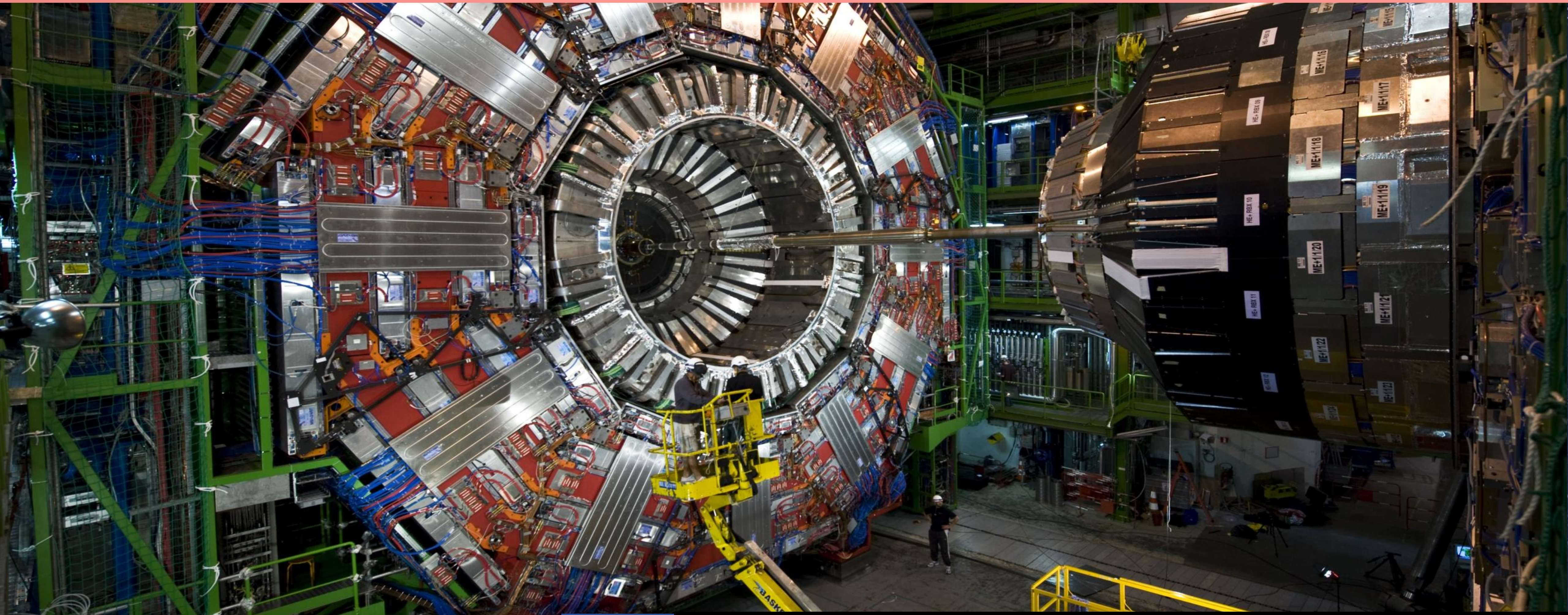
NOVEL MATERIALS AND PROCESSES TOWARDS A FULL CARBON COMPOSITE CRYOSTAT



María Soledad Molina González

10th April 2024

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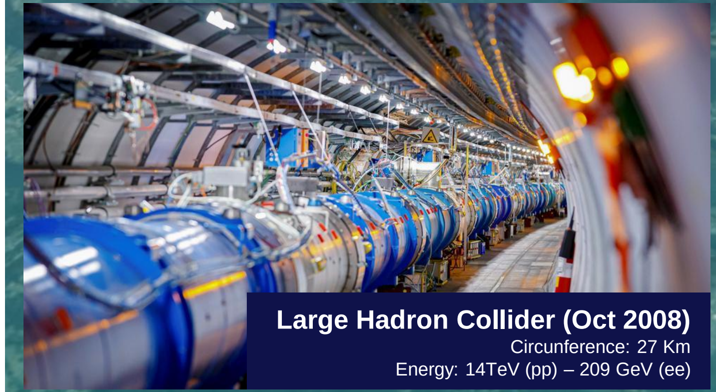
Novel Carbon Composite Cryostats for Future Experiments at CERN

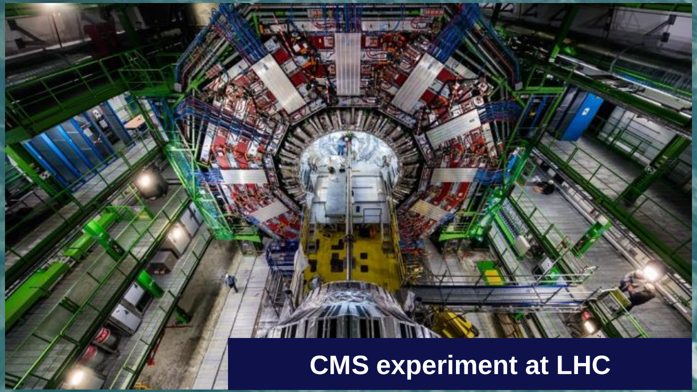
- State of the Art
- Hypothesis and Objectives
- Key Technologies Identified
- Finite Element Analysis (FEA)
- Profits of Carbon Composite
- Preliminary Design: CAD Model
- Assembly Sequence
- Conclusions and Benefits for Aerospace

https://ep-rnd.web.cern.ch

Future Circular Collider (2048)
Circumference: 90 – 100Km
Energy: 100 TeV (pp) – 350 GeV (ee)



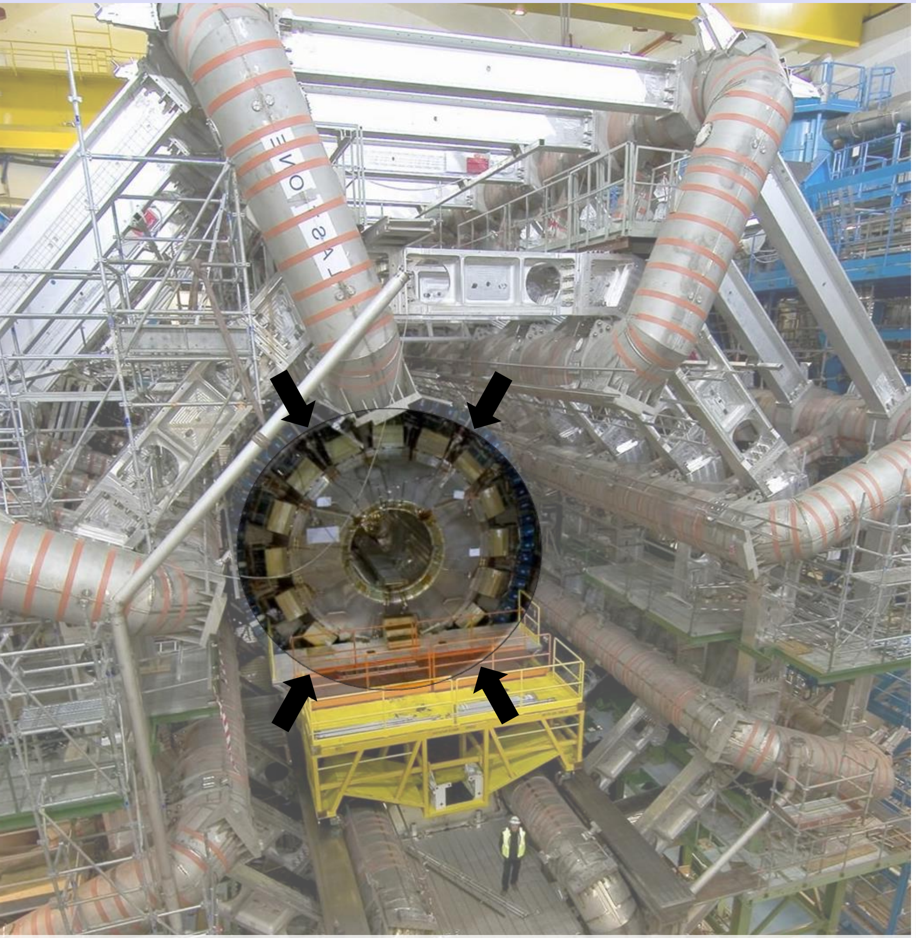
Large Hadron Collider (Oct 2008)
Circumference: 27 Km
Energy: 14TeV (pp) – 209 GeV (ee)



CMS experiment at LHC

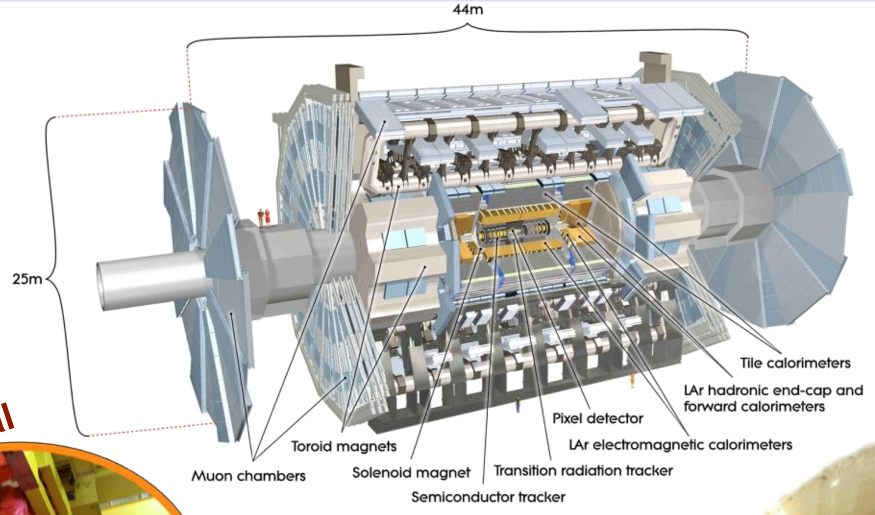
State of the art

✓ Superconductor magnets bends particles after collision in the accelerator and liquid argon calorimeter works as an energy detector to identify particles



Cryostats in HEP are still the purview of metals.

New design aims to ultralight cryostats for both magnets and calorimeters.



ATLAS Barrel Cryostat

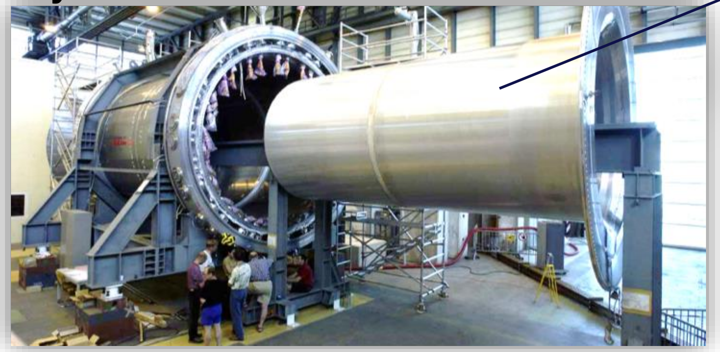
for the SC magnet and LArCal:

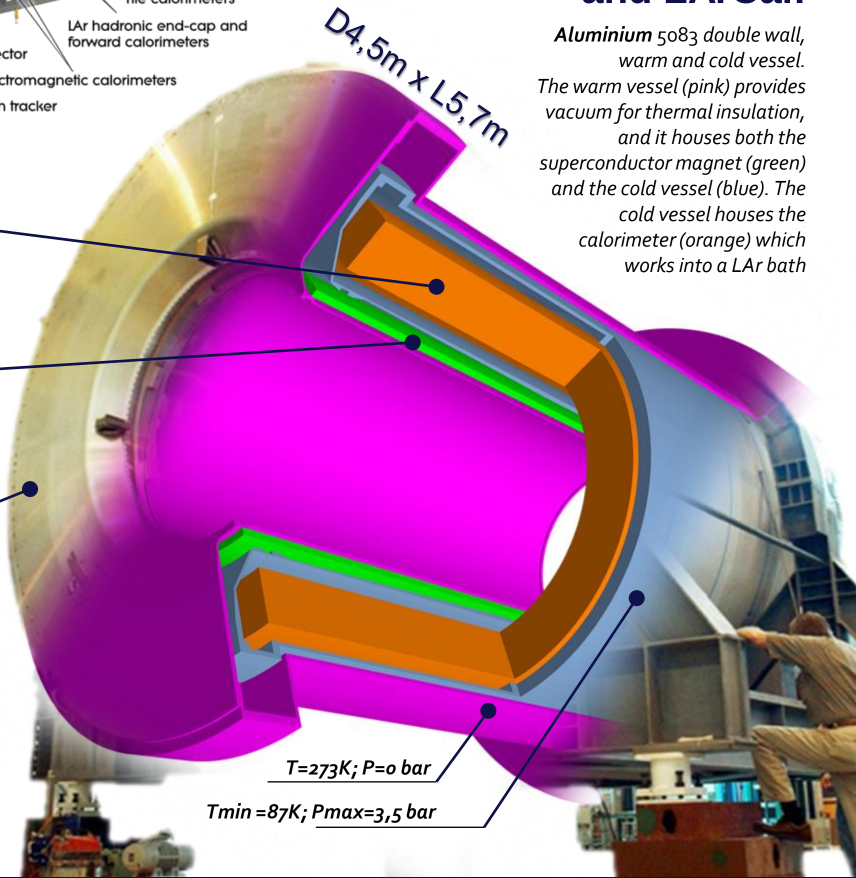
***Aluminium** 5083 double wall, warm and cold vessel. The warm vessel (pink) provides vacuum for thermal insulation, and it houses both the superconductor magnet (green) and the cold vessel (blue). The cold vessel houses the calorimeter (orange) which works into a LAr bath*

