ECFA
European Committee for Future Accelerators

LIGHTWEIGHT MECHANICS

Corrado GARGIULO

Task Force 8 Integration

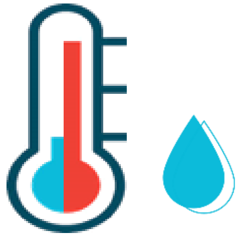
ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration
Wednesday 31 Mar 2021

TRACKING DETECTORS

CRYOSTATS FOR LAr CALORIMETERS AND SC MAGNETS

GLOBAL MECHANICS

LIGHTWEIGHT MECHANICS



Future detector mechanics based on light thermomechanical structures

Boundary conditions

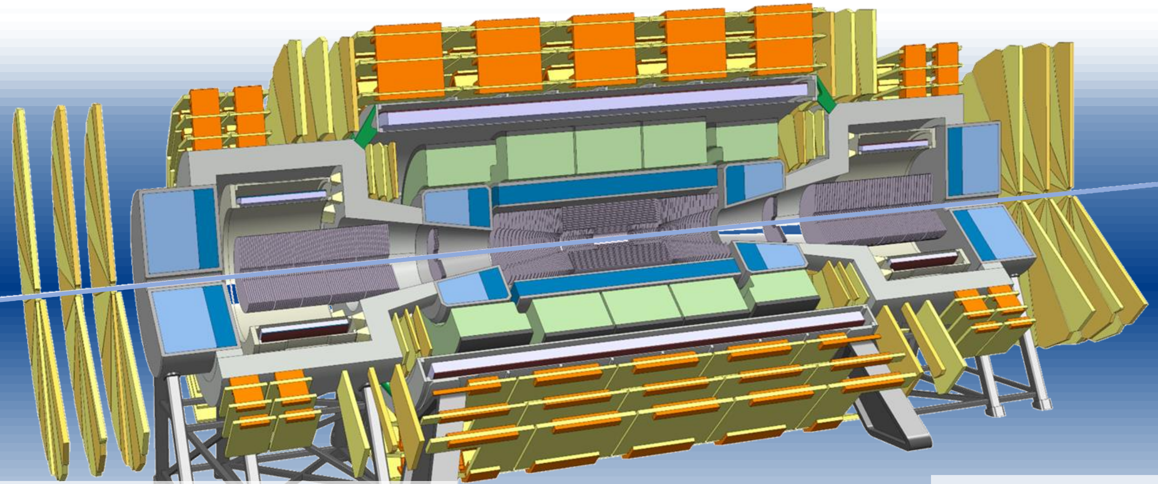
-high radiation levels
-external vibrations
-temperature and humidity variations

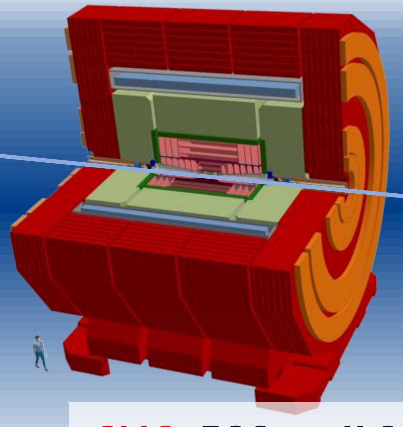
Requirements

-support the sensor in position, with minimum mass, low X/X_0
-provide high dimensional and dynamic stability
-provide thermal control and stability

➔ The design of the Detector mechanical structure is inherently linked to the cooling and material budget requirements

FUTURE REQUIREMENTS





FCChh*, *HE-LHC, …

hh collisions

e^+e^- collisions

CLIC*, *FCCee, ILC, CEPC,…

- **Large dimensions (50m)**
- **High radiation Level (up to 2.8 x10^{17}neq/cm2; 90MGy @10 year)**
- Central solenoid (10m) 4T, Forward solenoids 4T
- Silicon tracker **Tracker Radius 1.6m, Length 32m**
  radiation damage is a concern
- Barrel ECAL Lar/ Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr **2-4x better granularity than e.g. ATLAS**
  Silicon ECAL and ideas for digital ECAL with MAPS
- Muon system

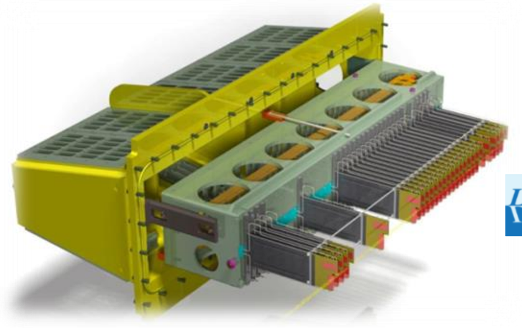
- Standard dimensions
- Low radiation Level, Radiation level NIEL (<4×10^{10} neq cm^{-2}/yr); TID (<200Gy/yr)
- Magnet 4T, 2T
- Silicon tracker
  - **unprecedented spatial resolution (1-5 µm point resolution)**
  - **very low material budget (0.1X%)** Dissipated power (vertex) (<50mW/cm^2)
- Barrel fine grained calorimeter
- Compact Forward calorimeter

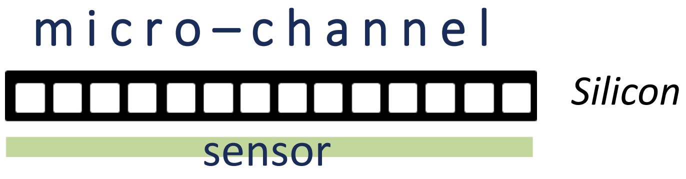
➔ Future detector mechanics has to cope with large range of demanding requirements
➔ FCC-hh and HE-LHC have very similar detector technology requirements in terms of resolution and radiation hardness
➔ FCC-hh, HE-LHC, FCC-ee have similar sensor technology requirements in terms of resolution and material budget

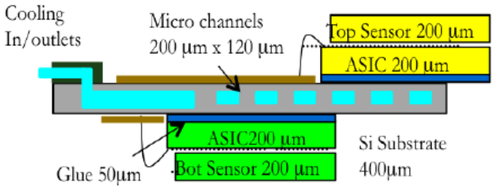
VERTEX-TRACKER

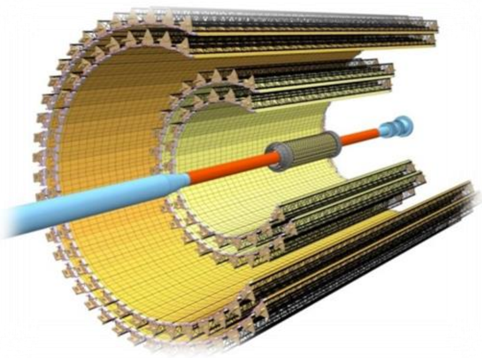
Lightweight mechanics

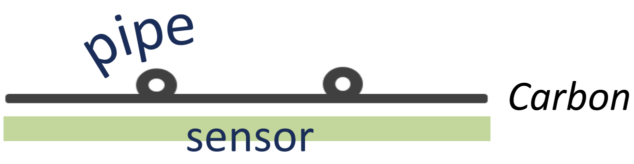
PRESENT DESIGN BASELINES

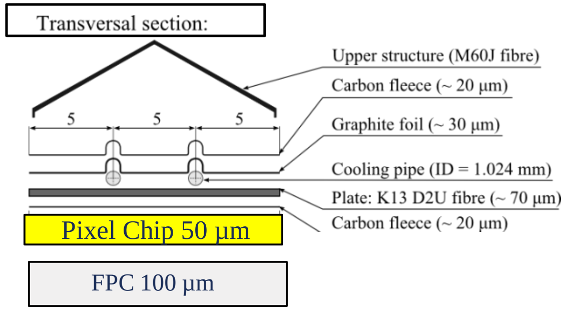


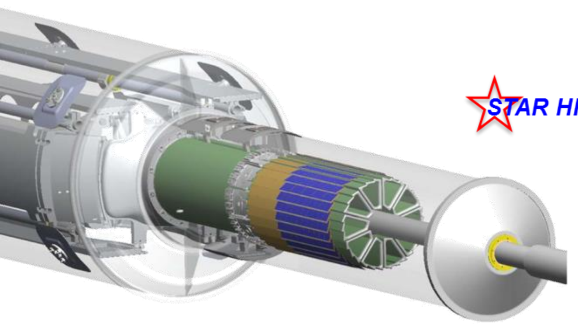


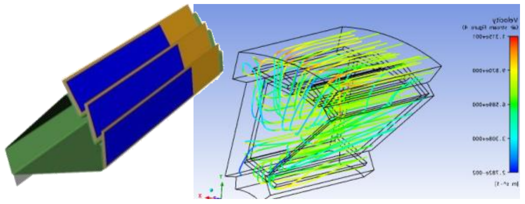












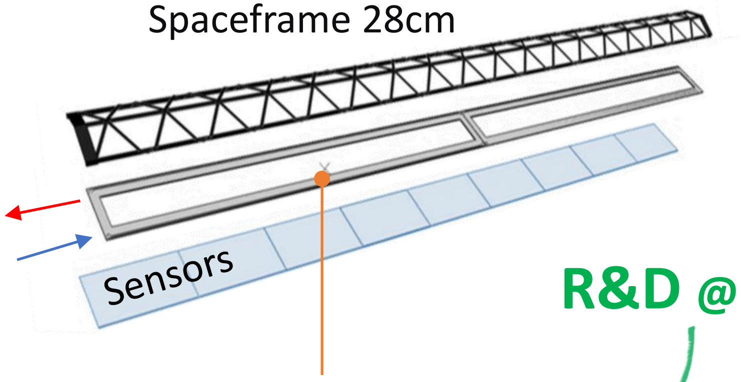
➔ Different designs implemented in present tracker to meet structural and thermal requirements

“MICROCHANNEL”

VERTEX - TRACKER

MICROCHANNELS

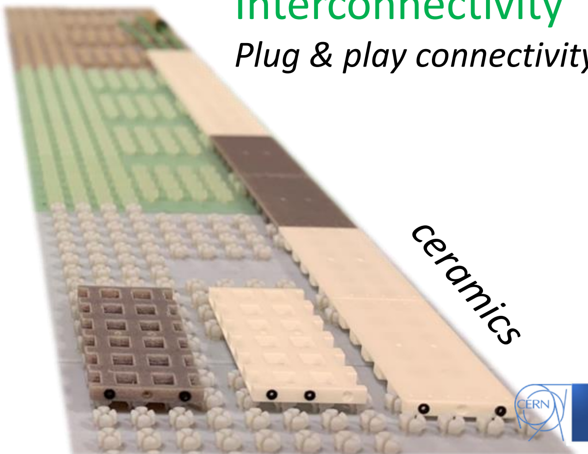
ALICE



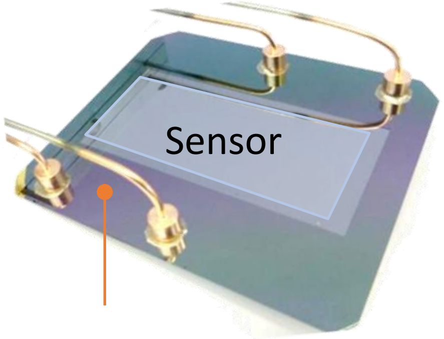
R&D @HEP

Interconnectivity

Plug & play connectivity



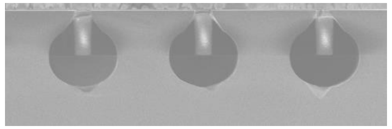
NA62



R&D

CMOS-compatible processes

Microchannels on the back of the sensor



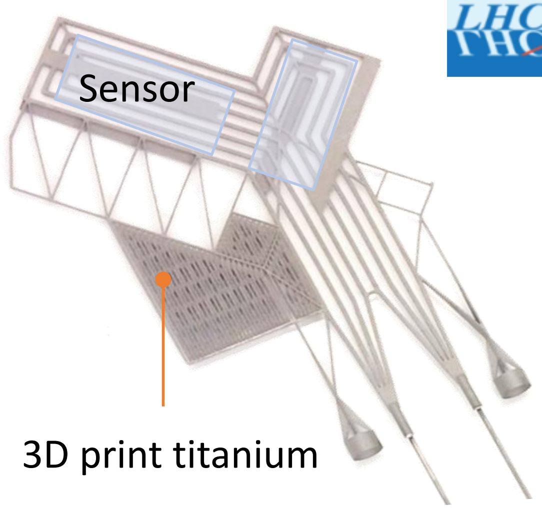
Tests on MALTA chip

Sealing of trenches by Parylene coating Or PECVD of SiO2…

CMi EPFL Center of MicroNanoTechnology

Tests on MALTA chip

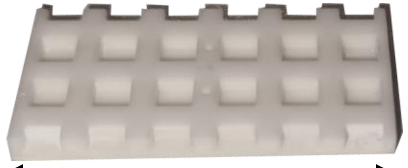
LHCb



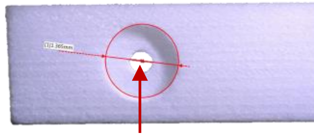
R&D

3D printed ceramic, …

different materials engineered for CTE compatibility



Up to 280 mm



D 0.4mm

… Al2O3, Zr, SiC, AlN

CERN EP R&D

➔ **R&D in HEP New heat exchanger for sensors cooling will aim at better performance and lower temperature in hh at the same time the substrate must guarantee mechanical stability and positioning accuracy with minimum material.**

In vertex detectors for hadron collider stringent cooling requirements will be driven by the minimisation of radiation damage. Different microfabrication techniques will be studied for ultra lightweight coldplates.

“PIPE”

VERTEX - TRACKER

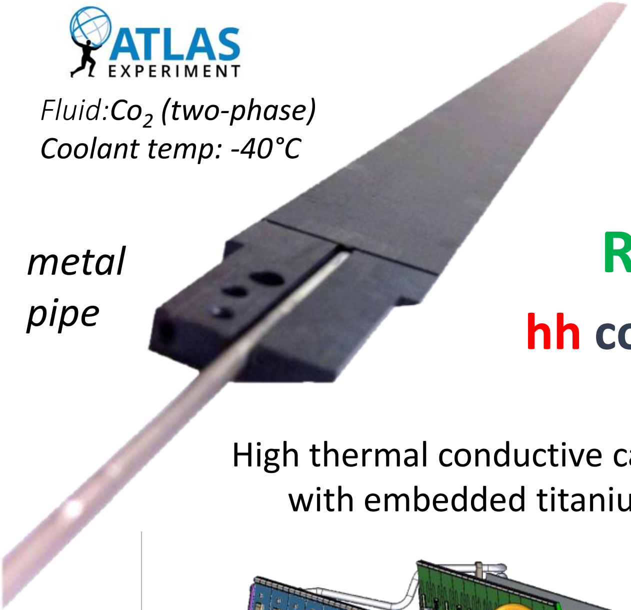
hh collisions **e^+e^- collisions**

"PIPE"

ATLAS EXPERIMENT

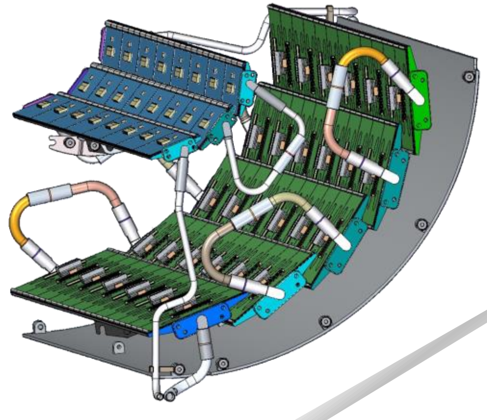
Fluid: CO_2 (two-phase)
Coolant temp: -40°C

