration. For more details on the CT scan of sample #4 watch the provided video by FZ Jülich [8].

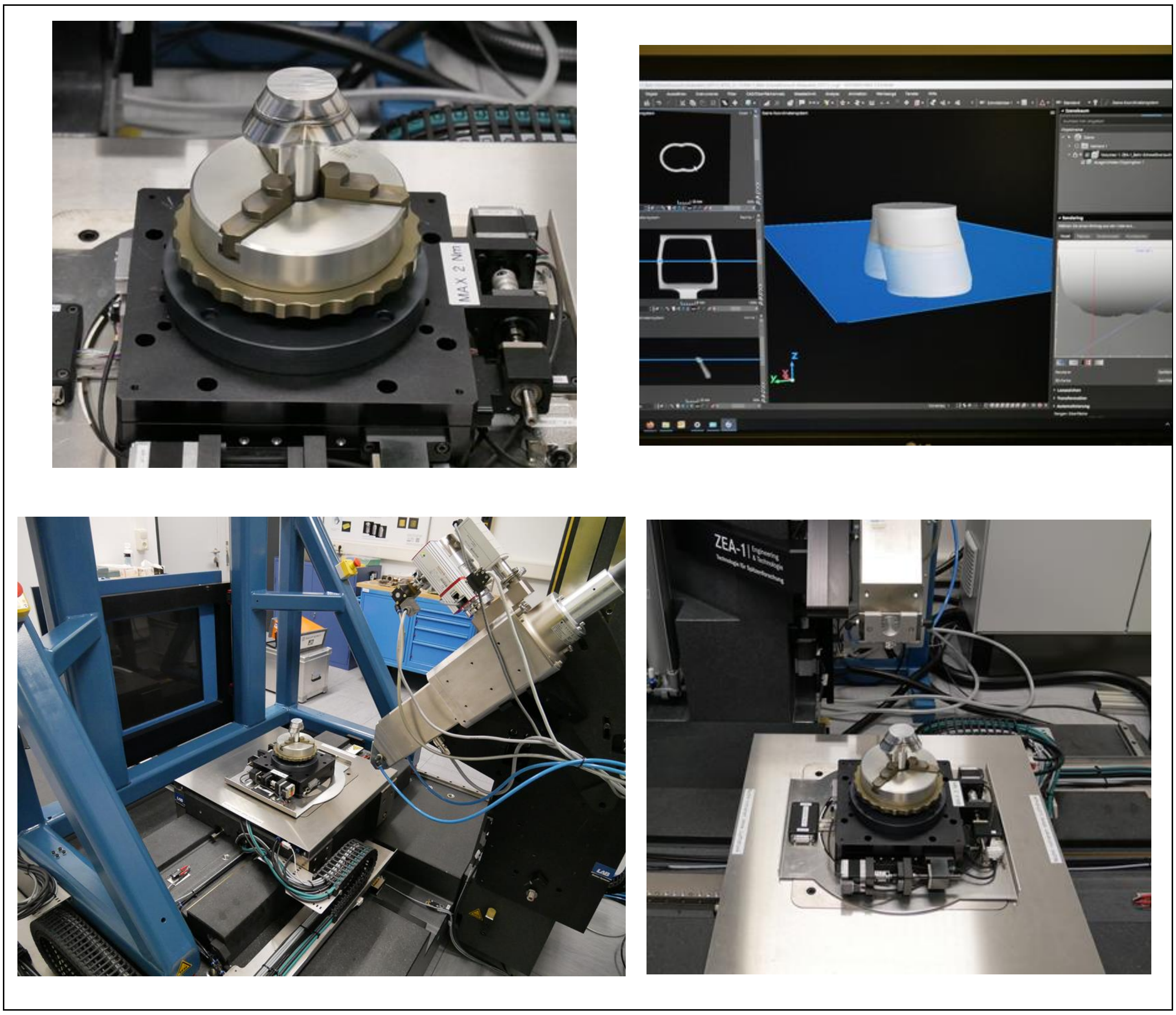


Figure 5.11: Welding sample of the hydrogen vessel on the CT machine

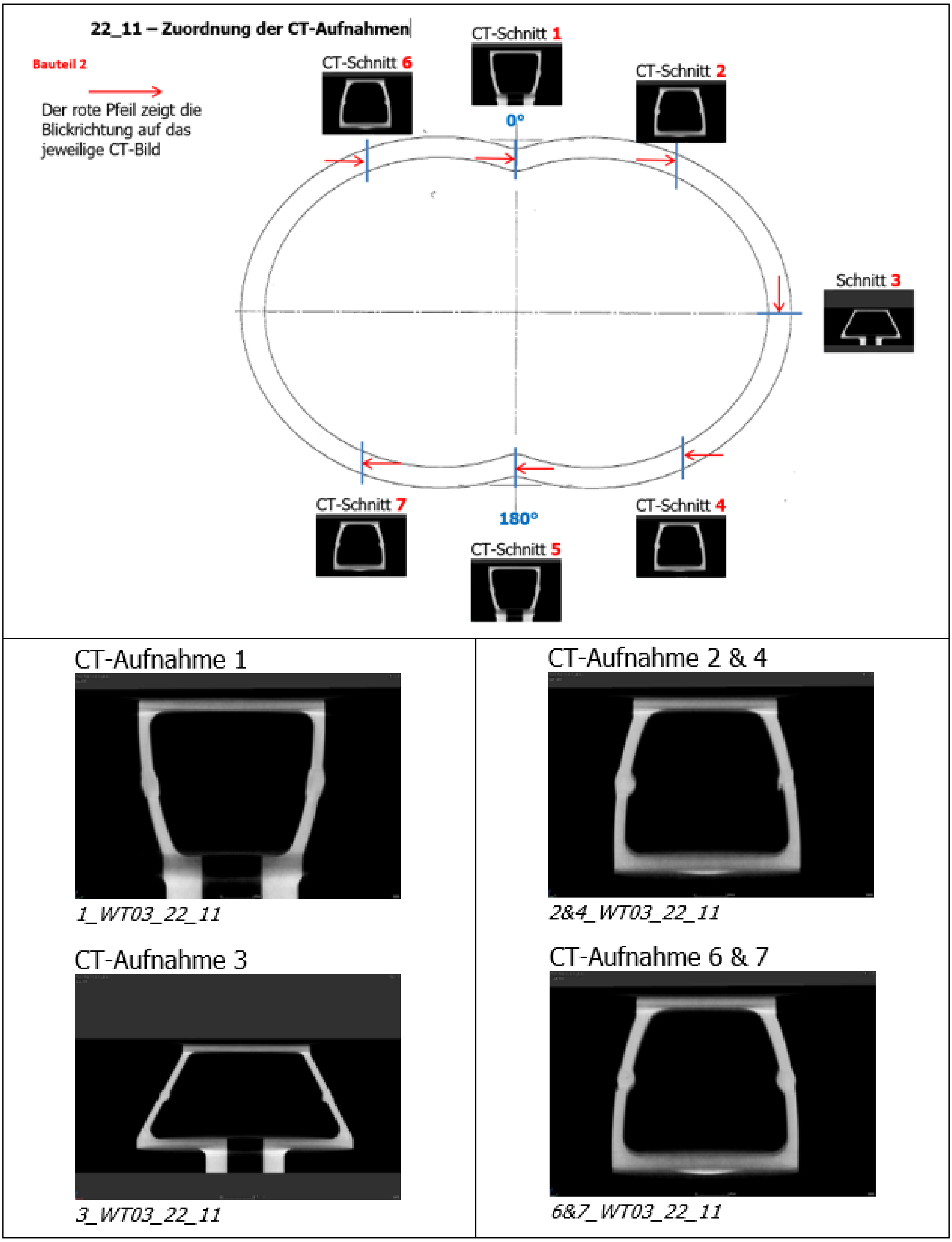


Figure 5.12: Non-destructive testing of sample #2: CT-scan after final pass

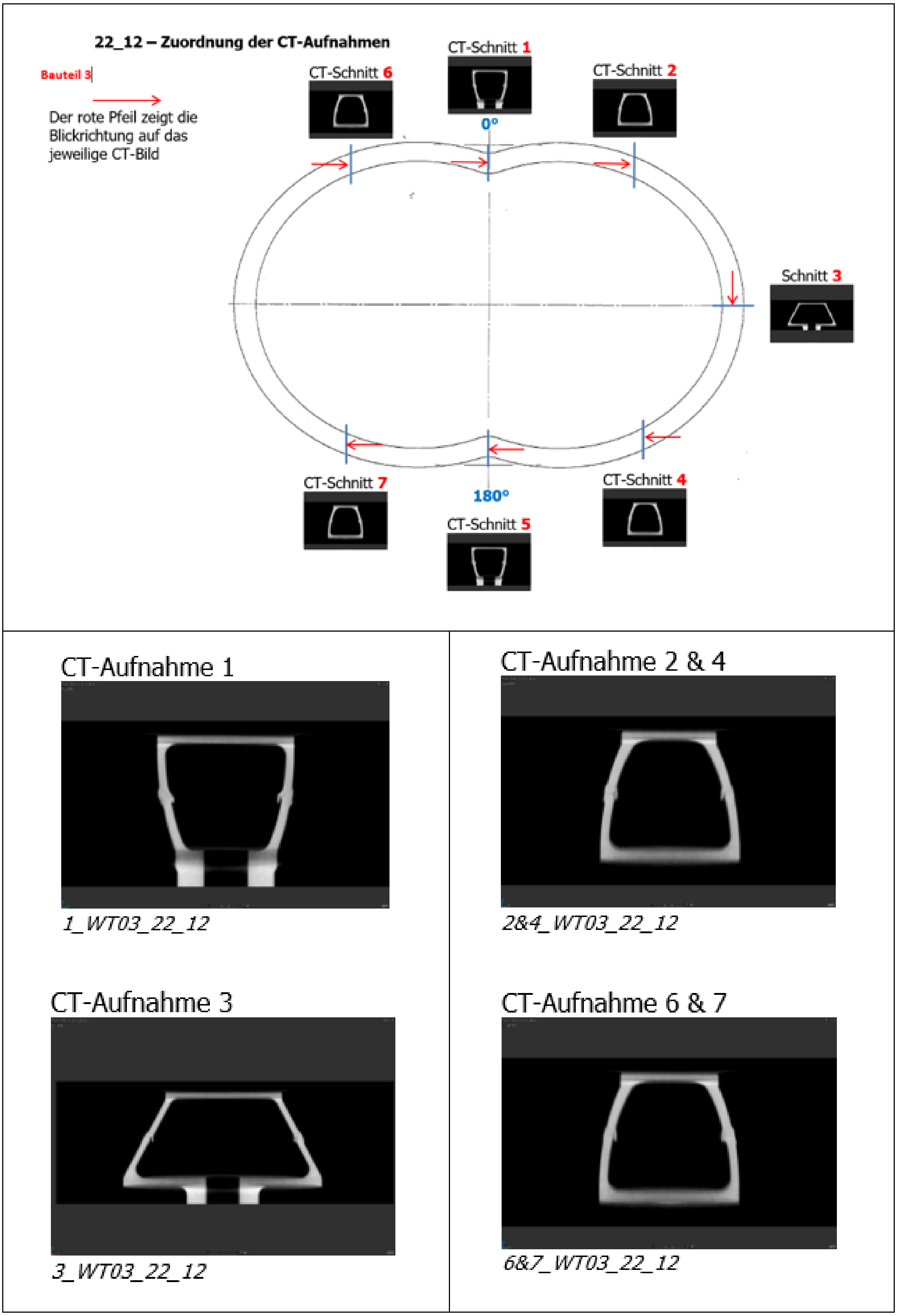


Figure 5.13: Non-destructive testing of sample #3: CT-scan after final pass

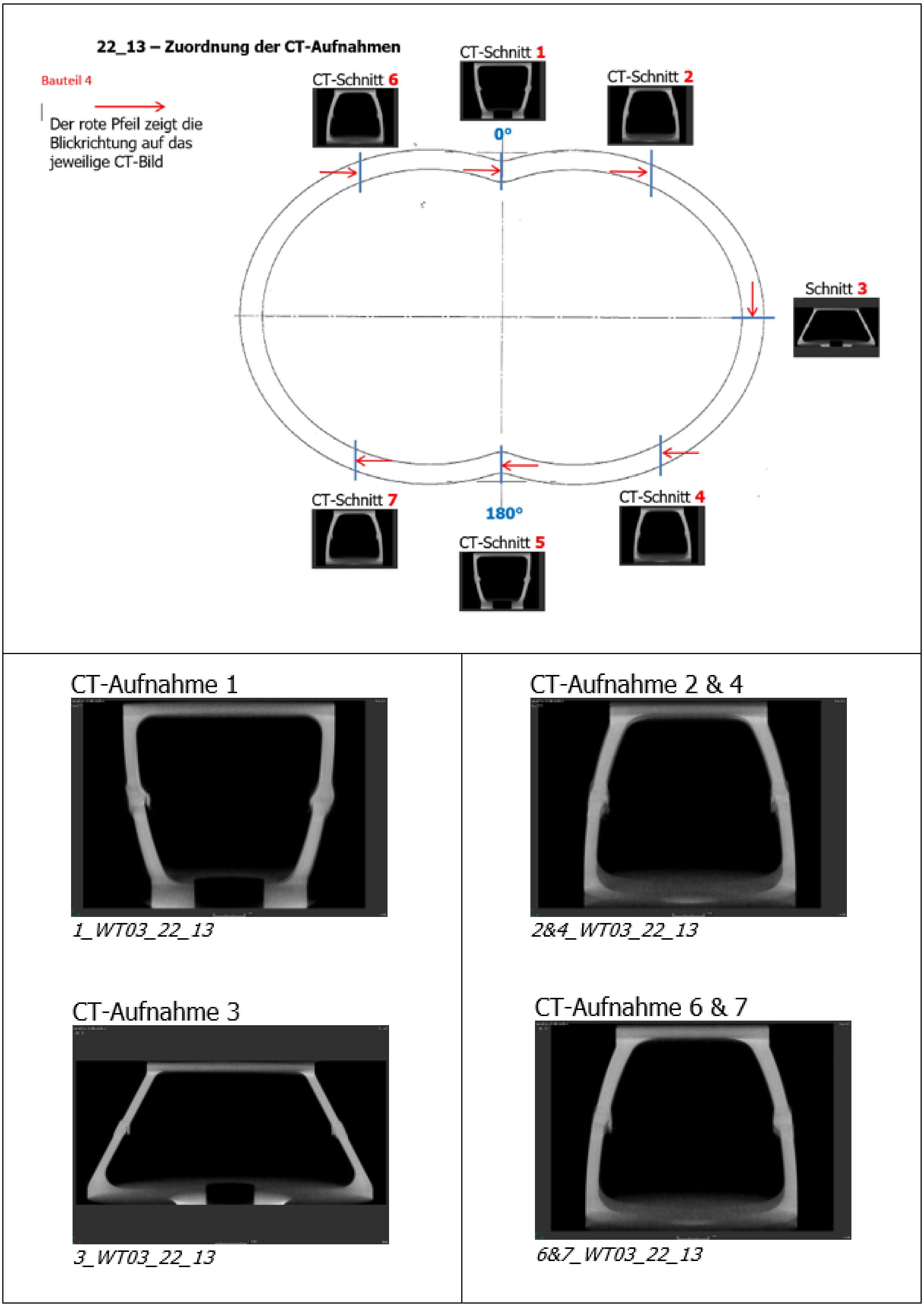


Figure 5.14: Non-destructive testing of sample #4: CT-scan after final pass

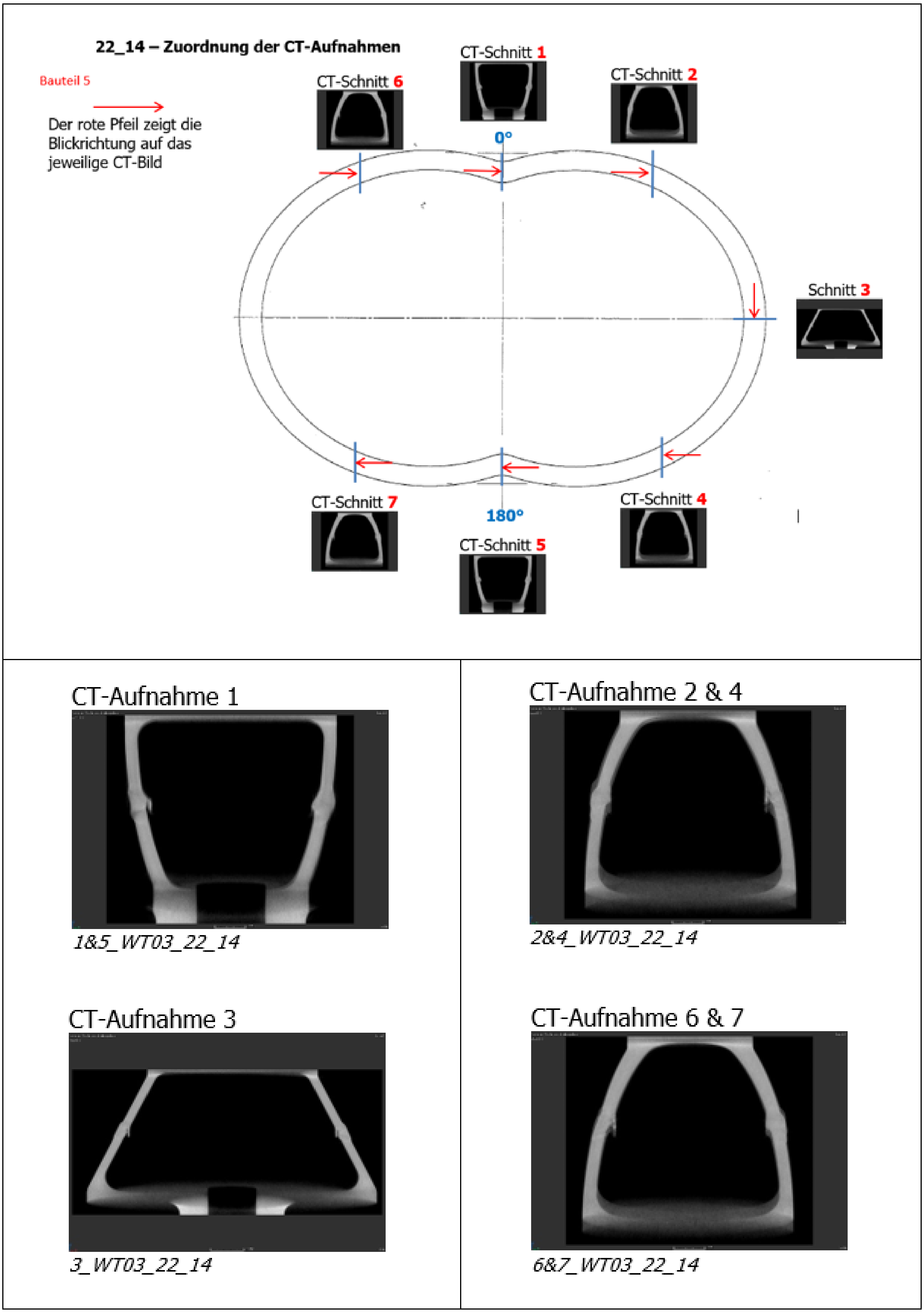


Figure 5.15: Non-destructive testing of sample #5: CT-scan after final pass

As a final step, all 5 welding samples of the hydrogen vessel were helium leak tested after the final welding procedure. As shown in Figure 5.16 all samples had a leak rate of ql ≤ $1x10^{-9}$ mbar*l/s.

Prüfübersicht - Helium Lecktest

SNS Tube-Moderator Hydrogen Vessel

Auftrags-Nr.: D.Z.004191

Kunde: Hr. Beßler

Bauteil-Nr.:	*Zeichnungs-Nr.:*	*Prüfdatum*	*Prüfer*	*Prüfergebnis*
01	298-000044-a	10.01.2022	Carsten Hoven	$ql \leq 1x10^{-9}$ $mbar \cdot l \cdot s^{-1}$ FZJ 4
02	298-000044-a	11.01.2022	Carsten Hoven	$ql \leq 1x10^{-9}$ $mbar \cdot l \cdot s^{-1}$ FZJ 4
