Daniel Lyngh 25/2/15
Engineering Assessment of Butterfly Cold Moderators Implementation
ESS-0027043

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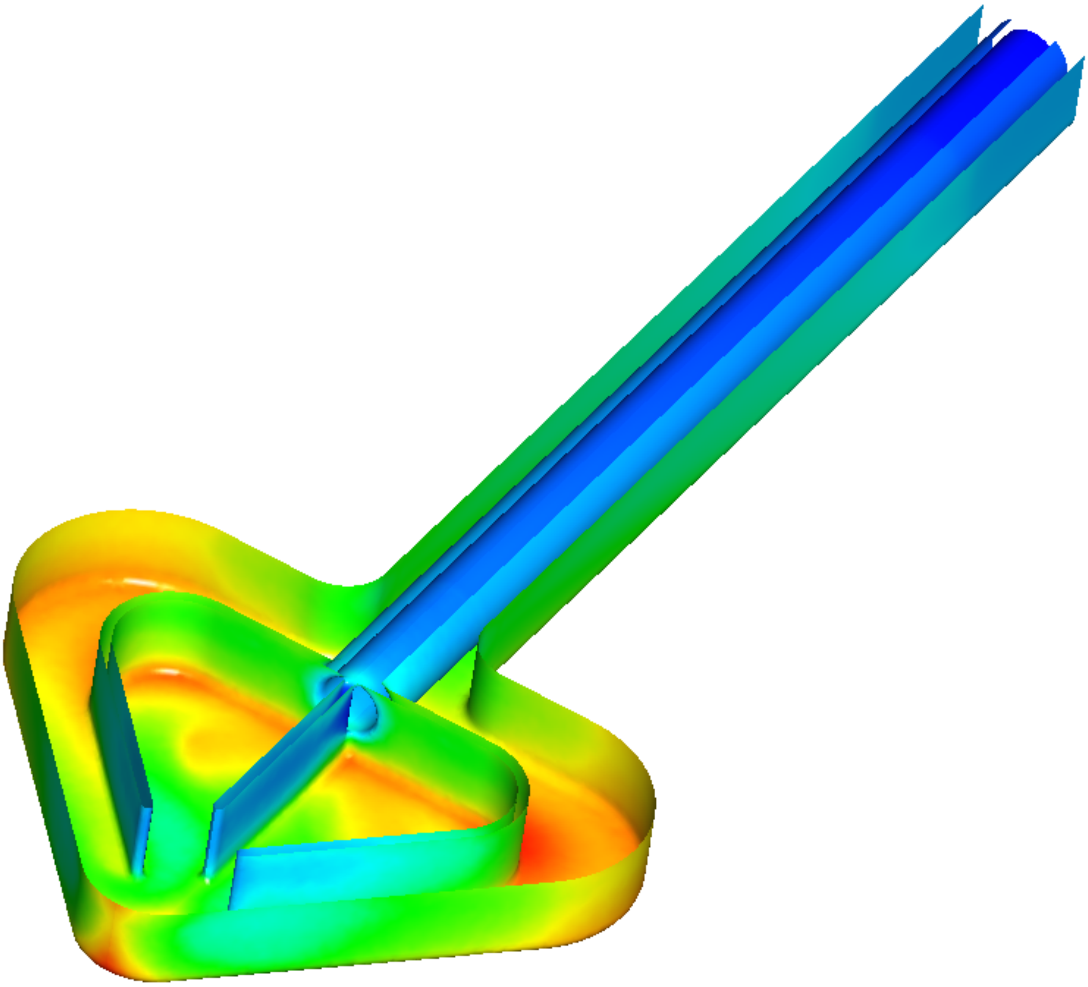

1 SUMMARY

The most critical for execution of WP 12.3 at this time is to decide on design for the pair of moderators and freeze the total heat load to allow the project to progress into its next phase.
It is urgently required to put constraints on the work-package, allowing it to be allocated to an in-kind partner.

1.1 Top Moderator

It is not considered that implementation of the BF2 as top moderator increases the technical complexity of the system significantly. Development of the BF2 up to the level of pancake moderator maturity will take an additional approximately 3 weeks, however no specific criticalities have so far been identified indicating that this could be hindered. BF2 introduces a slightly higher heat deposition requiring an additional 1,3 M€ to be added to the WP12.3 budget mostly due to increased size of the Cryoplant*.

1.2 Bottom Moderator

Changing from OT6 to BF1 or BF2 significantly increases technical complexity of the bottom moderator design. Both butterflies are significantly more complicated than the OT.
Total impact on schedule of the change will close be negligible if it is chosen to use the same design of moderator above and below (for example if both were BF1 or both BF2 with only the height unlike in the design allows parallel engineering contributing of each other, additionally due to the fact that limited amount of engineering work has been done developing the OT6 at this time)
For changing from OT to BF2 as lower moderator, heat deposition increases 89%, thus requiring an increase of the budget for WP12.3 of approximately 3,5€*.

*The cost are based on our internal assessments, increases will need to be verified through adjusted budgetary quotations.

1.3 Recommendation

It is recommended to exchange the pancake moderator to a BF2, the schedule consequence is little and could be executed with little delay and a small increase in budget.
It is recommended to keep the OT6 bottom moderator; a BF1, BF2 or Cold Heart instigates a significant cost increase due to the increase heat deposition. Out of a technical engineering viewpoint it introduces a more complex moderator design even though similar to the top one.
The overall assessment comes down to whether the flexibility of increased instrument viewing sectors[3]1 below and corresponding instrument layout flexibility[3] is worth the penalty of increased cost, technical complexity and reduced brightness[1,3].

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1. INTRODUCTION

This report presents an engineering assessment of primarily the BF2 3cm design to be introduced as top moderator, this assessment has been performed during January as the concept was introduced and deemed relevant in the reports issued by Luca Zanini[1][2] and Ken Andersen[3].

The pancake cold moderator designed was launched spring 2014, because of discussions concerning the selection the engineering team focused efforts on other parts of the work-package, in an attempt to avoid delaying the work package progress too much and rework due to the extended moderator decision process.

It needs to be mentioned that as a result of the work in this report the team considers the BF2 3cm to be developed to a level where there is comfort that no large issues will appear, the same goes for the pancake design. However, this is not the case for OT6, BF1 and especially the cold heart. The later three concepts have not been evaluated to such a degree yet.

But the moderators must be evaluated as a couple combining their individual features to maximize the total instrument performance. Due to this fact, the other concepts have only been briefly introduced and evaluated. This especially based on added heat deposition, as this property significantly changes the size of the cryogenic cooling system and hence the work package budget.

The different concepts have been evaluated based on three factors, Technical complexity, Schedule and Cost.

[1] L. Zanini et al, Neutronic Design and Optimizationof ESS Moderators, 08-01-2015.
[2] L. Zanini, Latest neutronic results for the ESS moderators 02-02-2015.
[3] K. Andersson, Pancake and Butterfly Moderators, 27-01-2015.

2 TECHNICAL DESCRIPTION

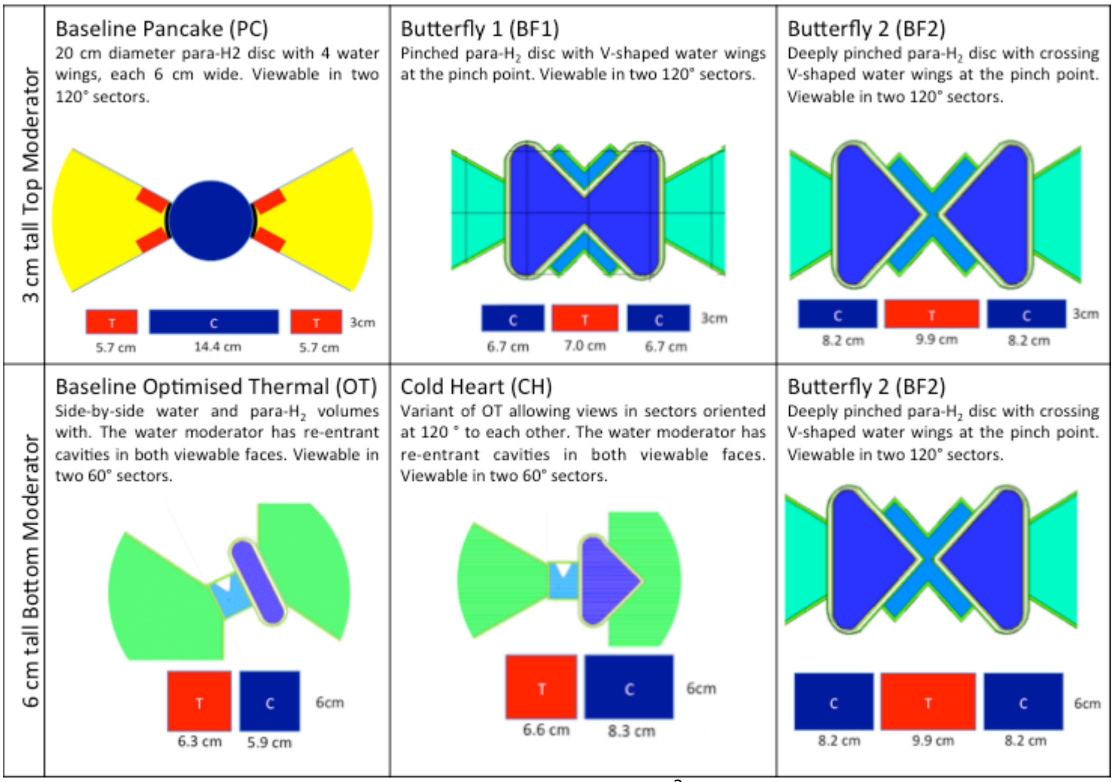

Figure 1, an overview of the six cold moderator concepts[2].

2.1.1 <u>Pancake</u>

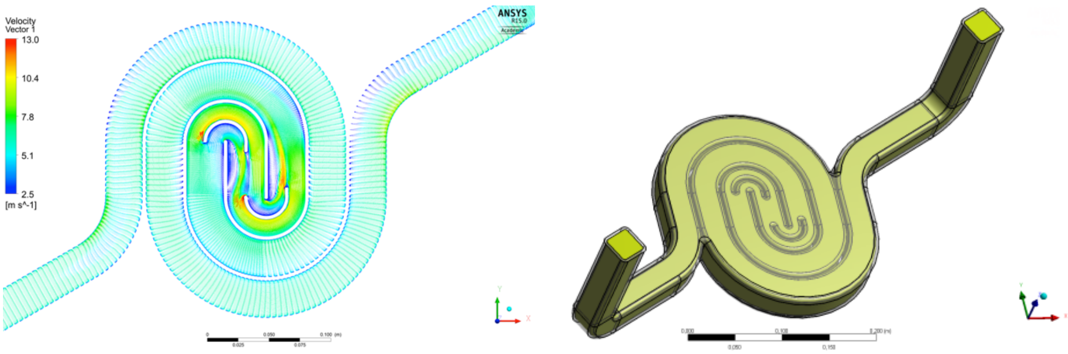

Figure 2, design of the pancake cold moderator.