LAr Cal

SC magnet

Cryostat





Hypothesis and Objectives

✓ **Future experiments, FCC-ee (2048) and FCC-hh (2070), will require cryostats with a similar design but lower material budget compared to the state of the art**

CRYOSTAT DESIGN REQUIREMENTS

1) He leak tightness for validation
He leak rate: 10^{-9} mbar.l / s (UHV)
Ultra High Vacuum design

2) Operating conditions
Cold vessel: T= 87 K; $P_{int,\ max}$ = 2.8 bar x 1.25 (SF)
Warm vessel: T_{room} ; P_{int} =10^{-5} mbar

3) Radiation Resistance
Total lifetime dose ~ 0.1 MGy

4) Minimize material budget
Liner-less full carbon composite walls

5) Large Scale manufacturing
Automated Fiber Placement, OoA curing

Main Scope of the R&D :

Decrease thickness and material budget of the next generation cryostats **using Carbon Fibre Reinforced Plastic** instead of metals

Definition: The material budget is the relation between the thickness of material that particles see when going through and the the length of that material (in cm) to reduce the energy of an electron by the factor 1/e

FCC-ee ALLEGRO Baseline

✓ **One cryostat to service both the SC magnet and the LArCal**

✓ ***More transparent* to particles, to improve the performance of the detectors (low material budget)**

✓ ***Thin walls for more compact design***

R&D to adapt aerospace technology to low material budget cryostats

EP R&D

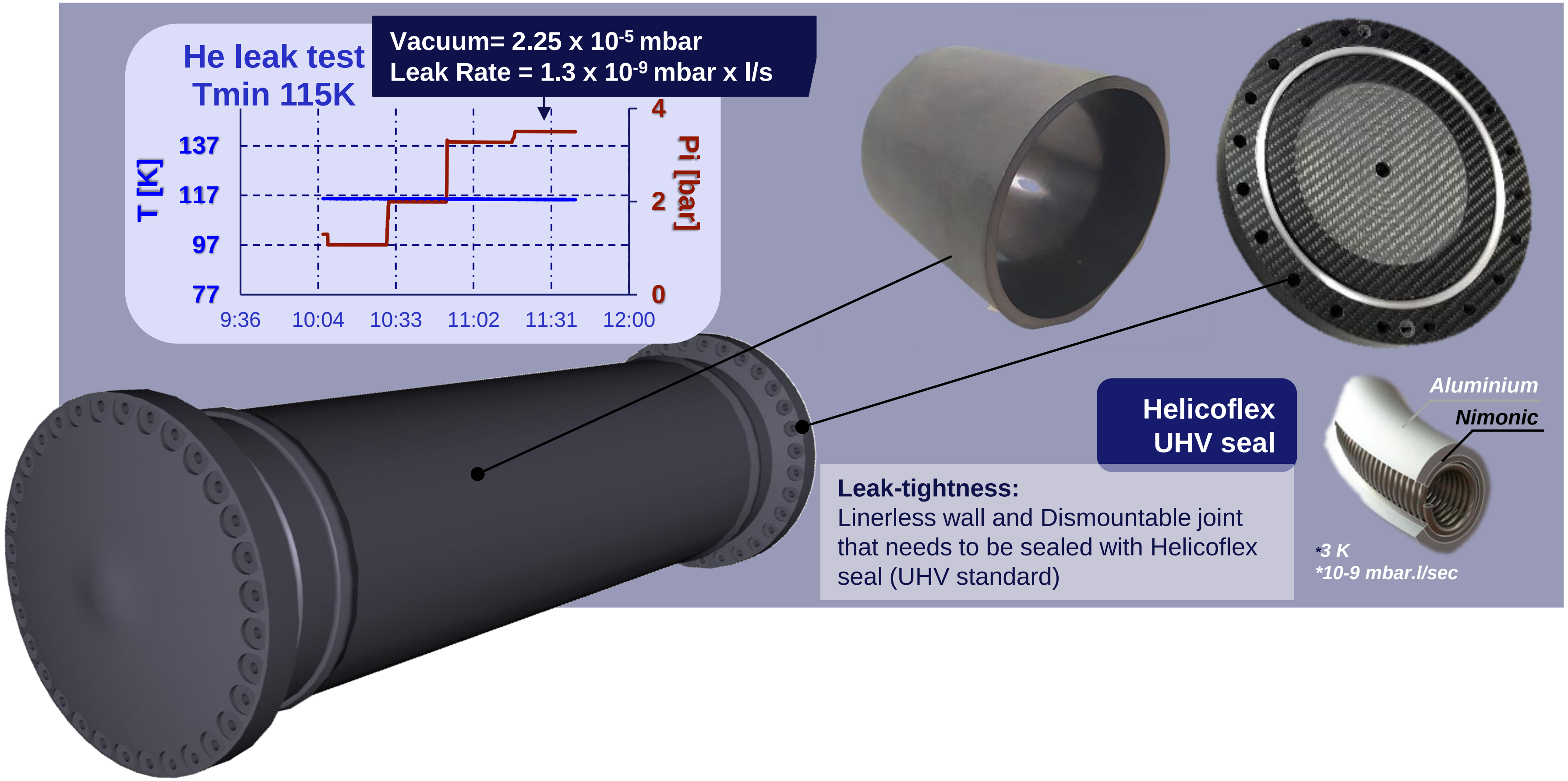
Geometry	Material and Processes

ATLAS cryostat
toroidal Al 5083
double wall
D4,5m, L5.7m

NASA's LH2 cryotank
Linerless carbon composite
thin wall
D5.5m, L5.8

Key Technologies Identified

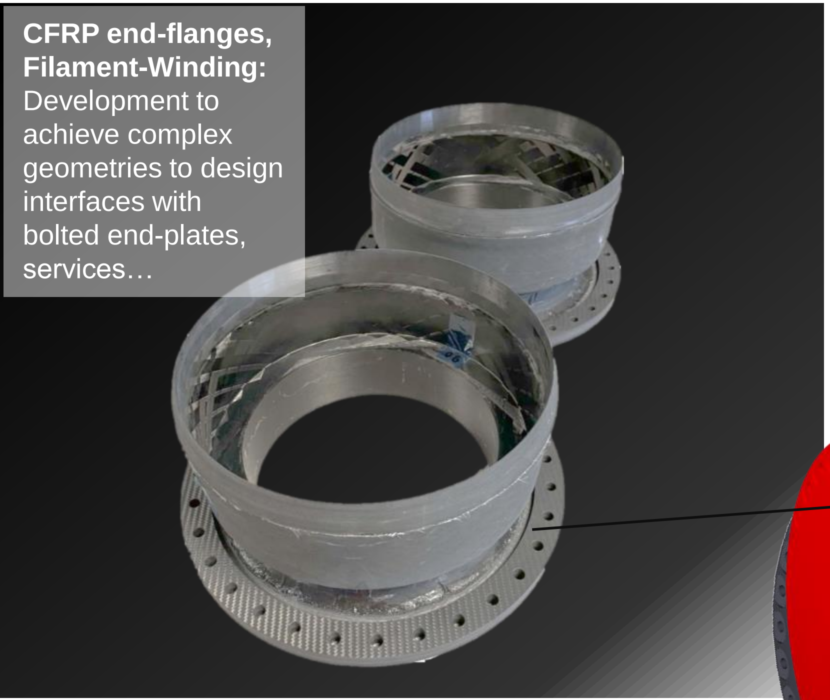
✓ **Linerless tank manufactured with wet filament winding (L=1m, D=0,30m) as result of process development for CERN specification.**

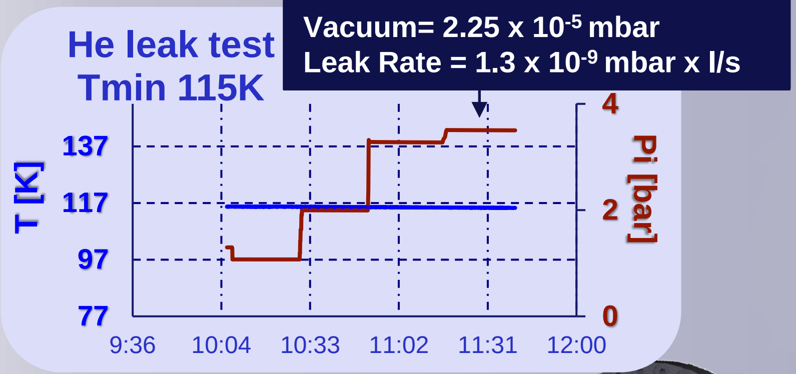


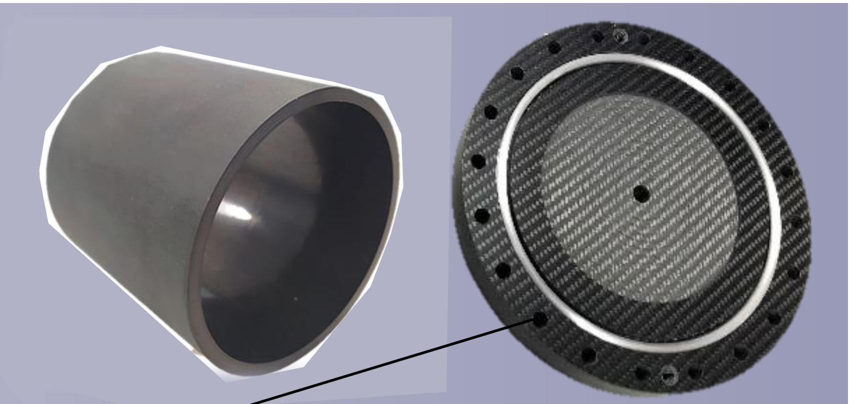
Key Technologies Identified

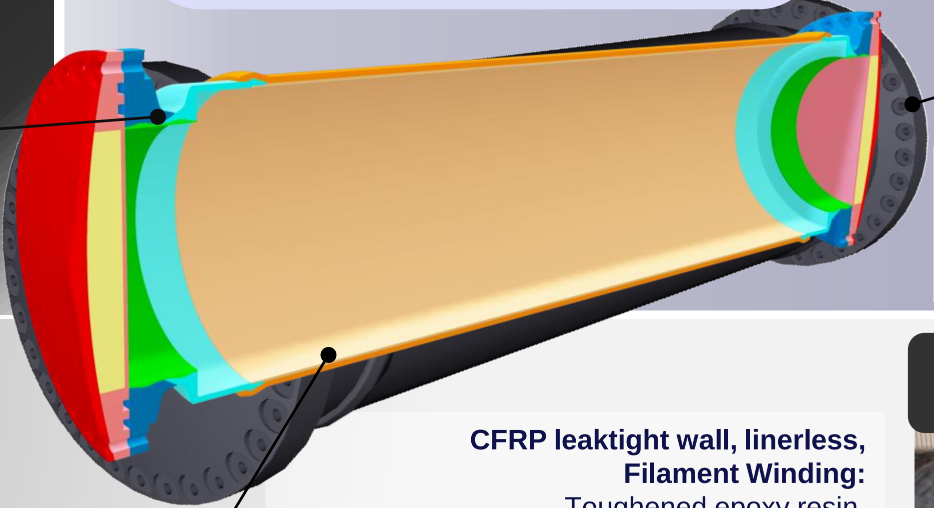
✓ Linerless tank manufactured with wet filament winding (L=1m, D=0,30m) as result of process development for CERN specification.

