LBNF cryostat design

Abstract

Initial engineering design and feasibility studies for a large LAr cryostat for LBNF.
## History of Changes

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<th>Version</th>
<th>Changes/Comments</th>
<th>Authors</th>
</tr>
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1 Introduction

The scope of the LBNF Cryogenics Infrastructure includes the design, procurement, fabrication, testing, delivery and installation oversight of four identical Cryostats to contain the liquid argon (LAr) and the time projection chambers (TPCs), as well as a comprehensive Cryogenic System that meets the performance requirements for purging, cooling down and filling the cryostats, acquiring and maintaining the LAr temperature within ±1 K around nominal temperature (88.3 K), and purifying the LAr outside the cryostats.

For the last few years, it became clear that large cryostats cannot be built anymore with the old and proven technique of vacuum insulation, because of the size and the complexity of a deep underground project. The membrane design is commonly used for liquified natural gas (LNG) storage and transport tanker ships and has been proven to be a viable option for LArTPC experiments. A membrane tank is made of a stainless-steel liner to contain the liquid cryogen. The pressure loading of the liquid cryogen is transmitted through rigid foam insulation to the surrounding structural support which provides external support for the liner. The membrane liner is corrugated to provide strain relief, resulting from temperature-related expansion and contraction.

During the recent three months, while the LBNF project was reshaped, the concept of four individual and somehow independent cavern emerged. Each underground cavern is designed to host a large cryostat capable of containing 17-18 Ktons of liquid argon. New in this proposal is the fact that the large membrane vessels are externally supported by a steel self-supporting structure, which is not in contact with the wall of the cavern.

The reasons behind this choice are multiple:
- the need to avoid any possible issue related to the geology of the underground side
- the possibility to monitor from outside any possible problem or failure in the membrane concept
- the possibility to gain time in the construction of the support structure
- the possibility to involve other groups/funding agencies to participate in-kind to the delivery of the ready cryostats

This document represents a first design feasibility study of a novel solution for these large membrane cryostats, based on an external Fe support structure. Most of the engineering has been devoted in the last two months to prove the feasibility of this concept. The engineering of the membrane itself is for the moment not discussed, because from that point of view, the Fe solution is not different from the previous LBNE solution.

If this Fe solution is encouraged by LBNF, then a detailed engineering study of the membrane vessels will be done, together with a licenced owner company in Europe or Japan.

A large R&D program is ongoing at Fermilab and at CERN to prove the feasibility of this concept, by constructing Ktons scale prototypes and assessing their performance with LArTPCs. This learning process, both technical and commercial, will be of great help to the final project.
2 The project constraints

Figure 2.1: LBNF cavern layout, 4 independent caverns hosting the individuals Fe cryostats.

Figure 2.1 shows the most recent layout of the four underground caverns, which is now the baseline for the LBNF project. The experimental far detector facility is placed ~1500 m underground, two access shafts will provide material and personnel access.

Each cavern hosts a Fe warm cryostat as shown in Figure 2.2. Detail of this layout, including dimensions, are presented in Section 3. Inside the warm cryostat the cold membrane cryostat is installed with its own insulation (see Section 4).

Figure 2.2: overall layout of the Fe warm vessel, installed in each cavern.

The dimensions requirements are dictated by the need to provide to each detector an active volume in excess of the 10 Ktons of LAr, while allowing the design of the single phase TPC existing layout to be maintained. This means a transversal internal dimension of the liquid volume of width = 15.1 m and height = 14 m. While the 10 Ktons
requirement impose a liquid volume of length $= 62$ m. Assuming a gas phase of $\sim 3\%$, this means $\sim 17'800$ tons of liquid argon.

As the cold vessel is based on the GTT membrane technology, the initial thermal requirements call for an insulation thickness of 90 cm, including the primary and secondary membrane. The GTT membrane technology will provide a first and a second level of containment. No requirement at this point to have an additional containment at the level of the warm Fe structure. A stainless steel enclosure just behind the insulation will provide an effective gas enclosure, which will allow controlling the nitrogen atmosphere inside the insulation volume.

LBNF has just issued an overall schedule (see Figure 2.3), with the sequence of operations for the 4 detectors. For the first cryostat construction the time allocation is of 18 months, starting on September 1$^{st}$ 2019. The second cryostat starts construction on 1$^{st}$ of May 2020, 9 months after the start of the first cryostat. Cryostats 3 and 4 follow with the same pattern.

