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# Distribution Feedbox for the Superconducting Link (SCLink) and Magnets of HL-LHC

**W Bailey[1], J Pelegrin[1], I Falorio[1,2], Y Leclercq[2], R Betemps[2], V Parma[2], A Ballarino[2] and Y Yang[1]**

[1] Institute of Cryogenics, University of Southampton, United Kingdom
[2] CERN, Geneva, Switzerland

wosb@soton.ac.uk,

**Abstract.** The High Luminosity LHC (HL-LHC) project aims at upgrading the LHC collider to increase its luminosity by about a factor of five. The electrical connection between the magnets in the LHC tunnel and the power converters in a new transverse tunnel will be supplied by a superconducting line (SCLink), consisting of ten $MgB_2$ cables housed into a 140 metre long flexible cryostat. This paper presents the detailed design for one of two types of distribution feedbox, (DFX) located between the magnet and the distribution feedbox. The vacuum barrier required to separate the vacuums of the upper SCLink and lower DFX sections; is to be integrated in the middle of the vertical section of DFX. A detailed study was performed, given the complexity of installing a vacuum barrier with a large diameter within a restricted height. Eccentric loading on the barrier is created by the "L-shape" vessel, necessary to accommodate the transition of the cable from vertical-to-horizontal. The solution considers a vacuum barrier assembly consisting of a flexible corrugated membrane (bellows) and deploys a lightweight "supporting cage" around the barrier and restraining rods in the horizontal section to ensure the barrier bares no substantial load or torque, and suffers no lateral or column type instability during operating and accidental conditions. The current design satisfies the mechanical and thermal design criteria outlined in the DFX specification.

## 1. Introduction
High Luminosity LHC (HL-LHC) project aims to upgrade the LHC collider in 2024-2026, increasing its peak luminosity by at least a factor five [1]. The expected radiation levels emanating from the colliding beams require the power converters (PC) to be relocated at the end of a new 50 metre long transverse tunnel above the existing LHC tunnel. New superconducting cables (SCLink) made from $MgB_2$ superconductors will be used for the electrical connections between the magnets and power converters [2]. Each SCLink will consist of 19 sub-cables rated between 0.6 kA to 18 kA, housed in a flexible cryostats approx. 140 metres long. The technology has been demonstrated, contained and validated in shorter lengths [3-4], prior to fabrication of the final lengths. This paper presents the detailed design for one of two types of distribution feedbox, (DFX) located between the magnet and the distribution feedbox containing the current leads that eventually connect to the power converters.

## 2. Cold powering infrastructure
The cold powering network for HL-LHC is presented in Figure 1(a). The transverse tunnel and LHC tunnel is connected via an eight metre vertical transit shaft. The shaft is one metre in diameter and bored wide enough for two flexible cryostats; (DSHX and DSHM) [5-6].

*2.1. Layout*

The block diagram in Figure 1(b) shows the DFX (zone 2) connecting directly to the SCLink (zone 3), whilst containing and providing access to two sets of splices. The DFX also includes the heaters required to generate GHe. DFX terminates at the λ-plate and before the magnet (zone 1). The λ-plate provides electrical through connection between the 1.9 K liquid bath on the magnet side and 4.2 K bath on the DFX side. The vacuum barrier positioned between zones 2-3 is part of DFX cryostat. This has helped to simplify the design of the flexible cryostat (DSHX) containing the SCLink. The vacuum barrier between zones 1-2 is part of the magnet cryostat and designed so it can withstand the high pressure (~24 bar) in the event of quench.