CFRP end-flanges, Filament-Winding:
Development to achieve complex geometries to design interfaces with bolted end-plates, services…



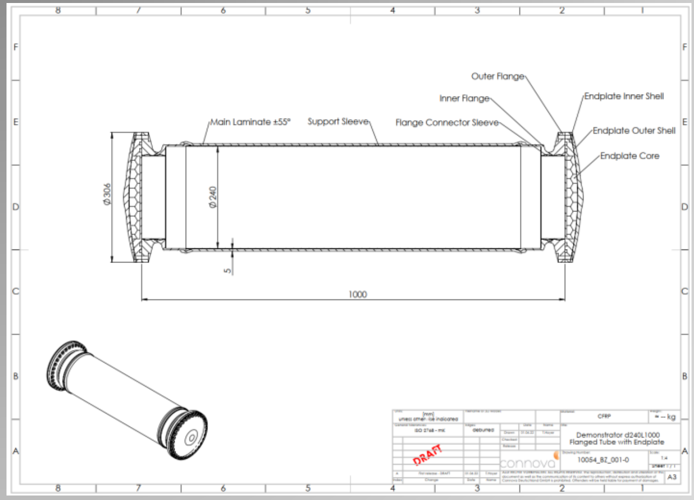




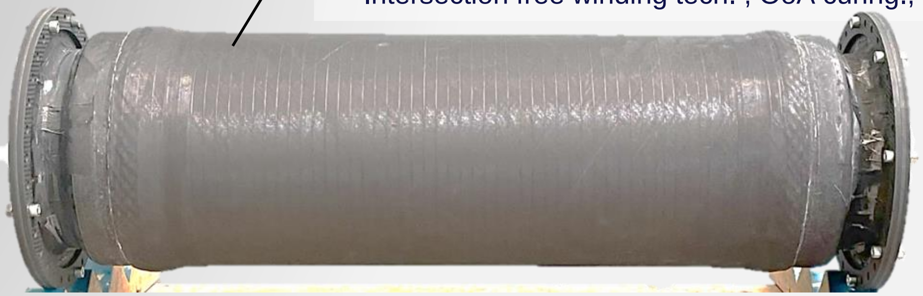


Helicoflex UHV seal

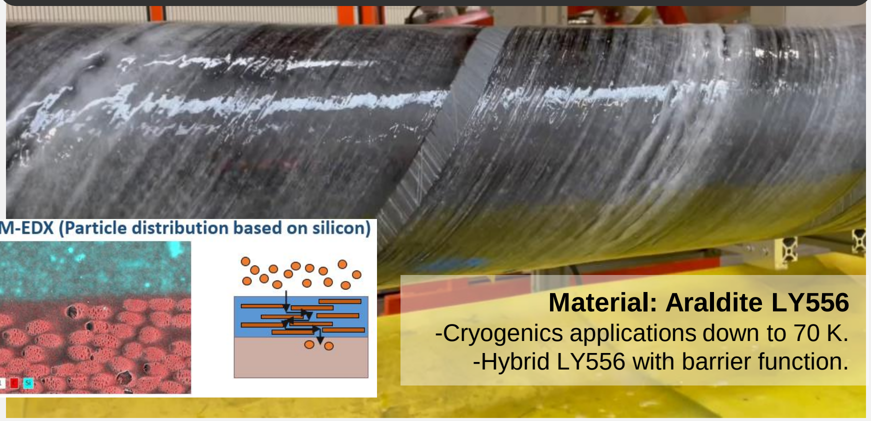
Leak-tightness:
Linerless wall and Dismountable joint that needs to be sealed with Helicoflex seal (UHV standard)



CFRP leaktight wall, linerless, Filament Winding:
Toughened epoxy resin,
Intersection free winding tech. , OoA curing.,



Wet Filament Winding to address Large Scale Manufacturing Tech.



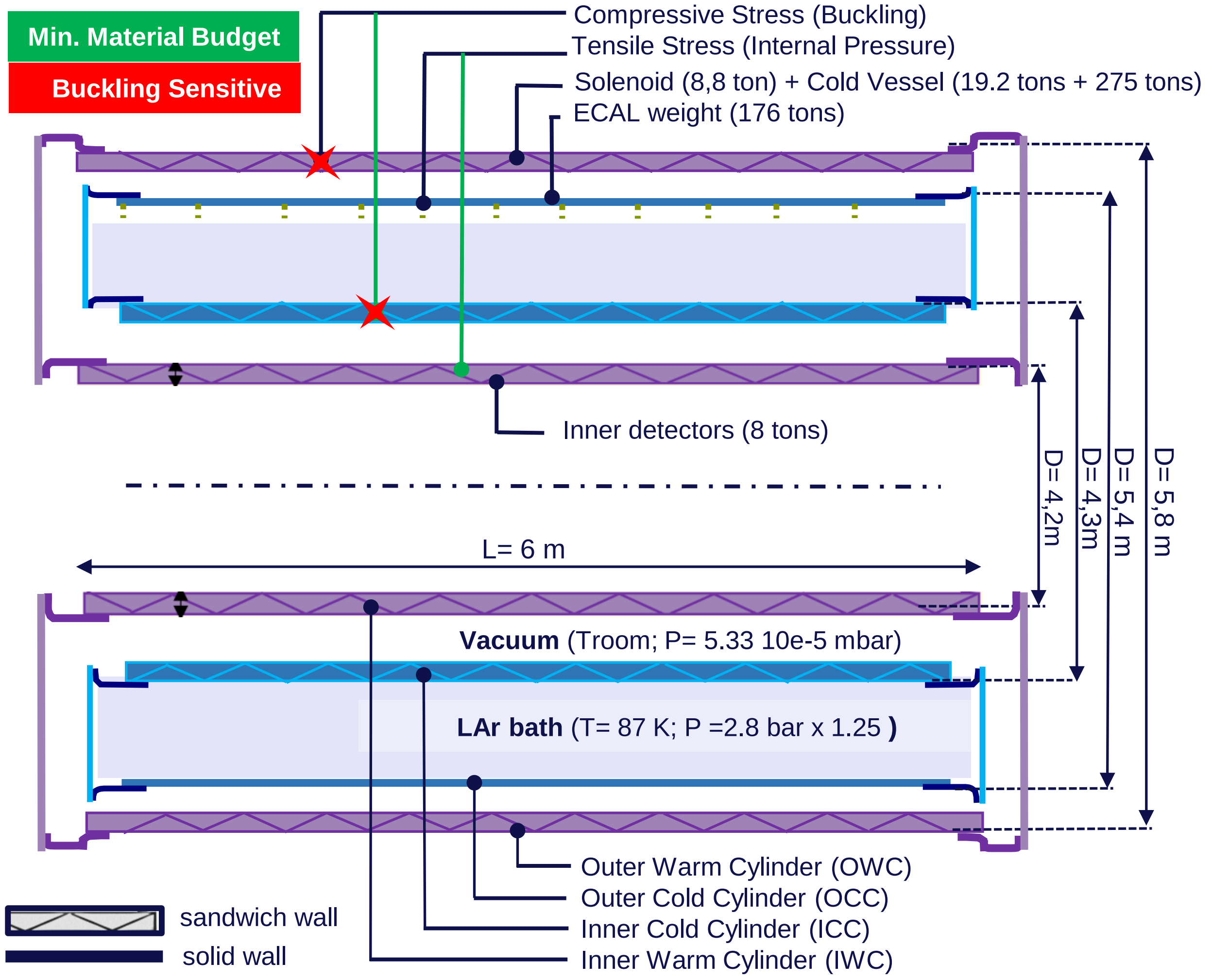
Material: Araldite LY556
-Cryogenics applications down to 70 K.
-Hybrid LY556 with barrier function.

FEA: Requirements

Schematic view of

Future ALLEGRO cryostat cross section

Material: Carbon Composite



Finite Element Analysis

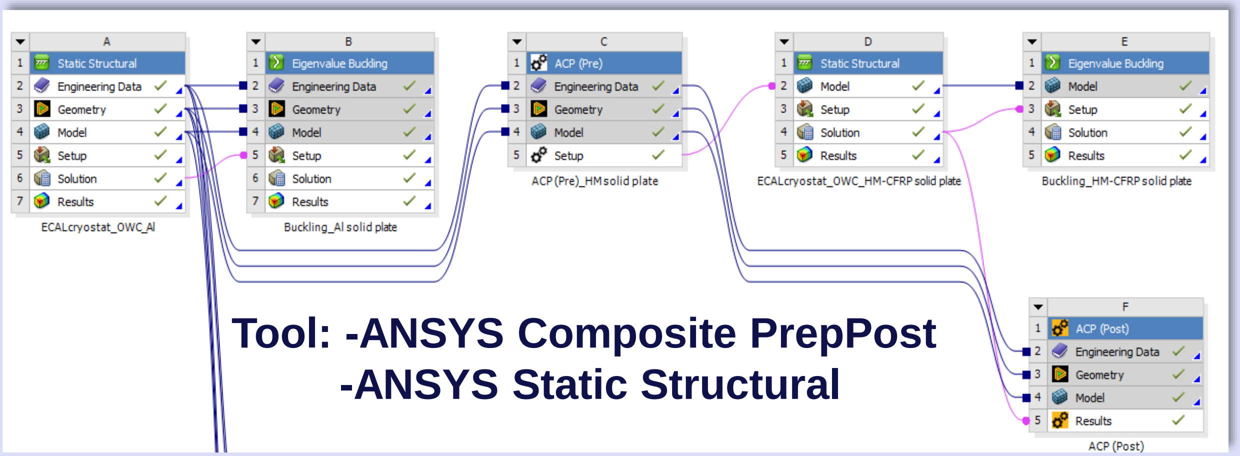
Minimum wall thickness and Material Budget to guarantee:

1) **Composite Failure Safety Factor > 2**

2) **Buckling Safety Factor > 2**

3) **Interlaminar Shear Stress < 4,8 MPa**
(glue shear strength*)

4) **Vertical Displacement < 2 mm**
(positioning tolerance of sensors in detectors)



Tool: -ANSYS Composite PrepPost
-ANSYS Static Structural

Profits of Carbon Composite compared to metal

✓ Full carbon composite design offers: 64% savings in Mat Budget, 30% savings in Optimal Thickness, and one order of magnitude lower CTE.

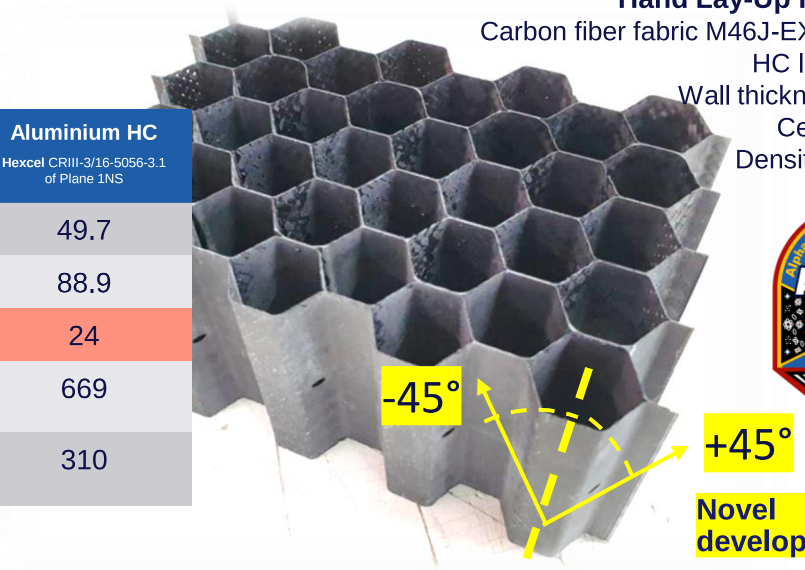
Full carbon honeycomb for walls with structural, mass and thermal constraints:

*Tested by CERN-MME-MM

Results:

-293 K-	Carbon HC (Preliminary)	Aluminium HC Hexcel CRIII-3/16-5056-3.1 of Plane 1NS
Density [Kg/m3]	**36**	49.7
X_0[mm]	**6000**	88.9
CTE [µm/m∗K]	**2.5** !!!!	24
E_z [MPa] Compression Modulus	**890**	669
E_{xy} [MPa] Shear Modulus	**380**	310

Hand Lay-Up Honeycomb
Carbon fiber fabric M46J-EX-1515 [±45°]
HC length 70 mm
Wall thickness 0.15 mm
Cell size 20mm
Density 36 Kg/m3



Novel Technology developed by CERN

Honeycomb (Core)	CFRP		Aluminium			
Skin:	CFRP		CFRP		Aluminium	
Wall	OWC	ICC	OWC	ICC	OWC	ICC
material budget X/X0	0.026	0.028	0.028	0.032	0.073	0.077
savings X/X0 [%]	-64%	-64%	-61%	-57%	REF	REF
Skin Th. [mm]	3.2	3.2	3.2	3.2	3	3
Core Th. [mm]	19.5	40	21.5	42	35	58
(Optimal)Total Th. [mm]	25.9	46.4	27.9	48.4	41	64
savings Th. [%]	-37%	-28%	-32%	-24%	REF	REF

Current Baseline: Material budget saving respect to traditional Solid Aluminum

R&D Baseline: full-carbon composite design for greater material budget savings

*CFRP: Carbon Fiber Reinforced Polymer
*CTE: Coefficient of Thermal Expansion

Results:

