UNIVERSITY OF LIVERPOOL

# Rome CEPC Meeting

# Development of CFRP Structures for Future $e^{+}e^{-}$ colliders at Liverpool

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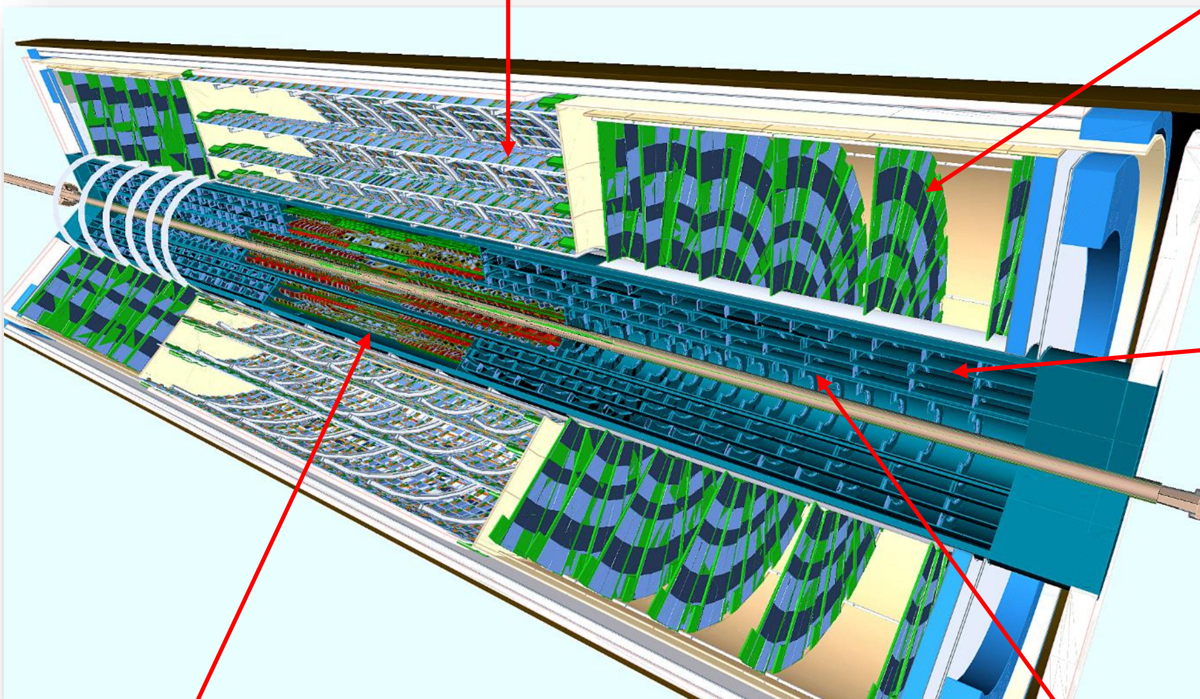
# Overview

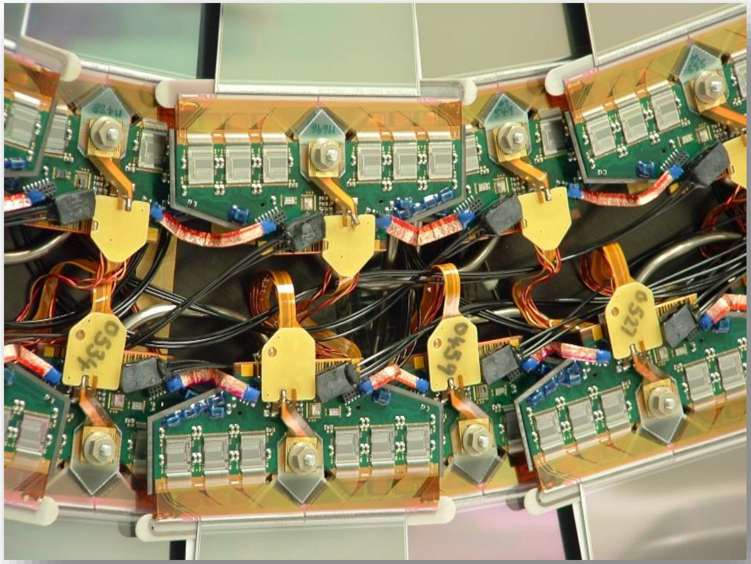
- Developments for ATLAS Itk
  - Motivations for Local Supports
  - LS requirements
- CFRP support structures for $e^+e^-$ experiments
  - Vertex Detector
  - Outer Silicon Tracker
- Liverpool Advanced Materials Lab
  - Facilities
  - Activities