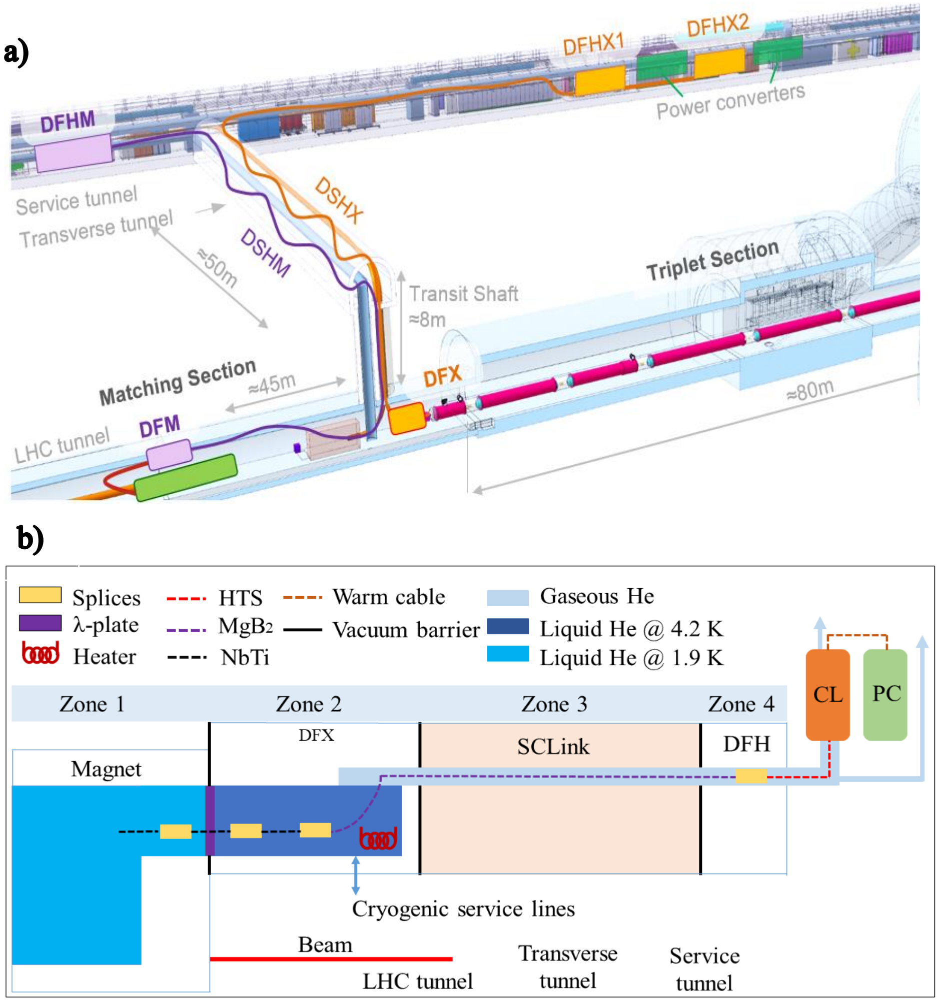


**Figure 1.** (a) Illustration showing the connection between the LHC tunnel and new transverse tunnel via the transit shaft, (b) block diagram showing the position of DFX in the cold powering scheme

*2.2. Constraints and integration*

A detailed 2-D view of the DFX is shown in Figure 2(a), formed in two main sections; i) vertical and ii) horizontal. The design is made modular (M1-M7) for easy carriage and assembly in the tunnel. Figure 2(b) shows M1, anchored to the ceiling and under the shaft ready to receive SCLink as it is lowered. The beamline will not be in position, and this space can be utilised to construct a hydraulic table to elevate M1, and support its weight while fixing it to the ceiling. At this point in the integration sequence, the SCLink includes the pre-fabricated $MgB_2$ splices housed in a protective one metre long rigid sleeve and 2.5 metre extended lengths of NbTi cable. The delicate splices are maintained vertical to avoid excessive handling, limit bending within a radius of 1.25 metres and achieve the vertical-horizontal transition within a height of < 1.7 metres available between the beamline and the ceiling of the tunnel. It is difficult for the SCLink to enter horizontally or even in an angled trajectory into DFX, without over complicating other designs aspects, such as in-situ tooling and compensation of thermal contraction. M2 is separated from M1, so the NbTi extensions can be formed with the "U-bend" shape with sufficient space to assemble tooling. The U-bend is essential to recoup height above the beamline reservation, and to provide positive slope in the direction of the λ-plate-to-shaft, thus encouraging bubbles to migrate towards the vertical section. It is likely, the λ-plate will be in position with its own NbTi extension supported in M6 & M7, before commencing lowering of the SCLink. The intersecting NbTi cables must therefore be laterally separated to provide an opening for modules M2-M5 to pass over on the shaft side. The NbTi cable attached to the λ-plate should remain straight, to avoid straining at the plate interface. Space is incorporated at each assembly stage in the sequence to allow the helium vessel to be manually welded in-situ. The NbTi-NbTi splices are produced with the helium and vacuum sleeves retreated to the DFX side, and the DFX assembly completed once two sleeves are welded and sealed respectively.

