DFX – Concept Design Summary

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Outline

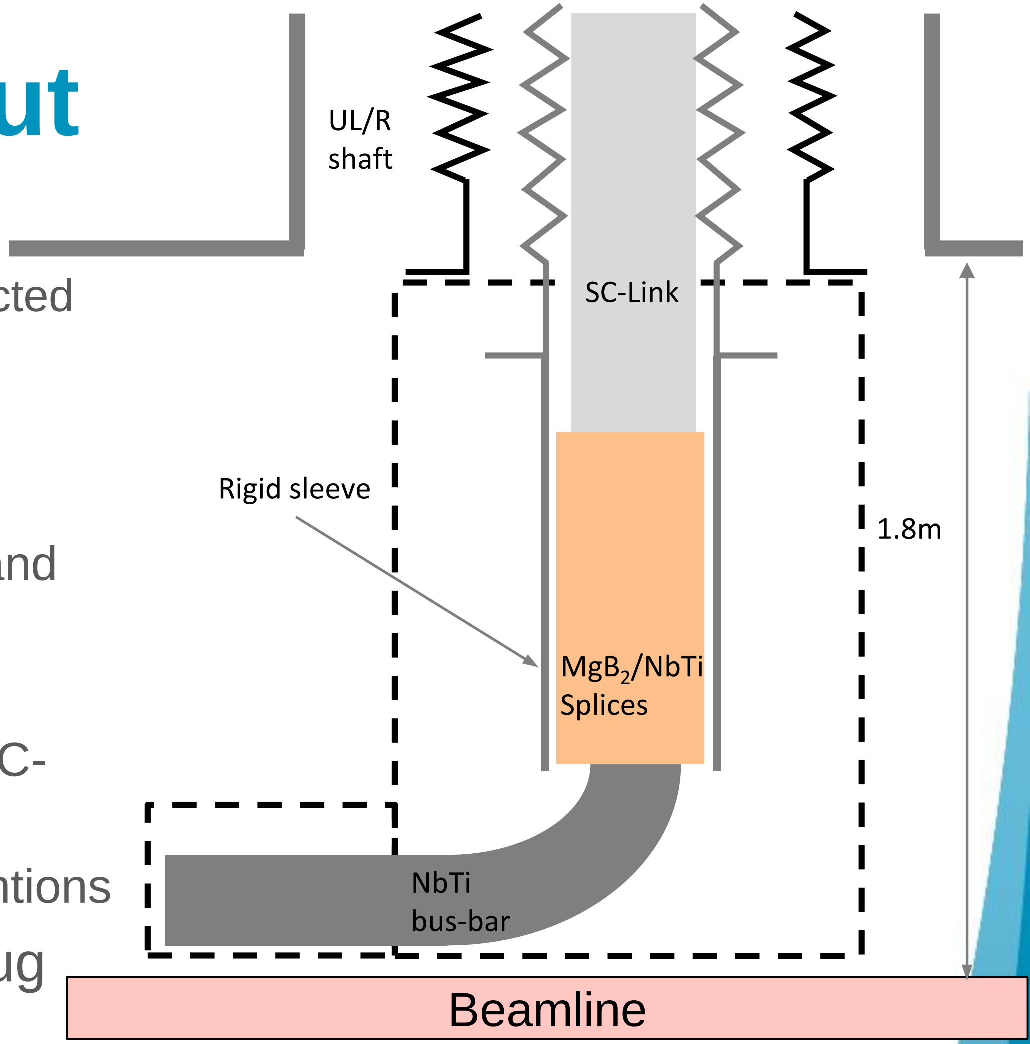
- Interfaces and functional specifications
  - Electrical
  - Cryogenics
  - Vacuum
- Constraints, design choices, DFX layout
  - SC-Link
  - Cryogenics
- Concept schematics
- Mechanical design for the interfaces/integration and functions
  - SC-Link
  - NbTi-NbTi splices
  - D1-plug
  - Cryogenic lines and cryo-jumper
  - Instrumentations
  - Controls
  - Maintainability/exchangeability
  - Safety devices
- Test and qualifications

Interfaces and functional specifications

- Electrical
  - SC-Link with MgB_2-LTS splices and LTS bus-bar
  - He-I/He-II plug with LTS bus-bar
  - LTS-LTS splices
  - Instrumentations
- Cryogenics
  - LHe inlet
  - GHe vent
  - Line E_2F in/out
  - Line E_2H in
- Vacuum
  - Barrier to SC-Link
  - Isolated from Cryo-jumper and D1
- Control
  - GHe flow for cooling the SC-Link, splices in DFH, HTS cables, and current leads
  - LHe level for MgB_2-NbTi splices

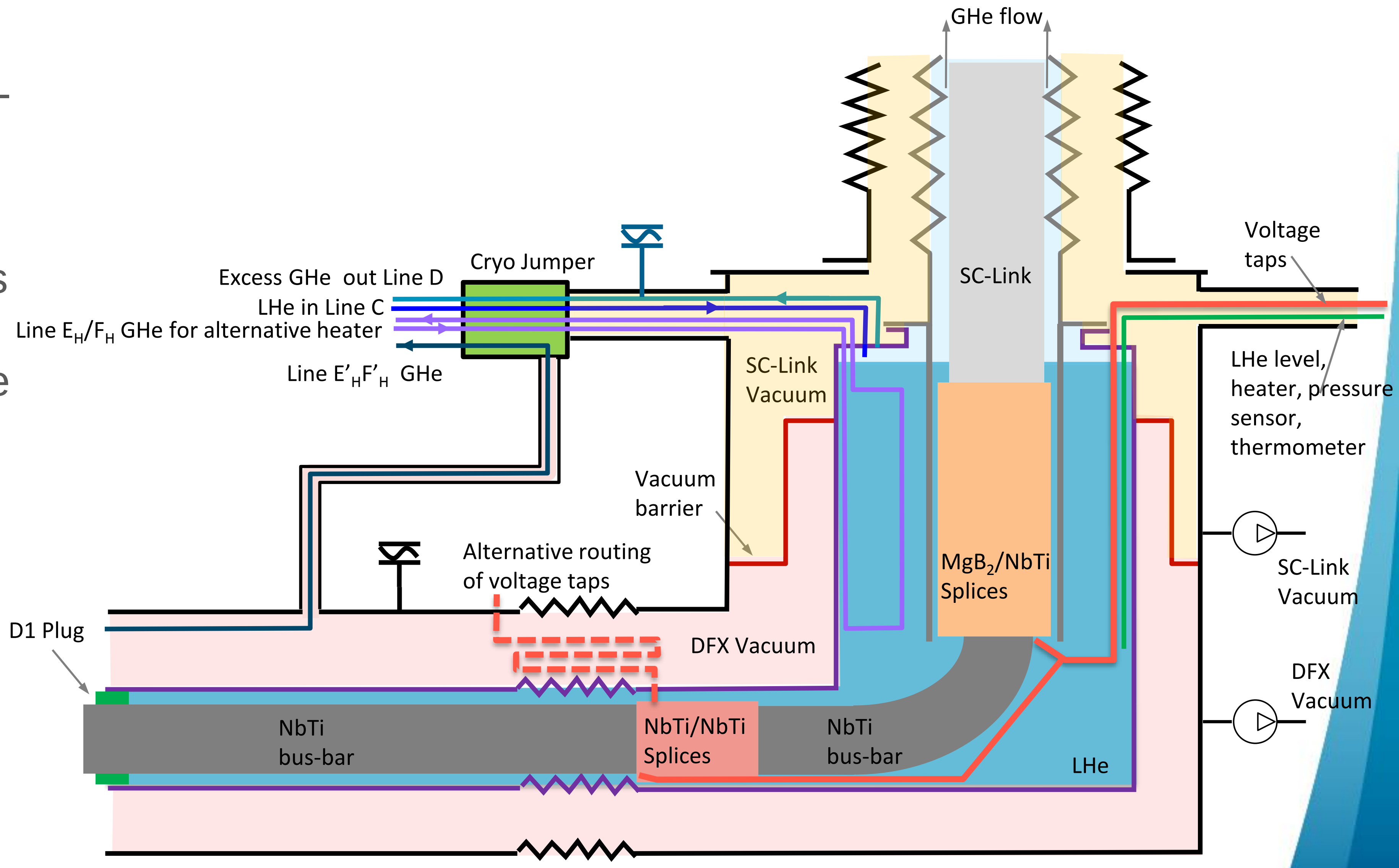
Constraints and DFX layout

- No handling of the SC-Link including the MgB_2-NbTi splices protected by a rigid sleeve
- SC-Link's minimum bending radius of 1.5m
- Vertical SC-Link integration under the UL/R shaft
  - Must fit within the height (~1.8m) between the shaft exit and the beamline and the width/depth of space reservation
  - No access to the shaft during assembly/integration
  - Must allow the bending of the NbTi bus-bar leading the SC-Link
  - Allow the SC-Link to be lowered for maintenance interventions
- Horizontal connection to the NbTi bus-bar from D1-plug with splices prepared in LHC tunnel
  - Allow a positive slope for LHe from the D1-plug to the vertical DFX
  - Allow dissembling in LHC tunnel for maintenance interventions



Concept Schematics

- SC-Link
- D1-plug with NbTi bus-bar and splice to SC-Link
- DFX LHe vessel
- LHe and GHe supplies
- Vacuum barrier
- DFX vacuum envelope
- Instrumentations and controls
- Additional cryogenic supplies
- Safety

