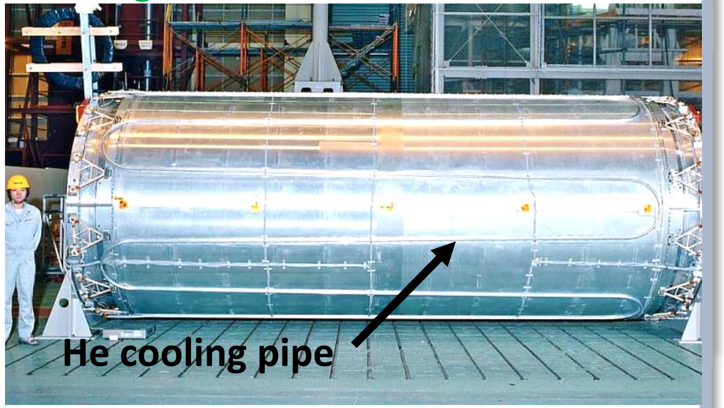
4th PBC Tech Workshop: Cryogenics
28th Sep 2022
https://indico.cern.ch/event/1180067/

Ultralight Cryogenic Structures for HEP experiments

EP R&D WP4:
Low Mass Cryostats for future Magnets & Calorimeter

Maria Soledad Molina Gonzalez

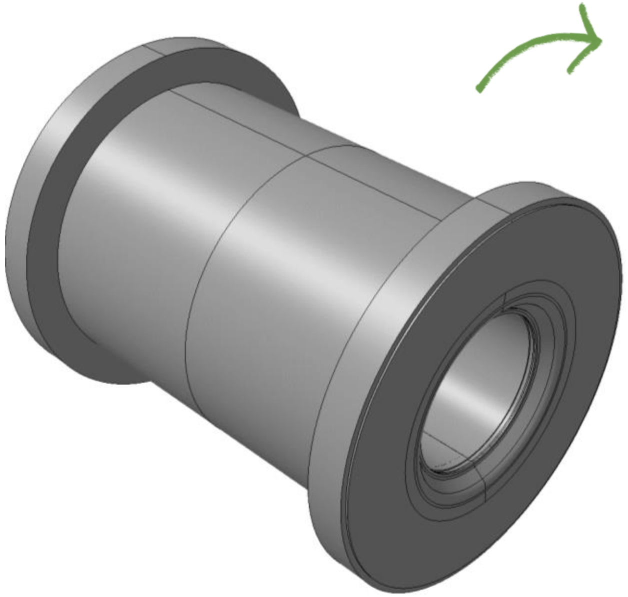
SC Magnet



LAr ECAL calorimeter

Cryostat for SC Magnet:

-Thermal insulation (10e-5 mbar , 293K)

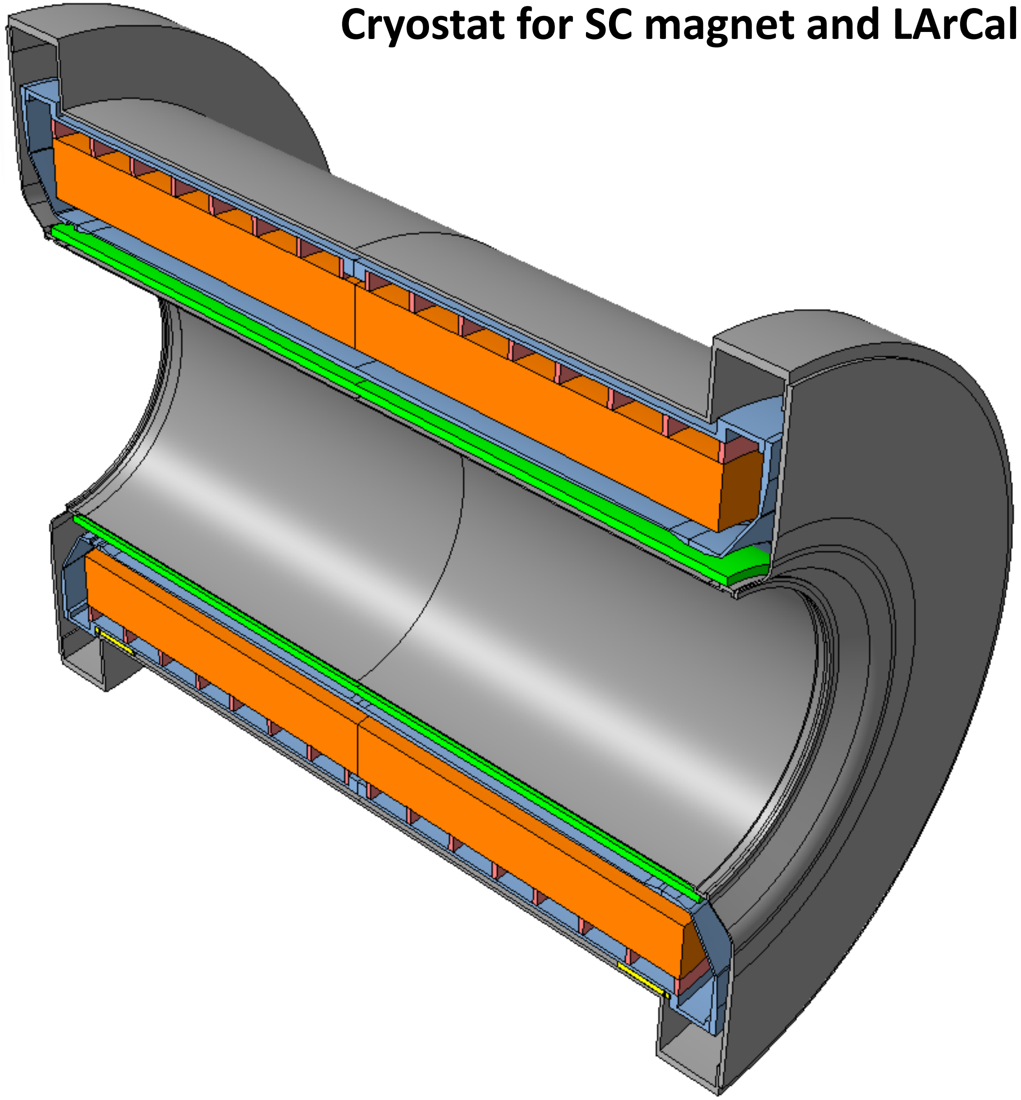


Cryostat for LArCal:

-LAr tightness (3 bars, 87K)

-Thermal insulation (10e-5 mbar, 293K)

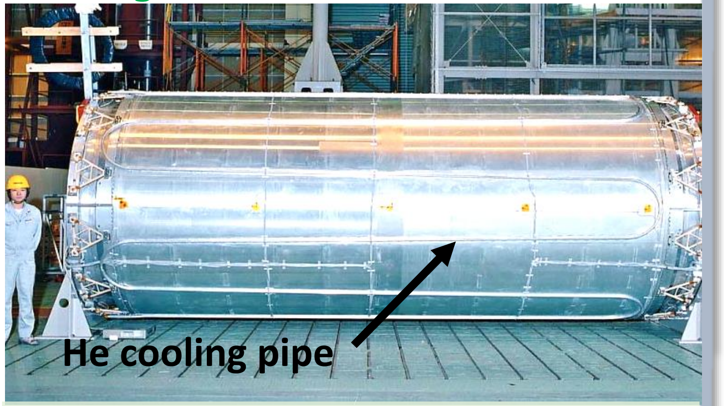
Cryostat for SC magnet and LArCal:



→ Design a cryostat to support LAr Calorimeters (ECAL) and SC magnets in future larger experiments (FCCee-hh)

Main scope

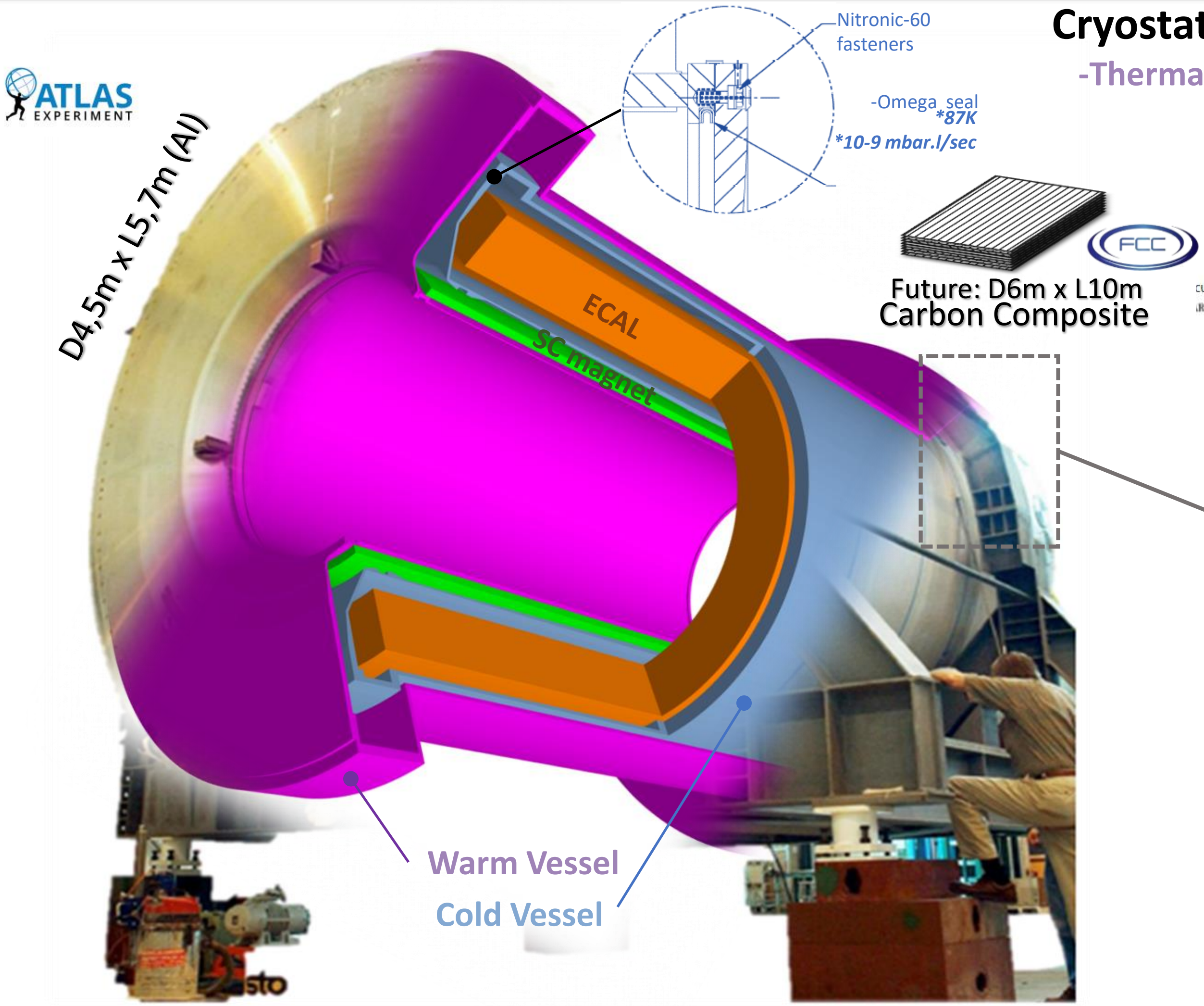
SC Magnet



Ultra-thin cryostat for compact assembly of experiments

LAr ECAL calorimeter

Low material budget cryostat for better detector performance

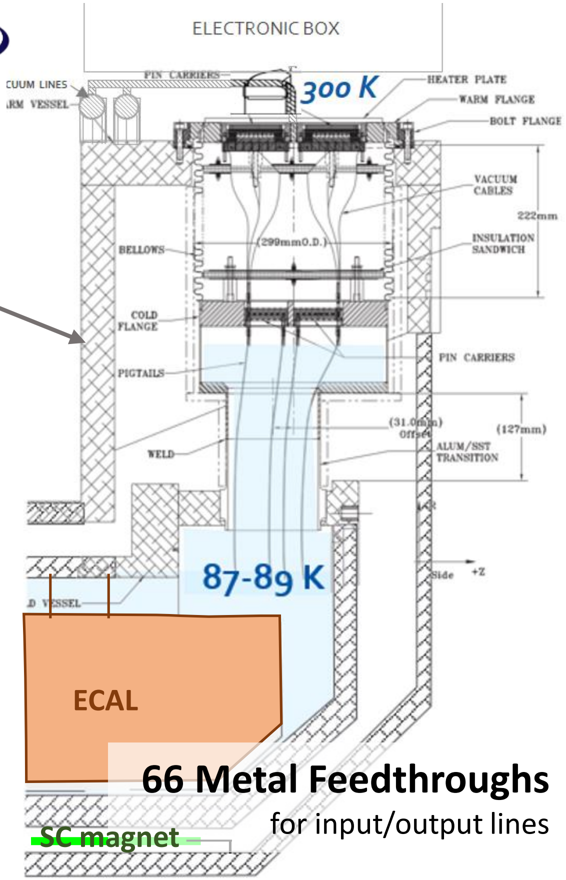


Future: D6m x L10m
Carbon Composite

Cryostat for SC magnet and LArCal:

-Thermal insulation: 10e-5 mbar and 293 K

-LAr tightness: 3.5 bar and 87 K

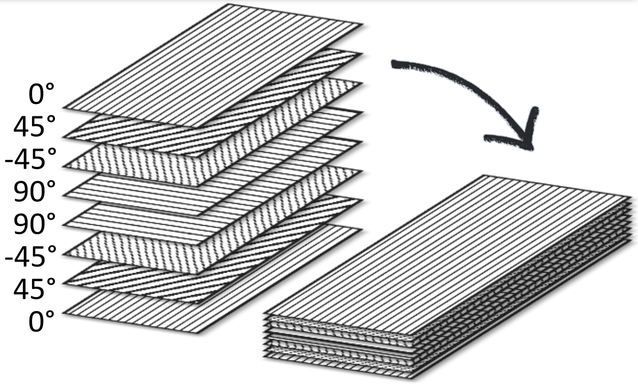


66 Metal Feedthroughs
for input/output lines

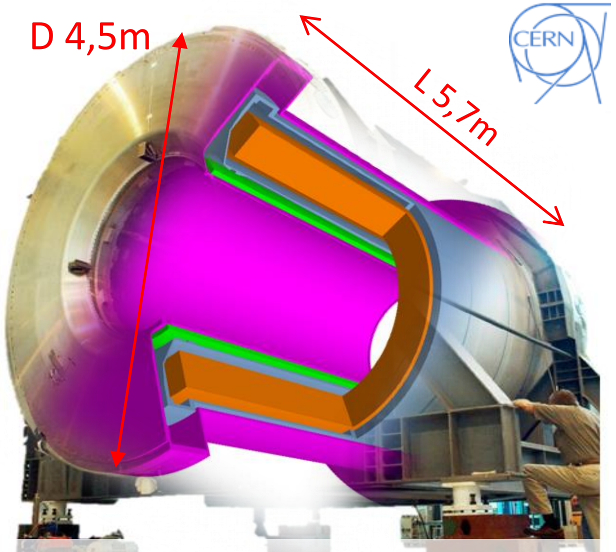
→ Carbon composite (CFRP) to design cryostats with lower material budget to improve future detectors performance.