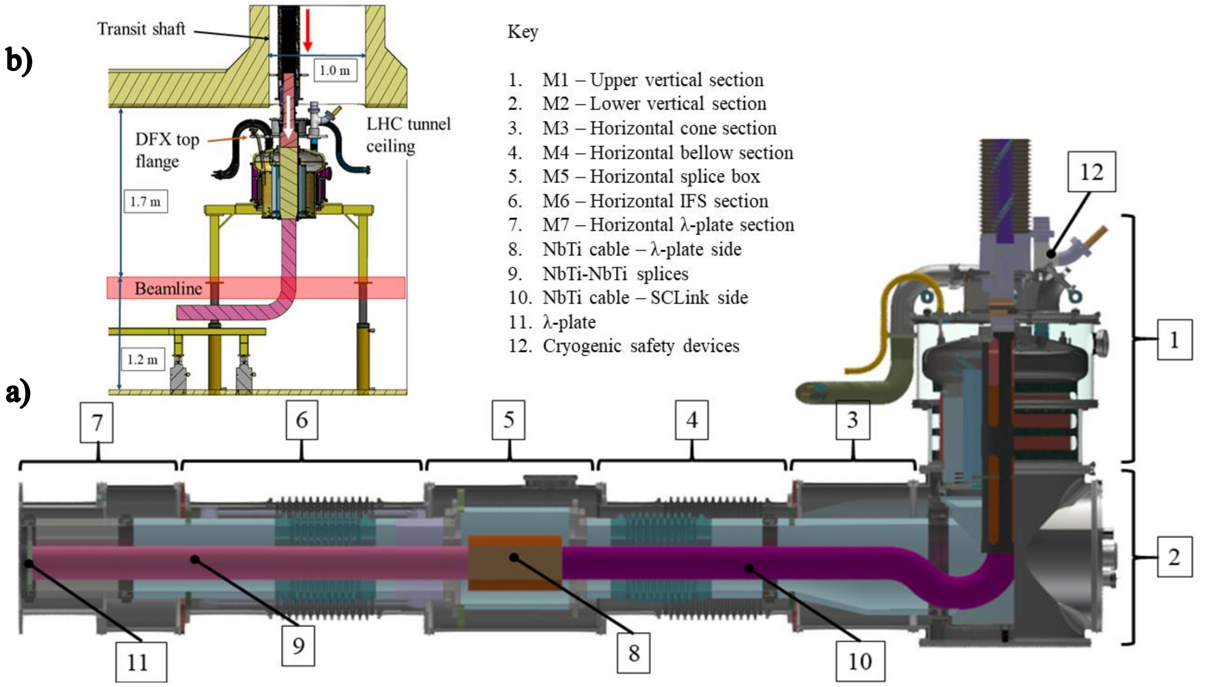


**Figure 2.** (a) 2-D drawing of the modular DFX cryostat, (b) inset – illustration showing the support DFX module 1 to the ceiling at the exit of the shaft to enable the SCLink to be lowered trough the bore of the module

## 3. Detailed design

A sliced sectioned view inside Module 1 (M1) is shown in Figure 3, and how it provides top entry for many services, including, the cryogenic jumper (LHe inlet, GHe bypass and gas heater inlet and outlet), safety relief device, and level sensors. By moving down the vacuum wall (5), there is space to add temporary support studs for integration in the tunnel, and a cutting machine to cut the SCLink from the DFX and gain access to the $MgB_2$-NbTi splices. Cut-outs in the rigid sleeve ensure the flow of LHe around the splices is unimpeded, and GHe can escape through the SCLink to DSH.

### *3.1. Cryogenic operation*

Figure 4 shows the fountain configuration in M1 that provides a separate inner annulus to ensure the vertical splices always remain fully immersed in liquid. The LHe inlet line from Line B [7], passes alongside the splices to bottom fill the cryostat. The overspill from the inner fountain, fills the outer annulus. The outer fountain is used to control the liquid volume needed to generate sufficient GHe for SCLink. Heaters, thermometers and levels sensors are installed in this reservoir. The tolerance in the

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LHe level is controlled within ± 75 mm, using the instrumentation and solenoid valve activated by PID controller. Sufficient liquid head (24 L) is available to protect the vertical splices for 5 minutes, maintaining the GHe flow rate at 10 g $s^{-1}$ in the event of stoppage/ blockage to Line B. The enlarged "bulb" shape of the domes significantly increases the volume of GHe above the liquid level. The distance between the liquid interface and the top of the dome is maximised to avoid risk of liquid entrainment, particularly when the quality of LHe from line B is low. The bottom filling and diffusing of LHe into the bath, is also aimed at minimising the effects of low quality injection. Consequently, the safety relief devices are elevated > 300 mm above the highest liquid level to avoid freezing the burst disc during normal operation.