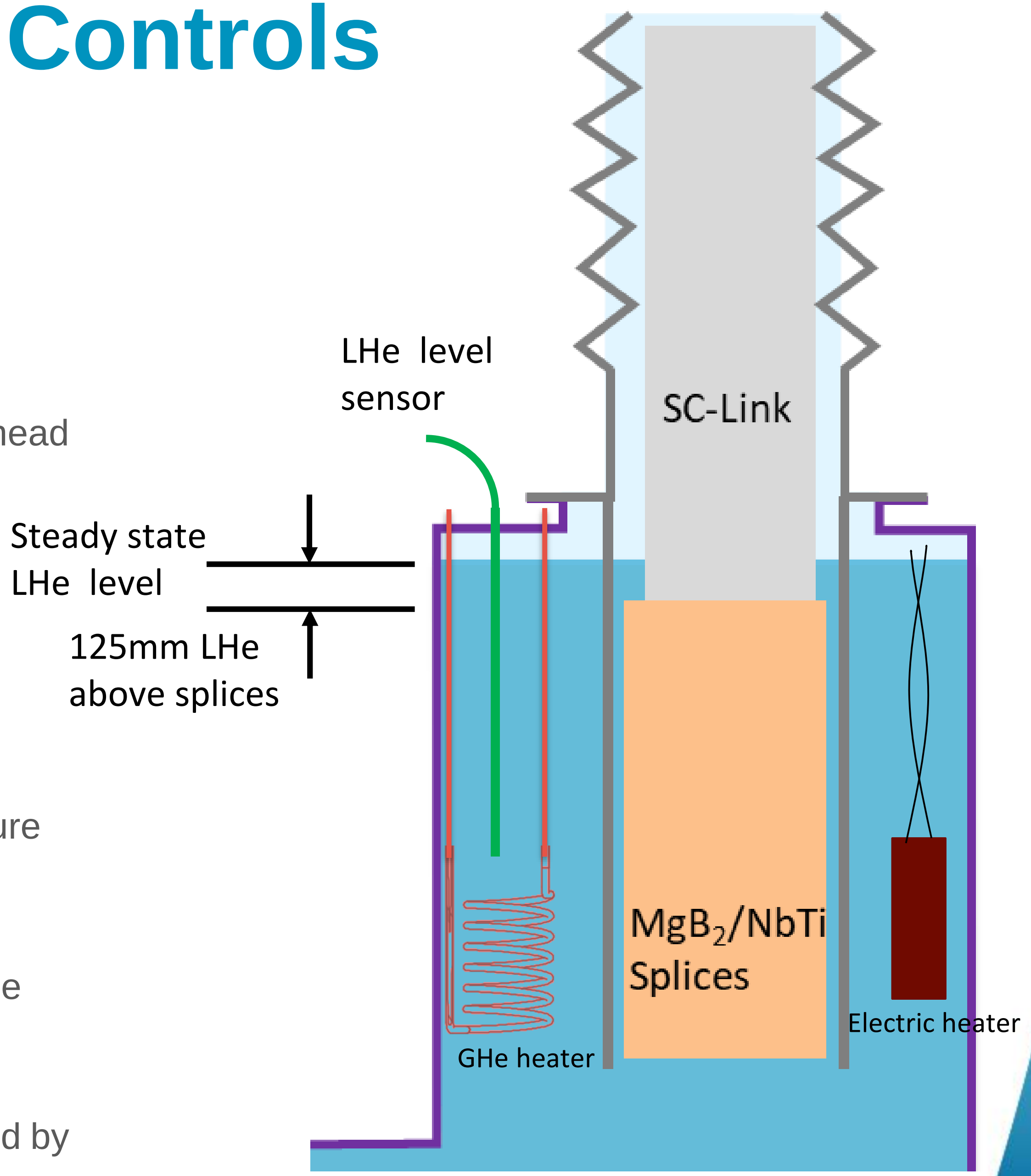


DFX Component Vessels

- Vertical DFX in two parts
  - **Upper**: inner and outer pre-assembled
    - Interfaces for cryo-lines and instrumentations on the side due to lack of access to the shaft
    - Rigid vacuum barrier linking the inner and outer
    - Flexibility by SC-Link cryostat
  - **Lower**: assembled and welded after the integration of SC-Link and bending of the NbTi bus-bar
- Horizontal DFX in several sections
  - Reversible splice section (location to be optimised)
  - Link sections to the vertical DFX on one side and D1-plug on the other
  - Assembled sequentially from the vertical DFX to D1-plug

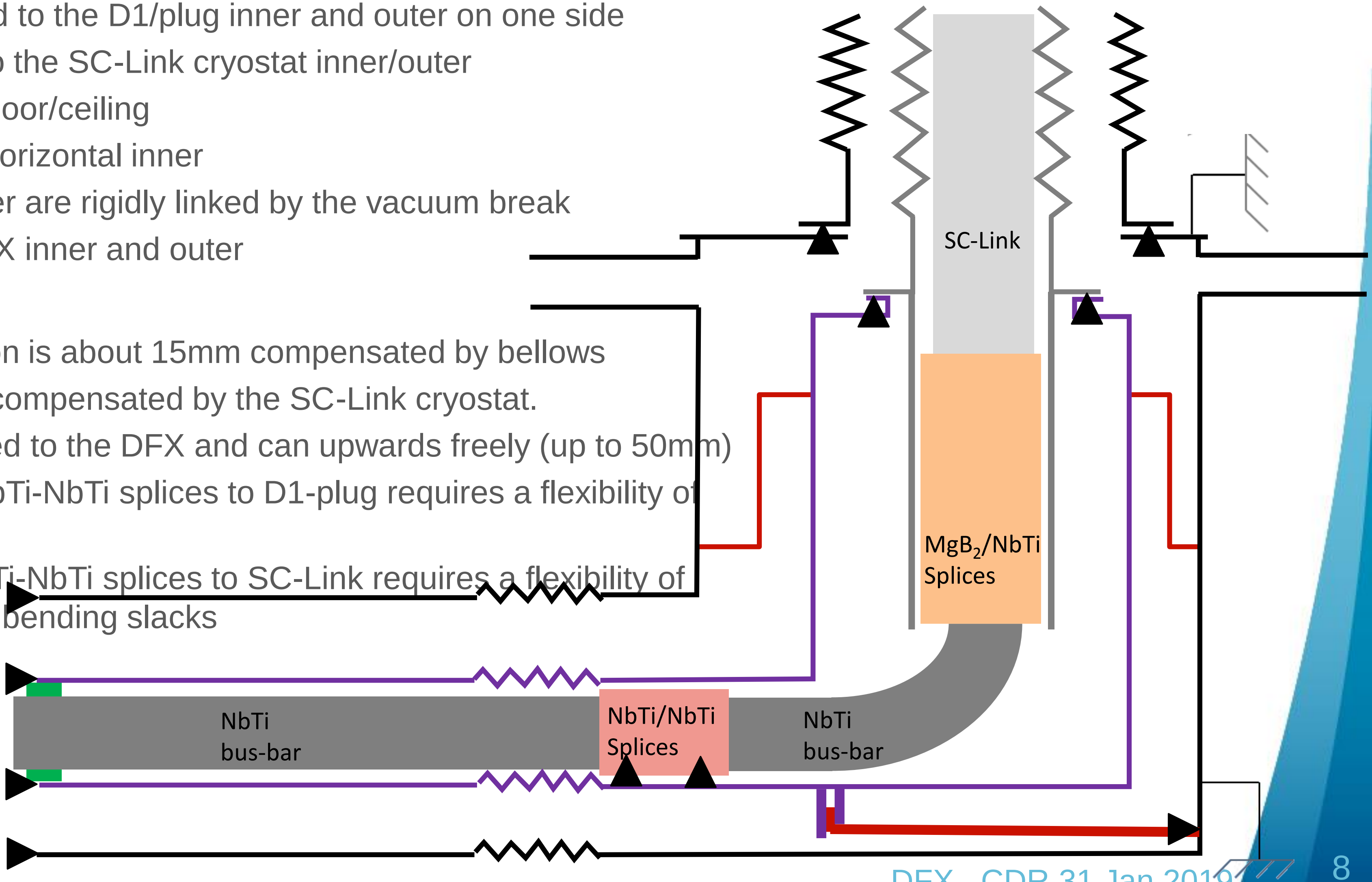
Cryogenic Controls

- Liquid helium level control
  - Fully submerged MgB_2-NbTi splices
  - Level controlled at 125mm above
  - PID control of Line C valve with level sensor reading feedback
  - A time constant of 10min for depletion of 125mm LHe head with Line C valve shut and heater on heater on 100% nominal for a 5g/s boil-off rate (see function specs)
- GHe flow control
  - wo types of heaters
    - "Passive" heater with Line E_H warm GHe
    - Electric heaters with redundancyy
  - PID control of Line E_H valve with MgB_2-HTS splice temperature and HTS-current-leads terminal temperature feedback
- No thermal shield in baseline DFX design
  - Overall heat inleak is well within the budget given by the functional specifications
  - No cold spots anticipated
  - TS can be introduced using Line $E'_H F'_H$ if issues spotted by detailed design modelling



Mechanical Fixed Points and Movements Compensation

- Fixed points
  - NbTi-NbTi fixed to the DFX horizontal inner cryostat
  - Horizontal DFX inner/outer fixed to the D1/plug inner and outer on one side
  - Vertical DFX inner/outer fixed to the SC-Link cryostat inner/outer
  - DFX is anchored to the tunnel floor/ceiling
  - Spokes/stars support for DFX horizontal inner
  - The vertical DFX inner and outer are rigidly linked by the vacuum break
  - Bending support for vertical DFX inner and outer
- Movements
  - Horizontal differential contraction is about 15mm compensated by bellows
  - Vertical differential contraction compensated by the SC-Link cryostat.
  - SC-Link and splices are not fixed to the DFX and can upwards freely (up to 50mm)
  - NbTi bus-bars from the fixed NbTi-NbTi splices to D1-plug requires a flexibility of <20mm
  - NbTi bus-bar from the fixed NbTi-NbTi splices to SC-Link requires a flexibility of ~35mm, accommodated by the bending slacks



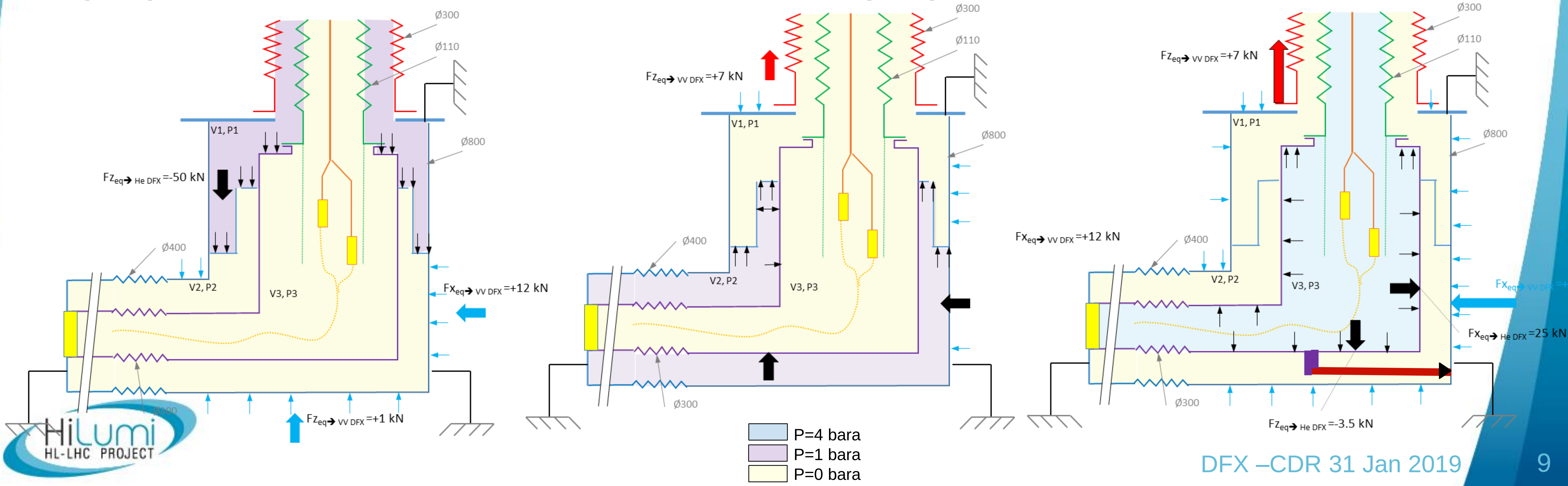
Mechanical Forces and Support

- The vacuum break sufficiently designed against buckling under 5 ton compressive force
- Bending moment supported by linking vertical DFX inner and outer horizontally