03	298-000044-a	12.01.2022	Carsten Hoven	$ql \leq 1x10^{-9}$ $mbar \cdot l \cdot s^{-1}$ FZJ 4
04	298-000044-a	18.01.2022	Carsten Hoven	$ql \leq 1x10^{-9}$ $mbar \cdot l \cdot s^{-1}$ FZJ 4
05	298-000044-a	19.01.2022	Carsten Hoven	$ql \leq 1x10^{-9}$ $mbar \cdot l \cdot s^{-1}$ FZJ 4

Figure 5.16: Test report helium leak tests

5.4 NDT of the final parts

5.4.1 NDT of the hydrogen vessel

After the final welding of the hydrogen vessel, the measurement of the assembly was performed on the CMM [9] [10].

- Shape and roundness of the three tubes
- Angle of the tubes and end caps
- Flatness of the and caps

The moderator vessel was also dye penetrant and leak tested and Figure 5.18 shows the additional CT scanning of the final piece. For more details watch the provided video by FZ Jülich [11].

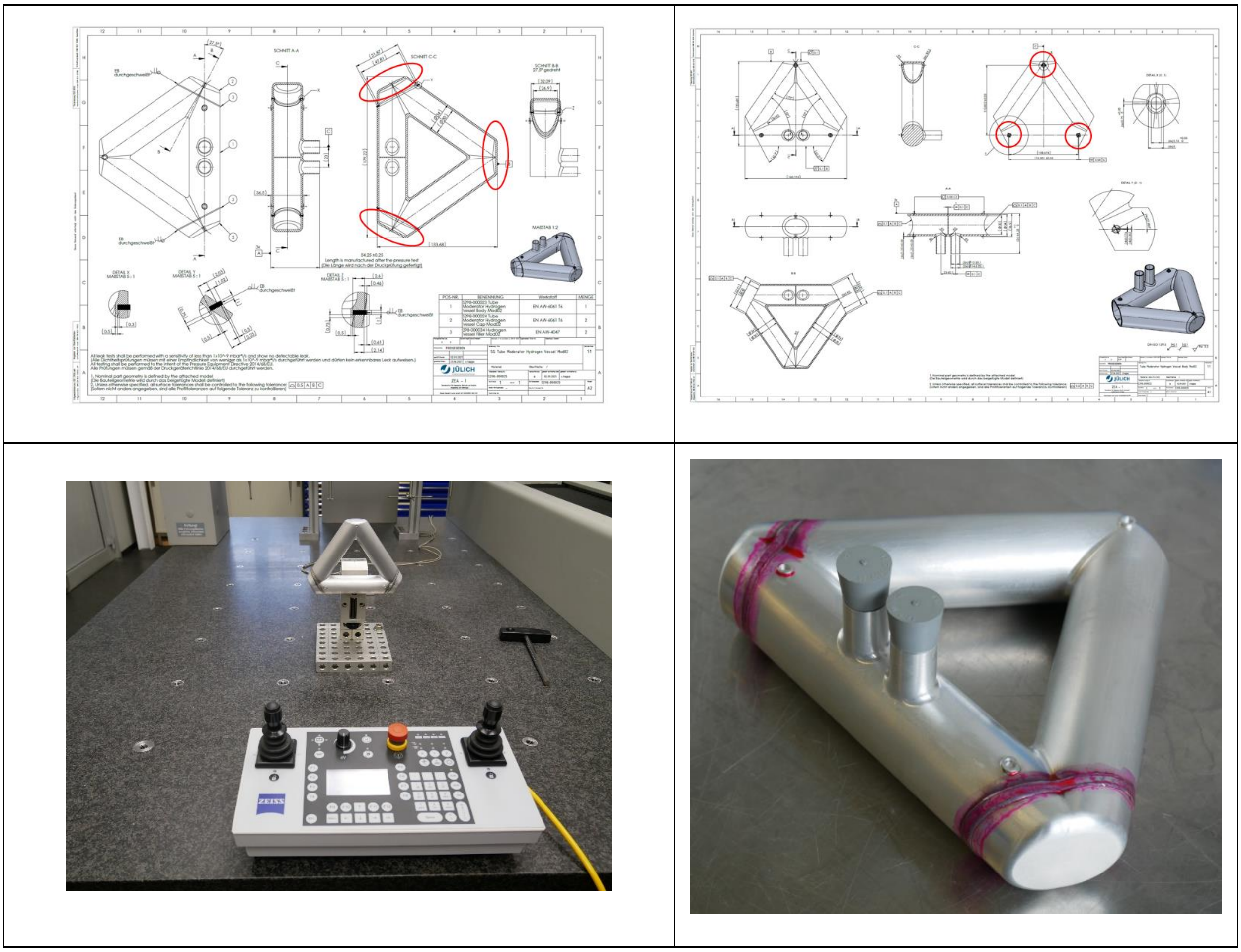


Figure 5.17: Different NDT of the hydrogen vessel

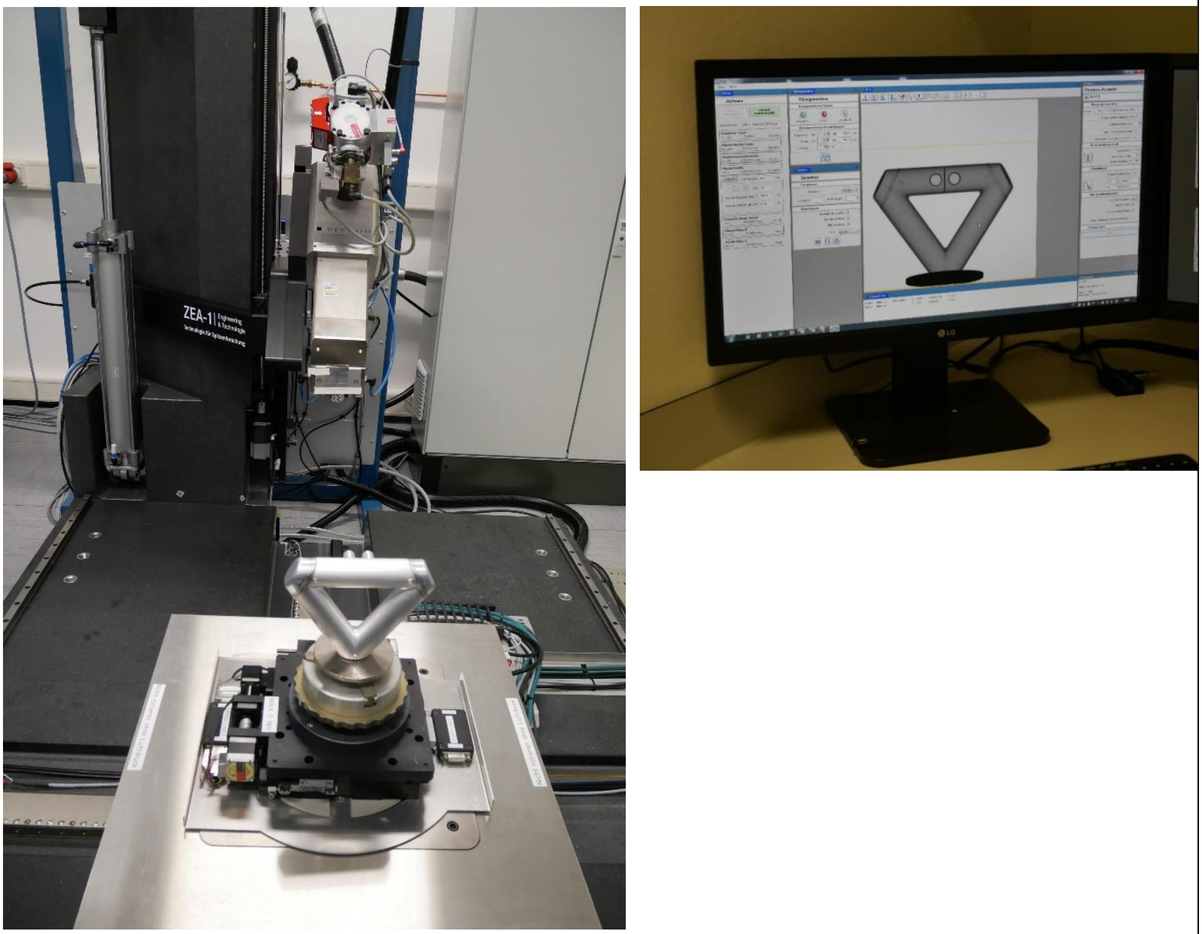


Figure 5.18: CT scan of the final hydrogen vessel

5.4.1.1 Evaluation of the electron beam weld seams of the hydrogen vessel

Evaluation of the electron beam weld seams according to EN ISO 13919-2 of the SNS tube moderator Hydrogen vessel.

