EP R&D Day 2021
Working package 4: Detector mechanics

CERN
11th November 2021

Activity 1.b
Low mass cryostats
for HEP experiments

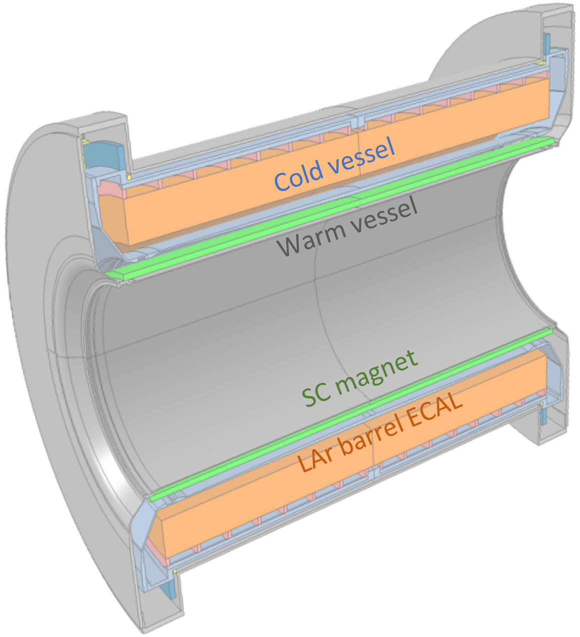
Maria Soledad Molina Gonzalez
On behalf of WG4

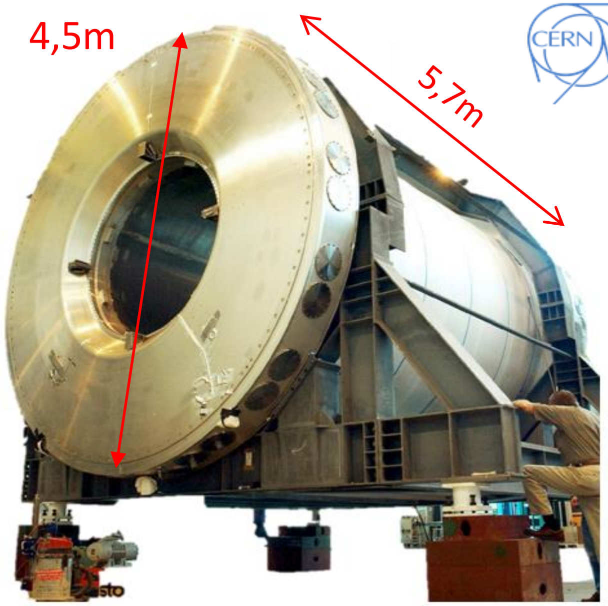
https://indico.cern.ch/event/1063927/

Main requirements

ATLAS barrel-cryostat

toroidal Al 5083 *double wall*





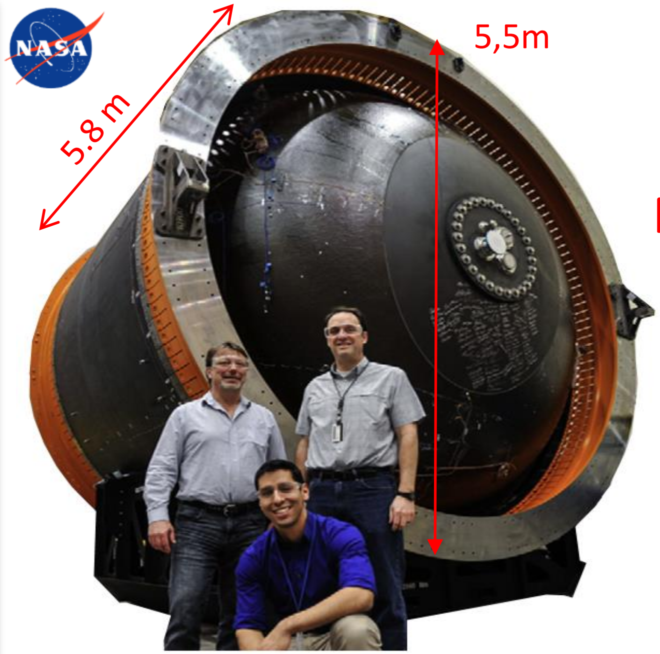
6 x 10m in future cryostats*

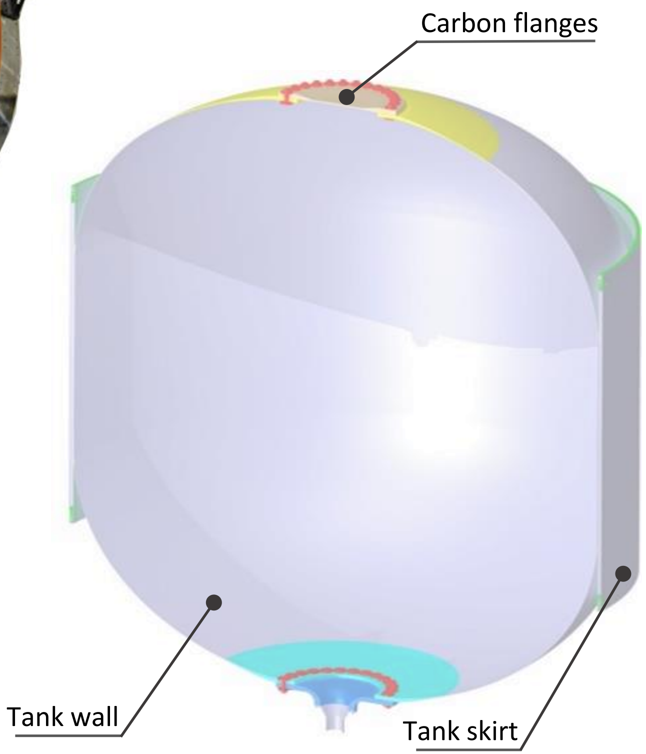
1. **Tightness in long term**
   Cold vessel: LAr leak-tight
   Warm vessel: Vacuum tight

2. **Operating conditions:**
   Cold vessel: T= 87 K; $P_{int, max}$ = 2.8 bar
   Warm vessel: T_{room} ; P_{int} =10^{-5} mbar

NASA's CCTD LH2 cryotank

All carbon composite thin wall





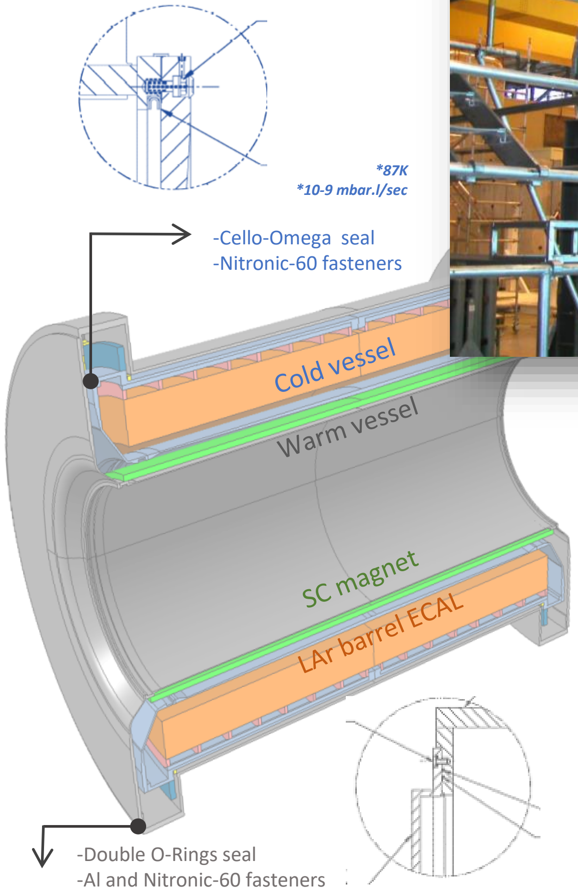
1. **Tightness in short term**
   Tank wall: LH2 (LOX) leak-tight
   Tank skirt: Vacuum tight

2. **Operating condition:**
   Tank wall: T=20 K; $P_{int, max}$ = 3.2 bar
   Tank skirt: T_{room} ; P_{int} =10^{-5} mbar

✓ **Cryostats to house the SC-magnet and LAr-ECAL have similar requirements with cryotanks to storage LH2 in launch vehicles**

ATLAS barrel-cryostat

toroidal Al 5083 *double wall*



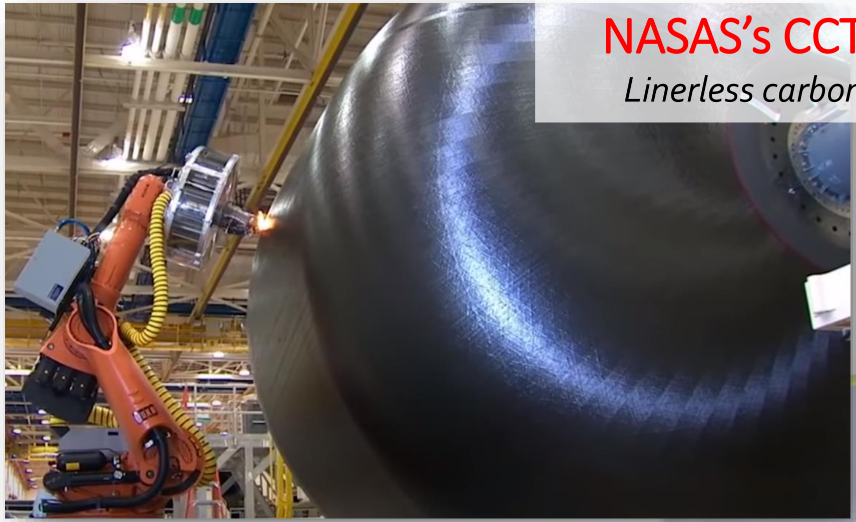
1. Material:
Aluminum 5083

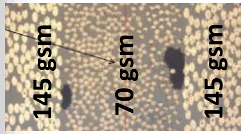
2. Process:
Forming, welding and machining

3.Joints:
Fasteners; polymeric seals (warm)
Fasteners; metallic seal → welded (cold)

NASAS's CCTD LH2 cryotank

Linerless carbon composite thin wall





CFRP hybrid laminate

1. Material
CFRP hybrid laminate (thick and thin plies)

a) Resin: Microcrack resistant (**CTD,** 5320-1, MTM45-1, M56, TC250…)
b) Carbon Fiber: IM7