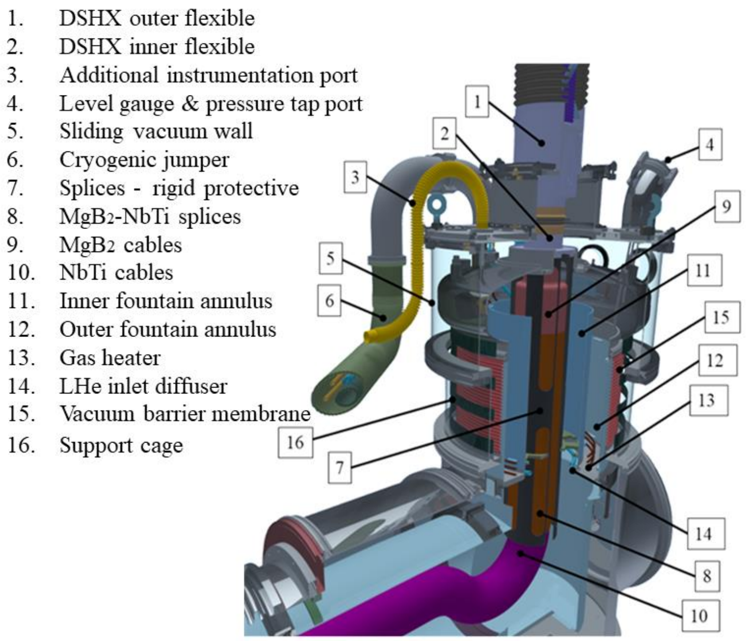


**Figure 3.** Sliced sectioned view inside DFX modules 1 & 2

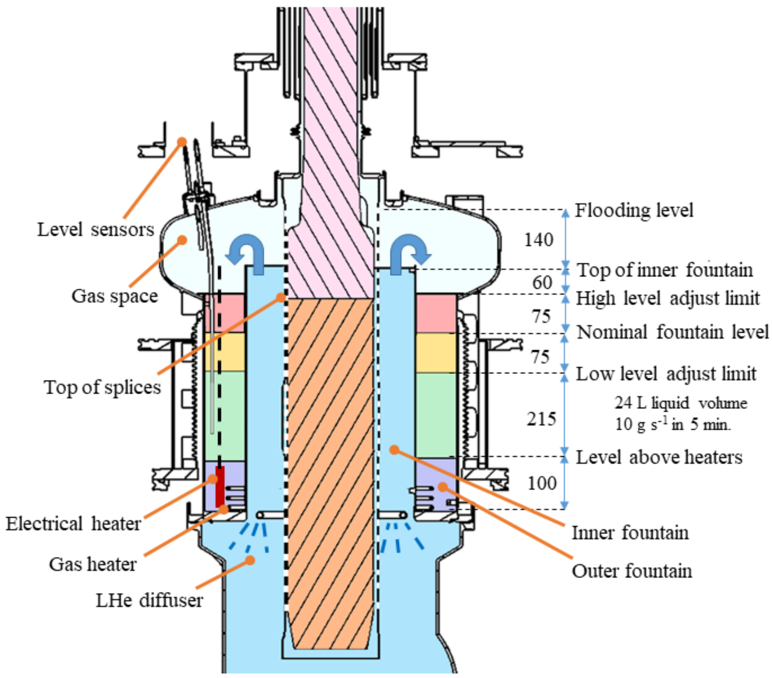


**Figure 4.** Diagram showing LHe control in DFX by fountain configuration

Two 100 W electrical heaters (one as redundancy) are installed as the primary heating devices. A copper coil installed in the outer fountain (with surface area equivalent to 1 $m^2$) can be used to circulate 60 K GHe in a closed circuit from Lines E and F. Given, the limited space between the top of the DFX and the LHC ceiling, the electrical heaters become irrecoverable components during routine interventions. The gas heater is a backup system ready to continue normal operation, until an exceptional intervention maybe required. The risk of failure of the gas heater is lower than for electrical heaters, and in time it may indeed become the primary heating device, once experience of its control and reliability is gathered.