Main features of the pancake moderator relevant for this evaluation is the following:

- One inlet and one outlet liquid hydrogen pipe, flexible placement (vertical or horizontal)
- Best cold brightness viewing the centre of the moderator
- Thermal wings on the sides of the cold moderator
- Complicated shape to manufacture
- Liquid hydrogen serial flow

2.1.2 Butterfly Version 1 (BF1)

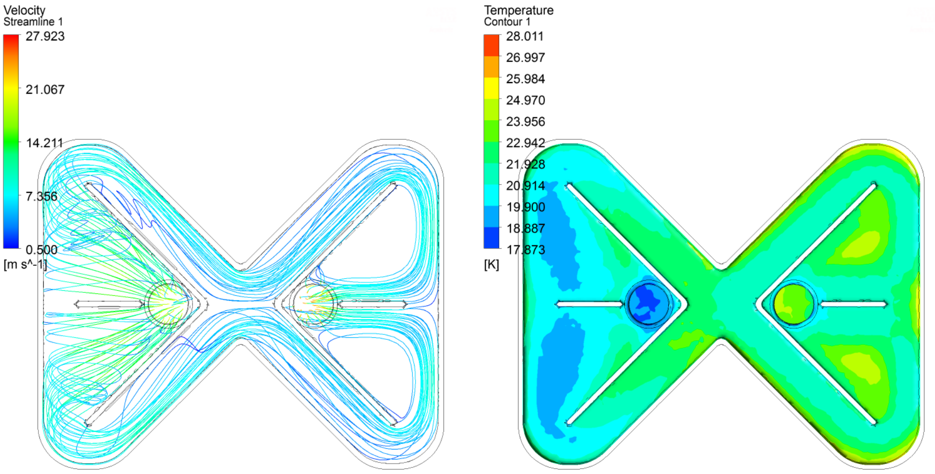

Figure 3, Initial CFD analysis of BF1.

BF1 is as a cold moderator from the engineering design a remodelled pancake, main features are:

- One inlet and one outlet liquid hydrogen, complicated inlet and outlet pipe design.
- Liquid hydrogen parallel flow(serial is preferred)
- Best cold brightness viewing at the sides of the moderator (2 focus points)
- Thermal wings in the centre of the moderator
- Slightly complicated shape to manufacture
- High heat deposition

2.1.3 Butterfly Version 2 (BF2)

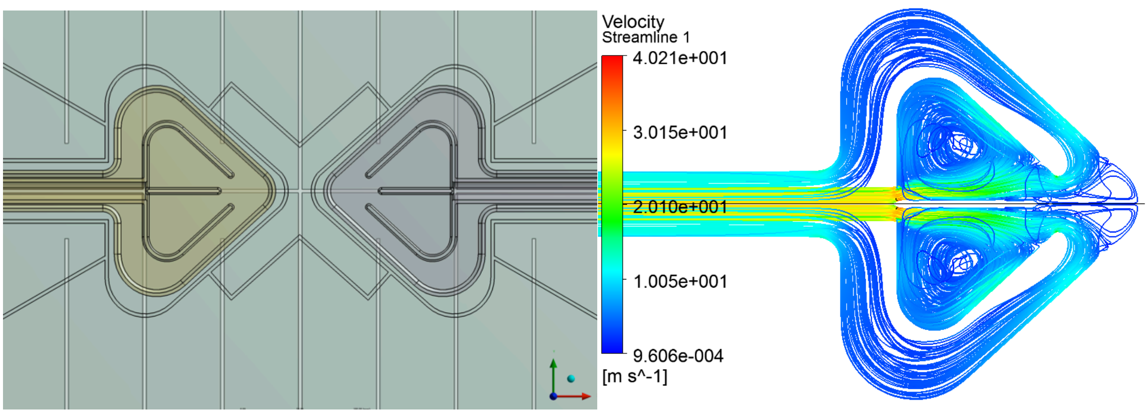

Figure 4, mechanical design of BF2 and an initial CFD plot.

BF2 is as a cold moderator from the engineering design, a significantly different design, bridging the two parts of the tanks seemed challenging and it was therefore continued with a split design, actually changing it into two independent moderators.
Main features

- One collinear hydrogen pipe for each triangle, inlet in centre, outlet around capped with vacuum. Close to half mass flow through each triangle. I.e. two collinear pipes going up, instead of two single pipes of approximately same size.
- Liquid hydrogen in parallel flow (serial is preferred)
- A jet nozzle design is required to reach the tip of the arrowhead that is also the area with the highest heat deposition and to be able to cool it.
- Best cold brightness viewing at the sides of the moderator (2 focus points)
- Thermal wings in the centre of the moderator
- Similar manufacturing challenges as the BF1 or pancake (two slightly simpler tanks, instead of one more complicated)
- High adjustability compromising thermal brightness, cold brightness against heat deposition as the sizes of the thermal wings, cold moderator arrows can be adjusted in two dimensions.

The report of the design study made during January with mechanical and CFD analysis of the BF2 concept is found in Appendix I, CFD and Mechanical Analysis.

2.1.4 Optimized Thermal (OT6)

Has only been considered as a heat deposition contribution. Mechanical design and CFD has not been initiated.
Main features:

- Small and simple design
- Serial flow appears possible
- Very low heat deposition
- Limited viewing angle
- One focus point

2.1.5 Cold Heart

Has only been considered as a heat deposition contribution. Mechanical design and CFD has not been initiated.
Main features:

- Mechanical design has not been assessed
- Flow pattern has not been assessed.
- Very high heat deposition
- Limited viewing angle
- One focus point

2.1.6 Heat Depositions

The combined heat deposition for the moderator pair is critical both for schedule as well as for cost for WP12.3. Already at the heat load from the base case the Target Moderator CryoPlant (TMCP) is a one of a kind and for its properties significantly bigger and more demanding to develop and build. A comparison as benchmark can be made to the following facilities:

J-Parc	6.45 kW@16K
SNS	7,5 kW@20K
ISIS	2x0,7kW@20K
ESS Baseline	25kW@17K

Based on the initial discussions with the two vendors that answered to the budgetary bid request, increasing it further will not cause added significant technical challenges compared to the existing plant, only that the same but larger components needs to be used.

The heat depositions for the different moderators have been listed below in Table 1. Due to the current detail level of the calculations a 20% inaccuracy is added to the Cryoplant dimensioning calculations.

Moderator Type	3cm	6cm
Pancake	8,2	NA
Optimized thermal	5,2	6,3
Butterfly ver. 1	10,6	NA
Butterfly ver. 2	9,4	11,9
Cold Heart(CH)	NA	11,2

Table 1, Heat depositions for the different cold moderator alternatives.

In Table 2 below the combined heat depositions for the scenarios presented[3] have been derived. The consequences of the increased heat deposition can be found in section 7 Appendix II, Cryoplant and Cryogenic Liquid Hydrogen System Analysis, attached to this report.

Estimated CAPEX, OPEX for TMCP and LH2 MCS moderator option designs

Scenario	Base case 3PC+ 6OT	3PC+ 6CH	3PC+ 6BF2	3BF1+ 6OT	3BF1+ 6CH	3BF1+ 6BF2	3BF2+ 6OT	3BF2+ 6CH	3BF2+ 6BF2
Top Moderator HD kW	8,2	8,2	8,2	10,6	10,6	10,6	9,4	9,4	9,4
Bottom Moderator HD kW	6,3	11,2	11,9	6,3	11,2	11,9	6,3	11,2	11,9
Total HD kW	14.5	19.4	20,1	16.9	22.8	22,5	15.7	20.6	21,3

Table 2, combined heat deposition cases

3 SCHEDULE

3.1 General regarding BF2

Based on the engineering done during the last weeks with the BF2 it is assessed that approximately 2-3 weeks of further engineering will bring it to the same detail level as the pancake design.
An additional delay of approximately 3weeks in addition to the time from the issue of this document to a concise decision will need to be added to the current baseline to continue with this solution.

3.2 Liquid Hydrogen System & He Cryoplant;

Total heat deposition for the moderator spread and corresponding pipe routing is essential to complete to design of the cryogenic cooling system. As most other activities has progressed

far in these packages just "capping" the total heat deposition within 2-3 weeks will allow these packages to progress and continue according to the current allocated Primavera schedule.
The design process for the cryogenic cooling system has been halting due to the extent of the moderator design process and will not be allowed to progress further until the number of moderators, physical design of them with pressure losses and required mass flow is set. Defining a maximum kW heat deposition will allow the Cryoplant to progress but hinder the Liquid Hydrogen from continuing engineering.

3.3 Build, delivery, installation & commissioning

No further delays in addition to those mentioned above have been identified related to the alternatives described in this document.

4 COST

4.1 General

The combined heat deposition for the moderator pair is the obvious critical issue when it comes to the cost for WP12.3. 77% of the total cost of the WP is direct material cost in the two work-units Helium Cryoplant and Cryogenic Liquid Hydrogen Cooling system.
In the table below the cost consequence for the different scenarios presented[3] have been assessed for the Cryoplant and Cryogenic Liquid Hydrogen System, the content of these alternatives are described in

Scenario	Base case 3PC+ 6OT	3PC+ 6CH	3PC+ 6BF2	3BF1+ 6OT	3BF1+ 6CH	3BF1+ 6BF2	3BF2+ 6OT	3BF2+ 6CH	3BF2+ 6BF2
Total HD kW	14,5	19,4	20.1	16,9	22,8	22.5	15,7	20,6	21.3
TMCP CAPEX k€	10,600	13,200	13,500	12,300	14,400	14,300	11,800	13,600	13,900
LH2 MCS CAPEX k€	2,000	2,530	2,600	2,260	2,790	2,860	2,130	2,660	2,740
TMCP OPEX k€	487	635	617	559	566	689	523	671	683
Total WU Material CAPEX k€	**12,600**	**15,730**	**16,100**	**14,560**	**17,190**	**17,160**	**13,930**	**16,260**	**16,640**
Required Budget Adjustment	0	+2,530	+2,900	+1,360	+3,990	+3,960	+730	+3,060	+3,440

Table 3, combined heat deposition cases and resulting costs

5 RECOMMENDATION

The most critical for execution of WP 12.3 at this time is to decide on a spread of moderators, freeze the total heat load to allow the project to progress into its next phase, thereby putting all focus on the optimization in the details of the moderators rather than comparing moderator designs with each other. At current time it is urgent to allocate the work package to a competent in-kind partner to allow them the opportunity to mobilize a team and take over the responsibility for the execution after the PDRs planned in 15Q2.

5.1 Top Moderator

There has been identified no objections to implement the BF2 3cm as top moderator, with a slightly increased cost due to increased heat deposition, otherwise technically similar complexity level and considered fully feasible.
The BF2 design introduces a slightly changed piping arrangement but in an overall context carries the same challenges as the previous concepts.

5.2 Bottom Moderator

Replacing the OT6 with a BF1 or BF2 below instigates a severe increase in heat deposition with a corresponding significant cost increase in addition to an increased technical complexity of the bottom moderator.

It is recommended to define a heat deposition, massflow and pressure loss with margin thereby sticking with the principles of the OT but allowing further optimization of the cold moderator within these limitations (through geometrical adjustments).