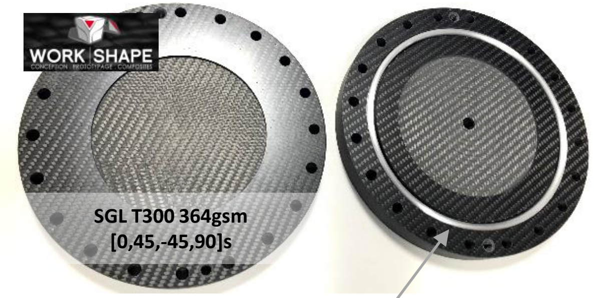
2. Process:
Robotic Automated fiber placement (RAFP)
Out of Autoclave (OoA) curing

3. Joints
Hot-bonded and co-cured
Fasteners, Belleville washers and Furon Seal

✓ **R&D required to adapt aerospace technology choices to HEP low mass cryostats**

1. sealing method for bolted composite flanges at cryo temperature

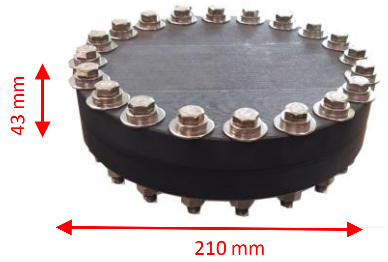
Design criteria: He leak-rate < 10e-9 mbar.|/s at 87K and 3.5 bar (2.8 bar x 1.5 safety factor)

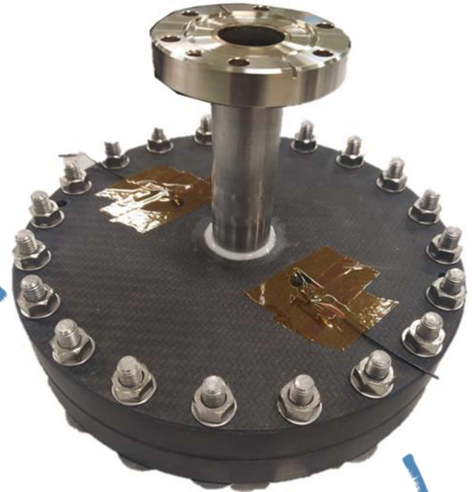


Helicoflex (UHV at CERN)

*3 K
*10-9 mbar.l/sec

Technetics GROUP





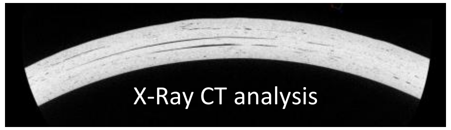
Test sample 1

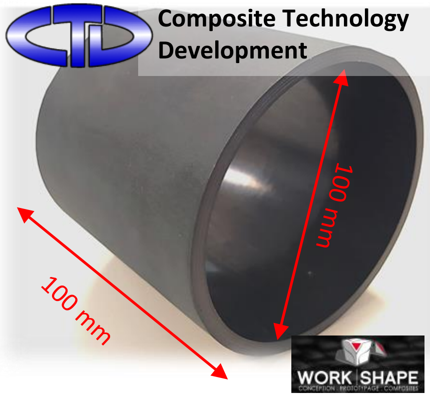
2. micro-crack and permeation resistant laminate for a thin-wall composite shell at cryo temperature

Design criteria: He leak-rate < 10e-9 mbar.|/s at 87K and 3.5 bar (2.8 bar x 1.5 safety factor)

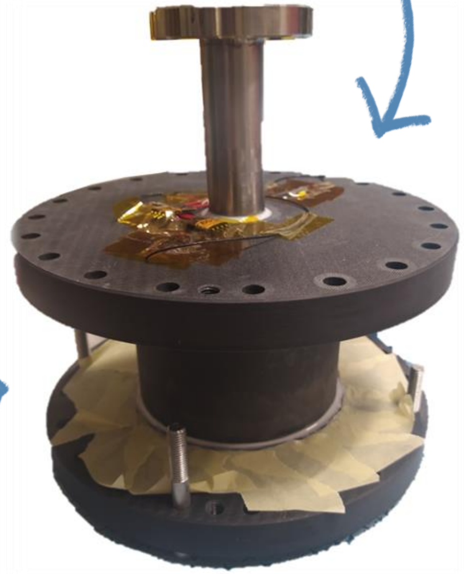
12 thick layers
12 thin layers
12 thin layers
12 thick layers
5mm

- **Material: CTD 133P**
  - -145 gsm prepreg
  - -70 gsm prepreg





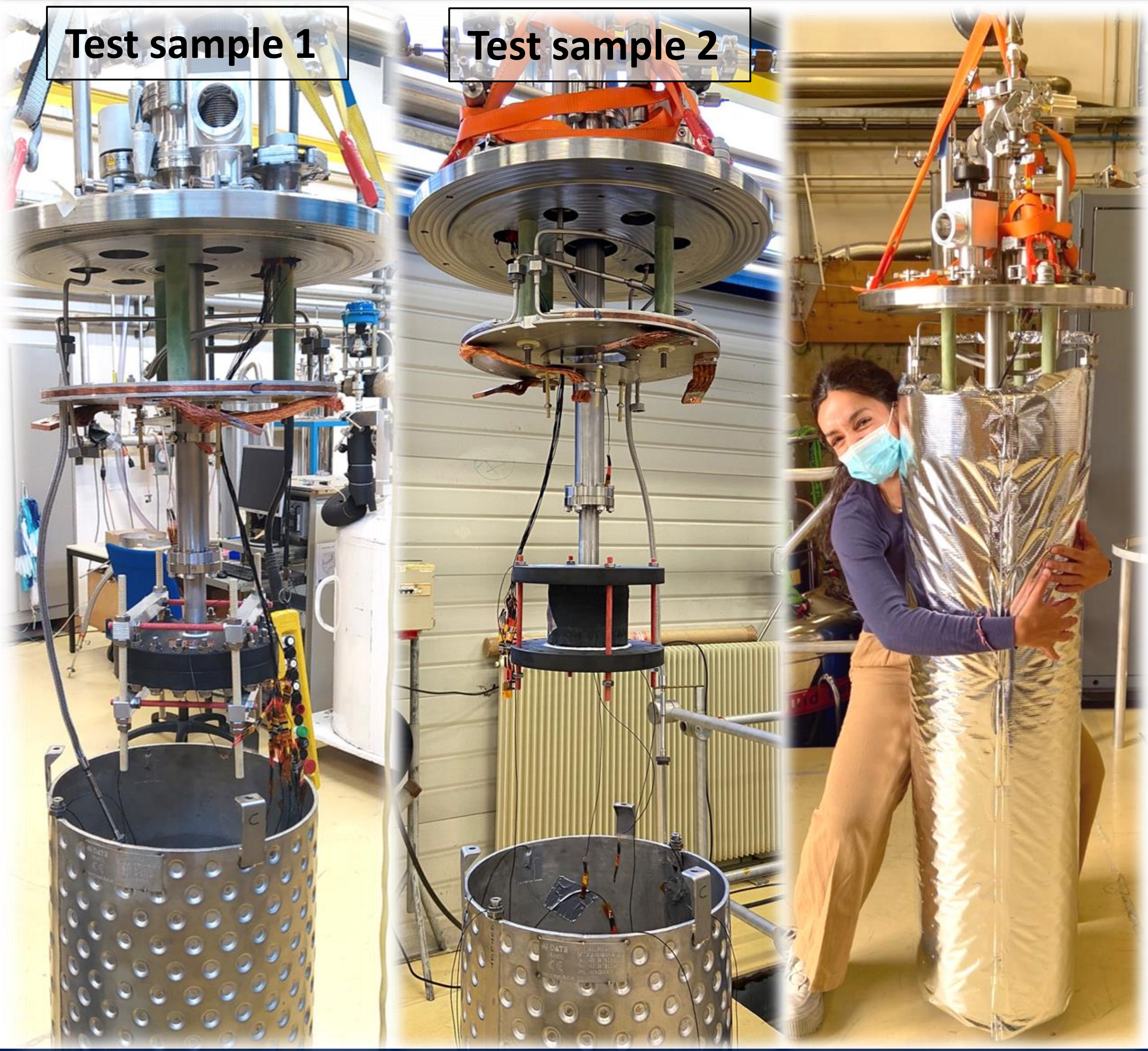
Machined groove and glued joint (EP37-3FLFAO)



Test sample 2

→ Two prototypes have been built to address wall tightness and sealed joint for CFRP cryostats

Test performance (CERN Cryolab Collaboration)



Thanks a lot to :
Martin Aleksa
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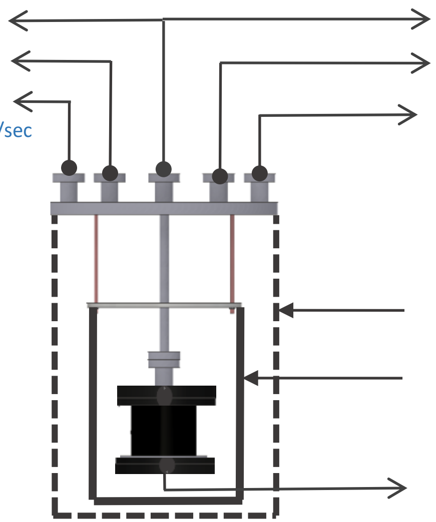
Michel Chalifour
Maria A. Barba
Agostino Vacca
Laetitia Dufay-Chanat
Sebastien Prunet

