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Simulation of the mechanical deformation of a feedthrough flange under high pressure conditions

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Summary

For future LAr calorimeters, a new generation of high-density signal feedthroughs has to be developed that ensures higher granularity and supports a larger number of signal wires. Therefore, 3D designs of different flange configurations were created and mechanical stress simulations were performed to investigate the deflection and the von Mises stress. In this document, the simulation results are presented and discussed.

Contents

1 Introduction

For future LAr calorimeters, a new generation of high-density signal feedthroughs has to be developed that ensures higher granularity and supports a larger number of signal wires. The LAr temperature of 87 K requires the use of cryostats. One of the major challenges is to bring the huge amount of signal wires out of the cryostat to the warm environment (295 K) through cold-to-warm feedthroughs. [5] In addition to the electrical constraints (total resistance, impedance and limited crosstalk), the feedthroughs have to be robust and leak-tight. [3] Prior to being fully assembled and tested experimentally, stress simulations are performed in order to study the von Mises stress and the deflection under critical pressure conditions (see [8] for reference data of ATLAS signal feedthroughs).

The goal of the work was to develop different designs of high-density signal feedthroughs for future LAr calorimeters and to perform stress simulations in order to evaluate the designs and propose final designs that need to be tested in an experimental setup. Therefore, the software *Autodesk Inventor Professional* was used. It is a computer-aided design application for 3D design, simulation and visualization. [2]

2 Design of the feedthrough flange

In this section, the design requirements are described and four different designs of feedthrough flanges are introduced.

2.1 Design requirements

The first task was to propose different designs of feedthrough flanges based on various geometrical requirements that endure a certain pressure at low and at high temperature. Electrical and thermal phenomena related to the signal wires are not considered here.
For reference, in the ATLAS detector there are a total of 64 signal feedthroughs of 1920 signal lines each with a diametre of 30 cm. For the next generation of signal feedthroughs, the number of signal lines should be increased to 20000 while doubling the diametre. Just as in ATLAS [4], there will be flexible kapton strip cables carrying 32 transmission lines each, so in order to reach the required number of signal wires, at least 625 strip cables have to be placed in the flange. The flange of the feedthrough is composed of several single pieces (main stainless steel structure, G10 pieces, compression plates, screws). An assembly of all the pieces is shown in Figure 1.
The **main stainless steel structure** (stainless steel 304L) has a diametre of 60 cm and a thickness of 20 mm. There should be an extra steel structure with a thickness of 10 mm and a width of 23 mm to place heaters in order to prevent condensation and frosting. In addition, there are two vacuum pump connections placed on top.
G10 pieces (thickness: 15 mm) with slits (length: 30 mm, width: 1 mm) are used as a pass-through for the strip cables. The kapton cables are fixed with glue inside the slits and have a distance of 3 mm one to the other. G10 is a fiberglass epoxy that has already been tested succesfully in cryogenic conditions. In order to increase the number of slits, simulations have also been performed with a reduced distance of 2 mm between the slits (new

samples with a reduced distance between the slits haven't been tested experimentally yet). The G10 pieces are fixed mechanically with **compression plates** and screws (optionally M5 or M6). They have a thickness of 10 mm and a width of 15.3 mm (M5) and 17 mm respectively (M6). Those dimensions correspond to the dimensions of the samples that have already been tested experimentally. The compression plate and the screws are also made out of stainless steel 304L.