Purging helium / SC link not pumped – DFX under vacuum

Purging helium / SC link under vacuum – DFX not pumped

SCLink & DFX under vacuum – DFX helium pressurised to PS



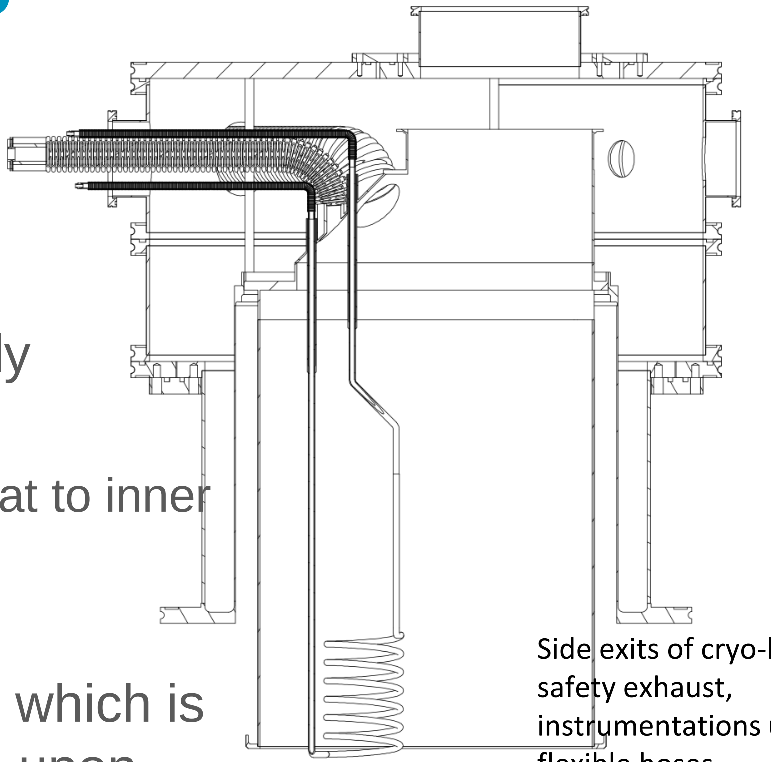
Warm Feedthroughs

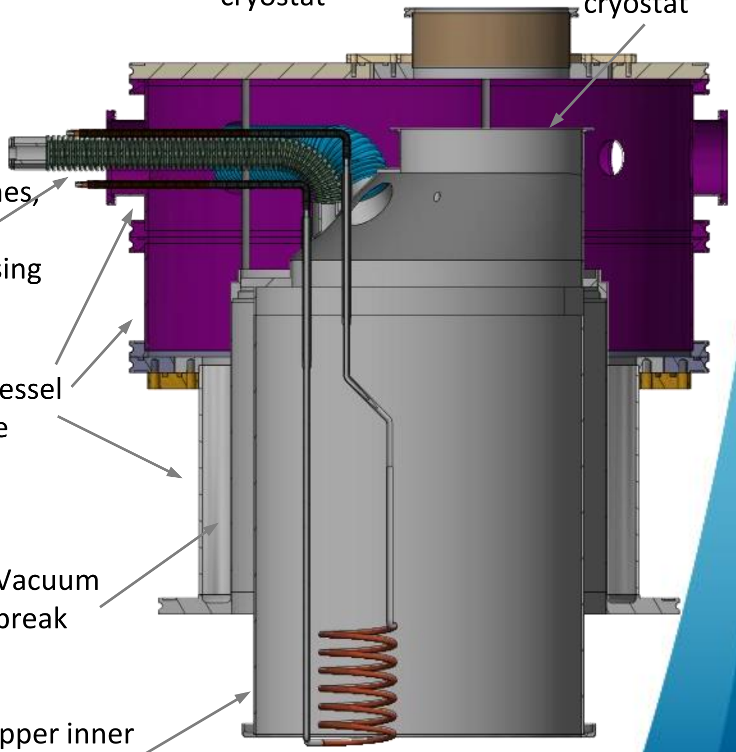
- 160 voltage wires from splices (JF)
- Heat load for 160x(10x0.1mm wire) is ~2W per metre length of wires, thus 2m lengths seems reasonable
- Assuming feedthroughs using 10-15 Fischers connectors or CERN equivalents, condensation is unlikely:
  - The thermal links to the warm wires on the feedthrough plugs
  - The thermal contact resistance between the voltage pins and the surrounding ceramic insulation followed by an effective natural convection area of 100-150cm^2.
- Wires for other instrumentations/controls (pressure, level, thermometers, heaters) are less than 30 in total

Mechanical design for interfaces and functions (1)

Vertical DFX upper vessels

- Interface to SC-Link
- Interface to cryogenic lines
- Instrumentations and controls
- Split outer vessel to allow assembly
  - Threading the flexible hoses
  - Welding the SC-Link inner cryostat to inner the upper vessel
- Vacuum barrier
- The inner vessel is pre-assembled which is welded to the SC-Link inner flange upon integration
- Flanges to vertical DFX lower vessels
- LHe level is in the middle of the coned section, which is 250mm high. Thus leave a 125mm head above the splices



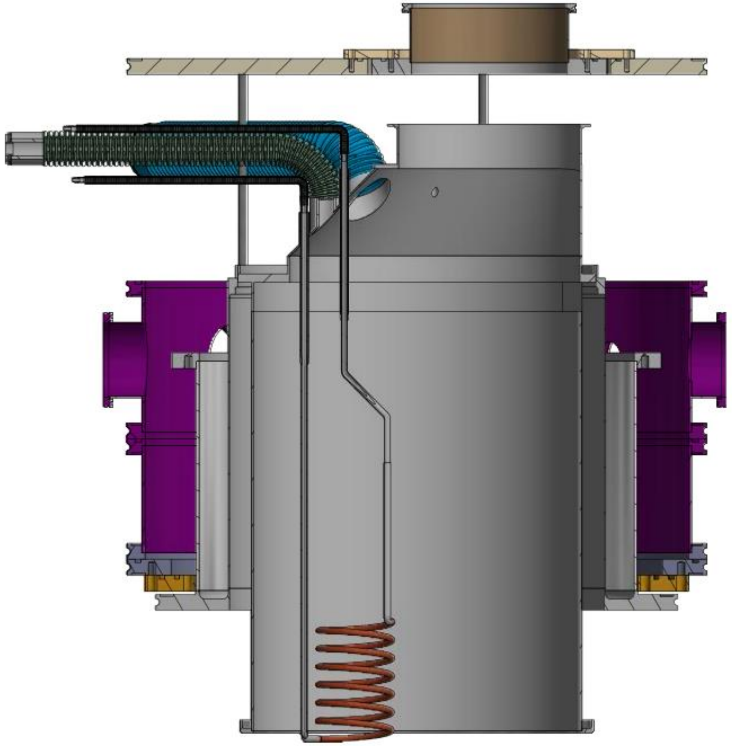


Mechanical design for interfaces and functions (2)

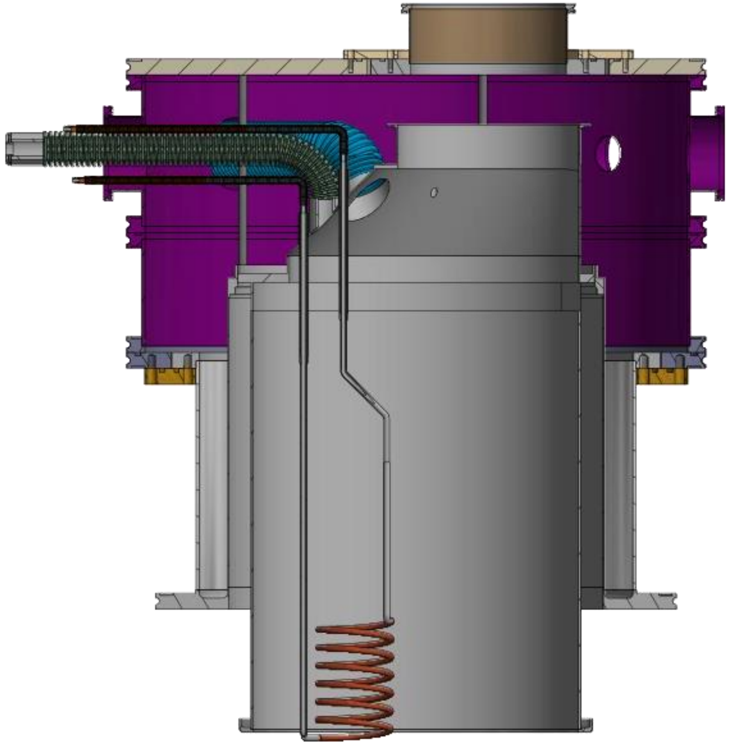
Vertical DFX upper vessels

- Split outer vessel to allow assembly
  - Threading the flexible hoses
  - Welding the SC-Link inner cryostat to the upper inner vessel

Split outer upper lowered for integration of SC-Link and flexible interface hoses



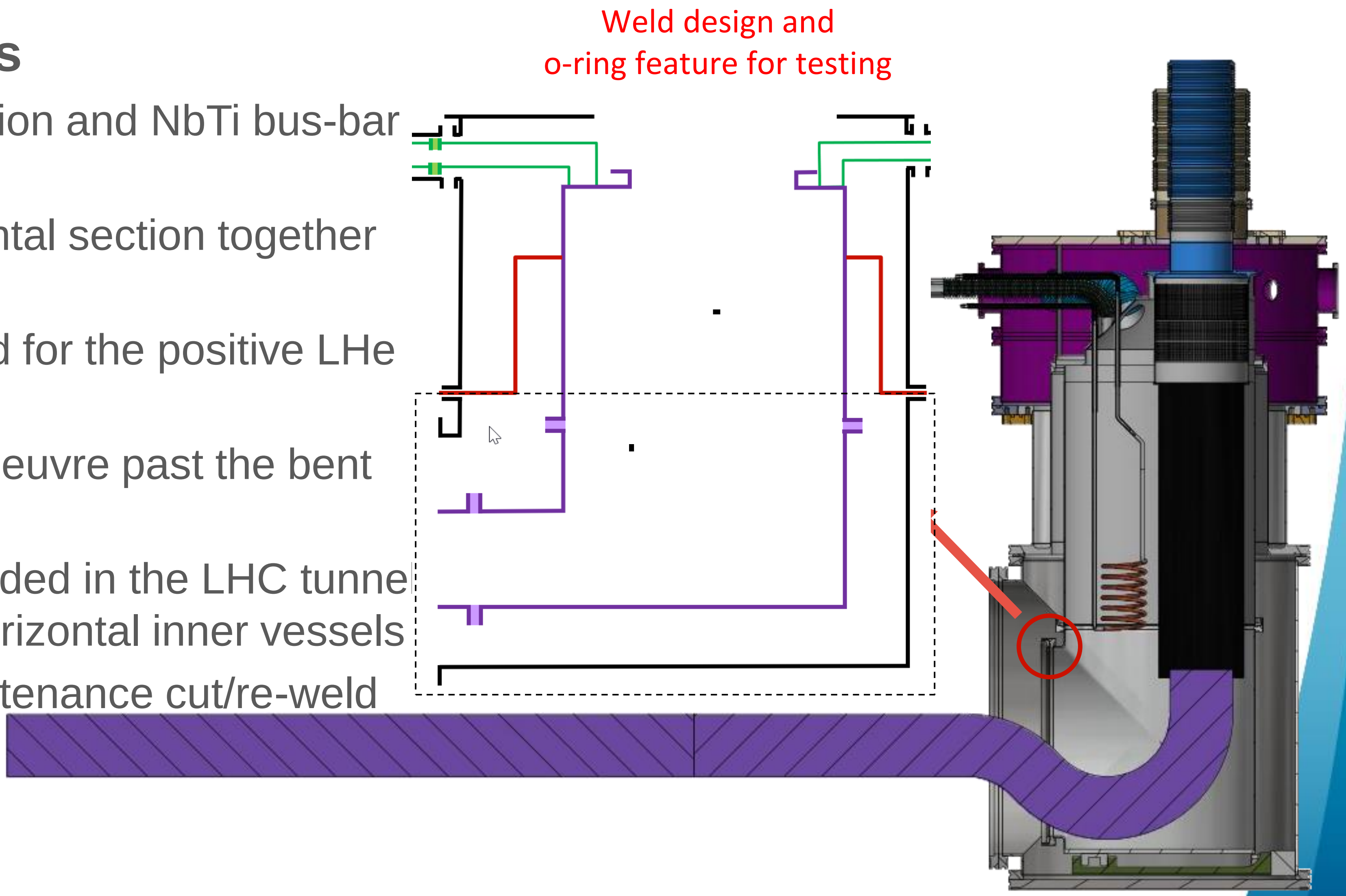
Split outer upper closed after integration



Mechanical design for interfaces and functions (3)