Figure 2.3: LBNF overall schedule
3 Fe warm cryostat design and layout

3.1 Design concept and main characteristics

The Fe warm structure represents the mechanical support of the inner membrane cold cryostat and its insulation. It consists of large vertical beams alternated with a web of metal frames, capable to stand the hydrostatic pressure of the argon liquids, the pressure of the gas volumes and all possible external constrains. Details of all mechanical constraints on the structure itself in term of deformations, stresses and connections between elements is described in section 5. To the inside of the structure, a skin of stainless plates is welded, such to provide a gas barrier to the outside.

The main requirement is that this mechanical structure just sits on top of the concrete floor of the cavern, with no additional point of contact or requirements to the cavern walls.

All external faces are accessible through a system of staircases and access platforms all around. The space all around and in particular, the floor of the cavern, will be considered by safety as a confined space, where access will be granted under special conditions. The distance between the cavern wall and the structure has to be optimised, but it might be of just 200-300 mm.

The top of the cryostat will be accessible for installation of the detectors, the electrical/signal feed-through, the detectors supports and other cryogenics services. Details of all this will be worked out in due time, once the technology of the detectors is defined.

The outer dimension of the Fe warm cryostat is: \( W = 19'196 \text{mm}, H = 18'096 \text{mm}, L = 66'096 \text{mm} \)

Figure 3.1 shows a general layout of the overall warm assembly, with all major components visible, as described in the next paragraphs.

![Warm vessel general layout, front view inside the LBNF pit](image)
3.2 The corner beams

The corner beams are the main elements of the floor of the warm structure and will be the first objects to be installed. They also serve as the principal supporting element for the main structural beams. They consist of HL 1100 x 607 standard profile. Their dimensions are 9’698mm (L) x 3’388 mm (H) and they are manufactured by two beams welded together at 90°. Two corner beams are bolted in pairs and are spaced 1’600 mm between the pairs, to form the bottom part of the main portal. The weight of each corner beam is 8’200kg.
3.3 The main structural beams

The main structural beams are the principal load bearing elements of the structure. Their purpose is to withstand the hydrostatic pressure from the LAr, as well as to support the roof load. They also consist of the same HL 1100 x 607 standard profile, with length of 14'658mm. They are directly bolted to the corner beams. Their weight is approximately 8’900kg.

![Figure 3.4: Details of a structural beam profile (left) and of web interlink structure (right)](image)

3.4 The web interlink structure

The web interlink structure purpose is to provide an adequate support of the polyurethane insulation of the membrane. They consist of IPE 300 profiles welded together, with dedicated flanges. They are installed in parallel to the main structural beams and connected together by means of bolting. The spacing between the grids of the web is 800 mm. The length of the web interlink elements for the side walls is 16’420mm, and 16’920mm for the floor and the roof. Their total weights are 4’262kg and 4’416kg respectively. Additional 10mm stainless steel plates are welded to the web interlink structure to create a gas containment barrier to the inside, as well as to ensure even better support for the membrane insulation. The web interlink structure is also used for the floor, in-between the corner beams, as well as for the roof structure.

3.5 The roof structure

The roof is done in similar manner by using the same HL 1100 x 607 standard profile with length of 16’920mm and weight of 10’250kg connected to a similar web interlink structure. The roof beams are bolted to the main structural beams to form the portals. The roof will serve also as a support structure for the detector and its services. From initial calculation, we expect a sag deformation in the order of 12mm at the centre in normal conditions, with a movement of the structure as a function of the pressure difference between inside and outside in the order of 1.5mm, every 50 mbar of pressure.
change. The effect of the weight of the detector has not been taken yet into consideration, but the deformation changes are expected to be marginal.

3.6 The access platforms and stairs

The access platforms and the stairs purpose is to provide an adequate access to all external parts of the warm structure. This is needed to enable an easy inspection of the status of the structure, at any moment. Standard walking aluminium platforms equipped with hand rails and vertical stairs have been implemented to the design. Four levels of platforms, completely surrounding the warm structure, have been provided. The different levels are installed every 3’200 mm in height, and vertical access stairs are provided every 6’400 mm.

To facilitate the access and to enable relatively easy movement of personnel in horizontal direction, 800mm access holes are provided in each of the main structural beams. As already mentioned the access to the cavern floor and to the side walls will be strictly regulated by safety and will require special training and special personal equipment.