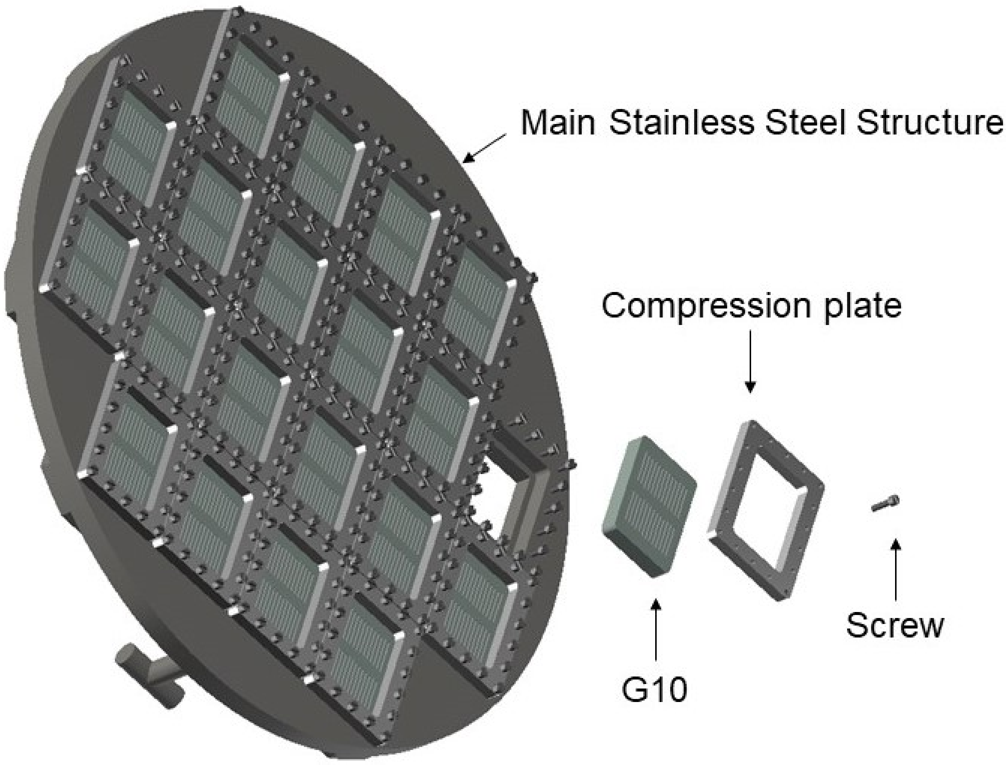

Figure 1: Flange assembly

2.2 Implementation

Four different flange design configurations have been developed, an overview is shown in Figure 2.

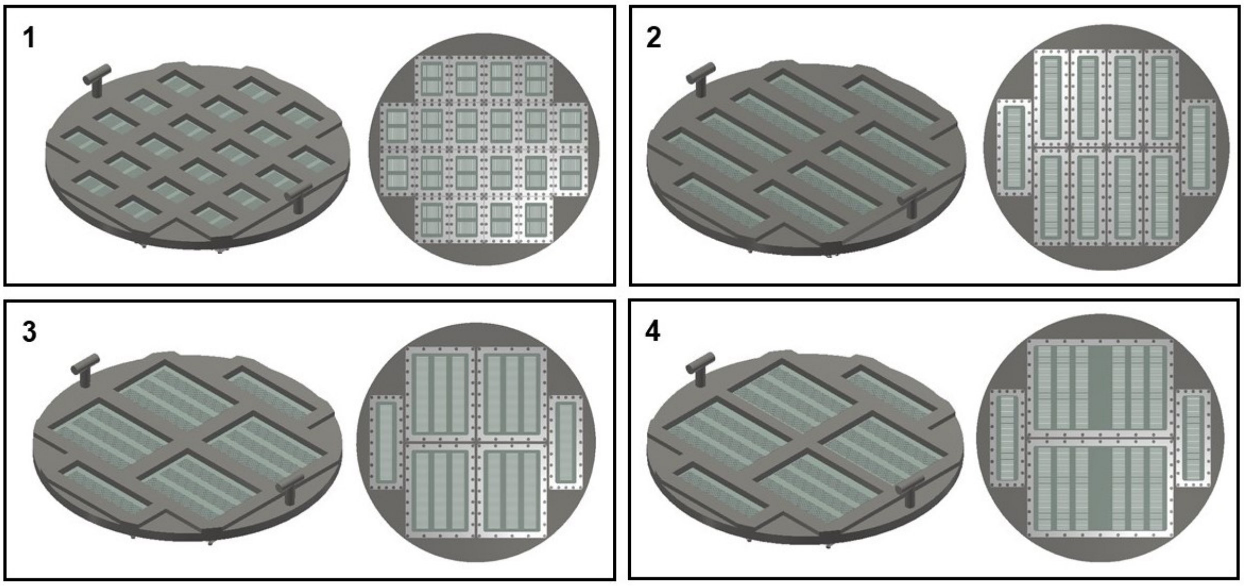

Figure 2: Overview of the designs

They differ in the number and size of the G10 pieces. In total, there are four different sizes of G10 pieces and each can carry a different number of cables. The size of the compression plates is fitted to the size of the G10 pieces. All the dimensions of the G10 pieces and the compression plates are presented in Table 1.