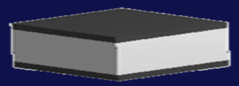
Buckling Sensitive *

Optimal Thickness calculated with FEA

	OWC	OCC	ICC	IWC
Wall Configuration	Sandwich	Solid	Sandwich	Sandwich
Skin Th. [mm]	3.2		3.2	1.6
Core Th. [mm]	19		40	30
(Optimal) Total Th. [mm]	25.4	27.2	46.4	33.2
Material Budget X/X0	0.026	0.105	0.028	0.015
Buckling Safety Factor	2.3	-	2.1	-
Min. Failure Safety Factor	2.7	5.1	2.38	4.7
SF Max Stress	7.47	6.64	2.6	7.3
SF Max Strain	15.9	6.59	5.5	5.4
SF Tsai-Wu	8.2	5.1	2.38	4.7
SF Core Failure	2.7	-	2.8	4.8
Max. total def. [mm]	1	4	2.6	1.7
Max. vertical def. [mm]	1	1.5	2	1.3
Equivalent Stress [Pa]	6.20E+07	7.33E+07	1.80E+08	9.60E+07
Shear YZ top skin [Pa]	4.39E+05	-	2.10E+03	6.80E+00
Shear XZ top skin [Pa]	4.39E+05	-	7.90E+05	2.20E+05
Shear YZ bottom skin [Pa]	4.39E+05	-	2.10E+03	5.00E+04
Shear XZ bottom skin [Pa]	4.39E+05	-	7.97E+05	2.50E+05

To calculate Material Budget

Radiation length X_0[mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al= 6000
Honeycomb CFRP = 12545



Sandwich Shell

Skin [0,45,-45,90]s
Core : Honeycomb
Skin [0,45,-45,90]s

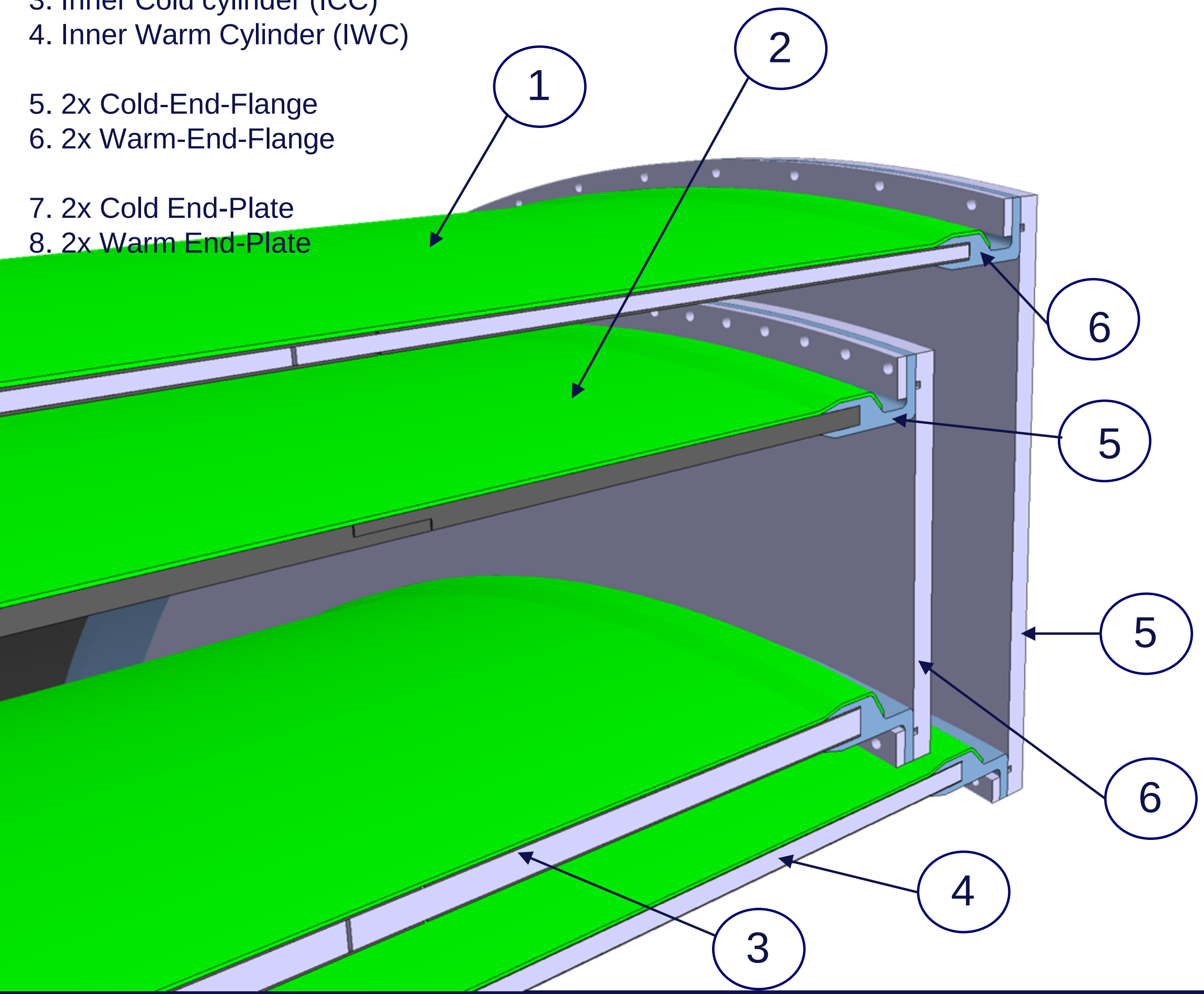
Preliminary Design: CAD Model

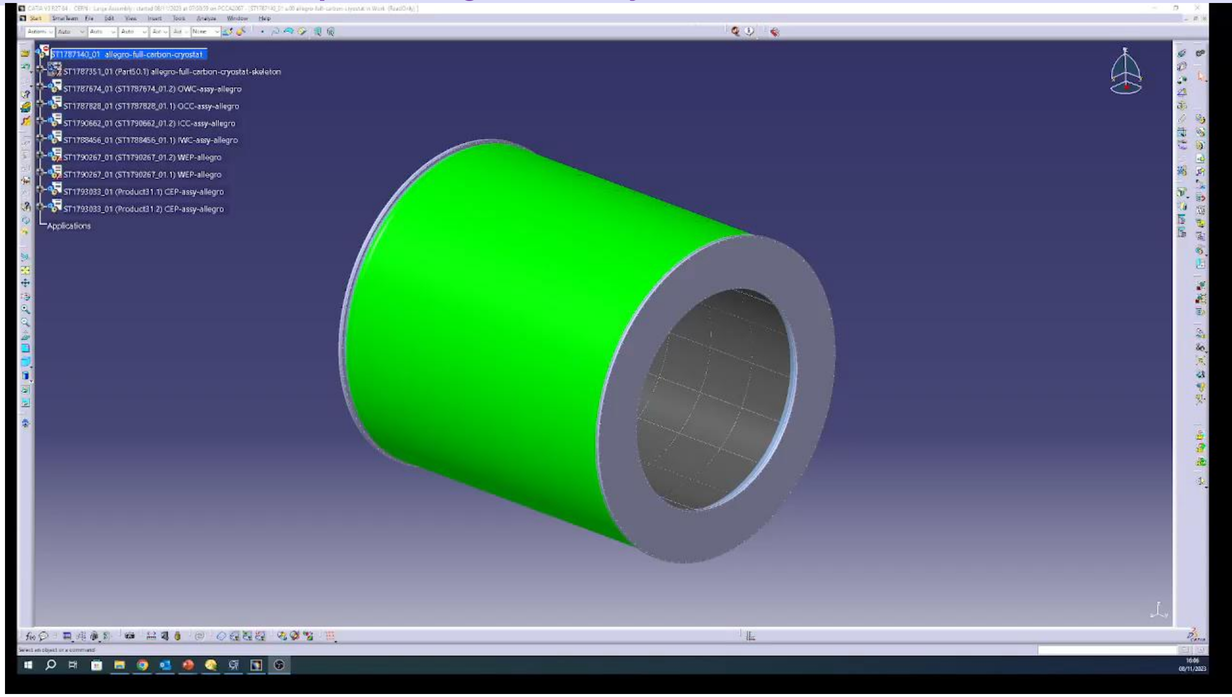
✓ The material and processes technology identified will be used to build a CAD model of a full carbon composite large-scale cryostat

Main Parts:
1. Outer Warm Cylinder (OWC)
2. Outer Cold Cylinder (OCC)
3. Inner Cold cylinder (ICC)
4. Inner Warm Cylinder (IWC)

5. 2x Cold-End-Flange
6. 2x Warm-End-Flange

7. 2x Cold End-Plate
8. 2x Warm End-Plate





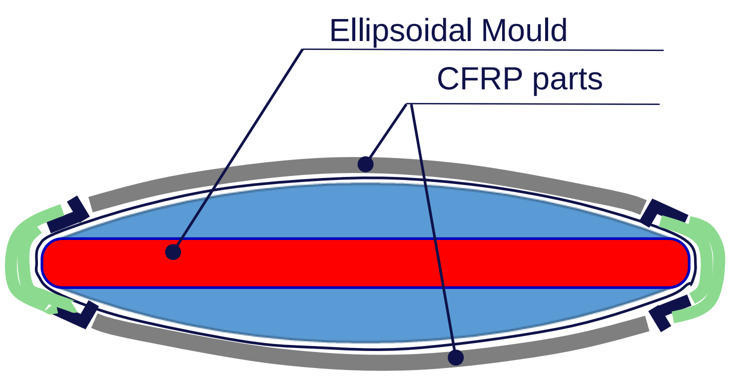
-All parts are designed to be manufacture using carbon composite (filament winding mainly, hand lay-up)

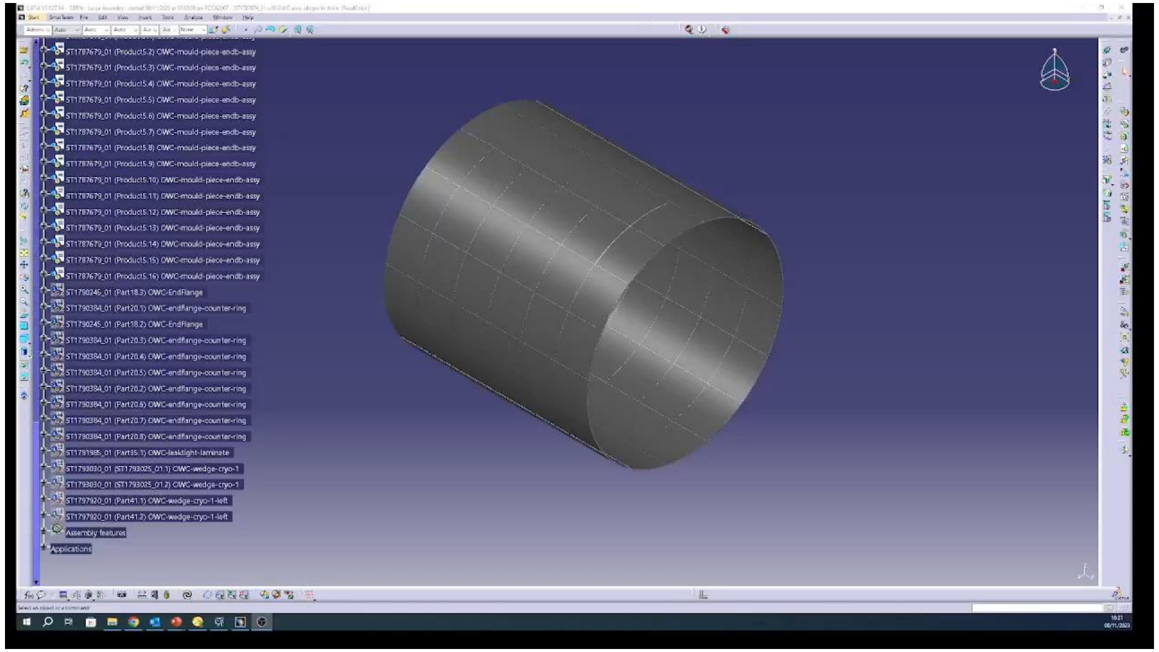
Each cylindrical wall is composed of:
- -Multipiece load-bearing mould *
- -Two end-flanges (2 in each side)
- -8 quarter counter-ring (4 in each end)
- -Continuous laminate on top to seal the joints by filament winding