The roof, once the layout of the service is better defined, will be equipped with walk ways for easy and safe access to each active component.
Figure 3.6: Access platforms and stairs
## 4 Warm cryostat steel components list

<table>
<thead>
<tr>
<th>Item Label</th>
<th>Quantity</th>
<th>Dimensions [mm]</th>
<th>Weight [kg]</th>
<th>Material</th>
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<td></td>
<td></td>
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<td>L</td>
<td>H</td>
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<td>The Web Interlink</td>
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<td>LW - Main</td>
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<td>16420</td>
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<td>310</td>
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<tr>
<td><strong>Main Structure</strong></td>
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<td>Main Beam</td>
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<td>Corner Beam LW</td>
<td>The corner beams for the long wall</td>
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<tr>
<td>Corner Beam SW</td>
<td>The corner beams for the short wall</td>
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<tr>
<td>Short Main Links</td>
<td>The short beams connecting the short wall to the rest (top, side and bottom)</td>
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<tr>
<td>Long Horiz Links</td>
<td>The long beams connecting the horizontal belts of the short wall to the rest</td>
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<tr>
<td>Roof Beam</td>
<td>The main beams of the roof</td>
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<td><strong>Web Interlink Structure</strong></td>
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<td>Long Wall – the main web interlink structure</td>
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<td>LW – Ext Top</td>
<td>Long Wall – the web pieces at the extremities (at the top)</td>
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<td></td>
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<tr>
<td>LW – Ext Mid</td>
<td>Long Wall – the web pieces at the extremities (at the middle)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>LW – Ext Bot</td>
<td>Long Wall – the web pieces at the extremities (at the bottom)</td>
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<td>SW – Side Top</td>
<td>Short Wall – the web pieces at the sides (at the top)</td>
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<td>Short Wall – the web pieces at the sides (at the middle)</td>
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<tr>
<td>SW – Side Bot</td>
<td>Short Wall – the web pieces at the sides (at the bottom)</td>
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<td></td>
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<td>SW – Cen Top</td>
<td>Short Wall – the web pieces at the centre (at the top)</td>
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<tr>
<td>SW – Cen Mid</td>
<td>Short Wall – the web pieces at the centre (at the middle)</td>
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<td>SW – Cen Bot</td>
<td>Short Wall – the web pieces at the centre (at the bottom)</td>
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<td>Floor – the main web pieces</td>
<td></td>
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<td>Floor – Ext Side</td>
<td>Floor – the web pieces at the extremities (at the sides)</td>
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<td>Floor – Ext Side Mid</td>
<td>Floor – the web pieces at the extremities (at the middle of the sides)</td>
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<td>Roof – Main</td>
<td>Roof – the main web pieces</td>
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<tr>
<td>Roof – Ext Side</td>
<td>Roof – the web pieces at the extremities (at the sides)</td>
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<td>Roof – Ext Side Mid</td>
<td>Roof – the web pieces at the extremities (at the middle of the sides)</td>
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</tr>
<tr>
<td>Roof – Ext Sec</td>
<td>Roof – the web pieces at the extremities (at the second row)</td>
<td></td>
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</tr>
<tr>
<td>Roof – Ext Main</td>
<td>Roof – the web pieces around the access structure (the main one)</td>
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</tr>
<tr>
<td>Roof – Ext Mid</td>
<td>Roof – the web pieces at the extremities (at the middle)</td>
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<td></td>
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</tr>
</tbody>
</table>
5 Cold membrane cryostat design and layout

The corrugated stainless steel primary barrier:

- Thickness: 1.2 mm
- Material: Stainless steel 304L
1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Steel structure with moisture barrier
6 Warm cryostat mechanical calculation

6.1 Relevant safety codes (Olga and Andrea)

Point of view design the warm cryostat will be treated as a low pressure vessel. The design of the pressure vessel is based, as main design technique, on Finite Elements Analysis Methods, using the commercial ANSYS code. The safety codes used are the Eurocode III and ASME Boiler and Pressure Vessel code Section VIII, Rules for Construction of Pressure Vessel.

As the design approach is to generate a detailed finite element model of the pressure vessel and to perform a detail stress analysis of each component, one refers to the ASME code section VIII, division II.

Part 5 of this division provides the so-called “design by analysis” requirements: i.e. requirements for the design of vessels and components using analytical methods.