Table 1: G10 pieces (above) and compression plates (below)

	G10_1		G10_2		G10_3		G10_4	
Size [mm]	96 × 65		217 × 65		217 × 155		335 × 217	
Slits distance	3 mm	2 mm	3 mm	2 mm	3 mm	2 mm	3 mm	2 mm
# Slits	26	34	51	67	153	201	306	402

	CP_1	CP_2	CP_3	CP_4
Size [mm]	120 × 89	235.6 × 83.6	235.6 × 173.6	353.6 × 235.6

In Table 2, an overview of all important information about the designs is given.

Table 2: Design information

	Design 1		**Design 2**		**Design 3**		**Design 4**	
# G10 pieces	20 × G10_1		10 × G10_2		4 × G10_3 2 × G10_2		2 × G10_4 2 × G10_2	
Slits distance	3 mm	2 mm	3 mm	2mm	3 mm	2mm	3 mm	2mm
# Strip Cables	520	680	510	670	714	938	714	938
# Signal Wires	16640	21760	16320	21440	22848	30016	22848	30016

3 Simulation

After describing the simulation conditions, the simulation results are presented and discussed in this section.

3.1 Simulation conditions

The stress simulations are performed under a pressure load of 3.5 bar on the bottom side of the flange (side where the compression plates are fixed). This pressure load has been chosen because it has been determined being the most stressful condition in the ATLAS signal feedthroughs (see [4]). This maximum pressure value can slightly change for the new generation of feedthroughs because the calorimeter hasn't been designed yet, so it represents a good approximation for first simulations with the new designs.
All the simulations are performed at two extreme conditions: at cryogenic temperature (76 K) and at room temperature (295 K). (The simulations should have been performed at liquid nitrogen conditions (77 K), as this corresponds to the experimental setup, but the material properties for G10 and Stainless Steel 304L could only been found at 76 K.) It can be assumed that all the possible deflection and stress values lay in between the values obtained from the simulations. The material properties used for the simulations are shown in Table 3 (Ref: [1], [6], [7]).

Table 3: Material properties of Stainless Steel 304L and Fiberglass Epoxy G10

	Stainless Steel 304L		**Fiberglass Epoxy G10**	
	76 K	295 K	76 K	295 K
Mechanical				
Young's Modulus	214.408 GPa	195 GPa	30.350 GPa	25.2 GPa
Poisson's Ratio	0.28	0.29	0.19	0.15
Density	8.000 g/cm^3		1.8 g/cm^3	
Strength				
Yield Strength	269 MPa	215 MPa	300 MPa	220 MPa
Tensile Strength	1524 MPa	505 MPa	640 MPa	450 MPa

3.2 Results

Deflection

Qualitatively, all the designs show the same behaviour: the maximum deflection is in the centre of the flange. It is shown in Figure 3. This corresponds to the data from the ATLAS signal feedthroughs presented in [8], where the maximum deflection of 68 microns is also located in the centre of the flange.