Limit values for the assessment of irregularities according to assessment group C.

According to the standard, the following irregularities were evaluated:

1) surface irregularities
2) internal irregularities
3) irregularities in the seam geometry

Result:

All visible irregularities are outside the nominal wall thickness. All irregularities can be found at the beginning of the welding backer (see Figure 5.19 - Figure 5.24). The weld seam melted the welding backer without interruption, but not over the entire width, which explains the visible irregularities (see Figure 5.19 - Figure 5.24). In addition, no surface pores, end crater cavities, lack of fusion, end crater notches and weld seam undercut were found.

The dye penetrant test showed no external surface cracks [9].The helium leak test showed a leak rate of ql ≤ $1x10^{-9}$ mbar*l/s [9]. The visual inspection from the outside and from the inside with an endoscope showed no impermissible irregularities [9].

➔ All requirements according to EN ISO 13919-2 assessment group C are met!

The following figures show representative examples of the CT evaluation:

- Figure 5.19 & Figure 5.20: Top view of weld No.1 and No.2 picture 1-4
- Figure 5.21 & Figure 5.22: Left weld (No. 1) side view picture 1-6
- Figure 5.23 & Figure 5.24: Right weld (No. 2) side view picture 1-6

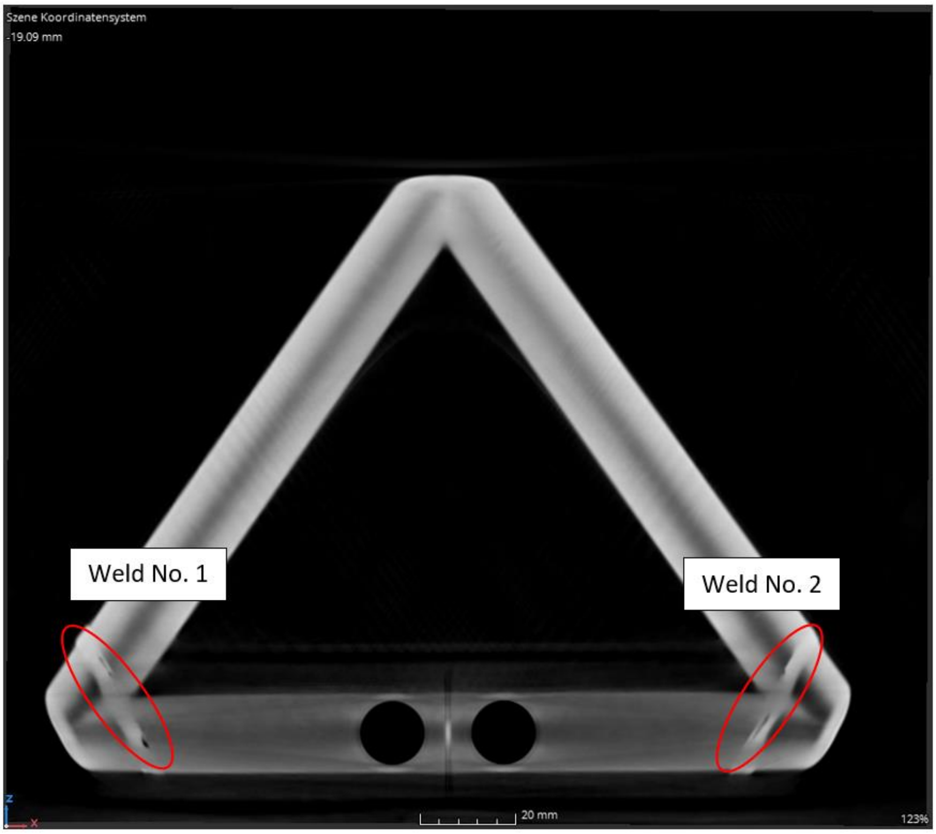


Figure 5.19: Top view of weld No.1 and No.2 picture 1-2

Figure 5.20: Top view of weld No.1 and No.2 picture 3-4

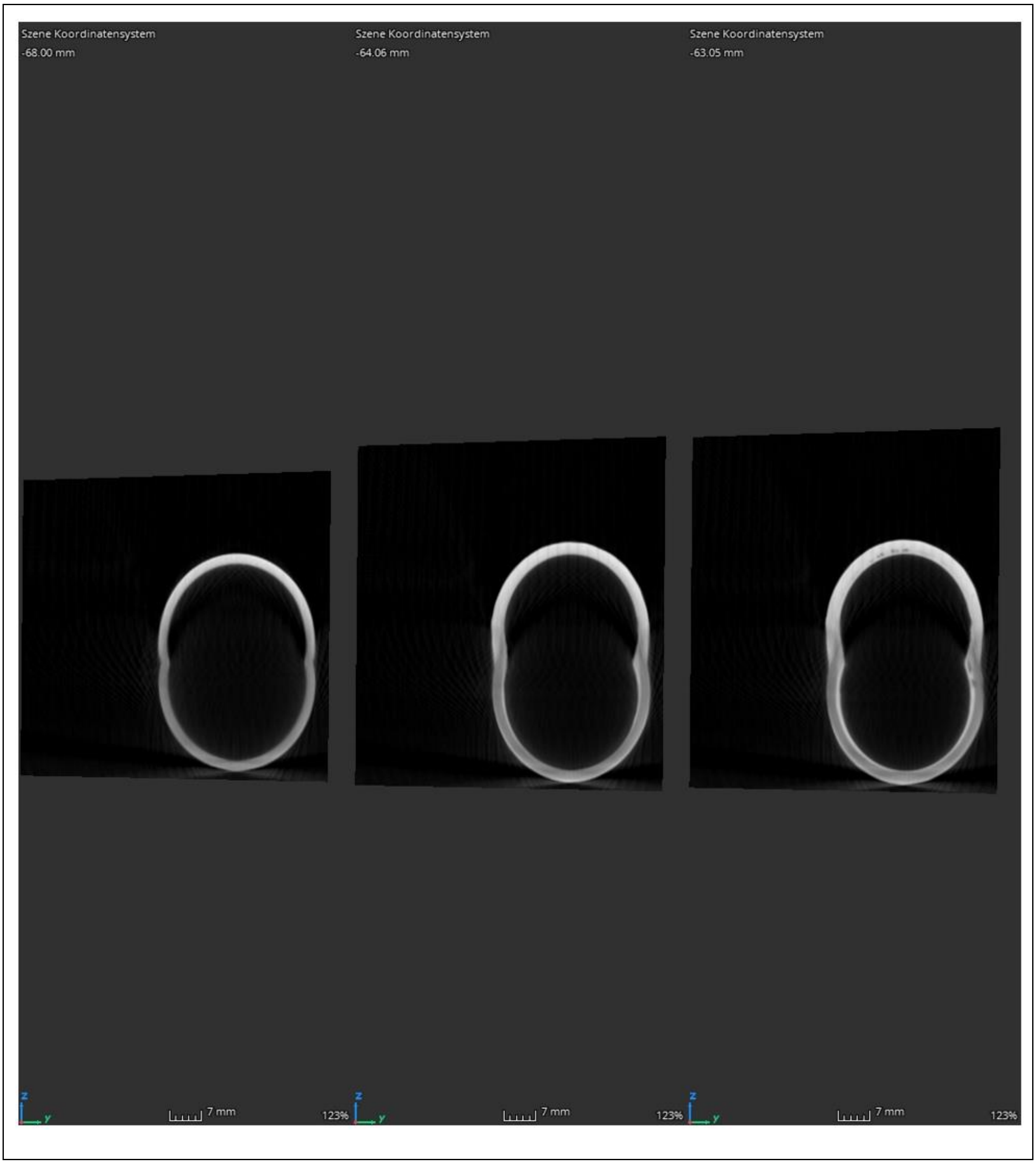


Figure 5.21: Left weld (No.1) side view picture 1-3

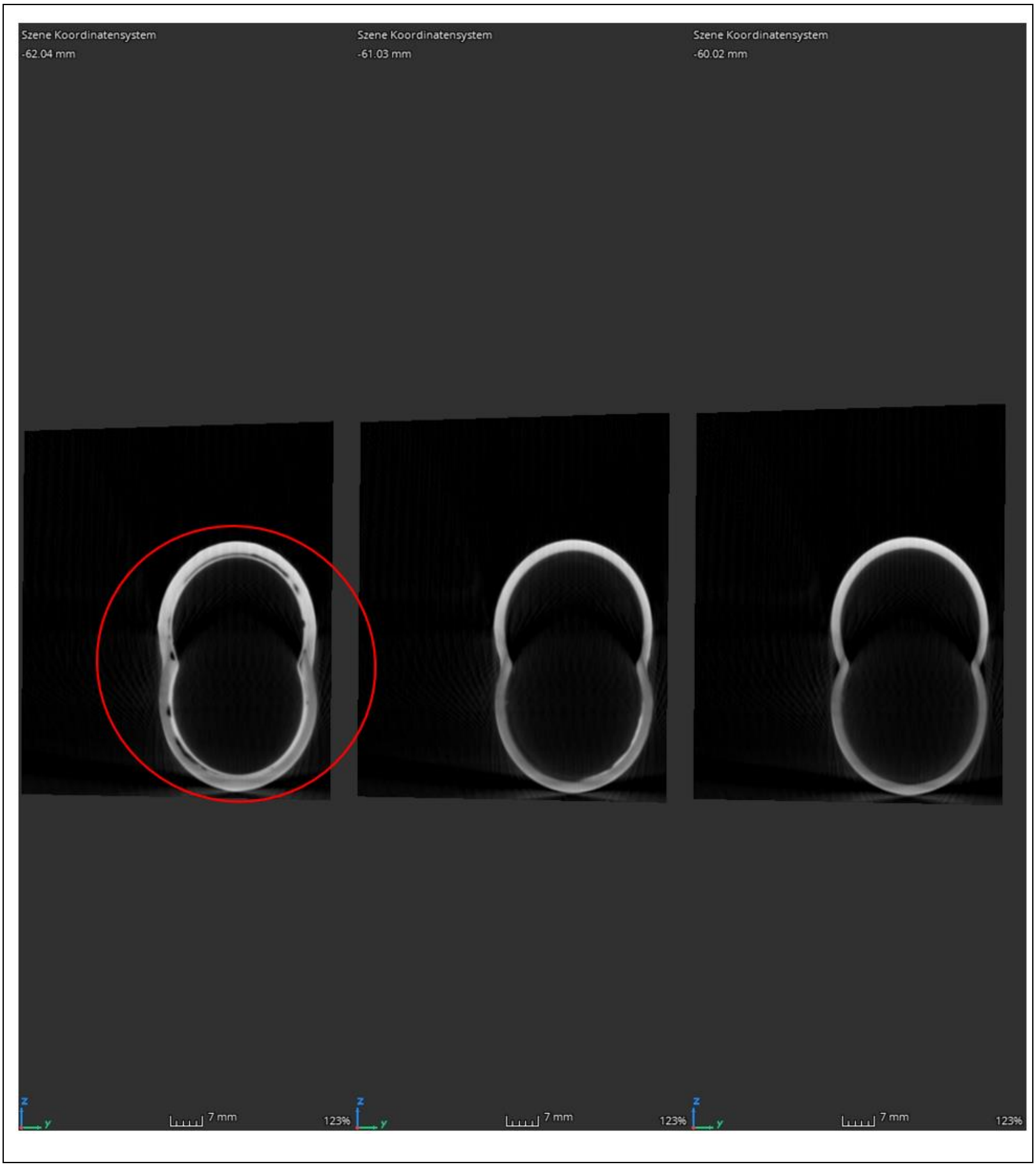


Figure 5.22: Left weld (No.1) side view picture 4-6

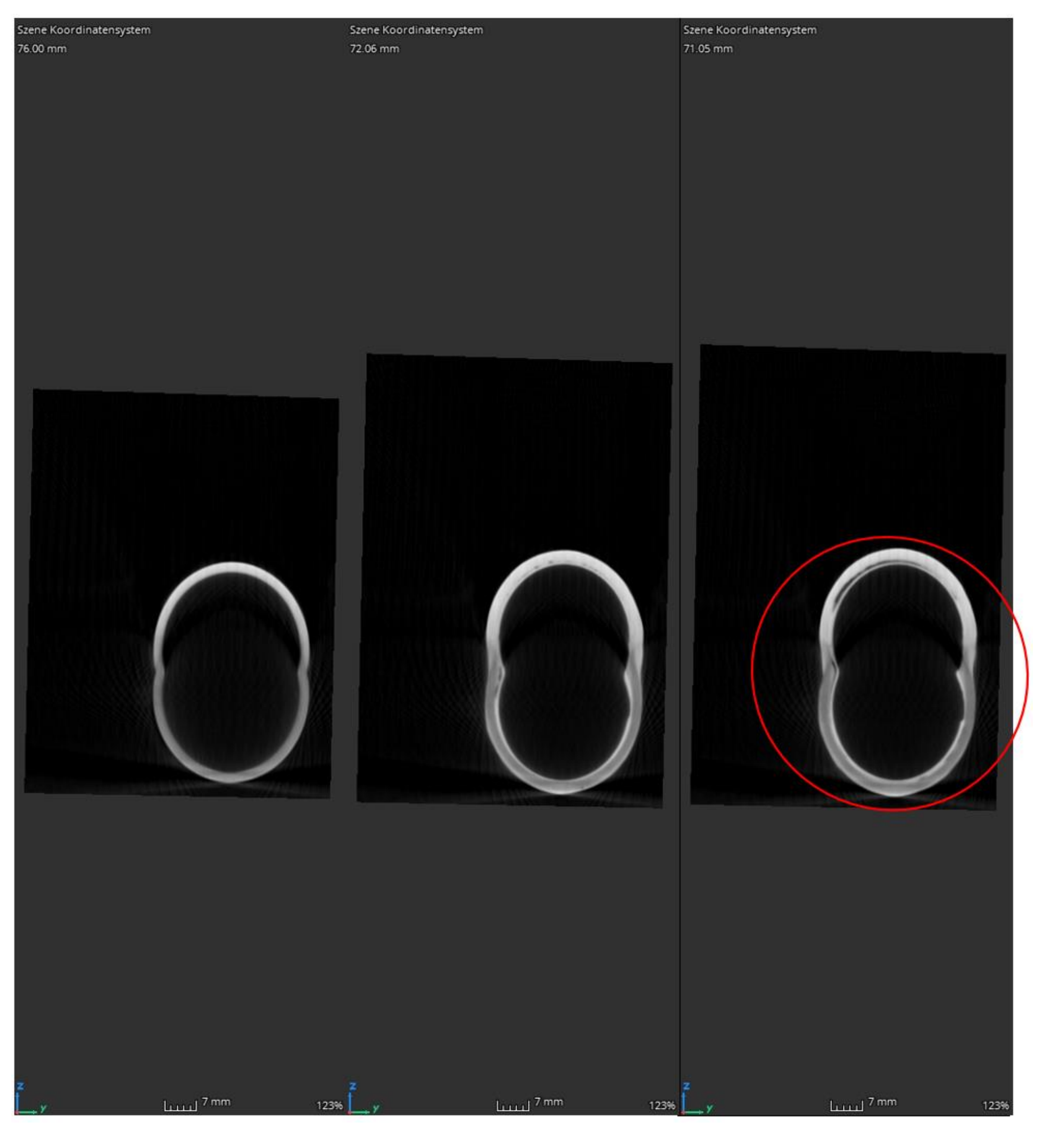


Figure 5.23: Right weld (No.2) side view picture 1-3

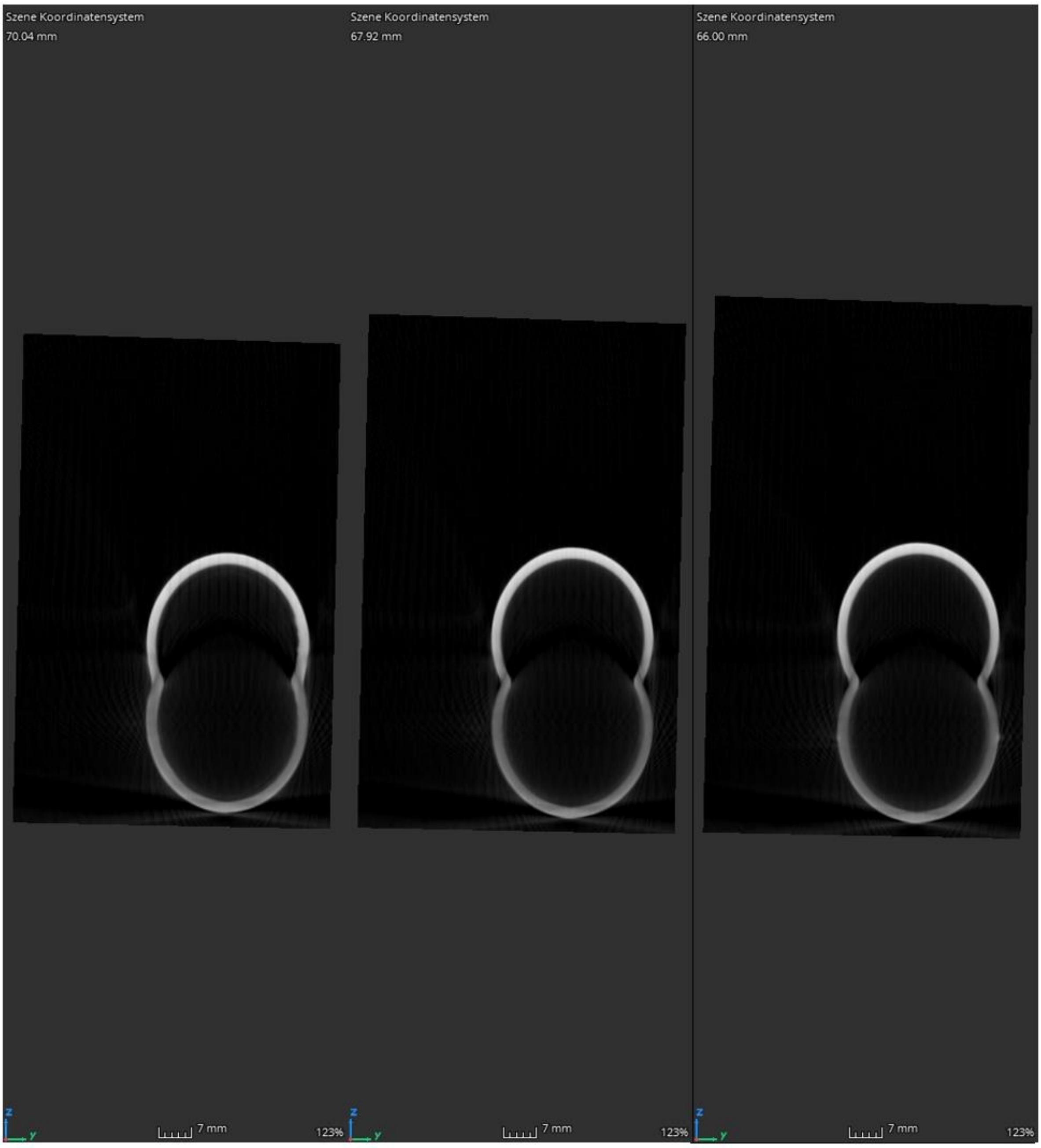


Figure 5.24: Right weld (No.2) side view picture 4-6

5.4.1.2 Cryogenic thermal shock cycling test of the hydrogen vessel