Carbon Fiber Reinforced Polymer (CFRP)

Properties at Troom *	SS 304 (CMS)	Invar 36	Al 5083 (ATLAS)	G10 (GFRP)	CTD-133 (CFRP)
Tensile Strength [MPa]	505	448	290	262 /48.2	2082 / 48.2
Density [Kg/m3]	8 000	8 050	2 600	1 800	1 130
Rad. Length [mm]			88.9	167	260
CTE [µm/(m x K)]	17.3	1.30	23.8	9.9 / 11.9	-0.3 / 50

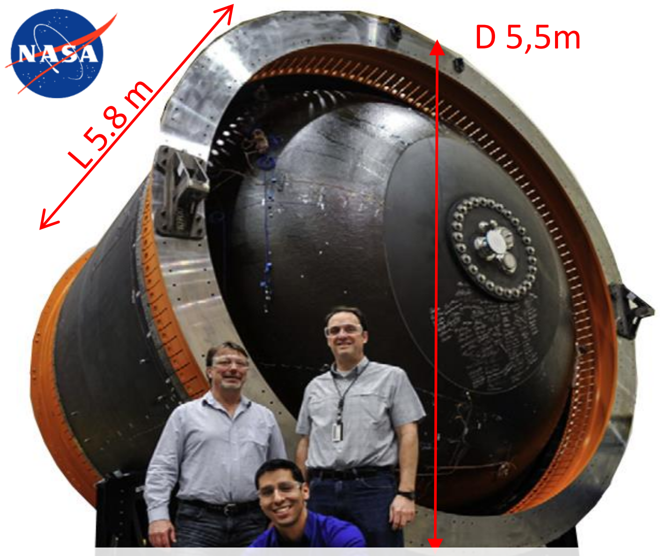


Laminate [0,45,-45,90]s



ATLAS barrel-cryostat

toroidal Al 5083 double wall



NASA's CCTD LH2 cryotank

All carbon composite thin wall

Done / Ongoing / R&D ++

1. **He-leak-tight (Troom & 87 K)?**
2. **Interfaces CFRP-Metal FTs?**

Bread Board Models

3. **Large Scale Manufacturability?**
4. **LAr-leak-tight (87 K) long term?**
5. **Vacuum tight (87K) long term?**

Engineering Model (CAD) + (Bread Board Model)

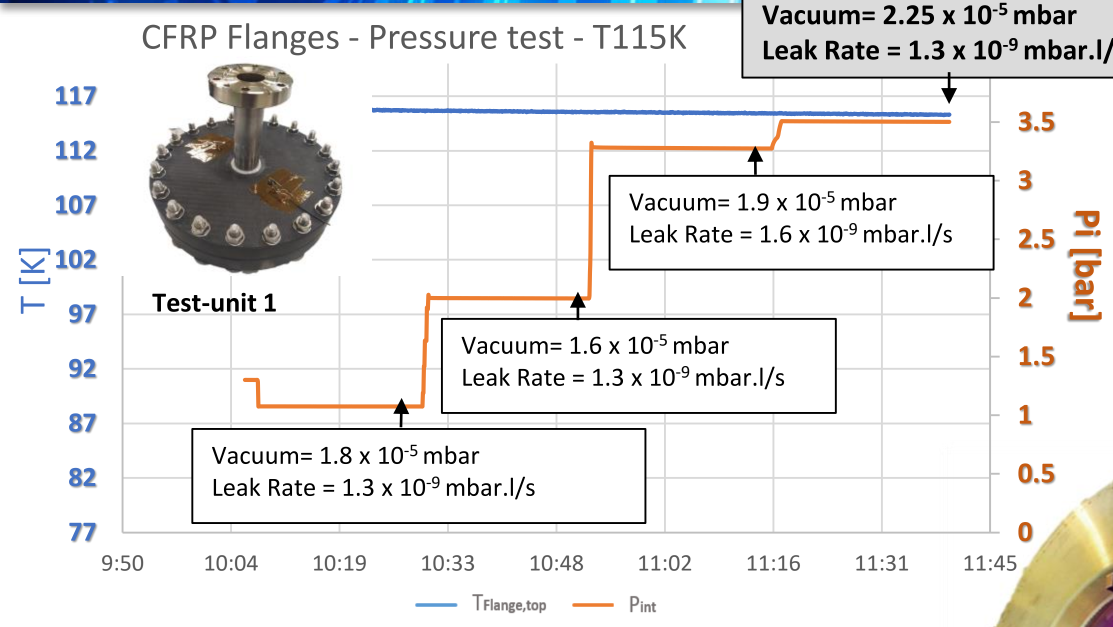
6. **Radiation Resistance (0.1MGy)?**

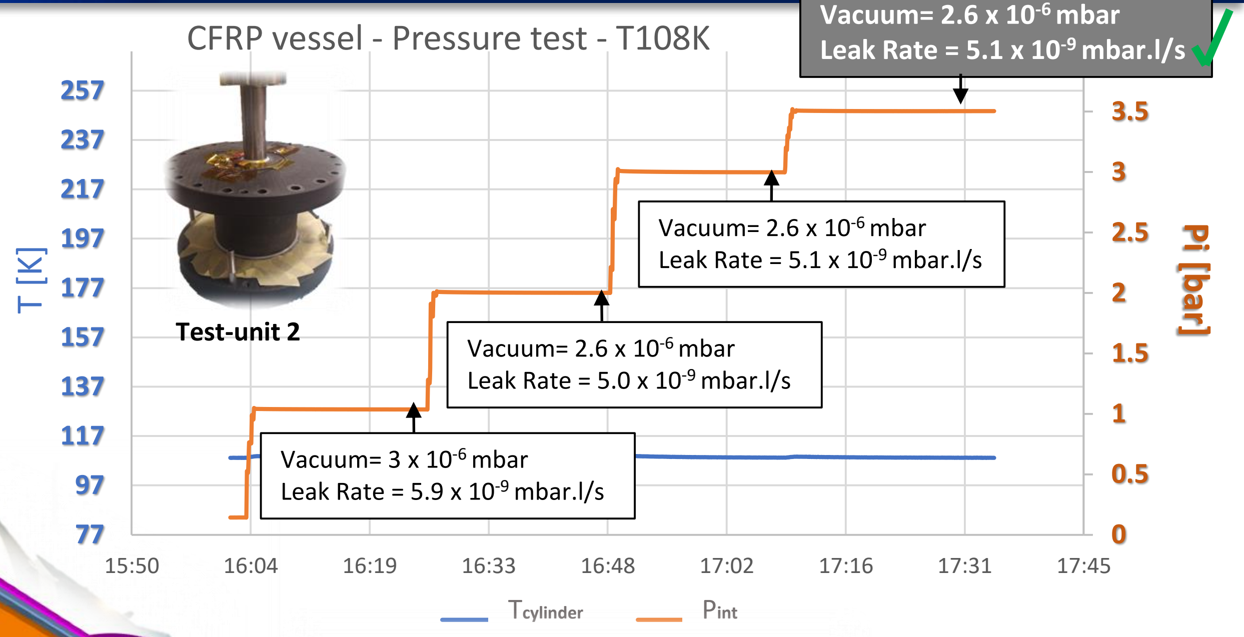
7. **Full carbon Composite Cryostat**

Engineering Model (CAD) + 1mD Concept Demonstrator

→ State of the Art: Aerospace Industry is adopting CFRP solutions for LH2 large scale cryotanks in short term applications

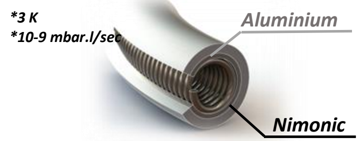
Breadboard Model: Leak-tightness

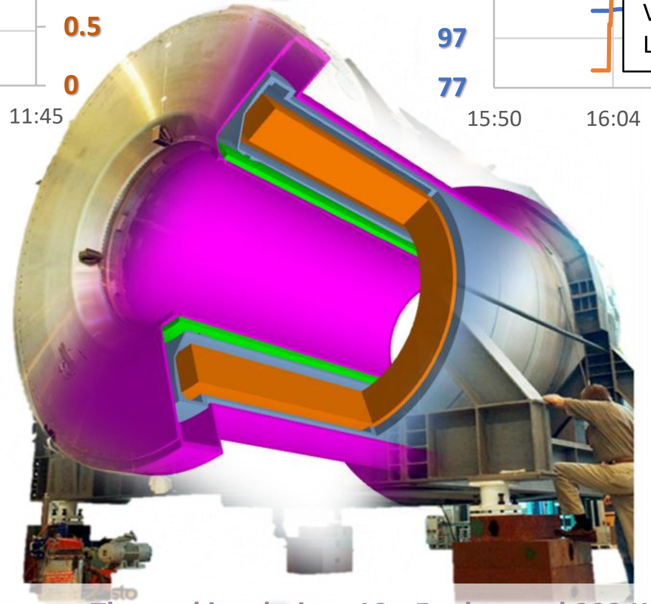




Dismountable joint for cryogenics

Helicoflex metallic seal validated at T=115K* and Pint,max = 3.5 bar



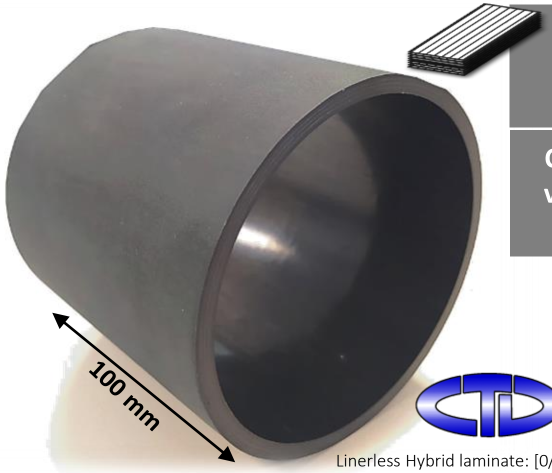


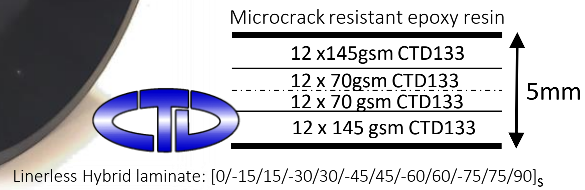
-Thermal insulation: 10e-5 mbar and 293 K

-LAr tightness (10e-9 mbar.l/s*): 3.5 bar and 87 K

Liner-less wall for cryogenics:

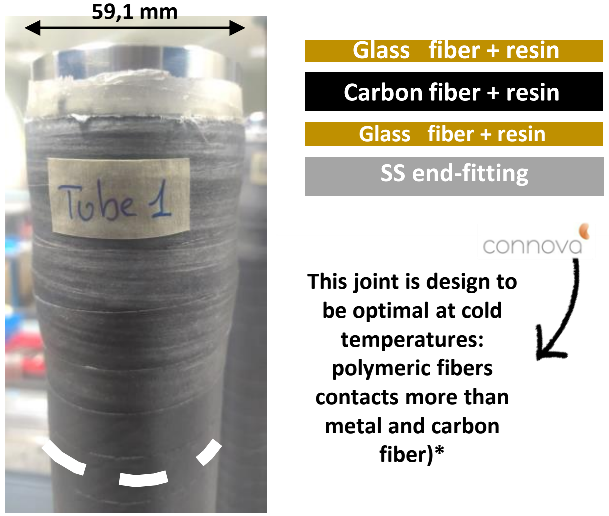
CTD-133 toughened resin validated at T=108K* and Pint,max = 3.5 bar



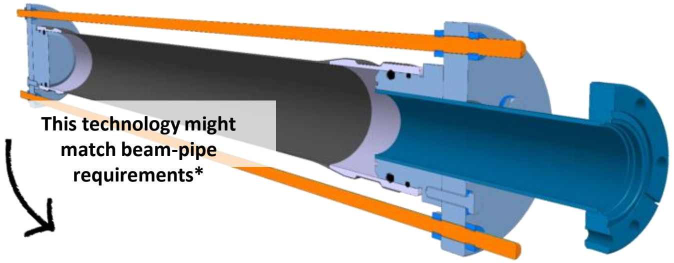


→ Two prototypes built and tested to address thin-wall tightness and sealed joint for CFRP cryostats.

