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To cite this article: H F P Silva et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 502 012084

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Design of an ultra-thin, radiation thickness minimized, metallic cryostat for a 2T/4m free bore detector solenoid

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Abstract. A 2T, 6m long, 4m free bore superconducting solenoid is being designed for the so-called IDEA detector for probing electron-positron collisions at the proposed Future Circular Collider at CERN. In order to drive the cost of the magnet down, the solenoid is positioned around the inner tracking detector for which presence of the magnetic field is mandatory. This approach reduces the dimensions of the magnet roughly to half bore size, and therefore significantly the cost. However, the new position adds a new and demanding requirement to the solenoid and cryostat designs as they need to be as thin and radiation transparent as possible. A full mechanical analysis of the cryostat including all the mechanical loads is performed to find the minimum effective wall thicknesses while respecting structural design norms. We will present a novel design of a cryostat using alternative approaches such as corrugated walls and honeycomb-like structures and compare to a classical solution of using solid uniform plate.

1. Introduction
When positioning the solenoid around the inner tracking detector instead of around the hadron calorimeter with twice the bore size, the radial thickness and the radiation length of the components become key design parameters. Hence, it is crucial to use materials with large radiation length while at the same time minimizing the space taken by the various parts of the magnet system. This paper concerns the minimization of the cryostat’s radiation thickness, which is defined as the ratio of the thickness over the radiation length \( s/X_0 \). For this purpose, various alloys and type of plates are analyzed by comparing their plastic and buckling limits.

The most common approach for a detector solenoid cryostat is to use two metal shells made of an aluminum alloy, which is very reliable and can be easily made [1] [2] [3]. For every cryostat found in literature the inner bore of the solenoid is made from uniform metal plate, which is explained by the fact that this element needs a certain strength that can only be reached by using a certain minimum thickness.

Conversely, on the outer shell of the solenoid’s cryostat, different approaches have been investigated to reduce the radiation thickness, such as the use of carbon fiber reinforced plastics [4], corrugated shells [5] or honeycomb sandwich panels [6]. Alternatively, one can use a shared cryostat for solenoid and electronic calorimeter, by which the outer shell will not be an obstacle for particles. This concept was used for the Central Solenoid of ATLAS, which is currently the detector solenoid in operation with the best normalized radiation transparency [7].
2. Methods
The different elements of the cryostat to be optimized can be seen in Figure 1. To simplify the study, the flanges of the cryostat are assumed rigid. Then the analysis of the inner bore shell and outer shell of the cryostat can be done independently. This is true in for a solenoid cryostat because a crucial function of end flanges is to support the cold mass and transfer load to the floor. Thus they are made inherently stiff, still leaving room for local material reduction as second order effect.

The dominating pressure load on the inner shell is 1 atm on the concave surface. Thus this component is under tension, and will not fail due to buckling. The optimization of this shell is simply by finding the cylinder with lowest radiation thickness still supporting the aforementioned load. Therefore, to minimize the radiation thickness, the material with the highest plastic figure of merit $\sigma_y \cdot X_0$ needs to be found.

| Table 1. Figure of merit of several metal alloys that can be used in the cryostat design. |
|-----------------|-------|-------|-------|-----------------|-------|
| Property        | Al 5083-O | Al 2095-T8 | Ti6Al-4V | SS 304L (cold worked) | SS 316L |
| Radiation length ($X_0$) [cm] | 9 | 9 | 3.7 | 1.8 | 1.8 |
| Yield strength ($\sigma_y$) [MPa] | 145 | 560 | 880 | 400 | 240 |
| Young modulus ($E$) [GPa] | 70 | 76 | 115 | 200 | 200 |
| Buckling figure of merit [$cm \cdot GPa^{1/3}$] | 37 | 38 | 18 | 11 | 11 |
| Plastic figure of merit [$cm \cdot MPa$] | 1300 | 5040 | 3260 | 720 | 400 |

Conversely, the outer shell of the cryostat has the same load on its convex surface and is thus under compression. It is prone to fail due to buckling, for which the figure of merit of a material is given by $X_0 E^{1/3}$. In Table 1, where the properties of several materials are summarized, it can be seen that Al 2095-T8 is expected to outperform the other materials for both inner and outer shells.

Unlike the inner shell where the only way to avoid reaching the plastic limit is by using a thicker cylinder; on the outer shell the buckling limit can be controlled by manipulating its flexural strength, or by effectively subdividing it in shorter cylinders by applying reinforcement rings. Consequently, for the outer shell four options are studied: the classical cylinder as a reference, a shell with reinforcement rings, a shell made of corrugated plate and a shell made of honeycomb sandwich plate.

From Table 1 it is clear that Ti6Al4V is not expected to outperform the aluminum alloys for the outer shell. However, by moving from a simple uniform cylinder to a more complex structure such as a sandwich plate, it is possible to approach the plastic limit of the material, which depends on its yield strength. Given its potential to outperform an aluminum alloy, use of this alloy was analyzed as well.