The LBNF vessel structure design is guided by the detailed design procedures provided in Part 5 to determine protection against the following failure modes: plastic collapse, local failure and buckling.

The material properties for use in stress analysis are determined using the data and material model from ASME, sect. VIII, div II, part 3. The allowable stresses associated to material for all product forms (except bolting) are provided in section II, part D, Table 5-A. The basis for establishing the maximum allowable stresses are provided in Section II, part D, table 10-100 reproduced in Figure 6.1.

---

![Table 10-100](image)

**Figure 6.1**

---
The Finite Elements Analysis calculations of the vessel structure use the Elastic Stress analysis method as detailed in ASME sect VIII, div.2 part 5. The loading conditions and load cases combinations used in the calculations are compatible with ASME section VIII, div. 2, 5.1.3. The load cases combination for Elastic Analysis method are provided in section VIII, div.2, part5, table 5.3. The stresses computed using the numerical FEA methods are compared to allowable stresses using the assessment procedure for Elastic Stress analysis detailed in ASME 5.2.2.4.

<table>
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<tr>
<th>Design Load Combination (1)</th>
<th>Allowable Stress</th>
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</thead>
<tbody>
<tr>
<td>(1) (P + P_2 + D)</td>
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<td>(2) (P + P_2 + D + L)</td>
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<tr>
<td>(3) (P + P_2 + D + L + T)</td>
<td></td>
</tr>
<tr>
<td>(4) (P + P_2 + D + S_t)</td>
<td></td>
</tr>
<tr>
<td>(5) (0.6D + \left(0.6W \text{ or } 0.7E\right))</td>
<td>(2)</td>
</tr>
<tr>
<td>(6) (0.9P + P_2 + D + \left(0.6W \text{ or } 0.7E\right))</td>
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</tr>
<tr>
<td>(7) (0.9P + P_2 + D + 0.75(L + T) + 0.75s_s)</td>
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<tr>
<td>(8) (0.9P + P_2 + D + 0.75(0.6W \text{ or } 0.7E) + 0.75L + 0.75s_s)</td>
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</table>

**Sorted based on the Stress Category shown in Figure 5.1**

NOTES:
1. The parameters used in the Design Load Combination column are defined in Table 5.2.
2. This load combination addresses an overturning condition for foundation design. It does not apply to design of anchorage (if any) to the foundation. Refer to ASCE/SEI 7-10, 2.4.1 Exception 2 for an additional reduction to \(W\) that may be applicable.
3. Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.
Figure 5.1
Stress Categories and Limits of Equivalent Stress

<table>
<thead>
<tr>
<th>Stress Category</th>
<th>Primary</th>
<th>Secondary Membrane plus Bending</th>
<th>Peak</th>
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<tbody>
<tr>
<td>Description</td>
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<td></td>
</tr>
<tr>
<td>General Membrane</td>
<td>Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.</td>
<td>Component of primary stress proportional to distance from centroid of solid section.</td>
<td>Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.</td>
</tr>
<tr>
<td>Local Membrane</td>
<td>Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.</td>
<td>Component of primary stress proportional to distance from centroid of solid section.</td>
<td>Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.</td>
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<table>
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<th>$P_L$</th>
<th>$P_o$</th>
<th>$Q$</th>
<th>$F$</th>
</tr>
</thead>
</table>

Diagram:
- Use design loads
- Use operating loads

1. Increment added to primary or secondary stress by a concentration (notch).
2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.
6.2 Dimensions and Table of actions (Andrea, Joao, Christophe, checked by Dimi)

Table with nominal loads (pressure, weight), dimensions, safety factors (Dimi with Andrea, Joao)

6.2.1 Dimensions:

The required internal dimensions of the cryostat, between the flat parts of the corrugated membrane are 62’000mm x 15’100mm x 14’000mm (L x W x H).