metal pipe



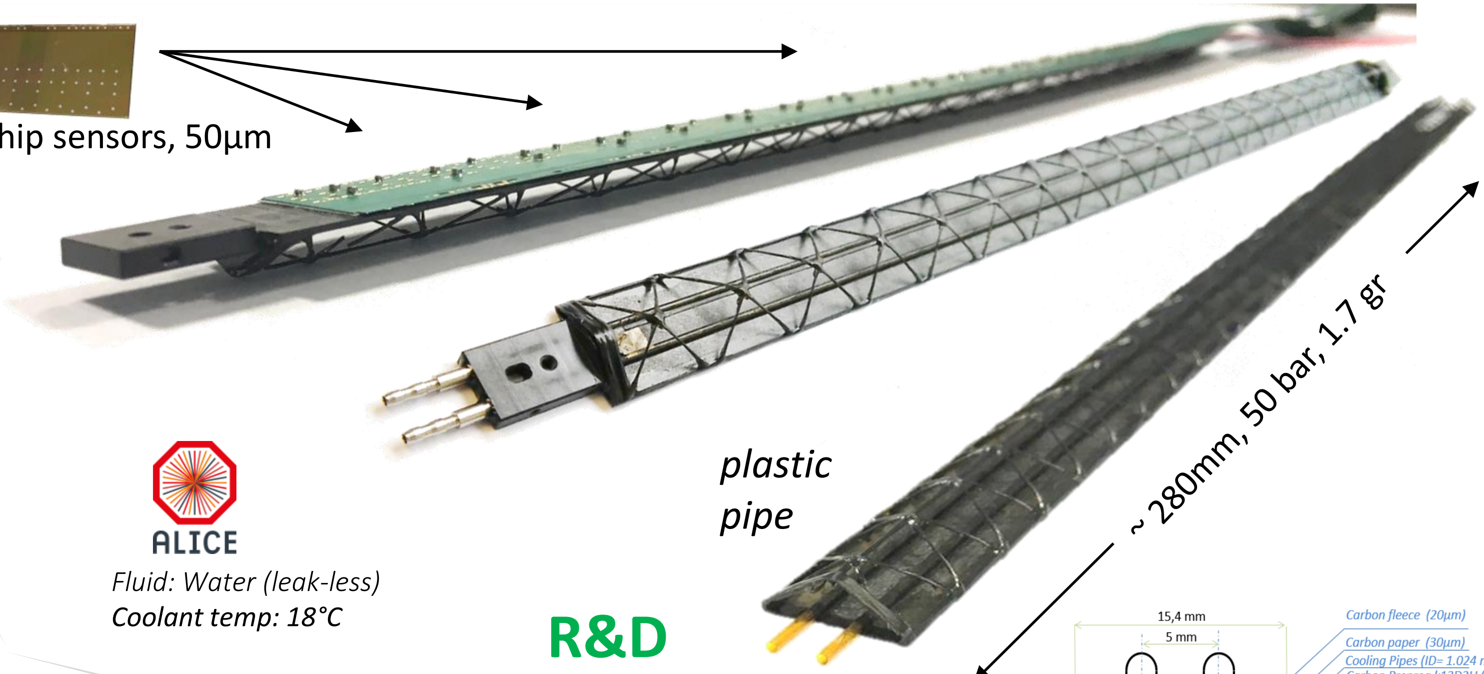
R&D
hh collisions

High thermal conductive carbon plate with embedded titanium pipes



9x

CMOS pixel chip sensors, 50µm



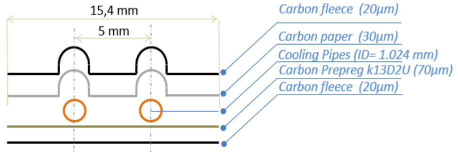
plastic pipe

~ 280mm, 50 bar, 1.7 gr

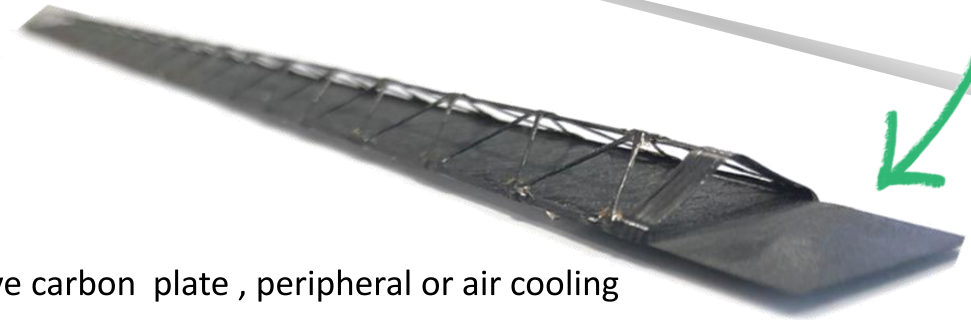
ALICE

Fluid: Water (leak-less)
Coolant temp: 18°C

R&D
e^+e^- collisions



High thermal conductive carbon plate with embedded Kapton pipes



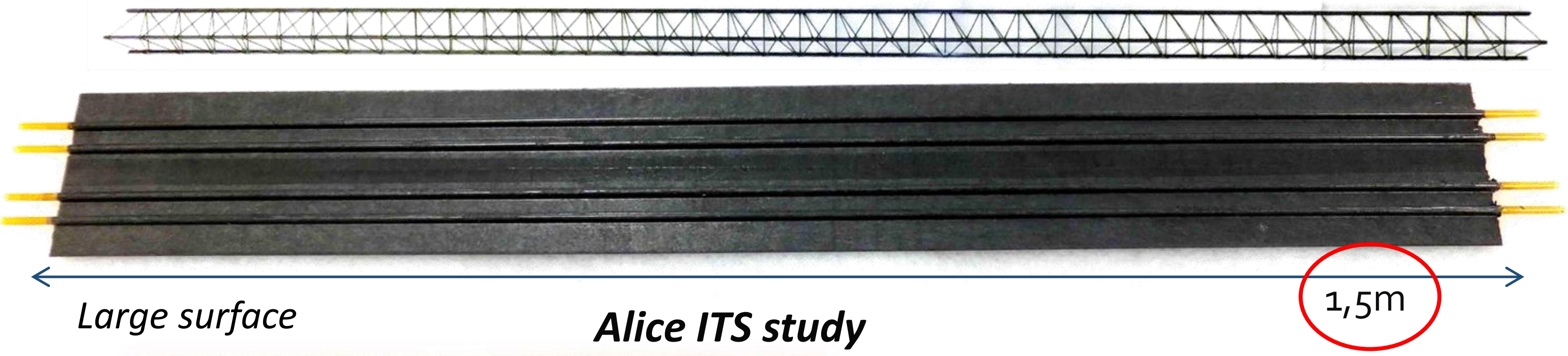
High thermal conductive carbon plate , peripheral or air cooling

➔ **R&D in HEP Sensors substrates from metal pipes to plastic pipes to no-pipes for material budget reduction.**
High Thermal Conductive (HTC) material carries the heat to a pipe with coolant.
R&D to adopt lighter pipes also in hh (thinner pipe, channels, microvascular carbon plate).
...or no pipe at all and peripheral cooling at the edge of the stave, air cooling.

"PIPE"

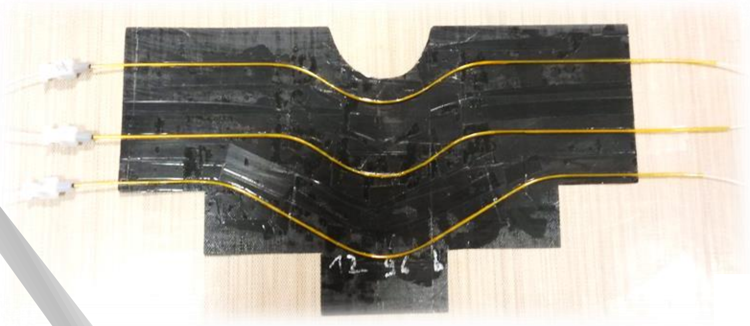
Alice ITS stave

R&D



Large surface

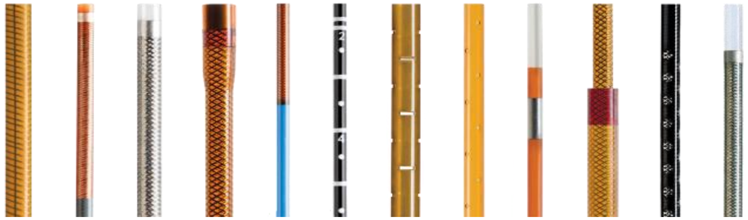
Alice ITS study



*Used in ALICE

**ID 1mm, Wall thick 0.0254*	*→ 50 bar*
ID 1mm, Wall thick 0.18mm	*→ 260 bar*
ID 0.051mm, Wal thick 0.0127	*→ 340 bar*

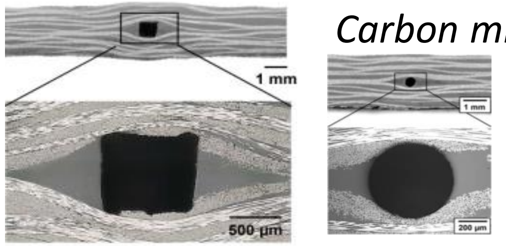
Alice MFT *Bending radius can be reduced with braided pipes*



Polyimide pipes

Available on the medical market, used in HEP and tested up to 50 bar, braided pipes allow for larger pressure value, (hoop strength almost double), and smaller bending radius.

CERN EP R&D



Carbon microvascular

hollow glass fibers, extraction of steel wire, melting of embedded solder [vaporization of sacrificial components

Stephen J.Pety et all

→ **R&D in HEP Investigate limits of ultra-light pipes embedded in carbon structures, thermal, pressure, fluids compatibility.**

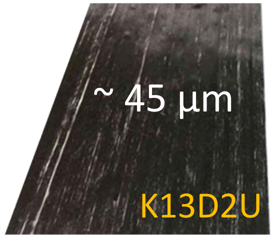
Future large surface coverage : compromise between minimum material, cooling performance and cost.

Cheap and flexible large substrate such as carbon fibre structures embedding polyimide pipes

→ **In Industry** Available in medical, pipes for surgery.

"PIPE" FIBRE & NANOMATERIAL

Roving



Unidirectional Prepreg

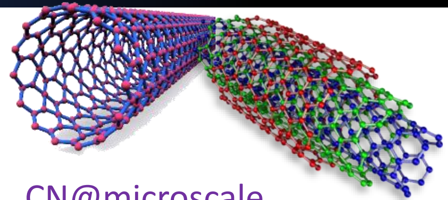
Thermal Pyrolytic Graphite

Fleece

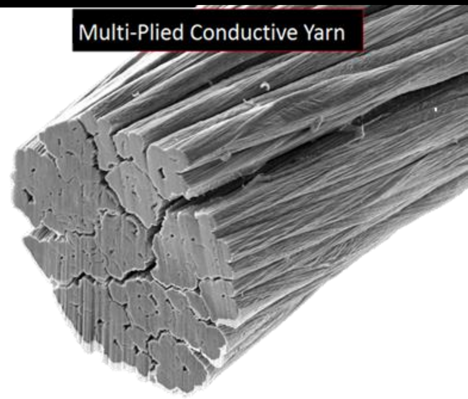
R&D

CARBON NANOTUBE FIBRE

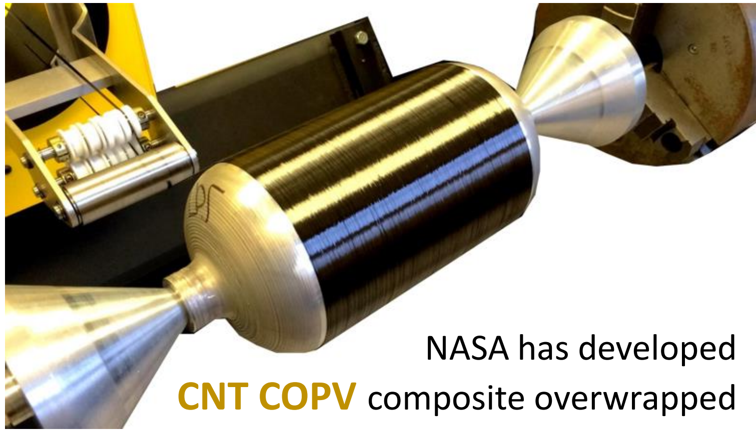
Nanocomp's Miralon®



CN@microscale
tensile strength, 200 GPa
moduli strain, 1400GPa
failure strains 20%GPa



The relatively short lengths of these tubes (a small fraction of a millimeter) wouldn't connect and form a network.
Without the tubes forming a network, it is impossible to bring to macroscale the electrical, thermal, and mechanical performance that the individual tubes exhibit.



NASA has developed **CNT COPV** composite overwrapped

NANOCOMP

Nanocomp generate tubes >1mm. As the tubes come together, attractive forces, called dispersion forces, makes them intertwine with each other forming a network.

Material	Composit.	Strength [Gpa]	Density [g/cc]	Specific strength [Gpa/(g/cc)]	Strain to failure [%]
Kevlar	Aramid	2.9	1.44	2.014	2,8
Carbon fibre	Carbon	4.1	1.75	2.343	1.4
Nanocomp Miralon	**Carbon tube**	**3.2**	**1.1**	**2.9**	**7**

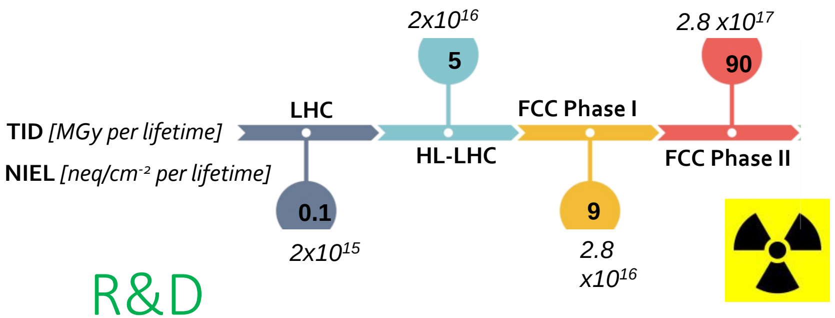
➔ **R&D in HEP** **Characterization of new materials with high mech/thermal properties for their use in HEP.**

➔ **New in industry** Graphene & nanotubes, from microscale to macroscale, to improve thermal and structural composite material properties, some recent advances in the large-scale synthesis towards integration in real applications

"PIPE" RESIN NANOMATERIAL

Thermosetting

Epoxy, most used, cheap, flammability can be an issue UL94-V0
Cyanate Ester (CE), more expensive, better radiation resistance, lower moisture absorption
Cyanate Siloxane (CSE), lower mositure absorption than CE, better dimension stability but high temperature curing 177°C, curing (Tg= 165°C)



Lifetime: LHC, HL-LHC: 7 years; FCC: 10 years

R&D

R&D

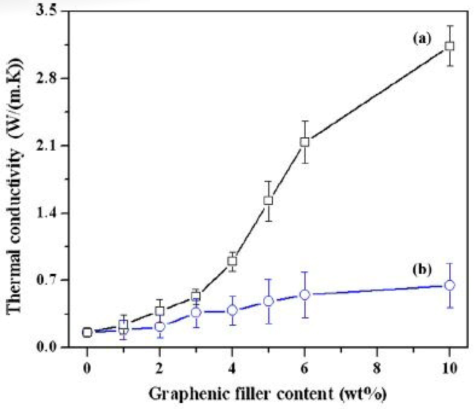
Thermoplastic

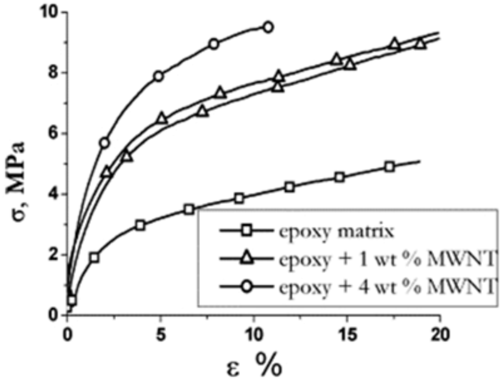
Thermoplastic composite design is 10% Lighter 20% cheaper than carbon/epoxy.
Polyamide polymers, improved resistance to delamination, the thermoset matrix are more brittle, curing at 250°C
PEEK

R&D

+ Carbon Nanotubes and/or Graphene

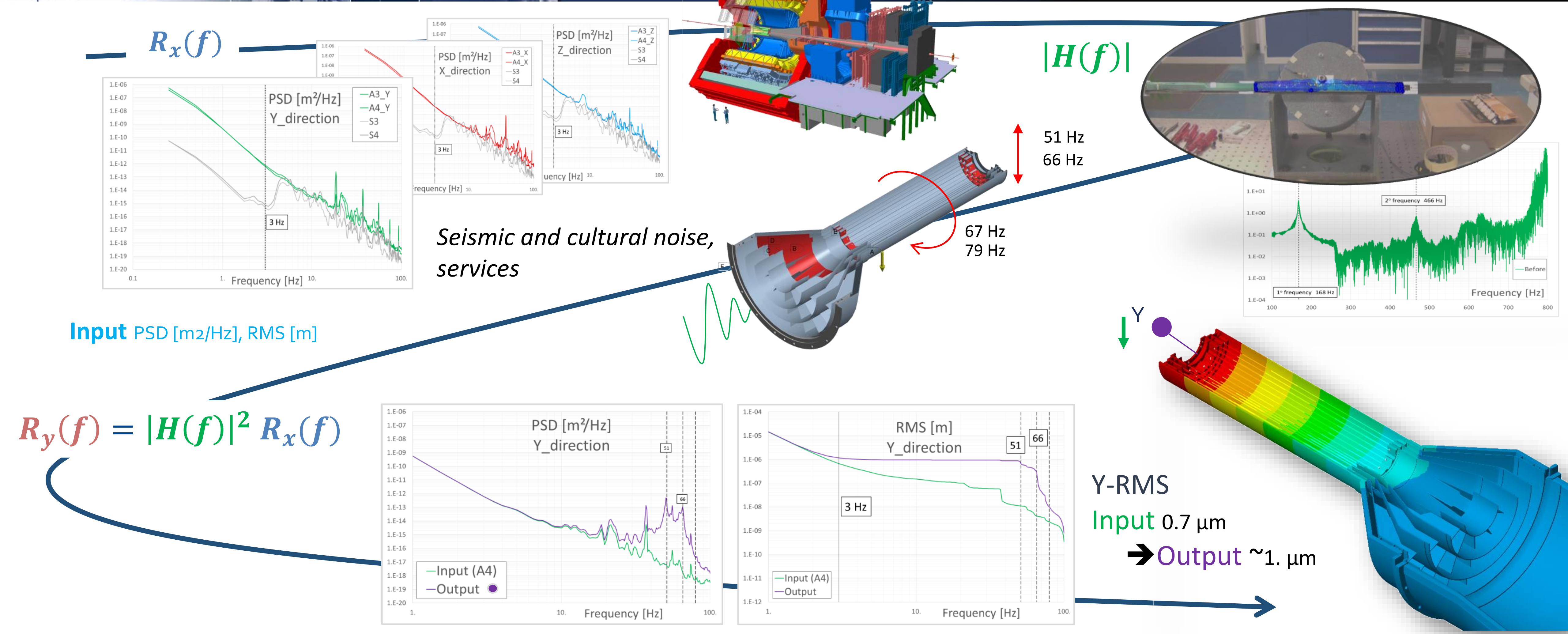
The ultimate goal of epoxy nanocomposites is to extrapolate the exceptional intrinsic properties of the nanoparticles to the bulk matrix.
The key aspects to reach this goal are the dispersion state of the CNTs, the filler-polymer interfacial adhesion and the orientation of the nanofillers.





➔ **R&D in HEP Characterization of new resin systems with better thermal and mechanical properties for higher radiation.**
➔ **In Industry** Resin systems more suitable for higher radiation environment: **Thermoplastic**
➔ **New in Industry Nano filled Resin system with enhanced mechanical and thermal properties.**

STABILITY DYNAMIC



➔ **R&D in HEP Numerical and experimental approach for design validation up to unprecedented stability requirements.**

Experimental Acquisition of vibration sources. Touchless deformation measurement: fibre Bragg grating, 3D laser scanning.