Vertical DFX lower vessels

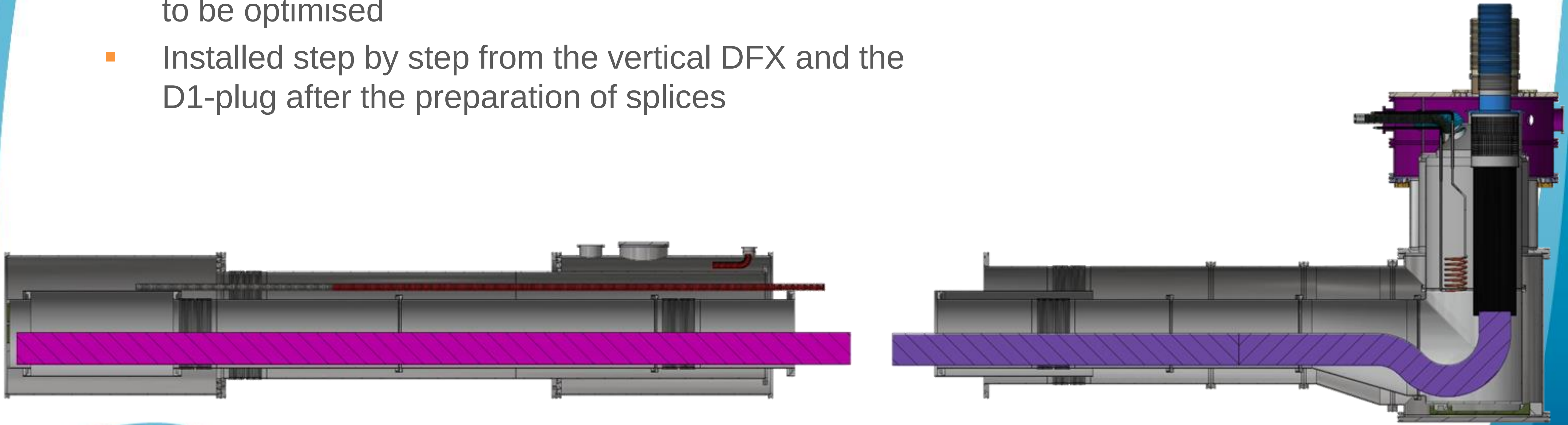
- Installed **after** SC-Link insertion and NbTi bus-bar bending
- Allow transition to the horizontal section together with the NbTi bus-bar
- Accommodate a double-bend for the positive LHe slope from D1-plug
- Special tooling used to manoeuvre past the bent NbTi bus-bar for installation
- The lower inner vessel is welded in the LHC tunnel to the upper inner and the horizontal inner vessels
- The weld design allows maintenance cut/re-weld and o-ring feature for pressure tests



Mechanical design for interfaces and functions (4)

Horizontal DFX vessels

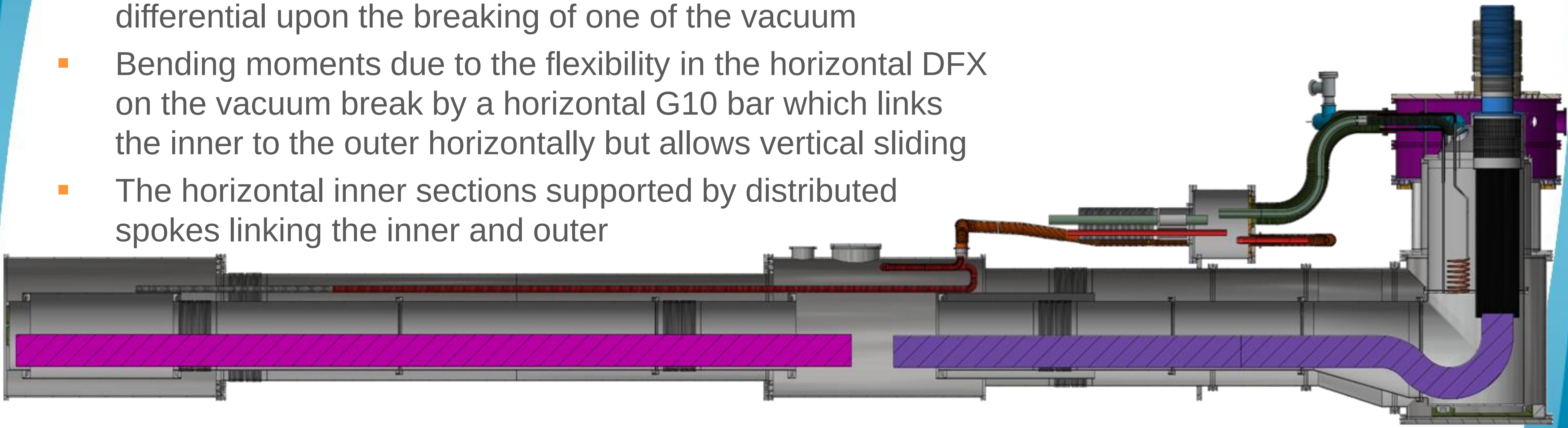
- Comprises of connection sections and a reversible NbTi-NbTi splice section
- Modular section to accommodate the splice position to be optimised
- Installed step by step from the vertical DFX and the D1-plug after the preparation of splices

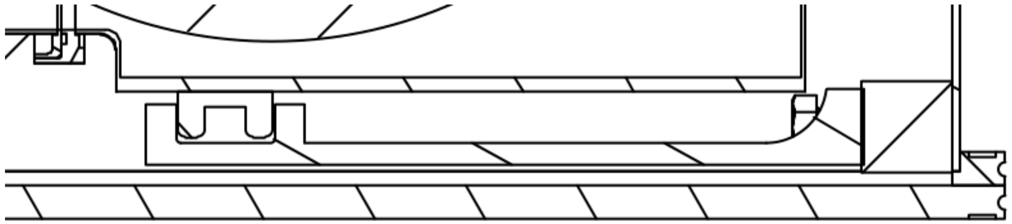


Mechanical design for interfaces and functions (5)

Mechanical support

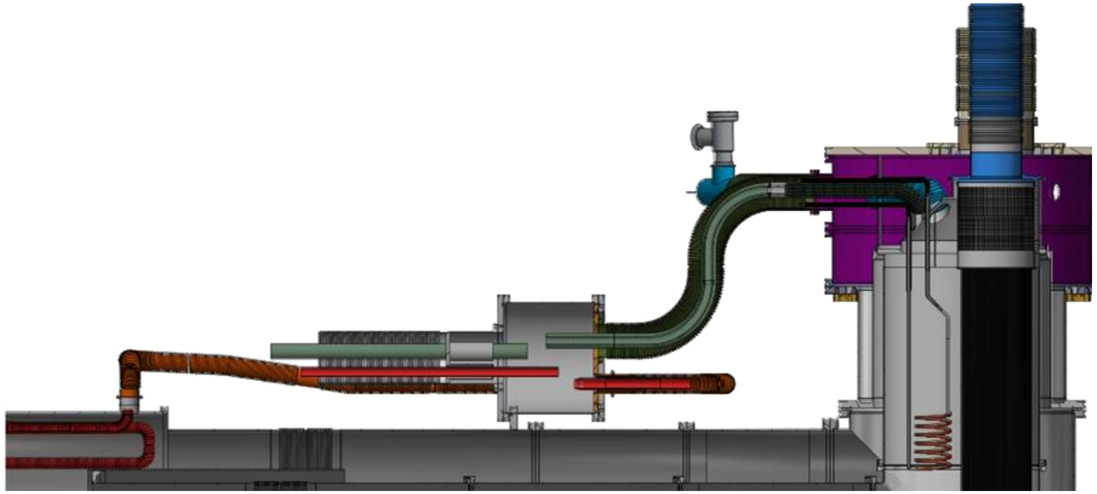
- Vertical inner vessel supported by outer via the rigid vacuum break which is designed to withstand the pressure differential upon the breaking of one of the vacuum
- Bending moments due to the flexibility in the horizontal DFX on the vacuum break by a horizontal G10 bar which links the inner to the outer horizontally but allows vertical sliding
- The horizontal inner sections supported by distributed spokes linking the inner and outer





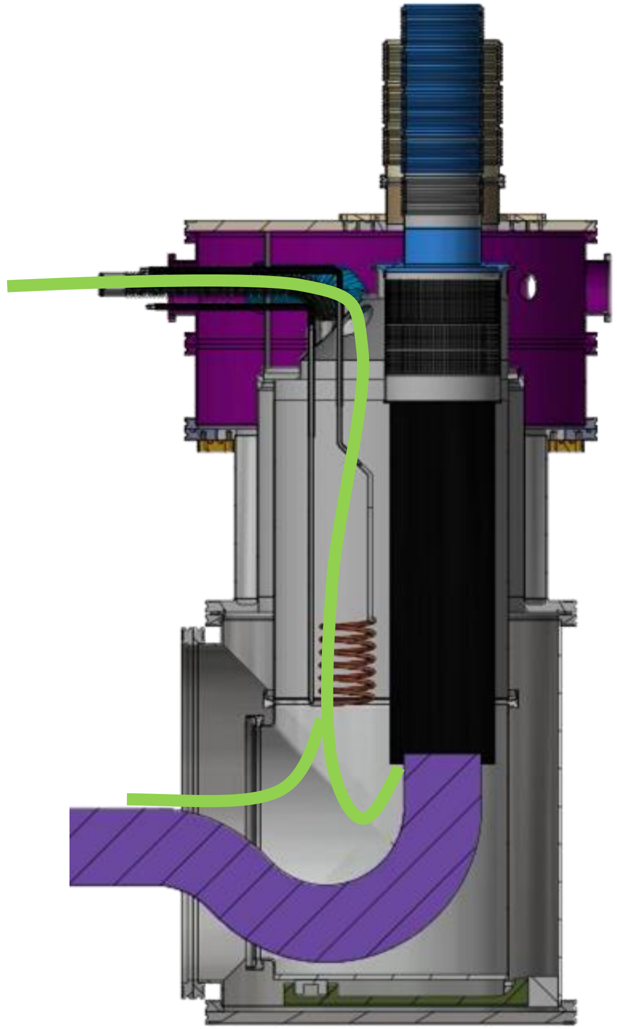
Mechanical design for interfaces and functions (6)

- **Interface to cryo-jumper**
  - Via flexible hoses with own vacuum
  - No specific constraints on the jumper location
  - Welded in-situ to the cryo-lines from the jumper in the DFX vacuum spaces enclosed by a sliding vacuum envelope
- **Level gauge**
  - Use a small flexible hose to admit a 3mm flexible LHe gauge to be qualified.
  - Can be replace while the system is cold
- **Heaters**
  - Passive heater using Line $E_H F_H$ will be integrated and tested in demo 2. They should offer a significantly lower probability of failure than electrical heaters
  - Electric heaters (including redundancy) will be also be installed
  - Replacement of the electric heaters will be very unlikely event but also an exceptional intervention requiring warming up and the removal of a short section of beamline



Mechanical design for interfaces and functions (6)

- **Instrumentation routing**
  - Use one or two flexible hoses (75mm OD) and extended outside DFX to warm Fischer connectors or similar
  - Alternatively use LHC cold-mass impedance feedthrough from cold to warm in the horizontal DFX
  - Possibly split the routing for splice voltages from cryogenic instrumentations/controls
- **Instrumentation maintenance**
  - All voltage wires have redundancy. Repair of wiring requires the same intervention as the repair of splices
  - Warm feedthroughs at the end of extended hoses can be repaired/rewired easily
  - Rewiring of the warm end connectors of the coldmass feedthroughs can be made readily



Mechanical design for interfaces and functions (8)

Safety Devices

- LHe vent upon vacuum loss or the quench of bus-bars/splices via a flexible hose of 75mm ID
- DFX vacuum space vent installed on a horizontal section, virtually no constraints on the vent size (DIN200+)

Test and Qualification

- Pressure vessel tests will be carried out according to the appropriate standards and working pressures stipulated in the functional specifications at component level as well as assembled system. Exact procedures including cryogenic cycling to be agreed with CERN
- Design features required for the tests are in place
- Warm leak tightness tests will be carried out on the assembled system

Conclusions

- Concept design compliant with the functional specifications, especially the constraints due to the SC-Link interfaces and LHC tunnel geometry
- The design is conservative/generous in dimensioning. The practicality of assembly has been checked at conceptual level and a little beyond
- The tightness of the scheduling to DDR and production is fully appreciated. The current concept has moved into considerable mechanical details than presented here