The dimensions are also presented at the table below:

<table>
<thead>
<tr>
<th></th>
<th>Length [mm]</th>
<th>Width [mm]</th>
<th>Height [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane Internal dimensions</td>
<td>62’000</td>
<td>15’100</td>
<td>14’000</td>
</tr>
<tr>
<td>SS plate Internal Dimensions</td>
<td>63’800</td>
<td>16’900</td>
<td>15’800</td>
</tr>
<tr>
<td>External Dimensions of the Structure</td>
<td>66’096</td>
<td>19’196</td>
<td>18’096</td>
</tr>
</tbody>
</table>

The dimensions of the main transverse portal frame are shown below:
6.2.2 Pressure loads and LAr weight

Filling ratio up to 98% of liquid (rounded in the following models at 100%)
Top pressure: working pressure between 50 to 120 mbar. Safety valve opening pressure set at 350 mbar, which becomes the design nominal pressure.
Static head of LAr (14 m). Density taken as 1400 kg/m3

\[ \Delta H = 14\cdot m \]

\[ \text{static\_head} = \rho \cdot g \cdot \Delta H = 1.922 \cdot \text{bar} \]

\[ p_{\text{grad}} = \frac{\rho \cdot g \cdot \Delta H}{L} = 0.126 \cdot \text{bar/m} \]

6.2.3 Masses

Self-weight of composing members.
Main beam members: **HL1100-607** (607 kg/m)

The weight of the insulation with the stainless steel and intermediate membranes shall be in the order of 90kg/m2, which will make it approximately 350T. In addition the weight of the 10mm SS plates is not included in the calculation above. It would add another 80kg/m2. I.e. total: 170kg/m2.

Small grid beam / m = 131.5 kg/m

Table with loads coming from all members, local reinforcements, bracings, inspection platforms, detector load, equipment load on the roof, etc - See for details. Reference source not found. **mass**, for estimates of the entire structure and unit cell (pitch of 1.6 m)
6.3 Calculation models:
Providing a bullet description and results from.

6.3.1 Structural members

6.3.2 Analytical models (stress, deflection and M,T diagrams) (Andrea and Joao)

In order to determine to extreme cases of top and bottom connection for the vertical main members, two analytical models were developed.
First models of a cell unit, a portal frame with a pitch of 1.6 m, loaded with pressure gradient, no structural self-weight, boundary conditions top pinned, bottom fully constrained, or pinned top and bottom

6.3.3 Global “box” models: to shows that a portal model is well representative (Piet? and Diego)

6.3.4 Static and buckling portal beam model (Andrea)

Parametric ANSYS apdl script for the calculation of one main transversal portal frame.
Elements: 3 nodes beam 189 and linear rotational spring combin14

Parameters:

\[
\begin{align*}
 w &= 18.058 \quad \text{! new beam neutral axis width} \\
 h &= 16.958 \quad \text{! new beam neutral axis height} \\
 \text{gap} &= 0.91 + 1.138/2 \quad \text{do not put gap to zero, rather 600: use it in this version V4 to offset the load top and bottom} \\
 \text{foam} &= 0.91 + 1.138/2 \\
 \text{divide} &= 20 \\
 \text{lockbottom} &= 6 \quad \text{! to get 4.75 +/- part touching the floor (from the old center axis)} \\
 \text{po} &= 3.5E4 \quad \text{! 3.5E4 Pa - 0.035 MPa - 350 mbar} \\
 \text{pitch} &= 1.6 \\
 \text{ro} &= 1400 \\
 \text{rotstiff} &= 1.25E9 \quad \text{! average top bottom - 1.2 top 1.3 bottom solid shell - minimal for factor 4 by PW = 0.5 x 1.7E7} \\
 \text{ymbeam} &= 2E11 \\
 \text{denbeam} &= 7800 \\
 \text{wf11} &= 0.410 \quad \text{! HL110-607 baseline beam} \\
 \text{wf21} &= 0.410 \\
 \text{hb1} &= 1.138 \\
 \text{thf11} &= 0.055 \\
 \text{thf21} &= 0.055 \\
 \text{thw1} &= 0.031 \\
 \text{wf12} &= 0.550 \quad \text{! option for top and bottom sections...}
\end{align*}
\]
wf22=0.550
hb2=1.2
thf12=0.075
thf22=0.075
thw2=0.040

Loading and boundary conditions:

Static and buckling results

6.3.5 Static and buckling shell portal model (Diego)
6.3.6 Table and Comparison of results above (Andrea and Diego)
6.4 Portal minimal stability calculations (Piet)
6.5 Bolted and welded connections
6.5.1 Design of main connections and analytical calculations (Joao)
6.5.2 Models and FEA results of connections (Diego)
6.5.3 Weld analytical calculations (Piet)
To provide a heavy moment connection for a beam 1138/410/31/55 mm against a thick plate, a dimensioning to the Eurocode spirit resulted in flange welds with \( a = 33 \text{ mm} \), web welds with \( a = 13 \text{ mm} \), and a moment capacity of \( M_0 = 7.29 \text{ MNm} \).