Breadboard Models: Metal-CFRP interface



This joint is design to be optimal at cold temperatures: polymeric fibers contacts more than metal and carbon fiber)*

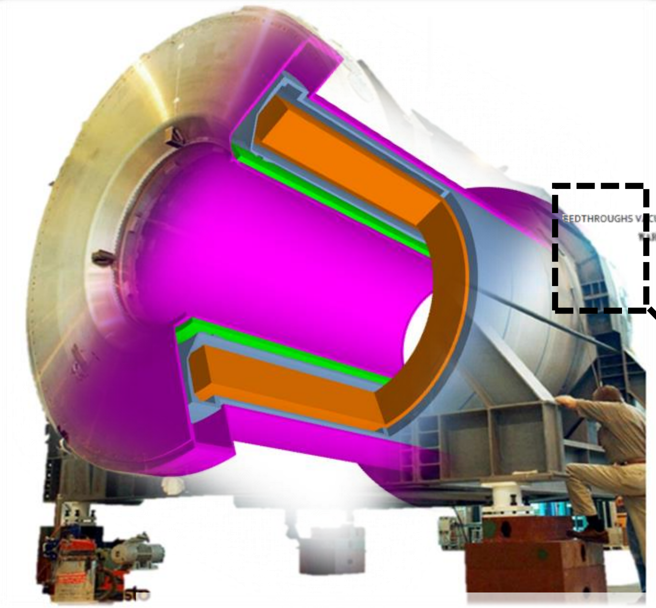


This technology might match beam-pipe requirements*

Cryostat for SC magnet and LArCal:

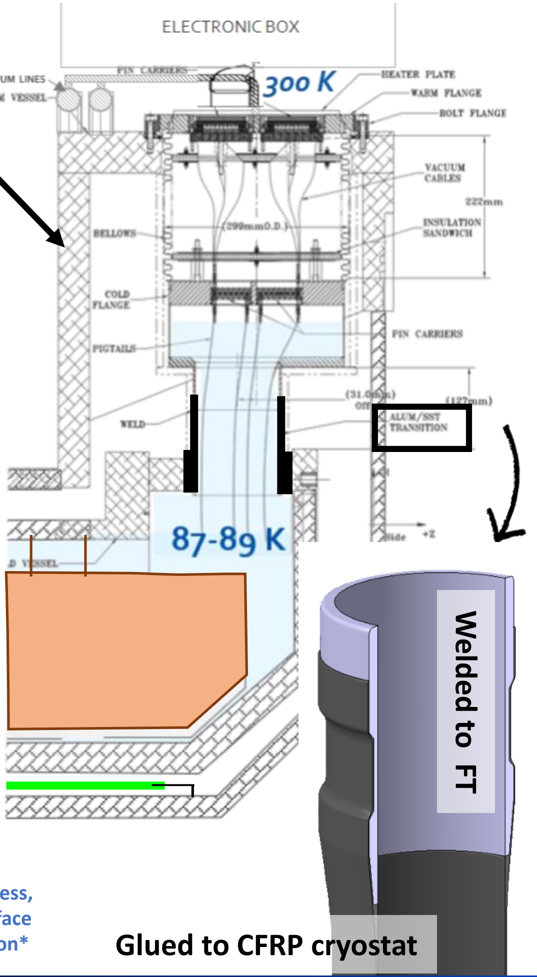
-Thermal insulation: 10e-5 mbar and 293 K

-LAr tightness: 3.5 bar and 87 K



66 Metallic Feedthroughs (FTs)

for input/output lines



Glued to CFRP cryostat

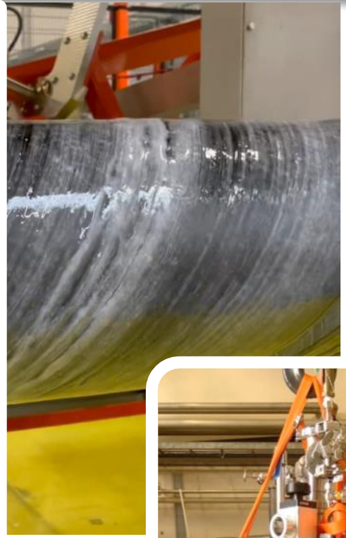
Interface very fragile : damaged along assy*

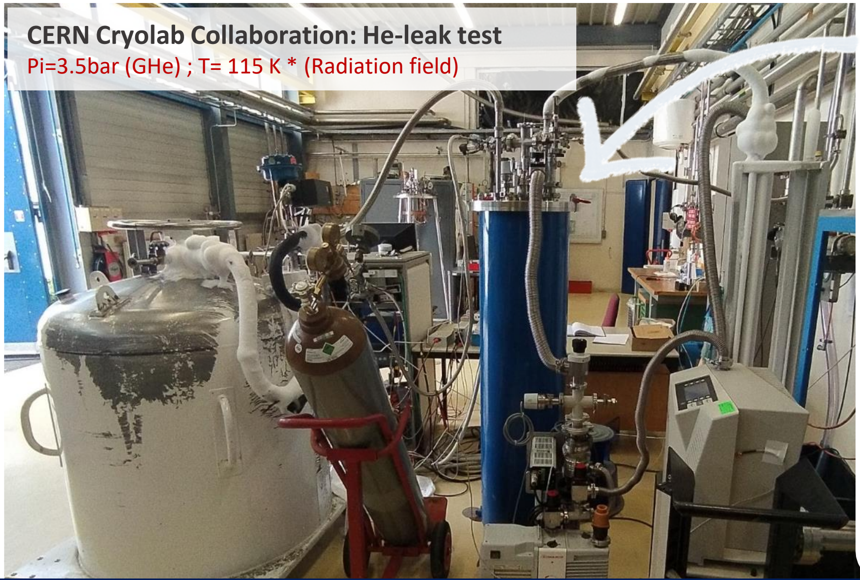
Tube	Resin	Fiber	Wall thickness	End-Fittings	He leak rate (293 K)	He leak rate (100K)
1	CTD-7.1	T800H	0.7 mm	SS 314	10e-9 mbar.l/sec	-
2	Araldite	T800H	1.5 mm	SS 314	10e-11 mbar.l/sec	leak < 10e-7 mbar.l/sec
3	CTD-7.1	T800H	1.5 mm	SS 314	10e-10 mbar.l/sec	-
4	Araldite	T800H	0.7 mm	SS 314	leak < 10e-7 mbar.l/sec	-

Pipe offers leaktightness, but metal-CFRP interface requires optimisization*

→ Leak-tight interface between carbon composite cryostat and metallic feedthroughs is under study.

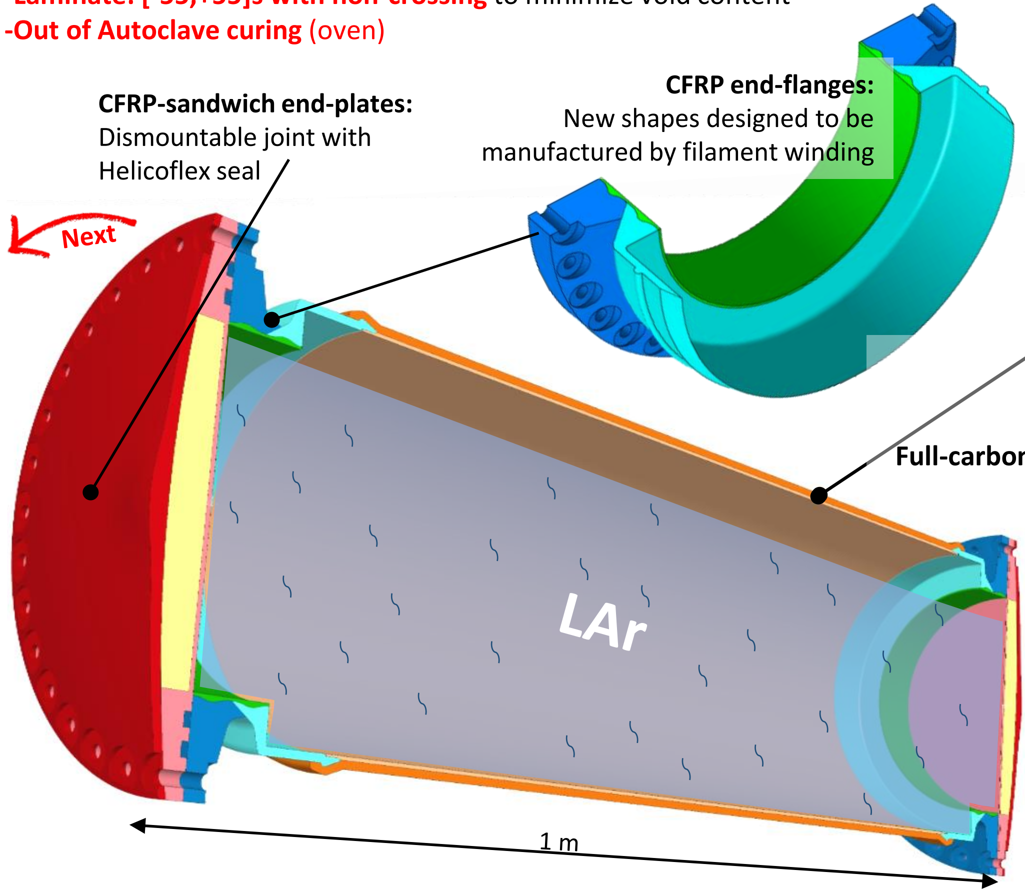
Engineering model: Large scale manufacturing

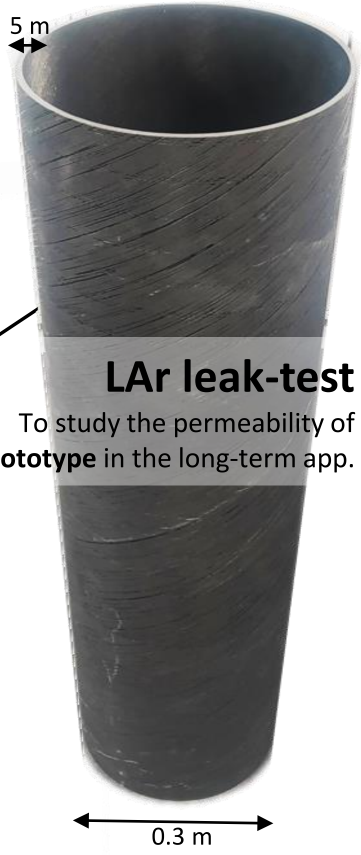




Process development for Wet Filament Winding as an alternative to RAFP tech.

-Optimize **resin bath** preparation and size to minimize void content: **CTD-7.1 and LY 556**
-Optimize **carbon fiber young modulus** (as high as the winding process allows it): **M40J**
-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)

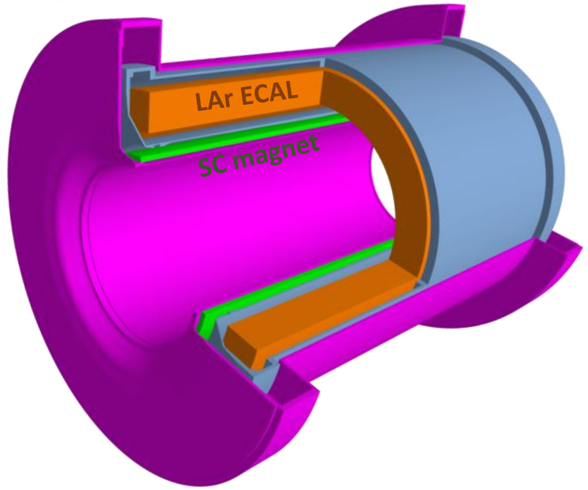


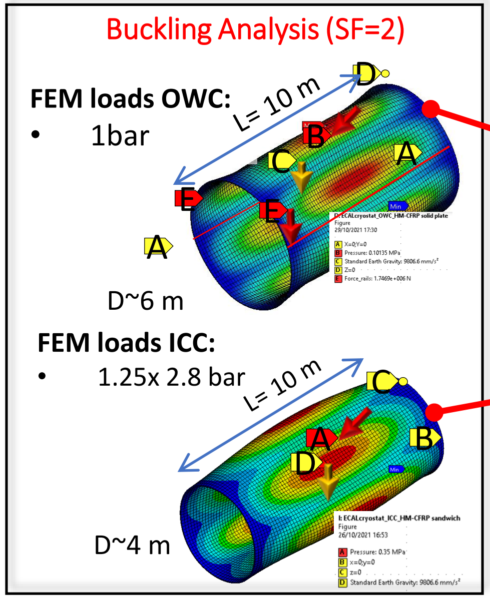


LAr leak-test
To study the permeability of
Full-carbon prototype in the long-term app.

→ Automated process for large-scale production is under development to achieve a laminate with minimal void content.

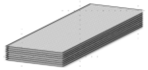
Carbon composite profits





Sandwich Shell

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

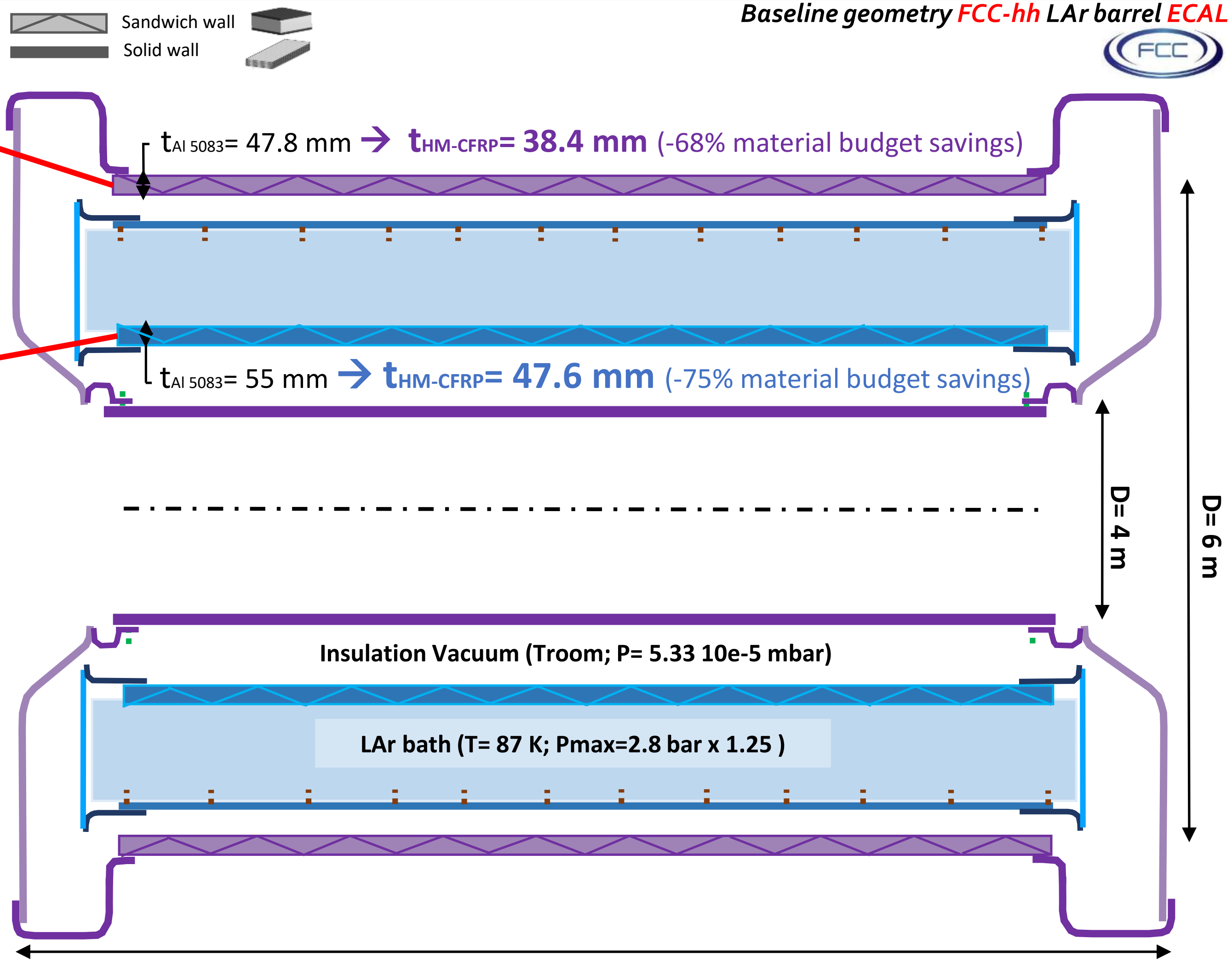


Solid Shell

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

Criteria: Safety Factor = 2	Sandwich shell				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%