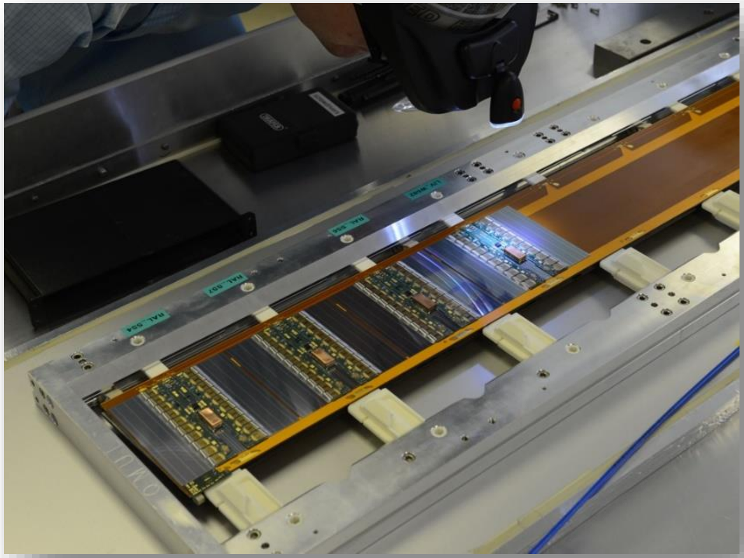
# ATLAS ITK Upgrade



# ATLAS ITk – Local Supports

- Current ATLAS strips
  - Individual back-to-back modules mechanically attached to large structures with ‘add-on’ services
- Future ITk Strips
  - Single-sided modules *glued* to ~30 module structures with *integrated* services



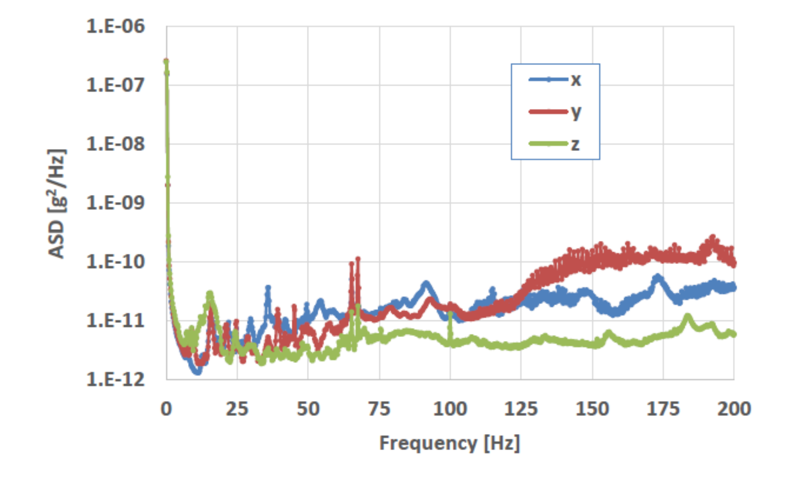


# ATLAS ITK Local Supports

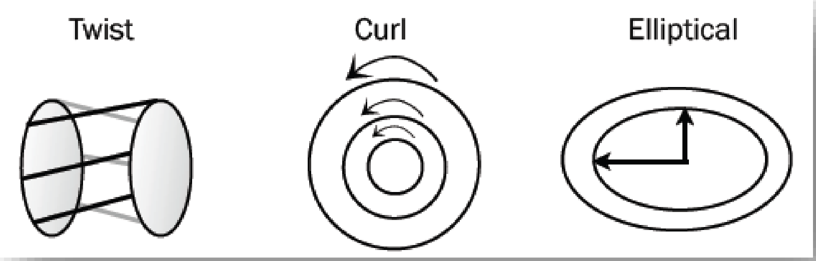
- Properties
  - Mechanical
    - Positioning requirements from physics (placement & stability)
    - Assembly, transport & integration
  - Electrical services
    - Serial / DCDC powering
    - Data I/O (strips only – data-rate too high for pixels)
  - Cooling
    - Integrated evaporative $CO_2$ ($T_{evap}$ ~ -35°C)
  - Radiation-tolerant materials
    - Plastics, adhesives/resins