Detector natural freq, Freq Resp Function (H(f) and dumping experimental determination,

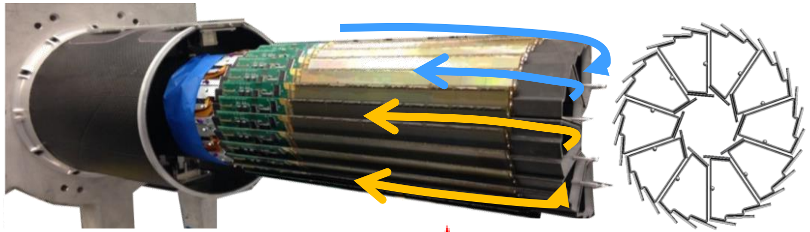
Dynamic response determination (analytical Ry (g-PSD)=|H(f)|2Rx and FEA). RMS of Dynamic response (integration 1Hz-100Hz)

“AIR”

VERTEX - TRACKER

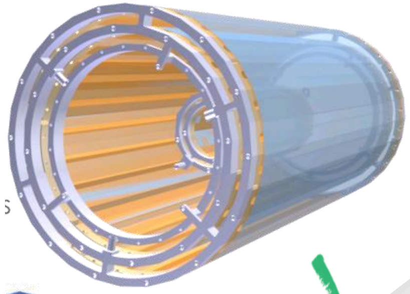
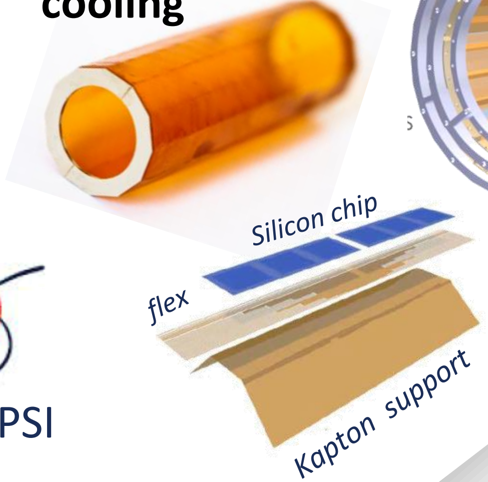
AIR COOLING

Air Flow



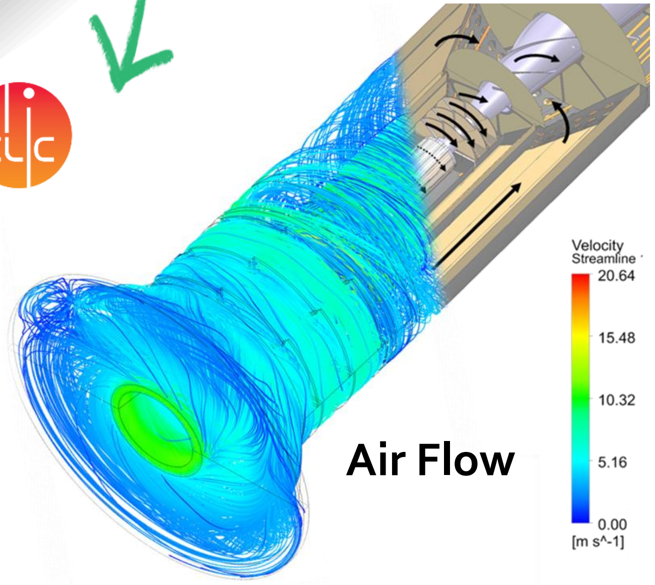
STAR HFT
in operation @LBNL

Helium gas cooling

Mu3e PSI

R&D



Curved Silicon sensors

ALICE

Reduction of thickness to about 20–40 µm open possibility of exploiting the flexible nature of silicon.

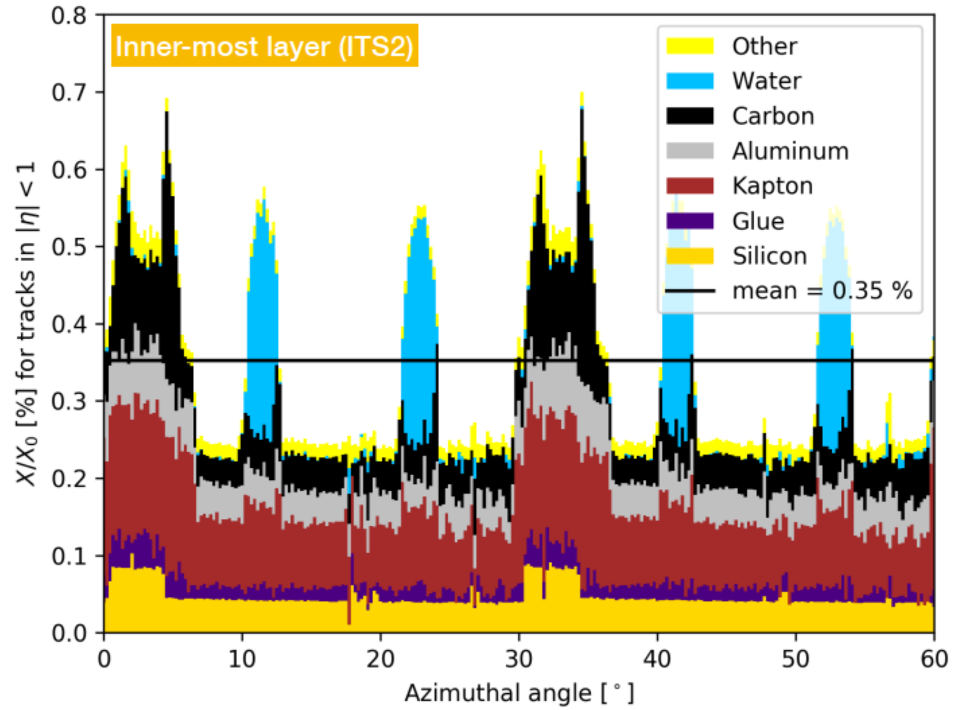
R&D

➔ **R&D in HEP The design of new vertex detectors in lepton collider will have to cope with unprecedented requirements on minimum material budget and dimensional stability.**

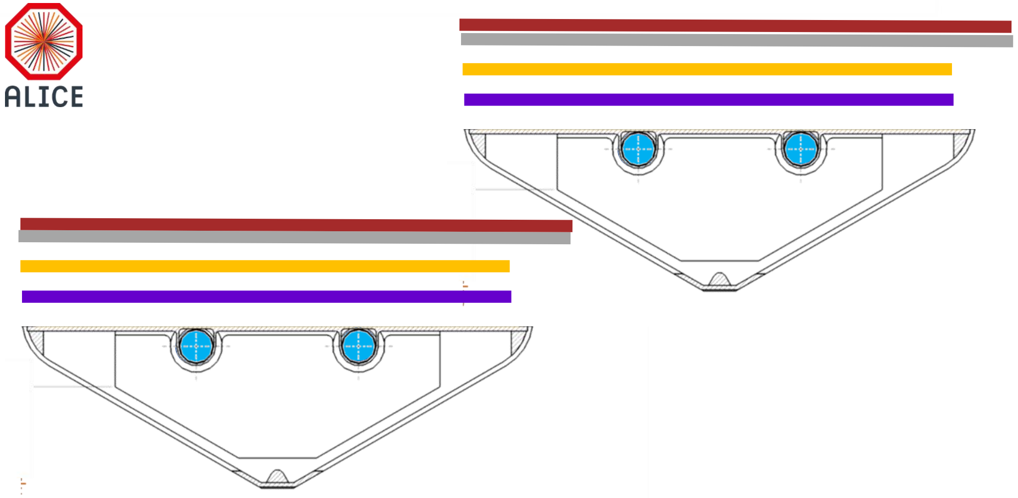
Reduction of material in front of the sensor will be pursued by investigating new sensors technologies and air /gas cooling.

Air/gas cooling flow to cope not only with thermal but also with structure vibration requirement.

MATERIAL BUDGET



ALICE



Si only 1/7 of total material

Non uniformity due to overlaps+ support/cooling

Remove water cooling

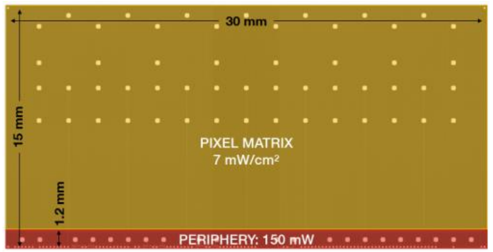
Possible by reducing power consumption in fiducial volume to <20mW/cm^2

Remove external data lines+ power distribution

Possible to make a single large chip and use that for distribution

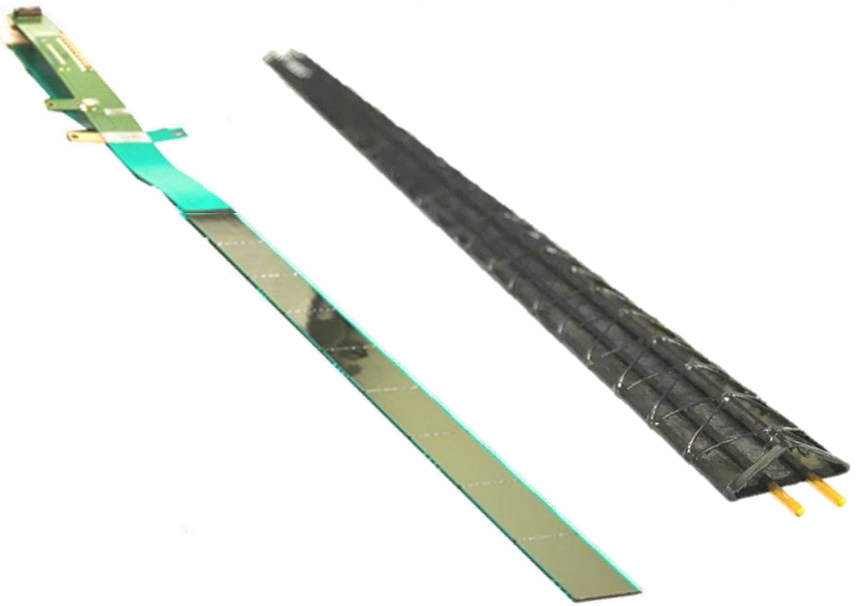
Remove mechanical support outside acceptance

Benefits from increased stiffness by rolling Si wafer



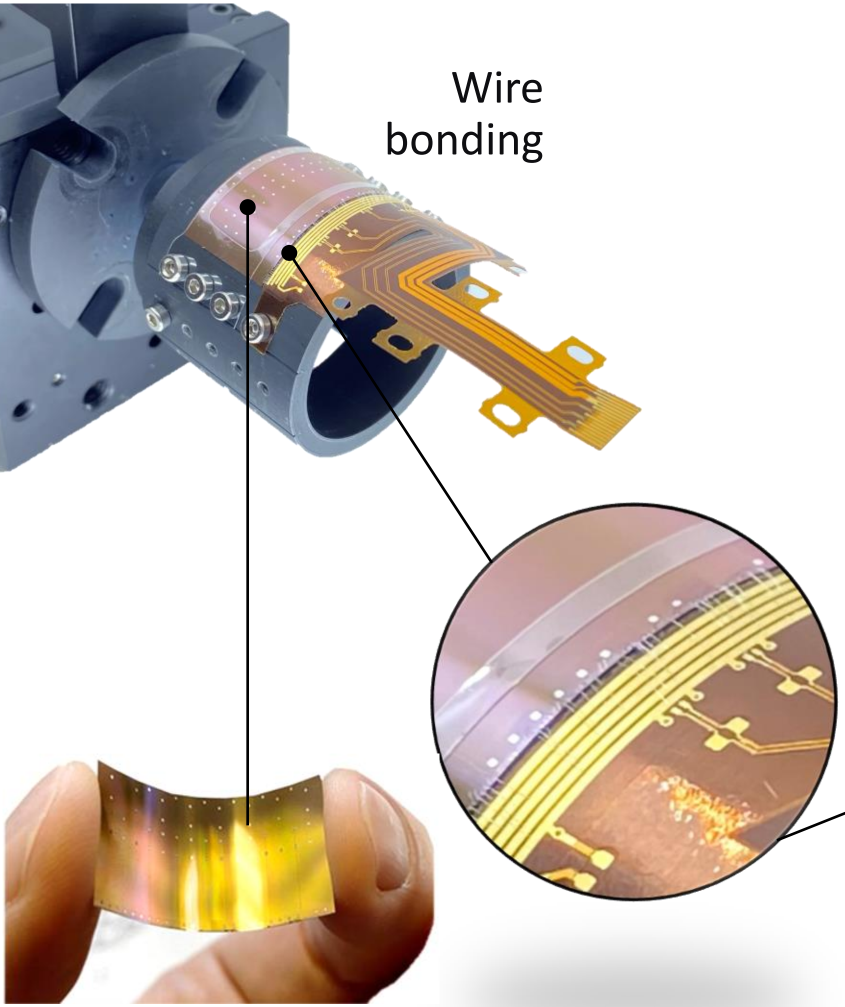
ALPIDE already close: ~40 mW/cm2

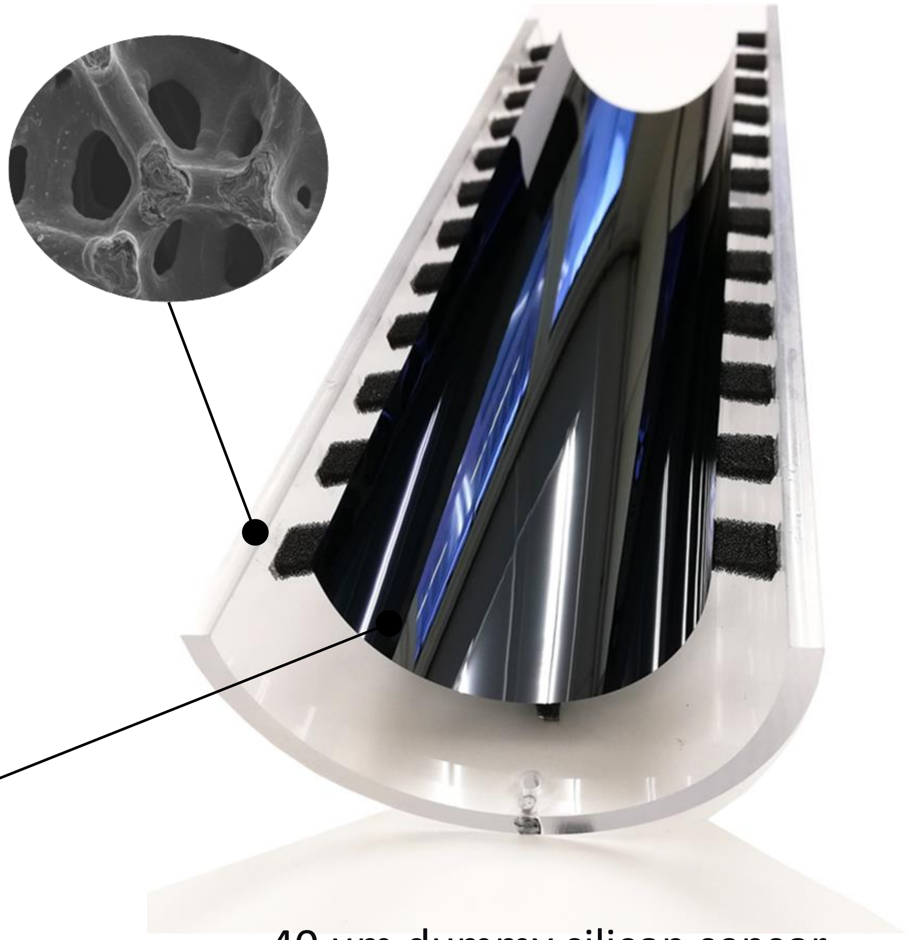
actually, largely sufficient if periphery outside fiducial volume

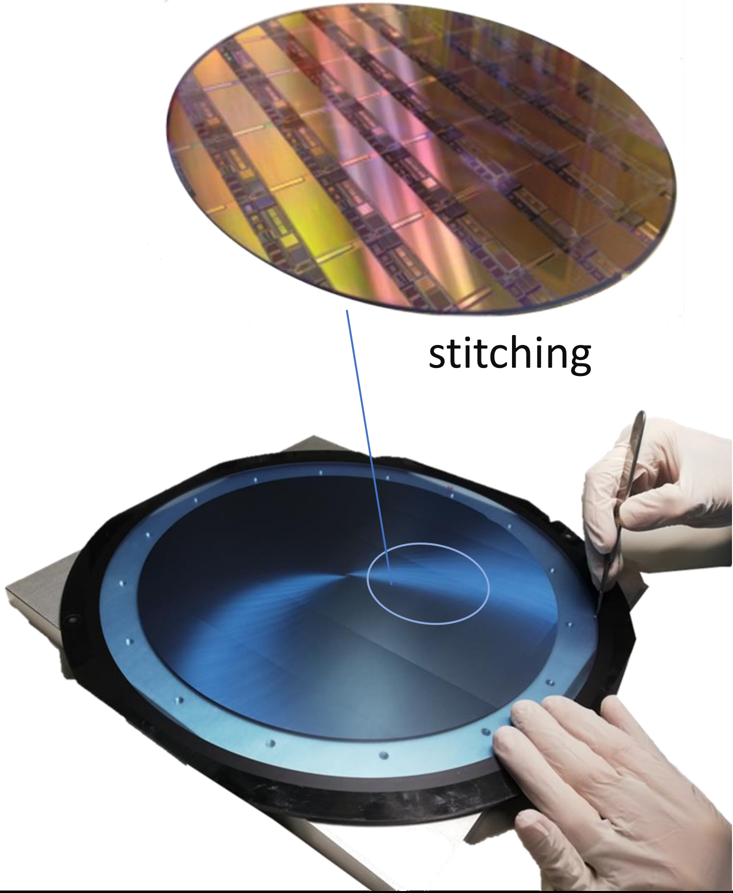


➔ **R&D in HEP Material reduction in front of sensors will be pursued by investigating new sensors technologies and air cooling.**