2.1. Analytical formulas
Where possible, analytical formulas are used to estimate the thickness of the plates for the different options presented as benchmark for the FEM analysis. Obviously, for a fair comparison, the models need to be exposed to the same load case and boundary conditions.

For a cylinder subjected to an outer pressure, the initial out-of-roundness $u$ will lead to an oval deformation, meaning that the strength of the outer shell of the cryostat will be reduced. The maximum pressure $p_p$ that such a cylinder can support before reaching the plastic limit is given by [8]:

$$p_p = \frac{2 \sigma_y s}{S_p} \frac{1}{D_a} \left(1 + \frac{1.5 u (1 - 0.2 D_a)}{D_a} \right)$$

$$= \frac{1}{S_p} \frac{1}{D_a} \left(1 + \frac{1.5 u (1 - 0.2 D_a)}{D_a} \right),$$

where, $D_a$ is the diameter of the cylinder, $\sigma_y$ the yield strength of the material, $S_p$ is the plastic safety factor, $c$ the allowance for corrosion and $l_b$ the length of the cylinder. The standard EN13458-2 [8] sets a limit for the out-of-roundness to 1.5%, a value used in all calculations hereafter.

For a cylinder subjected to a pressure on the concave face, the buckling limit formula can be written yielding the maximum pressure $p_k$ it can support [8]:

\[ p_k = \frac{I}{S_K} \left( n^2 - 1 + \frac{2n^2 - 1 - \nu}{1 + \left( \frac{n}{Z} \right)^2} \right) + \frac{K_M}{S_K \cdot (n^2 - 1) \cdot \left( 1 + \left( \frac{n}{Z} \right)^2 \right)^2} , \] (2)

Here, \( S_K \) is the buckling safety factor, \( Z = 0.5 \cdot \pi \cdot D_o / l_b \) and \( n \) is an integer larger than 2 and \( Z \) that minimizes this equation. The value \( n \) is the number of lobes produced by the buckling. Bending and tensile stiffness are given by \( I \) and \( K_M \), respectively. The maximum pressure that an outer shell is able to withstand is given by the minimum of \( p_k \) and \( p_p \). For a simple cylindrical shell \( I \) is given by [8]:

\[ I = \frac{E \cdot t^3}{12(1 - \nu^2) \cdot R^3} , \] (3)

where, \( t \) and \( R \) are thickness and radius of the shell and \( \nu \) the Poisson ratio. Similarly, for a honeycomb sandwich cylinder its flexural strength is given by [9]:

\[ I = \frac{E}{(1 - \nu^2) \cdot R^3} \left[ \frac{2}{3} \left( \frac{d}{t} + t \right)^3 - \frac{1}{12} d^3 \right] , \] (4)

where \( t \) is the thickness of each sheet of metal and \( d \) the height of the honeycomb core.

### 2.2. FEM analysis

In the FEM analysis, the boundary conditions applied to the inner shell of the cryostat are: self-weight, atmospheric pressure and 100 kN applied on two rails on the horizontal plane, representing the load transfer lines of the inner tracker weight in the cryostat bore. As for boundary conditions, the cylinder extremities are fixed representing stiff flanges. On the outer shell, the loads are: self-weight, atmospheric pressure, and 0.35 MN of force axially on the ends representing the vacuum load on the flanges. As boundary condition, the end flanges are made rigid and only allowed to translate in the axial direction.

The elastic limit was also estimated by FEM by performing a linear mechanical analysis on a pre-deformed cylinder (\( \epsilon = 1.5\% \)), under 1 atm and applying a safety factor of 1.1 in the yield stress.

When analyzing the different options several constraints are imposed. Firstly, all options for the outer shell were limited to around 100 mm in height. This means a maximum wave amplitude of 50 mm for the corrugated plate, and 100 mm height for the sandwich plate core and reinforcement rings. Furthermore, the number of reinforcement ribs is limited to 10 and the number of corrugations to 100.

### 3. Results

#### 3.1. Classical solution of uniform shell thickness

For an inner shell of 2 m inner radius and 6 m length, the best performing alloy is A2195-T8; an Aluminum-Lithium alloy. In Table 2, it can be seen that the same aluminum alloy is the best performing material for the classical outer shell of 2.25 m inner radius. However, the gain is negligible compared to A5083-O, which is a more affordable material that can be reliably welded and machined.

| Material | Thickness [mm] | Inner shell radiation thickness \( \times 10^{-3} \) | Mass [t] | Outer shell thickness [mm] | Outer shell radiation thickness \( \times 10^0 \) | Mass [t] |
|----------|----------------|----------------------------------|---------|-----------------------------|----------------------------------|---------|
| SS 304L  | 0.80           | 44                               | 0.48    | 14.0                        | 0.77                             | 9.3     |
| SS 304LN | 0.70           | 39                               | 0.42    | 14.0                        | 0.77                             | 9.3     |
| SS 201LN | 1.1            | 61                               | 0.66    | 14.0                        | 0.77                             | 9.3     |
| A5083-O  | 2.2            | 25                               | 0.45    | 20.9                        | 0.24                             | 4.8     |
| A2195-T8 | 0.80           | 9                                | 0.16    | 20.3                        | 0.23                             | 4.6     |
| Ti-6Al-4V| 0.36           | 10                               | 0.12    | 17.2                        | 0.48                             | 6.5     |

#### 3.2. Alternative solutions

For a corrugated outer shell, the number of corrugations and their amplitude were varied. It can be seen in Figure 2 that the best performing corrugated shell has 10 corrugations with a wave amplitude of...
40 mm. As the plastic limit is not reached, the failure mechanism is given by the buckling analysis, thus the minimum mass for an aluminum corrugated outer shell is 2.5 t.