Baseline geometry FCC-hh LAr barrel ECAL

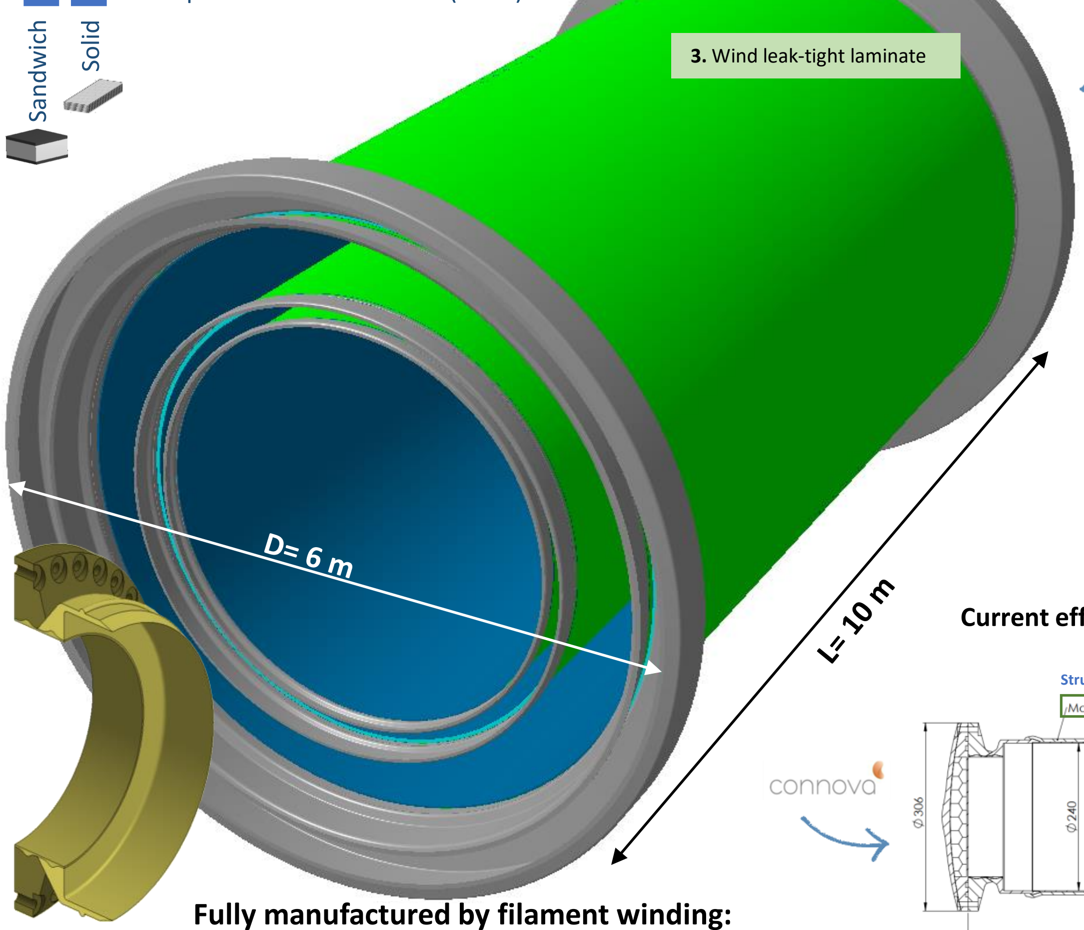


→ CFRP cryostat walls will provide savings in terms of material budget/thickness with respect to an aluminum cryostat

Full-CFRP Cryostat (R&D ++)

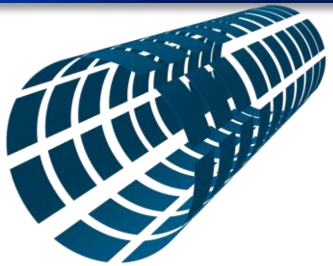
Design criteria: Minimum material budget

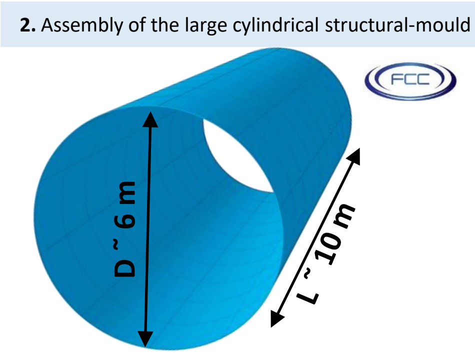
- Non-crossing laminate (leak-tight CFRP)
- Multi-piece structural mould (CFRP)



Multipiece Structural Mould

To simplify production and integration due to the large dimensions expected in future detectors.

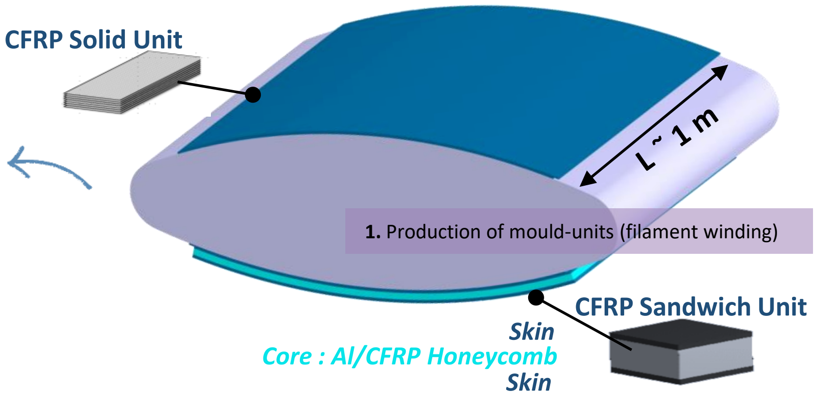




Development of a large multifunctional carbon composite mould

A) Tool: to wind cryostat walls (toughened epoxy resin at cryogenics)

B) Structural part: carry the loads expected in each of the cylindrical walls of future cryostats

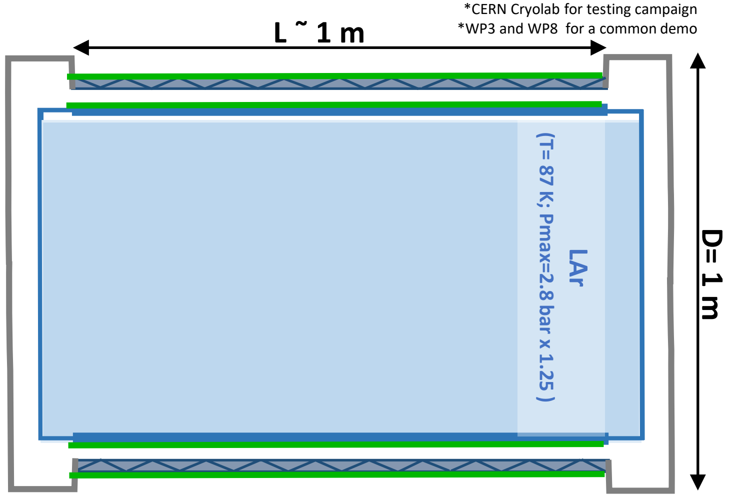


FULL-CARBON LARGE-SCALE concept demonstrator (2024)

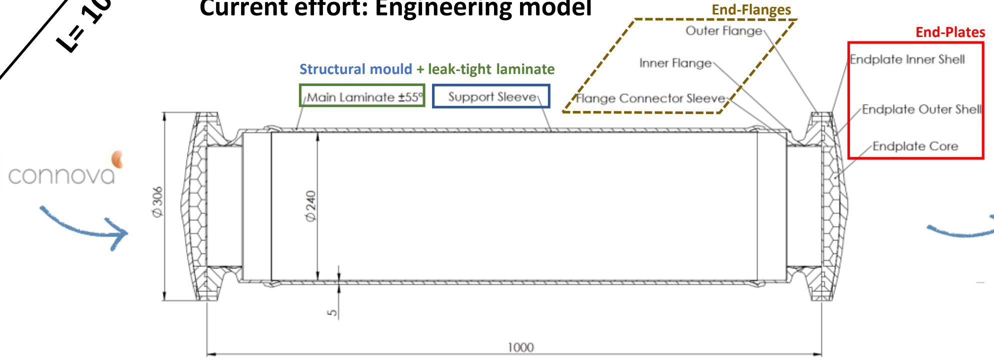
Collaboration

*CERN Cryolab for testing campaign

*WP3 and WP8 for a common demo



Current effort: Engineering model



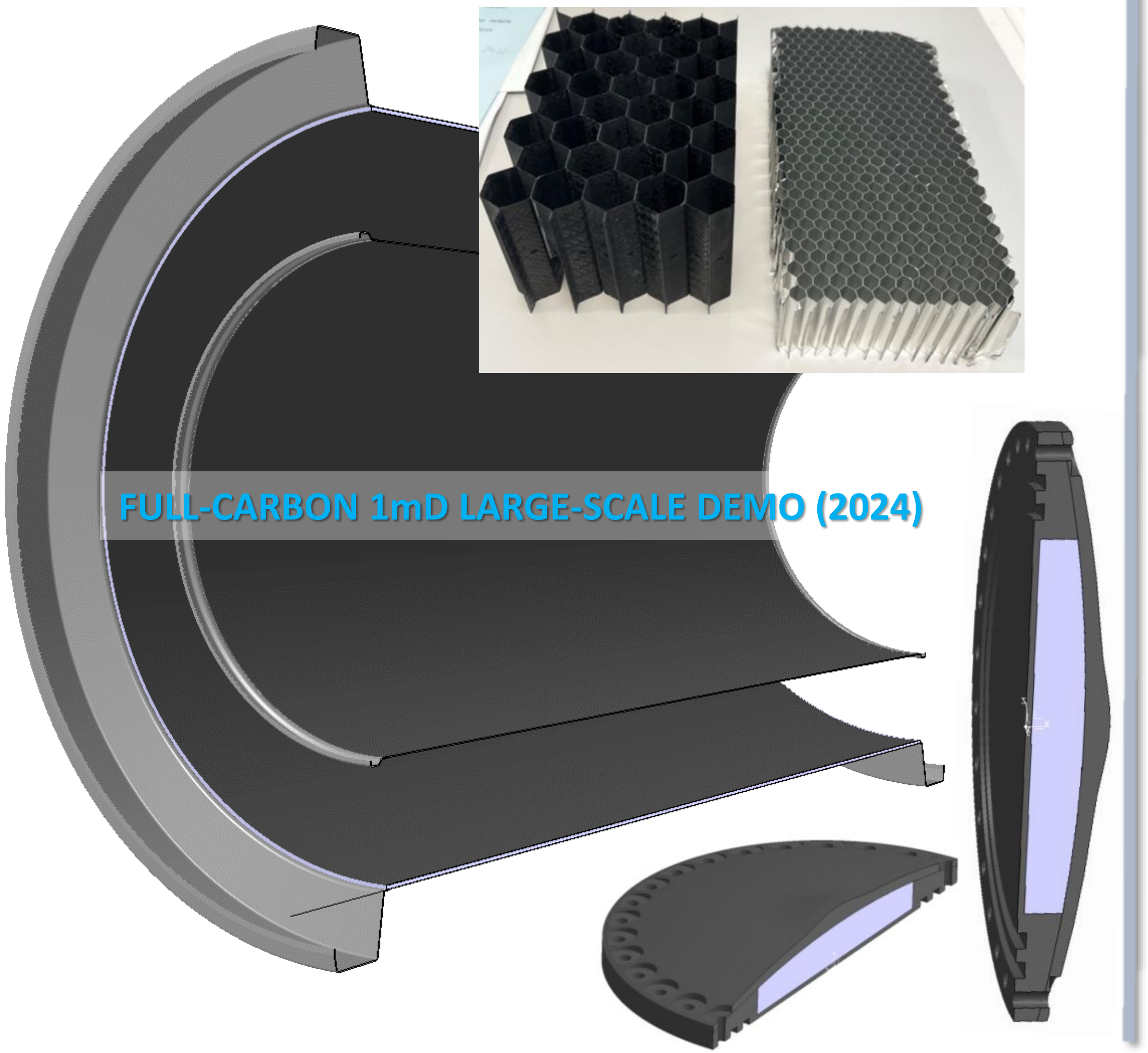
Fully manufactured by filament winding:

*Leak-tight integration with cylindrical walls

*Carrying axial and radial loads

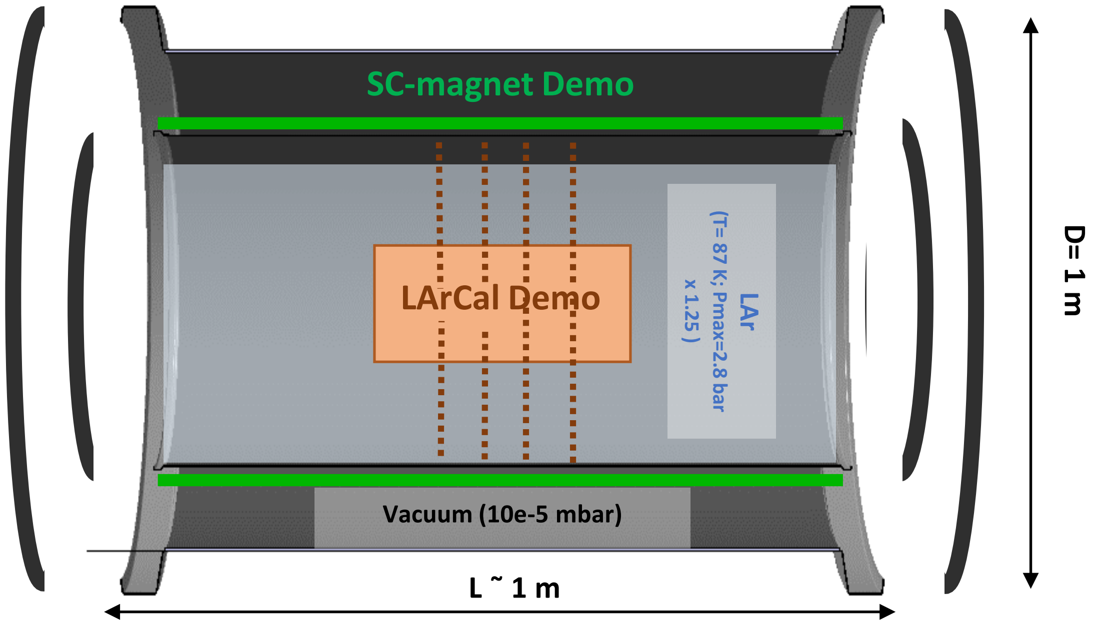
→ Full carbon composite demonstrator based on learnings from breadboard models and large-scale concept development.

Collaboration for R&D++



WP3 LArCal - Requirements & Concept Demonstrator
WP8 SC magnet - Requirements & Concept Demonstrator
Connova & Workshape –Prototyping & Large-Scale Manufacturing, Material
CERN Cryolab - Assessment & Testing (Lar and He leaktightness)
CERN EN/MM – Mech characterization at Troom and 87K
CERN SY/STI - Radiation Hardness
ALICE 3 – Cryostat and services for a Large SC Magnet (Cryo & Power)
AMS - Full carbon HC core

...