ALICE ITS3



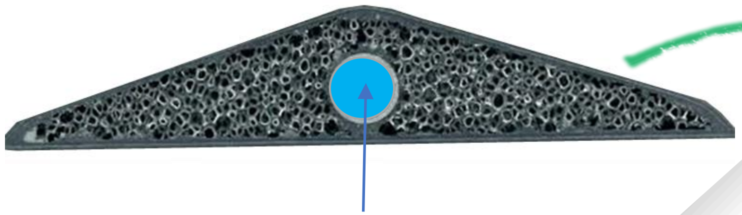




➔ **R&D in HEP Directions towards unprecedented vertex minimum layers materials**
wire bonding on curved Si Sensor, Bending Si wafers + circuits, minimum material support and cooling

➔ **R&D with Industry Chips stitching**, i.e. aligned exposures of given parts of a reticule to produce a larger sensor

CARBON FOAM RADIATOR

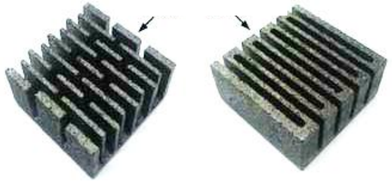


Liquid Cooling

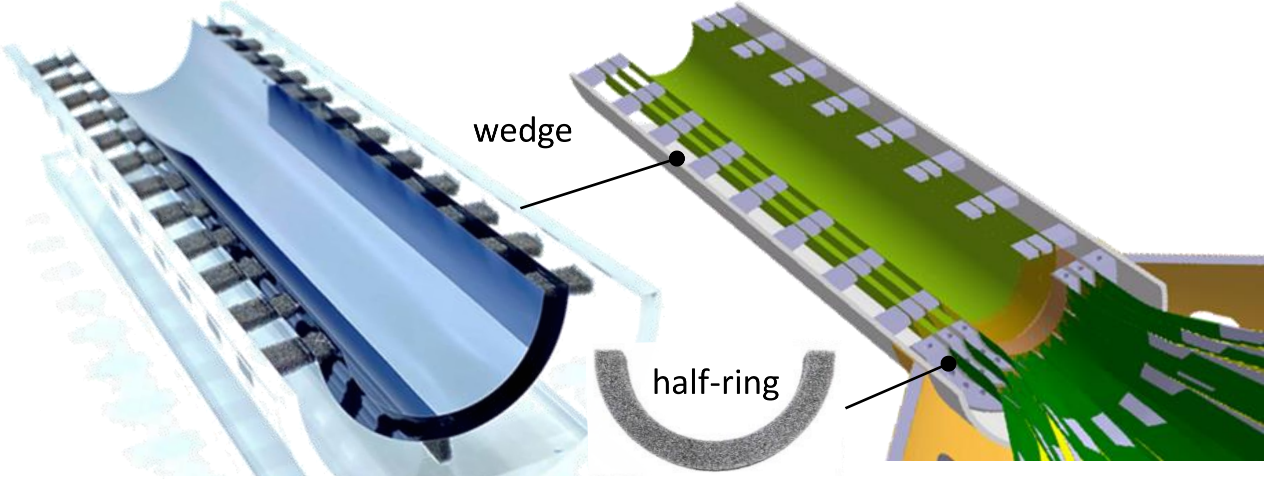
Graphite foam used as conductive media between Titanium pipe and sensor

R&D

Air Flow

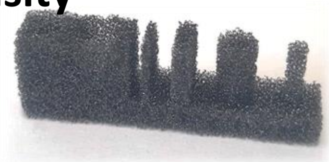


Graphite foam used as heat radiators in Gas cooling solution



Convective heat transfer enhancement allowing air to flow across the foam bonded to the chip sensor

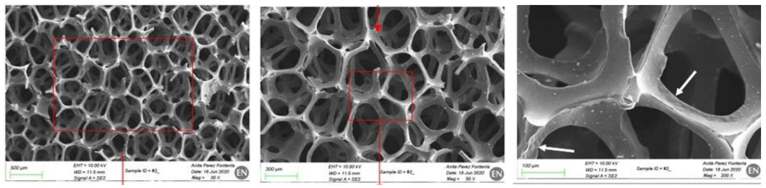
Low density



ERG DUOCEL_AR

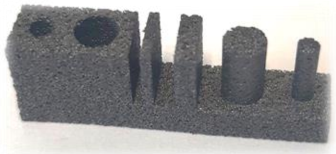
0.06 kg/dm^3

0.033 W/m·K



Used as support (wedge)

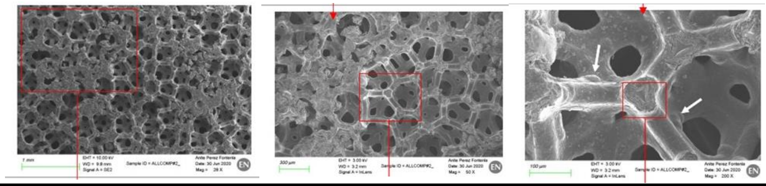
High thermal conduction



ALLCOMP_HD

0.45-0.68 kg/dm^3

85-170 W/m·K



Used as heat radiator (half-ring)

➔ **R&D in HEP Carbon foam used as radiator in detector GAS cooling applications.**

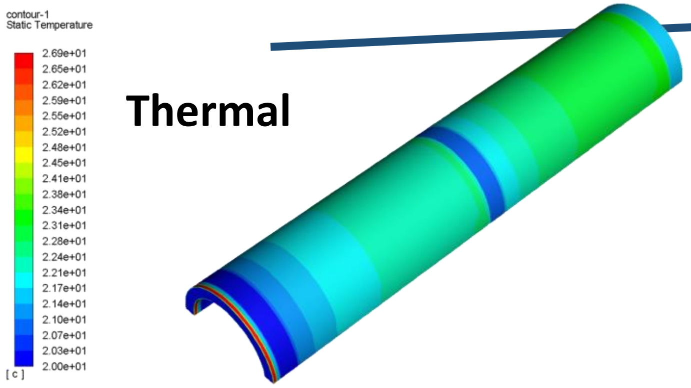
Best compromise between thermal properties and low density needs devoted studies

Radiator geometries optimisation to reduce pressure drop require specific studies

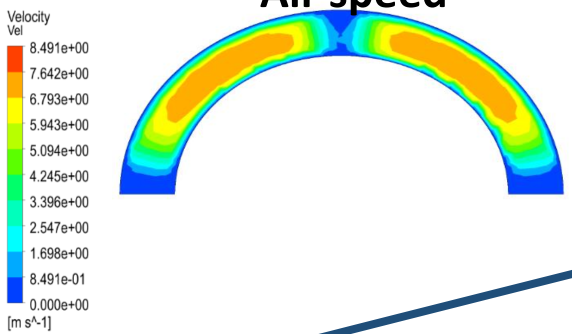
➔ **In Industry Different foams available from Aerospace.**

ANALYTIC APPROACH

Thermal

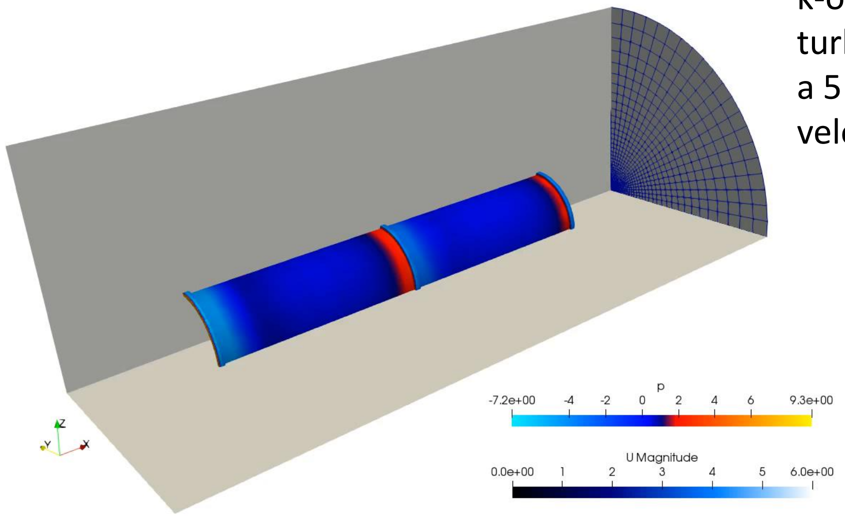


Air speed

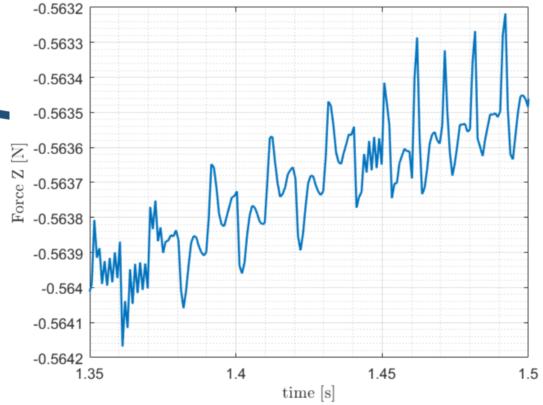


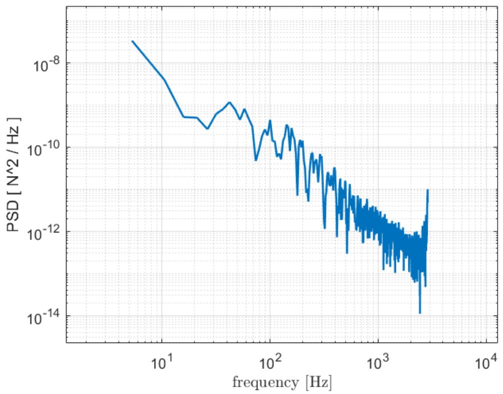
OpenFOAM

k-omega-SST RANS turbulence model, a 5 m/s flow velocity along x

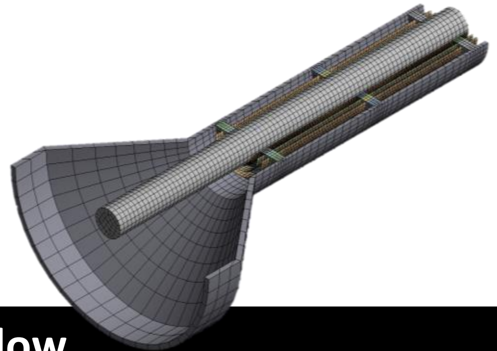


pressure and viscous forces acquired on the yellow part of the structure





Input to structural



➔ **R&D in HEP Develop numerical procedure for determination of detector stability under cooling flow.**

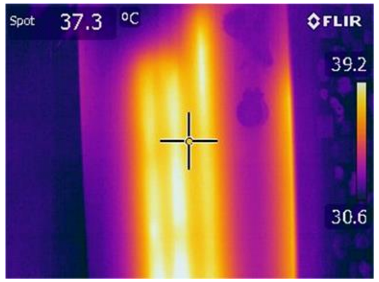
Thermal requirements define gas flow and temperature.

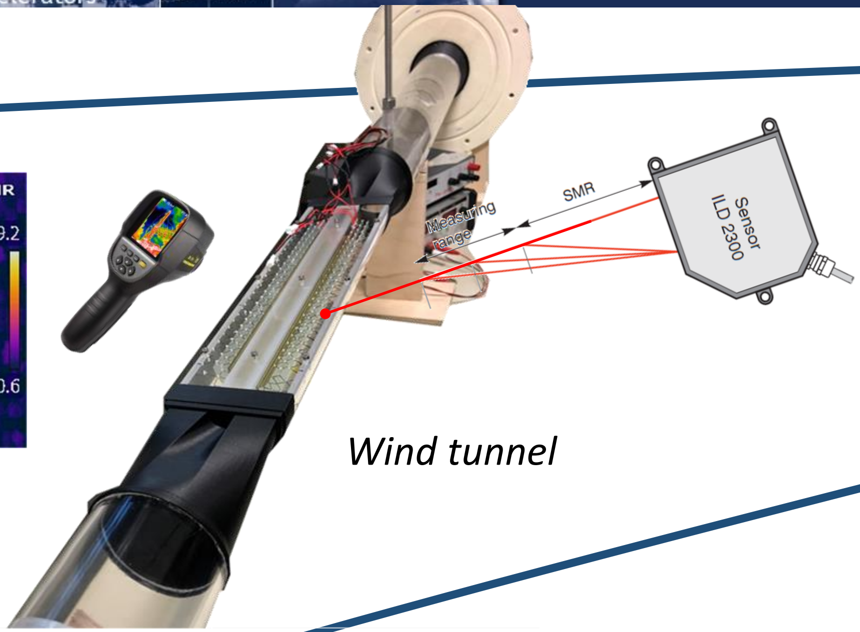
Based on gas flow aerodynamic loads are first calculated using CFD.

Aerodynamic loads are used as an input for the FEA model to determine dyanamic responce

EXPERIMENTAL APPROACH

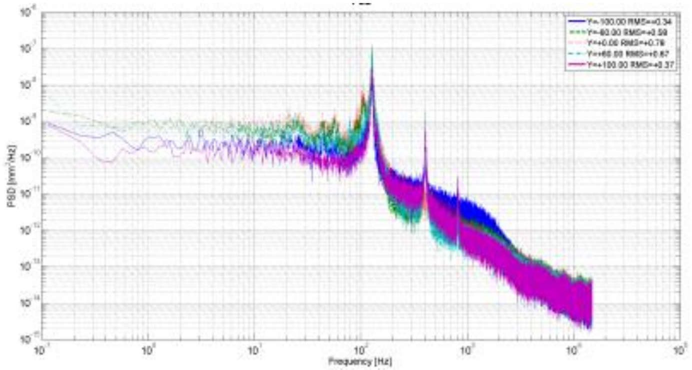
Thermal



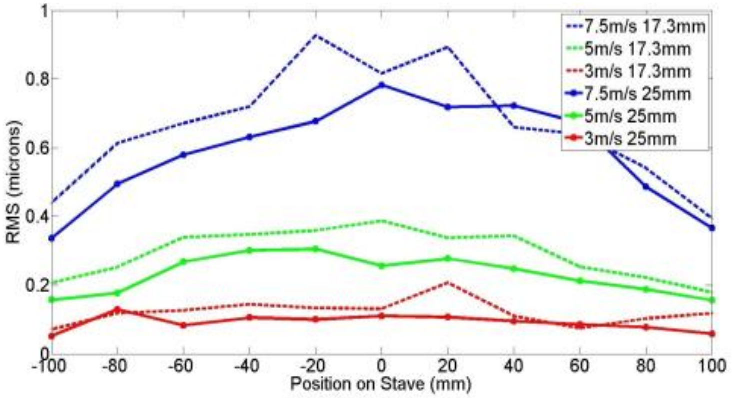


Wind tunnel

Dynamic



Out-of-plane vibrations
Power Spectral Density (PSD) measured at different locations



RMS displacements
of Dynamic response

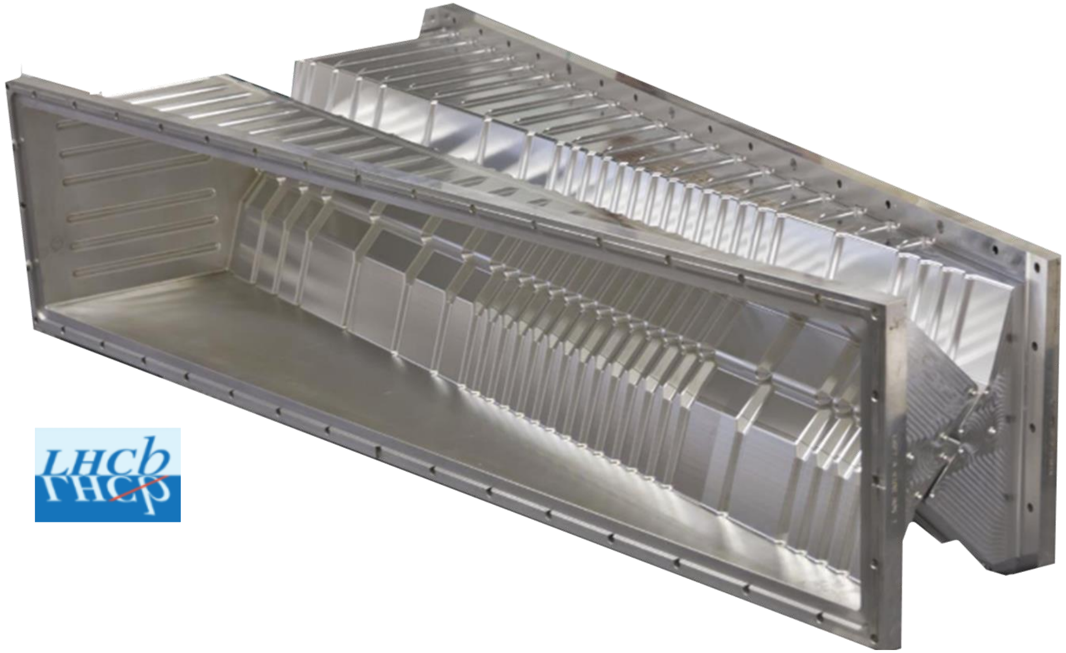
MAX DISPLACEMENT

→ **R&D in HEP Wind tunnel experimental testing procedure, necessary for the final validation.**
Gas speed and temperature are determined to achieve sensor operative temperature requirements in a wind tunnel.
The out-of-plane vibrations Power Spectral Density (PSD) of the detector are measured.
RMS displacements of Dynamic response (integration 1Hz-100Hz).