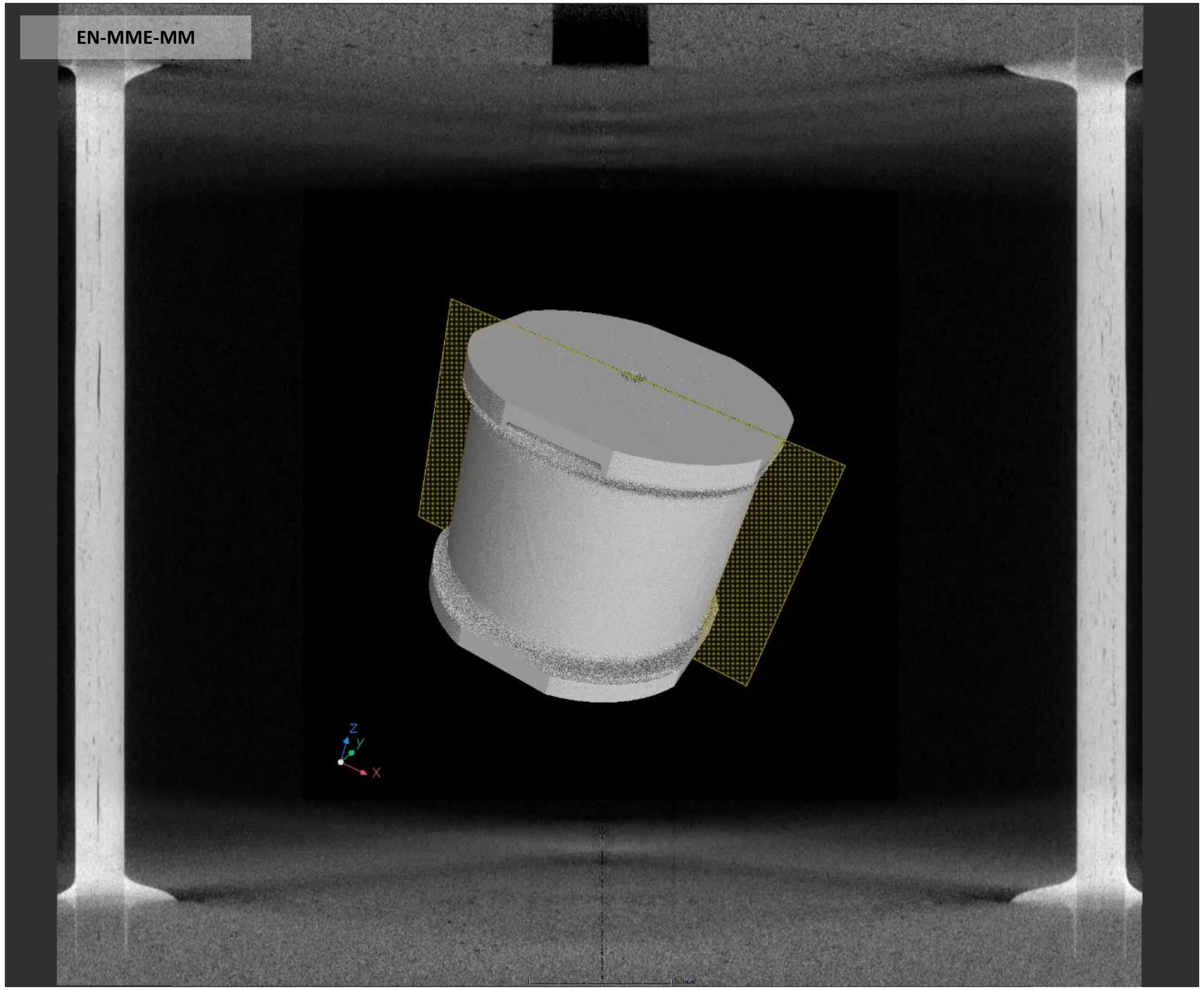


$Q_{rad} = \varepsilon \times \sigma \times (T_1 - T_2)$

Test Procedure :

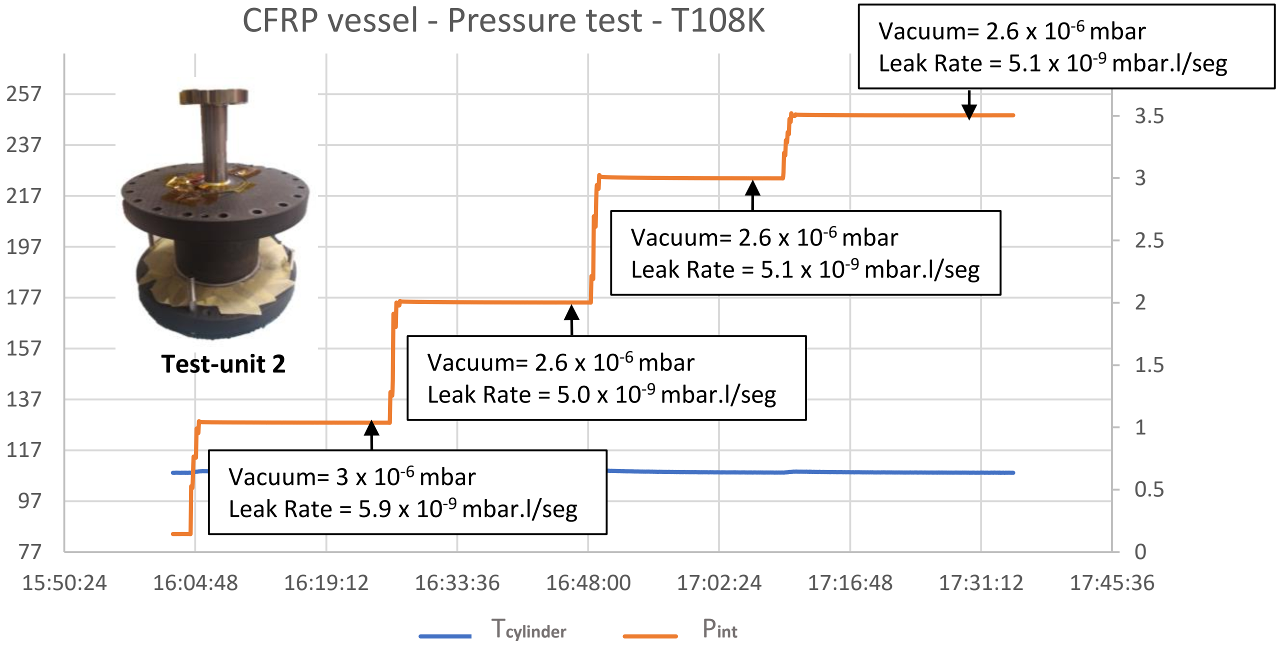
1. Pressure and leak test at Troom (1h30 min)
2. Cooling down (5 days)*
3. Pressure and leak test at Tcryo (1h30min)
4. Warming up (1 week aprox.)

→ Experimental setup was designed to check He leakage at 3.5 bar and ~110K (test setup limit)



* Minimum temperature driven by tets setup limits (LAr 87K)

CTD toughened resin validated for thin wall carbon composite shells at 108K* and $P_{int,max}$ = 3.5 bar



→ **Non He-leakage was detected along cryo-tests in both samples**

Manufacturing process for larger scale production

Thanks a lot to:
Taylan Toprak (Connova) - Business Development Head
Thomas Leschik (Connova) - Operations Head
Tobias Hoyer (Connova) – Project Engineer
Mark Seeber (CTD) - Commercial Office Head

Process development for Wet Filament Winding as alternative to RAFP

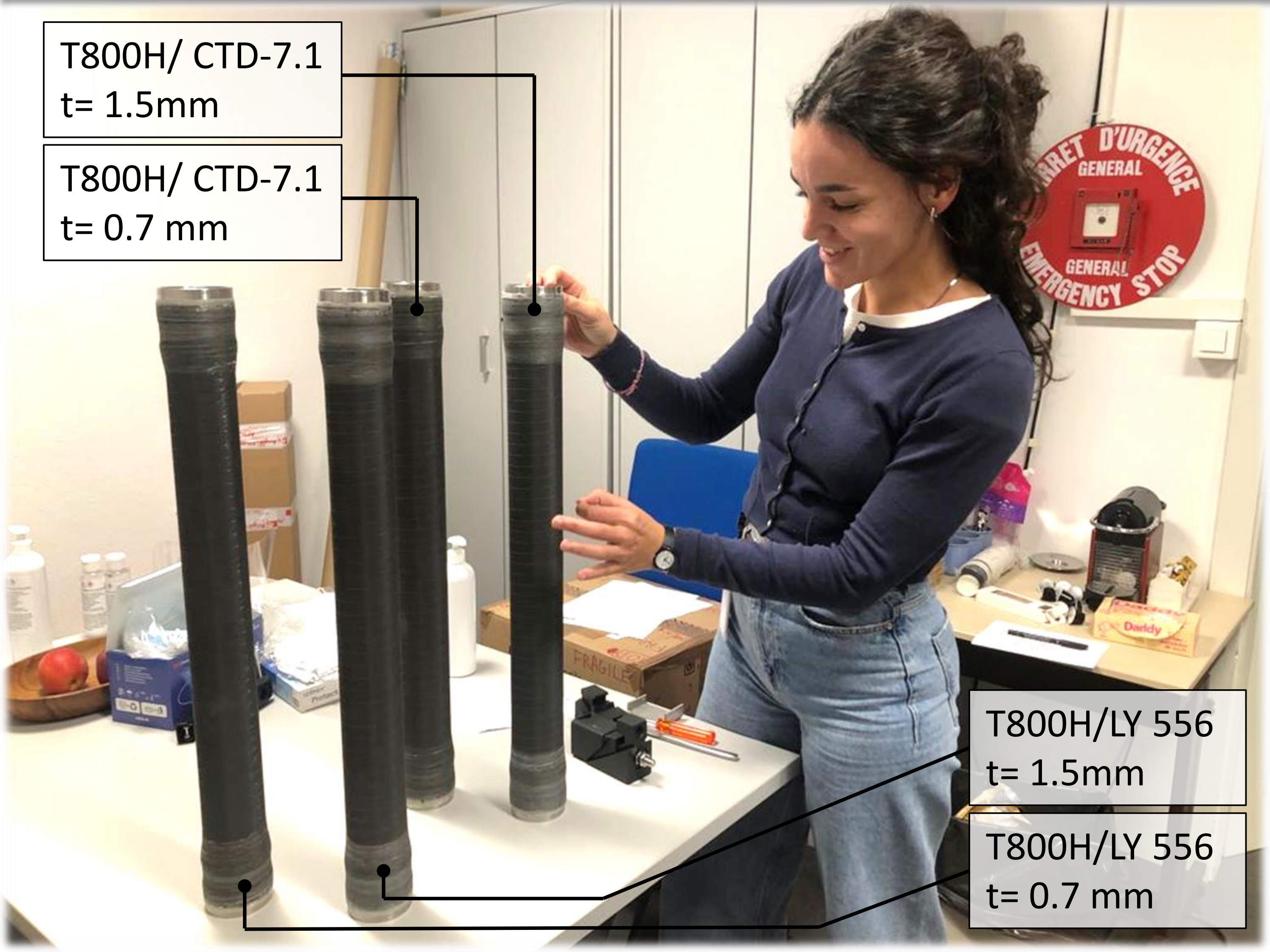
-Optimize **CTD-7.1 resin bath** preparation and size.
-Optimize **carbon fiber tension** to increase cross plies density (permeation resistance)
-Laminate: **[-55,+55]s with non crossing** to minimize void content
- Out of Autoclave curing (oven)

Micro-crack resistant resin at cryogenics includes toughened additives. **Vacuum evacuation** of resin system is needed **to improve void content before winding** and to get high mechanical properties.