Thank you for your attention

Operation of Helium Gas Heater

- It's a heat exchanger with the LHe side at constant temperature $T_c = 4.5\text{K}$ and Line $E_H F_H$ GHe side cooling down from $T_{h,i} = T_E$ and $T_{h,o}$ determined by mass flow rate $\dot{m}_h$ demanded by the boil-off rate $\dot{m}_c$. With $L = 1\text{m}$ length of DIN6 pipe, the area for boiling is $A = \pi DL = 180\text{cm}^2$. At $\dot{m}_c = 5\text{gs}^{-1}$, heat load is $\dot{Q} = \dot{m}_c h_{fg} = 100\text{W}$, thus the boiling is nuclear with $h_c \sim 0.5 - 1\text{Wcm}^{-2}\text{K}^{-1}$. The heat transfer coefficient on the hot side is determined with:

$$\dot{m}_h c_p\left(T_{h,i} - T_{h,o}\right) = \dot{Q} \rightarrow \dot{m}_h \geq \frac{100}{5.3 \times (60 - 4.5)} = 0.34\text{gs}^{-1}$$

$$\text{Re}_d = \frac{4\dot{m}_h}{\pi d \mu} > \frac{4 \times 0.34}{\pi \times 4 \times 7.5 \times 10^{-6}} = 14430 \rightarrow \text{turbulence} \rightarrow \text{Nu}_d = 0.023\text{Re}_d^{0.8}\text{Pr}^{0.4} \sim 0.01\left(\frac{\dot{m}_h}{\mu}\right)^{0.8}$$

$$h_h = \text{Nu}_d \frac{k}{d} \sim 0.01 \times \frac{k}{0.004}\left(\frac{\dot{m}_h}{\mu}\right)^{0.8} = 2.5k(\bar{T}_h)\left(\frac{\dot{m}_h}{\mu(\bar{T}_h)}\right)^{0.8} > 0.1\left(\frac{0.34}{7.5 \times 10^{-6}}\right)^{0.8} = 531\text{Wm}^{-2}\text{K}^{-2} = 0.053\text{Wcm}^{-2}\text{K} \ll h_c$$

$$\therefore U \sim h_h$$

- Use trial-and-error to determine $\bar{T}_h = (T_{h,i} + T_{h,o})/2$ and $\dot{m}_h$ to satisfy:

$$Q = \dot{m}_h c_p(\bar{T}_h)\left(T_{h,i} - T_{h,o}\right) = UA \cdot \text{LMTD} = 2.5Ak(\bar{T}_h)\left(\frac{\dot{m}_h}{\mu(\bar{T}_h)}\right)^{0.8} \frac{T_{h,i} - T_{h,o}}{\ln \dfrac{T_{h,i} - T_c}{T_{h,o} - T_c}}$$

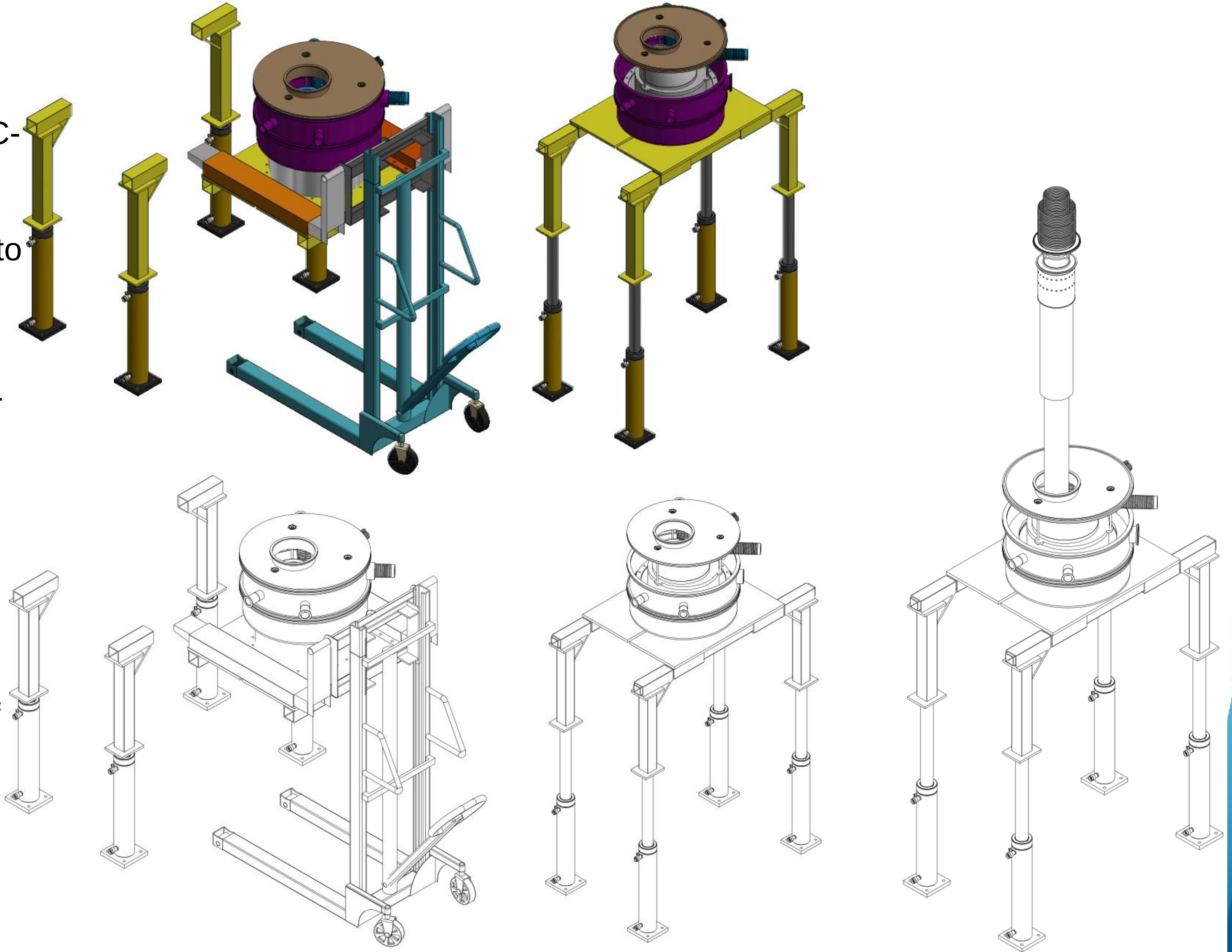
$$\dot{m}_h = \left(2.5A \frac{k(\bar{T}_h)}{c_p(\bar{T}_h)\mu(\bar{T}_h)^{0.8} \ln \dfrac{T_{h,i} - T_c}{2\bar{T}_h - T_{h,i} - T_c}}\right)^5 \quad \text{and} \quad \dot{m}_h = \frac{Q}{2c_p(\bar{T}_h)(T_{h_i} - \bar{T}_h)}$$

- $\bar{T}_h = 32.28\text{K}$, i.e. the 60K GHe exits the heater at a temperature just above the liquid temperature at 4.5K. The flow rate is 0.34g/s
- Is the flow rate too low to control? Likely to go to film boiling for a 10g/s boil-off rate. Perhaps 3m long tube is better for keeping in nuclear boiling regime.

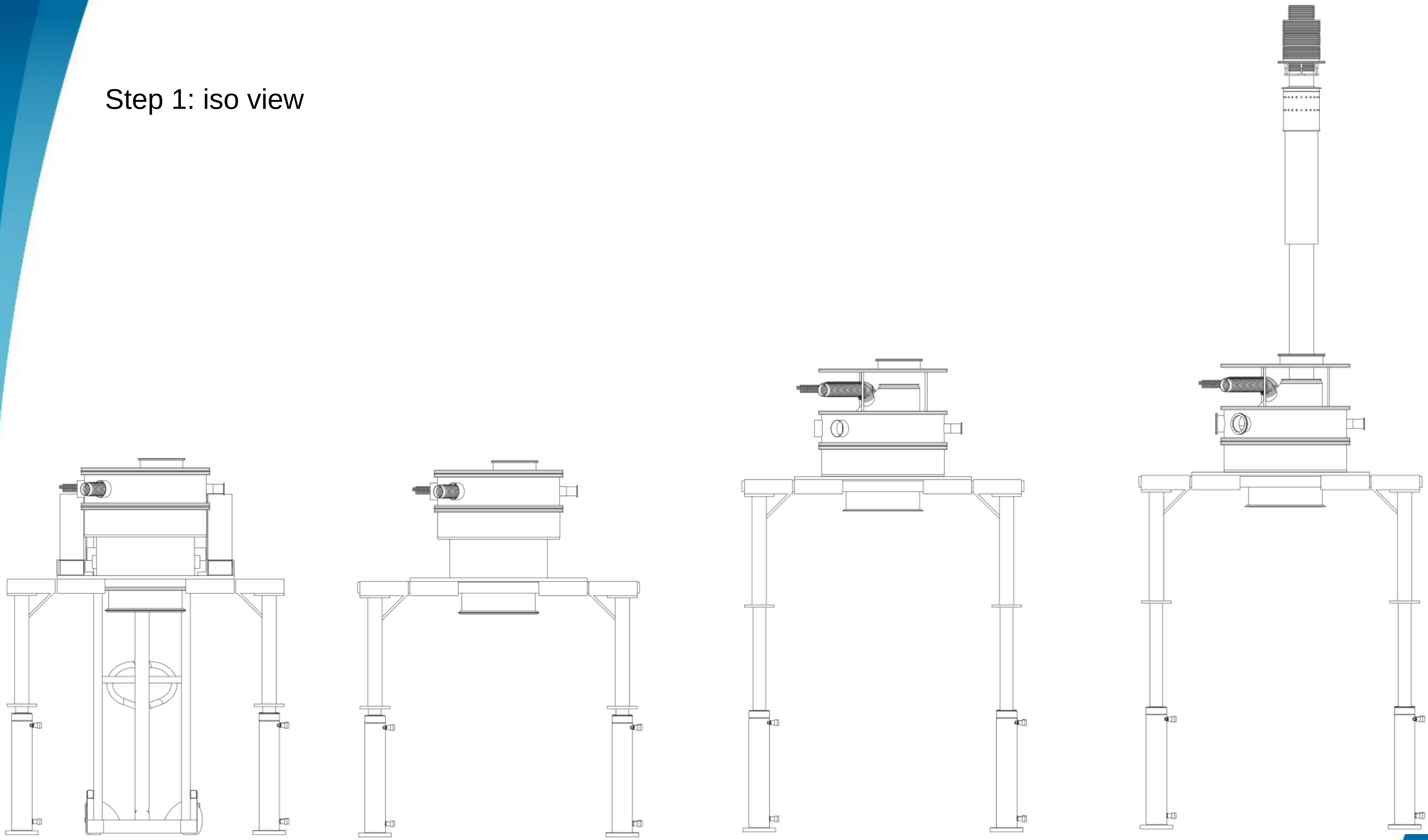
Assembling in LHC tunnel and possible toolings

Step 1: Setting up pre-assembled upper vertical module under the shaft for SC-Link integration

1. Use a hydraulic lift trolley to transport to the location
2. Set up the support frame for installation. The frame can be disassembled later when the support is eventually transferred to the bottom of the lower vertical section
3. The vertical DFX upper module is lifted to the desired position by the hydraulic lift on the legs of the supporting frame.
4. 4. Ready for SC-Link Insertion