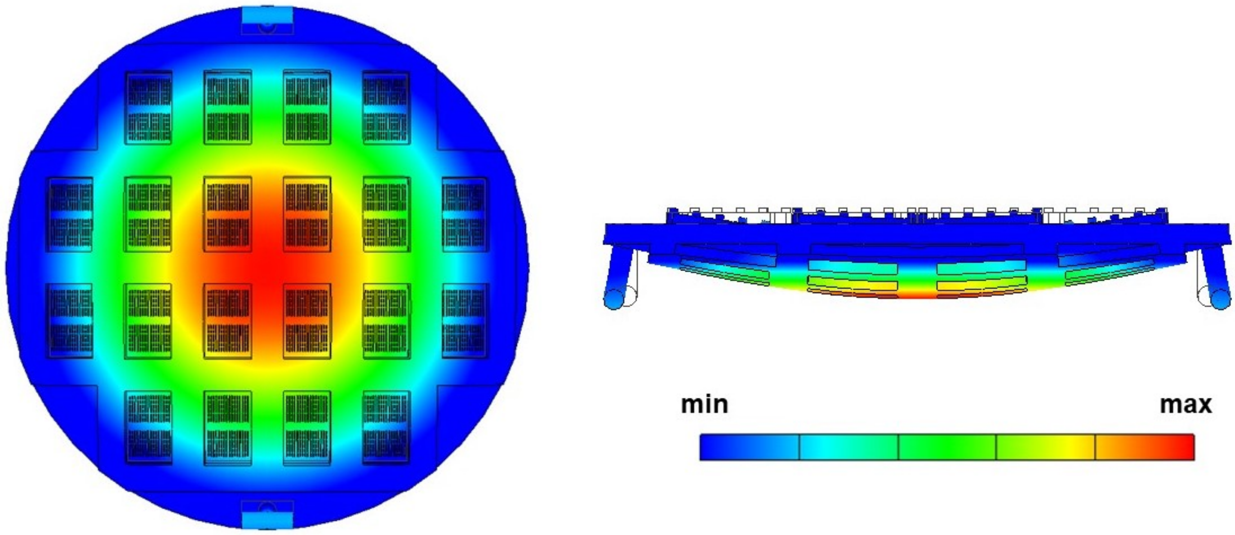

Figure 3: Deflection of the flange under a pressure load of 3.5 bar

The exact values obtained from the simulations are listed in Table 4.

Table 4: Maximum Deflection of the flange
(above: 3 mm distance between the slits, below: 2 mm distance between the slits)

Design	Max. Deflection (295 K) [µm]		Max. Deflection (76 K) [µm]	
	M5	M6	M5	M6
1	517.3	527.2	470.9	480.1
2	634.1	639.8	574.9	580.1
3	795.3	779.5	719.5	705.4
4	851.9	875.1	766.9	788.0

Design	Max. Deflection (295 K) [µm]		Max. Deflection (76 K) [µm]	
	M5	M6	M5	M6
1	512.6	521.4	466.8	474.8
2	625.0	631.0	556.8	572.3
3	775.6	760.3	702.0	688.3
4	829.0	852.4	746.5	767.7

First of all, one can remark that the deflection at low temperature conditions is always smaller than at room temperature. This result is to be expected because the materials (Stainless Steel 304L and G10) are more flexible at higher than at lower temperatures. Comparing the values for the M5- and the M6-Design, it can be seen that the difference between the values is only between 5 and 25 µm. On a large scale, this is not a big difference which brings us to the conclusion that according to the deflection, both M5- and M6- screws can be used. It can also be noticed that the trend is not consistent for all designs, i. e. sometimes

the configuration with M5 screws shows a larger deflection (Design 3) and sometimes the configuration with M6 screws shows a larger deflection (Design 1, 2 and 4).
Furthermore, one can cleary see that the deflection increases with decreasing number of G10 pieces (which implies an increasing size of G10 pieces, thus there is less steel support).
The simulation results also show that the deflection of the flange is even slightly smaller when the distance between the slits is reduces to 2 mm. This result is assumed to be mathematically correct. Nevertheless, it has to be verified experimentally that samples with a reduced distance between the slits pass the leak test because in the simualtions the kapton strip and the glue haven't been considered yet.

Von Mises Stress

The qualitative evaluation of the von Mises stress is more complicated because the location of the maximum von Mises stress is not consistent in the designs. For reference, the maximum von Mises stress is located in the corner of the weld region of the pin carrier for ATLAS signal feedthroughs [4][8] (corresponds more or less to the inner corner of the compression plate in our designs).