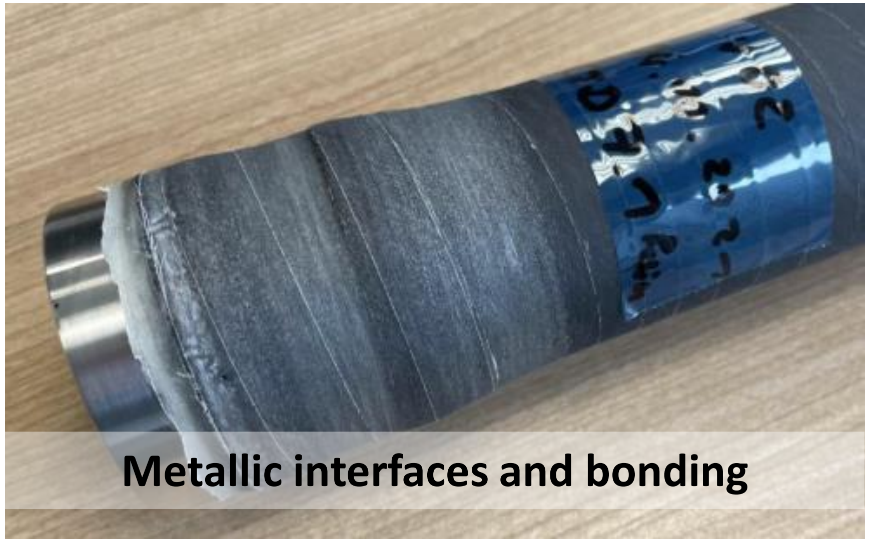
Peel-ply as final layer to compact laminate and **evacuate voids**

→ **Next samples to address filament winding technology as an efficient manufacturing process for larger scale**

Filament winding thinner samples



Carbon composite thin tubes with Stainless Steel (1.4301) end-fittings embedded into laminate



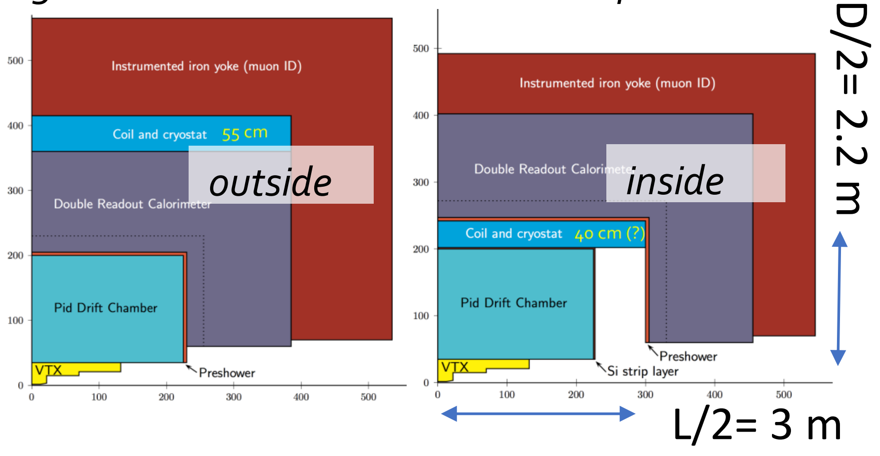
This technology might match beam pipe requirements*

→ **CFRP thin laminate tubes to be tested for vacuum tightness and LAr tightness**

Baseline geometry, FCC-ee

a very challenging 2T solenoid "ultra-thin and transparent"

e^+e^- collisions



Minimum material budget

Buckling resistance

Patm →Vacuum

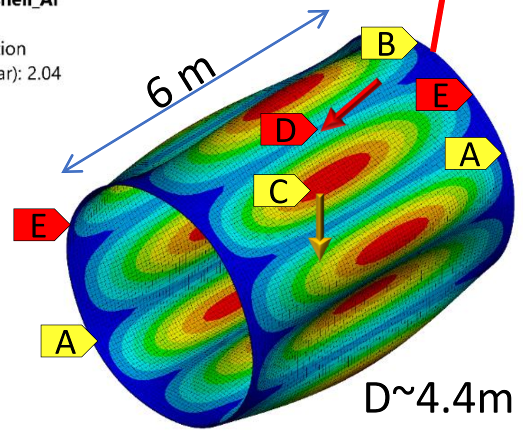
Sandwich

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

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

Criteria: Safety Factor = 2	Honeycomb Al		Solid shell	
	HM CFRP	Al	HM CFRP	Al
Material budget X/Xo	0.017	0.045	0.065	0.24
Xo % savings	-62%	REF	44%	433%
Skin Th. [mm]	1.6	1.7		
Core Th. [mm]	26	40		
Total Th. [mm]	29.2	43.4	16.8	20.9
Thickness % savings	-33.00%	REF	-61%	-52%

G: Buckling_Outer_shell_Al
Total Deformation
Type: Total Deformation
Load Multiplier (Linear): 2.04
Unit: mm



FEM loads OWC:

- 1 bar

A: Outer_shell_Al
Static Structural
Time: 1. s

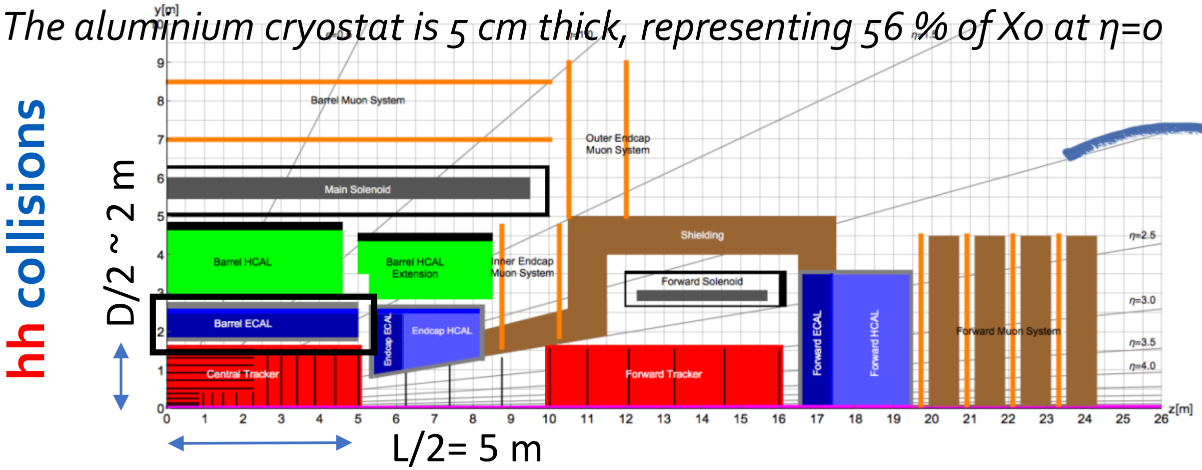
- A X=0; Y=0
- B Z=0
- C Standard Earth Gravity: 9.81e+003 mm/s²
- D Pressure: -0.101 MPa
- E Force: 3.5e+005 N

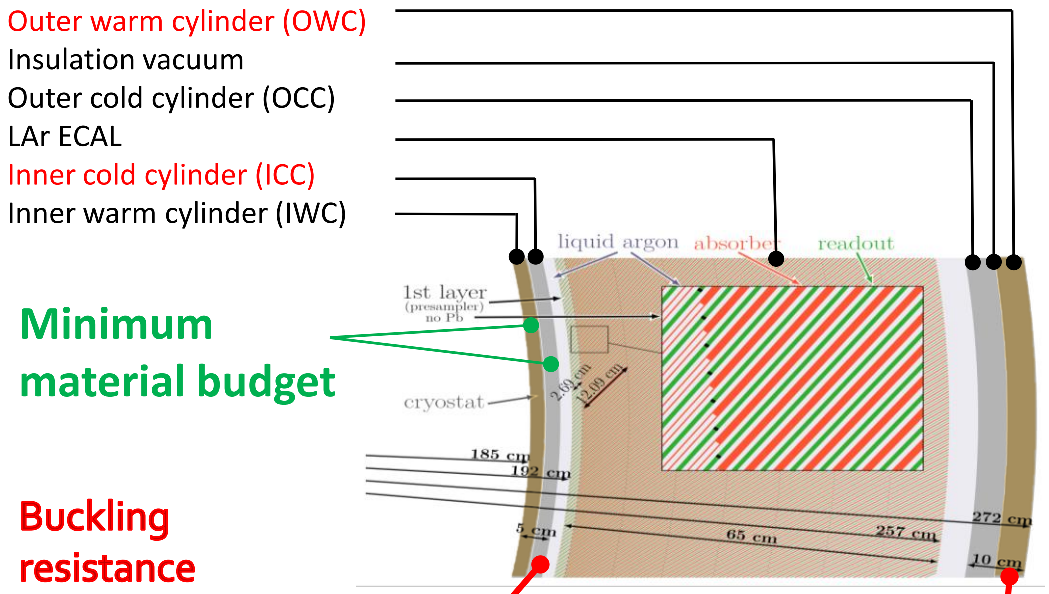
→ CFRP cryostat wall will provide savings in terms of material budget/thickness respect to Aluminum

Next design for the calorimeter cryostat

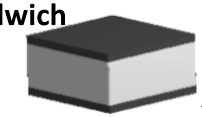
Baseline geometry, FCC-hh LAr barrel ECAL :

The aluminium cryostat is 5 cm thick, representing 56 % of Xo at η=o





Sandwich



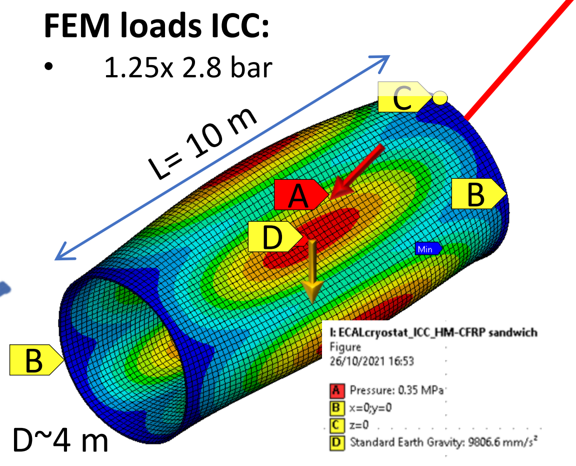
Skin [0,45,-45,90]s
Core : Al Honeycomb
Skin [0,45,-45,90]s