→ Full carbon composite demonstrator based on learnings from breadboard models and large-scale concept development

Thank you very much

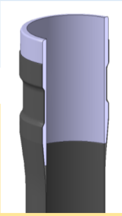
Back-Up

1. What has been done?

a) Design requirements, materials and processes

b) CFRP liner-less wall leak-tight at cryogenics (breadboard model tested)

c) Dismountable joint between CFRP parts at cryogenics (breadboard model tested)



2. Ongoing …

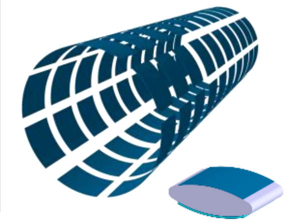
a) Interface between CFRP cryostat and metallic feed-throughs (samples to be tested)

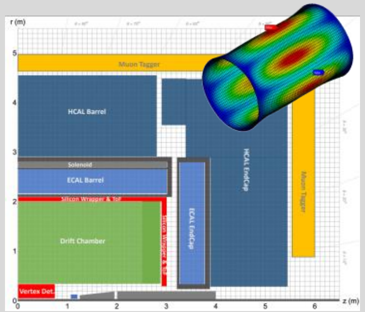
b) Automated manufacturing process for large-scale CFRP cryostat (engineering model to be tested)

3. What is next?

a) Detailed analysis of a large CFRP cryostat for FCC Detector Concept

b) 1m diameter concept demonstrator **(R&D ++)**



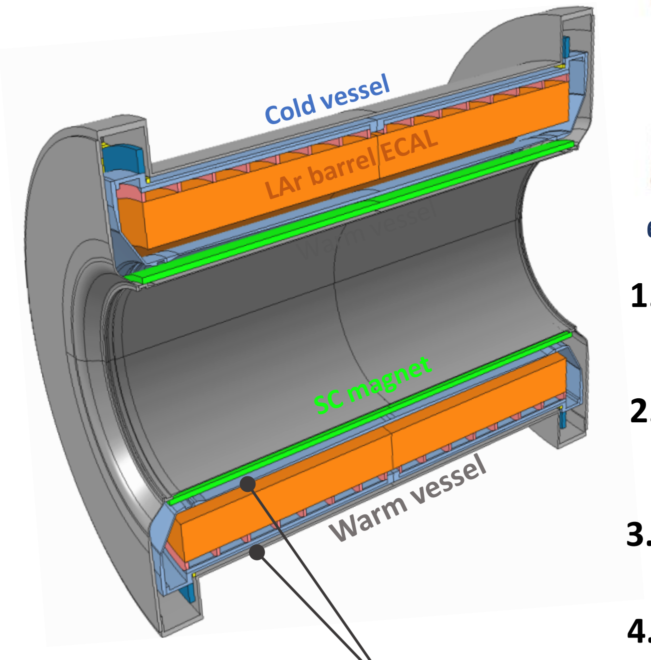


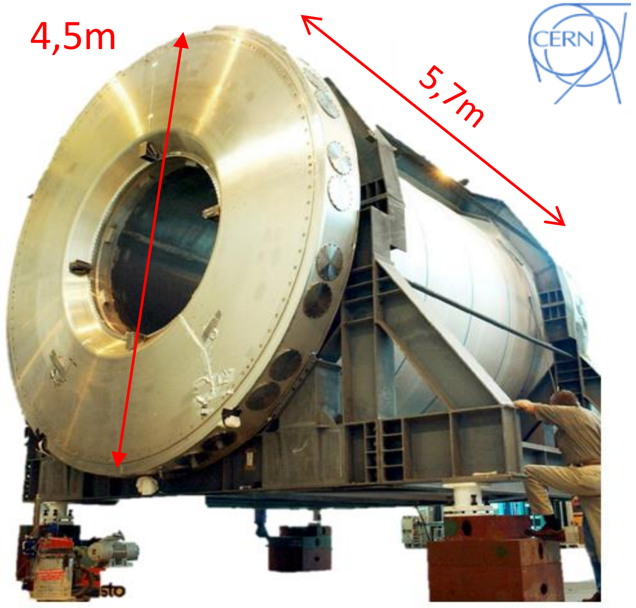
Thank you very much !

Main design requirements

ATLAS barrel-cryostat

toroidal Al 5083 *double wall*



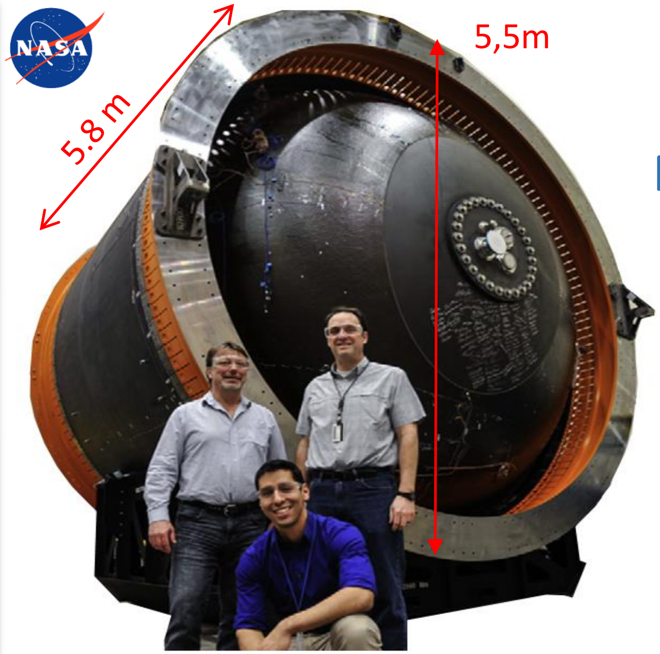


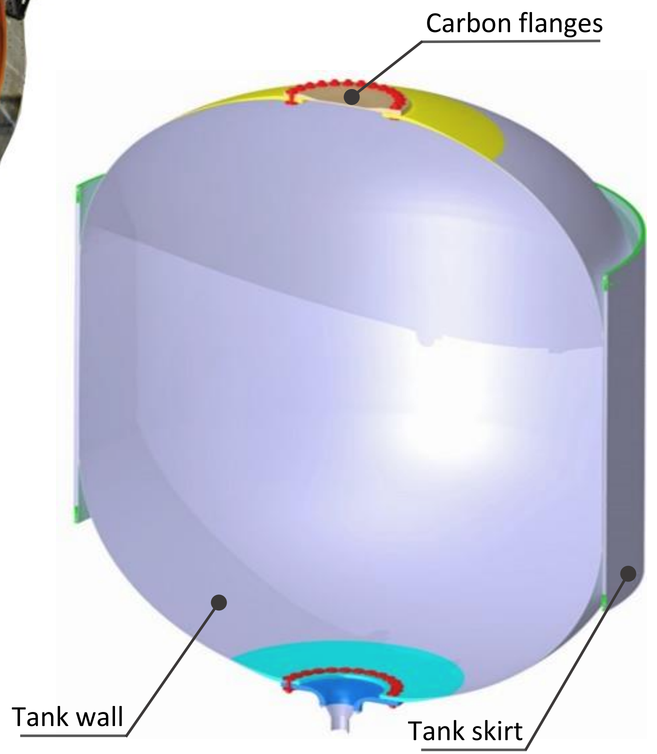
6 x 10m in future cryostats*

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
3. **Radiation Resistance:**
   Total lifetime dose < 0.1 MGy
4. **Minimize material budget**
   Al 5083 thin wall+ buckling resistant design *

NASA's CCTD LH2 cryotank

All carbon composite thin wall



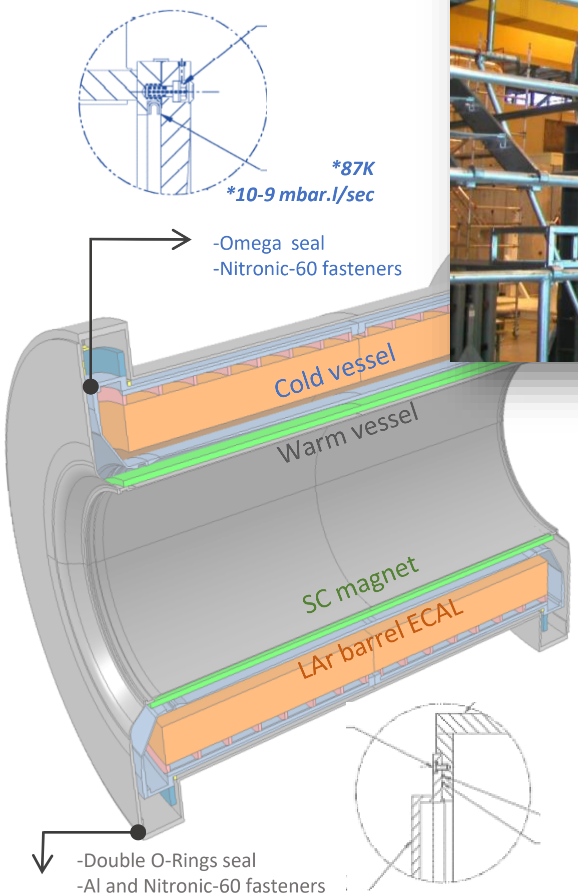


1. **Tightness in short term**
   Tank wall: LH2 (LOX) leak-tight
   Tank skirt: Vacuum tight
2. **Operating condition:**
   Tank wall: T=20 K; $P_{int,\ max}$ = 3.2 bar
   Tank skirt: T_{room} ; P_{int} =10^{-5} mbar
3. **Minimize mass**
   CFRP thin wall + stiffening skirt

✓ **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*



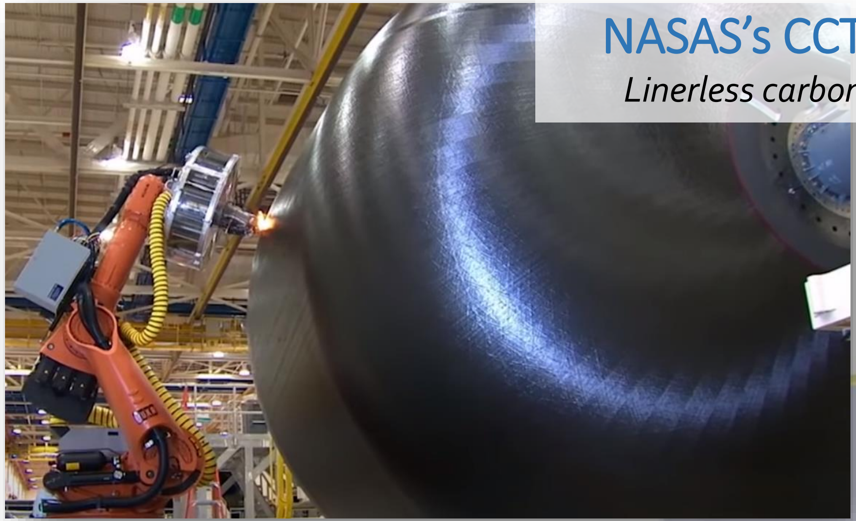
1. Material:
Aluminum 5083

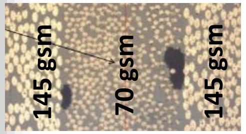
2. Process:
Forming, welding and machining

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

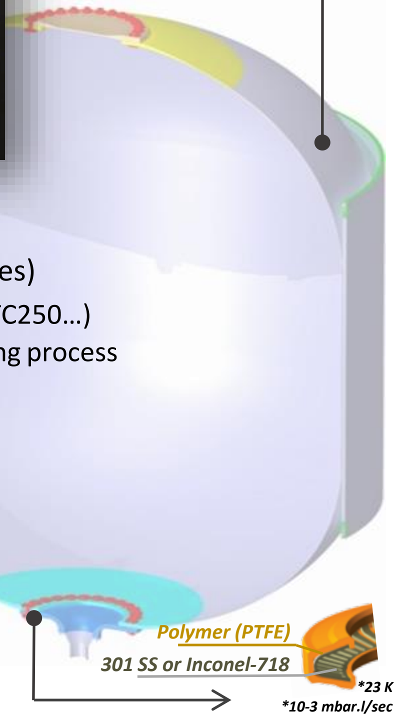
NASAS's CCTD LH2 cryotank

Linerless carbon composite thin wall





CFRP hybrid laminate



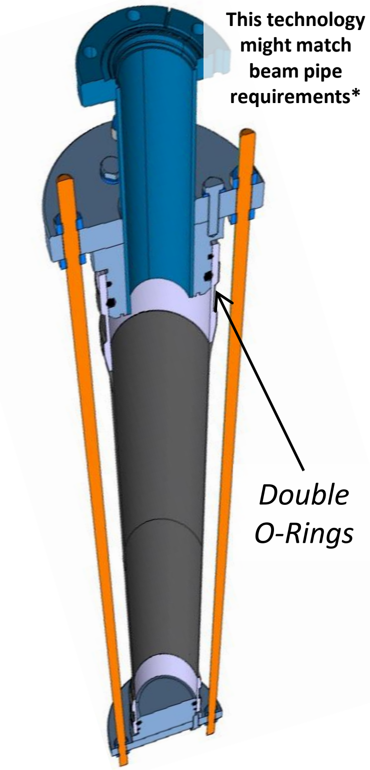
1. Material
Leak-tight linerless wall: CFRP hybrid laminate (thick and thin plies)
a) Resin: Microcrack resistant (**CTD,** 5320-1, MTM45-1, M56, TC250…)
b) Carbon Fiber: higher modulus compatible with manufacturing process

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

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

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

Breadboard Models: Carbon-Metal Interface II



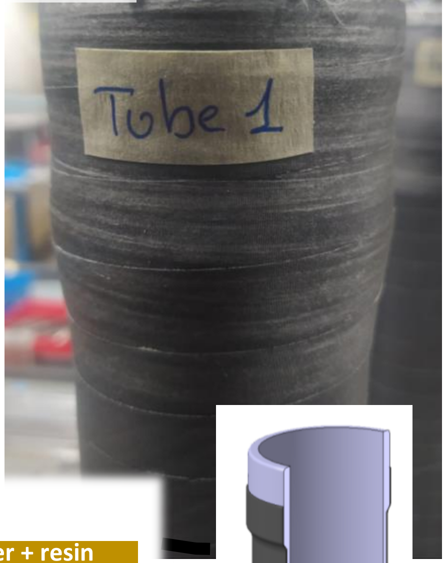
This technology might match beam pipe requirements*

Tube	Resin	Fiber	Wall thickness	End-Fittings	He leak rate (Troom)
1	CTD-7.1	T800H	0.7	SS 314	10e-9 mbar.l/sec
2	Araldite	T800H	1.5	SS 314	10e-11 mbar.l/sec
3	CTD-7.1	T800H	1.5	SS 314	10e-10 mbar.l/sec
4	Araldite	T800H	0.7	SS 314	leak < 10e-7 mbar.l/sec -> interface