However, in addition to the cost consequence, i.e. requirement for increased budget and consequences defined in the Neutronics and Instruments reports, there is no other objections are made against introducing BF1 or BF2 as bottom moderator.
There is an opportunity to reduce risk and save time on engineering by choosing moderators of very similar design, thus enabling prototype tests to, to a large degree represent both developments. More risk is placed in on one design however more effort in risk reducing efforts can be put in optimizing that design.

6 APPENDIX I, CFD AND MECHANICAL ANALYSIS

Mateusz Pucilowski, Marc Kickulies & Anders Olsson

Contents

1. INTRODUCTION

The main goal of this report is to preliminary evaluate the butterfly BF2 concept from the engineering point of view and compare it to the previous serial pancake design. The comparison must be seen in the content of engineering maturity of the two concepts. The engineering concept of the pancake has been developing for a couple of months compared to the BF2 concept which is under engineering development for a couple of weeks now. Therefore the engineering maturity of the BF2 is today lower compared to the serial pancake.

2. BUTTERFLY FLOW ASSEMBLY BF2

The considered BF2 geometry is shown in Figure 2-2. The biggest differences from the previous designs are splitting of the hydrogen tank into two separate containers and locating a water volume between them. Presented engineering concept is only an example of the butterfly flow solution and may be modified. Engineering analyses will point out several differences connected to this design compared to the pancake design. It has to be noted that the results are not the final absolute numbers but rather an approximation.

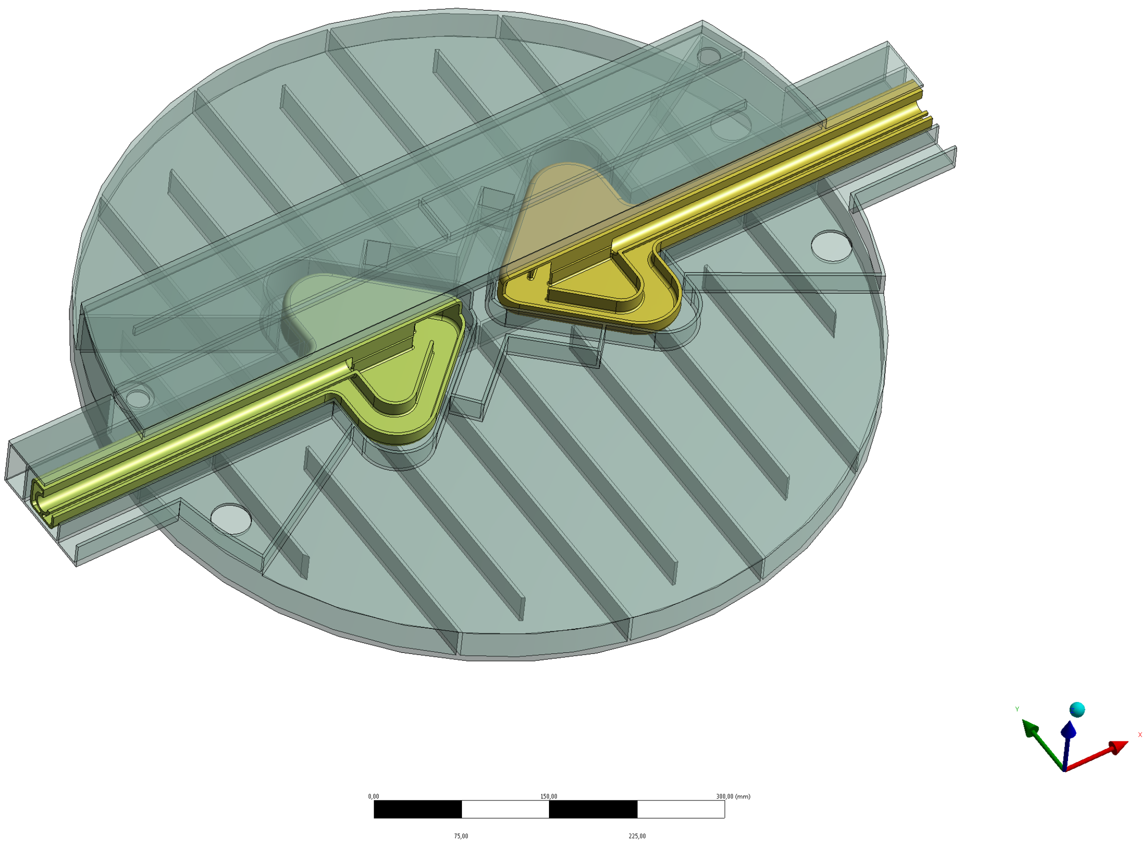

Figure 2-1: The BT2 flow proposal assembly - top view.

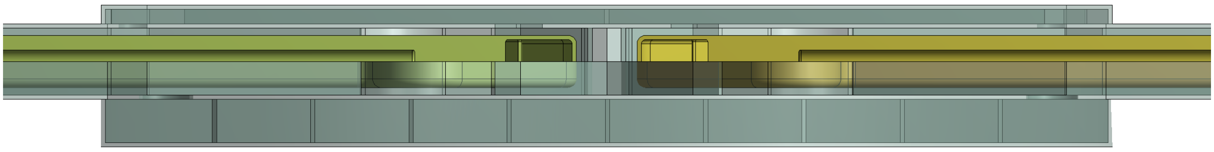

Figure 2-2: The BT2 flow proposal assembly – side view.

3. MATERIAL PROPERTIES

The solid material should be the aluminum alloy AL6061-T6. It is the material that is used in the mechanical calculations together with its limitations. Cold moderator contains liquid hydrogen at 15 bar where inlet temperature is 17K. Thermal moderator is cooled by water at 5bar with the inlet temperature of 30 C. The temperature dependence for the various material properties is considered in the simulations.

4. HEAT DEPOSITION MONTE CARLO

The interpretation of the heat deposition data used is presented. Simulations does not include entire 3-D table calculated with the Monte Carlo. Instead conservative linear approximations are used based on the horizontal heat load distribution at several height levels.
The cold moderator includes radial heat load functions at the two different aluminum layers and additional one which is equal in the entire hydrogen volume with average load of 5W/cm^3, Figure 4-1.

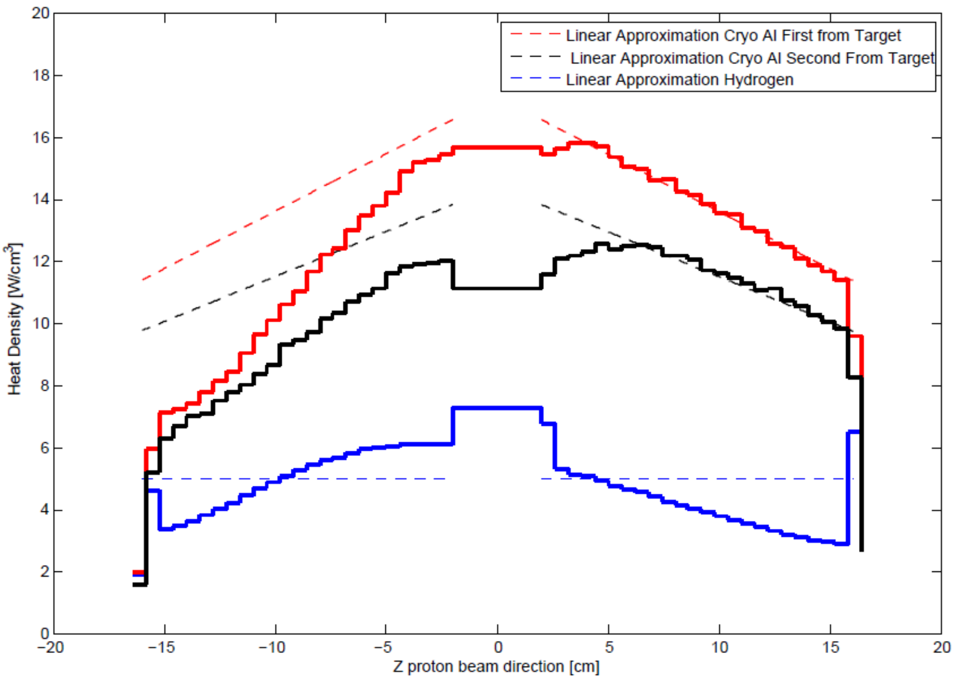

Figure 4-1: Heat load distribution in the proton beam direction in the cold moderator.

The thermal moderator includes four different heat load functions, which represents two aluminum layers in the bottom respective upper plate and two water layers at the corresponding heights, Figure 4-2.

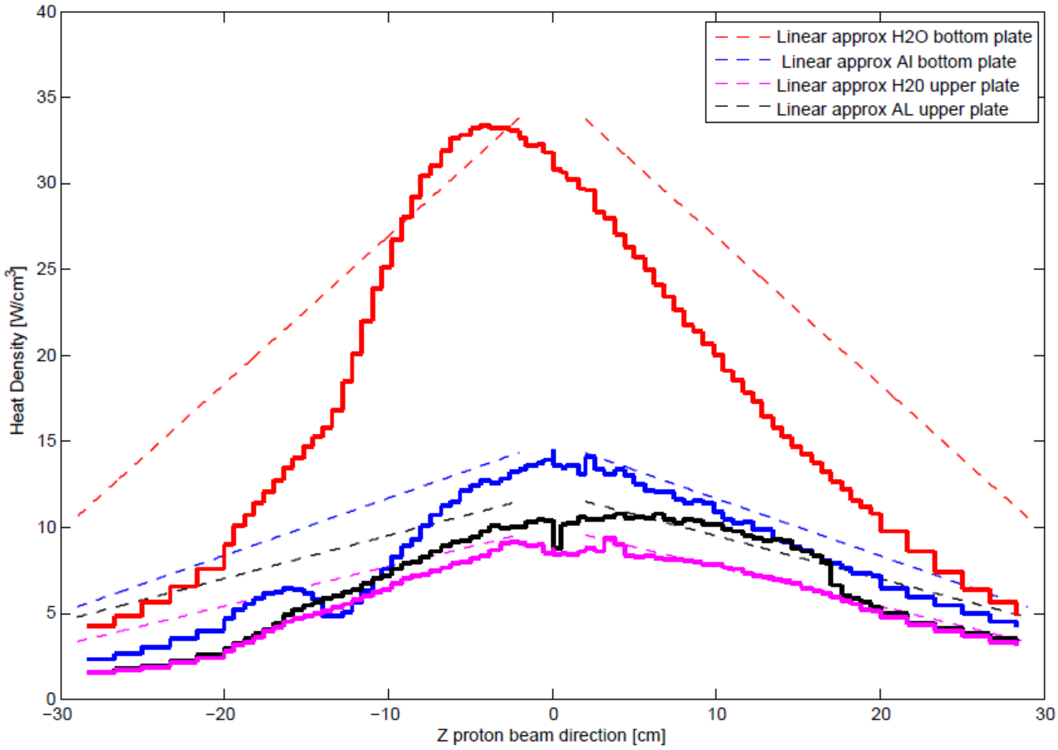

Figure 4-2: Heat load distribution in the proton beam direction in the thermal moderator.

5. COLD MODERATOR

The idea is to use collinear hydrogen pipes and create an impingement jet striking at the tip of the moderator, Figure 5-1. This area will be demanding for the simulations and any further development, but still considered to be achievable. The other two corners have been rounded with a bigger radius compared to the neutronic model. The effect needs to be analyzed in the neutronic model. However, this way the fluid flow is smoother and better in cooling the walls. The performance of this concept will also depend on the radius of the tip where the jet hits the wall.