“CLOSER TO IP”

VERTEX - TRACKER

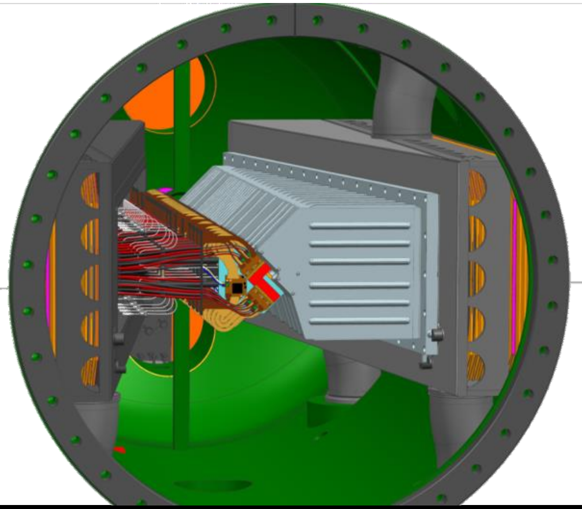
BEAM PIPE



LHCb

LHCb RUN3

	BP
Min radius	3.5mm
Min wall thick.	0.15mm
Material	Al 5083



	Inner radius/ thickness			[mm]
	RUN1	RUN2	RUN3	Run 4
ALICE	29.2/ 0.8	29.2/ 0.8	18.2/ 0.8	16/ 0.5
CMS	29.2/ 0.8	21.7/ 0.8	21.7/ 0.8	
ATLAS	29.2/ 0.8	23.5/ 0.8	23.5/ 0.8	
LHCB	5/ 0.3	5/ 0.3	3.5/0.15	

ALICE

ALICE RUN3

	BP
Min radius	18.2 mm
Min wall thick.	0.8 mm
Material	Beryllium

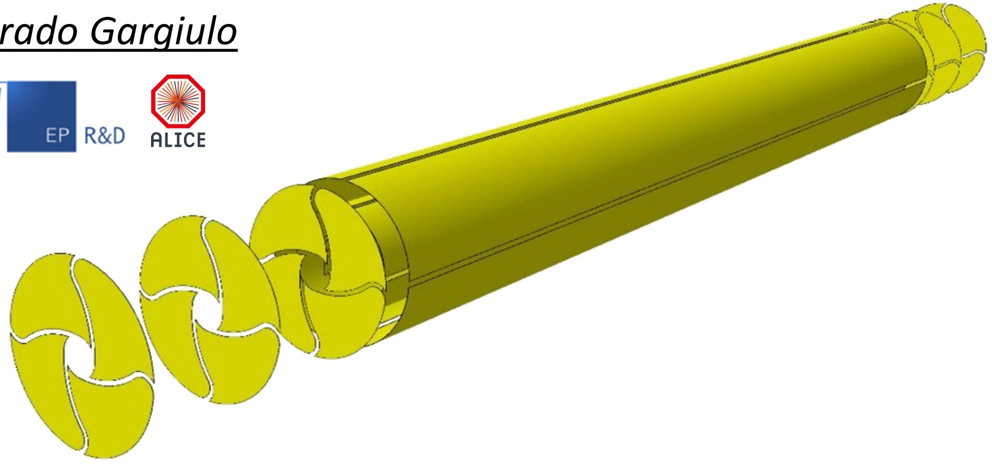
→ **R&D in HEP Going closer to IP with the innermost detection layers**
Minimize material between IP and first layer (thinner BP)

A FUTURISTIC TRACKER CONCEPT

IRIS TRACKER

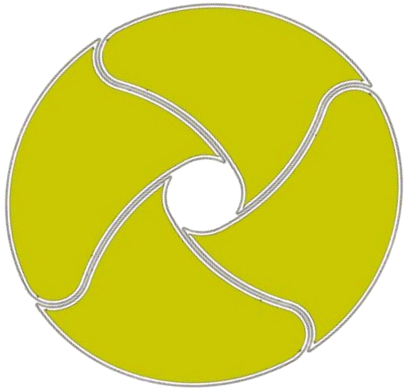
Corrado Gargiulo

CERN EP R&D ALICE

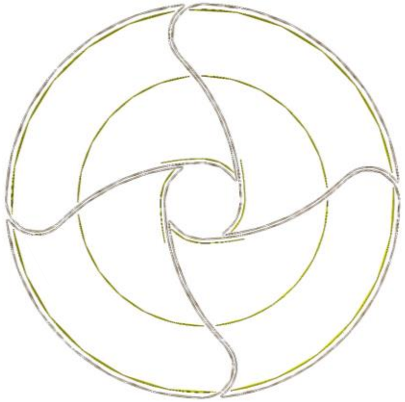


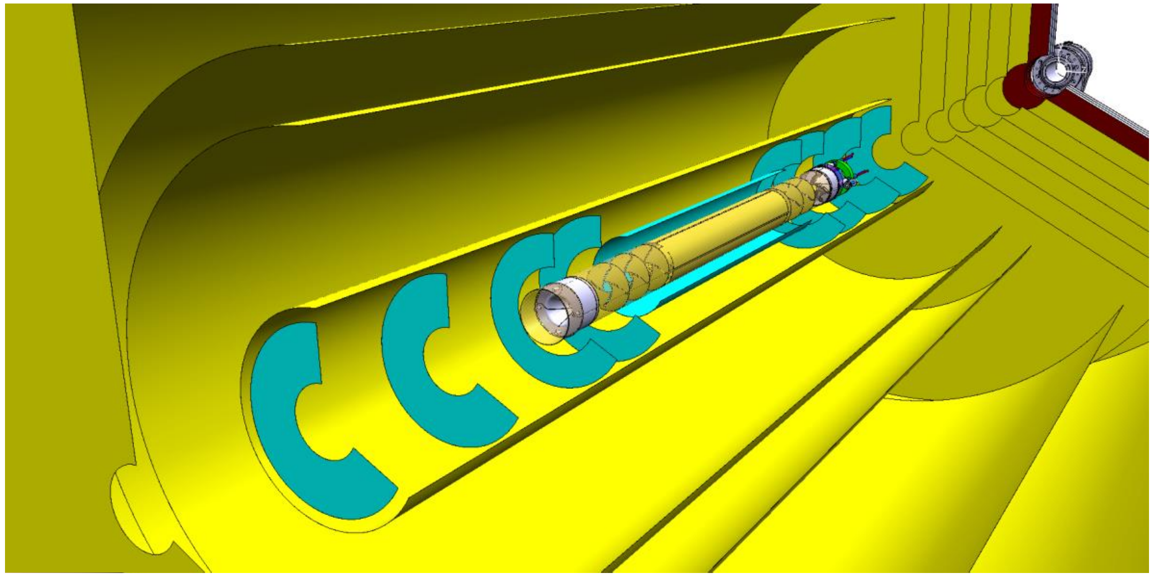
detector- layers

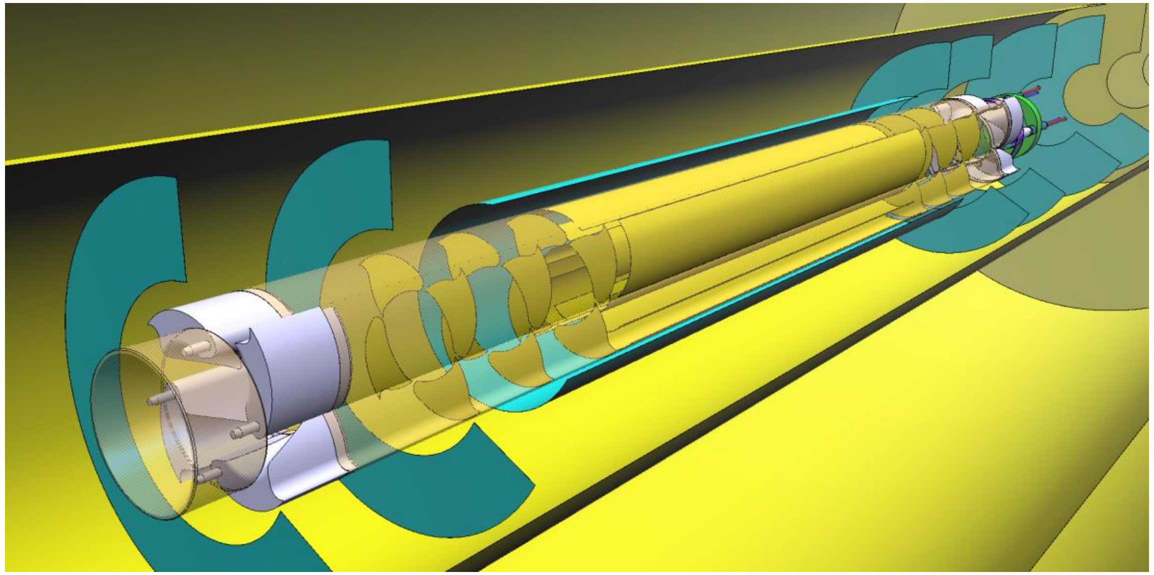
detector- disks



From 15 to 5mm





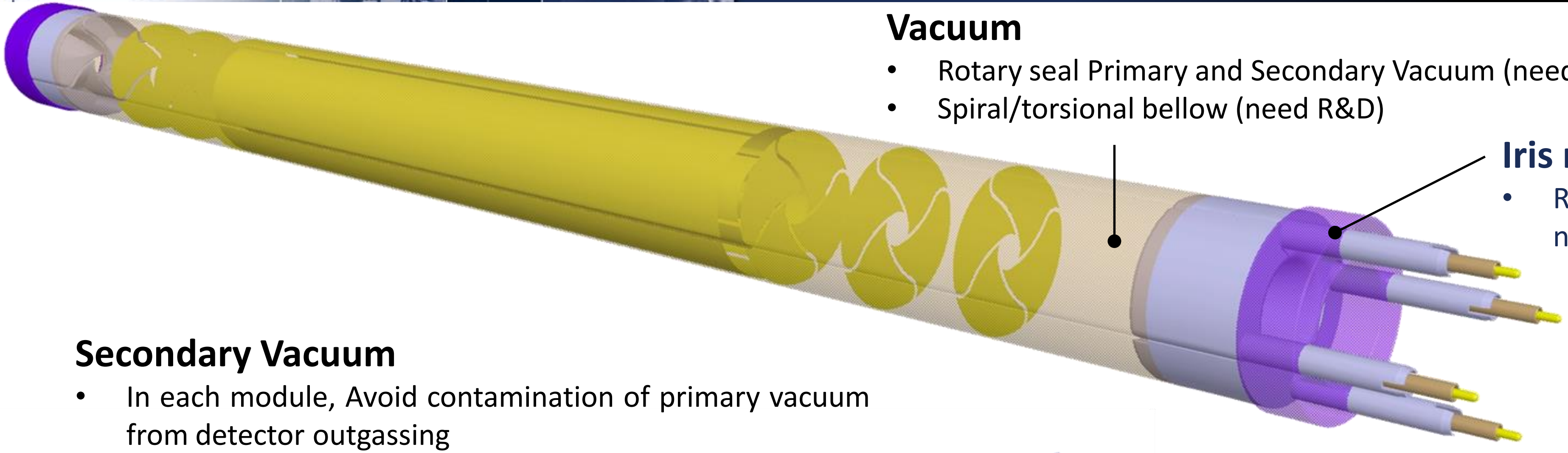


→ **R&D in HEP** **Insert a tracker inside the beampipe.**

Provide the tracker is retractable, it can open at the beampipe injection to respect requirements on N1

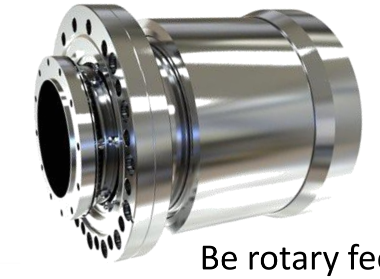
IRIS TRACKER: MODULE

Corrado Gargiulo



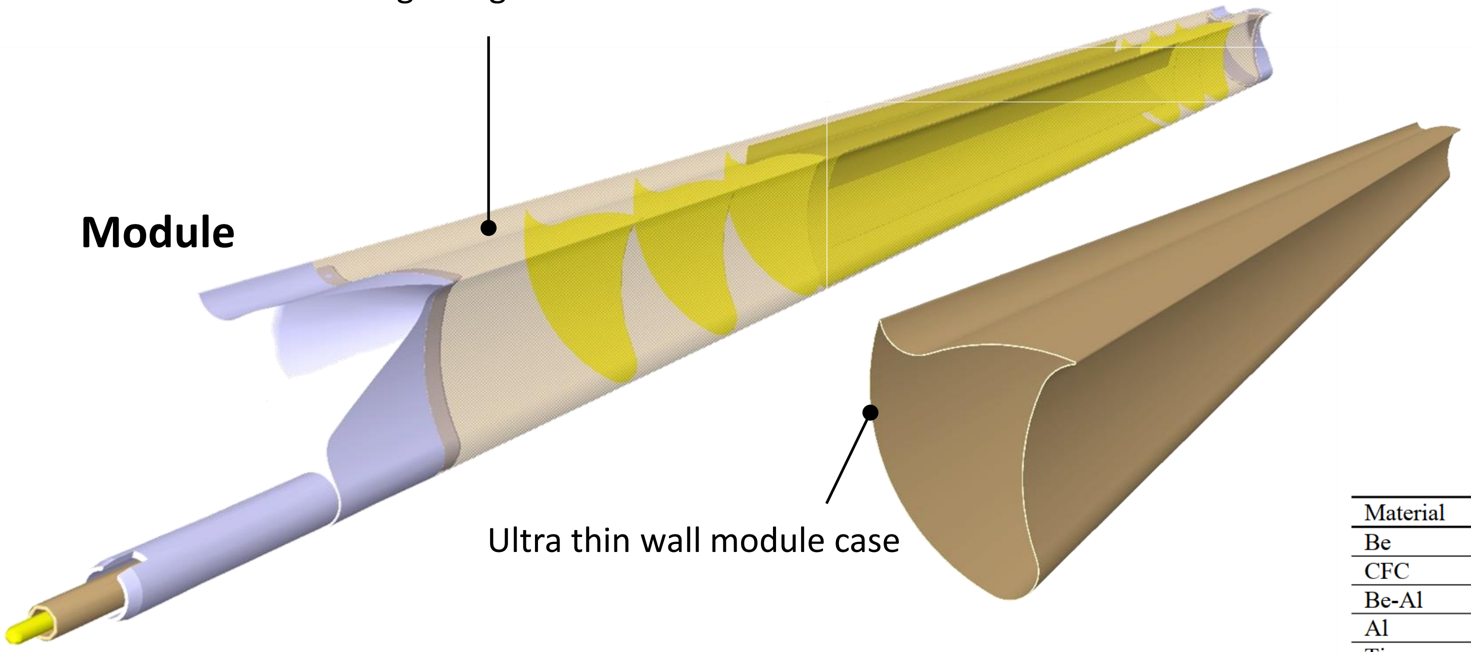
Vacuum
- Rotary seal Primary and Secondary Vacuum (need R&D)
- Spiral/torsional bellow (need R&D)

Iris mechanics (opening-closing)
- Rotary feed through (available on the shelf, need R&D for specific application)


Be rotary feedthroughs

Secondary Vacuum
- In each module, Avoid contamination of primary vacuum from detector outgassing

Module


Ultra thin wall module case

Module structure
- 0.1- 0.15mm Aluminum foil welded and formed (similar process done at CERN with Al bellow 0.2mm- R&D)
- 0.1-0.15 Beryllium foil formed and joined (at the limit of present technology - R&D)
- Al-Be material (AlBemet®)(R&D)
- Beryllium 3d printed (few application in aerospace industry, different geometries –R&D)
- Carbon Composite?