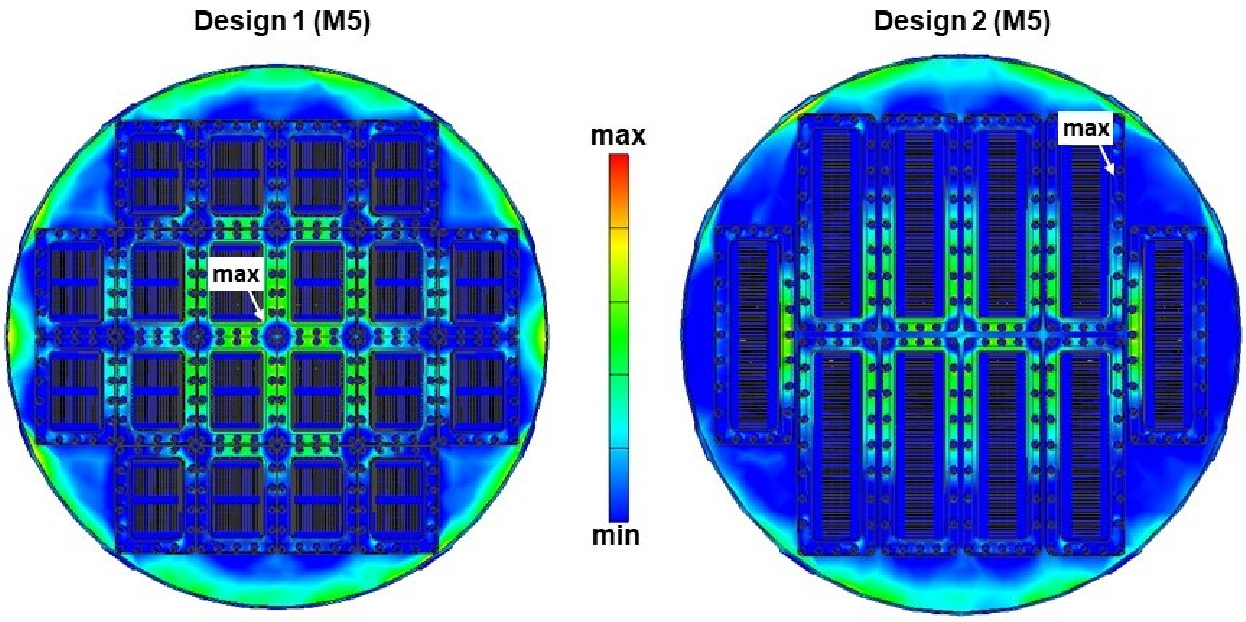

Figure 4: Von Mises Stress of the flange under a pressure load of 3.5 bar

In some cases (Design 1 (M5, M6), Design 3 (M6)), the maximum stress is located in the inner corner of the compression plate. For the other designs (Design 2 (M5, M6), Design 3 (M5) and Design 4 (M5, M6)), the maximum stress was found to be on the long side of the compression plate. A reason for this could be that the screws in the corners have more distance to the inner edge of the compression plate than the screws on the side. Additional simulations have been performed in order to study the stress behaviour and can be found in Section 4.

Table 5 shows the von Mises stress simulation results. It can be seen that the stress is mostly dependant on the geometry of the pieces, it is hardly dependant on temperature. Just as for the deflection, the trend is not consistent for all design. For Design 1 and 2, the maximum stress is smaller in the M5- than in the M6-Design, whereas in Design 3 and 4, it is the other way around. Design 3 shows a remarkable difference of around 80 µm between the two configurations, the reason for this has to be investigated more. For comparison, ATLAS signal feedthroughs showed a maximum von Mises stress of 115 MPa (see [8]). Therefore, the obtained results seem to be valid and reasonable.

Table 5: Maximum Von Mises Stress of the flange
(above: 3 mm distance between the slits, below: 2 mm distance between the slits)

Design	Max. Von Mises Stress (295 K) [MPa]		Max. Von Mises Stress (76 K) [MPa]	
	M5	M6	M5	M6
1	92.13	95.66	91.87	95.57
2	105.7	109.3	105.2	109.1
3	224.6	148.1	223.8	154.4
4	150.3	139.5	149.8	138.7

Design	Max. Von Mises Stress (295 K) [MPa]		Max. Von Mises Stress (76 K) [MPa]	
	M5	M6	M5	M6
1	91.72	94.72	91.53	94.54
2	103.4	108.3	103.8	108.1
3	218.9	140.6	218.3	140.1
4	146.3	135.4	145.8	134.8

4 Additional simulations

Additional simualtions have been performed in order to have a better understanding of the simualtion results described in the previous section.