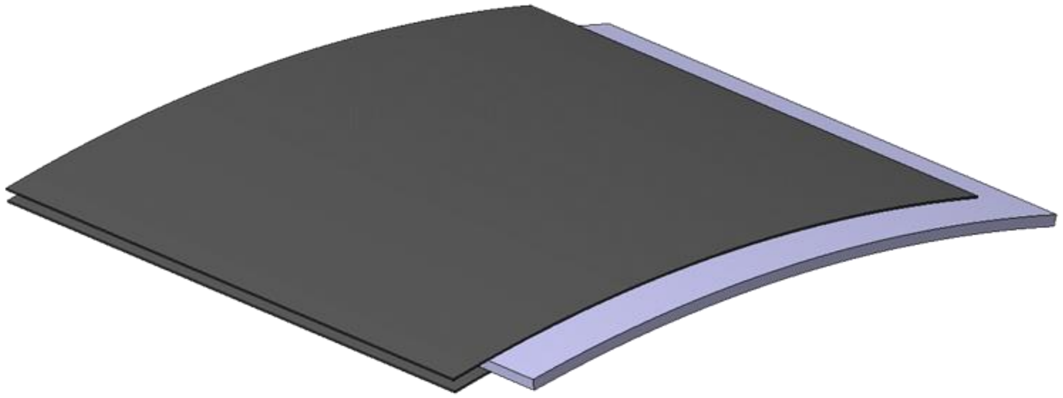
Preliminary Design: CAD Model

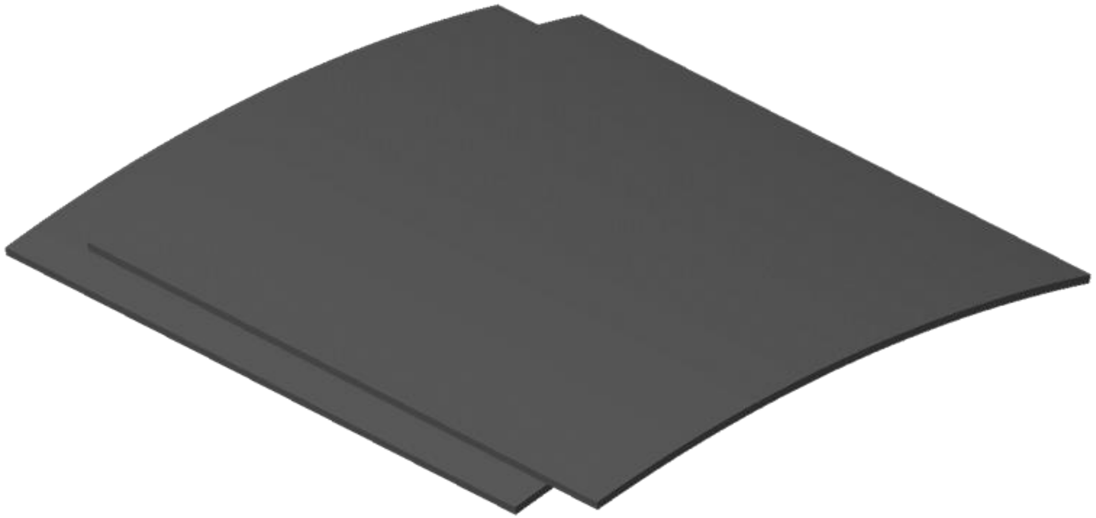
✓ **The multipiece mould has been engineered to deal with structural demands, while the final wound laminate on top guarantee leak-tightness.**

Mould pieces are designed to be manufacture by filament winding using an ellipsoidal metallic tool. This will simplify serial production







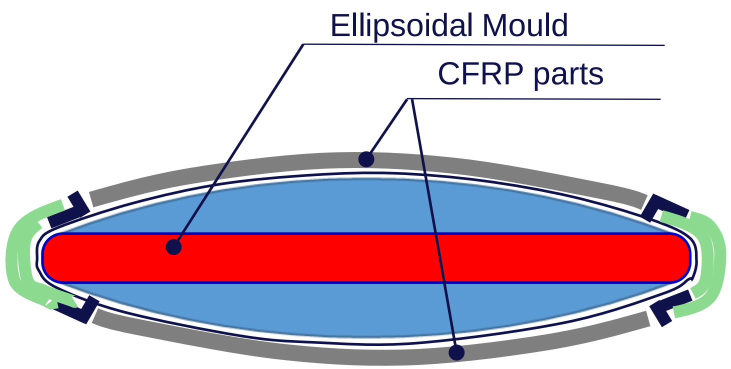


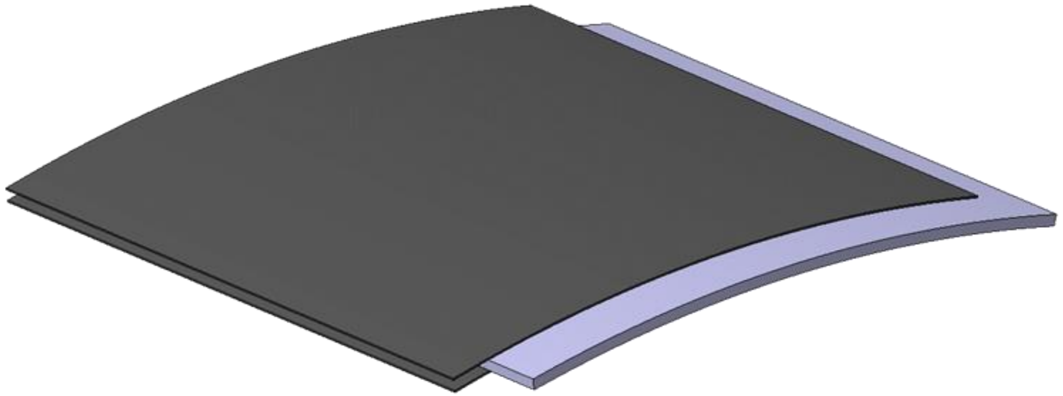
Bonded Joint: nominal thickness honeycomb to simplify production. This approach aligns with min material budget and continuity criteria-

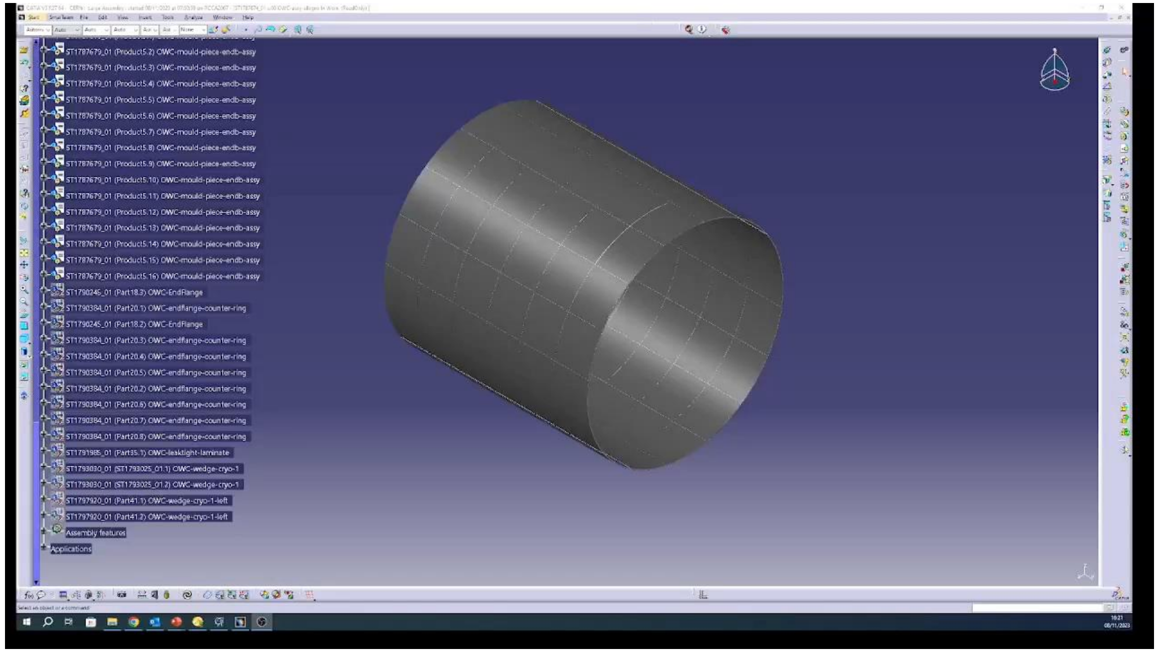
Preliminary Design: CAD Model

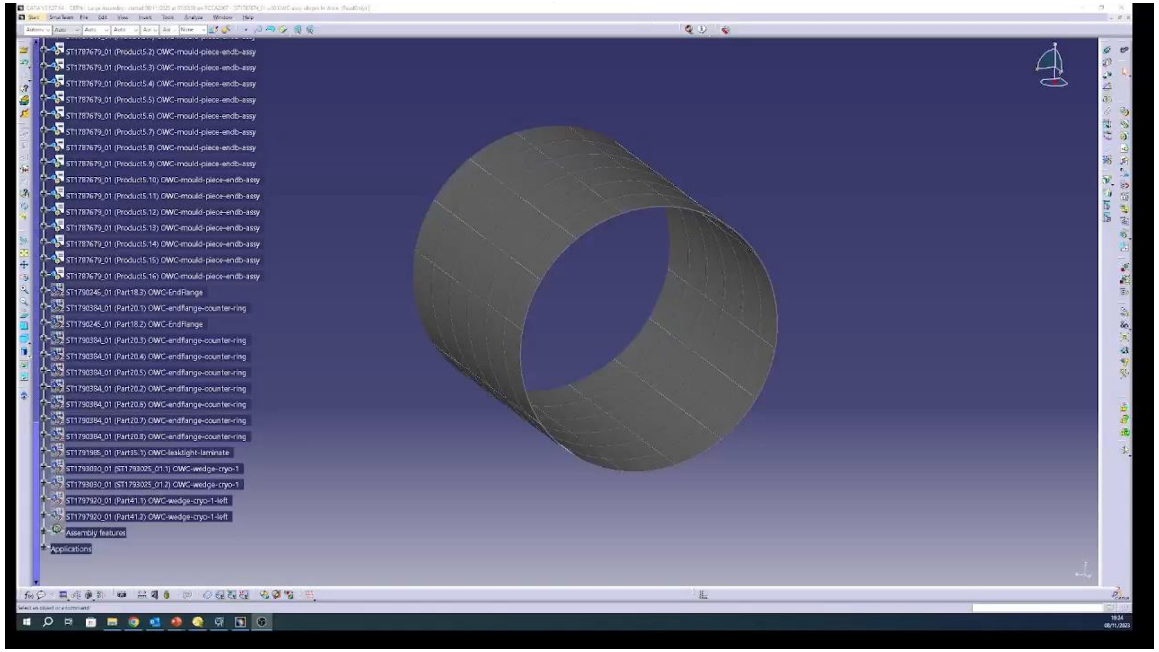
✓ **The material and processes technology identified will be used to build a CAD model of a full carbon composite large-scale cryostat**

Mould pieces are designed to be manufacture by filament winding using an ellipsoidal metallic tool. This will simplify serial production