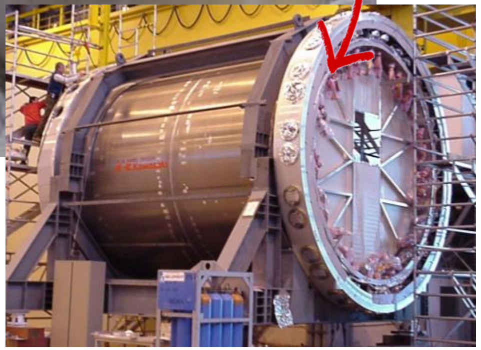
We are in need of collaboration to validate it this joint at 87K*

Atlas cryostat: 64 signal FT + 2 HV TF + Solenoid chimney

This joint is design to be optimal at cold temperatures: polymeric fibers contacts more than metal and carbon fiber)*

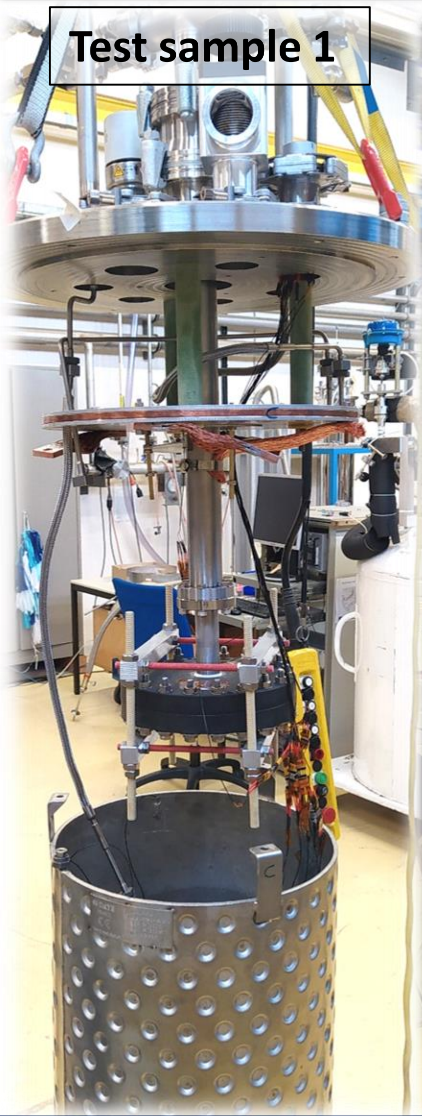


- Glass fiber + resin
- Carbon fiber + resin
- Glass fiber + resin
- SS end-fitting



→ Non conventional bonding between metal-carbon parts needs to be validated at LAr temperature (87 K)

He-leak Test (CERN Cryolab Collaboration)



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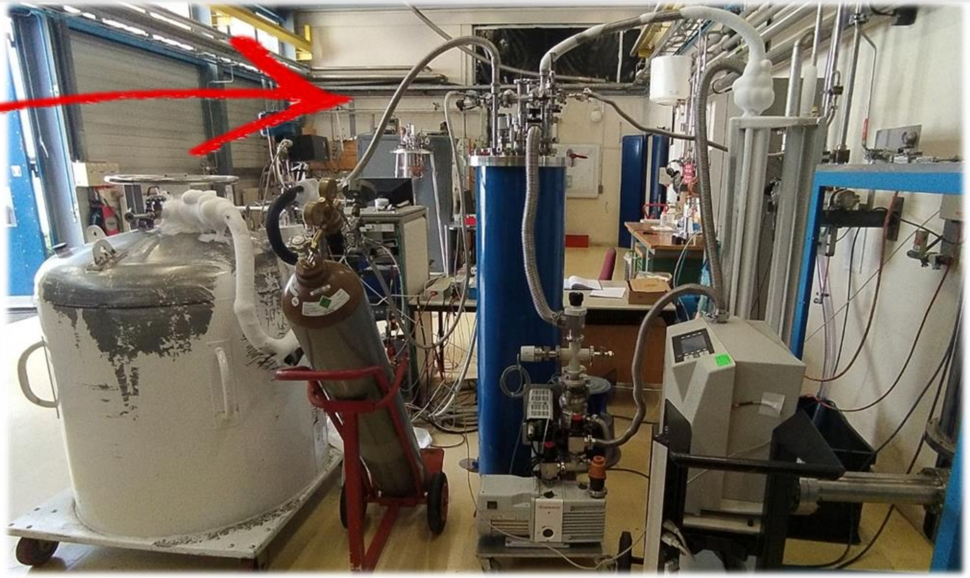
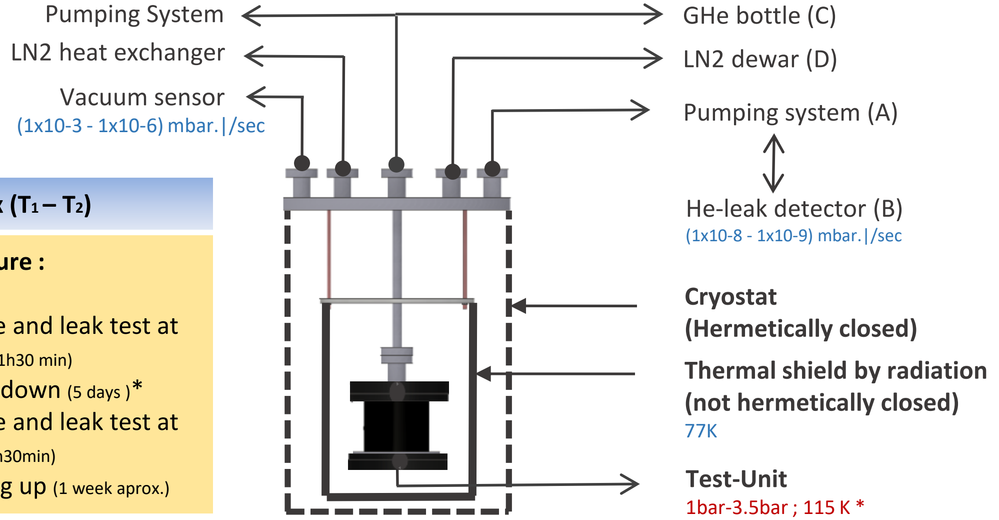
Michel Chalifour
Maria A. Barba
Agostino Vacca
Laetitia Dufay-Chanat
Sebastien Prunet





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

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 allowed us to check He leakage at 3.5 bar and ~110K (test setup limit)

Large scale manufacturing II

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-crossings** 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.

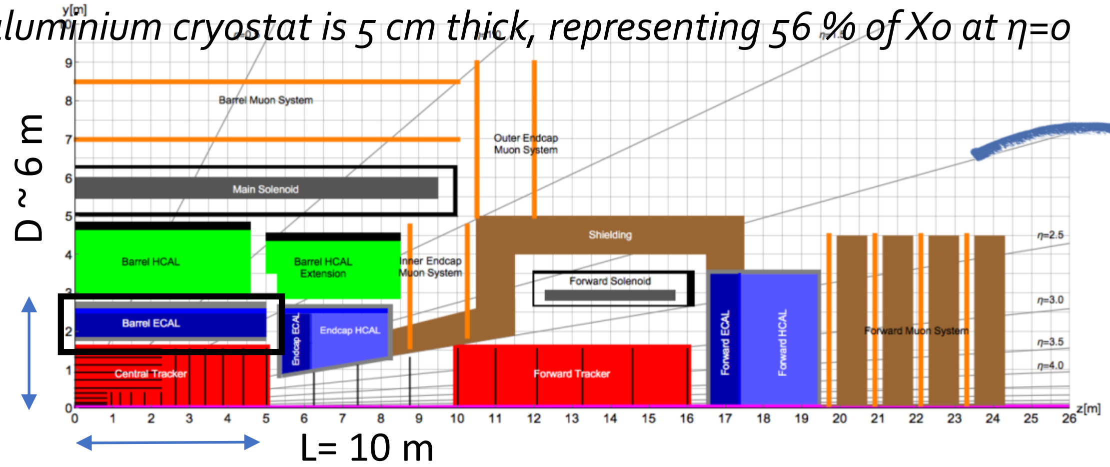
Peel-ply as final layer to compact laminate and **evacuate voids**

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

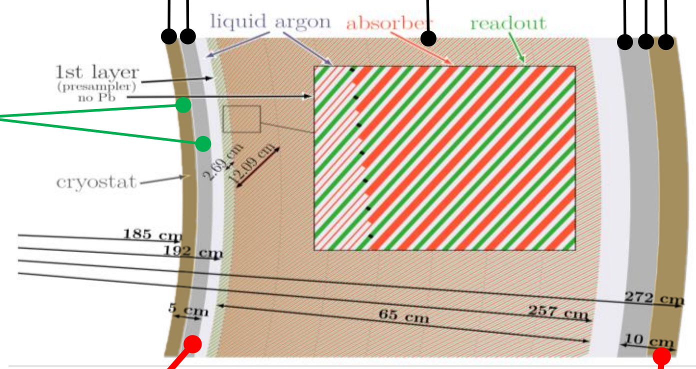
Baseline geometry, FCC-hh LAr barrel ECAL :

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

hh collisions



Outer warm cylinder (OWC)
Insulation vacuum
Outer cold cylinder (OCC)
LAr ECAL
Inner cold cylinder (ICC)
Inner warm cylinder (IWC)

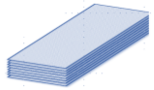


Minimum material budget

Buckling resistance

Sandwich Shell

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



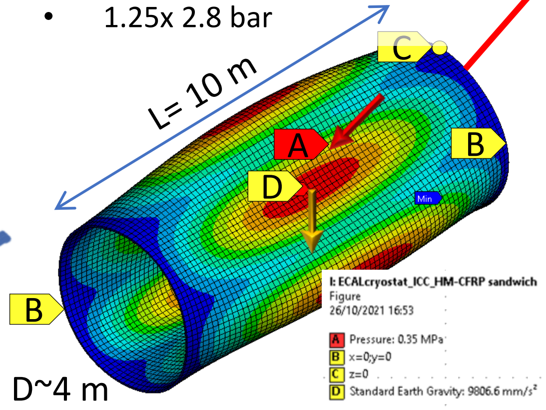
Solid Shell

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

Criteria: Safety Factor = 2	Sandwich shell				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%

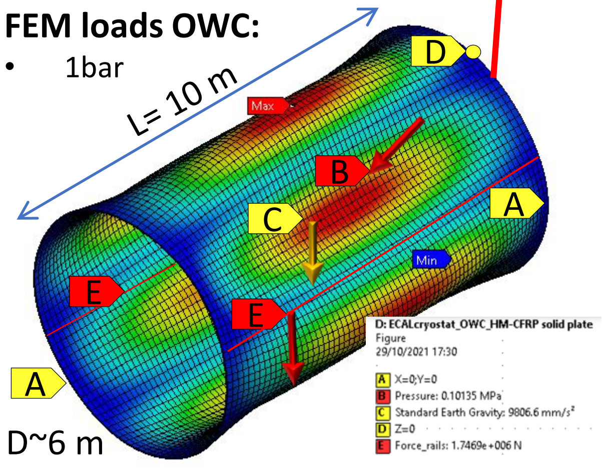
FEM loads ICC:

- 1.25x 2.8 bar



FEM loads OWC:

- 1bar



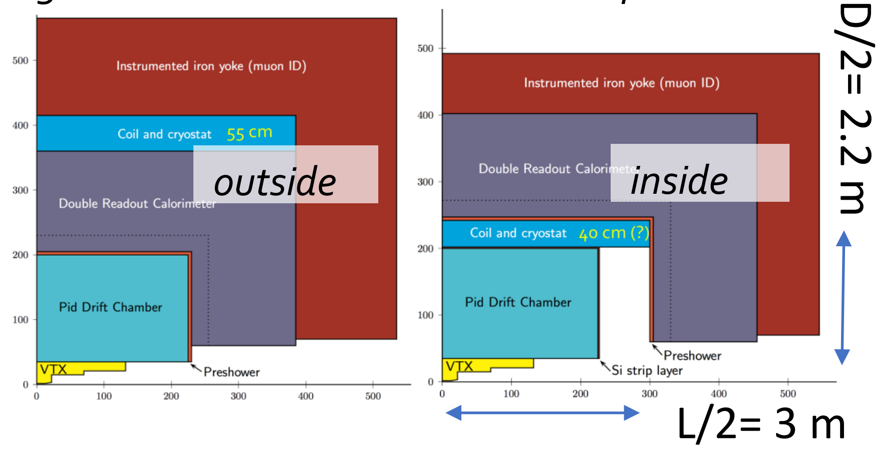
→ **CFRP cryostat walls will provide savings in terms of material budget/thickness respect to Aluminum**

Carbon composite profits II

Baseline geometry, FCC-ee

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

e^+e^- collisions



Sandwich

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

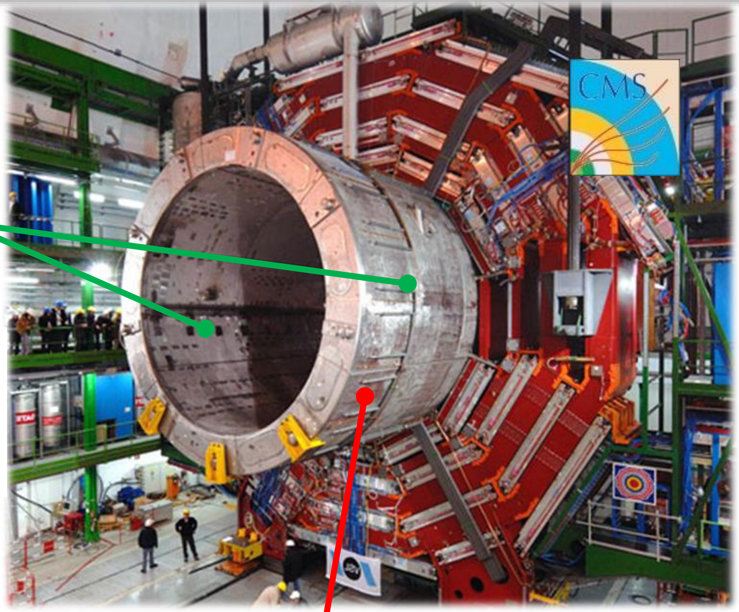
Radiation length X_0[mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al= 6000