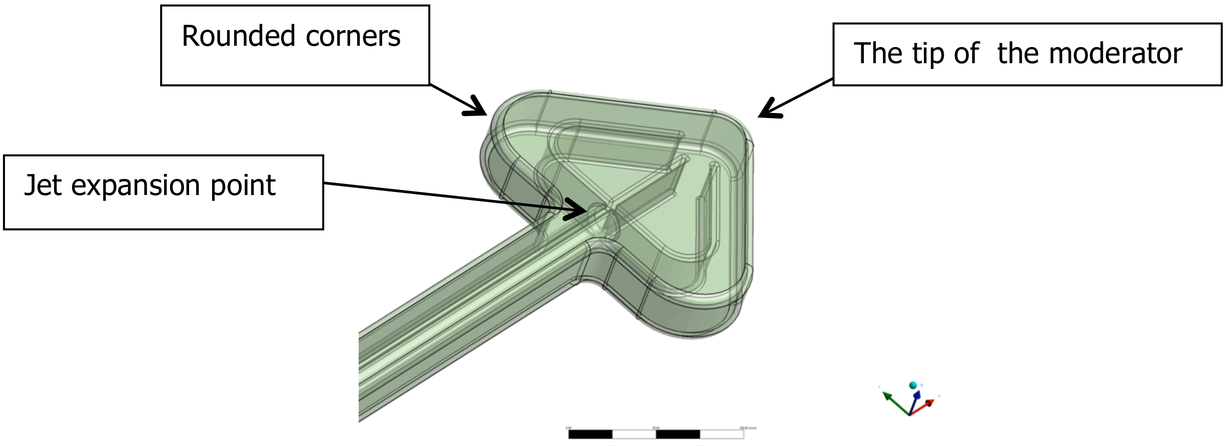

Figure 5-1: Single hydrogen tank design with rounded corners and jet flow.

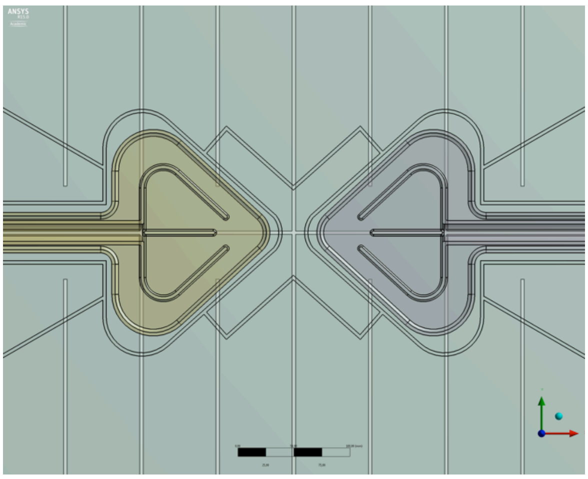

Figure 5-2: Located hydrogen tanks into the vacuum space.

5.1 CFD ANALYSIS

Boundary conditions used in the CFD simulation are following. The inlet temperature in a single moderator (single arrow) is 17K with the mass flow 200g/s. Since there are two hydrogen tanks, parallel connection is considered. It means that the total mass flow from the serial pancake design 400g/s has been divided equally into the two hydrogen tanks with parallel connection for the BF2.

The co-axial pipe solution includes the heat leak between the inlet and the outlet hydrogen layer, which is one of the disadvantages of this solution. The heat leakage for this specific pipe length 240mm, located close to the moderator has been roughly approximated to an order of 30W.
The flow concept is presented in Figure 5-3. It starts at the expansion of the free jet. Then the flow enters the central part of moderator so that the hydrogen begins to rotate as a result of the jet expansion itself and in the next turn as a result of collision with the flow guides. The rest of the jet is striking straight forward in order to reach the tip of the moderator. From that point the flow is then divided into two parallel channels along the outer shape of the moderator towards the outlet.
The pressure drop is caused mostly due to the jet expansion and the rapid flow bends. It is also sensitive to the mass flow, which in the next turn depends on the required cooling performance. Again the tip of the moderator will require some effort to optimize the cooling. Perhaps an asymmetric solution, which would move the stagnation point further from the tip, would improve the cooling effect in this hot region.

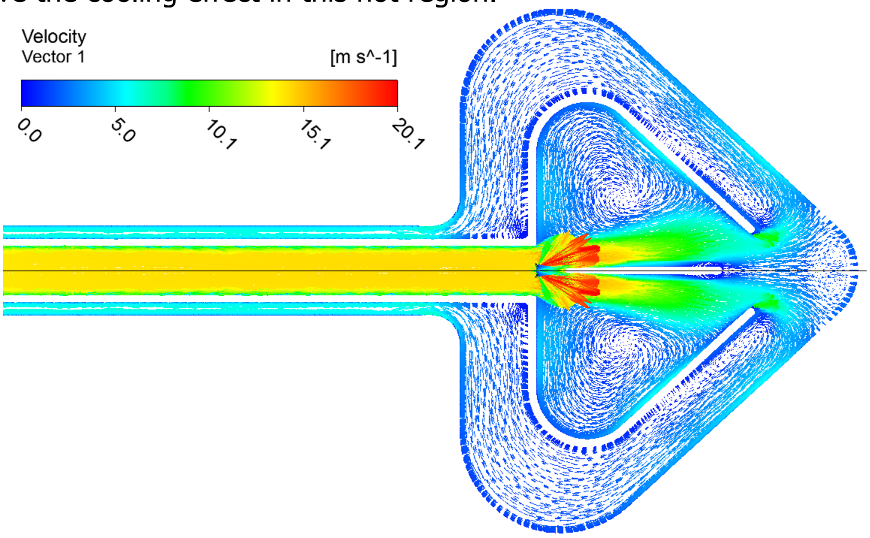

Figure 5-3: Velocity field at the middle cross section.

The temperature of the hydrogen is shown in Figure 5-4. It should stay between 17K and 20K as it could be observed in the serial pancake designs.
The following temperature plots show the inside and the outside aluminium surfaces in Figure 5-5 and Figure 5-6. The average maximal temperature should stay below the critical point of the hydrogen 33.15K, so that the heat load introduced by the heat pulses can be still easily transported away. If the max average temperature stays above the 33.15K then there is a risk for a rapid hydrogen density variation due to the pulses. However, the jet flow concept after the optimization phase should be capable to avoid this risk.

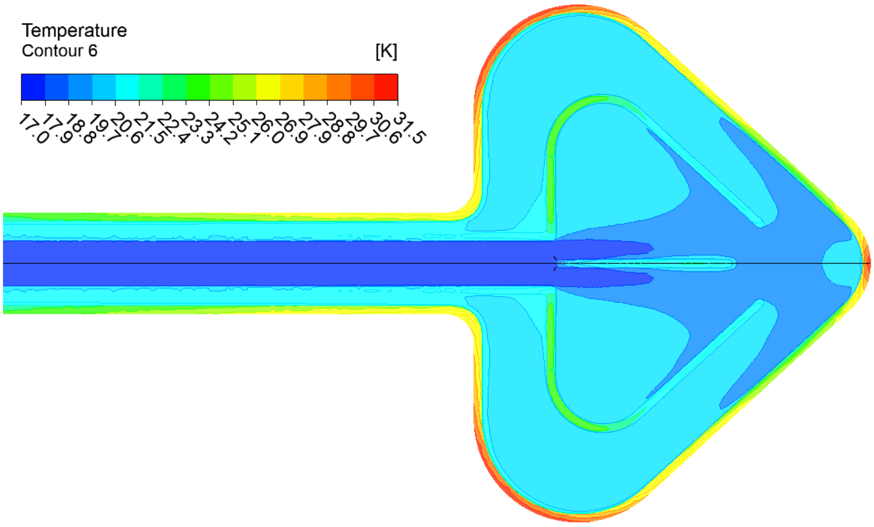

Figure 5-4: Temperature field at the middle cross section. Average hydrogen temperature is between 17K and 20K.

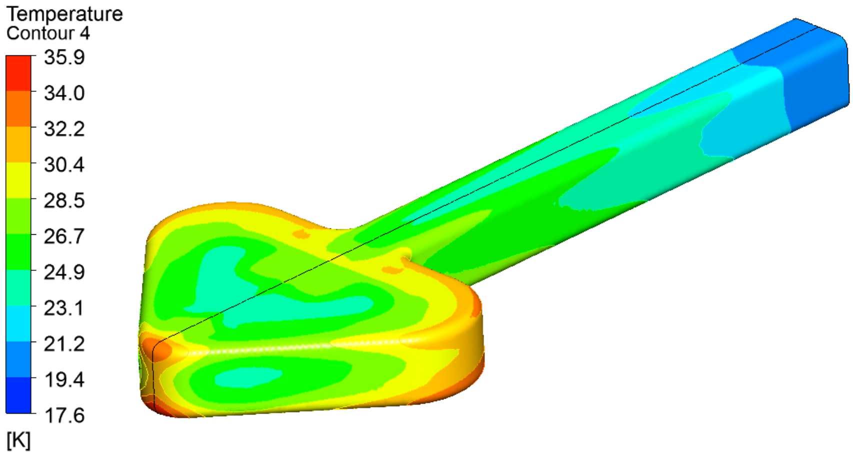

Figure 5-5: The temperature plot at the outside aluminium surface.

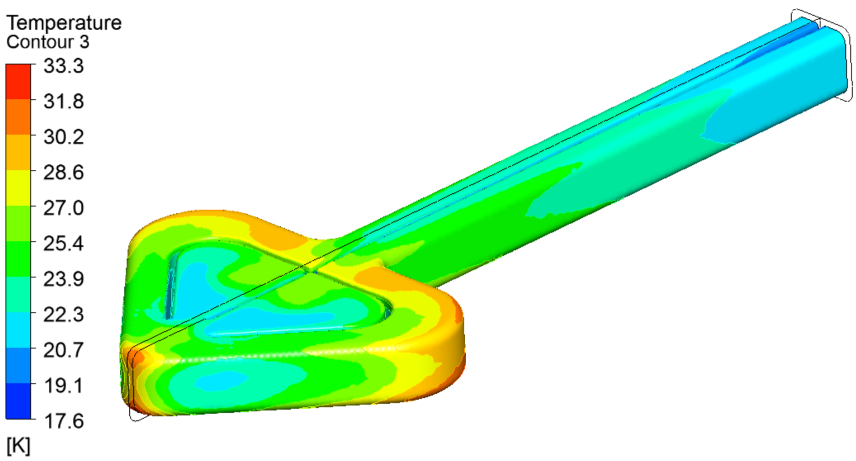

Figure 5-6: The temperature plot at the inside aluminium surface.