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

Criteria: Safety Factor = 2	Honeycomb Al				Solid shell			
	HM CFRP		Al		HM CFRP		Al	
	OWC	ICC	OWC	ICC	OWC	ICC	OWC	ICC
Material budget X/Xo	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
Xo % savings	-68%	-75%	REF	REF	-2%	-29%	262%	159%
Skin Th. [mm]	3.2	4.8	3.9	7.5				
Core Th. [mm]	32	38	40	40				
Total Th. [mm]	38.4	47.6	47.8	55	24	30.4	30	39
Thickness % savings	-20%	-13%	REF	REF	-50%	-45%	-37%	-29%

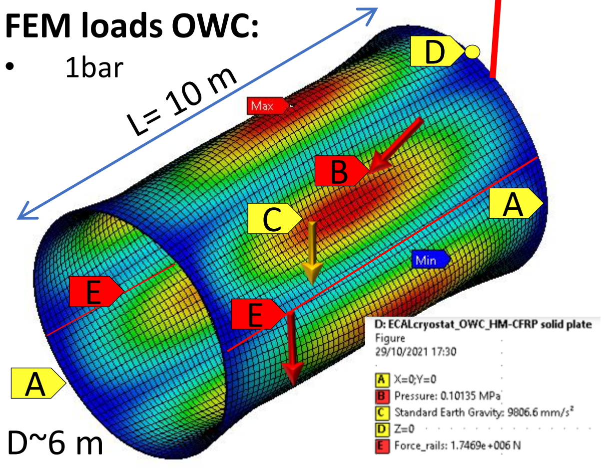
FEM loads ICC:

- 1.25x 2.8 bar



FEM loads OWC:

- 1bar



→ **CFRP cryostat wall will provide savings in terms of material budget/thickness respect to Aluminum**

R&D mailstone: 1m Diameter concept demonstrator

Fiber tension along winding to optimize cross laminate density

Toughened epoxy resin system compatible with winding

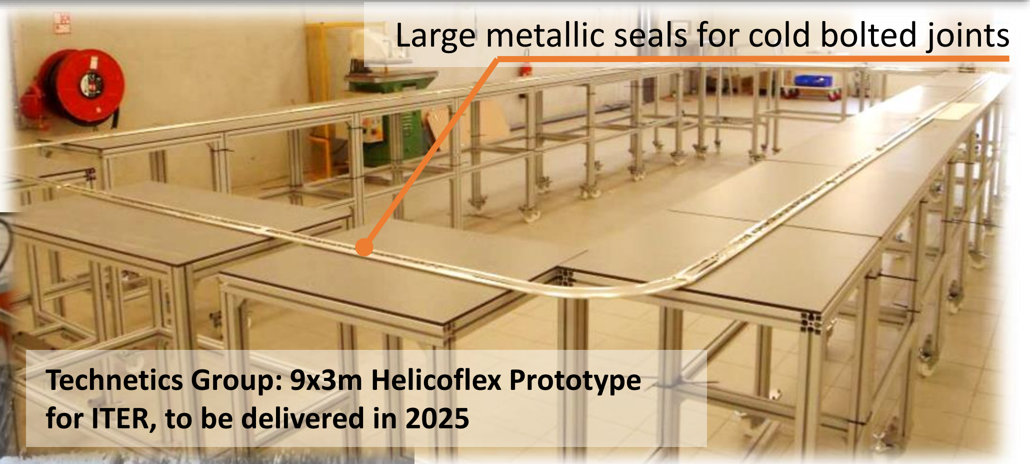
Laminate QI [-55,+55]s for torsion and internal pressure

Peel-ply to remove excess of resin and evacuates voids

Laminate without crossing to minimize void content

Scaling up filament winding tooling and samples

Large metallic seals for cold bolted joints



Technetics Group: 9x3m Helicoflex Prototype for ITER, to be delivered in 2025

High modulus carbon fiber compatible with winding

Voids evacuation of resin and efficient fiber impregnation

Concept demonstrator: 1m in diameter HM-CFRP vessel with a sandwich structure:

- **Buckling resistant**
- **Leak tightness to vacuum and LAr**
- **Filament winding technology** **…**

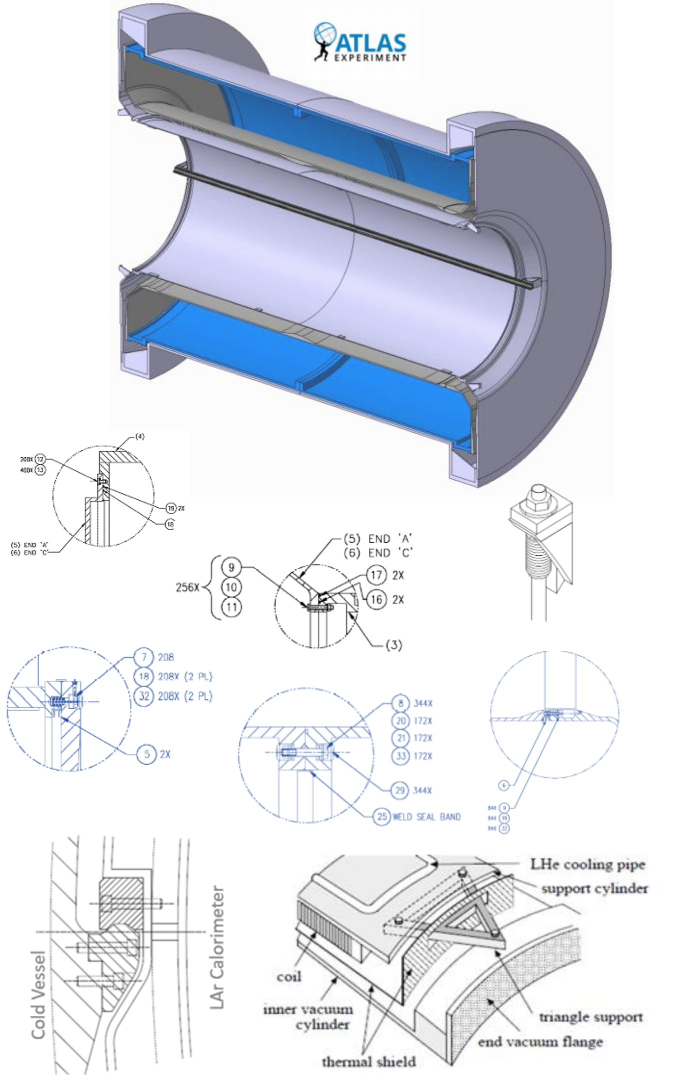
CTD, Technetics, Connova, LZS, CERN Cryolab, EN-MME-MM, RUAG …

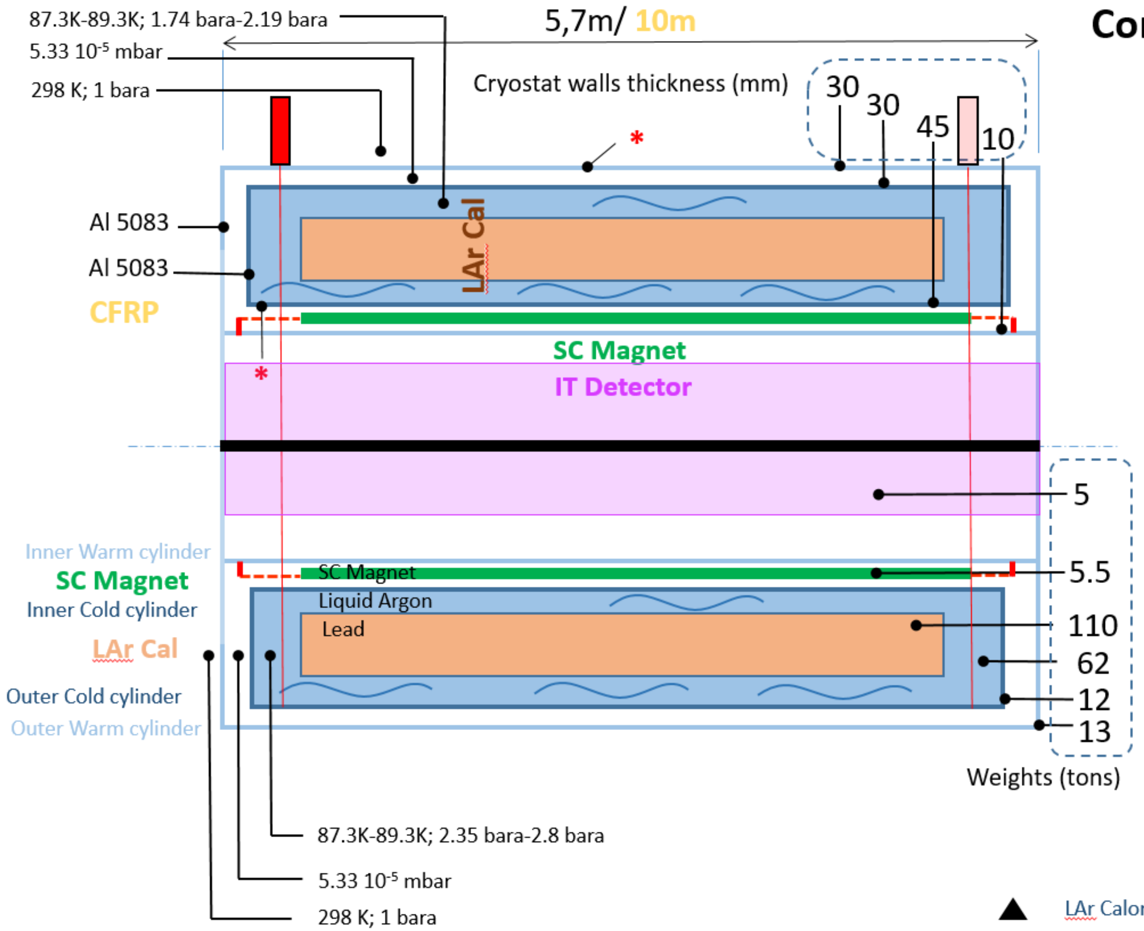
→ Large CFRP cryostats requires a buckling resistant design that will be targeted by a 1m in diameter concept demonstrator