For the cryogenic thermal shock cycling test, the moderator is immersed in a bath filled with liquid nitrogen. The temperature is monitored with a type K thermocouple, which is attached to the inner shell of the moderator. After the temperature on the inner shell of the moderator has adjusted to a constant temperature (approx. 77K), this is maintained for at least 10 minutes. The moderator is then removed from the liquid and warm air from a hot air dryer is circulated around it for a faster warm-up period.

When the temperature at the inner shell is higher than 273.15K, the hot air dryer is switched off. After a waiting time of 5 minutes the temperature is equally distributed in the entire moderator structure.

This cycle of cryogenic thermal shocking and heating of the moderator is carried out a total of 10 times.

Figure 5.25: Picture of the moderator shortly before it is immersed into liquid nitrogen (left) and in the immersed state (right).

Figure 5.26 shows the temperature vs duration profile during the test setup.

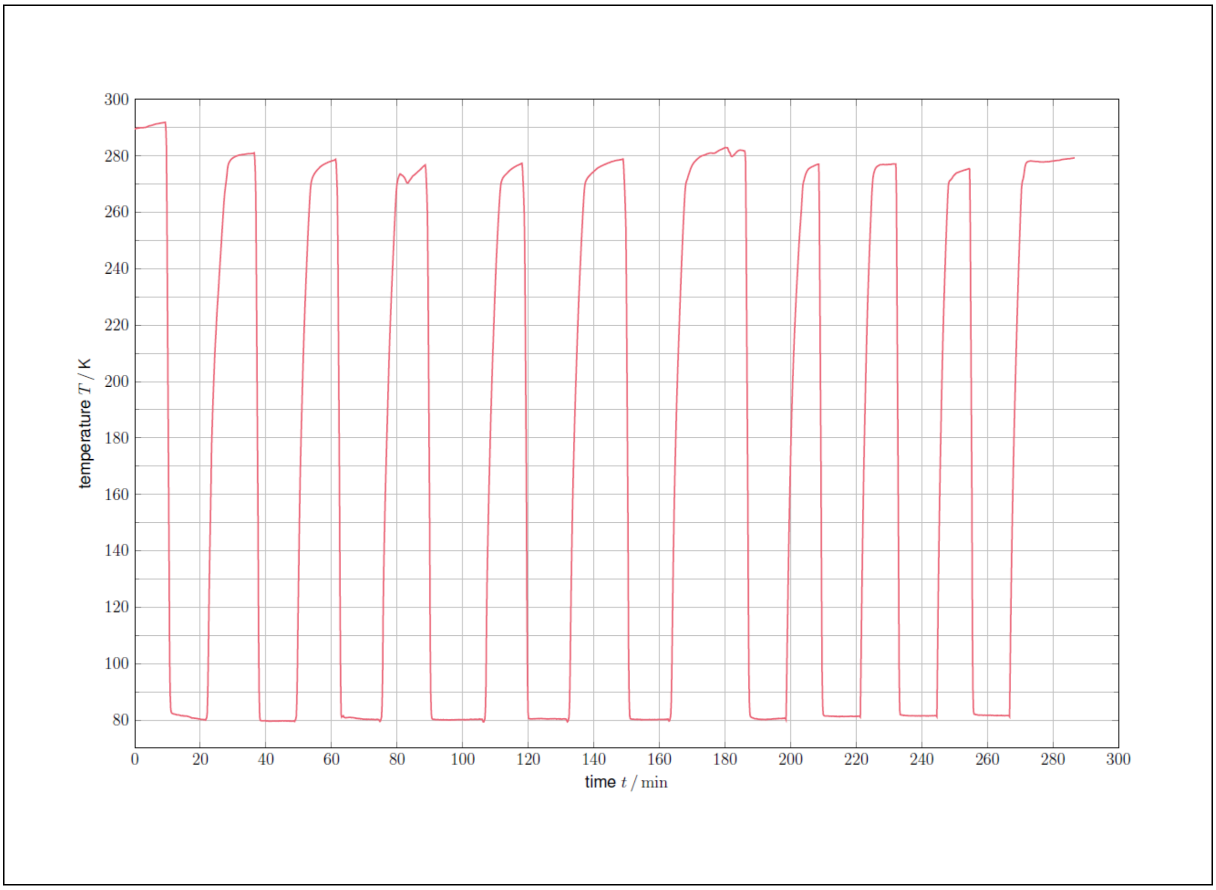


Figure 5.26: Temperature sequence during the cryogenic thermal shock test of the moderator.

5.4.1.3 Pressure test of the hydrogen vessel

As a further functional test, a pressure test with water was performed.

For this test, the moderator is filled with water until a pressure of p_O > 19bar is reached. This pressure is kept for the duration of 30 minutes. After this holding time, the pressure is increased to $p_T > 1.43*p_O$ (= 27,2bar). This increased pressure is also maintained for another 30 minutes.

Figure 5.27 shows the setup of the pressure test and the manometer values are shown in Figure 5.28.

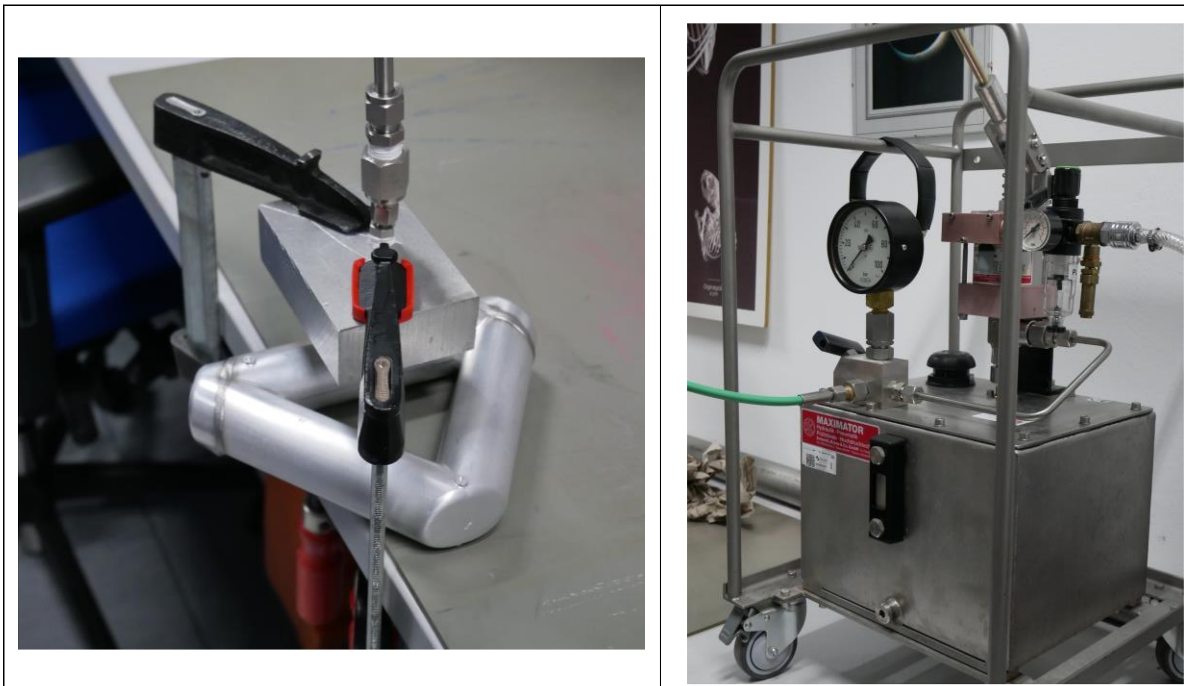


Figure 5.27: Pressure test setup

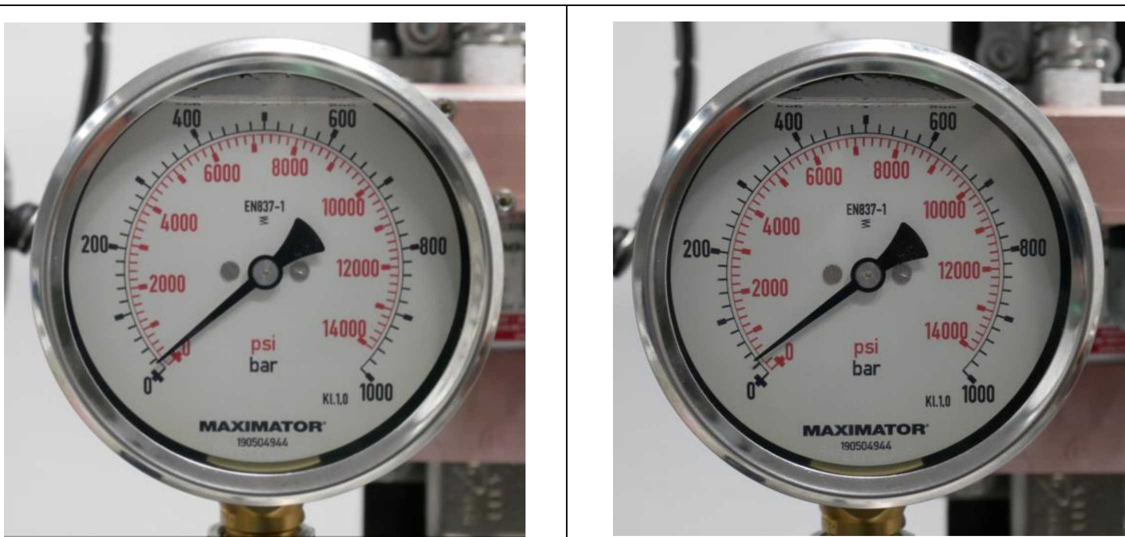


Figure 5.28: Manometer values p_O (left) and p_T (right)

5.4.2 NDT of the vacuum vessel

To be able to adapt the shape of the filler material to match the belonging groove in the vacuum vessel, it was decided to measure the exact shape of the groove contour, which is shown in Figure 5.29.