5.2 FEM ANALYSIS

The following stress conditions needs to be met:
General primary membrane stress

$$\overline{P_m} \leq S_m(\theta_m)$$

The local primary membrane stress

$$\overline{P_L} \leq 1.5S_m(\theta_m)$$

The primary membrane plus bending stress

$$\overline{P_L + P_b} \leq 1.5S_m(\theta_m)$$

General membrane primary and secondary equivalent stress

$$\overline{P_m + Q_m} \leq S_{em}^{A}(\theta_m, G_{tm})$$

Total primary and secondary equivalent stress

$$\overline{P_L + P_b + Q + F} \leq S_{et}^{A}(\theta\ \ , G_t)$$

The allowable stresses depend on temperature and radiation. For the temperature the allowable stress increase for lower temperature and since the maximum temperature for the cold moderator is 20°C the allowable stresses are calculated for this temperature. For the radiation the estimation is $25 \cdot 10^{21}$ thermal neutrons/cm^2 and year. For two years of operation, the total and maximum radiation is $50 \cdot 10^{21}$ n_{th}/cm^2. This result in the following allowable stresses according to RCC-MRx [1].

$\overline{P_m} \leq S_m(\theta_m)$=87 MPa
$\overline{P_L} \leq 1.5S_m(\theta_m)$=130 MPa
$\overline{P_L + P_b} \leq 1.5S_m(\theta_m)$=130 MPa
$\overline{P_m + Q_m} \leq S_{em}^{A}(\theta_m, G_{tm})$=292 MPa
$\overline{P_L + P_b + Q + F} \leq S_{et}^{A}(\theta\ \ , G_t)$=604 MPa

The allowable stresses in the welds are not considered here since the welding method and placement is not set jet but S_m for the weld is 55MPa according to RCC-MRx [1]. Assuming a full penetration fillet or T weld with volumetric examination and surface examination of one side results in a joint efficient factor of 0.85 so the total allowable membrane stress in the weld becomes 46MPa.

At this stage only internal pressure (15 bar) is considered. The stresses in the shell scaled against allowable membrane stress is shown in Figure 5-7 where also the section with highest membrane + bending stress is shown. The stresses are rather low and the linearized membrane and membrane + bending stress is shown in Figure 5-8. The membrane + bending stress is 100 MPa, i.e. well below the allowable stress of 130 MPa.

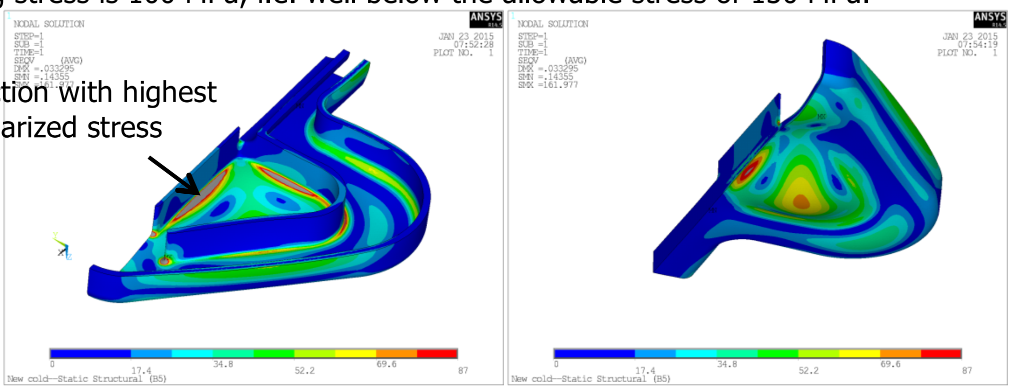

Figure 5-7: Stresses in the shell scaled against allowable membrane stresses.

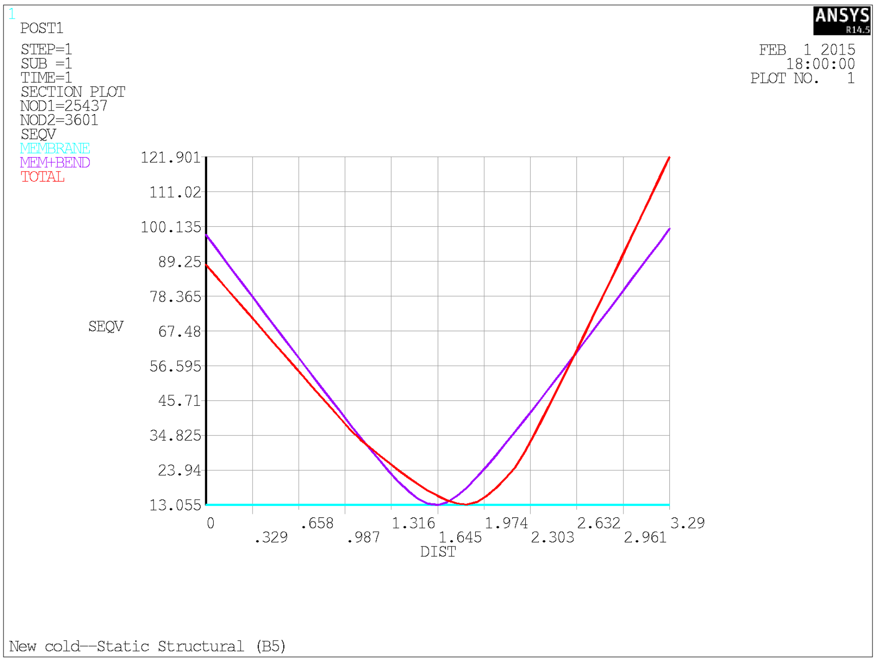

Figure 5-8: Maximum linearized stress.

The maximum peak stress is shown in Figure 5-9 and is 161MPa and way below the allowable value of 604MPa.

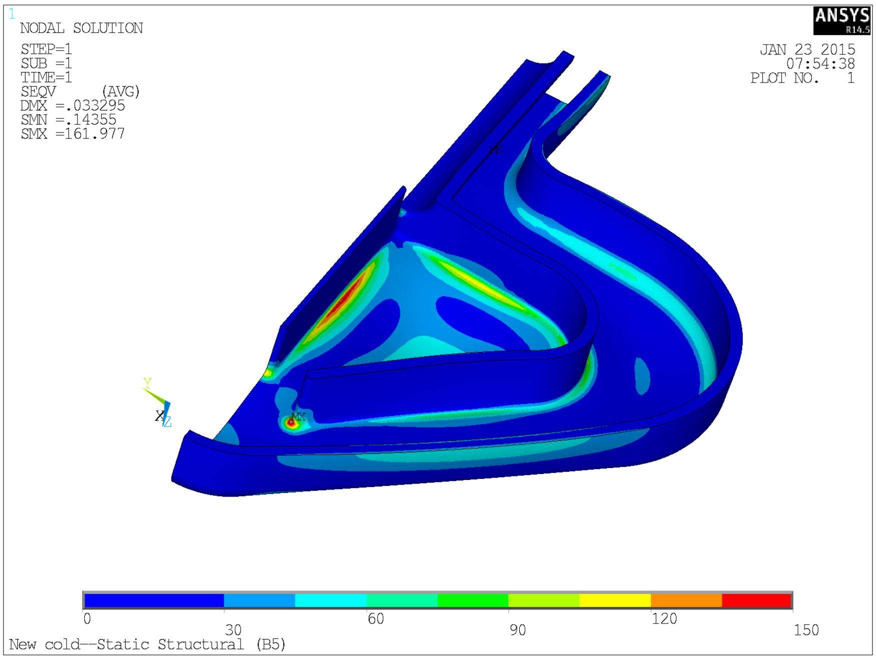

Figure 5-9: Maximum peak stress

The conclusion is that for the internal pressure the allowable stresses are well within allowable limits. Compared to the pancake design the stress is at the same magnitude.

At this stage the wall thickness is set to 3 mm everywhere for both the BF2 and the pancake design but this could probably be optimized. Still the manufacturing demands on minimal wall thickness must be considered.

6. THERMAL MODERATOR

The butterfly thermal moderator concept is presented in Figure 6-2. It has an additional water volume in form of the cross between the hydrogen tanks, Figure 6-2.

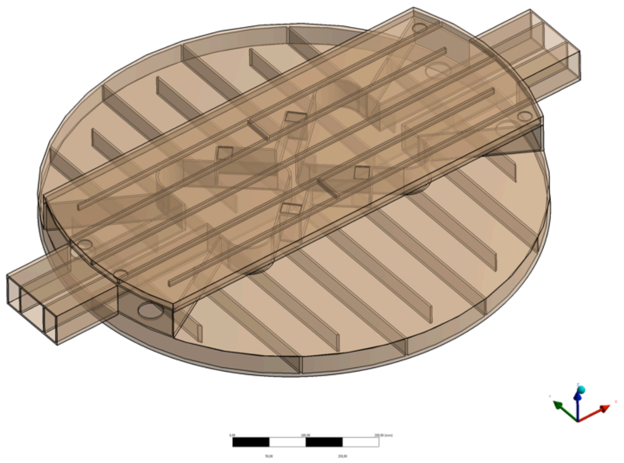

Figure 6-1: The butterfly thermal moderator BT2.

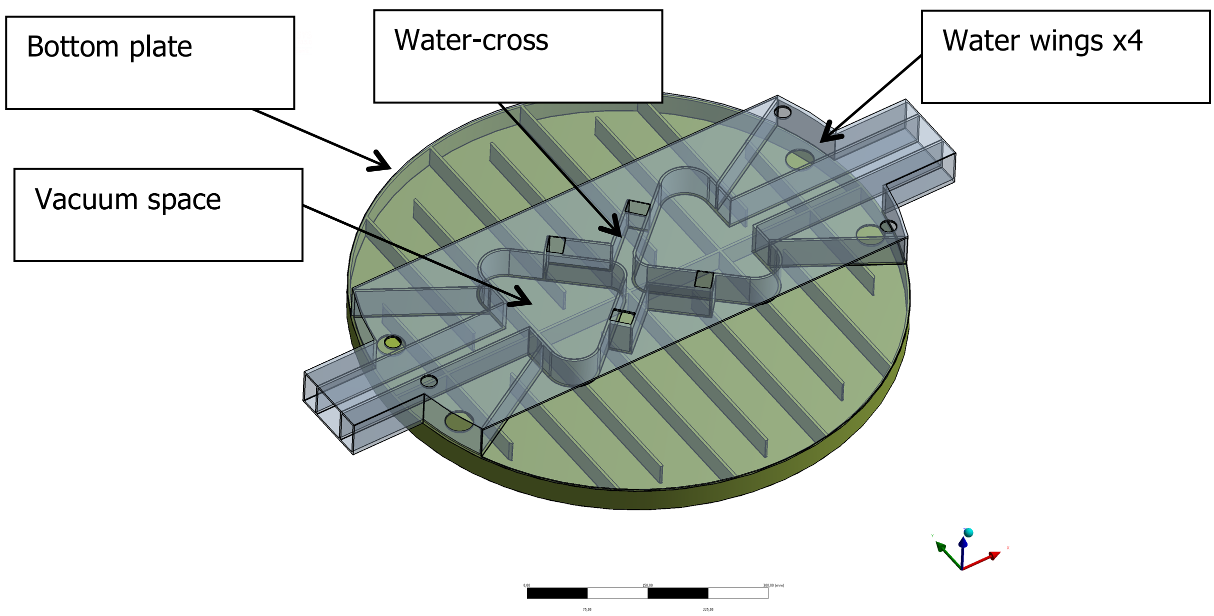

Figure 6-2: The bottom plate solution together with the water wings, vacuum space and the water-cross.