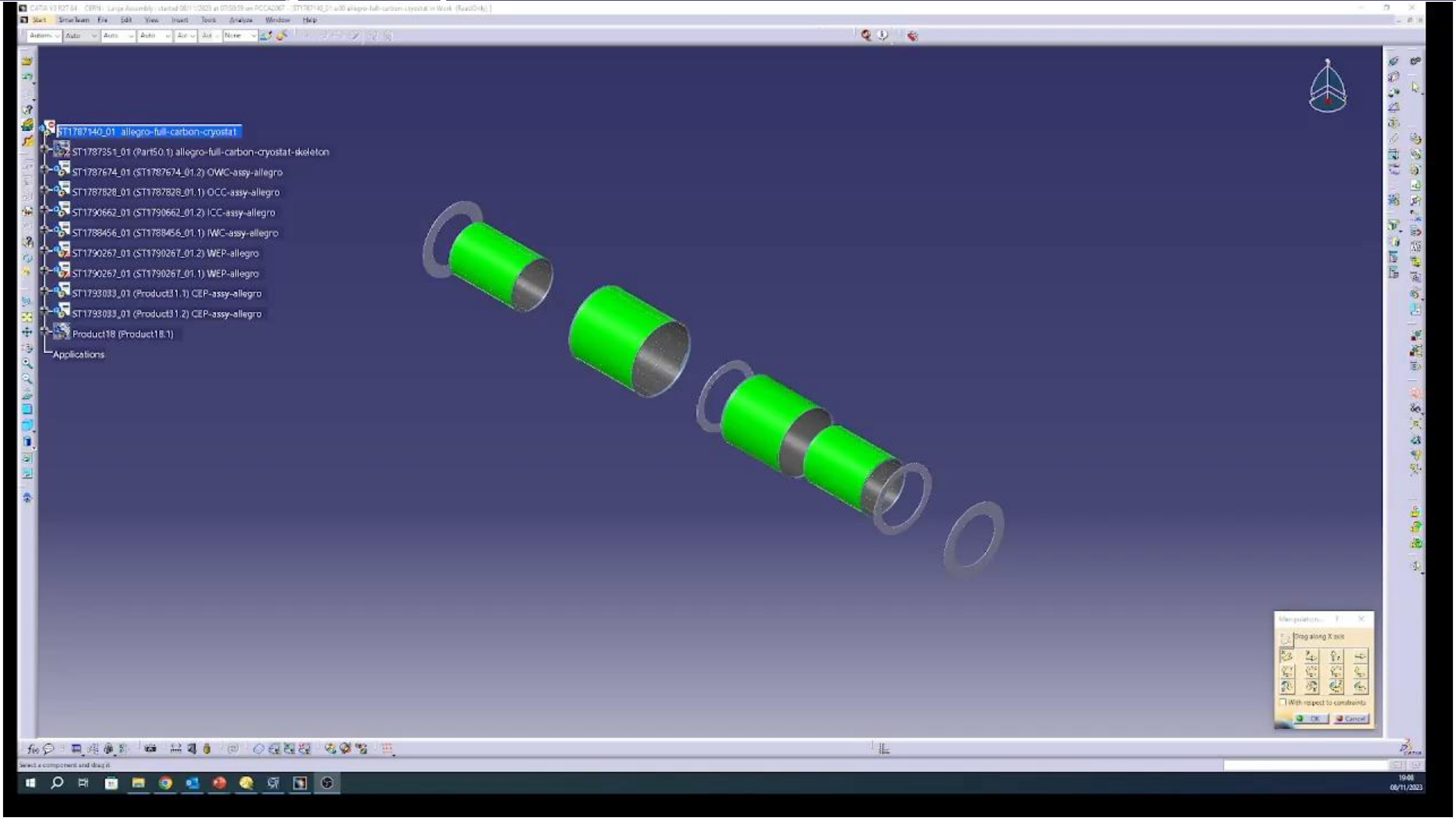






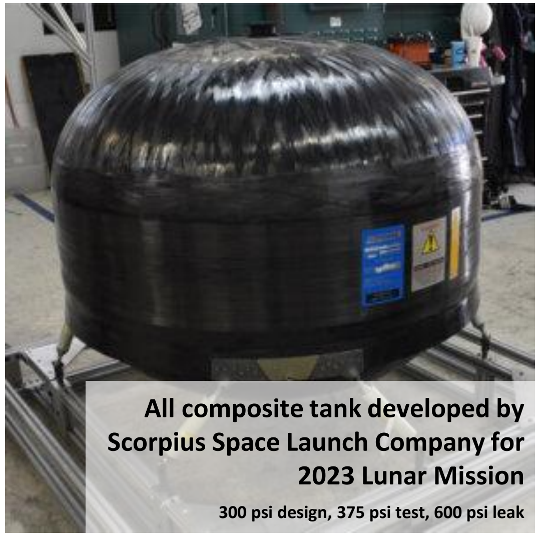


Assembly Sequence



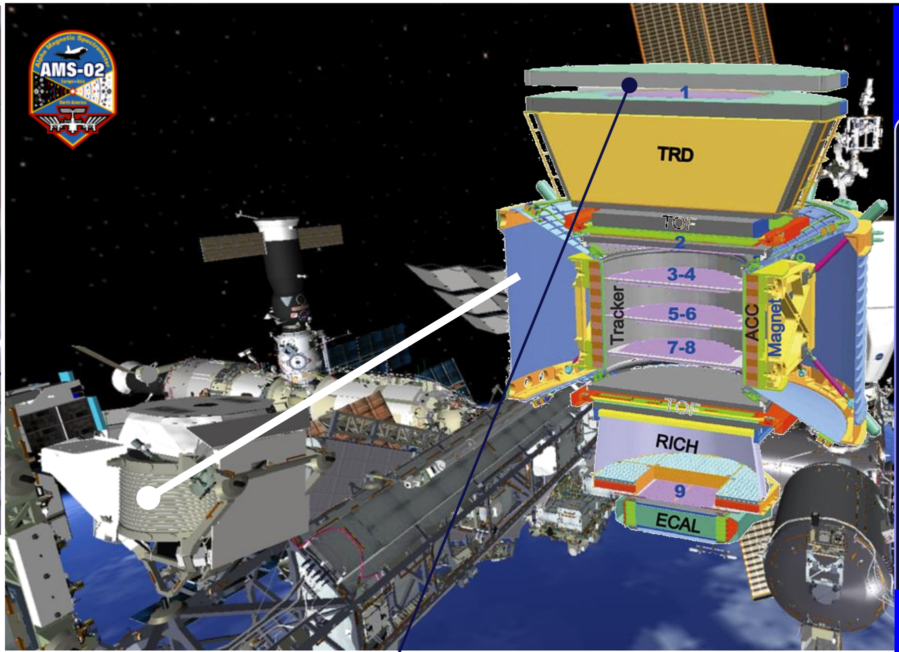
Conclusions and Benefits for Aerospace

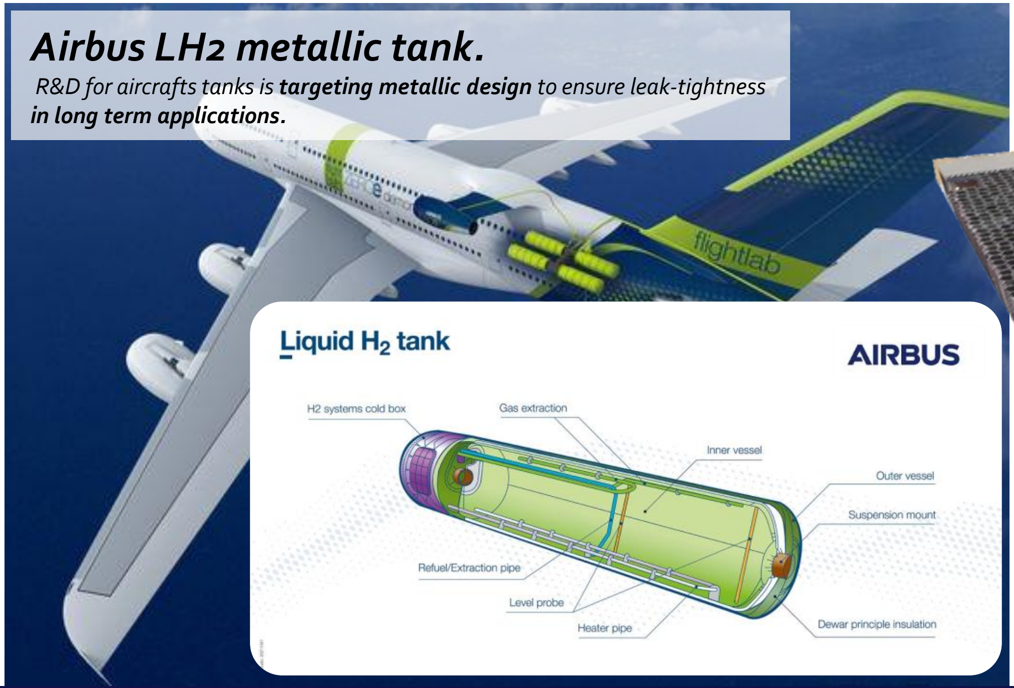
✓ CERN technology will focus on carbon composite leak-tight design that can operates at cryogenic temperature in a long-term application.



All composite tank developed by Scorpius Space Launch Company for 2023 Lunar Mission

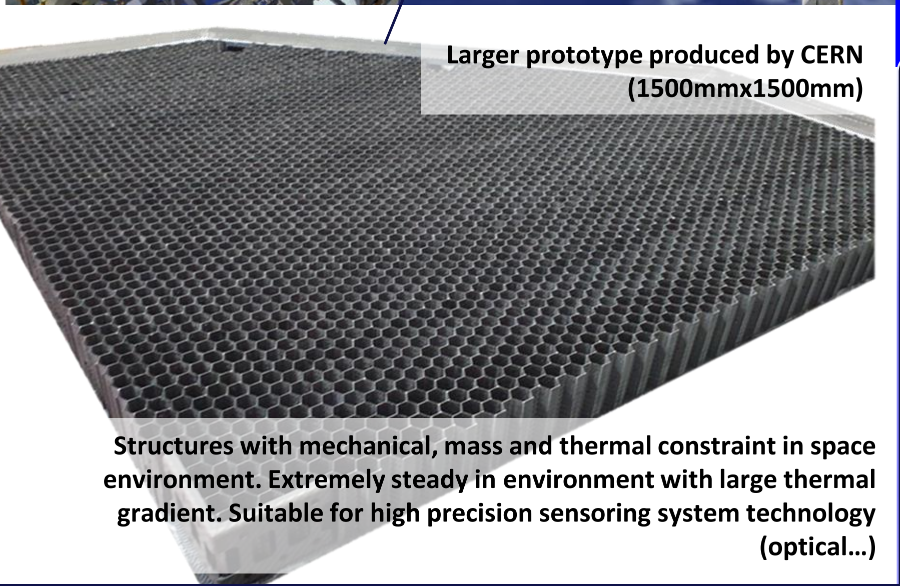
300 psi design, 375 psi test, 600 psi leak





Airbus LH2 metallic tank.

*R&D for aircrafts tanks is **targeting metallic design** to ensure leak-tightness **in long term applications.***



Larger prototype produced by CERN (1500mmx1500mm)

Structures with mechanical, mass and thermal constraint in space environment. Extremely steady in environment with large thermal gradient. Suitable for high precision sensoring system technology (optical…)

CERN R&D Conclusions

- ✓ Materials
- ✓ Processes
- ✓ UHV Sealing in Dismountable Joints
- ✓ Large scale

CERN R&D Future work

- ✓ Build 1m in diameter concept demonstrator
- ✓ Validation campaign (CERN Cryolab)
- ✓ FEA to optimize CAD
- ✓ Design support system for detector integration

Bibliography

Low Mass Cryostat for Future Experiments at CERN

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THANK YOU

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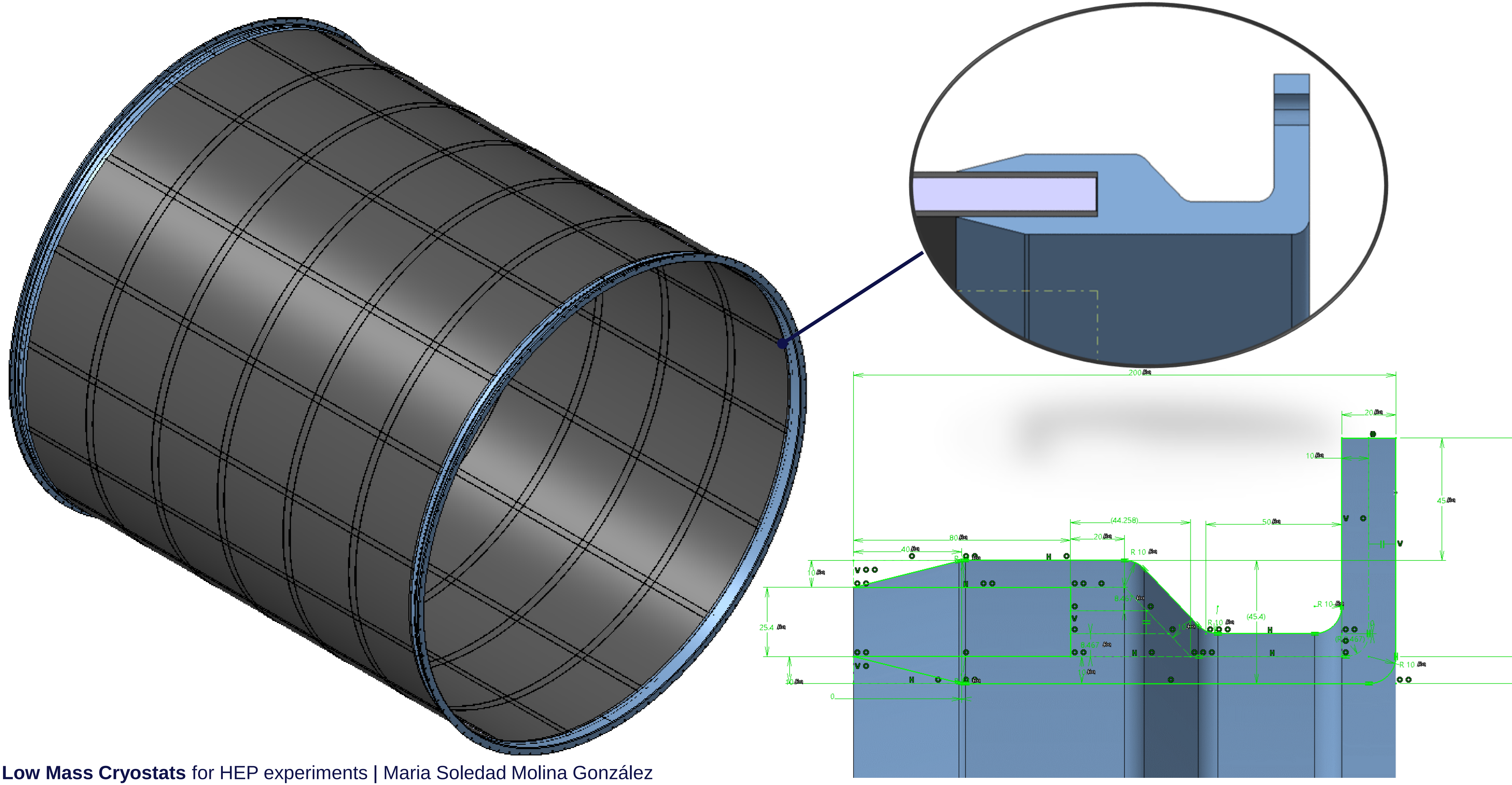
CERN
EP-DT-EO