This is necessary, because the filler material groove is defined by several partners, as the inner and the outer groove are affected by the manufacturing tolerances of the main body and the lid at the same time.

For this purpose, the main body and the lid were measured on a CCM and the resulting contour data was used to define the outer tolerance of the filler material before manufacturing [12].

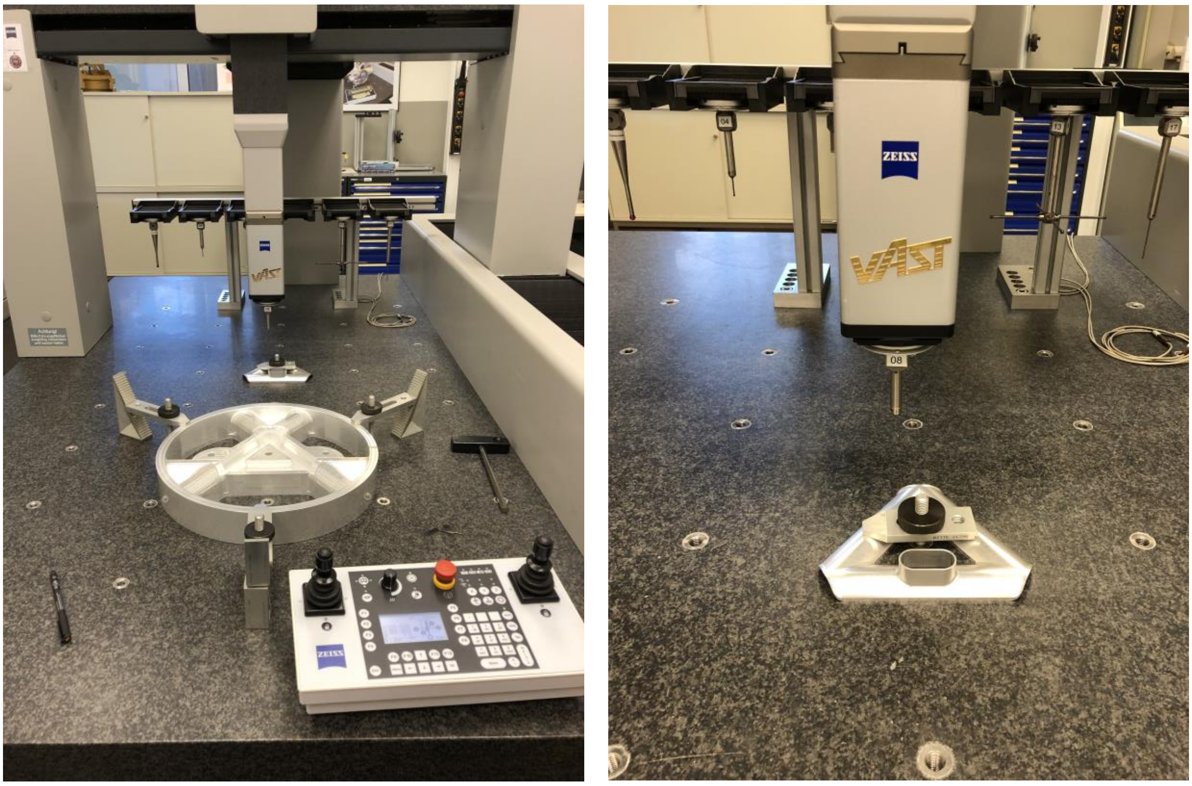


Figure 5.29: Measurement of the vacuum vessel

After the final machining of the vacuum vessel, the measurement of the assembly was performed on the CMM [13] .

The vacuum vessel was also dye penetrant and leak tested. Furthermore, an additional CT scan of the final unit was performed. For more details watch the provided video by FZ Jülich [14].

Figure 5.30: NDT of the vacuum vessel

5.4.2.1 Evaluation of the electron beam weld seams of the vacuum vessel

The evaluation of the electron beam weld seams according to EN ISO 13919-2 of the SNS tube moderator vacuum vessel was not possible due to the lack of resolution.

5.5 Burst Tests

5.5.1 Water burst test of the hydrogen vessel welding sample

One of the final welding samples, that represents a corner of the hydrogen vessel and that was welded with the final parameters, was tested with a water burst test.

For this test a Swagelok® fitting (SS-6M0-1-4) was attached to the sample and water with constantly increasing pressure was pumped into the assembly.

The sample was expected to burst at the end cap according to the FEA simulation report [2] and did not crack anyway near the welding track and the heat effected zone.

The sample did burst at a pressure of approx. 250bar.

Figure 5.31: Hydrogen vessel welding sample - water burst test

5.5.2 Water burst test of the vacuum vessel welding sample

The second of the final welding samples, that represents the upper corner of the vacuum vessel was tested with a water burst test.

For this test a Swagelok® fitting (SS-6M0-1-4) was attached to the sample and water with constantly increasing pressure was pumped into the assembly.

The sample did crack open at a pressure of approx. 117bar at the inner EB weld seam at the transition to the vacuum vessel cap [15].

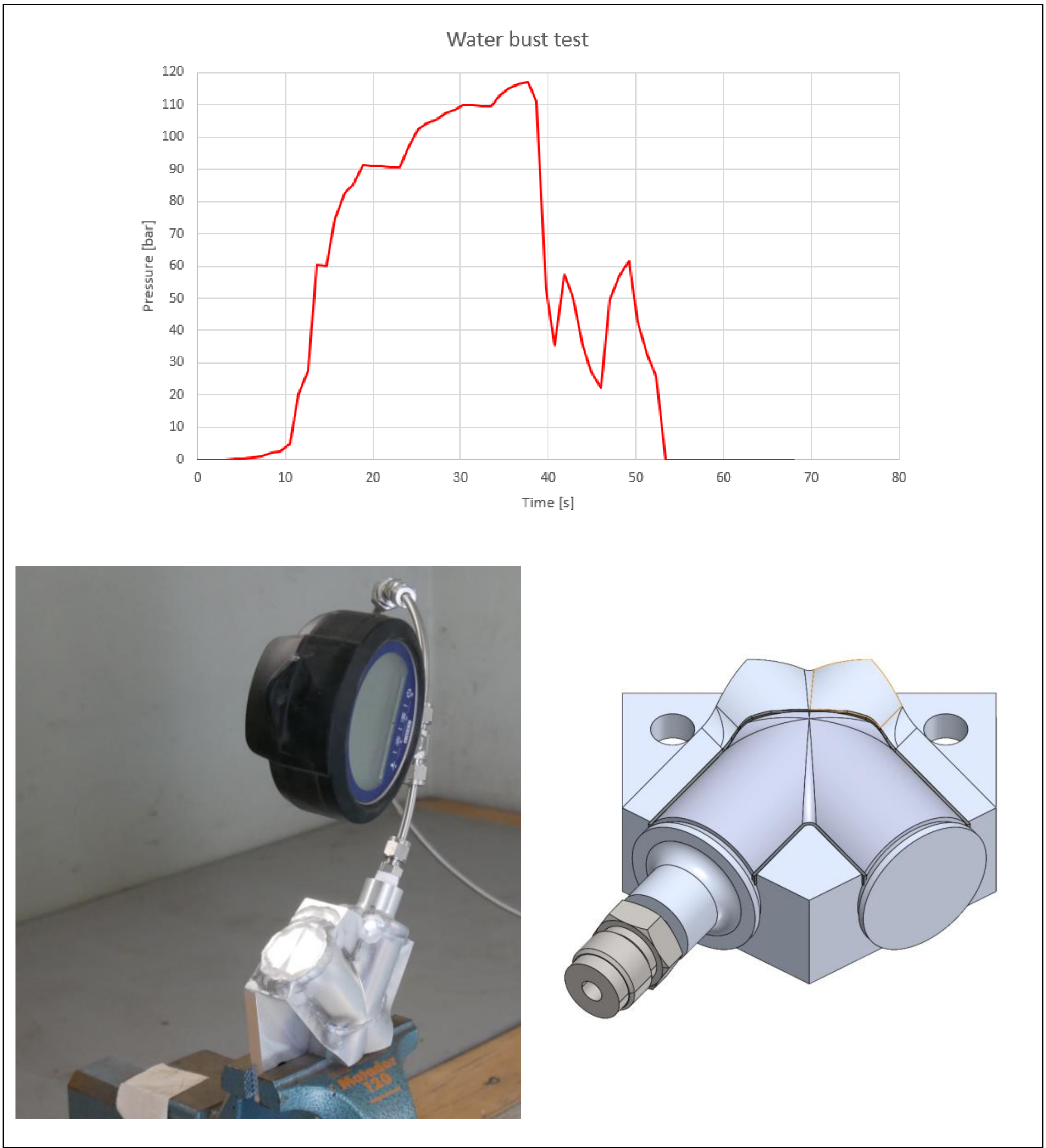


Figure 5.32: Vacuum vessel welding sample - water burst test

5.5.3 LN_2 burst test of the final hydrogen vessel

As a milestone for the manufacturing development of the hydrogen vessel, a burst test at liquid nitrogen temperatures was performed. For this purpose, a stainless-steel Swagelok® fitting (SS-6M0-1-4) with an EN AW-6061 adapter was TIG-welded to the inlet tube of the hydrogen vessel. The outlet tube was closed with a solid plug of EN AW-6061 by EB-welding. [Figure 5.33].

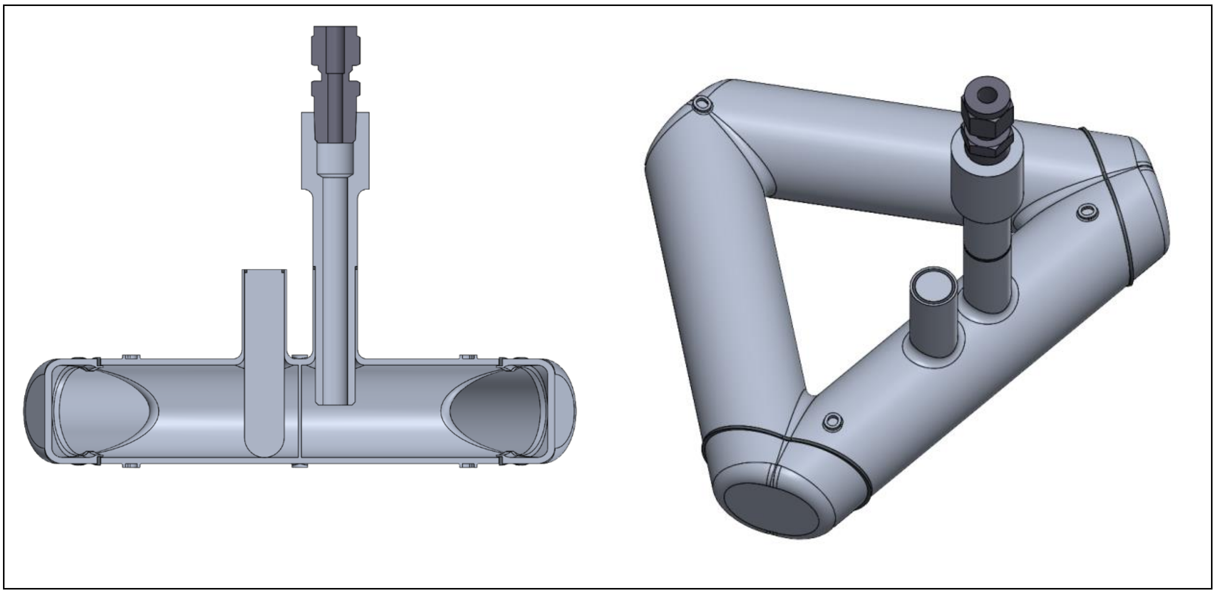


Figure 5.33: Burst test preparation of the hydrogen vessel

The test took place in the ZEA-1 test bunker facility. After all preparations were completed the moderator vessel to be tested was immersed in a liquid nitrogen bath, cooling its structure down to 77K from the outside. Then gaseous nitrogen was released from a compressed gas cylinder at a pressure of 20 bar into the moderator vessel. Due to the higher internal pressure, the condensation temperature of the nitrogen is around 115K. This means that the gaseous nitrogen is liquefied inside the cold vessel. During the filling phase, which took approximately 15 minutes, the moderator vessel was completely re-filled with liquid nitrogen. Once filled the vessel with 100% liquid was disconnected from the gas supply and a remote cryogenic high-pressure solenoid valve sealed the moderator volume against the gas supply.

Now the moderator was lifted out of the nitrogen bath by a remote lifting device until it had reached its previously defined camera position. The heat input from the environment increases the pressure inside the moderator vessel until its structure finally cracks. To measure the pressure, a WIKA Pressure transmitter Model A-10, Type 12696839 with a measuring range of 0...400 bar gauge was connected to the moderator vessel via Swagelok fittings and pipes.