4.1 Simulations with single pieces

Stress simulations under the same pressure load of 3.5 bar have been performed separately with the main stainless steel structure and the G10 pieces. The results are shown in Table 6.

Table 6: Deflection of the single pieces

Design	Main Stainless Steel Structure Max. Deflection [µm]		G10 piece Max. Deflection [µm]	
	295 K	76 K	295 K	76 K
1	227.5	207.4	8.386	6.927
2	266.0	242.2	4.979	4.124
3	267.7	243.6	130.07	107.8
4	244.5	222.4	649.5	530.5

Design	Max. Von Mises Stress [MPa]		Max. Von Mises Stress [MPa]	
	295 K	76 K	295 K	76 K
1	42.17	42.14	20.93	20.7
2	57.69	57.73	13.7	13.5
3	57.59	57.63	96.07	96.14
4	51.85	51.86	326.8	319.0

Taking a look at the results, one can clearly see that the deflection of the main stainless steel structure determines the deflection of the flange.
Evaluating the deflection of the G10 pieces, the piece from Design 2 (size: 217 $\times$ 65 mm) seems to be the most robust against pressure load. The deflection increases with increasing size of the piece but there is a remarkable difference of more than 100 microns between Design 1 and 2 compared to Design 3. Similarly for Design 4, the deflection seems to increase exponentially with the size, but it must be noted here that the results for the single G10 piece of Design 4 aren't entirely representative because there is an extra steel support in the middle of the piece (see Figure 2) and this hasn't been considered in the single part simulation.

For the evalutaion of the von Mises stress simulation results, it is important to compare the results listed in Table 6 with the material properties (yield and tensile strength) in Table 3. For Design 4, the simulation results of the single G10 piece exceed the yield strength of G10. For Design 4, there is a risk of breakage when using a piece of such a large size. For Design 1, 2 and 3, none of the material properties are exceeded, so there is no risk of breakage of the pieces.

4.2 Stress simulation of a flange with one single G10 piece

In order to have a better understanding of the stress behaviour, a simple flange with only one G10 piece in the middle (one flange per G10 piece size) was designed. To go further, two configuarations were made: one with an extra steel structure for heaters on top and one without.
The results (see Design 1 in Figure 5) show that for all four sizes of G10 pieces, the maximum stress is located in the corner of the compression plate when the main stainless steel structure is plane on top, just as it has been observed in the ATLAS feedthroughs (see [8] for reference).

In contrast, when there is an additional structure for heaters, the maximum stress is found to be on the long sides of the compression plates.