Back Up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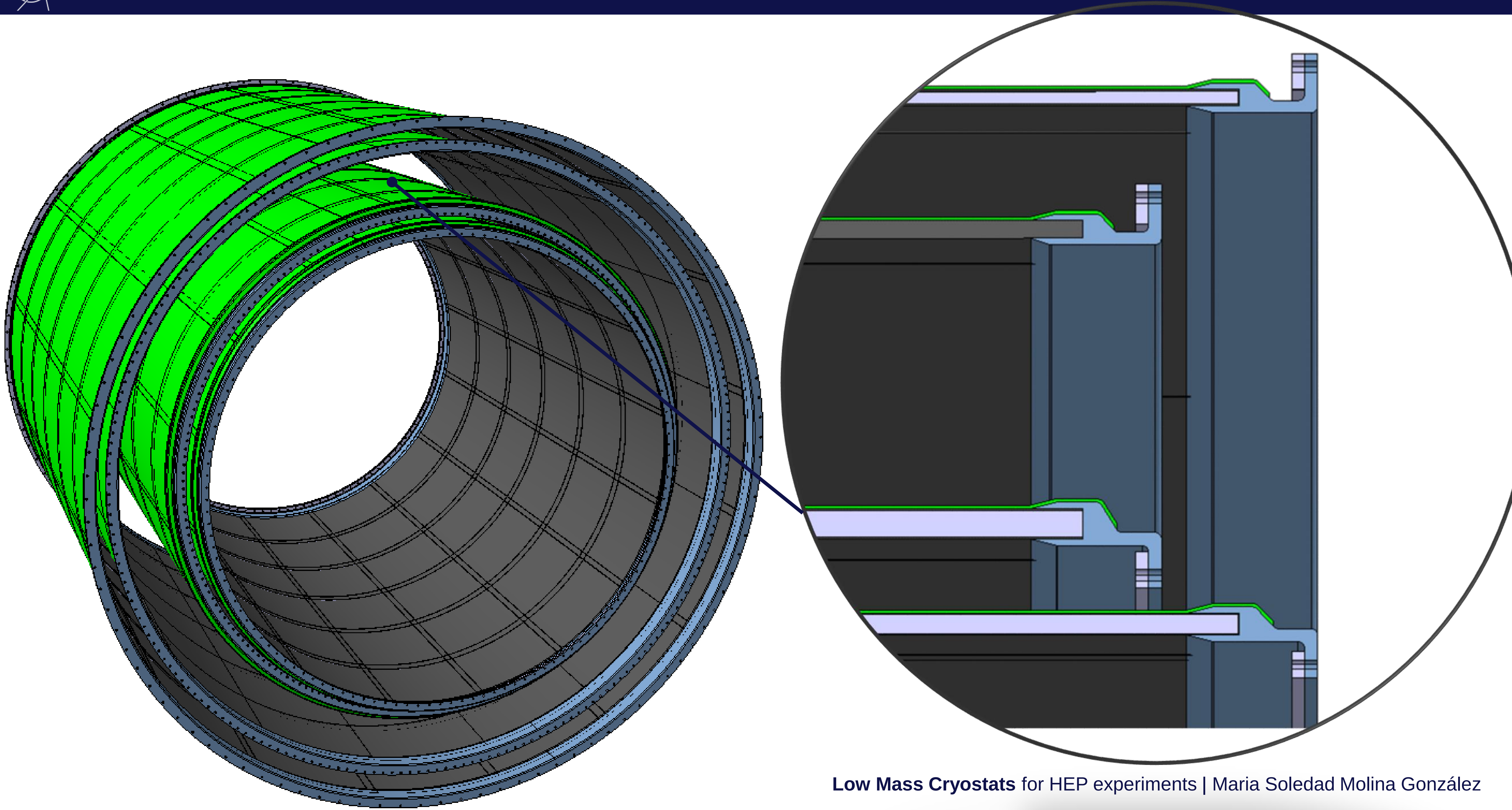
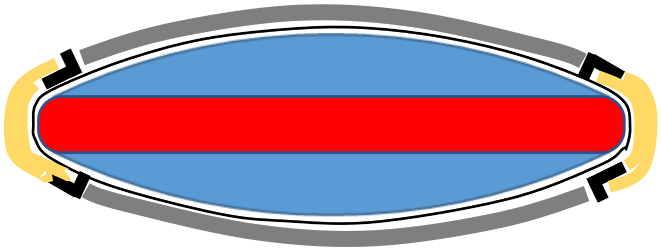
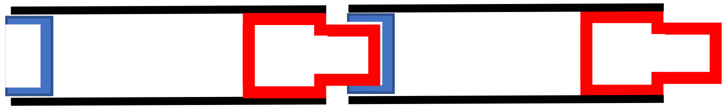
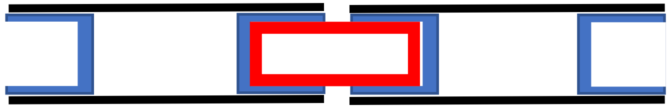


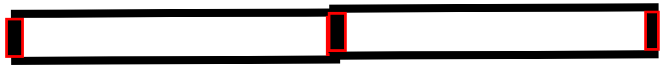




OPTION 1:
2x insert while winding, they can be glued
Step brings complexity, high mat budget



OPTION 2:
1x insert while winding, 1 insert for gluing
Simpler, higher material budget

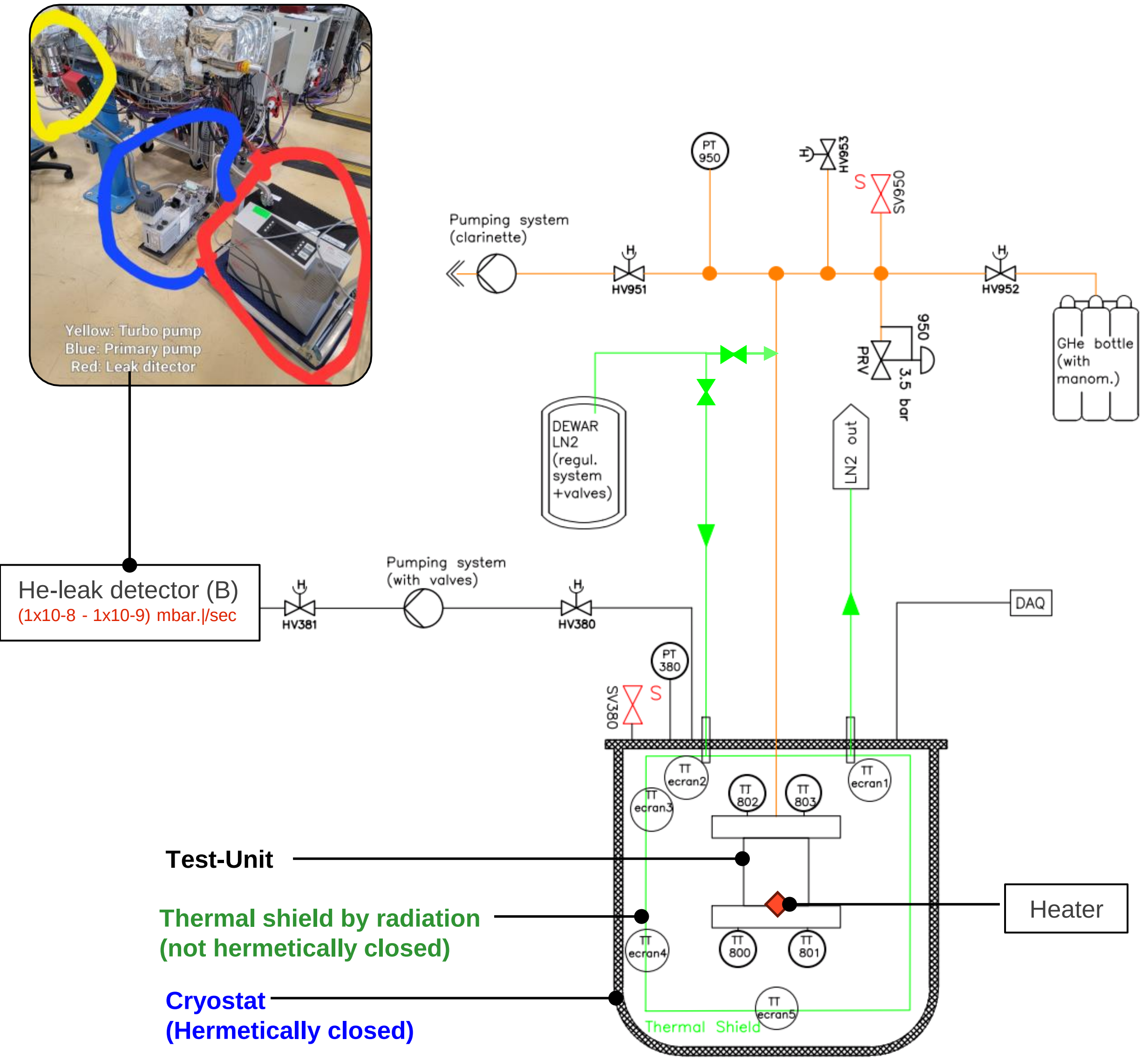


OPTION 3:
carbon plates inserted and locked in location after installation
Optimal

Several other options possible but they require some preassembly on the moulds
-> nominal thickness honeycomb to simplify production. This approach aligns with min material budget and continuity criteria->bonded joint

Validation Campaign

✓ **A experimental setup to carry on leak test with pressurized He at both room and low temperature has been build in collaboration with CERN Cryolab**

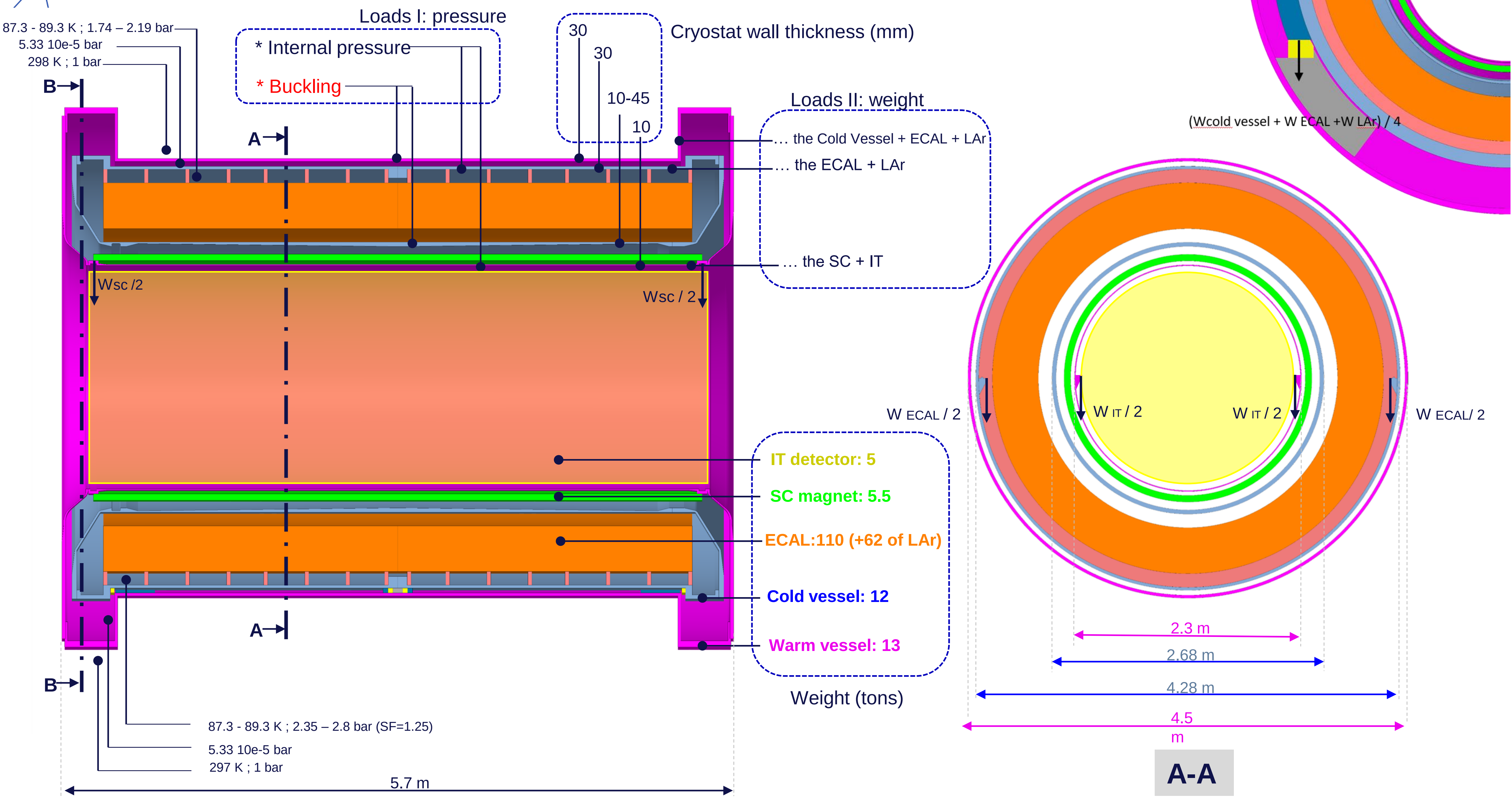


Test Procedure :