In order to simplify, we assume the moment \( M_0 \) as the only loading, and we neglect the web welds. The loading to the flange welds, again somewhat simplified:

- Generalized traction: \( F = \frac{M_0}{L_A} = 6.73 \text{ MN} \)
- Where the lever arm: \( L_A = (1138-55) \text{ mm} = 1083 \text{ mm} \)

Now, with a useful seam length: \( L = 2 \cdot 410 \text{ mm} - 31 \text{ mm} - 6a = 591 \text{ mm} \),

(optimistic insofar as the corner rounding of the profile has been neglected), we have:

\[
\begin{align*}
    f_t &= \frac{F}{L} , \\
    f_n &= 0 , \\
    f_s &= |f_t| = \frac{f_t}{\sqrt{2}} , \\
    \sigma_\perp &= |\tau_\perp| = \frac{f_t}{\sqrt{2a}} \quad (= \sigma_0) = 244 \text{ MPa} , \\
    \sigma_{\text{von Mises}} &= \sqrt{\sigma_\perp^2 + 3\tau_\perp^2} = 2\sigma_0 = 488 \text{ MPa} ,
\end{align*}
\]

hinting at some generalized yielding of the seam(s) when loaded at its nominal capacity \( M_0 \).
6.6 EC3 verification – SCIAeng® verification (Joao)
SCIA verification (Joao) – all structure

6.7 Comparison EC3 and ASME global safety factors
6.7.1 Capacity and safety margins (Piet, Joao)
6.7.2 ASME allowable stresses (Olga, Andrea)

6.8 Possible future optimizations
6.8.1 Lighter roof, smaller floor, (Piet)
6.8.2 Bracings (Dimi, Joao)
6.8.3 Thickness of Stainless steel outer membrane (Dimi)
7 Installation sequence
7.1 Logistics (Marzio)
7.2 Installation operations (Dimie, Crhistoph)

7.3 Schedule (Marzio)
# Overall Schedule of procurements and operations

To fit into the overall installation schedule of LBNF and trying to avoid to double the teams of specialist during construction, the proposal is in a skematic way illustrated in **Figure 8.1**.

![Figure 8.1: installation schedule for the cryostats assuming the overall LBNF schedule presented Figure 2.3. In blue the installation schedule for the warm cryostat assuming the proposed dates for the building occupancy. In red the installation operation for the membrane vessel and in yellow the time allocated to pressure tests. The grey line is the time allocated to these operations in the overall LBNF schedule.](image)

To realize this the first contracts and tendering procedures have to start in the first semester of 2017, such that material can be ordered, teams organized and material shipped to the SURF premises in due time. The first activity in sequence is the warm cryostat erection, followed by the membrane installation and welding. Point of view of logistic, one assumes that all the necessary material is delivered and stored in a dedicated storage facility by the time the first installation activities of each of the cryostats start.

No mechanical activities will take place in such a storage area. Then as a function of the needs, the material is moved to SURF and then is brought underground and assembled mostly during the night.

The main idea is that the first 2 detectors installation will happen according to today’s LBNF schedule, which in our case profits from the fact that both cryostats (1 and 2) are ready. The detector cooling down should happen just once the second cryostat is ready, such to be able in case of problems to empty the first cryostat into the second vessel, without scrapping a large amount of cryogenic liquid. The same strategy is also adopted for the subsequent cryostats.

The warm vessel assembly will take 4 months + 1 month of tests and eventual contingency.

The membrane installation operations are very demanding and are today compressed in a one year period per cryostat. This will require that a proper analysis is done with the main engineering licenced firm after a deep analysis. Typically the plan is to run 3 shifts per
working day, for the positioning and welding of the membrane panels and to move the material into the pit from the surface down, during the nights.

Just after the end of the membrane installation a set of test are foreseen for a period of 3 months, including pressure tests. This will require part of the cryogenics infrastructure to be in place.

The schedule of the cryogenics system installation is somehow more diluted and the first milestone is given by the necessity to run pressure tests. The full cryogenics must be ready into operation for the first vessel when the detector is ready and installed inside its own cryostat, about 44 months after the start of the warm cryostat assembly.
9 Summary