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%

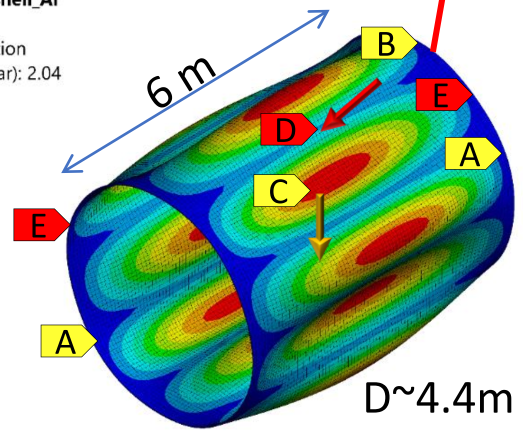
Minimum material budget

Buckling resistance

Patm →Vacuum



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

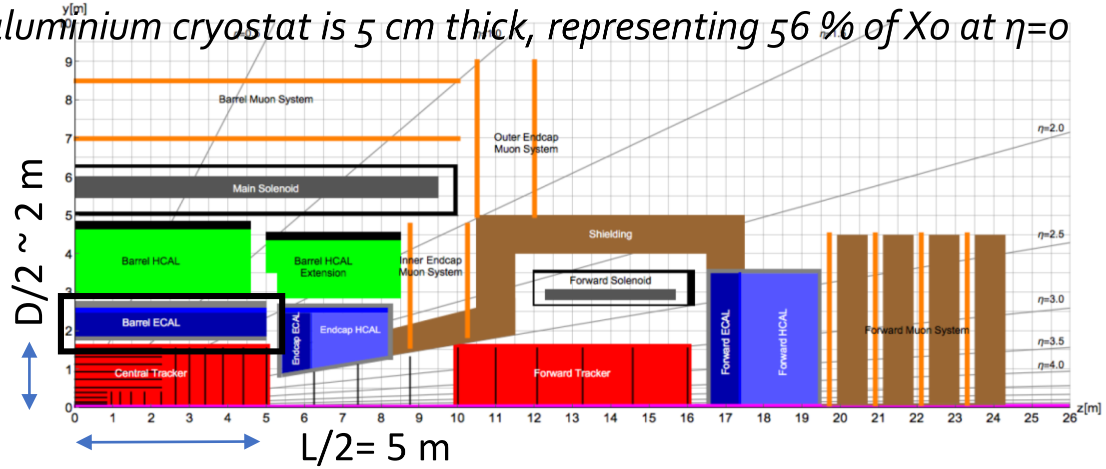
- A X=0; Y=0
- B Z=0
- C Standard Earth Gravity: 9.81e+003 mm/s²
- D Pressure: -0.101 MPa
- E Force: 3.5e+005 N

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

hh collisions

Baseline geometry, FCC-hh LAr barrel ECAL :

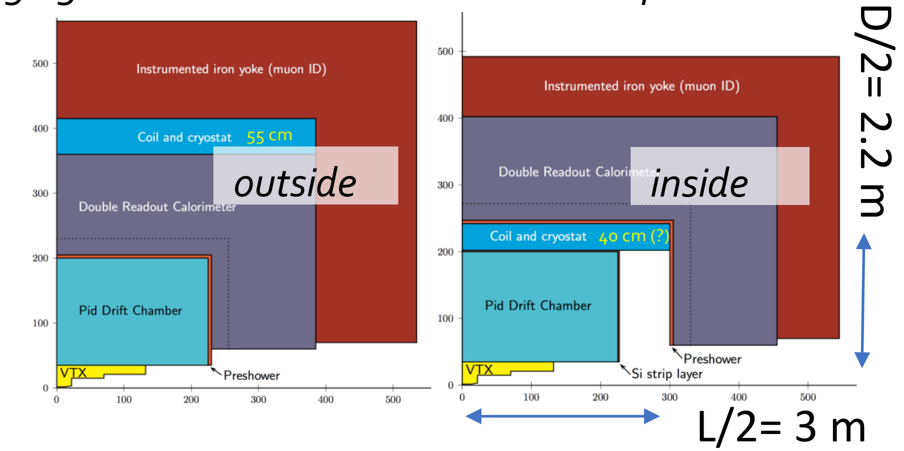
The aluminium cryostat is 5 cm thick, representing 56 % of Xo at η=0



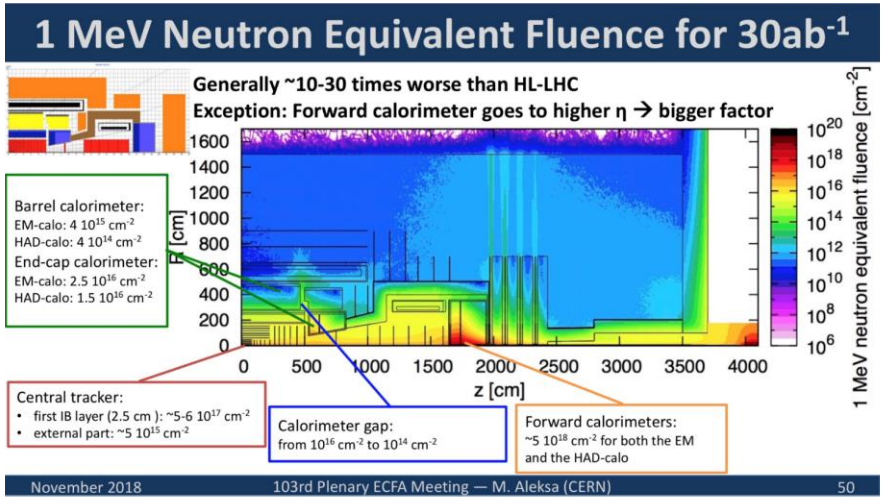
e⁺e⁻ collisions

Baseline geometry, FCC-ee

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



FLUKA simulations



FCChh: The estimated **radiation** levels at the barrel EM-calorimeter are relevant to the **choice of resin and glue.**

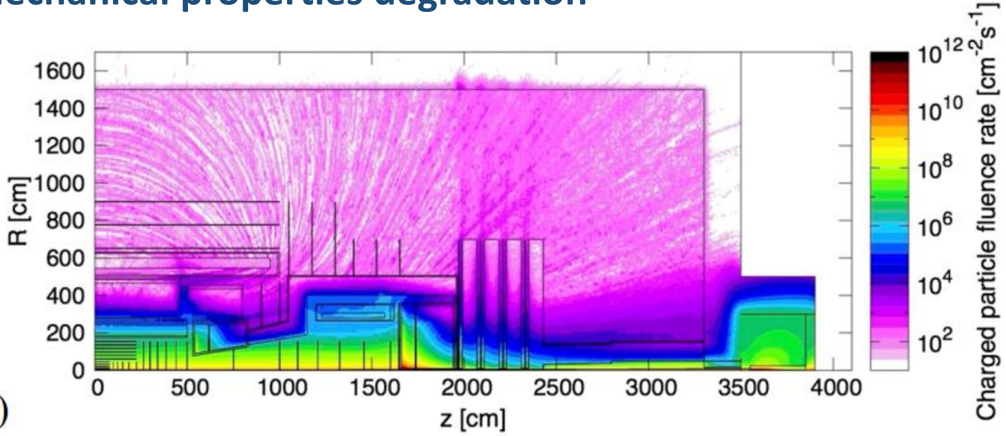
FCCee: radiation level is almost **negligible.**

→ **The CFRP cryostat for FCChh ECAL must be resistant to radiation in long term application (30ab-1 of integrated luminosity)**

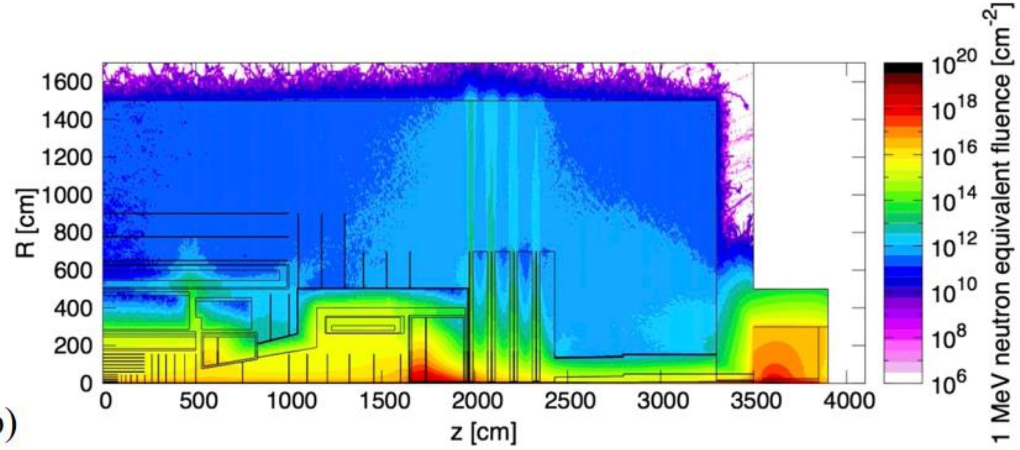
Radiation types:

- **EM waves**
- **Particle Radiation (by charged and neutral particles) → Displacement damage: changes structures of atoms → Resin becomes brittle → Mechanical properties degradation**

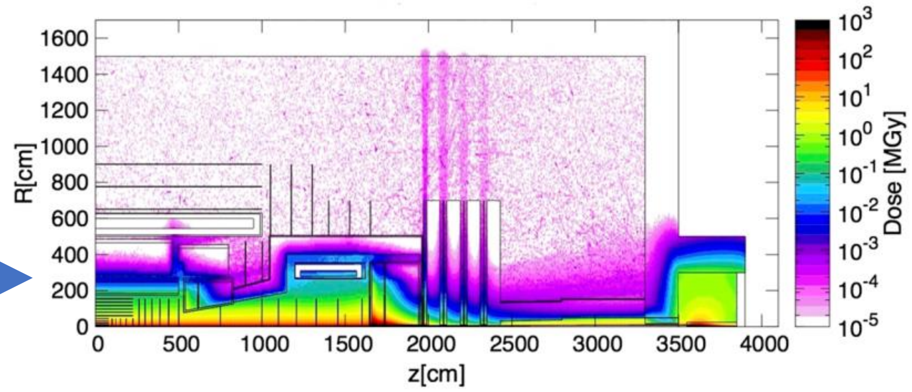
FLUKA simulations



a)



b)



Validate material to be resistant to:

a) 10e6 charged particles/ cm2.s

b) 4 x 10e15 neutrons/cm2 for 30ab-1 (~30 years)

c) 10e4 photons/cm2.s

Long term damage: 1MeV neutrons (fast neutrons)

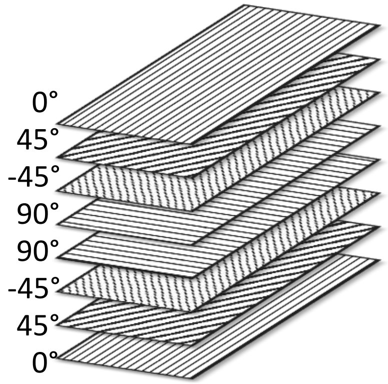
10e-1 MGy total dose

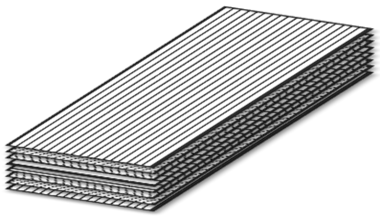
→ Total ionizing dose for 30ab-1 of integrated luminosity expected in ECAL is 0.1 MGy (max. amount of rad over its lifetime)

COURTESY OF WP4
Massimo Angeletti

Cryostat for future detectors at CERN

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





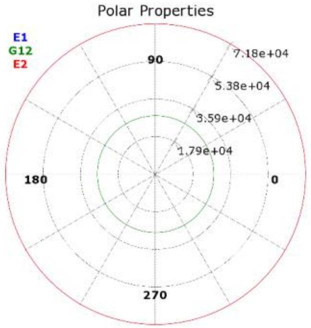
CFRP

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

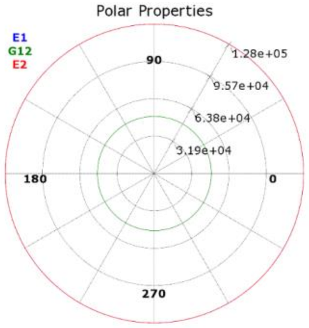


High Modulus (HM-CFRP)

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

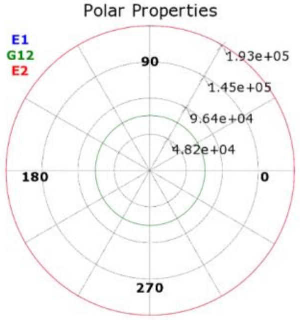


Ultra High Modulus (UHM-CFRP)

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

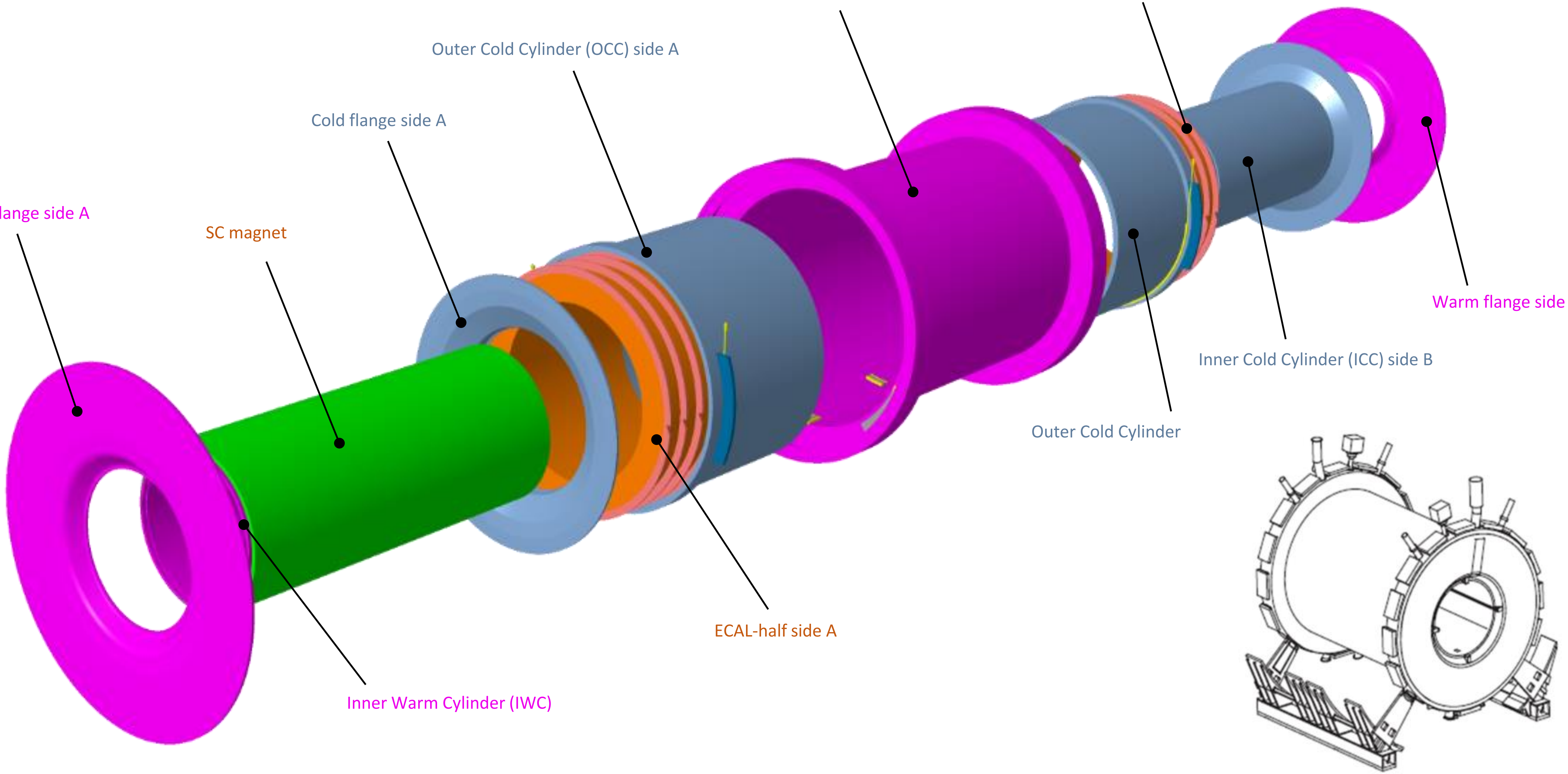
Lamina:
Carbon Unidirectional Prepreg
YS-95A/EX-1515 60% Vf
E1=540GPa, Thickness=0,1mm
0° Tensile strength = 1900MPa
0° Compression strength = 340MPa
90° Tensile strength = 25MPa
In-plane shear strength = 50MPa