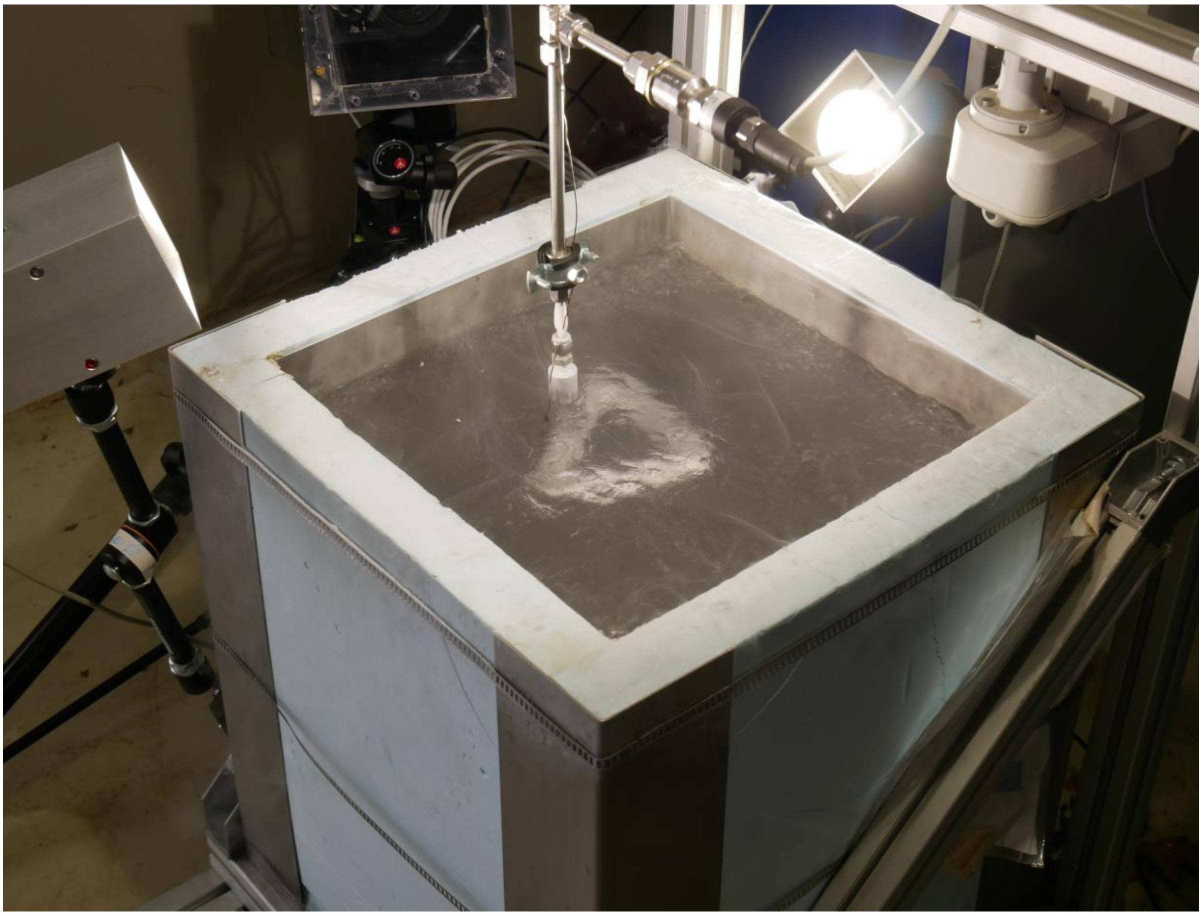


Figure 5.34: Moderator vessel to be tested immersed in a liquid nitrogen bath at the end of the filling phase

The measurement data (temperature and pressure) were recorded by a data logger, ALMEMO® 710. The measured temperature was only used to determine whether or not the moderator vessel was immersed in the liquid nitrogen bath. To visually assess the cracking of the moderator wall two cameras recorded the “burst” event. The cameras are Photron high-speed cameras of the type Fastcam Mini AX100 equipped with Sigma 24-70, 1:2.8 DGHSM lenses. The camera and its lens are housed in a steel case that is sealed with a plexiglass plate to protect them from eventually flying parts. The moderator in its final camera position is illuminated with 4 high power led modules to provide enough light for the high-speed cameras. Due to the amount of light available, the desired resolution and the required temporal resolution a recording speed of 16000 fps were chosen. At this speed the image resolution is 786 x 512 pixel. The cameras have a ring buffer that allows a maximum recording time of 1.7s with the given parameters. The storage of the images is triggered by an end trigger, which means that the previous images are saved when the cameras get a synchronal trigger signal. Figure 5.35 shows a series of 6 pictures with a time interspace of 62.5µs between each of them.

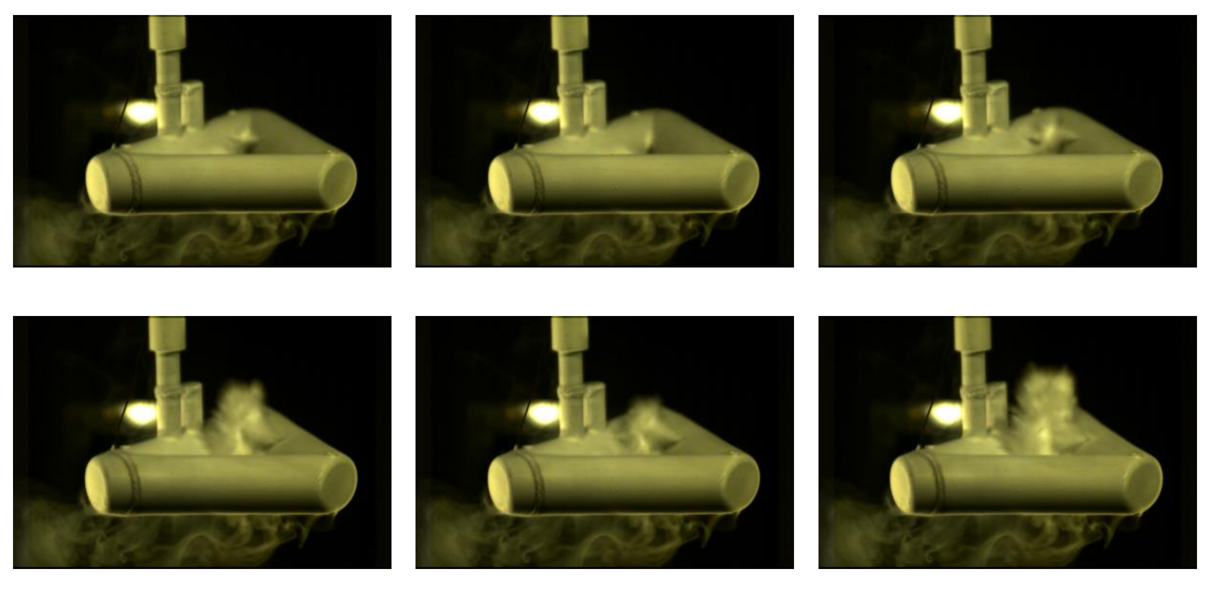


Figure 5.35: Series of images during the failure of the moderator vessel structure at 263.38±1.32 bar

In the second upper picture, the development of a crack in the rear inner corner becomes visible for the first time. Figure 5.36 shows an enlarged picture of the incipient crack formation. For more details watch the provided video by FZ Jülich [16].

This area is also visible as a high stress area in the FEA simulation report by SNS [Figure 2.18].

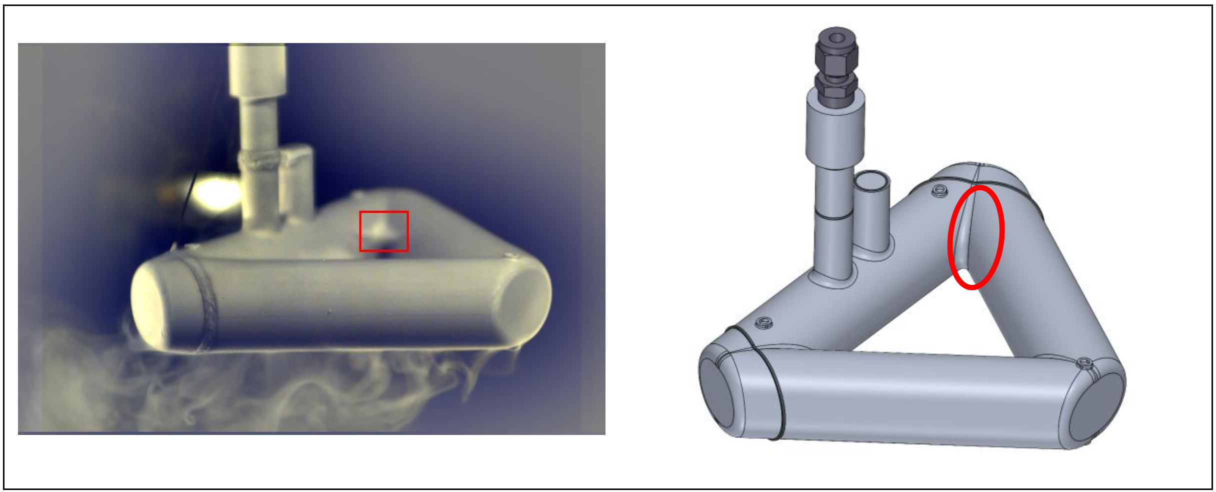


Figure 5.36: Enlargement of the incipient crack formation

Figure 5.37 shows the measured pressure data inside the moderator vessel during the test. Initially, while the vessel was immersed, it was filled with a pre-pressure of 20 bar (filling phase). Then the vessel was pulled out and after leaving the bath, an additional pressure of 244bar built up within about 3 minutes. Finally, the moderator vessel bust at a pressure of 263.38±1.32bar.

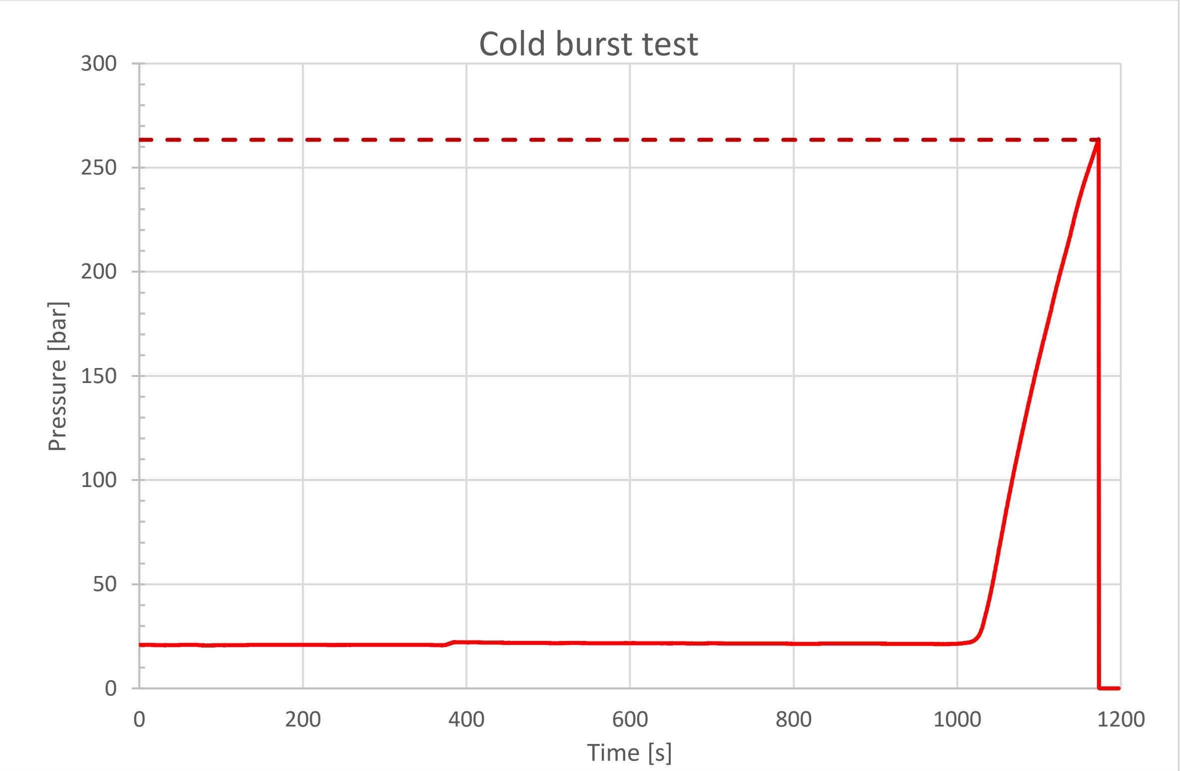


Figure 5.37: Measured pressure data inside the moderator vessel during the test

Finally, Figure 5.38 shows two pictures of the moderator vessel after the burst test. It can be seen that the moderator is torn in the rear corner and that the cracks start from the rear inner corner.

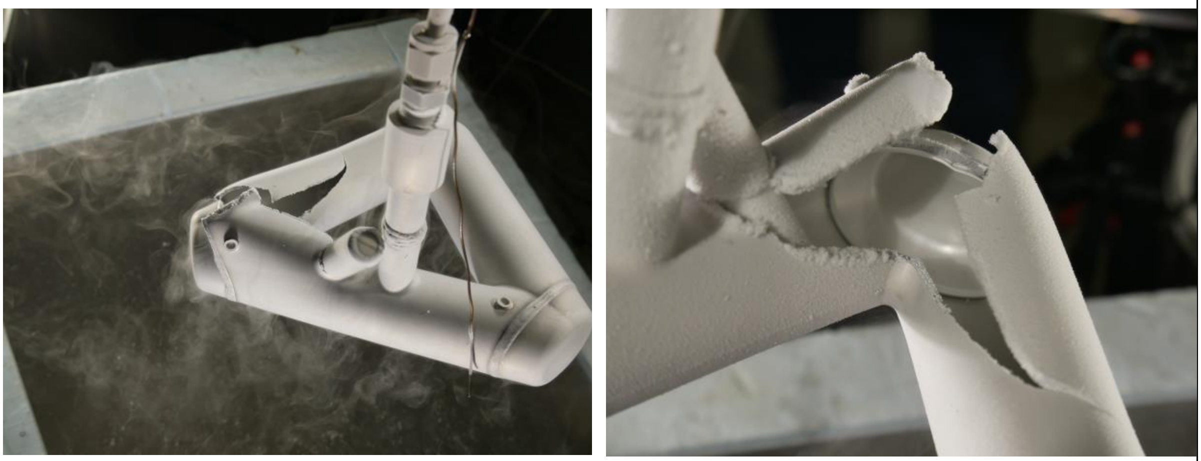


Figure 5.38: Pictures of the moderator vessel after the burst test

6 DISCUSSION

6.1 Non-conformity of dimensions or tests

1) Some inner radii in the hydrogen vessel could not be manufactured as intended [Figure 6.1]. It was not finally attempted to manufacture these radii, but it should be possible with much effort by using a special electrode. This is a matter of cost vs. benefit.