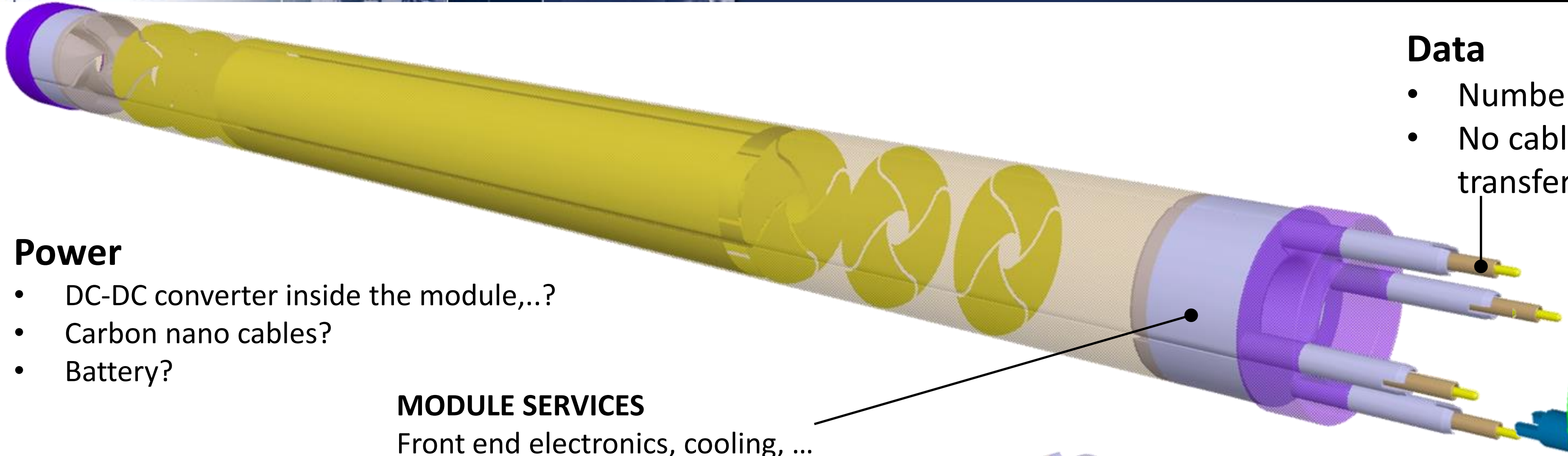
Material	E (GPa)	X_0 (m)	$X_0 E^{1/3}$
Be	290	0.353	2.34
CFC	200	0.271	1.58
Be-Al	193	0.253	1.46
Al	70	0.089	0.37
Ti	110	0.036	0.17
Fe	210	0.0018	0.11


Be Sound woofer thick<0.1 mm

➔ **R&D in HEP module mechanics with ultrathin wall.**

IRIS TRACKER: MODULE SERVICES

Corrado Gargiulo



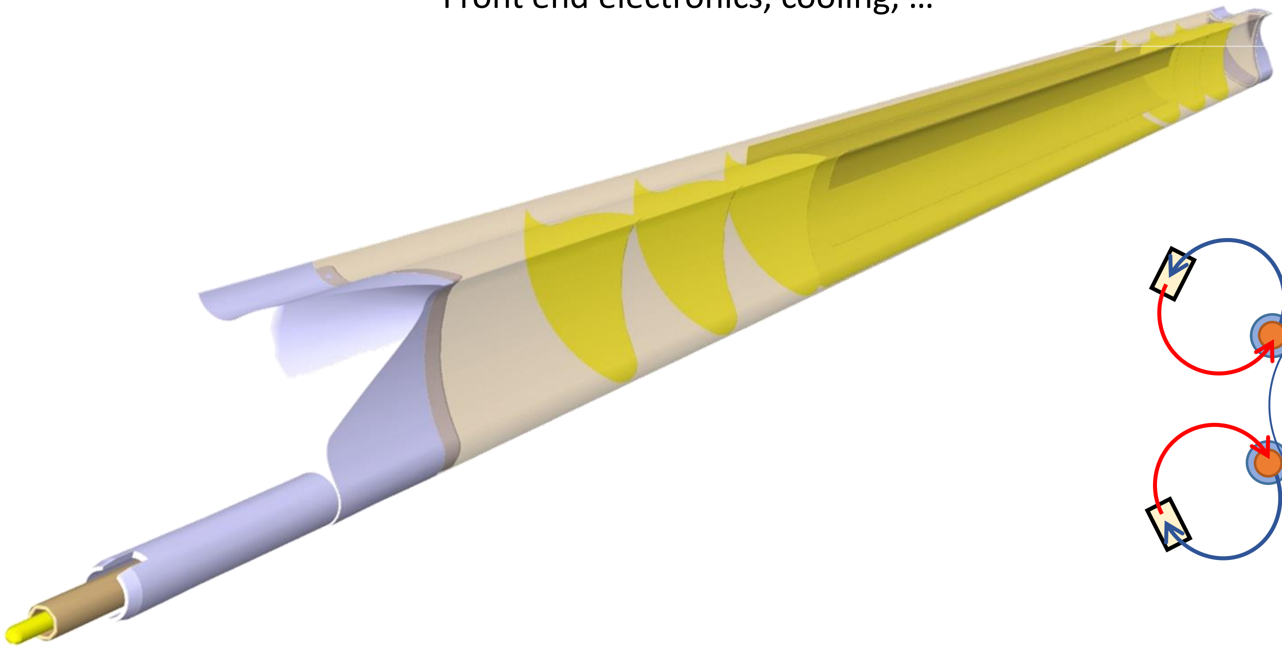
Data

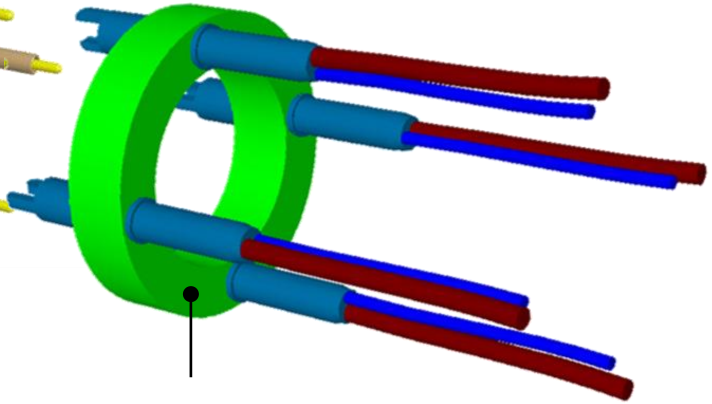
- Number of cables?
- No cables? Wireless links for radial transfer of tracking data to external layers

Power

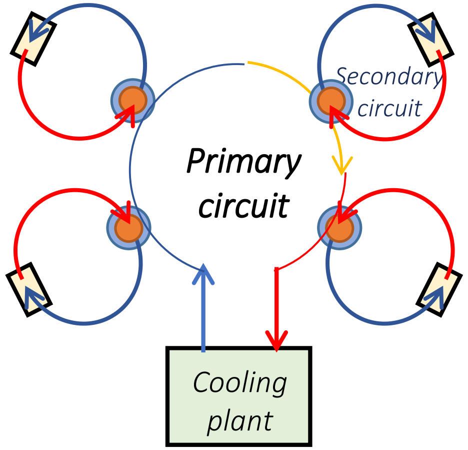
- DC-DC converter inside the module,..?
- Carbon nano cables?
- Battery?

MODULE SERVICES
Front end electronics, cooling, …





Service External Module
Front end electronics & cooling

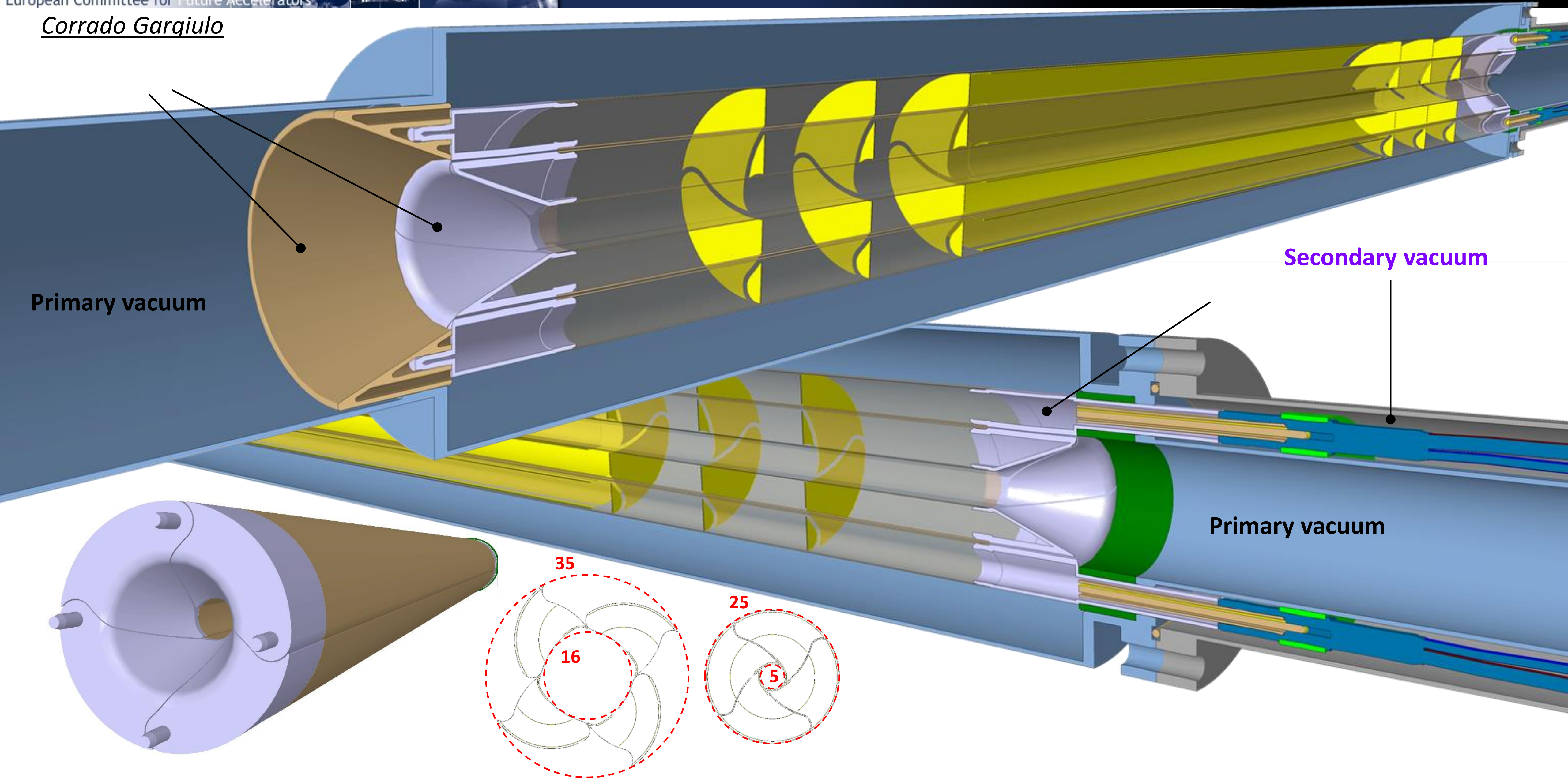


Cooling

- Active cooling
  Loop Heat Pipe, secondary circuit,
- Passive Cooling
  Conductive strap, secondary circuit

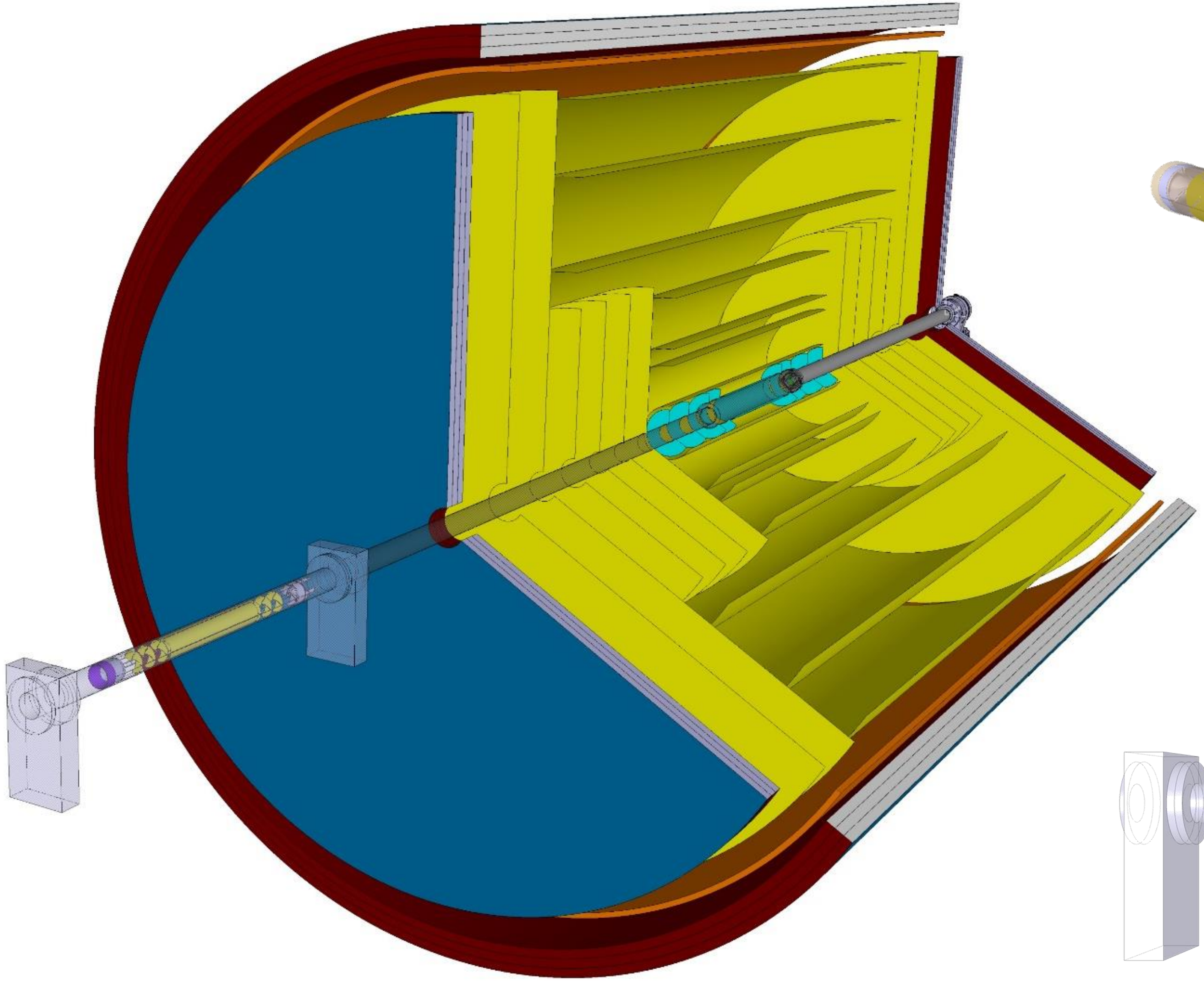
IRIS TRACKER: APERTURE, IMPEDANCE, VACUUM DYNAMICS

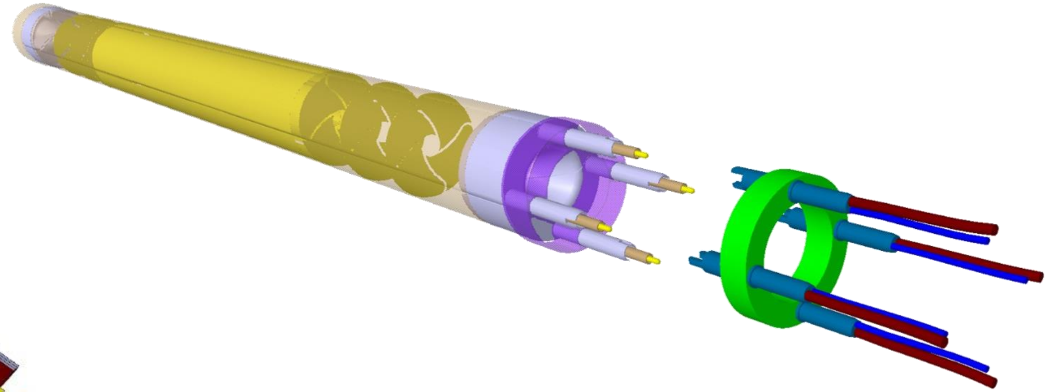
Corrado Gargiulo



→ **R&D in HEP Fulfill beam requirements**

Corrado Gargiulo

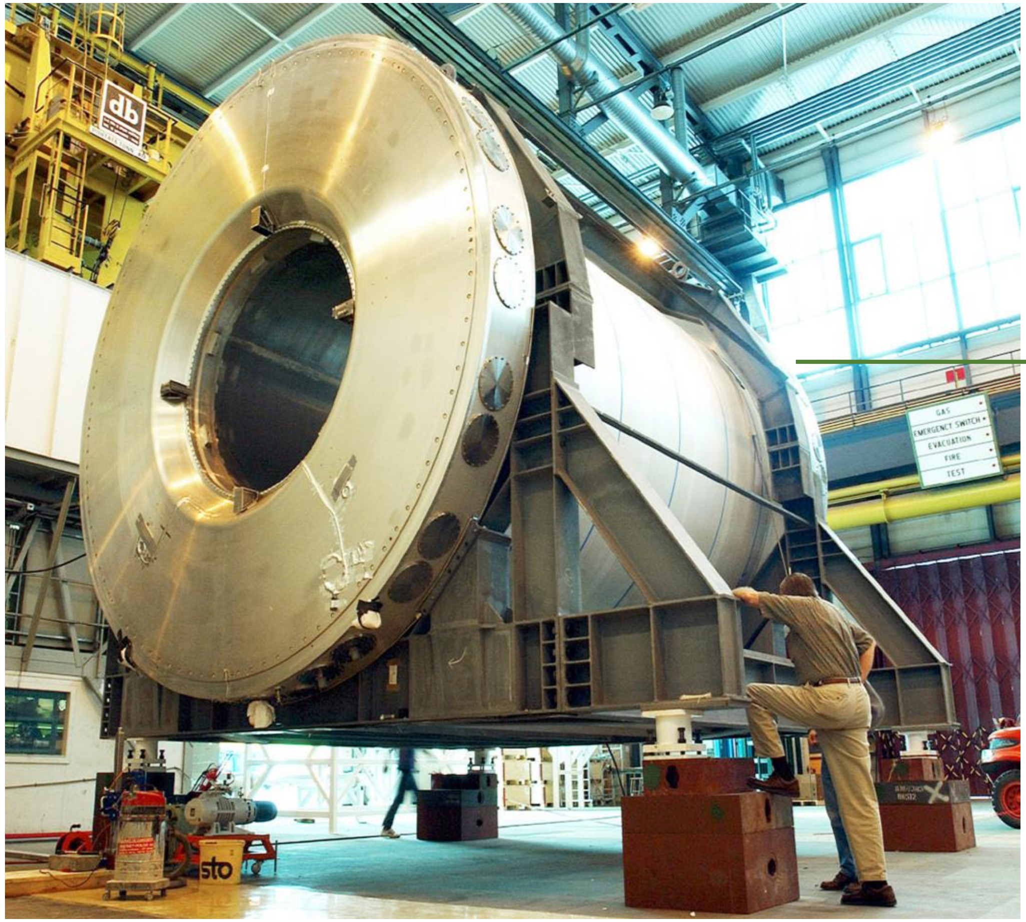


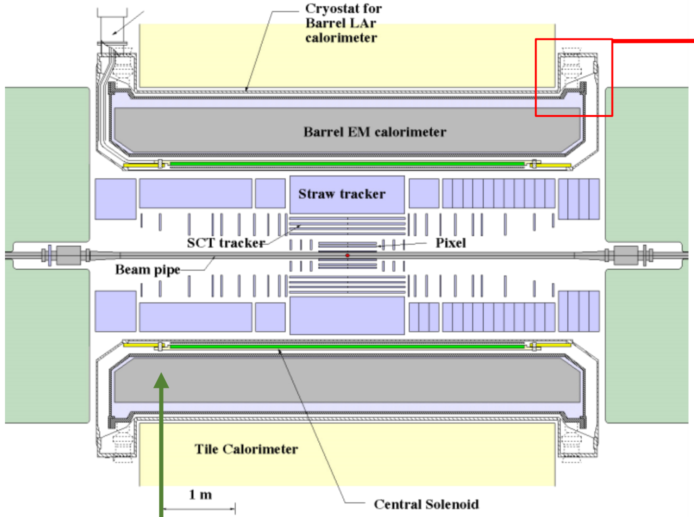


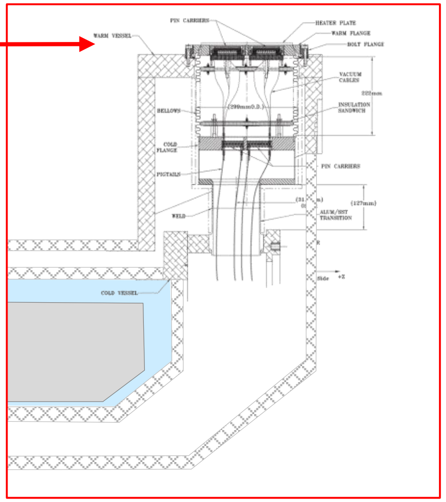
→ R&D in HEP Airlock for extractable detector