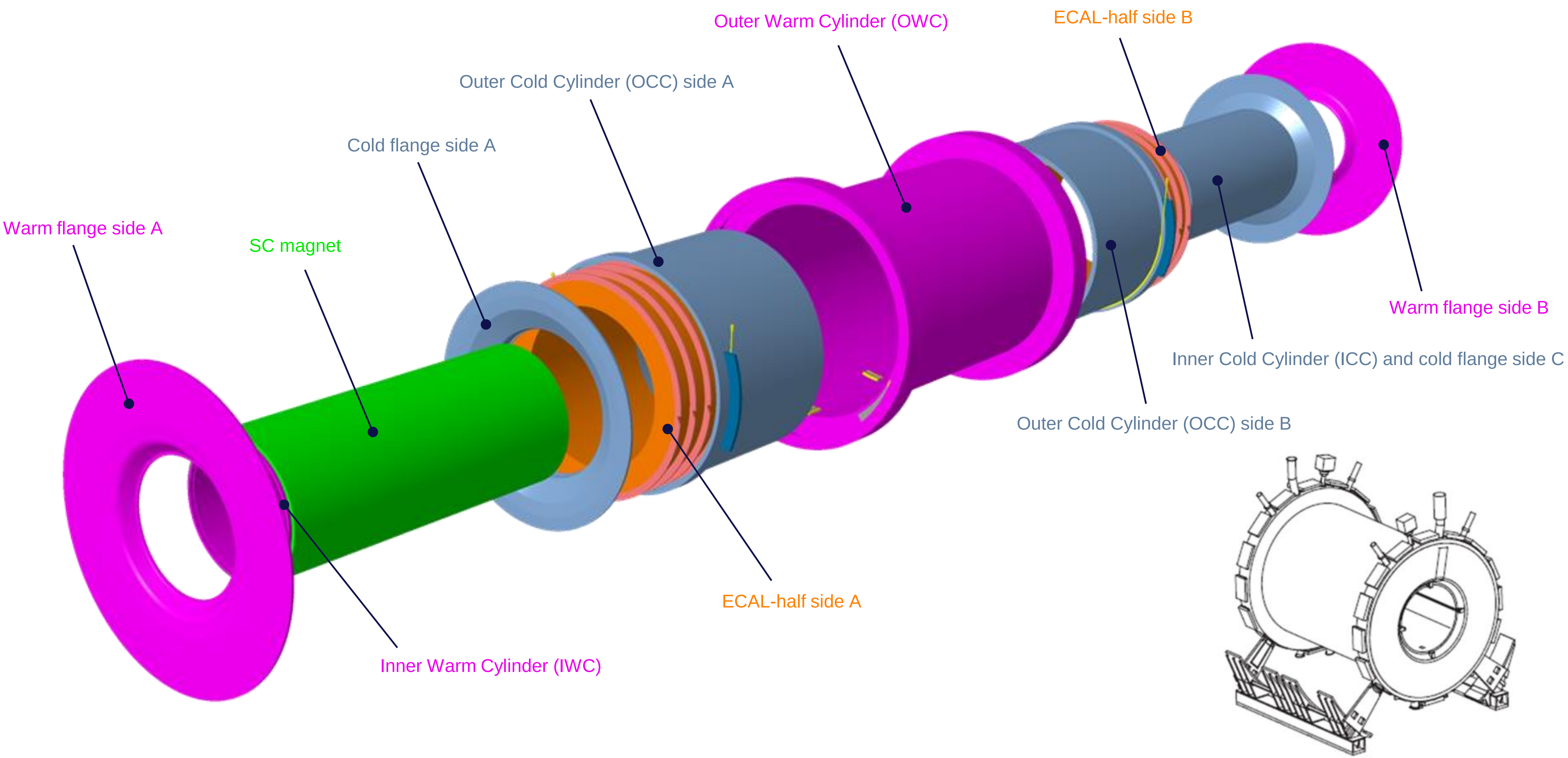
$Q_{rad} = \varepsilon \times \sigma \times (T_1 - T_2)$

1. **Pressurize** with GHe and **He leak test at Troom** (1h30 min)
2. **Cooling down** with LN2 **radiation thermal shield**, down to **110 K** (5 days)*
3. **Cooling down** filling the test-unit **with LN2**, down to **77K**
4. **Evacuate LN2** from test unit using an electric heater to evaporate LN2
5. **Pressurize** with **GHe and He leak test at 77 K** (1h30min)
6. Warming up (1 week aprox.)

Loads and operating conditions



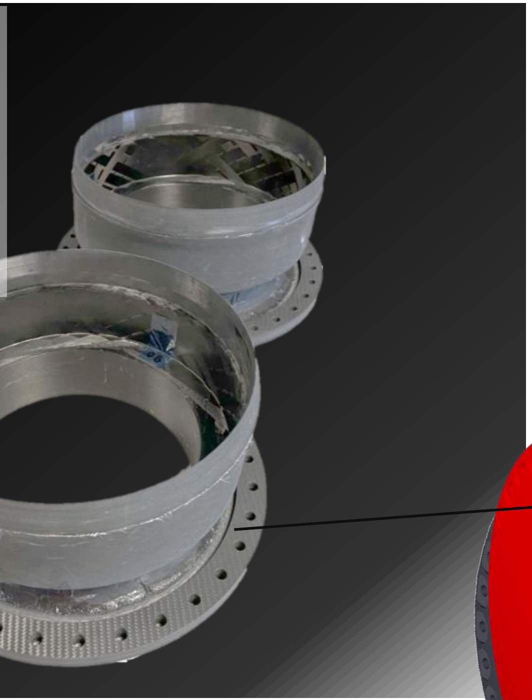
Assembly and Detectors Integration

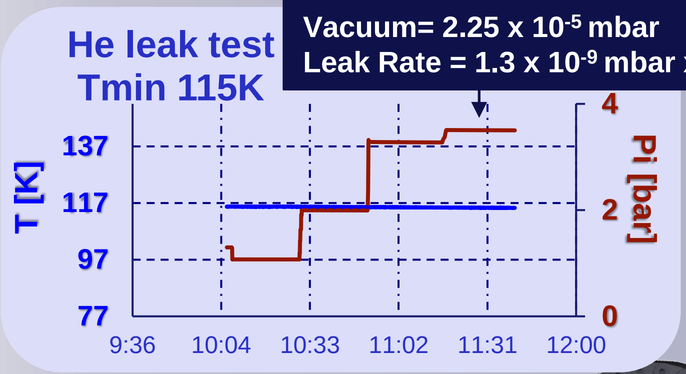


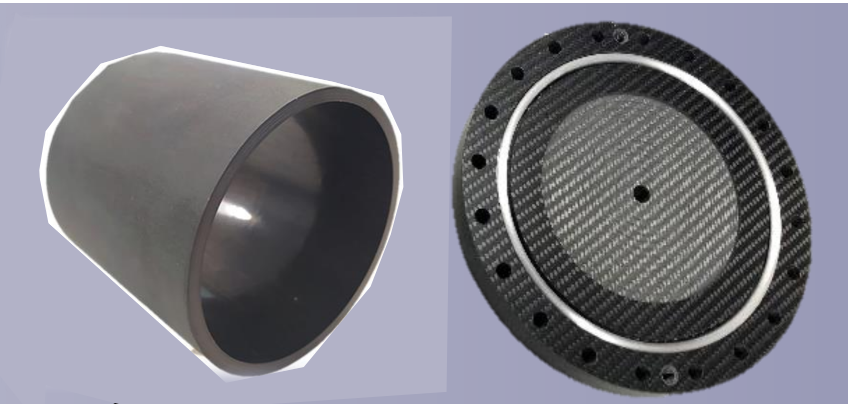
Key Technologies Identified

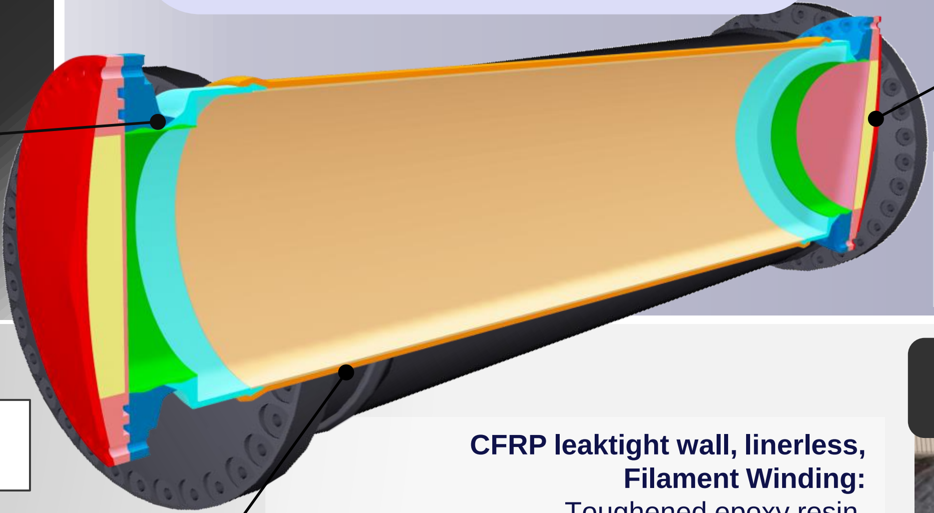
✓ Linerless tank manufactured with wet filament winding (L=1m, D=0,30m) as result of process development for CERN specification.

CFRP end-flanges, Filament-Winding:
Development to achieve complex geometries to design interfaces with bolted end-plates, services…







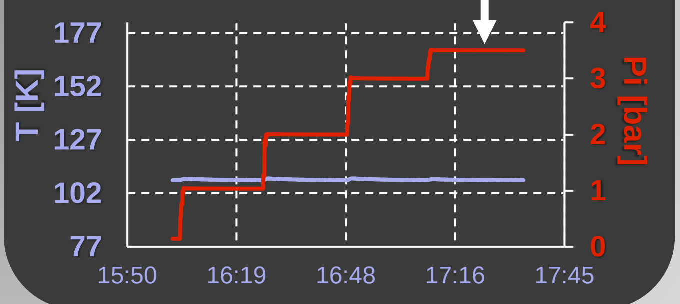


Helicoflex UHV seal

CFRP sealed end-plates, Hand Lay-Up:
Dismountable joint sealed with Helicoflex seal (UHV standard)

He Leak Test
(scaled prototype)
Tmin 108K

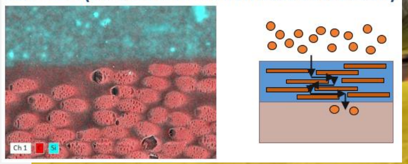
Vacuum= 2.6 x 10-6 mbar
Leak Rate = 5.1 x 10-9 mbar x l / s



CFRP leaktight wall, linerless, Filament Winding:
Toughened epoxy resin,
Intersection free winding tech. , OoA curing.,

Wet Filament Winding to address Large Scale Manufacturing Tech.

SEM-EDX (Particle distribution based on silicon)



Material: Araldite LY556
-Cryogenics applications down to 70 K.
-Hybrid LY556 with barrier function.