For an aluminum sandwich plate, the results are shown in Figure 3, and a good agreement between the analytical formula and the FEM result is observed. The honeycomb core was modeled as an orthotropic material, whose properties are taken from Plascore® PCGA-XR2 3003. In this case, the plastic limit is reached for a honeycomb height of 40 mm, resulting in a face sheet thickness of 1.7 mm.

Finally, a rib-reinforced cylinder is analyzed by which strengthening rings are made of hollow profile but still respecting the minimum second moments of area imposed by EN13458-2 [8]. The standard allows the use of lighter ribs with thinner cylinders, allowing to drop the average thickness even further for each added ring. Figure 4 shows that after 8 ribs the drop in mass becomes less than 4%, making adding extra reinforcements objectionable since each rib creates a region of higher radiation thickness.

4. Discussion
Following Table 4 the use of titanium alloy is not advantageous, except for a hybrid honeycomb sandwich plate. This is achieved by having the honeycomb core made of aluminum alloy and the face sheets of Ti6Al-4V. However, compared to the full aluminum alloy option, the diameter of the system would be about 12 cm larger for a slight reduction in radiation thickness. For this reason, the aluminum honeycomb option is the best regarding radiation transparency, manufacturability and overall thickness.
Second best is an aluminum-corrugated shell, which has an average radiation thickness of about 50% less than the conventional metal cylinder. The least favored option is the reinforced shell that has a similar radiation thickness as the corrugated option, but the combined disadvantages of both honeycomb and corrugated shells as it takes more space than both other options and locally the radiation transparency is higher (0.29 $X_0$ compared to 0.09 $X_0$).

The honeycomb sandwich plate can be improved by replacing the honeycomb core by a filler with a more homogeneous radiation thickness such as a corrugated plate. This way the advantages of both options are merged; compact and low radiation thickness through the sandwich plate, and a more homogeneous thickness using the corrugated shell.

### Table 4. Summary of the results for the different outer shells made of Al5083-O and Ti6Al4V.

|                      | Honeycomb | Reinforcement rings | Corrugation | Not reinforced |
|----------------------|-----------|---------------------|-------------|---------------|
|                      | Al        | Ti                  | Al          | Ti            | Al  | Ti  | Al  | Ti  |
| Average thickness [mm] | 4.0       | 1.5                 | 13.2        | 9.9           | 10.7| 8.3 | 20.9| 17.2|
| Avg. radiation thickness [$X_0$] | 0.045      | 0.034              | 0.11        | 0.23          | 0.12| 0.23| 0.24| 0.49|
| Height [mm]          | 43        | 101                 | 109         | 107           | 81  | 68  | 21  | 17  |
| Number of rings      | 8         |                     |             |               |     |     |     |     |
| Number of corrugations| 10        | 20                  |             |               |     |     |     |     |

The distribution of mass and radiation thickness over the different components of the solenoid cryostat are listed in Table 5. After optimization, the overall radiation thickness of the system is 0.74 $X_0$. By using a sandwich plate for the outer shell, we are able to drop the radiation thickness of the cryostat by 76% compared to the classic approach of using uniform thickness shells.

### Table 5. Thickness, radiation thickness and mass of each component of the optimized magnet system.

|                  | Inner shell | Inner shield | Cold mass | Outer shield | Outer shell (honeycomb) | Total |
|------------------|-------------|--------------|-----------|--------------|-------------------------|-------|
| Average thickness [mm] | 1.3         | 0.35         | 60        | 0.35         | 4.0                     | 66    |
| Avg. radiation thickness [$X_0$] | 0.015       | 0.004        | 0.675     | 0.004        | 0.045                   | 0.74  |
| Mass [kg]         | 260         | 74           | 13 000    | 76           | 930                     | 14300 |

### 5. Conclusion

The optimized cryostat option summarized in Table 5 is efficient in terms of radiation thickness. But, given that it has dissimilar materials in both shells and it uses a sandwich plate, the vacuum sealing and the overall design of the cryostat becomes more complex. For simplicity of design, manufacturing as well as minimizing risk, one could chose for a more conventional aluminum alloy (Al5083-O) on both shells, and this would cause and increase in the overall radiation thickness by 2.5% only.

Compared to the classical cryostat option, the proposed magnet system has 21% lower radiation thickness. However, now the cold mass accounts for 91% of the overall radiation thickness, thus further optimization of the cryostat will not yield substantial gain.

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