### *3.2. Vacuum barrier membrane and support cage*

The barrier that separates the vacuums of the DFX and SCLink cryostats at the interface between modules M1 & M2, must have a large diameter (562 mm) to fit around the fountain, while leaving space for multi-layer insulation. The distance between the dome and the vacuum flange at the mid-section is very short (325 mm); therefore, the membrane will be fabricated as a fully corrugated structure to increase its effective length, reduce heat ingress, and resist buckling, if suddenly the vacuum in the SCLink side of the system is lost. Figure 5(a) shows the buckling behaviour of only the corrugated membrane under an external pressure of 1.5 bar, thermal contraction and a hanging mass of 200 kg, to account for the weight of the M1 & M2. Using ANSYS, the calculated Eigenvalue Load Multiplier (ELM) = 4.62, (target value ≥ 5.00). However, the stresses developed in the 0.5 mm thick single ply corrugation, exceeds 240 MPa, and the membrane is unable to cope without additional support. Table 1. summarises the ELM calculated for a range of studies that introduce a support “cage” structure around the membrane. The number of straight sections of tube wall connecting the flange to the dome (pillars) was varied. Both 3-pillar and 4-pillar cages with equivalent cross-section were compared. The 3-pillar cage in Figure 5(b) performed effectively under loading, with the addition of 2 mm stiffening rings to reinforce the hoop connection between pillars. The combined assembly of membrane + 3-pillar cage in Figure 5(c), produced a viable ELM = 5.76, without having to further increase the ply thickness of the membrane. The buckling mode appeared first in the cage hoops, and the local stresses at the cage-to-dome interface and radii of the cut-outs were < 175 MPa. The total heat ingress from the vacuum barrier assembly is ~11.7 W, and is about one third of the total heat ingress budget for DFX. To finalise the checks upon this vacuum barrier design; the final model should include the full vacuum envelope to enable the fixed boundaries to be realistic and representative and the correct distribution of service ports in the top dome to inspect the impact of circumferential asymmetries.

**Table 1.** Vacuum membrane and support cage combinations and dimensions investigated

| Description | Membrane thickness (mm) | Cage thickness (mm) | Stiffening ring thickness (mm) | Eigenvalue load multiplier |
|---|---|---|---|---|
| Corrugated membrane (only) | 0.50 | n/a | n/a | 4.62 |
| 3-pillar cage (only) | n/a | 1.50 | 2.00 | 5.17 |
| 3-pillar cage + membrane | 0.50 | 1.50 | 2.00 | 5.76 |
| 3-pillar cage + membrane | 0.50 | 1.00 | 2.00 | 3.21 |
| 3-pillar cage + membrane | 0.50 | 1.25 | 2.00 | 4.14 |
| 4-pillar cage + membrane | 0.50 | 1.00 | 1.00 | 1.71 |
| 4-pillar cage + membrane | 0.50 | 1.00 | 2.00 | 2.54 |