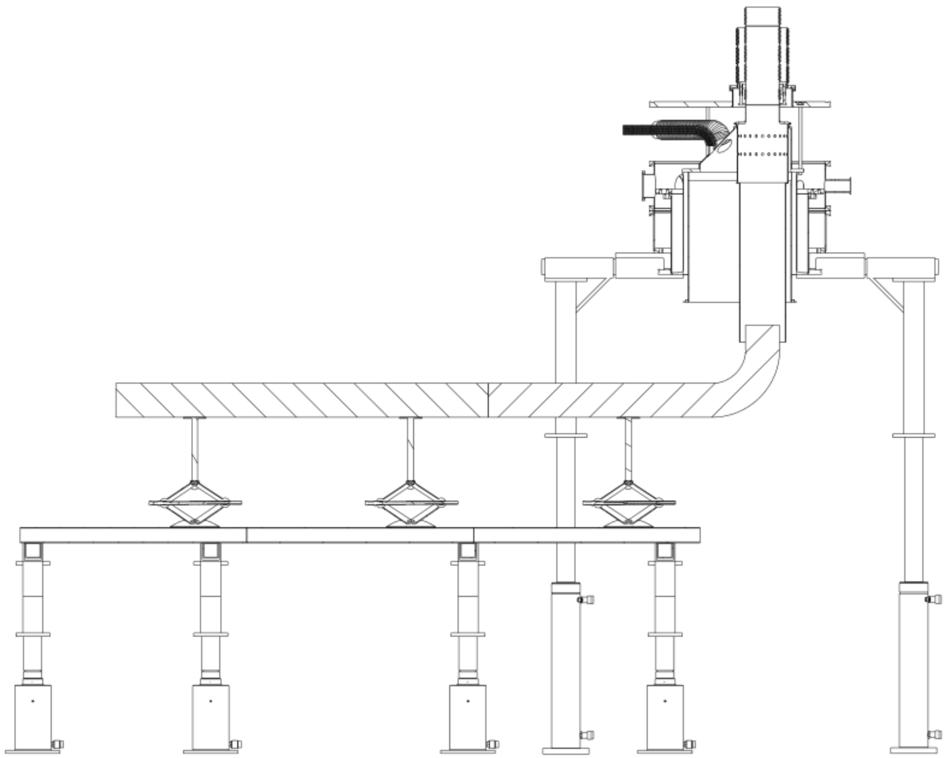


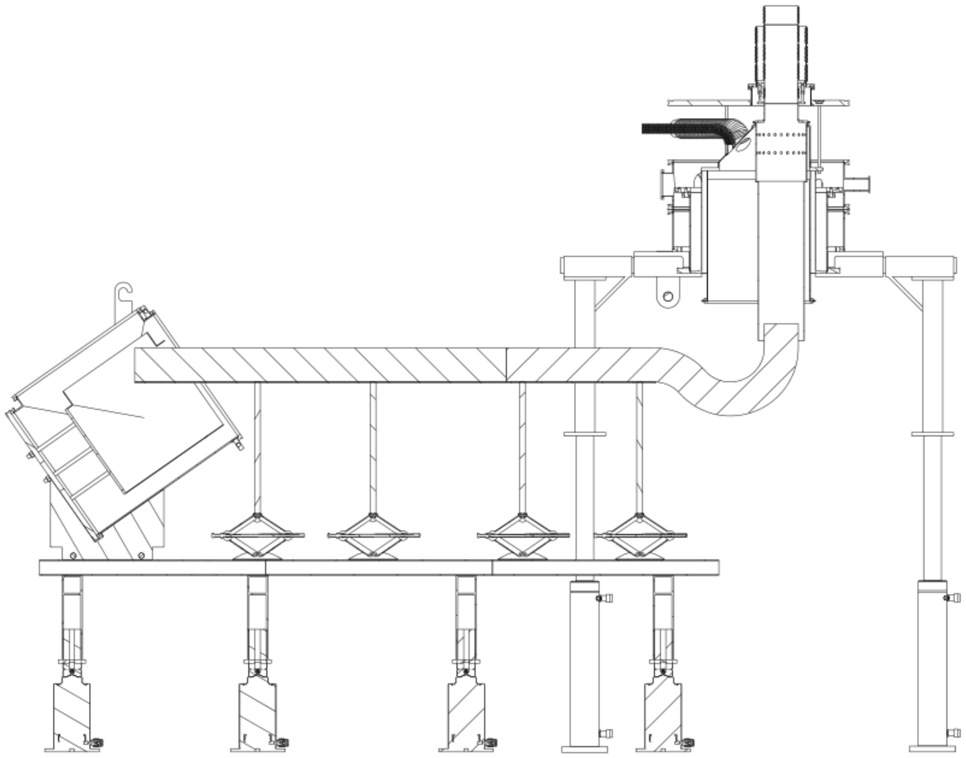
Step 1: iso view



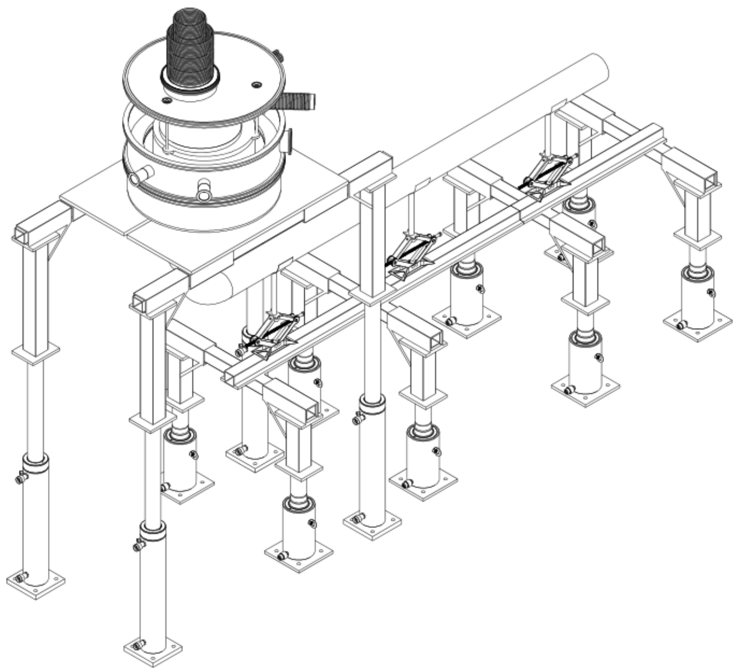
Step 2: Bending of the LTS bus-bar to horizontal position and adding an addition bend

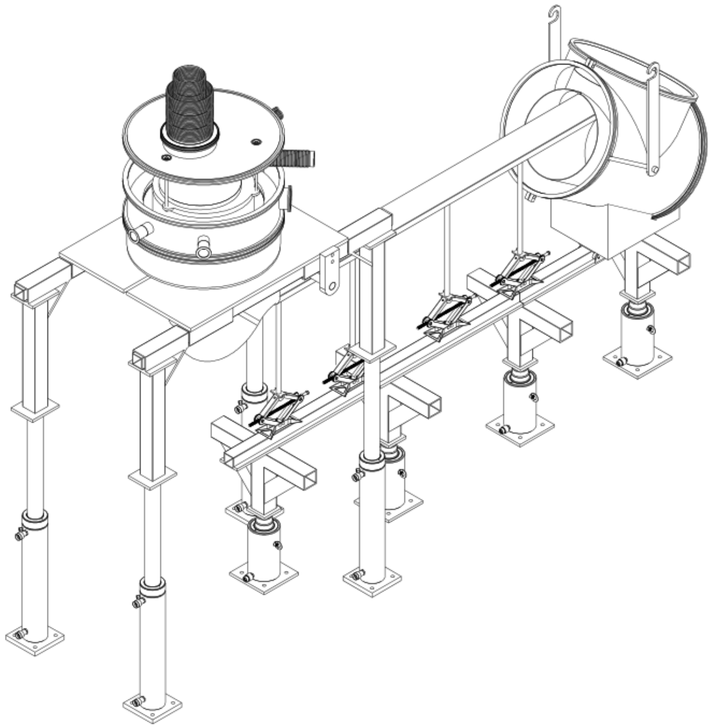
1. Set up an horizontal frame to support the horizontal bus-bar as it is bent to horizontal in the open space underneath the upper module of the vertical DFX
2. Adding the addition bend and raise the bus-bar according
3. The operation will be carried out by trained CERN technicians/engineers
4. Using the horizontal supporting frame to set up the runner for installing the lower vertical module





3d view of Step 2





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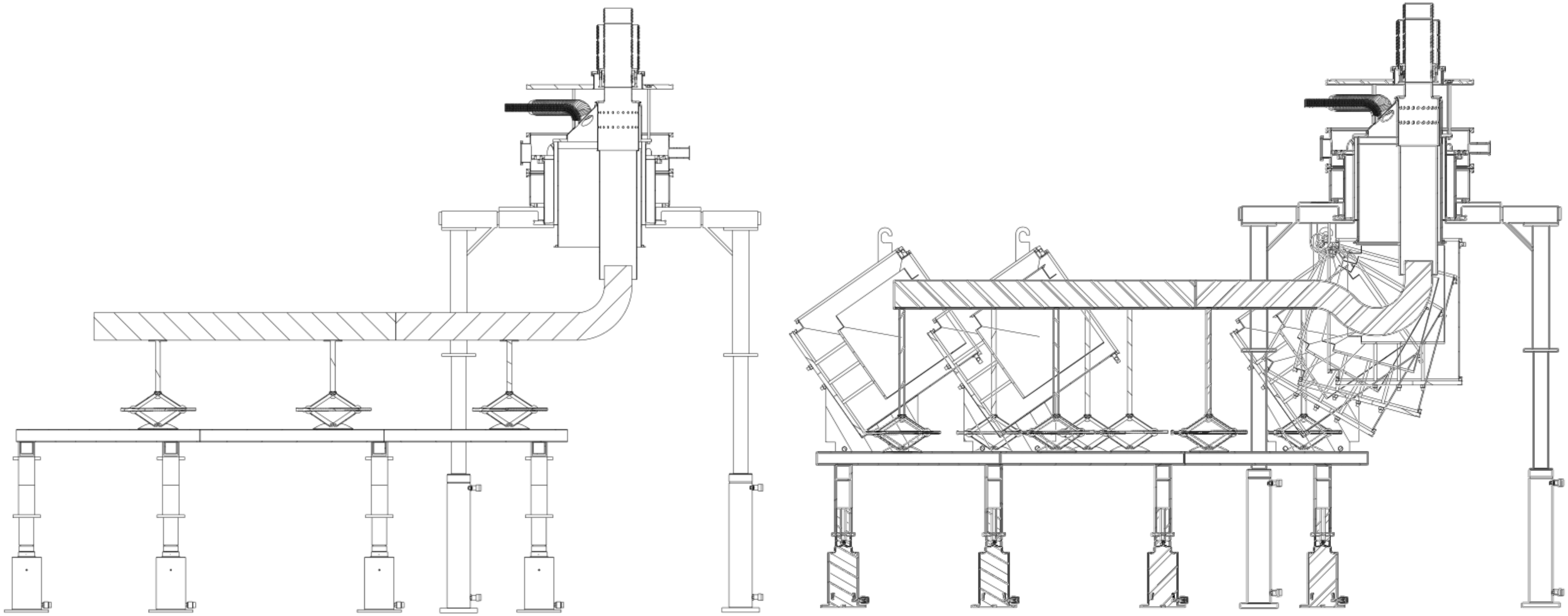
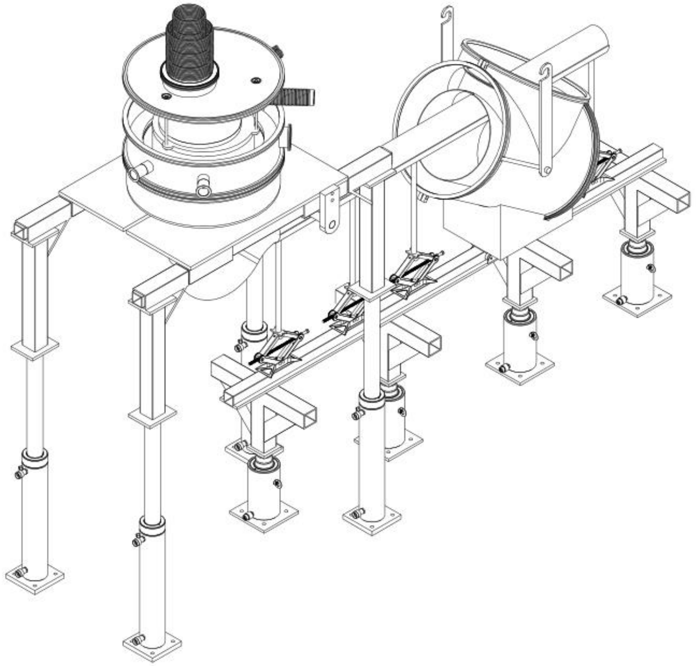
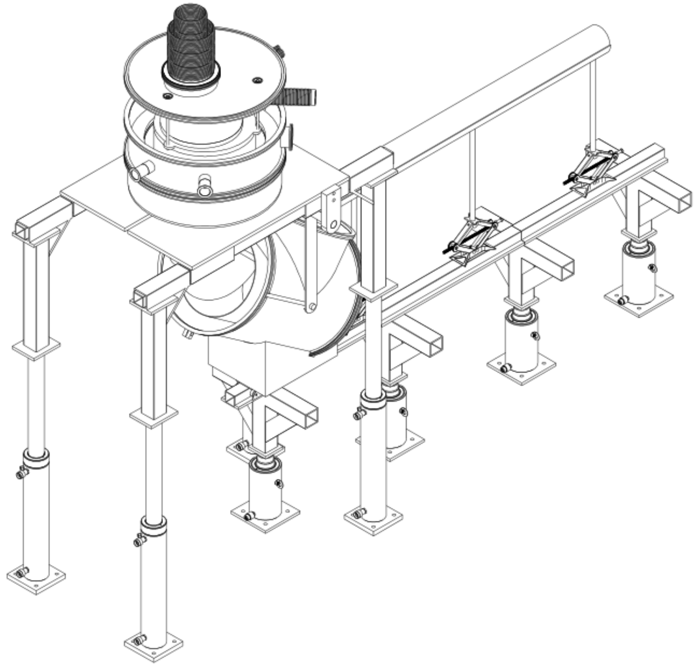
Step 3: Installation of the lower vertical module