The idea is to fill this volume with water coming from a single channel in the upper plate as shown in Figure 6-3. This single channel is divided by a wall into two shorter channels with openings downward to the water-cross at each side of the wall. This way the water will cover the first shorter channel and then go down to the water-cross, then through the water-cross and then go up [...] cond shorter channel.

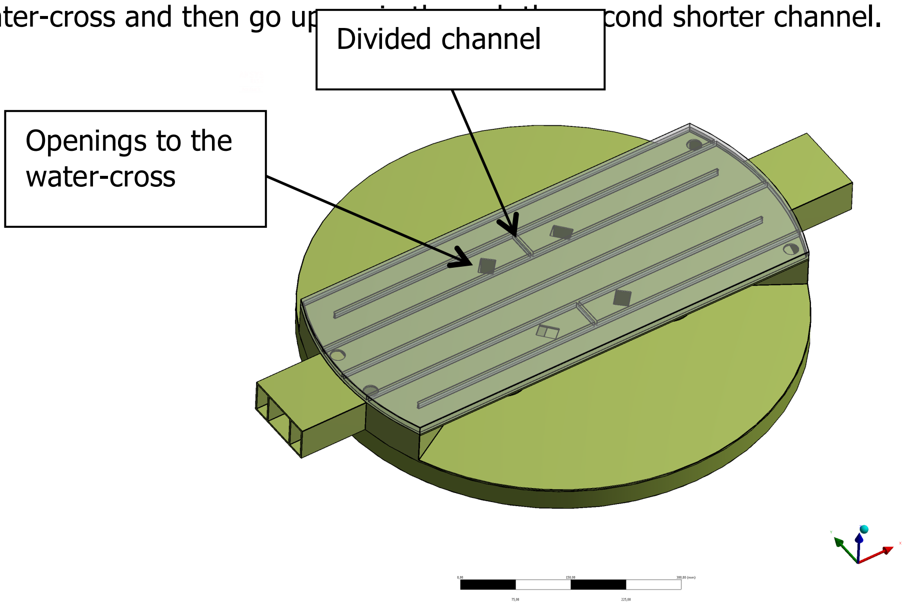

Figure 6-3: The upper plate solution with openings downward to the water-cross and the divided single channel.

Another noticeable modification is the inlet pipe assembled from the three rectangular cross sections. The two side sections are the water sections which embrace the middle vacuum section. The middle vacuum section will include the cryogenic pipes with the cold moderator. This solution should simplify the vacuum cooling problem along the pipes as well as it suites the thermal moderator design.

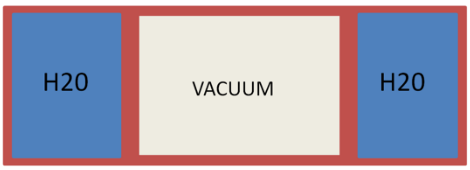

Figure 6-4: The inlet pipe arrangement.

6.1 CFD ANALYSIS

The cooling fluid is water. There are no strict numbers for the mass flow and the pressure drop, since the water loop is not as sensitive as the hydrogen system. The flow pattern in the proposed design is flexible due to the two separated water loops.
In the concept phase the operating pressure is assumed to 5bar, and the total mass flow to 2kg/s with the inlet temperature 30C.
The cooling performance of the proposed design is sufficient and again can be easily modified. An advantage of the butterfly thermal moderator is the reduced size of the emission window, the most heated surfaces due to heat deposition. The water-cross, gives an additional cooling contact to this emission window. This is positive especially for the mechanical analysis.

The flow streaming lines for a few different views and the temperature plot of the outside aluminum surface are presented in Figure 6-5 and Figure 6-6.

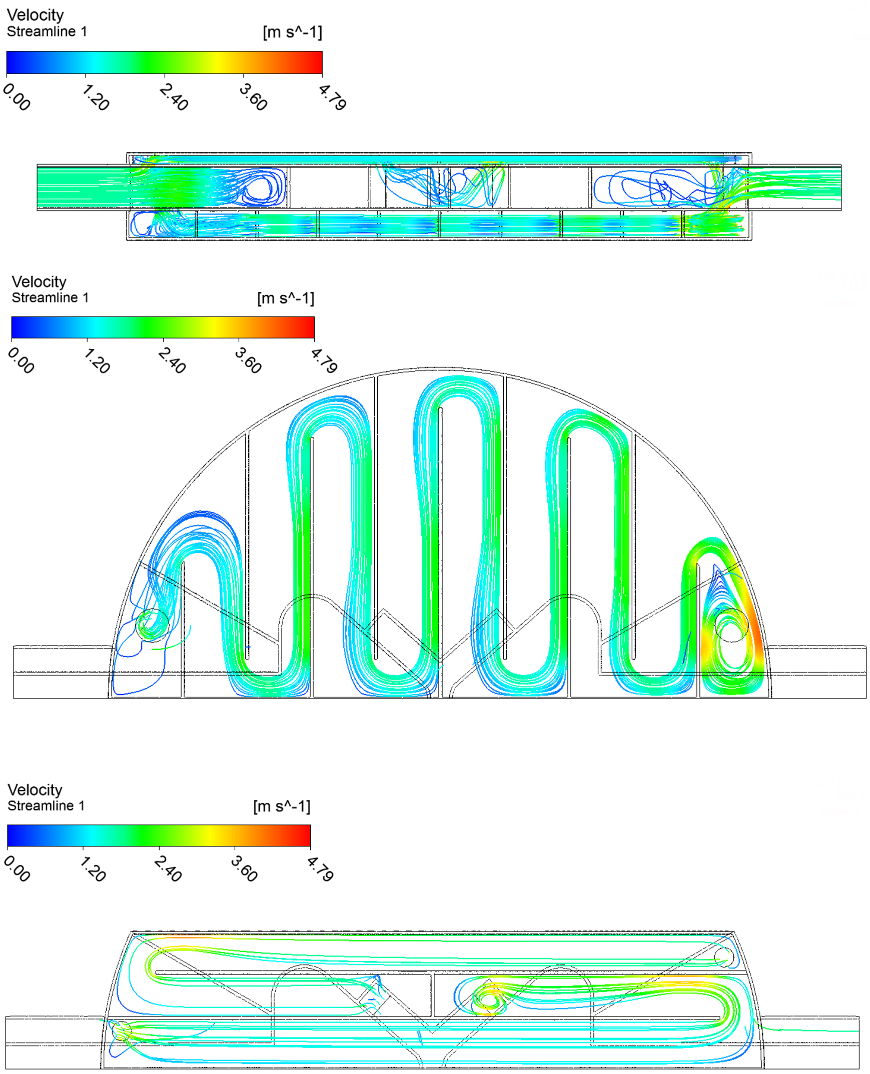

Figure 6-5: The velocity streaming lines through the upper and bottom plate.

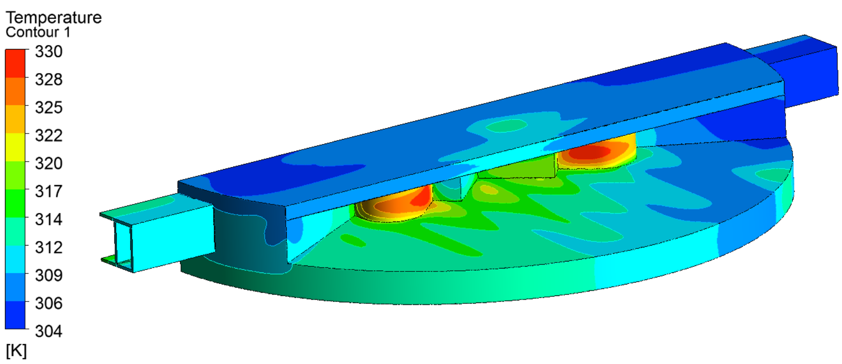

Figure 6-6: The temperature plot of the outside aluminum surface.

6.2 FEM ANALYSIS

For the thermal moderator somewhat lower allowable stresses are used due to the higher temperature. A temperature of 100°C is used as input number in RCC-MRx [1].

$\overline{P_m} \le S_m(\theta_m)$=84 MPa

$\overline{P_L} \le 1.5S_m(\theta_m)$=126 MPa

$\overline{P_L + P_b} \le 1.5S_m(\theta_m)$=126 MPa

$\overline{P_m + Q_m} \le S_{em}^A(\theta_m, G_{tm})$=113 MPa

$\overline{P_L + P_b + Q + F} \le S_{et}^A(\theta\ \ , G_t)$=283 MPa

For the welds the same allowable stress are as for 20°C apply.

Pressure stresses

Global membrane stress is not decisive so only membrane + bending stress is shown, see Figure 6-7.

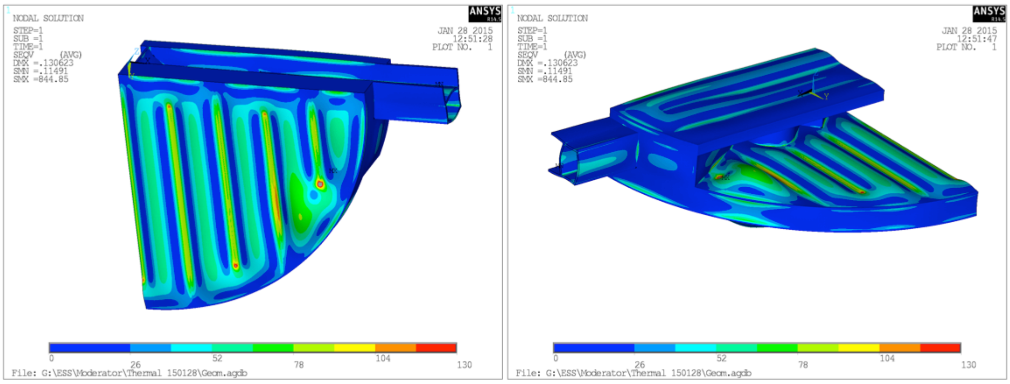

Figure 6-7: Stresses in the shell scaled against allowable membrane + bending stresses.

In general the stresses are below allowable value. However, locally inside the moderator the stresses between the internal guides and the outer shell are too high, see Figure 6-8. The problem is the thinning of the guides at the edge together with a straight edge connected to the outer shell with a relatively small radius. Instead the straight edge should be curved in order to lower the stresses in the area. Then we also have the manufacturing issue. If welding is to be made according to Figure 9-2 the allowable stress, where there already is high stresses, will be reduced significantly.