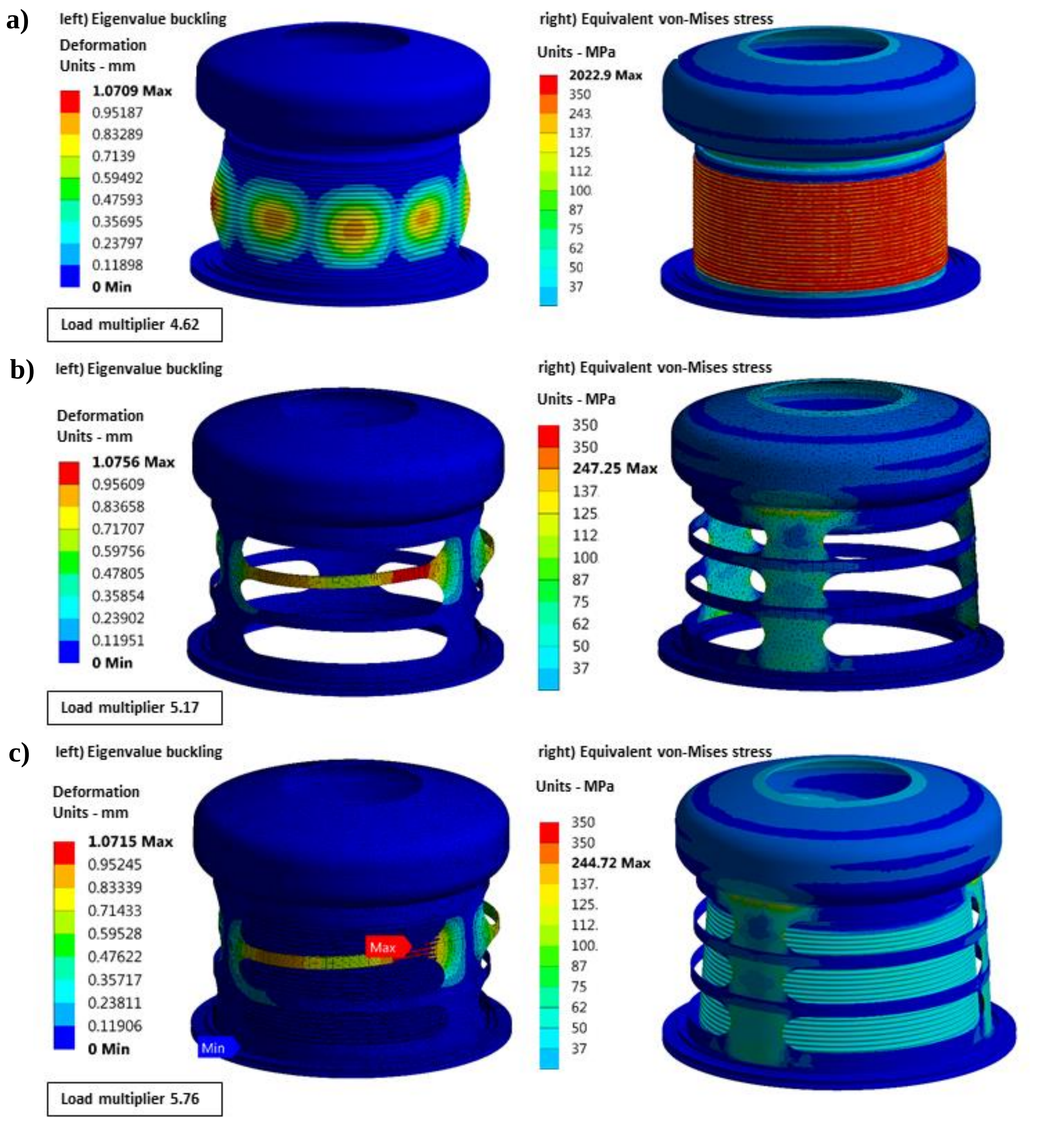


**Figure 5.** Thermo-mechanical stress analysis results, (a) 0.5 mm thick corrugated vacuum barrier membrane – (left) ELM, (right) von-Mises stress, (b) 1.5 mm thick 3-pillar cage structure with hoop reinforcement – (left) ELM, (right) von-Mises stress, (c) combined membrane and 3-pillar cage – (left) ELM, (right) von-Mises stress

### *3.3. Restraint under pressure and varied temperature*

The reaction developed in the "L-shape" cryostat when under pressure, causes a bending moment to evolve in the direction shown by the black arrows in Figure 5(a). The moment tends to squeeze the inner edge where M1 and M2 meet, with further risk of buckling the support cage. The simulated results obtained from a representative structural COMSOL® model are presented. Figure 6 (a-b) show the relative displacements developed for the fully enclosed helium cryostat at room temperature and 4.2 K under an internal pressure of 3.5 bar. The corresponding stresses are displayed in Figure 7 (a-b). The position of the bellows are highlighted in Figure 6(a), and the positions of the guide supports maintain the concentric movement of the horizontal stretch of helium vessel with respects to the outer vacuum vessel. The flange supporting vacuum barrier membrane and cage was placed on a roller support, free in the z-plane. The λ-plate was fixed along with the back edge of both retraining arms. The direction of movement in the z-direction is negative when the internal pressure is applied as expected, with the back edge of the cage displacing most. Studies found it best to fix the restraining arms to the vertical rib attached to elbow section in M2, at its vertical centreline. The tubular arms have an OD of 25 mm, a wall thickness of 5 mm, and the arms are effective at minimising displacement and works in tension to resist the reaction force of ~32 kN measured at the fixed point, without developing stress above 50 MPa. The same arms work effectively at 4.2 K, with the same internal pressure. The arms were able to pull back the vertical section by 3 mm, without developing high stresses (~100 MPa). The reaction force remained ~ 32 kN, and the arms continue to work in tension, although they are sized accordingly to cope with a critical buckling load of 45.7 kN (safety margin = 1.4). At cryogenic temperatures, the largest stresses in Figure 7(b), are found at radii of the cut-out in cage support, and similar magnitude to those established in the ANSYS modelling of the vacuum barrier configuration (145 MPa). The application of overpressure (1.5 bar) in the DFX vacuum space should also be checked with both FE-models, but the impact is expected to be less, given the counterbalancing of pressures. Further studies at the nominal operating pressure (1.3 bar) and (0 bar) at 4.2 K and 300 K will be conducted to complete qualification of the design.