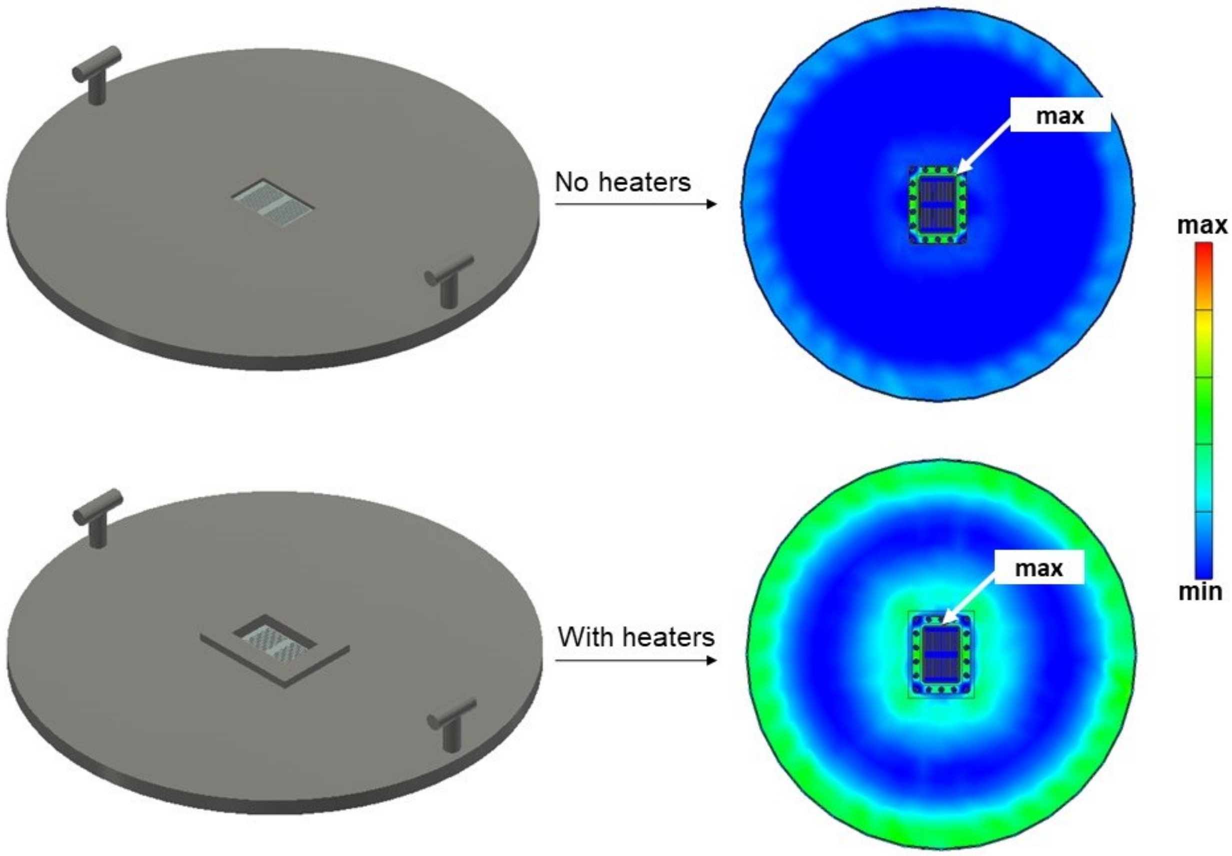

Figure 5: Flange with a single G10 piece

5 Conclusion

After having evaluated the simulation results, conclusions can now be drwan to determine which of the proposed designs should be considered as final designs.
Design 1 has many advantages compared to the other designs. First of all, it shows the smallest deflection and stress under pressure load which is mainly related to the dominant main stainless steel structure. Furthermore, smaller pieces are more convenient and efficient to replace in case of damage, i. e. it's better to replace a piece with 34 strip cables than a piece with over 200 strip cables if only one of them is damaged. The fact that all the G10 pieces have the same size faciliates the industrial production. A disadvantage of this design is that when the distance between the slits is defined to 3 mm, the number of signal wires is limited to 16640. Only if the distance is reduced to 2 mm, the design provides place for more than 20000 signal wires (21760 strip cables). Actually, the samples already tested in the experimental setup correspond more or less to the dimensions of the pieces in Design 1, which is another argument for considering it as final design and conducting further studies

with it.
Design 2 has no advantages over Design 1 (e. g. it provides place for less signal wires while having a larger deflection), so there is no reason to consider it as a final design.
Eventhough the maximal deflection of **Design 3** is almost 300 microns larger than Design 1, it shouldn't be excluded yet because it offers the possibilty to put a large amount of signal wires. Even with a distance between the slits of 3 mm, the required number of 20000 signal wires is clearly exceeded (22484 signal wires). When the distance is reduced to 2 mm, 30016 signal wires can be placed in Design 3, which means a significant increase in the number of signal wires. Concluding, it should be considered to change the experimental setup in order to verify the simulation results for the pieces of Design 3.
Design 4 is composed of two very large G10 pieces. Even if in the flange there is an extra steel support in the middle of those pieces, the results presented in Section 4.1 show that there is a risk of breakage of the G10 pieces. Additionally, considering the fact that there is no increase in the number of signal wires compared to Design 3, Design 4 can be excluded from further studies.

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