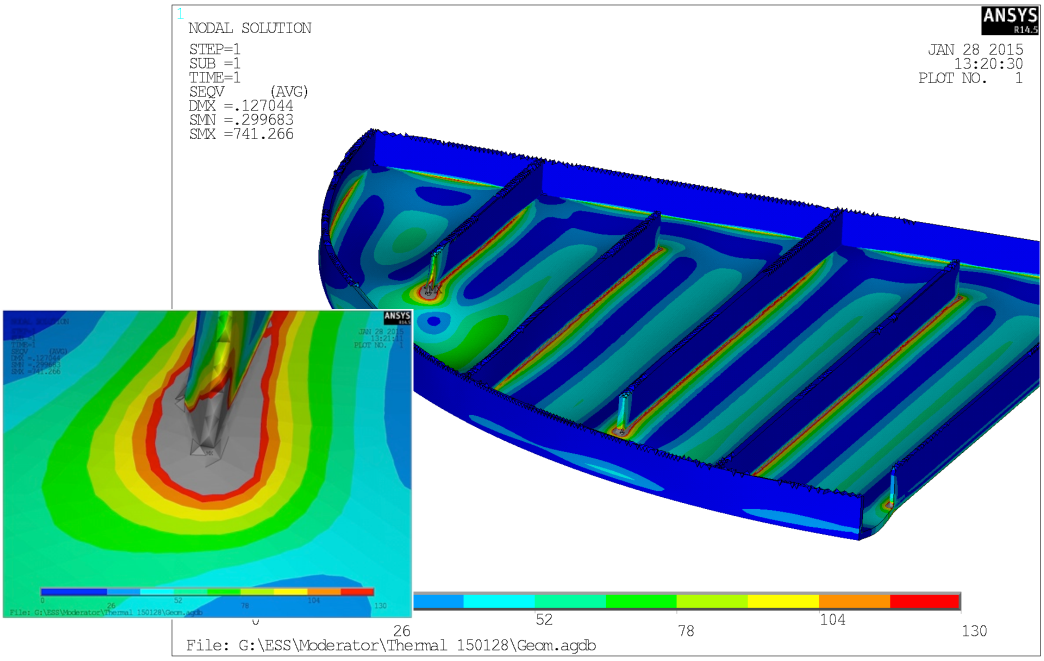

Figure 6-8 Local stresses

7. PIPING

The piping assembly for a pancake moderator is shown Figure 7-1. However, to have a parallel flow of two times 200g/s for each of the cold moderator vessels BF2, a different pipe arrangement is needed.

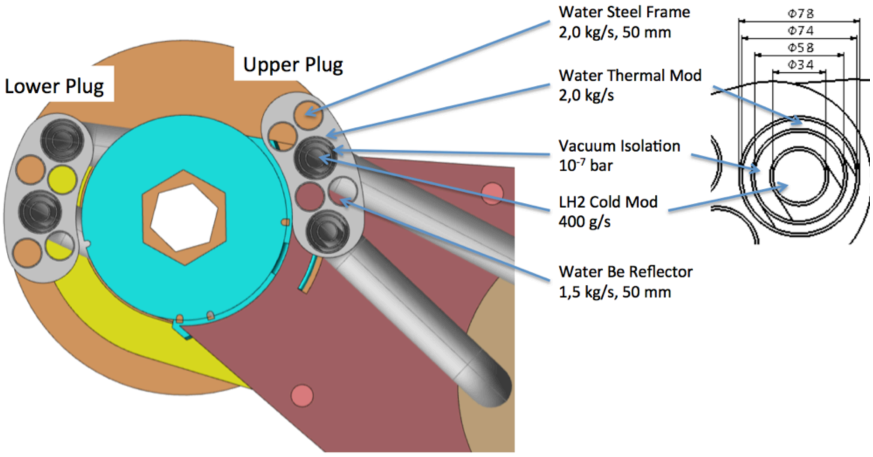

Figure 7-1: Piping along the shafts for the pancake moderator

In order to achieve the correct flow for each of the cold vessels the hydrogen flow needs to be divided outside the helium vessel to get access and possibility to control the flows.
It doesn't seem to be a feasible alternative to archive parallel flow to the two BF2 cold moderator vessels with a manifold close to the plug itself down in the monolith would be difficult. Neither, that there is space for the manifold.
That means instead of having one inlet and one outlet hydrogen (for a single moderator) there will be two inlets and two outlets for each of the two vessels. This means we will have 4 instead of 2 hydrogen cryogenic bayonet connectors.
An additional manifold close at the top of the monolith is necessary to archive hydrogen-in and hydrogen-out in a coaxial piping. This is needed in order to not increase the amount of piping down to the MR plug. The result is a coaxial pipe with hydrogen-in, hydrogen-out, vacuum and water, which is one layer more compared to today. As a result the pipe outer diameter of 78mm of today need to be increase slightly.
The split butterfly design is less rigid. It is a 300mm free pipe horizontally hanging which needs to be supported with cryogenic vacuum spacers.

8. VACUUM SYSTEM

As we split the cold moderator in two separated vessels, the vacuum insulation volume around the cryogenic parts will also be **split** in half. It needs to be analyzed how it will affect the vacuum system with respect to the vacuum quality and the amount of the vacuum zones (one zone for each cold moderator vessel).

9. MANUFACTURING

The cold moderator vessel shall be made of aluminium alloy Al6061-T6 material. The intended manufacturing method is to mill the base structure of the cold moderator from a full piece of aluminium with high speed milling. The same will be done for the thermal moderator. Then the parts need to be assembled and closed by top aluminium plates which have to be welded along the geometry contours. The principle can be seen in Figure 9-1.

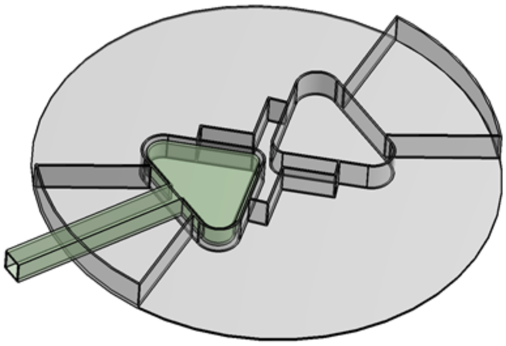

Figure 9-1: High speed milling and assembly of cold and thermal moderator parts

There is a concern about this manufacturing method because it is based on the high quality electro beam through-welding as shown in Figure 9-2.
The welding tests that have been done in the TDR for the volume moderator design with different aluminium alloys so far, have not taken the through-welding method into the consideration.

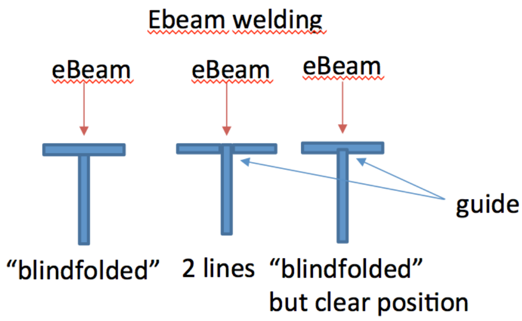

Figure 9-2: Electro beam through welding of aluminium

For the earlier concepts of the volume moderator, all welds could be done from the outside. For the pancake moderator some different alternative of welding according to Figure 9-2 (middle and right picture) have been developed to have an alternative, if through-welding of aluminium would not be feasible to archive with the right quality.

For the butterfly concept:

- Welding test of electro beam through-welding need to be done to confirm feasibility
- And more conventional manufacture principles need to developed in case electro beam through-welding is not feasible

This work is on-going. Through-welding test need to be done as soon as possible.
Finally, the current design of the butterfly moderator consists of many welds close to each other that should be made in a thin material of 3 mm wall thickness. More effort need to be spend to optimize the design according to manufacturing demands, particular how the amount of welds can be minimised and/or be located in less stress demanding areas.

10. TESTING

X-ray testing of the butterfly cold and thermal moderator is a challenge task as a lot of welds are overlapping each other which will result in shadowing pictures, which is difficult to judge correctly.

11. SUMMARY

The findings of this report can be summarized as following:

- **The butterfly cold moderator** works as a free jet flow. This is an increase in complexity of the flow comparing to the serial flow in the pancake. It may require an additional effort in the further development. However there are no critical issues at the moment that could eliminate this concept straight away. Furthermore the design also introduces collinear hydrogen pipes, causing additional effort in the pipe connections. Mechanical stresses and manufacturing issues remain about the same as in the previous pancake design.

- **The butterfly thermal moderator** is designed in the same manner as in the pancake assembly. The challenge is to add the water-cross volume in the center of the geometry and feed it from the either upper or the bottom plate. There are no bigger issues connected to the flow design or heat load removal. Furthermore the vacuum volume is split in half resulting in two separated vacuum zones.
  The manufacturing methods based on electro beam through-welding were already an issue in case of the pancake design. The water-cross in the butterfly thermal moderator introduced even more complex weld zones that might cause manufacturing difficulties.

12. REFERENCES

[1] AFCEN RCC-MRx code. DESIGN AND CONSTRUCTION RULES FOR MECHANICAL COMPONENTS OF NUCLEAR INSTALLATIONS. Edition 2012.

7 APPENDIX II, CRYOPLANT AND CRYOGENIC LIQUID HYDROGEN SYSTEM ANALYSIS

John Jurns & Jesper Ringnér

7.1 Cryogenic cooling of the moderators

7.1.1 Introduction.

The LH2 system plays an important role for the instruments. Liquefied hydrogen at 20K act as a moderator and provides cooling for the fast neutrons created when the proton beam hits the target wheel, scattering neutrons.
To optimize instrument performance high demands on the hydrogen is set. The density shall keep within a narrow range at the same time as a significant heat load is added. This sets a number of constraints on the cooling system that provides the cold hydrogen. Even though hydrogen has a good specific heat coefficient, a large mass flow is needed to remove the heat.
At 17-20K the specific heat (C_p) for hydrogen is average 8,43 J/g*K. This gives that the mass flow needed to cool of 1kW of heat load 3K, approx 39,5g/s.

$$Q = c * m * \Delta T \Rightarrow \frac{Q}{c * \Delta T} = m$$

The density of hydrogen 18.5K@1.5MPa is 74,43kg/m^3. This gives the volume flow needed 0.53l/s/kW to maintain ΔT=3K.

7.1.2 Moderator design options

Moderator can design is subject to design changes and as a direct consequence of this is a changing heat load for the hydrogen cooling system.
Evaluation of the consequences is done for following scenarios.

Scenario	Base case 3PC+ 6OT	3PC+ 6CH	3PC+ 6BF2	3BF1 + 6OT	3BF1 + 6CH	3BF1 + 6BF2	3BF2 + 6OT	3BF2 + 6CH	3BF2 + 6BF2
Top Moderator HD kW	8,2	8,2	8,2	10,6	10,6	10,6	9,4	9,4	9,4
Bottom Moderator HD kW	6,3	11,2	11,9	6,3	11,2	11,9	6,3	11,2	11,9
Static HD kW	4	4	4	4	4	4	4	4	4
Total HD kW	18,5	23,4	24,1	20,9	25,8	26,5	19,7	24,6	25,3
Estimated Equipment Cost M€	2,000	2,530	2,600	2,260	2,790	2,860	2,130	2,660	2,740

Table 4, Heat Loads and corresponding material costs.

Since the heat load for the most likely configurations is approx 20 or 26kW, the analysis will focus on those two scenarios.

7.2 Equipment impact

7.2.1 Pumps

Typically not a off shelf item and will be designed especially for our requirements. The difference in flow rate, pressure drop etc. will probably not affect the price very much even though it is a significant difference in performance.
The performance is also dependant of the choice of pump configuration.

Description	Mass flow rate/pump	Pressure drop	Full redundancy	Heat Load
Two pumps in parallel/series	800g/s	0.075/0.15kPa	Yes	20kW
One pump per loop	400g/s	<0.15kPa	No	20kW
Two pumps in parallel/series	1030g/s	0.075/0.15kPa	Yes	26kW
One pump per loop	515g/s	<0.15kPa	No	26kW

Table 5, pump arrangements.