Thank you very much

Back-Up

ATLAS barrel cryostat - Requirements





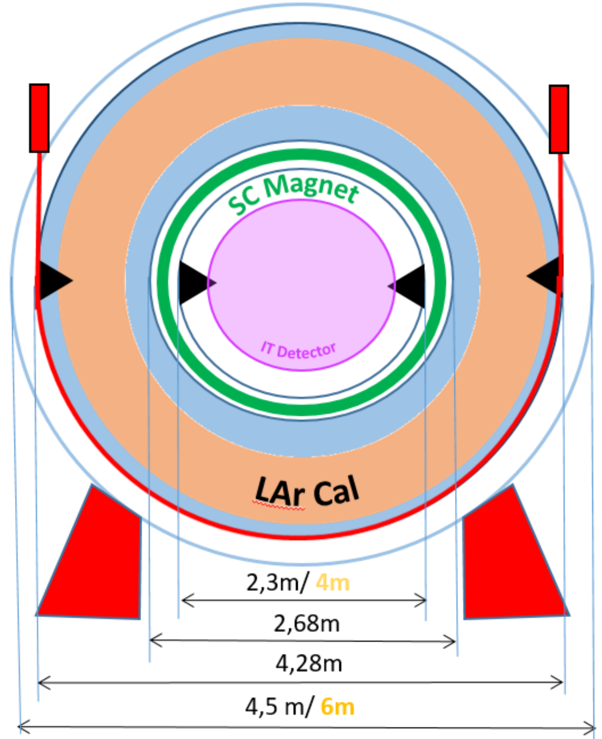
Note:* Buckling sensitive, each shell that is subjected to an external press larger than the internal

** SC Magnet cooled by closed circuit, He serpentine on the structural shell

Combined SC Magnet & Calorimeter

Existing cryostat (TDR)

Future cryostat



▲ LAr Calorimeter and Inner tracker supports: rails

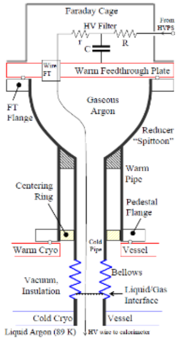
Cold Vessel supports: straps from the outer warm cylinder

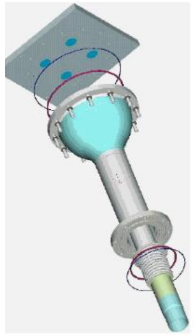
SCM support: fixed at the end flange of the warm inner cylinder

→ **The ATLAS barrel cryostat houses the LAr calorimeter and the SC magnet, supports the IT and it is supported by Tile-CAL**

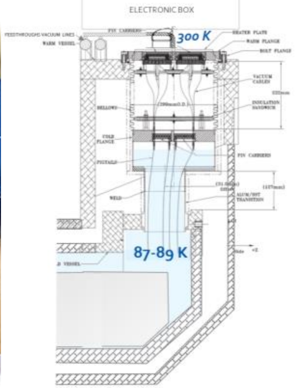
ATLAS barrel cryostat - Feedthroughs

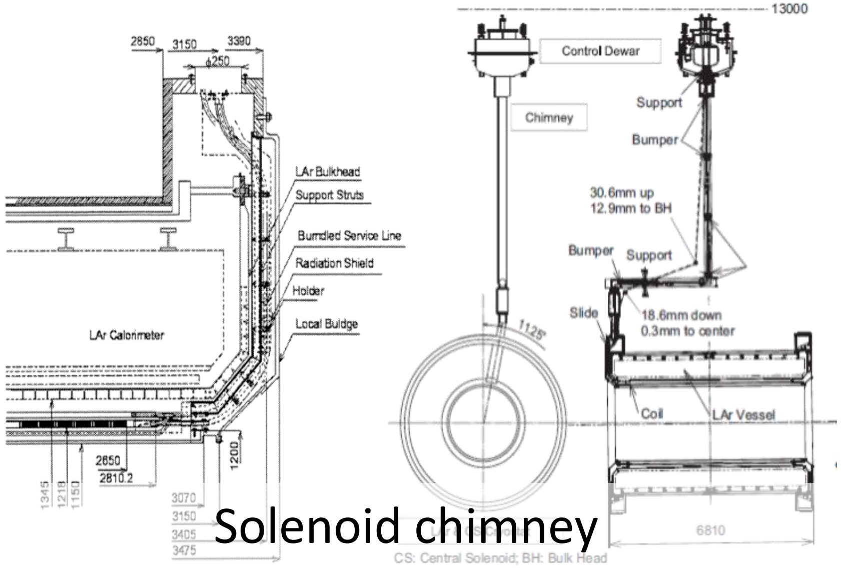
HV FEEDTHROUGHS



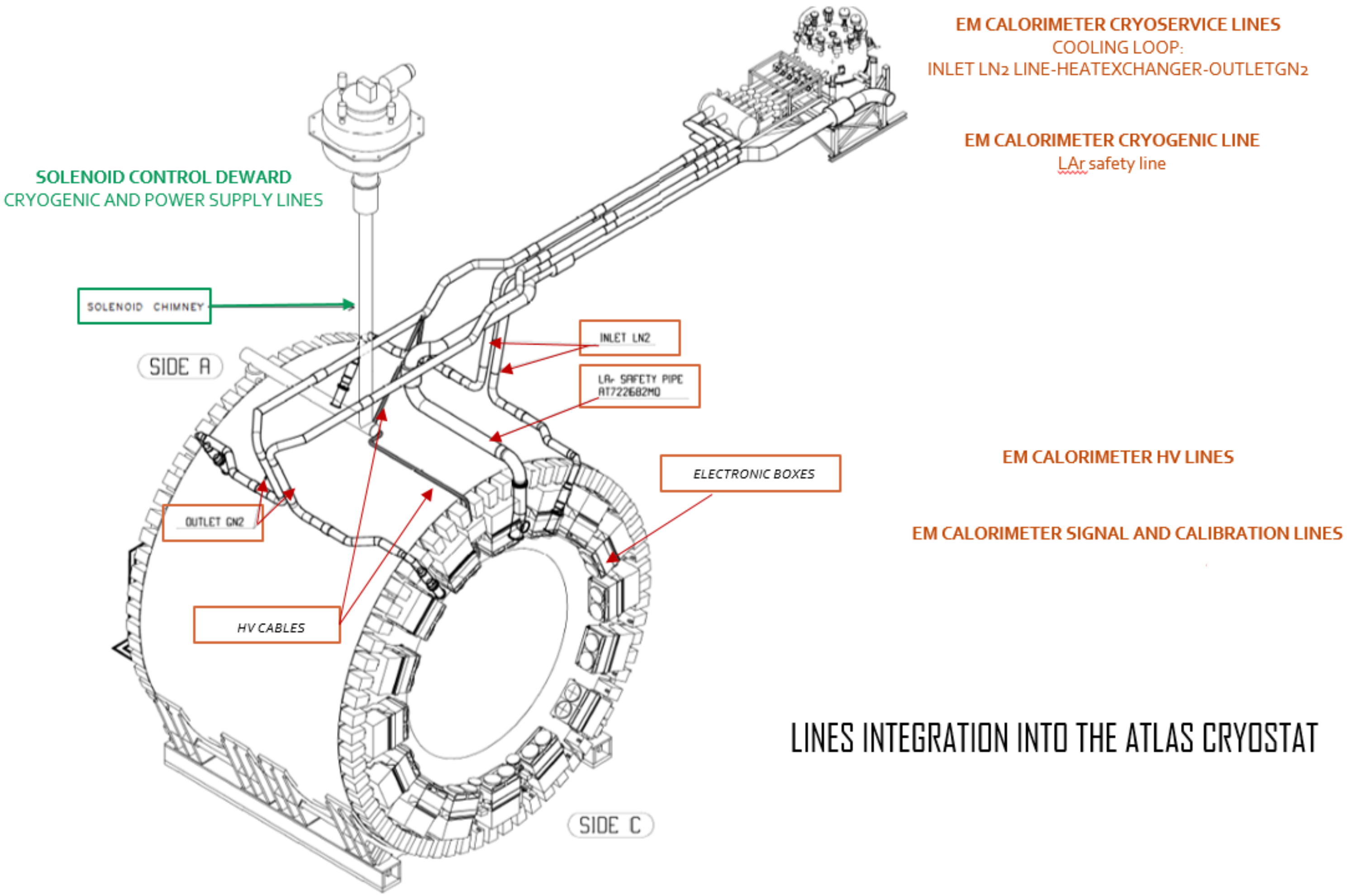


SIGNAL FEEDTHROUGHS





Solenoid chimney

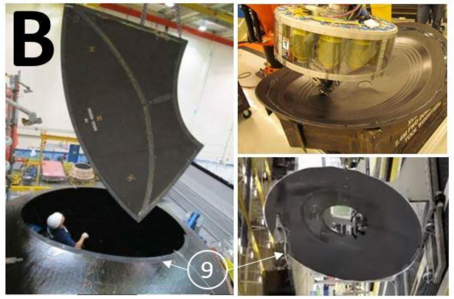


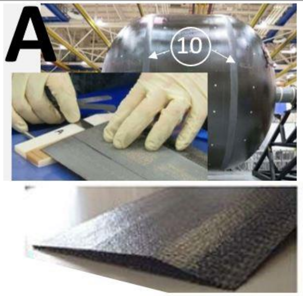
LINES INTEGRATION INTO THE ATLAS CRYOSTAT

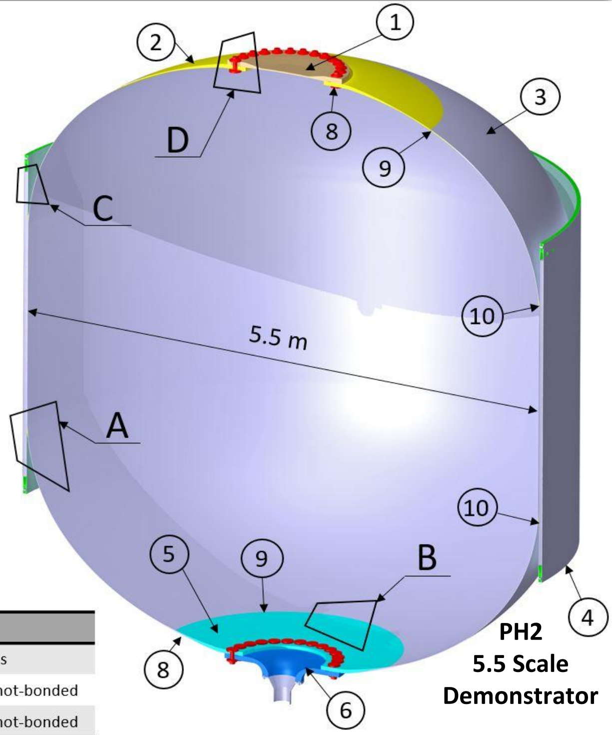
→ **Feedthroughs are allocated on both ends of the cryostat to accommodate lines supporting LAr Calorimeter and SC magnets**