# Mechanical LS Requirements

- Mechanical
  - Geometric Stability
    - ASD < $10^{-9}$ $g^2$/Hz in ATLAS
    - Translates into sub-µm RMS motions for $f_0$ > 10Hz
    - Verified by in-situ FSI system
      - Large movements - cooling/power & magnet
  - Minimize sensitivity to 'weak modes'
    - Coherent deformations of large-scale structures
    - Hits form a track but parameters are wrong
  - Robust enough to survive assembly, transport & integration

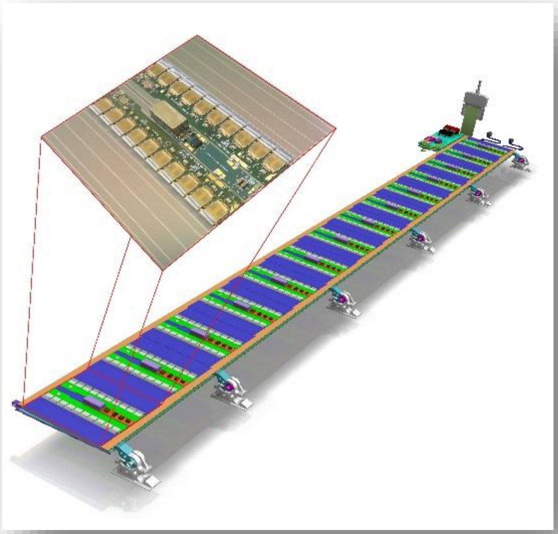


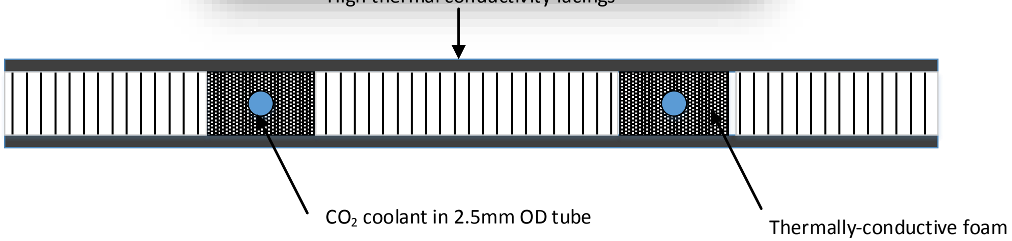

| | $\Delta f(r)$ | $\Delta f(\varphi)$ | $\Delta f(z)$ |
|---|---|---|---|
| $\Delta r$ | radial expansion | elliptical | bowing |
| $\Delta\varphi$ | curl | clamshell | twist |
| $\Delta z$ | telescope | skew | *z* expansion |



# Thermal LS Requirements

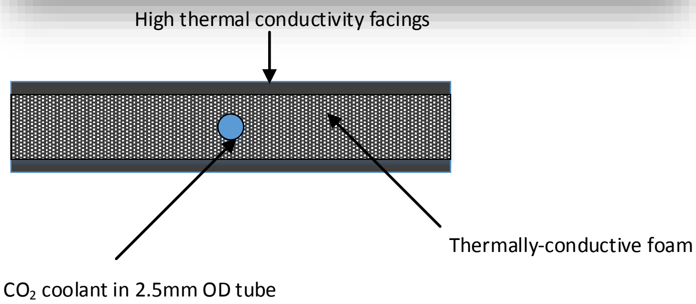
- ATLAS Itk Strip
  - Power = 60mW/cm$^2$