7.2.2 Valves

Larger mass flow requires larger pipe dimensions. Cost impact might be +30% at 26kW. No additional technical risk.

7.2.3 Heat exchanger

Calculated and designed for our needs. Cost impact might be if the new flow demands one or more sizes larger heat exchanger. No additional technical risk.

7.2.4 Cryostat, transfer lines

Due to lager mass flow the pipe dimensions will be larger. This mostly to be able to handle the increasing pressure drop. Cost impact is probably negligible, hydrogen inventory will increase. No additional technical risk.

7.2.5 Pressure and temperature control

Larger heat load and hydrogen mass flow increases the expansion volume. Depending of solution, cost impact can be significant.
Comparison to 20kW

Description	Cost impact at 26kW	Physical size	Proven technique
Heater + accumulator	High	Larger	Yes
Passive Expansion vessel	Equal	Slightly Larger	Unproven in H_2 system
Active Expansion vessel	Equal	Equal	Unproven
He heater/by pass	High	Equal	Yes

Table 6, change analysis.

7.2.6 OP convertor, instruments, control system

No noticeable impact

7.2.7 Operation impact

The larger heat load will probably drive operational cost slightly upwards.

7.2.8 System impact

The impact that a larger heat load will cause the LH_2 system, is probably not significant.

- It's already several times larger than any existing cold sources cooling system. This means the design solutions chosen at f.ex. SNS and J-Parc isn't applicable at ESS.
- Most critical parts is tailor made and the difference in design/performance vs. cost is probably small. If comparison was between off shelf item for 20kW and tailor made for 26kW the difference would not be defendable.
- The biggest issue will be increased hydrogen inventory. Preliminary calculation indicates 20% more hydrogen, 360l compared to 300l today. Safety aspect must be re-evaluated.

7.2.9 Summary

Change of moderator design/heat load will impact the system design but with an increased cost and a slightly increased technical risk. To minimize the impact on the schedule a decision of the chosen moderator design is needed soon.

7.3 Impact of changing Target cold moderator design on TMCP

7.3.1 Introduction

Target project is currently assessing several options for the cryogenic moderator design. These designs result on different heat loads on the cryogenic H_2 circuit, and consequently the Target Moderator Cryoplant (TMCP). The purpose of this report is to assess the impact of these design options on:

- Cost
- Schedule
- Technical Risk

7.3.2 Assumptions

Safety factors for TMCP heat loads are shown in Table 7:

	Safety Factor
Neutronic Heating	1.15
H_2 Circulators	1
Static Heat load H_2 Box	1.5
Static Heat load He CTLs	1.3
Operational Margin	1.1

Table 7, Safety factors for TMCP heat loads

Total estimated TMCP refrigeration duty and electrical power required based on Target Project heat load estimates and safety factors from Table 7 are shown in Table 8.

Capital cost of cryoplants estimated based on recent budgetary quotes from ALAT and LindeKryotechnik for TMCP.

Energy costs estimated at 50€/MWhr electricity, waste heat energy recovery price estimated at 17€/MWhr.

Operating cost assumes 100% power for full operation, ~ 25% power required for Maintenance operation. Operating hours based on (ref ESS-0003989):

- Full operation hours 5856
- Maintenance hours 2808

7.3.3 Impact

TMCP capital cost – An increase in refrigeration power results in a larger capacity cryoplant. The base case TMCP cost is based on recent budgetary quotes from ALAT and LindeKryotechnik. TMCP costs for other moderator options have been scaled based on refrigeration loads shown in Table 9. Figure 3 shows estimated cost *differential* from baseline for the different moderator options. Total estimated CAPEX for TMCP for all moderator options is shown in Table 9.

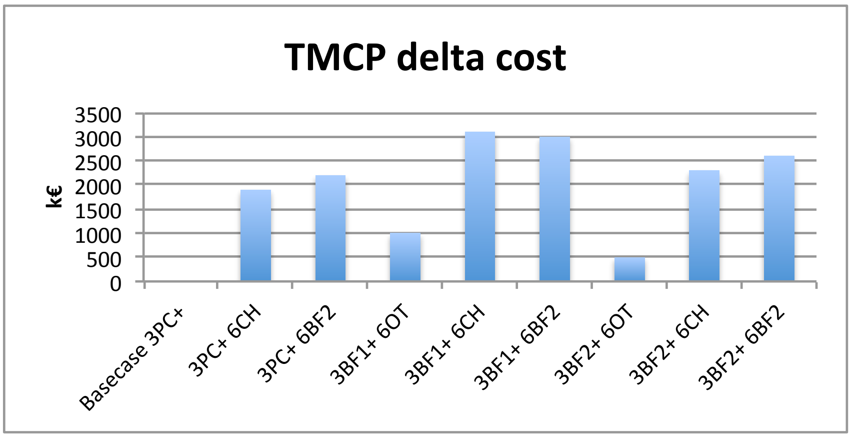

Figure 3, Cost delta from baseline TMCP cost for moderator options

Increased TMCP capacity will result in increased flow rate of cryogenic helium to the H_2 cold box in the target building. However, calculated estimates of pressure drop through the Cryogenic Transfer Line (CTL) for all cases indicate that no increase in vacuum jacketed pipe size or cost is anticipated.

Site Infrastructure cost–Increased TMCP capacity will increase the size of equipment, particularly in the G04 compressor building. However, based on the estimated size of the base case, there still appears to be sufficient space in both the compressor building and the cold box room in building G02 to accommodate a larger TMCP. *The only anticipated increased SI cost would be for additional 200-900 kW electrical power*.

Operating cost – Larger TMCP size will result in greater operating cost. Assuming a cryoplant efficiency factor (electrical power/refrigeration power) of about 90 for a 17K helium supply, the increase in refrigeration capacity results in significant increase in required electrical power. Operating cost is estimated based on costs detailed in the "assumptions" section, and includes both electrical power cost, and income realized from sale of waste heat to the Lund district heat system. Figure 4, shows estimated annual operating cost *differential* from baseline for the different moderator options. Total estimated OPEX for TMCP for all moderator options is shown in Figure 4.

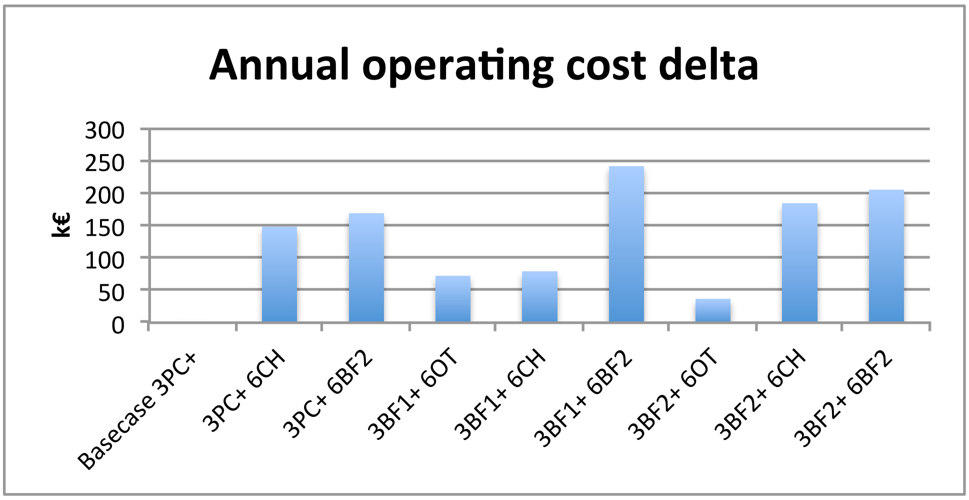

Figure 4, Annual TMCP operating cost delta from baseline for moderator options

7.3.4 Schedule

At this point in the project, ESS has not requested tenders for the TMCP. Assuming a decision on the moderator design is made in February, we should still be able to complete the TMCP specification, call for tenders, and complete the project on the current schedule. *We anticipate no further schedule impact.*

7.3.5 Technical Risk

The TMCP is a commercially procured system. Up to a point, there are no additional technical risks anticipated by increasing the refrigeration capacity. Based on a recent discussion with one of the helium cryoplant manufacturers, the design they proposed for the TMCP includes two warm helium compressors and two cryogenic turboexpanders. This configuration could accommodate an increased load up to a certain point by increasing compressor capacity, heat exchanger size, etc. However, it is TBD at what point additional equipment would be required to accommodate the larger refrigeration loads. We assume that the existing site infrastructure can accommodate a larger TMCP. However, *until we receive tenders, we cannot determine definitively if there will be any space limitations* in buildings currently under construction.

7.3.6 Summary

If the cold moderator design is changed, the only significant impact is on required refrigeration capacity of the TMCP. There are no significant technical or schedule risks for this change, only change in cost. Option 3BF1+6CH results in the greatest increase in cost, and 3BF2+6OT results in the smallest increase in cost when compared with the baseline design of 3PC+6OT.

7.3.7 Tables

Scenario	Basecase 3PC+ 6OT	3PC+ 6CH	3PC+ 6BF2	3BF1+ 6OT	3BF1+ 6CH	3BF1+ 6BF2	3BF2+ 6OT	3BF2+ 6CH	3BF2+ 6BF2
Total HD kW	14,5	19,4	20.1	16,9	22,8	22.5	15,7	20,6	21.3

TMCP duty including margins

Moderator heat load kW	18.3	24.50	25.40	21.40	28.80	28.50	19.90	26.10	26.90
H_2 Circulating pumps kW	3.3	4.4	4.6	3.8	5.2	5.1	3.6	4.7	4.8
Static Heat load H_2 Box kW	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Static Heat load He CTL kW	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Total est'd heat load for TMCP kW	**24.2**	**31.5**	**32.5**	**27.7**	**36.5**	**36.1**	**25.9**	**33.3**	**34.3**

TMCP Electrical power required kW	**2250**	**2931**	**3028**	**2583**	**2612**	**3362**	**2416**	**3098**	**3157**

Table 8, Estimated overall heat loads for TMCP for moderator option designs.

7.4 Total WU Cost Analysis

Scenario	Base case 3PC+ 6OT	3PC+ 6CH	3PC+ 6BF2	3BF1+ 6OT	3BF1+ 6CH	3BF1+ 6BF2	3BF2+ 6OT	3BF2+ 6CH	3BF2+ 6BF2
Total HD kW	14,5	19,4	20.1	16,9	22,8	22.5	15,7	20,6	21.3
TMCP CAPEX k€	10,600	13,200	13,500	12,300	14,400	14,300	11,800	13,600	13,900
LH2 MCS CAPEX k€	2,000	2,530	2,600	2,260	2,790	2,860	2,130	2,660	2,740
TMCP OPEX k€	487	635	617	559	566	689	523	671	683
Total WU Material CAPEX k€	**12,600**	**15,730**	**16,100**	**14,560**	**17,190**	**17,160**	**13,930**	**16,260**	**16,640**
Required Budget Adjustment	0	+3,130	+3,500	+1,960	+4,590	+4,560	+1,330	+3,660	+4,040

Table 9, Estimated CAPEX, OPEX for TMCP and LH2 MCS moderator option designs