NASA's CCTD – State of the art of CFRP cryotanks

Part	Feature	2.4m in diameter Precursor Tank	5.5m in diameter Scale Demonstrator
Tank Wall	Construction	Monocoque wall with nominal thickness to withstand pressure load	Monocoque wall with nominal thickness to withstand pressure load
		*Pressure scaled up to achieve same stresses in tank joint than Scale Demonstrator	*Design Pressure=3 bars
	*Fiber Placement	Robotic Automated Fiber Placement (RAFP)	Robotic Automated Fiber Placement (RAFP)
	*Curing	Out-of-Autoclave processing (low pressure)	Out-of-Autoclave processing (low pressure)
	Layup	Hybrid laminate with centred 6 thin plies	Hybrid laminate with centred 6 thin plies
	Material	IM7/5321-1, 70 gsm and 145 gsm RAFP slit-tape tow (STT)	IM7/5321-1, 70 gsm and 145 gsm RAFP slit-tape tow (STT)
	Tooling	Multipiece C/E mandrel (24 segments), RAFP cell, Oven	Multipiece C/E mandrel (20 segments), RAFP cell, Oven
	SHM	Acoustic Emission sensor-based system	Acoustic Emission sensor-based system (20 sensors required)
	SE Y-Joint	Baseline hot-bonded softening strip	Optimized hot-bonded softening strip
	SE Scarf Joints	Scarf shape included in muiltipiece mandrel	Scarf shape included in muiltipiece mandrel
	NDI	Trough-Transmission Ultrasonic (TTU)and Pulse Echo (PE)	Trough-Transmission Ultrasonic (TTU), Pulse Echo (PE)and Flash thermography
Skirt	Construction	Monocoque thick skirt	Fluted core (Inner skin+flute pannels+outer skin)
	*Fiber Placement	Robotic Automated Fiber Placement (RAFP)	Robotic Automated Fiber Placement (RAFP)
	*Curing	Out-of-Autoclave processing (low pressure)	Out-of-Autoclave processing (low pressure)
	Layup	Thick ply laminate	Inner skin thick ply laminate + flute panel laminate + Outer skin thick ply laminate
	Material	IM7/5321-1, 145 gsm RAFP slit-tape tow	Skins: IM7/5321-1, 145 gsm RAFP slit-tape tow
			Flute panel: C/E fabric (facesheets) and thin tapes (angled web members)
	Tooling	Skirt Alignment Fixture, RAFP cell, Oven	Flute layup mandrel, Skirt Alignment Fixture, RAFP cell, Oven
	SE Y-Joint	Co-bonded and hot-bonded softening strip	Co-bonded and hot-bonded softening strip
	End-Joint	None, designed to ease of handling	Load-bearing design, to vent leaks and to apply flight axial loads along tests
Forward Cover	Construction	Monocoque dome with nominal thickness to withstand pressure load	Monocoque dome with nominal thickness to withstand pressure load
		*Pressure scaled up to achieve same stresses in tank joint than Scale Demonstrator	*Design Pressure=3 bars
	*Fiber Placement	Single-headed Robotic Automated Fiber Placement (RAFP)	Single-headed Robotic Automated Fiber Placement (RAFP)
	*Curing	Autoclave processing (0.57 Mpa with 94.8kPa vacuum)	Autoclave processing (0.57 Mpa with 94.8kPa vacuum)
	Layup	Hybrid laminate with centred 6 thin plies	Hybrid laminate with centred 6 thin plies
	Material	IM7/5321-1, 70 gsm and 145 gsm RAFP slit-tape tow (STT)	IM7/5321-1, 70 gsm and 145 gsm RAFP slit-tape tow (STT)
	Tooling	Forward cover mold, RAFP cell, Autoclave	Forward cover mold, RAFP cell, Autoclave
	SE Scarf Joint	Co-bonded and hot-bonded (scarf shape included in cover mould)	Co-bonded and hot-bonded (scarf shape included in cover mould)
Sump Cover	Construction	Monocoque dome with nominal thickness to withstand pressure load	Monocoque dome with nominal thickness to withstand pressure load
		*Pressure scaled up to achieve same stresses in tank joint than Scale Demonstrator	*Design Pressure=3 bars
	*Fiber Placement	Single-headed Robotic Automated Fiber Placement (RAFP)	Single-headed Robotic Automated Fiber Placement (RAFP)
	*Curing	Autoclave processing (low pressure)	Autoclave processing (low pressure)
	Layup	Hybrid laminate with centred 6 thin plies	Hybrid laminate with centred 6 thin plies
	Material	IM7/5321-1, 70 gsm and 145 gsm RAFP slit-tape tow (STT)	IM7/5321-1, 70 gsm and 145 gsm RAFP slit-tape tow (STT)
	Tooling	Forward cover mold, RAFP cell, Autoclave	Forward cover mold, RAFP cell, Autoclave
	SE Scarf Joint	Co-bonded and hot-bonded (scarf shape included in cover mould)	Co-bonded and hot-bonded (scarf shape included in cover mould)
Forward Flange	Construction	Carbon Composite thin close-out	Carbon Composite thick flange
	*Fiber Placement	Hand layup	Hand layup
	*Curing	Autoclave processing (0.57 Mpa with 94.8kPa vacuum)	Autoclave processing (0.57 Mpa with 94.8kPa vacuum)
	Layup	Hybrid laminate with centred 6 thin plies	Hybrid laminate with centred 6 thin plies
	Material	IM7/5321-1, 70 gsm and 145 gsm hand-lay up layers or STT??	IM7/5321-1, 70 gsm and 145 gsm hand layup layers
	Tooling	Close-out mold, ancillary cure tools and stands (Al and steel), Autoclave	Flange mould, ancillary cure tools and stands (Al and steel), Autoclave
	Joint	co-bonded and hot-bonded scarf joint	Bolted joint (torque limited bolts, Belleville washers and Furon seals)
Sump Flange	Construction	Carbon Composite thin close-out	Carbon Composite thick flange
	*Fiber Placement	Hand layup	Hand layup
	*Curing	Autoclave processing (0.57 Mpa with 94.8kPa vacuum)	Autoclave processing (0.57 Mpa with 94.8kPa vacuum)
	Layup	Hybrid laminate with centred 6 thin plies	Hybrid laminate with centred 6 thin plies
	Material	IM7/5321-1, 70 gsm and 145 gsm hand-lay up pre-preg layers	IM7/5321-1, 70 gsm and 145 gsm hand layup pre-preg layers
	Tooling	Autoclave	Autoclave
	Joint	Bolted joint (torque limited bolts, Belleville washers and Furon seals)	Bolted joint (torque limited bolts, Belleville washers and Furon seals)







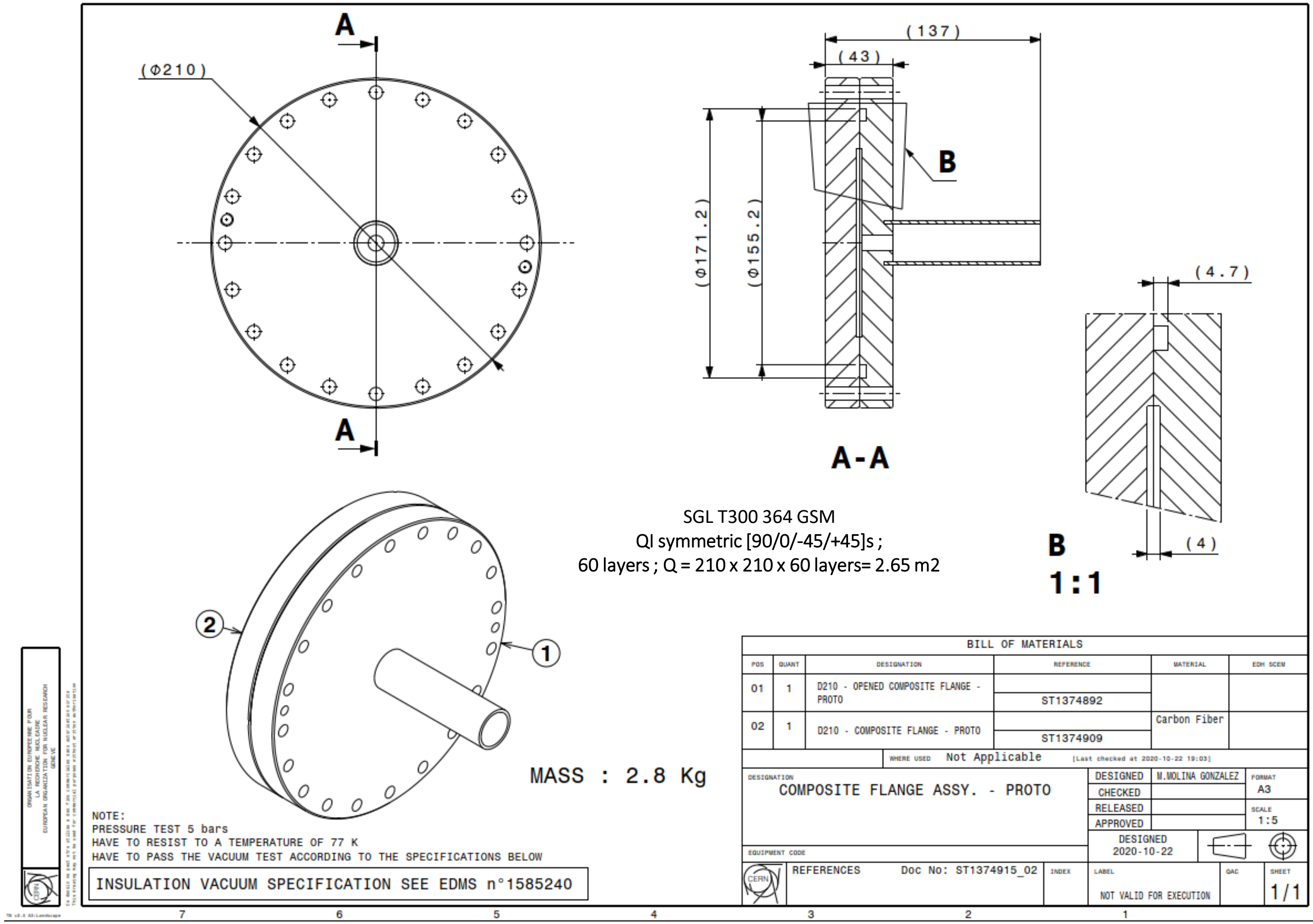
Item	Component	Material (CFRP)
1	Forward Flange	5320-1 hybrid laminate
2	Forward Cover	5320-1 hybrid laminate
3	Tank Wall	5320-1 hybrid laminate
4	Skirt	5320-1 thick plies
5	Sump Cover	5320-1 hybrid laminate
6	Sump Flange	5320-1 hybrid laminate
7	Flute panel core	5320-1 Thin plies