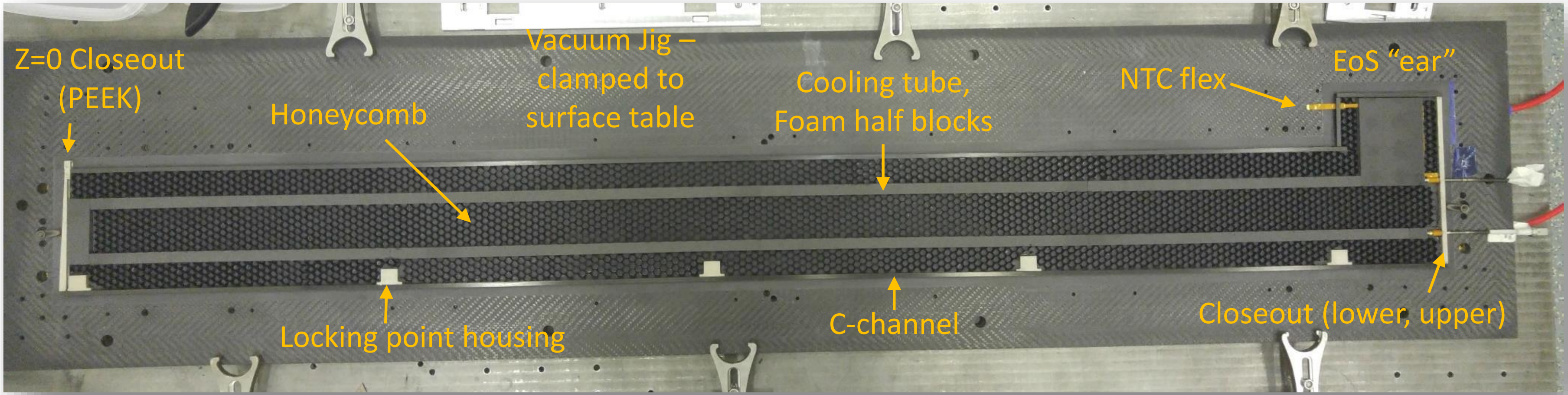

Support, electrical services & cooling: 0.7%Xo

- ATLAS ITk Pixel
  - Power = 700mW/cm$^2$

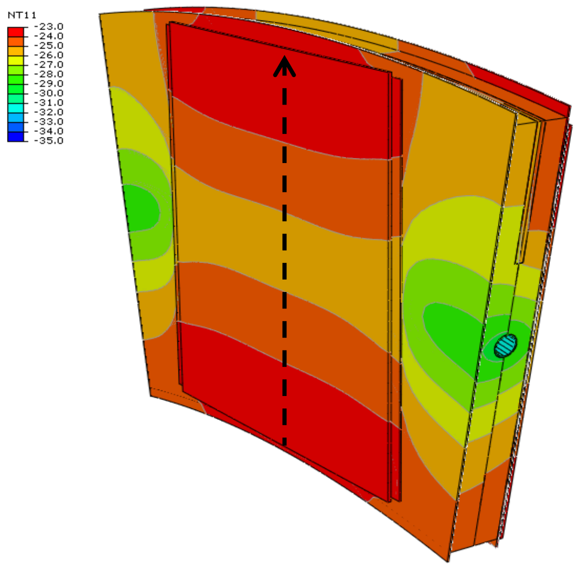


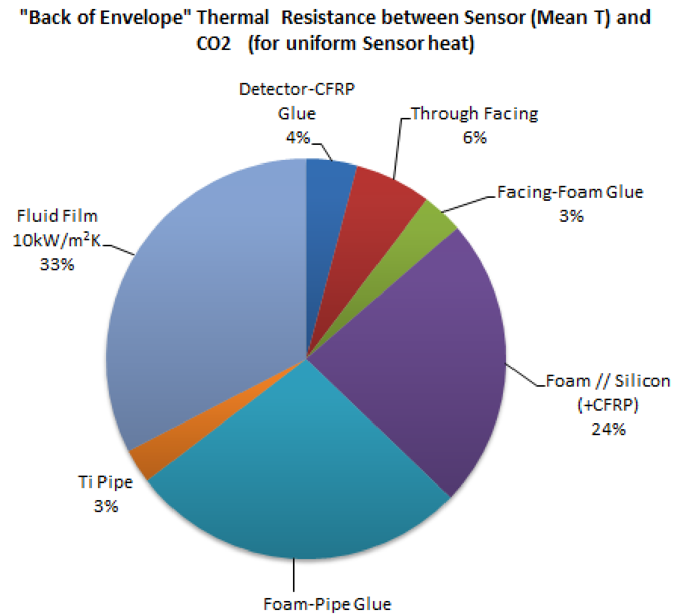