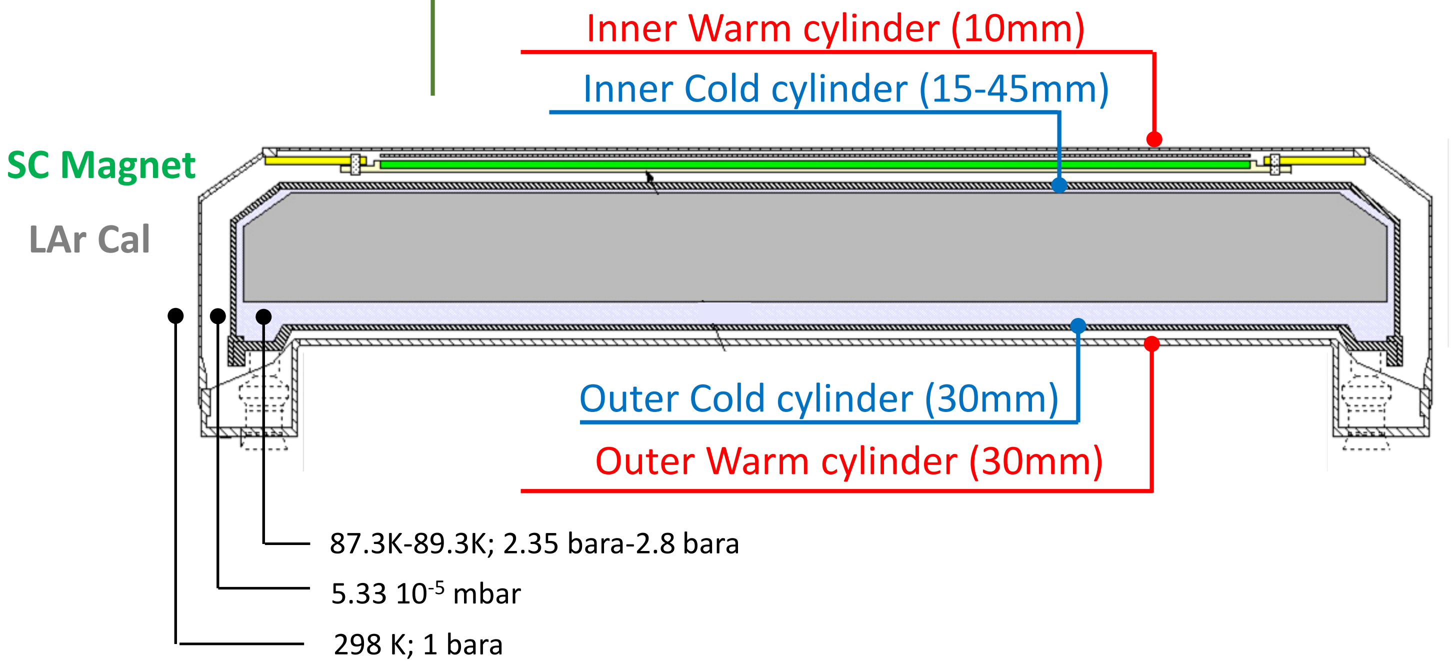
DETECTORS CRYOSTAT

Ultralight solutions







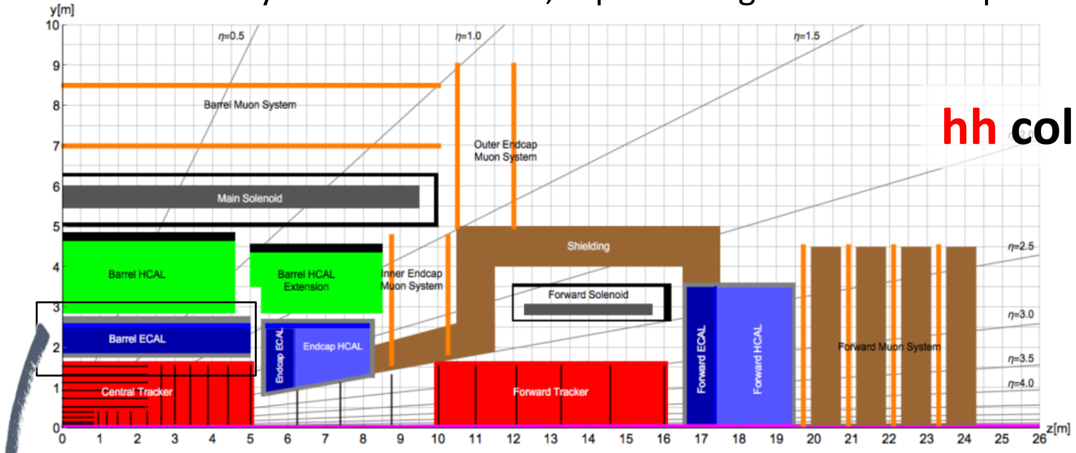


ATLAS barrel cryostat, toroidal Al 5083 double wall, warm and cold vessel, with a feedthrough flange and a flexible bellows welded between them and pumped down to about 10^{-3} mbar vacuum.

→ Cryostats in HEP are still the purview of metals.

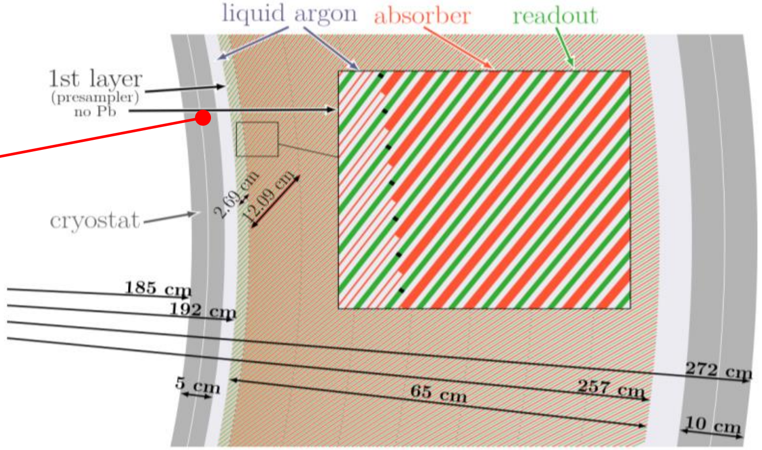
Baseline geometry, FCC-hh LAr barrel ECAL :

The aluminium cryostat is 5 cm thick, representing 56 % of X0 at η=0



hh collisions

Cryostat calorimeter (double vessel)



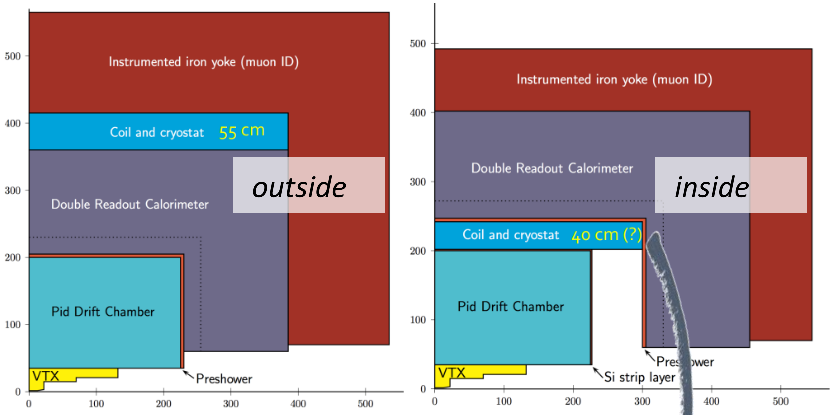
minimum material

Baseline geometry, FCC-ee :

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

e$^+$e$^-$ collisions

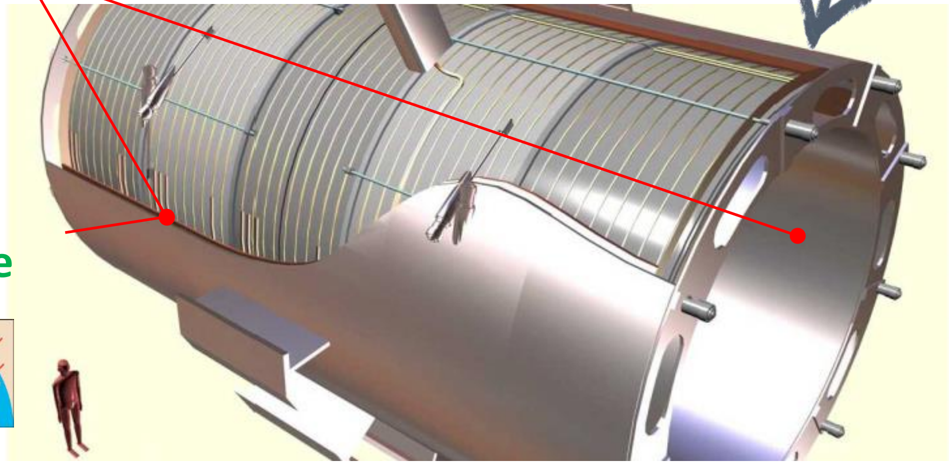
Solenoid outside or inside calorimeter



Cryostat magnet

minimum material

buckling resistance



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

CYLINDER SHELL ANALYSIS

Comparative analysis: Quasi Isotropic Lay-up used in this analysis only for overall considerations, final layup will be driven by load/boundary conditions.

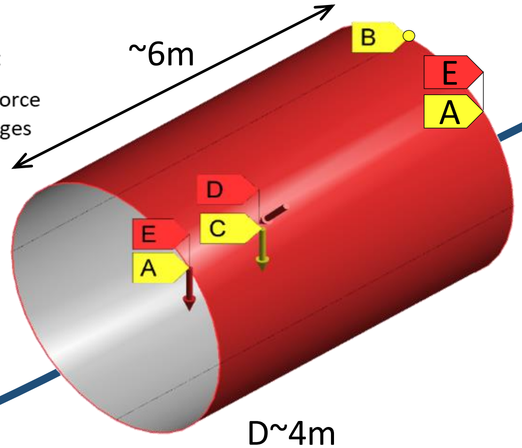
BC:

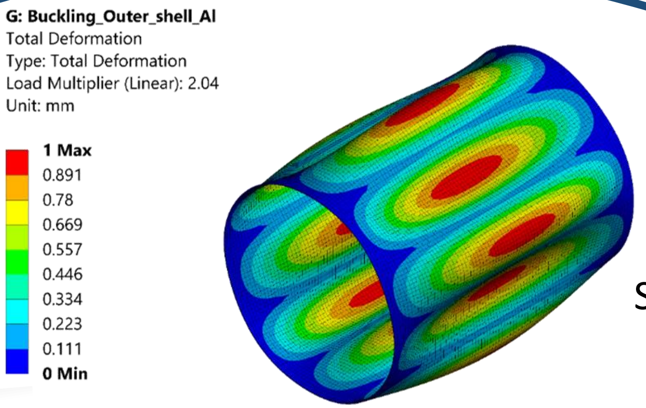
FEM loads:

- 1 atm pressure
- Rigid end flanges allowed to move axially
- Self weight
- 350 kN of force on the flanges

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



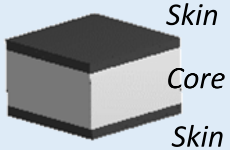


Requirement
Safety factor = 2.0

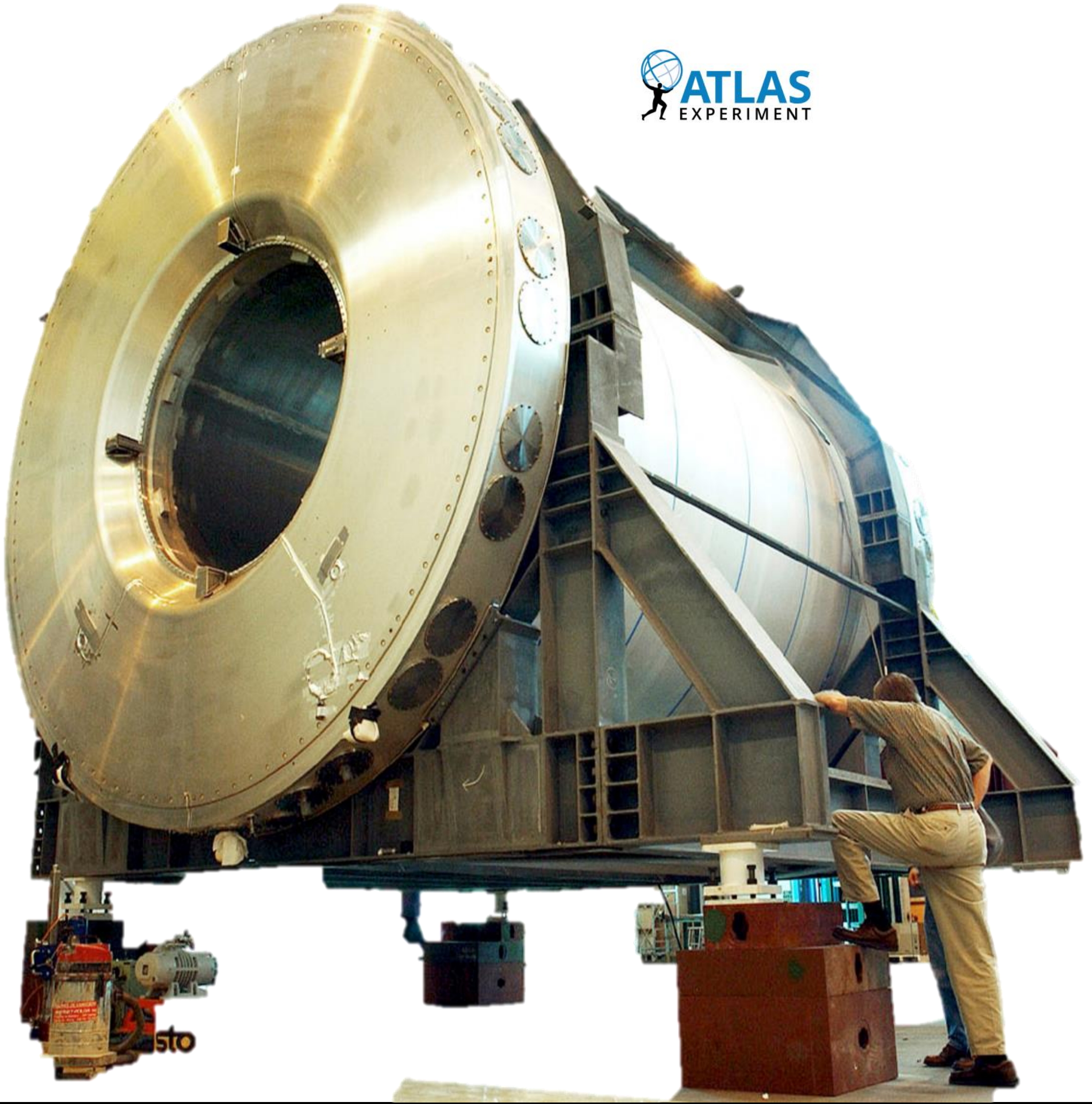
	Sandwich			Baseline		Solid plate				
	UHM CFRP	HM CFRP	IM CFRP	Al	Ti	UHM CFRP	HM CFRP	IM CFRP	Al	Ti
Avg. Th. [mm]	3.5	3.8	4.9	4.0	1.5	13.6	16.8	20.8	20.9	17.2
Material budget X/X_0	0.0134	0.0147	0.0189	0.045	0.034	0.052	0.065	0.08	0.24	0.49
X_0 + %	-70%	-67%	-58%	X_0	-24%	+16%	+44%	+78%	+433%	+989%
Skin Th.[mm]	1.2	1.2	1.6	1.7						
Core Th. [mm]	25	33	40	40						
Total Th. [mm]	27.4	35.4	43.2	43.4	101	13.6	16.8	20.8	20.9	17.2
Thickness + %	-37%	-18%	0%	T	+133%	-69%	-61%	-52%	-52%	-60%

Radiation length X_0[mm]
Al = 88.9
Ti = 35.1
UHM/HM CFRP = 260
Honeycomb Al= 6000

Sandwich

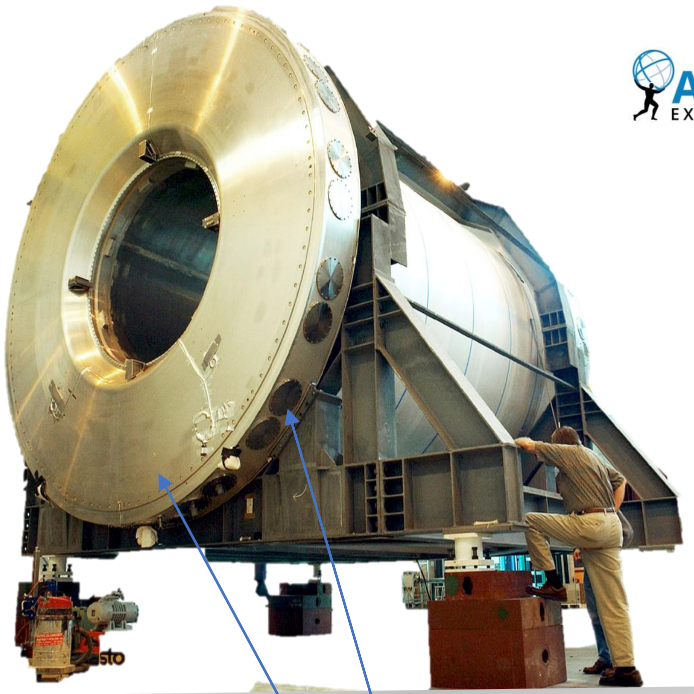


→ **In order to decrease the thickness and material budget, lightweight and strong composite materials will be considered**