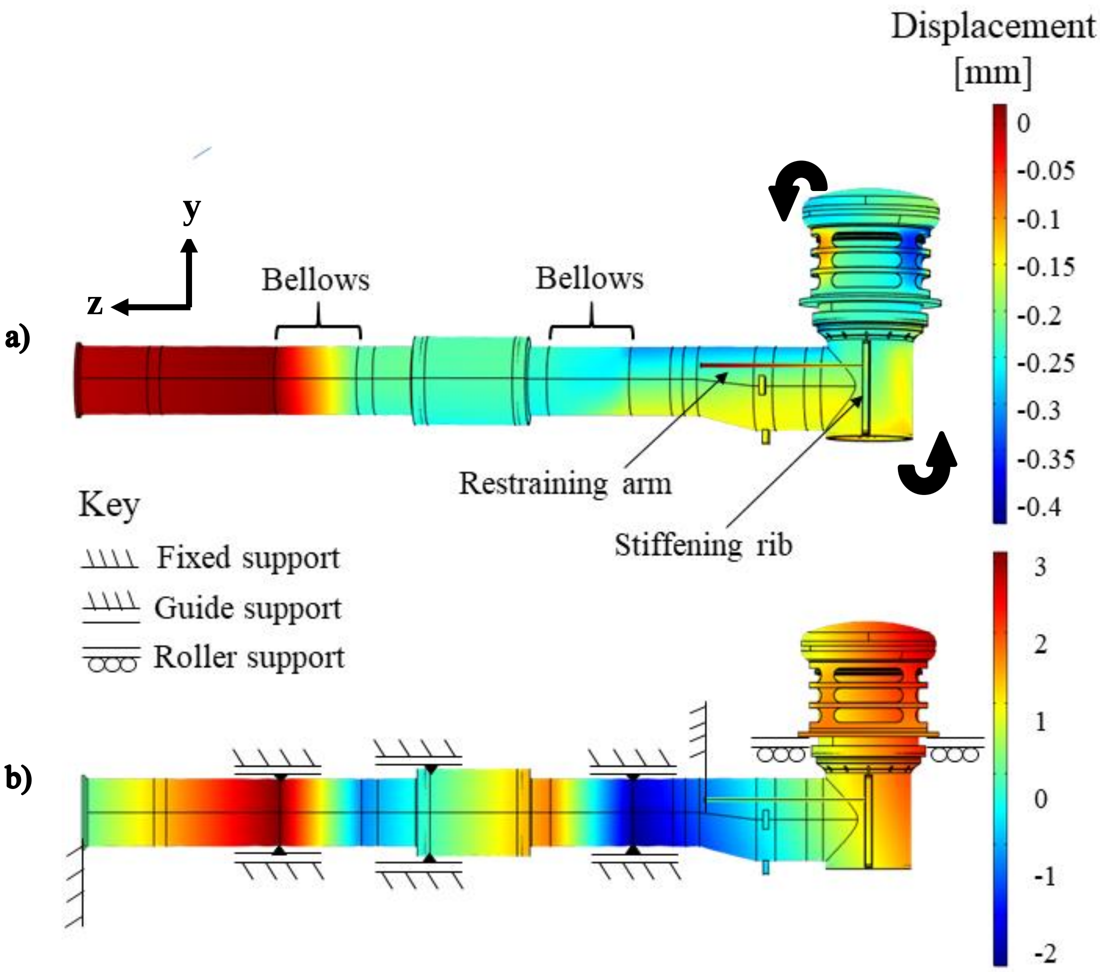


**Figure 6.** DFX helium vessel under pressure of 3.5 bar; (a) room temperature (300 K) – displacement, (b) LHe temperature (4.2 K) – displacement