Support, electrical services & cooling: 1.5%Xo

# ATLAS ITk Stave Core

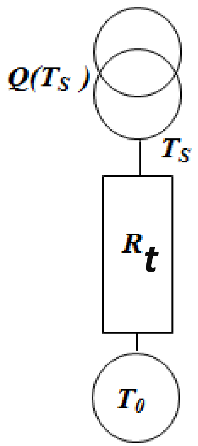


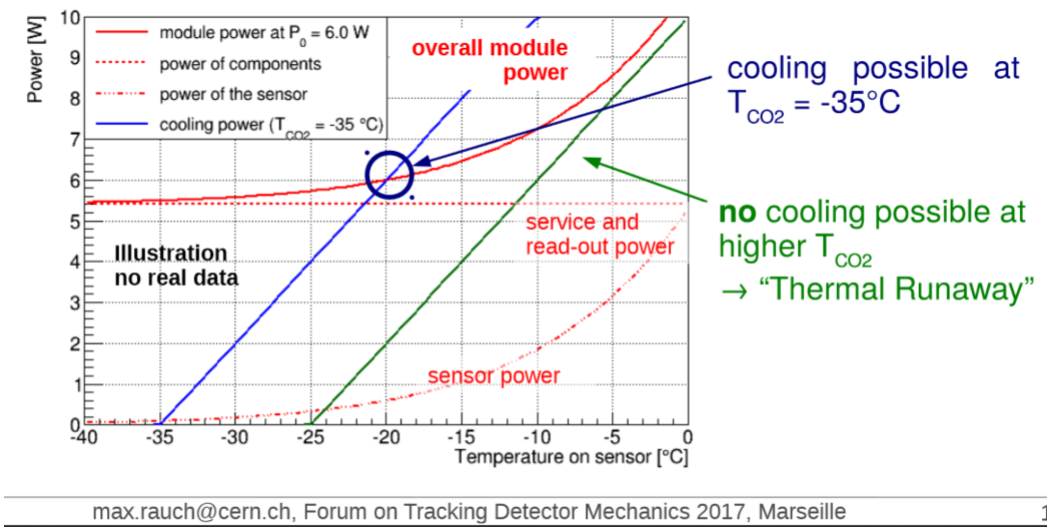
# Thermal Runaway (eg Pixel rings)