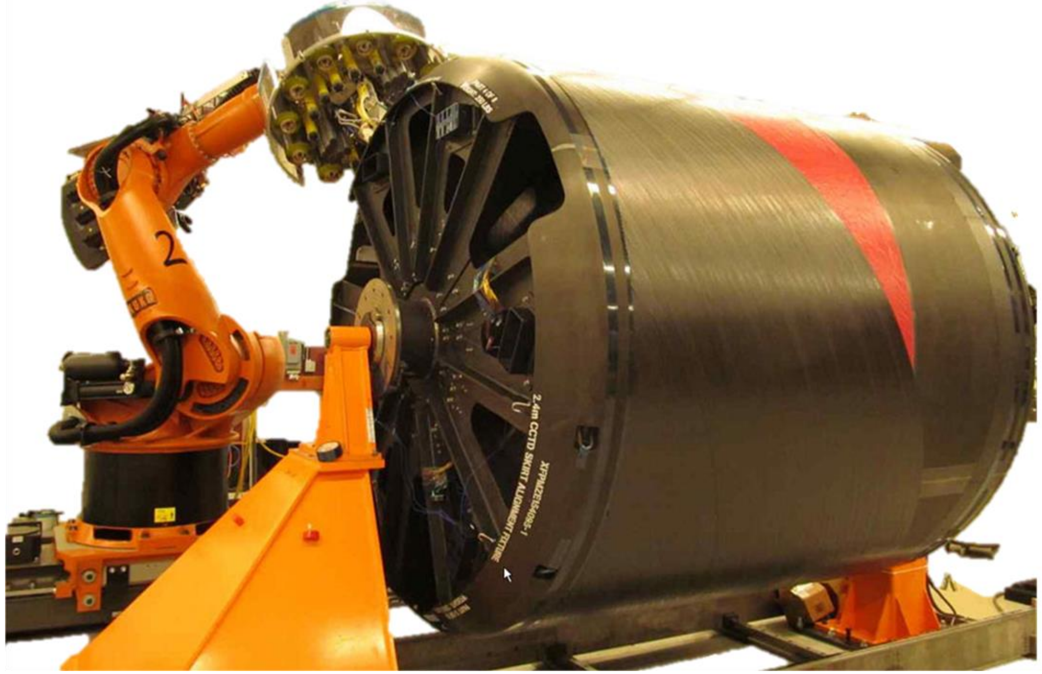


➔ **New in Industry** : similar development in aerospace cryotanks for LOx and LH2: CHATT, CCTD, SpaceX

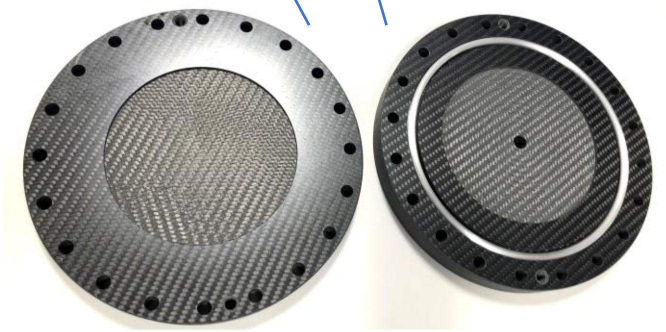
➔ **R&D with Industry** sandwich/flute design, carbon layup (thin ply), Out of Autoclave curing, Winding/tape deposition



ATLAS EXPERIMENT

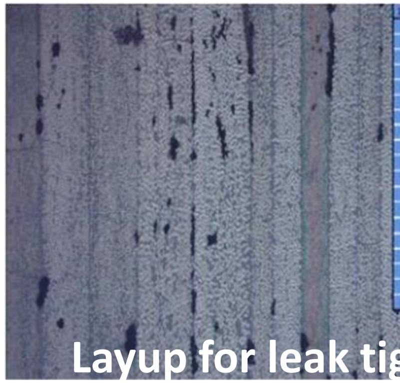


Out of Autoclave curing, Winding/tape deposition



CERN EP R&D

Carbon UHV sealed joint



17 ply IM7/5320-1			
Ply ID	Orientation	Thickness	
1	12	0.00545	Thick
2	-12	0.00545	
3	-45	0.00545	
4	45	0.00545	
5	65	0.00545	
6	-65	0.00545	
7	60	0.0025	Thin
8	-60	0.0025	
9	0	0.0025	
10	-60	0.0025	
11	60	0.0025	
12	-65	0.00545	Thick
13	65	0.00545	
14	45	0.00545	
15	-45	0.00545	
16	-12	0.00545	
17	12	0.00545	
	Total	0.0779	

Layup for leak tightness

Carbon sandwich/ flute layout

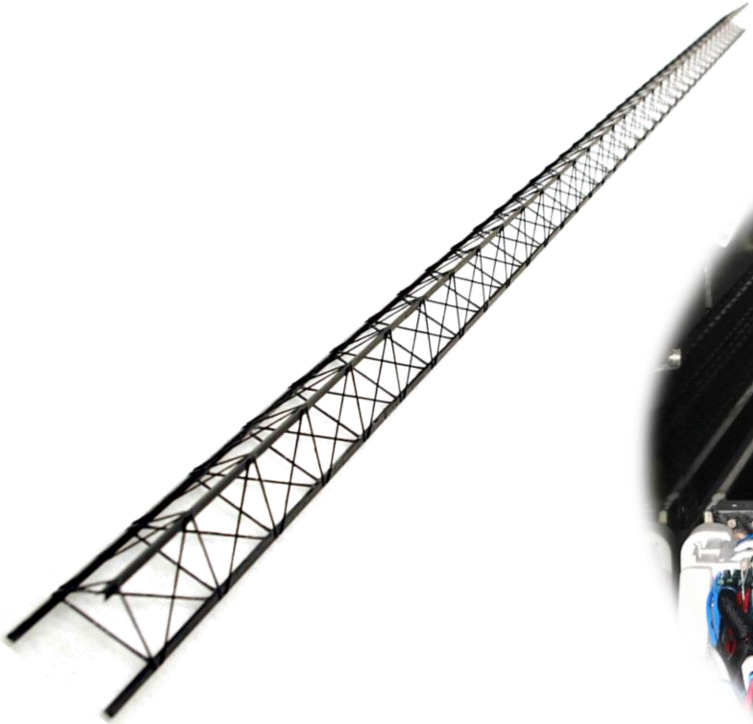
➔ **R&D in HEP** carbon joints and feed through requires specific R&D on sealing

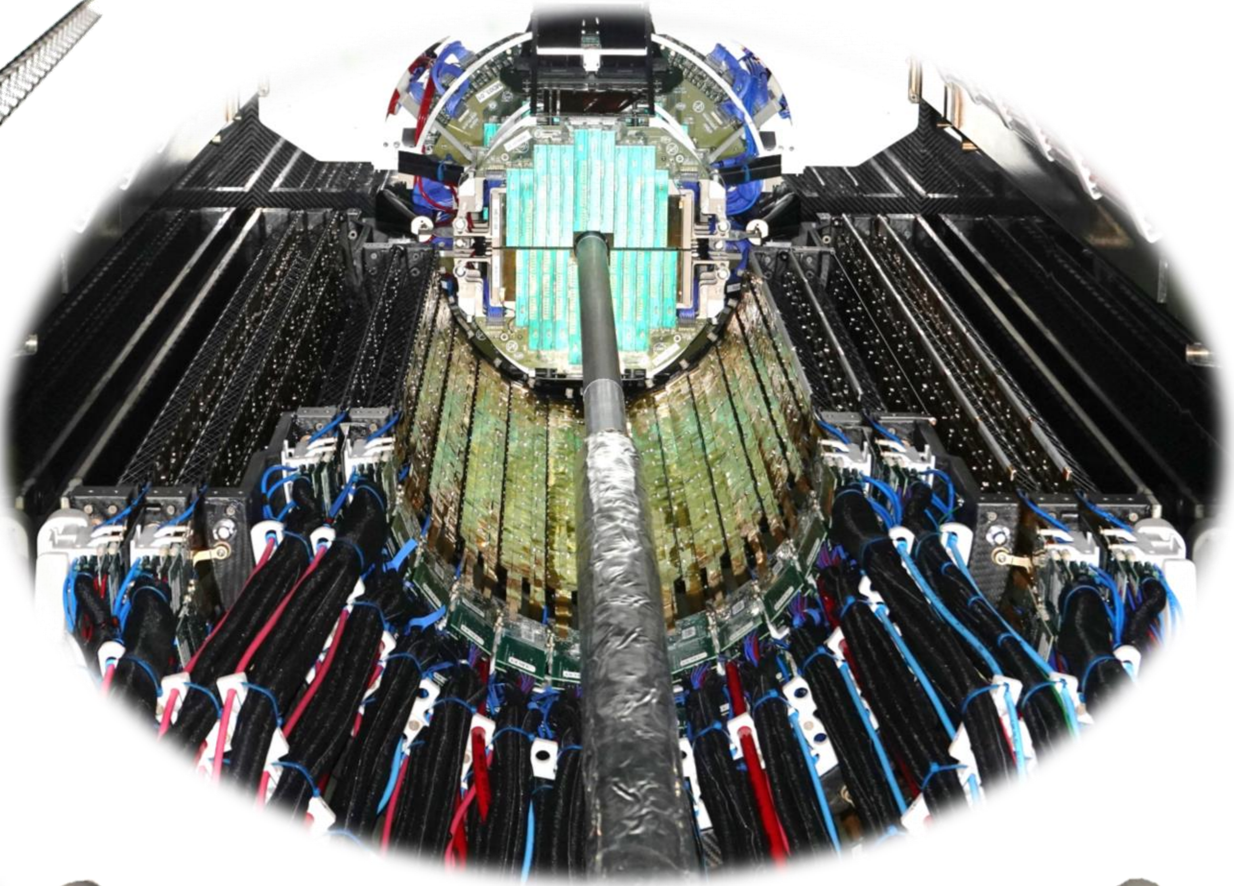
➔ **R&D with Industry** sandwich/flute design, carbon layup (thin ply), Out of Autoclave curing, Winding/tape deposition

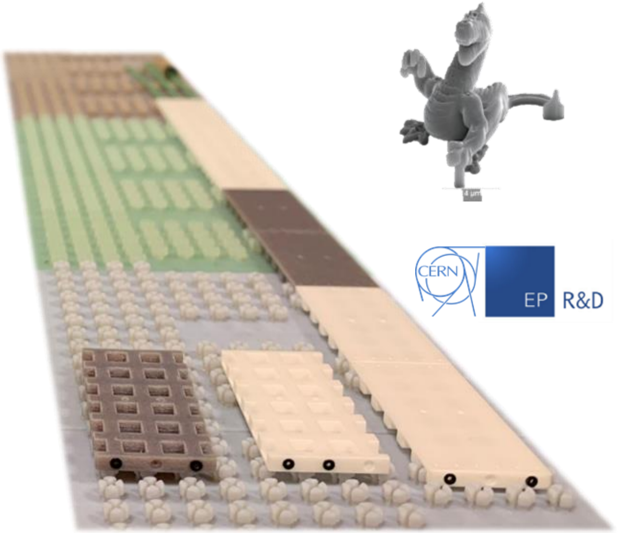
GLOBAL MECHANICS

ADDITIVE MANUFACTURING

ADDITIVE MANUFACTURING

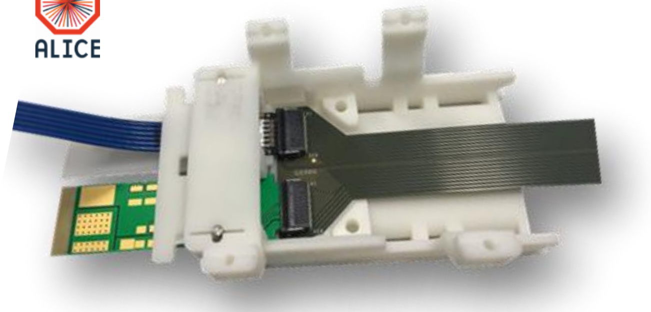




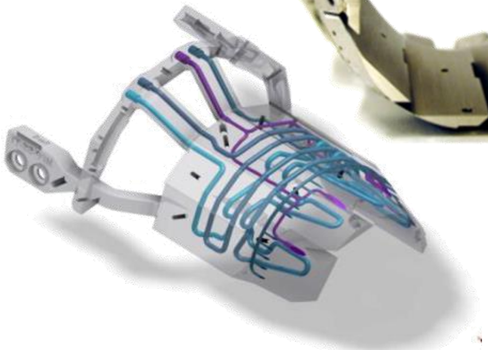


CERN EP R&D

ALICE



ATLAS EXPERIMENT



Belle II

➔ Additive manufacturing already largely used in different detector’s mechanics from micro to macro structural and cooling components….also used to print detectors!

ADDITIVE MANUFACTURING, GLOBAL MECHANICS

Topology optimization (MX3D)

Large dimensions (MX3D)

Fuel tank for Rocket (Relativity Space)

Robotic assembly in place and AM technics (Tethers Unlimited)

CLIC

ALICE

➔ In Industry Topology optimization

➔ New in Industry Robots arms used to extend additive manufacturing capabilities

➔ R&D in HEP full exploitation of new design possibility introduced by 3D manufacturing at micro and macro scale

CONCLUSIONS

Light mechanics for future detectors:

some areas of development

Light mechanical substrates for vertex sensors in hh at colder temperatures

requirement: Lower temperature, High radiation environment

→ **technologies**: microfabrication/additive manufacturing/interconnectivity

→ **R&D**: standardized process, materials engineered for CTE compatibility and Thermal Conductivity, LEGO concept for connectivity and rework

→ **technologies:** macro/micro-vascular carbon substrate macro (>1mm) & micro (<1mm)

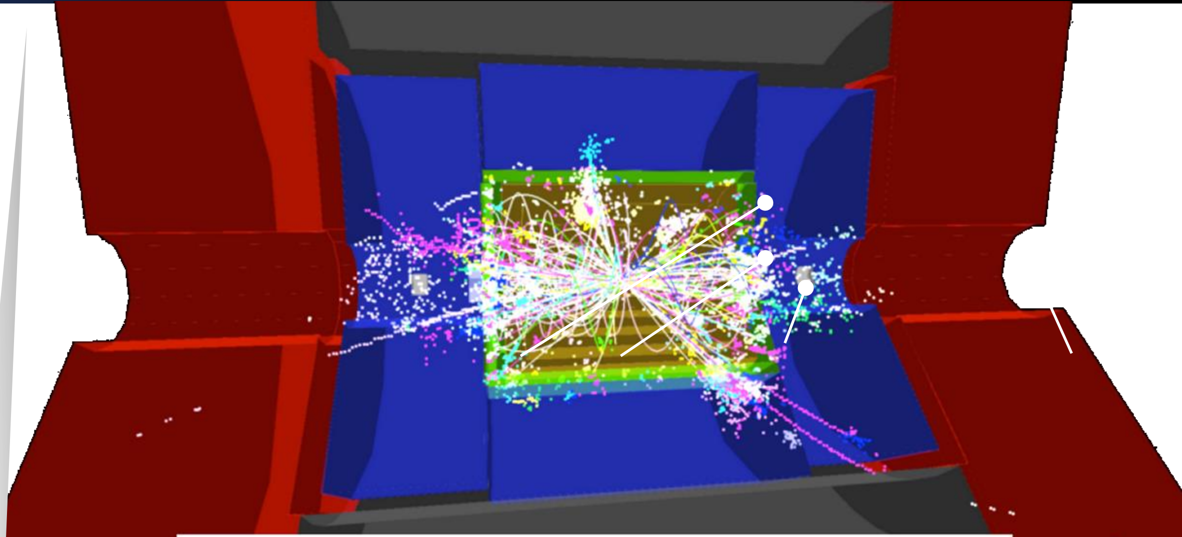
→ **R&D:** Characterization of carbon nano fibres and resin tailored to HEP application and radiation environment; use of light pipes/vascular network and their characterization vs new coolants and high pressure

Light mechanical substrates for vertex sensors in e+e-

requirement: low material budget, position stability

→ **technologies:** Silicon sensor Stitching, Bending, air/gas cooling, cooling radiator, carbon foam

→ **R&D**: air and cold gases established procedures for thermal and vibrational characterization both numerical and experimental, optimization heat exchange, carbon foam characterization, pressure drop, radiation,…



Trackers, SC magnet, Calorimeters, Global mechanics

Vertex sensors closer to the IP

requirement: place first layers at few mm form IP

→ **technologies:** UHVacuum, wireless data, loop heat pipes, stitching, bending, thin Al-beryllium forming

→ **R&D**: forming of ultrathin wall module, ultrahigh vacuum feedthrough, design to fulfill Beam requirements (n1, impedance,..)

Lighter thinner Cryostat for SC Magnet/Calorimeter

requirement: low material budget, low thickness

→ **technologies:** Tape winding, Out of Autoclave, Ultrathin CFRP

→ **R&D**: leak tightness Vs LAr and Vacuum, Sealing carbon structure joints, Carbon sandwich wall (with industry)

Global Mechanics

requirement: low material, low cost, large scale automated production

→ **technologies:** 3d printing

→ **R&D:** design topology optimization, replace large metallic frames with light carbon structures, exploit advantages of robot 3d print in situ manufacturing (*with industry*)