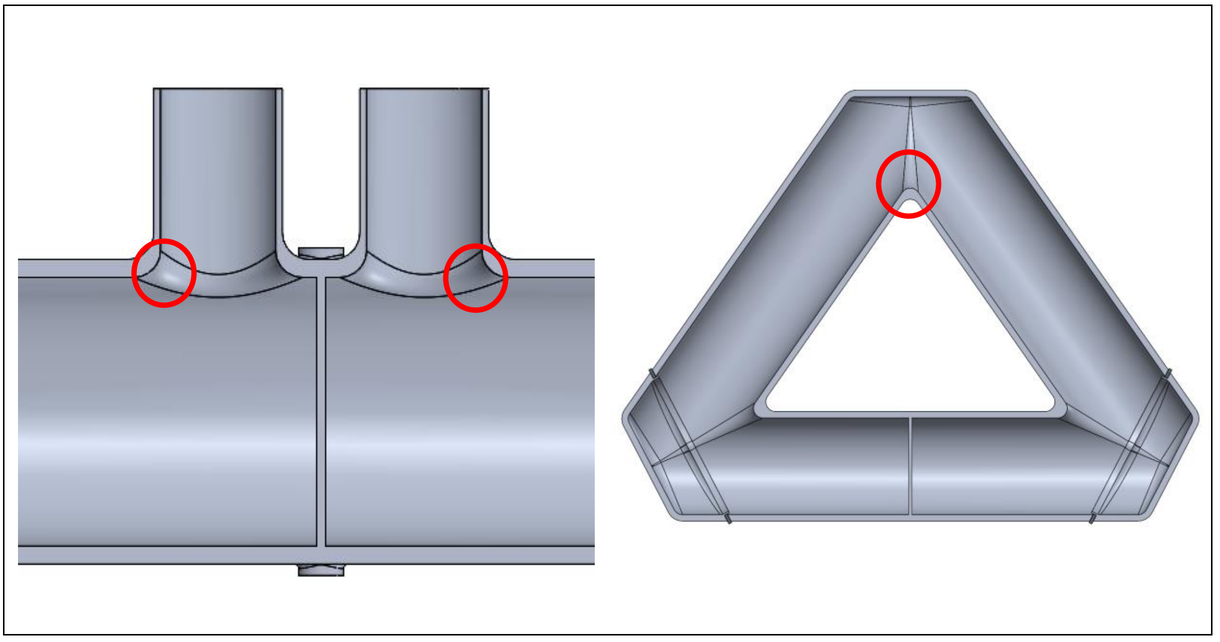


Figure 6.1: Not manufactured radii of the hydrogen vessel

2) The inner radius at the beam window of the vacuum vessel had to be increased to 3.5mm from 3.0mm. This was due to vibration during the milling manufacturing [Figure 6.2].

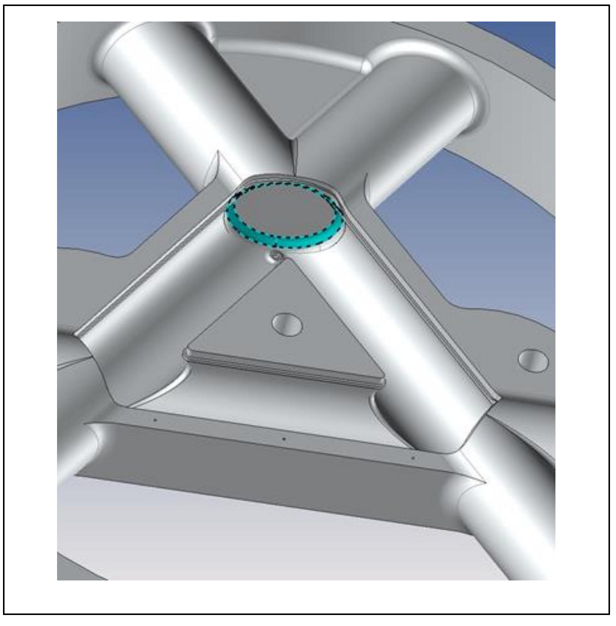


Figure 6.2: Enlarged inner radius

3) The inner radii shown in Figure 6.3 inside the tube meeting area of the vacuum vessel could not be manufactured properly. It was not finally attempted to manufacture these radii, but it should be possible with much effort by using a special electrode. This is a matter of cost vs. benefit.

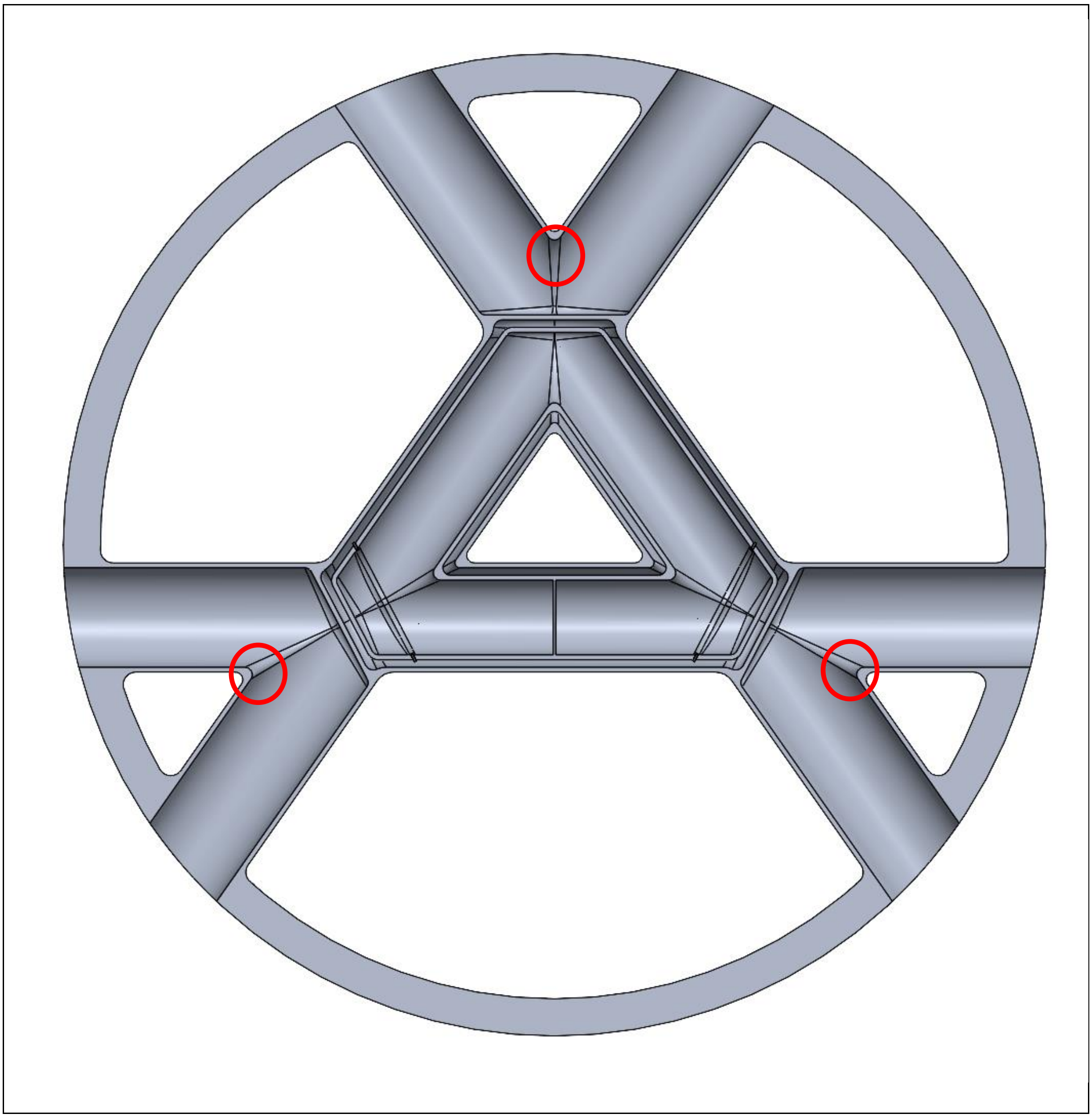


Figure 6.3: Not manufactured radii of the vacuum vessel

4) Because the final vacuum vessel assembly needs to be machined from two sides, it was necessary to re-align the component during re-clamping in the final machining process. This alignment leads to small deviations of the final shape in areas, where the machining from the upper side transitions into the machining from the bottom side, see Figure 6.4. This is normal in a certain extent and cannot be avoided completely.

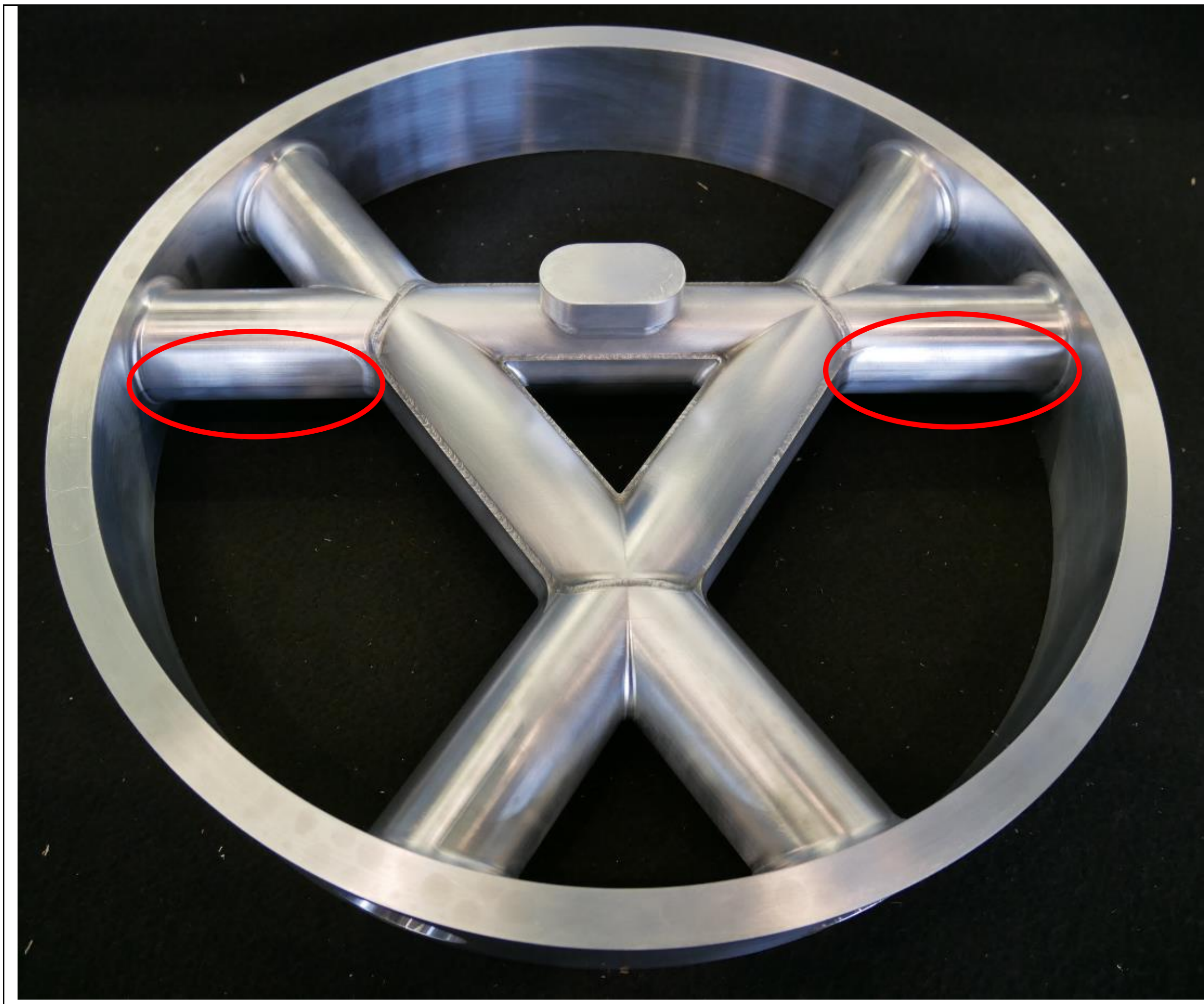


Figure 6.4: Final Tube Moderator

5) Some measurements of the final vacuum vessel assembly did not match the requirement of an overall profile tolerance of 0.50mm [13] & [Figure 6.5]:
   a. The outer surfaces of the beam windows after final EDM machining (MP 10, MP 11 & MP 12)
   b. The height of the connection nozzle on top of the vessel (MP 01)