Item	Joint	Material	Components	Note
8	Torque limited bolts	Metal ?	Flanges-Covers	Belleville washers and Furon seals
9	Scarf Joint	C/E	Covers-Tank wall	Structurally efficient co-bonded hot-bonded
10	Y-Joint (softening strip)	E/E	Skirt-Tank wall	Structurally efficient co-bonded hot-bonded

Equivalency Tests (PH1)	Out-of-Autoclave				Autoclave		
ATK	IM7/M56 145hlu, 70hlu		IM7/5320-1 145hlu,70hlu				IM7/8552-1 145hlu
Boeing			IM7/5320-1 145fp,70fp		IM7/BXA 145fp	IM10/8552-1 70fp	
Lockheed Martin	IM7/M56 145fp, 70hlu	IM7/ MTM45-1 145fp,70hlu		IM7/TC250 145fp,70hlu			
Northrop Grumman		IM7/ MTM45-1 70hlu			IM7/BXA 70hlu		

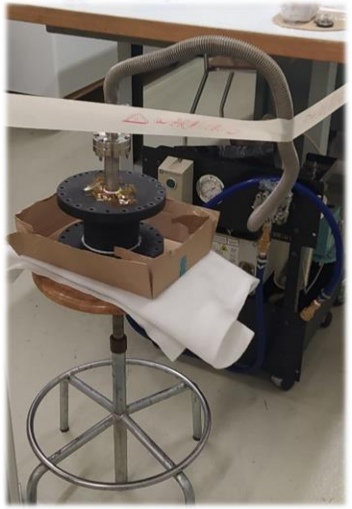
Ply thickness: 145= 145gsm FAW ; 70= 70gsm FAW / Manufacturing technique: hlu= hand layup ; fp= fiber placed

→ NASA CCTD 5.5m in diameter demonstrator is the most advanced cryotank in literature reviewed (Successfully tested)

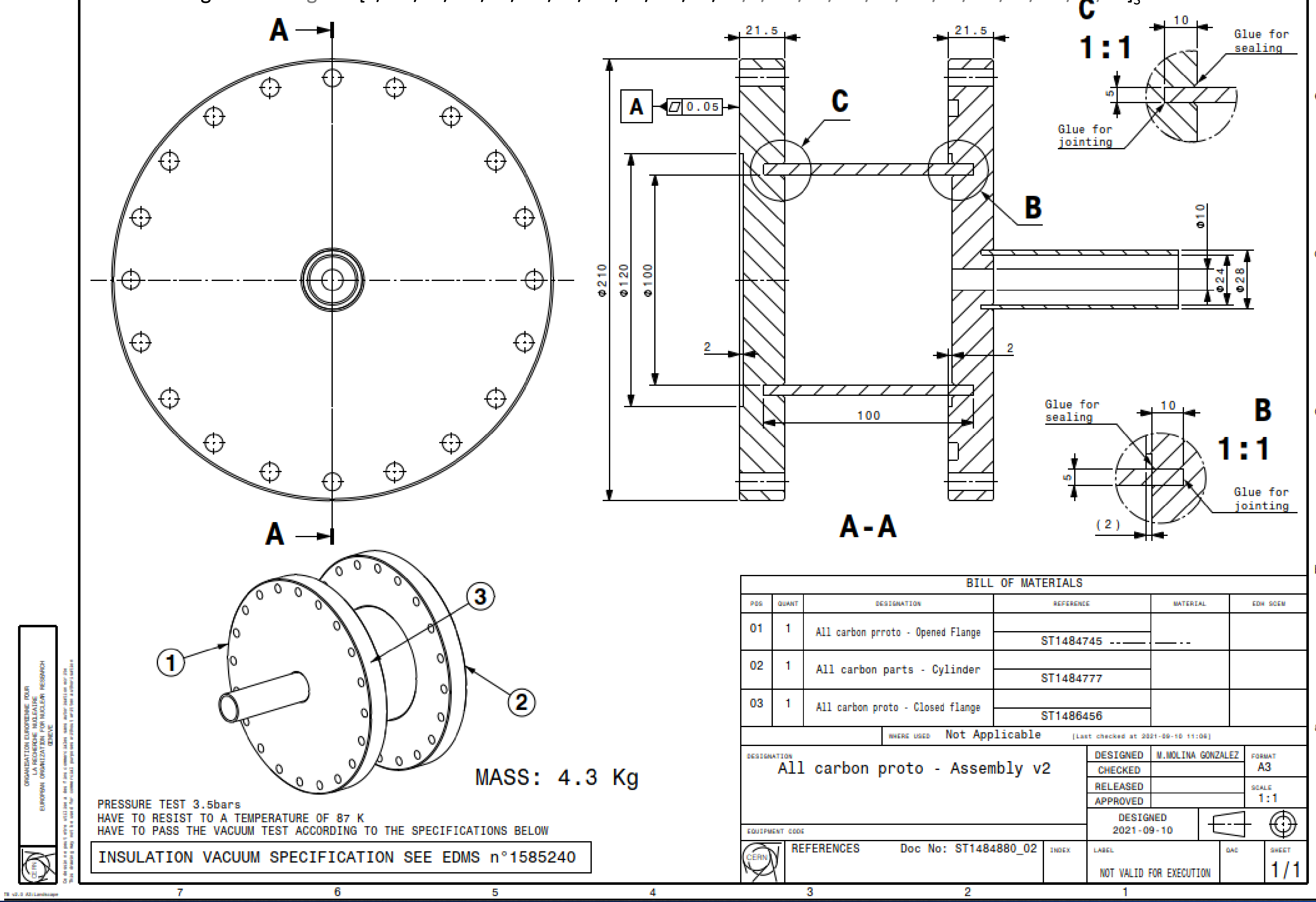


→ **Production drawing and laminate**

Feasibility study – Test Unit 2



CTD133P 145gsm and 70 gsm : $[0/-15/15/-30/30/-45/45/-60/60/-75/75/90/0/-15/15/-30/30/-45/45/-60/60/-75/75/90]_S$

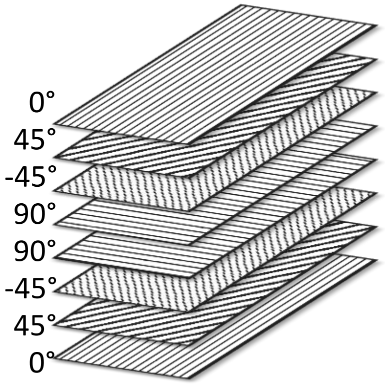


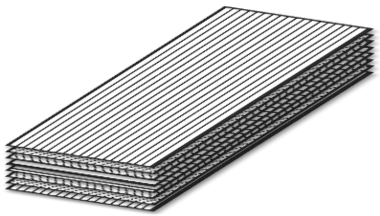
→ Production drawing and laminate

COURTESY OF WP4
Massimo Angeletti

Cryostat for future detectors at CERN

Stacking of plies into a composite laminate with different angles of fibre reinforcement





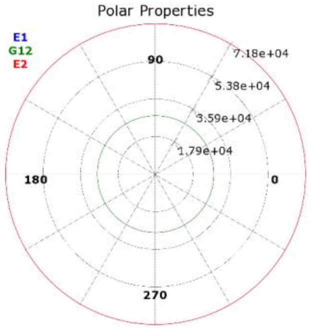
CFRP

Intermediate Modulus (IM-CFRP)

Carbon fiber:
IM10, E1=310GPa

Lamina:
Carbon Unidirectional Prepreg
IM10/8552 60% Vf
E1=190GPa, Thickness=0,1mm
0° Tensile strength = 3310MPa
0° Compression strength = 1793MPa
In-plane shear strength = 128 MPa

Laminate:
Quasi-isotropic stack-up = [0,45,-45,90]s
Laminate stiffness E1=E2=71.8 GPa
Laminate shear stiffness G12=27.8GPa

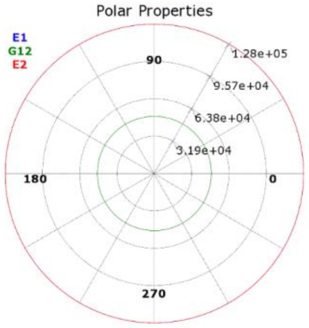


High Modulus (HM-CFRP)

Carbon fiber:
M60J, E1=588GPa

Lamina:
Carbon Unidirectional Prepreg
M60J/EX-1515 60% Vf
E1=360GPa, Thickness=0,1mm
0° Tensile strength = 2010MPa
0° Compression strength = 790MPa
90° Tensile strength = 34MPa
In-plane shear strength = 55MPa

Laminate:
Quasi-isotropic stack-up = [0,45,-45,90]s
Laminate stiffness E1=E2=128 GPa
Laminate shear stiffness G12=49GPa

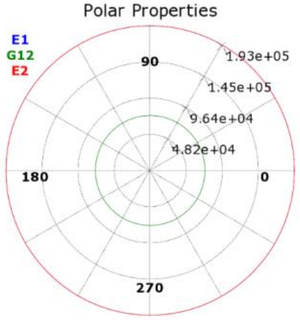


Ultra High Modulus (UHM-CFRP)

Carbon fiber:
YS-95A, E1=920GPa

Lamina:
Carbon Unidirectional Prepreg
YS-95A/EX-1515 60% Vf
E1=540GPa, Thickness=0,1mm
0° Tensile strength = 1900MPa
0° Compression strength = 340MPa
90° Tensile strength = 25MPa
In-plane shear strength = 50MPa

Laminate:
Quasi-isotropic stack-up = [0,45,-45,90]s
Laminate stiffness E1=E2=193 GPa
Laminate shear stiffness G12=73GPa



→ Preliminary analysis showed the use of CFRP can improve metallic design for both, solid plate and sandchich structures