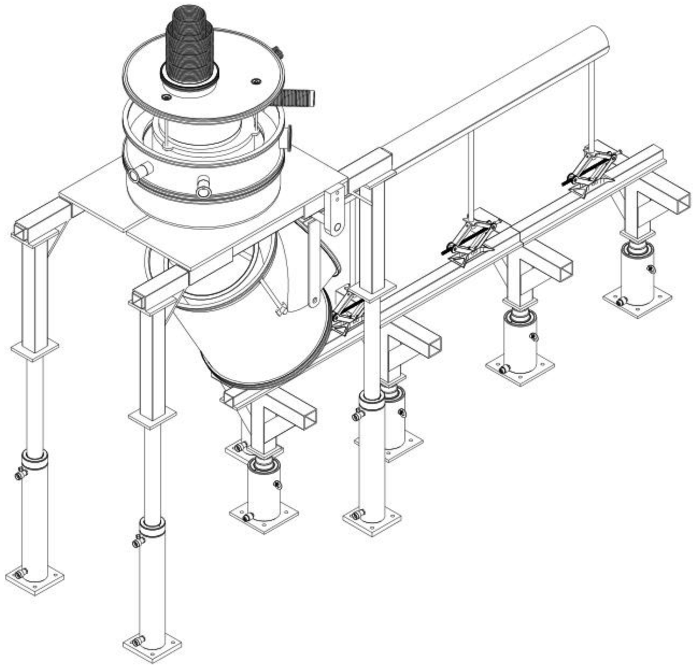
1. The lower module for the double-bend LTS bus-bar must have the inner captive inside the outer for installation
2. The combined modules travel along the horizontal rail and pass through with the shuffling of the support for the LTS bus-bar. A cradle us used to secure the combined modules at a desired angle
3. The combined modules is hooked up to a pivot point on the vertical support frame and swung into the vertical position

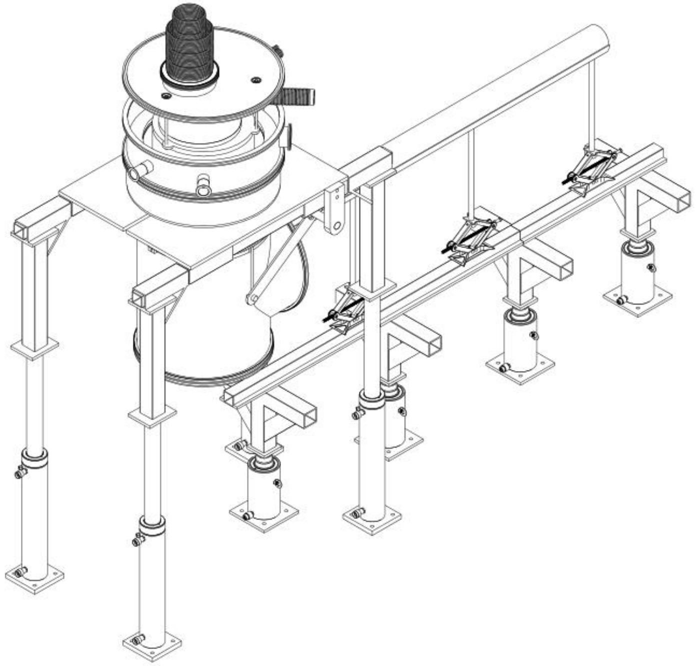


3d view of Step 3



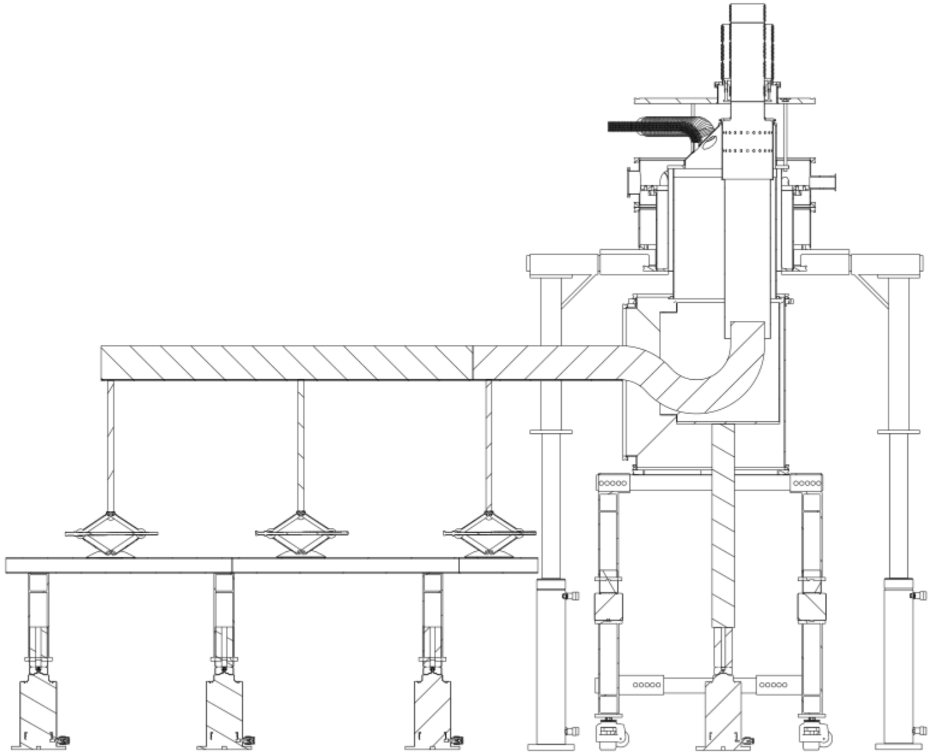


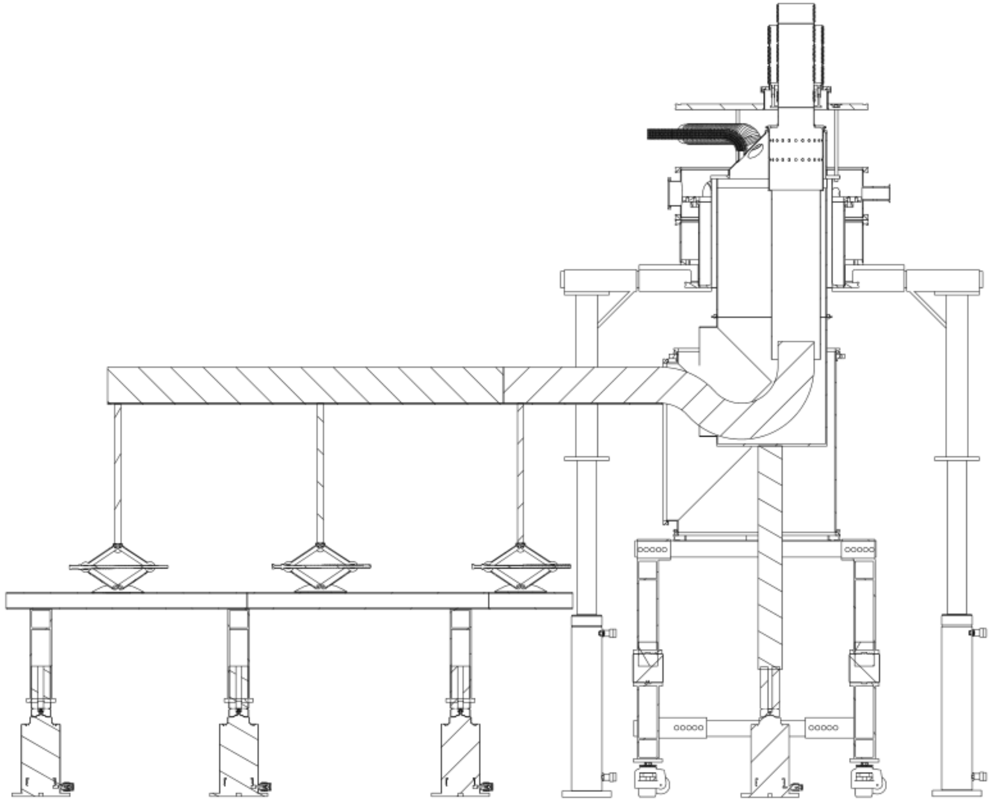




Step 4: Welding of the vertical DFX

1. The combined modules are separated by a vertical post taking up the weight of the inner vessel while a trolley takes up the weight of the outer
2. **Lower** the outer to allow the inner upper and lower vessels to be welded together
3. The inner of SC-Link cryostat is also welded to the inner of the upper DFX