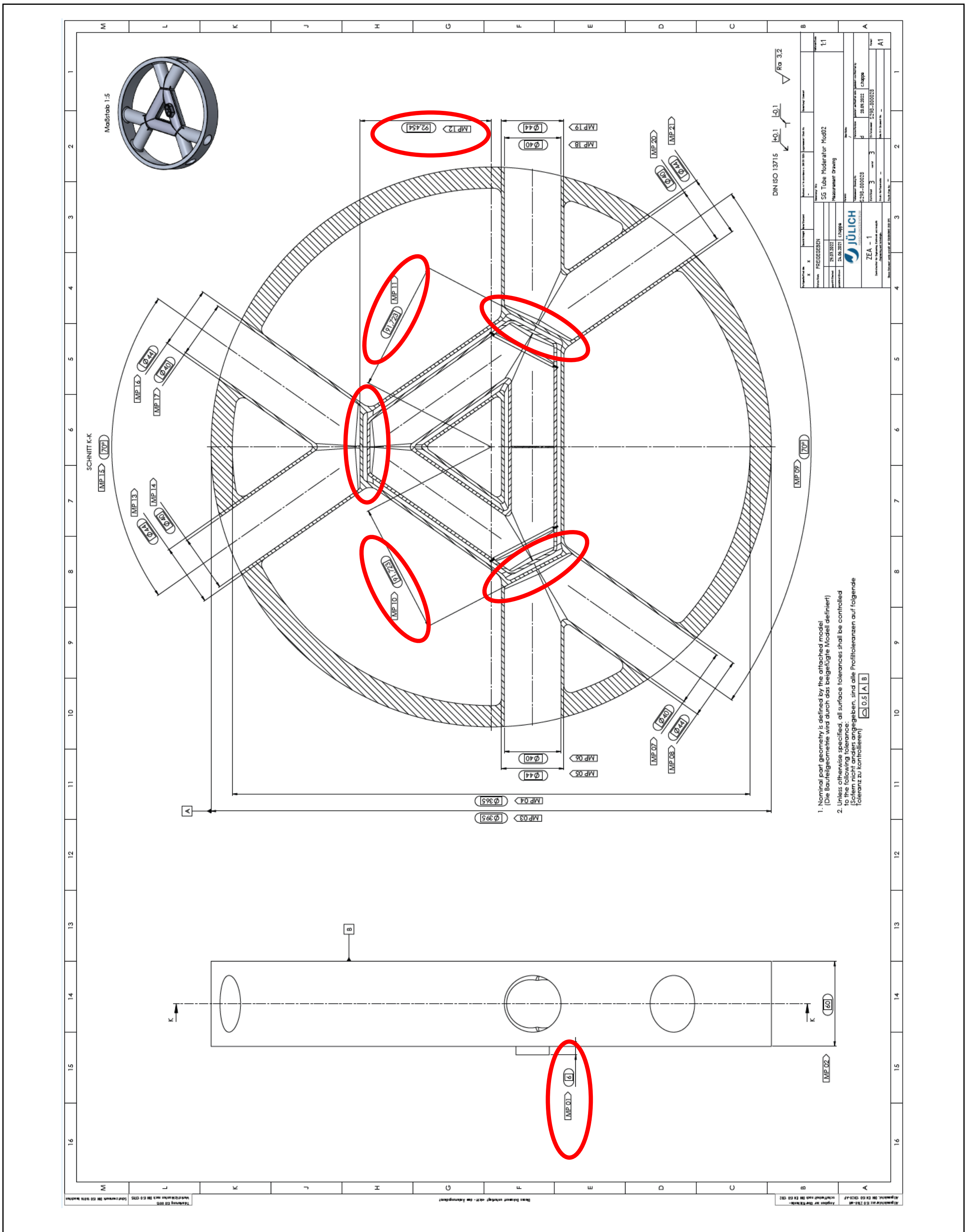


Figure 6.5: Measurement Drawing S298-00028d - Sheet 3

6.2 Suggested design changes

1) The small distance between the upper two pipes caused problems during welding of the connection adapters for the burst test [Figure 6.6].

   Reflected heat from one pipe’s weld seam interfered with the other pipe, so this other weld had to be protected with a small heat shield.

   FZ Jülich suggests to enlarge this distance, by moving the tubes away from each other (by angle, or by transversal distance).

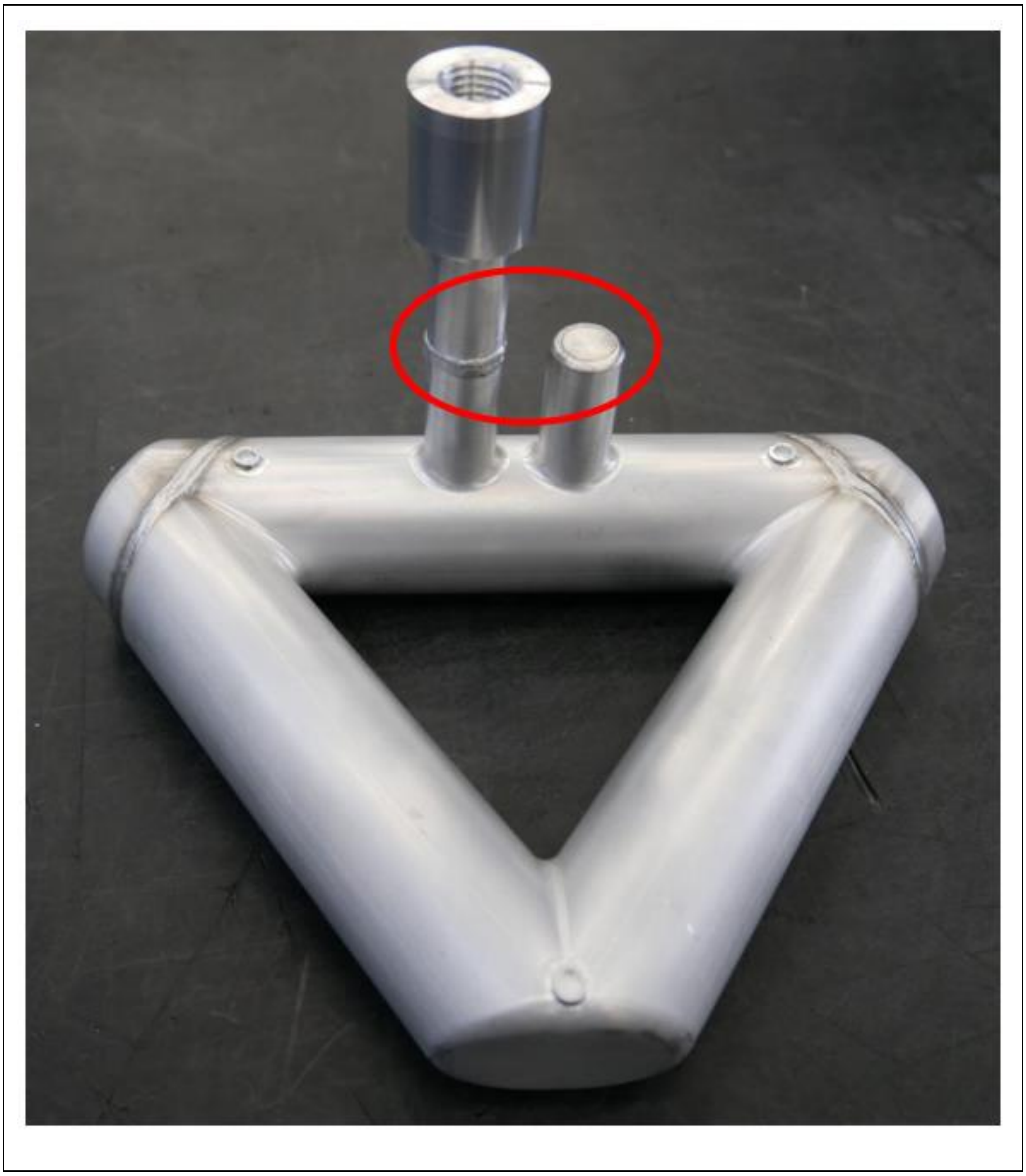


Figure 6.6: Distance of tubes on the hydrogen vessel

2) The fit of the upper resting points on the hydrogen vessel and on the ones in vacuum vessel lid for the titanium pins should be switched. On top of the hydrogen vessel, the resting area should be circular. At the vacuum vessel lid the resting area should be slot shaped. This would make the assembly easier, because the titanium pins on top of the hydrogen vessel are resting in a more defined position, when putting on the vacuum vessel lid [Figure 6.7]. Also challenging for the manufacturing process is the multiple-fit situation that occurs, because the hydrogen vessel is resting on the titanium pins and the vacuum vessel lid is also resting on titanium pins on top of the hydrogen vessel. In addition, the lid of the vacuum vessel should sit on the main body without noticeable play between these two parts.

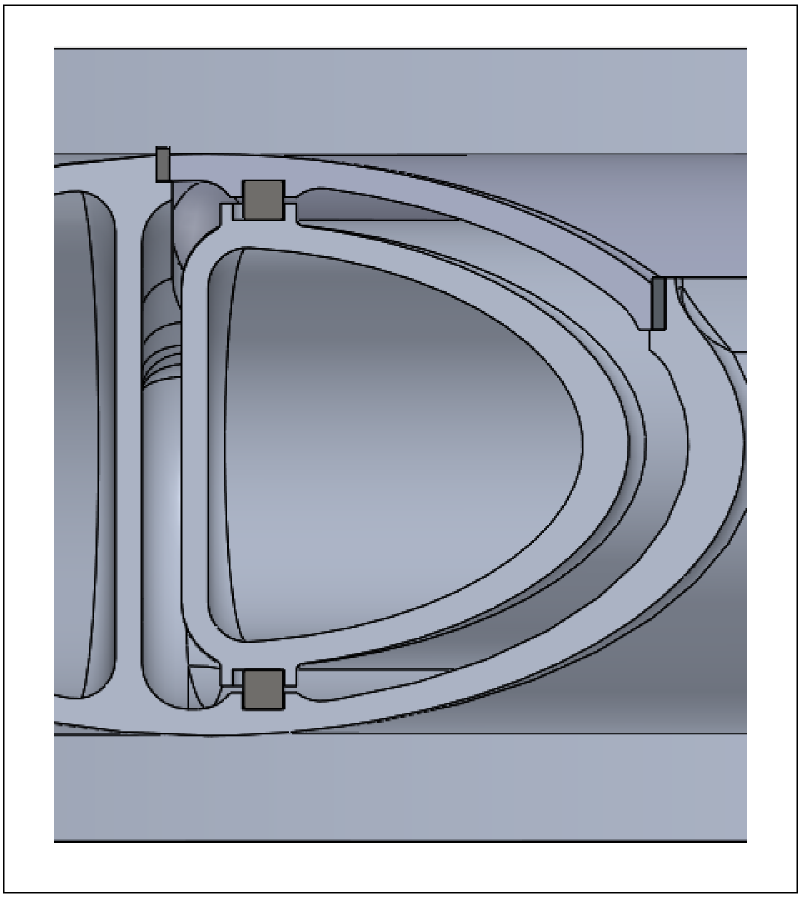


Figure 6.7: Moderator resting points

3) Deformation of the vacuum vessel assembly after the final welding led to partial deviation of the reference holes for further machining. This caused difficulties in the alignment of the following EDM-machining of the beam window holes and the final milling of the outer contour. It could be beneficial to process the EDM machining of the beam window holes before the final welding, to ensure their correct location and the belonging wall thicknesses. Also, more material allowance on the outer “wheel”-shape can help achieving the required tolerances in the final machining process.

   Generally speaking, the requirement of an overall profile tolerance of 0.50mm on all surfaces of the final welded tube moderator should be discussed. It may be better to define areas with perhaps even more precise requirements, such as alignment surfaces, and other areas with looser tolerances. This can help speeding up the manufacturing process and make it more cost efficient.

4) Considering the complexity of the welds on the vacuum vessel, which also represent the final joining process of the assembly, Forschungszentrum Jülich, as the company conducting this feasibility study, expresses great concern about the reproducibility of these final welds.

   In addition, non-destructive testing of the weld seam in the CT, or with other volumetric measurement methods, is difficult due to the specific, complex geometry and the other internal components, which makes it extremely difficult to evaluate the results.

   The vacuum vessel assembly also has to be finished on its outer contour after final welding by milling, and the weld seam on the outer edge may be partially exposed. Therefore, it cannot be ruled out that internal pores, which can always occur in the welding process and are also tolerated to a certain extent, may be exposed during final machining and thus become external leaks. This would result in a faulty product.

   Due to these difficulties, the customer is recommended to fundamentally think about a change in the design of the vacuum vessel, in order to be able to ensure the success of the manufacturing and welding process. FZ Jülich suggests to change the outer shape of the vacuum vessel. The geometry of the weld seam should be flat and not have any change in height and a constant weld penetration depth should be ensured. However, at least two sets of the assembly should be manufactured in the future, in order to be prepared for a failure of the welding process at this point.

7 REFERENCES

[1] J. Janney, *Tube Moderator Manufacturing Development Statement of Work,* 2020.

[2] J. Janney, *TubeHydrogenStressOverview.pptx,* 2020.

[3] AFCEN, *RCC-MRx:2012, Design And Construction Rules for Nuclear Power Generating Stations - Design And Construction Rules for Mechanical Components of Nuclear Installations,* 2012.

[4] FZ Jülich, *298-DOC-008-Cleaning of Aluminum Materials.pdf,* 2013.

[5] FZ Jülich, *WPS SNS Hydrogen Vessel_05b.pdf,* 2022.

[6] FZ Jülich, *WPS SNS Tube Moderator_30b.pdf,* 2022.

[7] FZ Jülich, *WPS SNS Tube Moderator_31b.pdf,* 2022.

[8] FZ Jülich, *CT-WT03_22_13.mp4 (CT-Scan of Hydrogen Vessel Welding Sample),* 2022.

[9] FZ Jülich, *Prüfbericht_Tube-Moderator-Hydrogen-Vessel_91003642-2.pdf,* 2022.

[10] FZ Jülich, *298-20220530-Point_Cloud_Hydrogen_Vessel.txt,* 2022.

[11] FZ Jülich, *CT-Tube-Moderator.mp4 (CT-Scan of final Hydrogen Vessel),* 2022.

[12] FZ Jülich, *298-20220609-Groove_Contour_Vessel_And_Cap.zip,* 2022.

[13] FZ Jülich, *Prüfbericht_SNS Tube Moderator Mod02-2.pdf,* 2022.

[14] FZ Jülich, *CT-Vacuum-Vessel.mp4 (CT-Scan of the final Tube Moderator),* 2022.

[15] FZ Jülich, *Bersttest_ SG Tube Moderator.pdf,* 2022.

[16] FZ Jülich, *SNS_Tube-LN2-burst-test.mp4 (Video of LN2 burst test),* 2022.