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

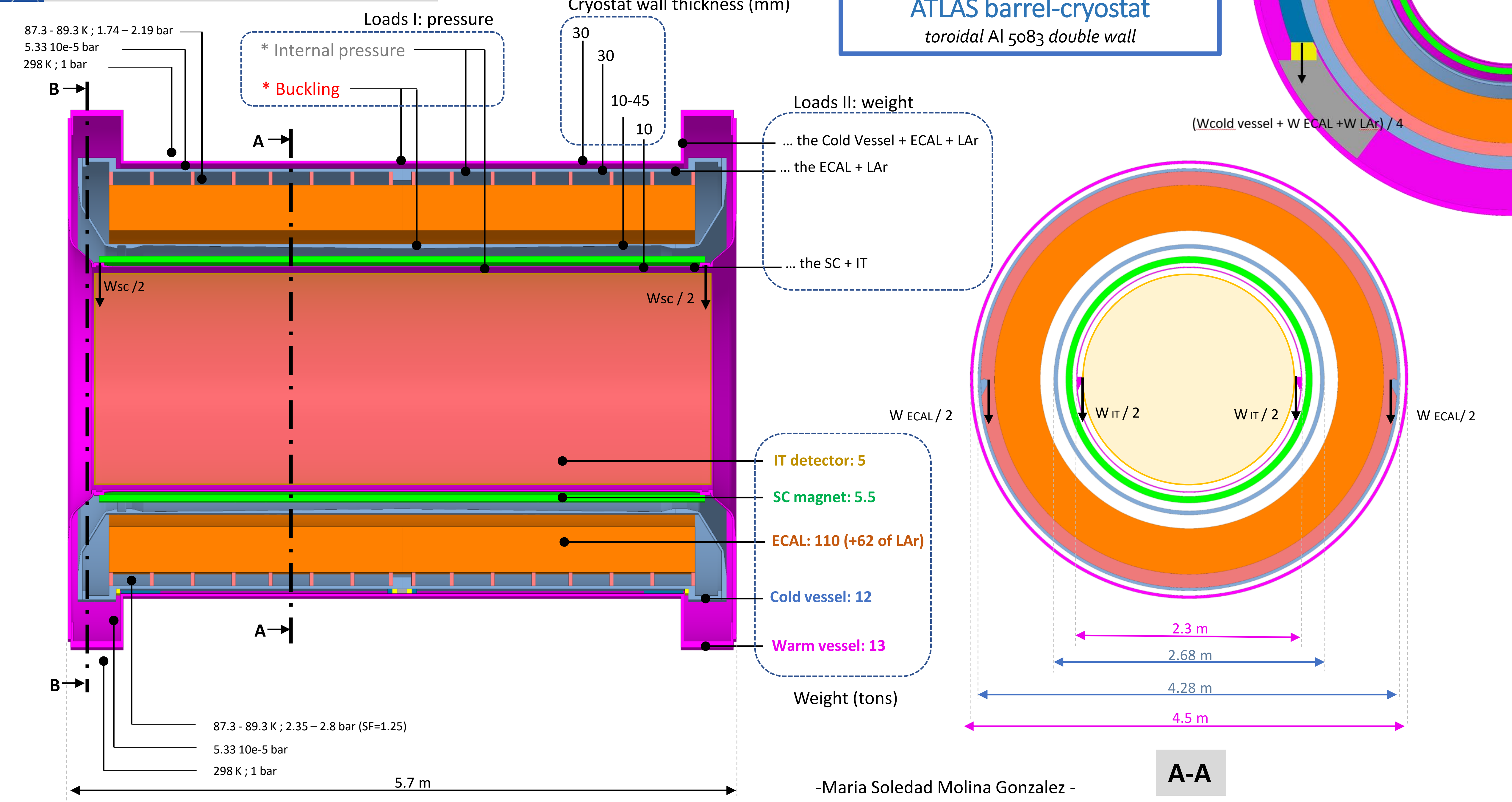
Assembly and Detectors Integration



ATLAS barrel-cryostat
toroidal Al 5083 *double wall*

-Maria Soledad Molina Gonzalez -

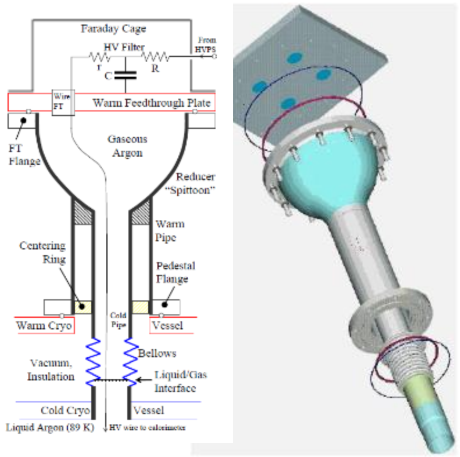
Loads and operating conditions



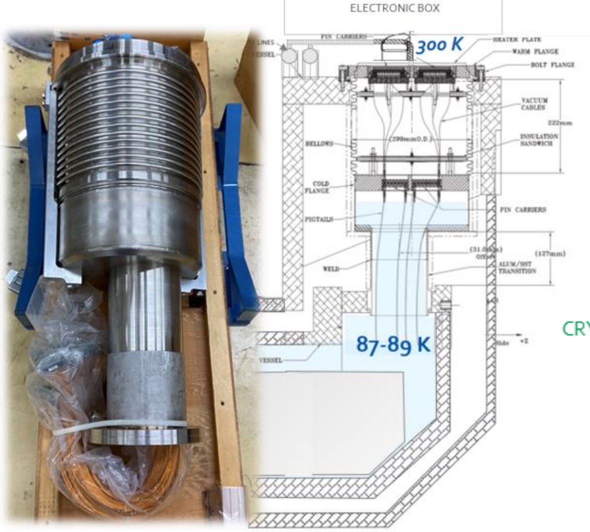
-Maria Soledad Molina Gonzalez -

Services Integration: Cryo and Power lines for LArCal and SC-magnet

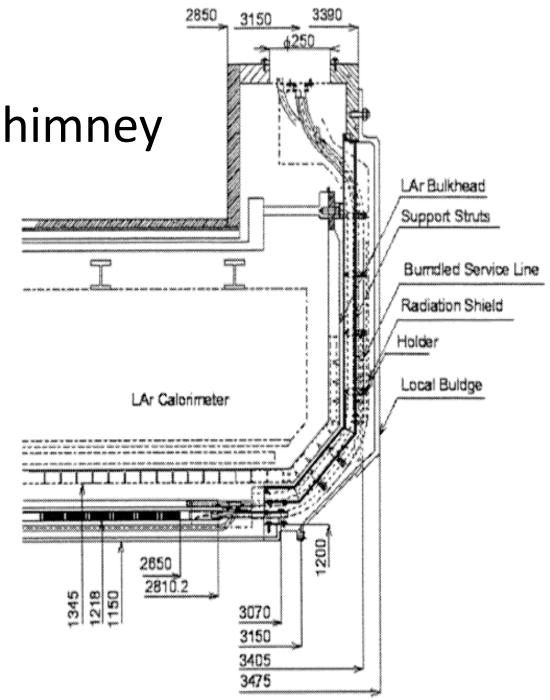
2 HV FEEDTHROUGHS



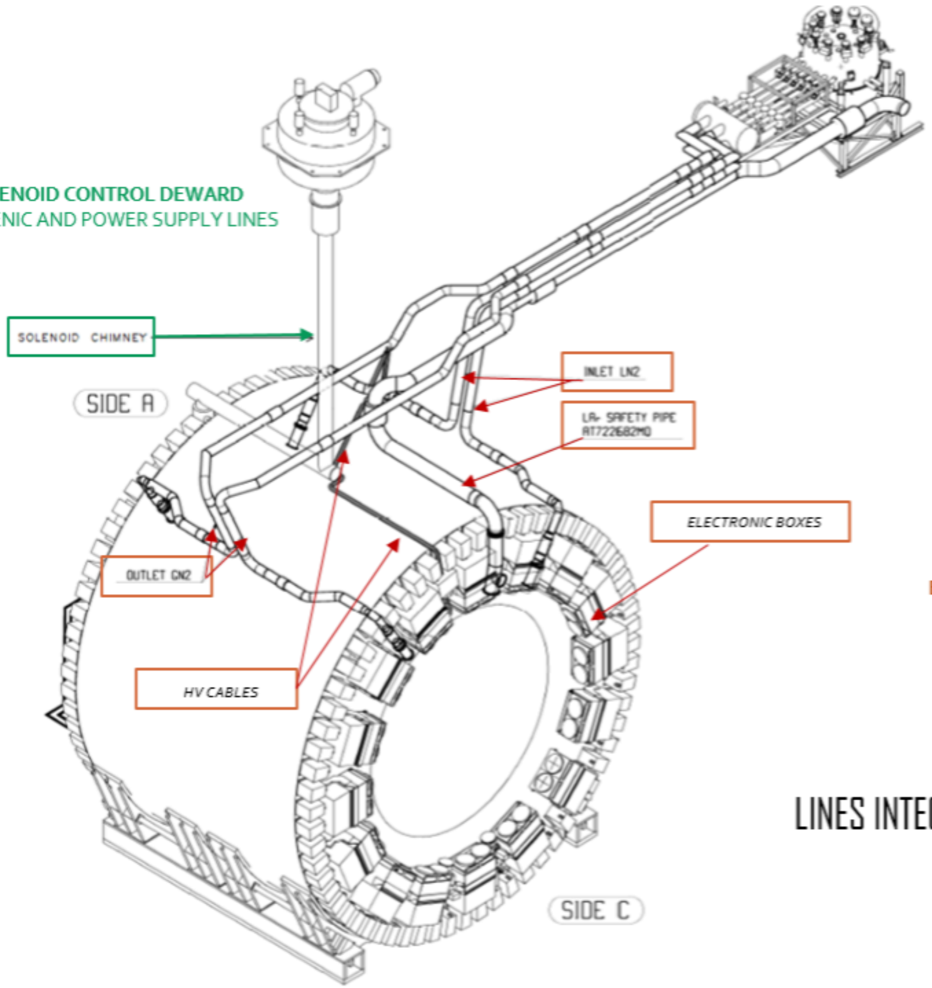
64 SIGNAL FEEDTHROUGHS



Solenoid chimney



SOLENOID CONTROL DEWARD
CRYOGENIC AND POWER SUPPLY LINES



EM CALORIMETER CRYOSERVICE LINES
COOLING LOOP:
INLET LN2 LINE-HEATEXCHANGER-OUTLETGN2

EM CALORIMETER CRYOGENIC LINE
LAr safety line

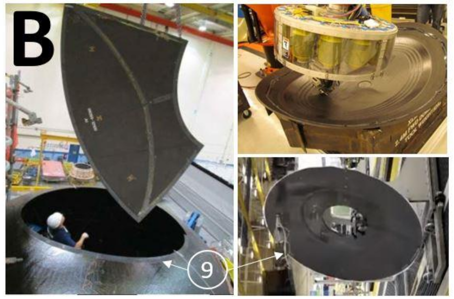
EM CALORIMETER HV LINES
2 HV Fe

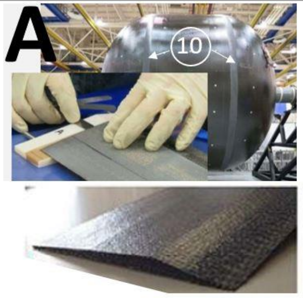
EM CALORIMETER SIGNAL AND CALIBRATION LINES
64 signa

LINES INTEGRATION INTO THE ATLAS CRYOSTAT

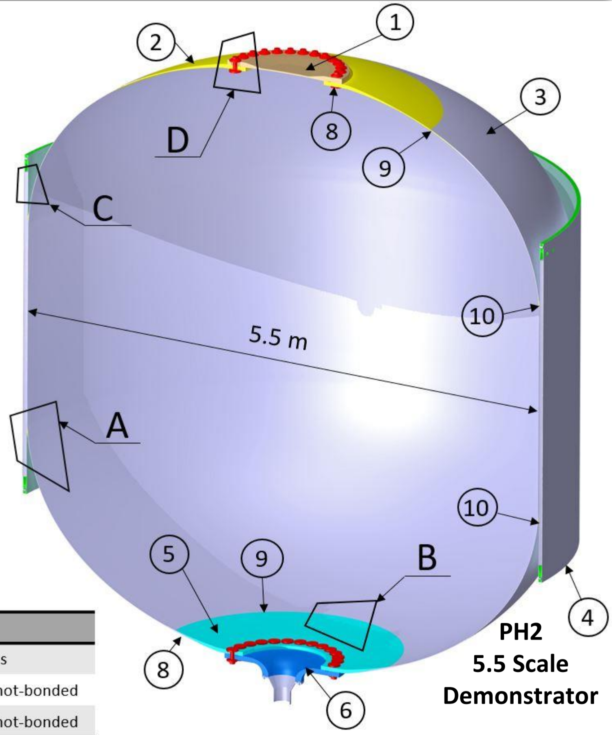
NASA’s CCTD – State of the art of CFRP cryotanks

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 panels + 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 94.8 KPa 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)