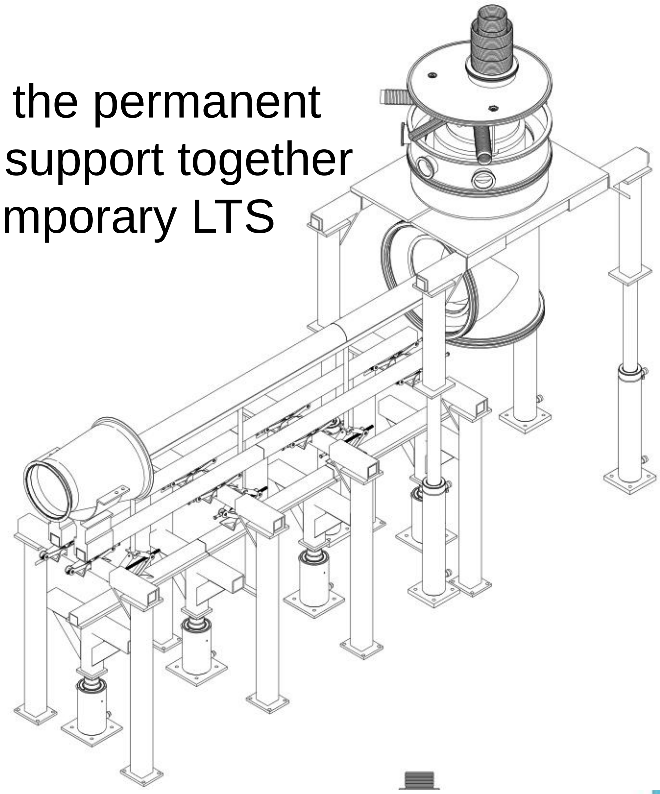


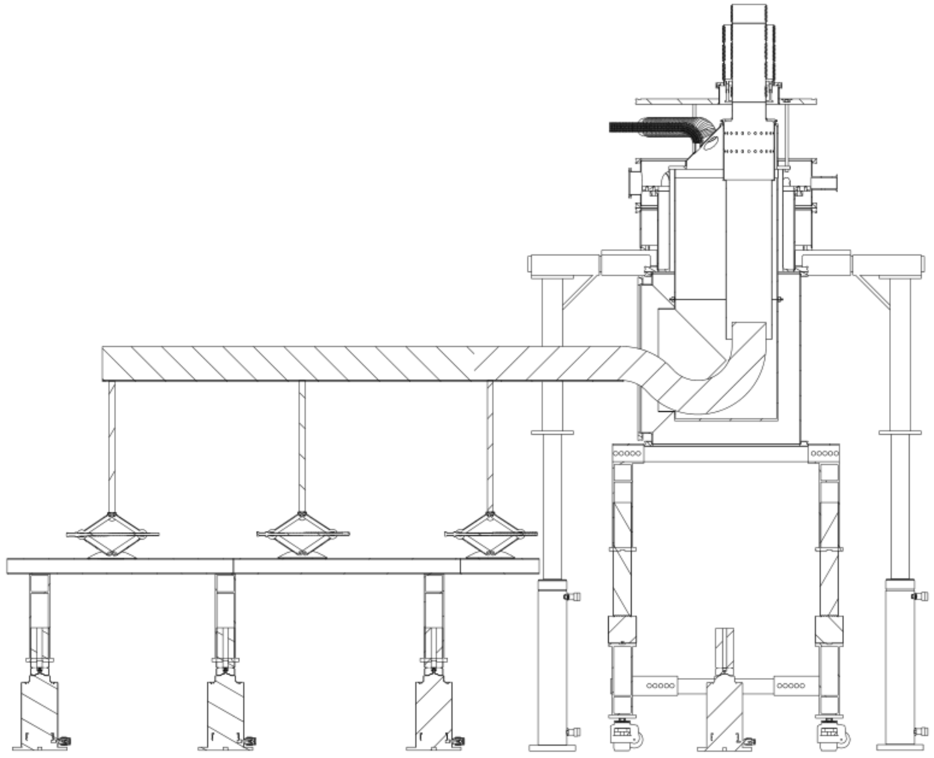


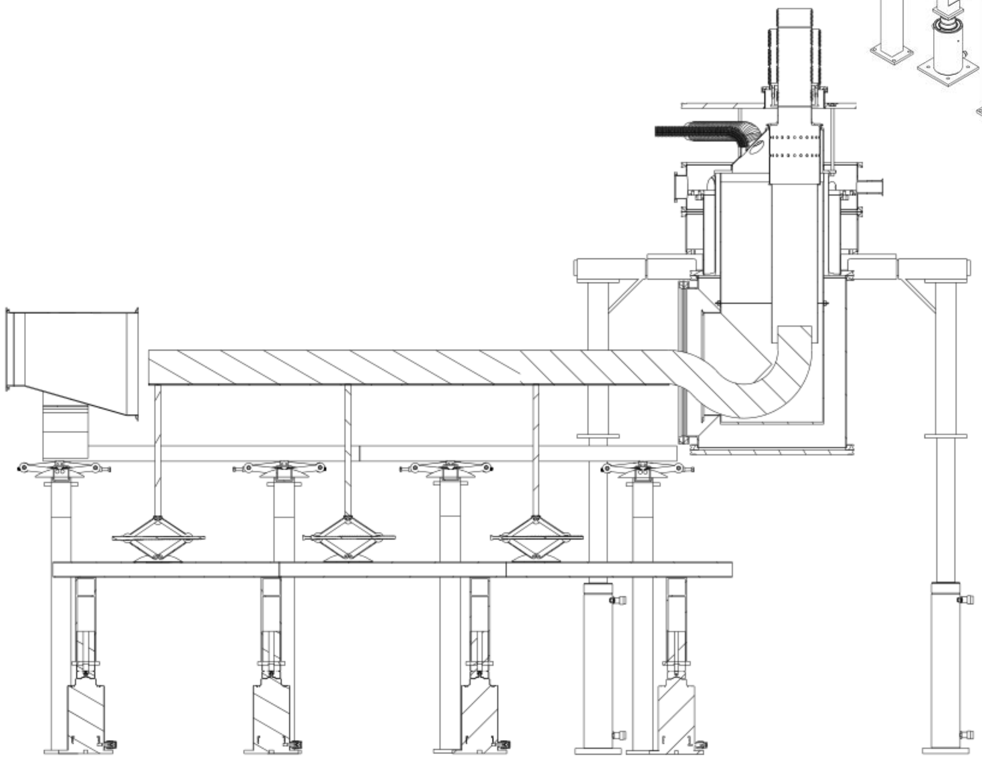
Step 5: Ready for installation of the horizontal modules

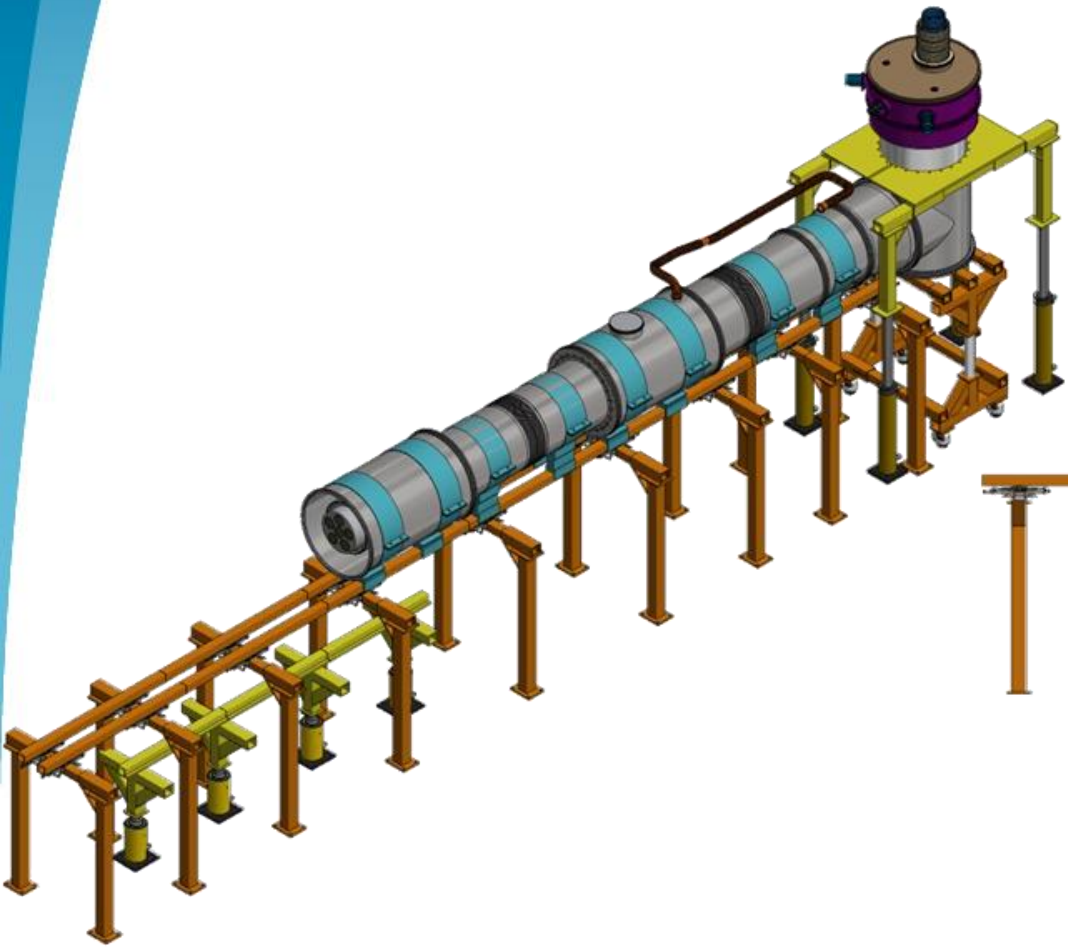
1. The vertical inner vessel is fully assembled
2. Lift the lower outer to be assembled with upper outer
3. The permanent horizontal support is put in place
4. The LTS support frame remain in place to assist the installation
5. The vertical support frame can be removed by transferring the vertical DFX support to the bottom in order to make room for welding the inner vertical to horizontal (not shown, to be updated)

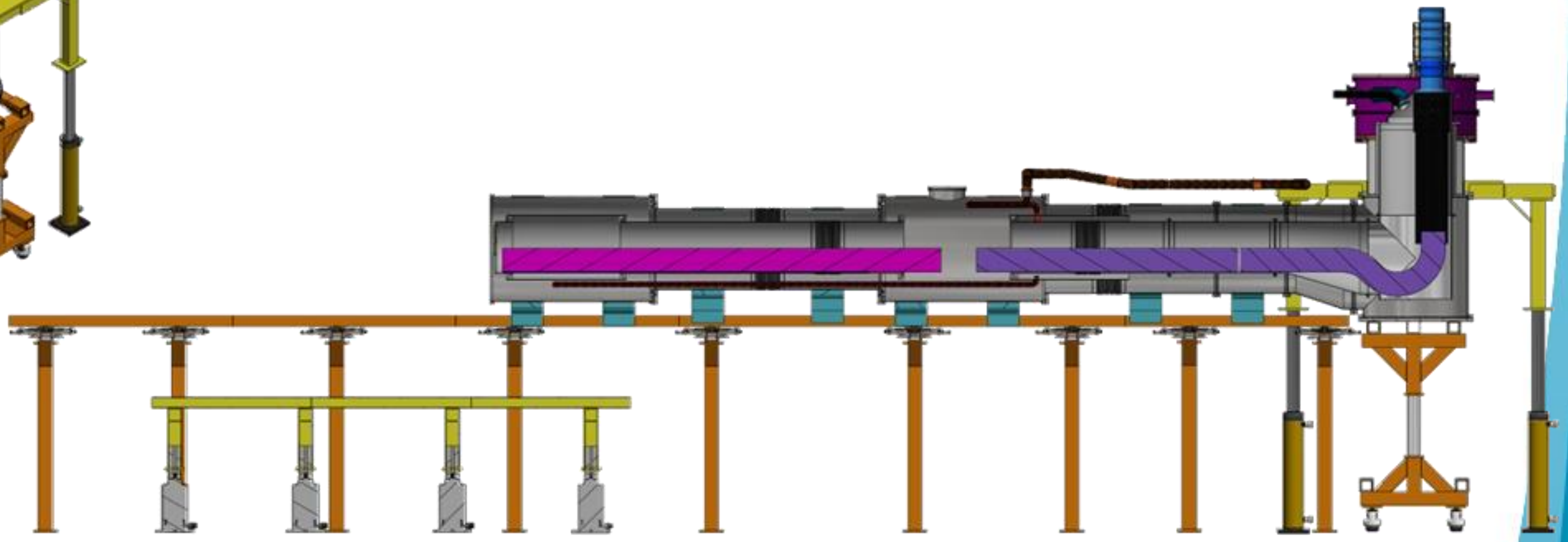
3d view of the permanent horizontal support together with the temporary LTS support











Mechanical design for interfaces and functions (7)

Intervention of the splices

- NbTi-NbTi can be repaired in situ by sliding open the outer and inner of the splice section
- (Still being iterated) Repair of the MgB_2-NbTi splices is possible but a major intervention consisting of
  - Removing a section of the beam line up to 3m long
  - De-solder the NbTi-NbTi splices
  - Remove horizontal DFX sections (splice and connection to vertical DFX)
  - Remove DFX lower vessels to expose fully the NbTi bus-bar
  - Cut the cryo-lines in the extended hoses outside the vertical DFX
  - De-solder the instrumentation wires from the warm feedthroughs
  - Lower the vertical DFX upper vessels while tread back the flexible hoses attached to the vertical DFX inner vessel
  - Lower the SC-Link together with the vertical DFX inner vessel (as shown)
  - Cut the “hat” off the vertical DFX inner at a specially integrated feature to remove the DFX inner. The cut is either below the hat or at the top (desired)
  - Lower the SC-Link with the outer and inner cryostat so that the rigid MgB_2-NbTi splice section is exposed fully and the SC-Link can be bend to horizontal if necessary