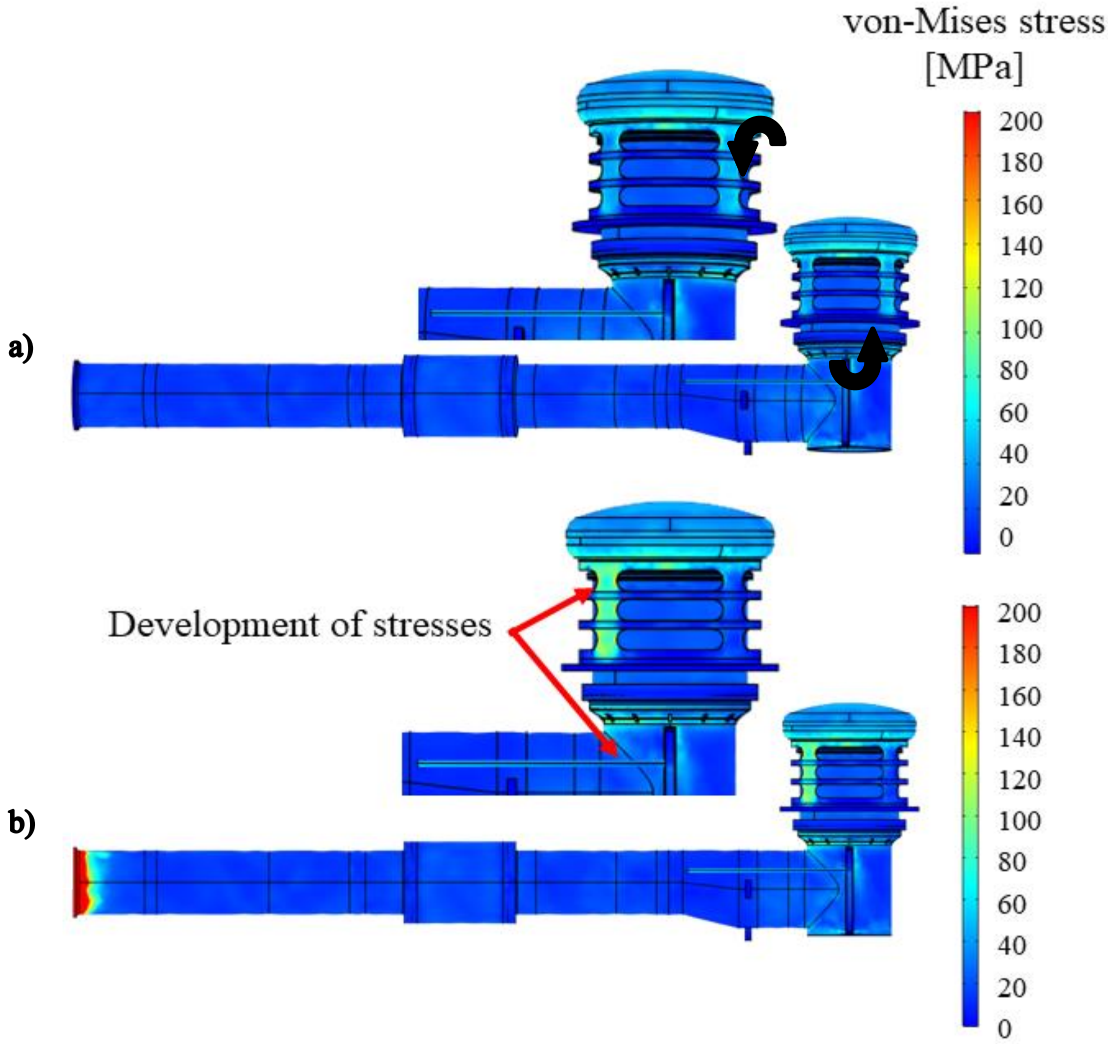


**Figure 7.** DFX helium vessel under pressure of 3.5 bar; (a) room temperature (300 K) – von-Mises stress, (b) LHe temperature (4.2 K) – von-Mises stress

## 4. Conclusions

The detailed design of the distribution feedbox required for the interconnections between the SCLink and the magnets in the HL-LHC scheme is approaching completion. The DFX design satisfies all constraints imposed by the LHC tunnel and solves a number of integration issues with its modular design. The cryogenic operation works by adopting an overspilling fountain arrangement, which separates the main LHe bath, (where the $MgB_2$-NbTi splice remains immersed and vertical) from an outer annular volume of LHe used to generate the GHe for the SCLink. Through thermo-mechanical modelling, a solution was found for accommodating the vacuum barrier in the mid-section of the vertical part of DFX. The combination of a corrugated membrane, reinforced structurally with an outer cage works effectively to counteract the complex thermal contraction, created by the enlarged "bulb" shape domes needed to provide sufficient gas volume. The combination of the cage and membrane resist non-linear buckling modes with sufficient margin and within acceptable heat ingress limits. The bending moment imposed during pressurisation of the "L-shape" vessel was solved by fixing a pair of restraining arms to the centreline of M2 (elbow module) to the vacuum wall in M3. Despite being rather long and susceptible to buckling, the tubular restraint was shown to work in tension at 300 K and 4.2 K at 3.5 bar, while adding minimal heat ingress to the total cooling budget. The design is ready to be fully evaluated by the "Design-by-Analysis" rules in EN 13445-3 Annex B [8] to ascertain compliance with the Pressure Equipment Directive 2014/68/EU [9].

## 5. References

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