$\boldsymbol{Q} \propto \boldsymbol{T^2} \exp[-1.2\text{eV}/2\boldsymbol{kT}]$



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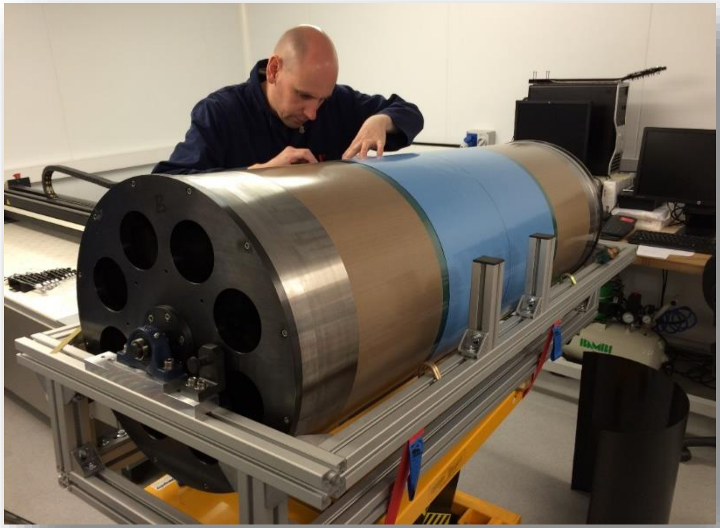
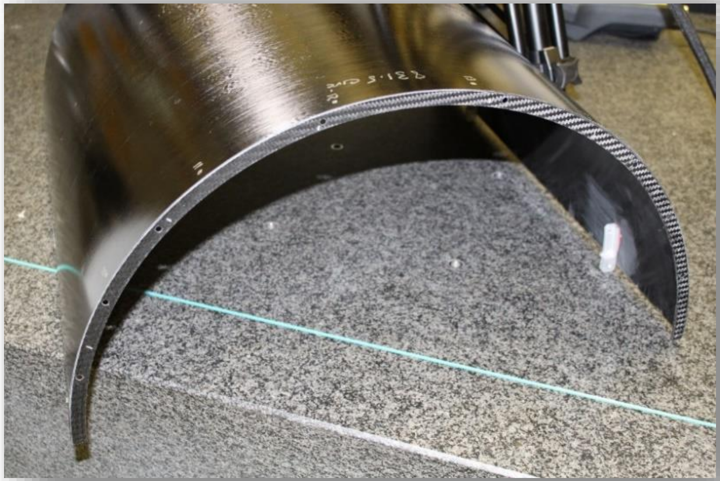
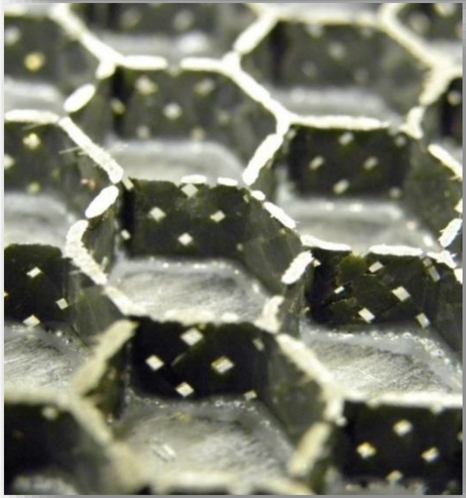
# ATLAS ITk Prototyping

- Pixel endcap



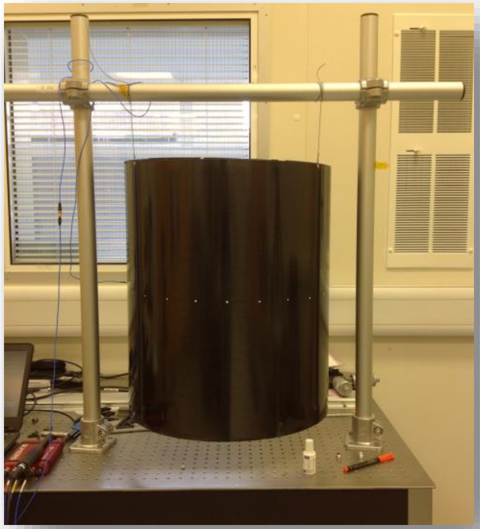


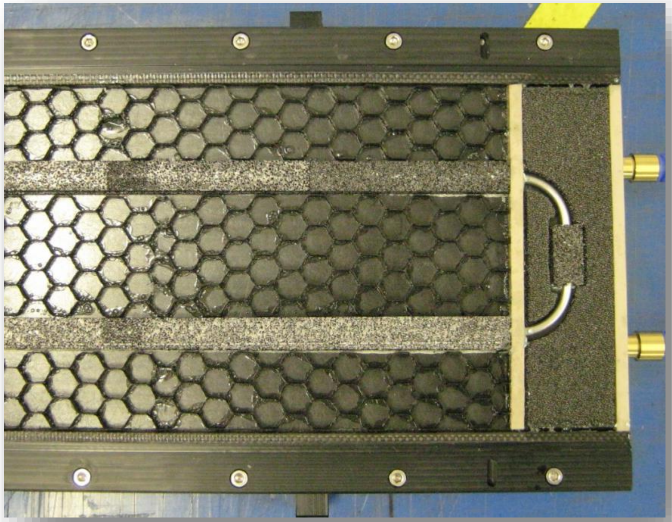
- Strip Tracker

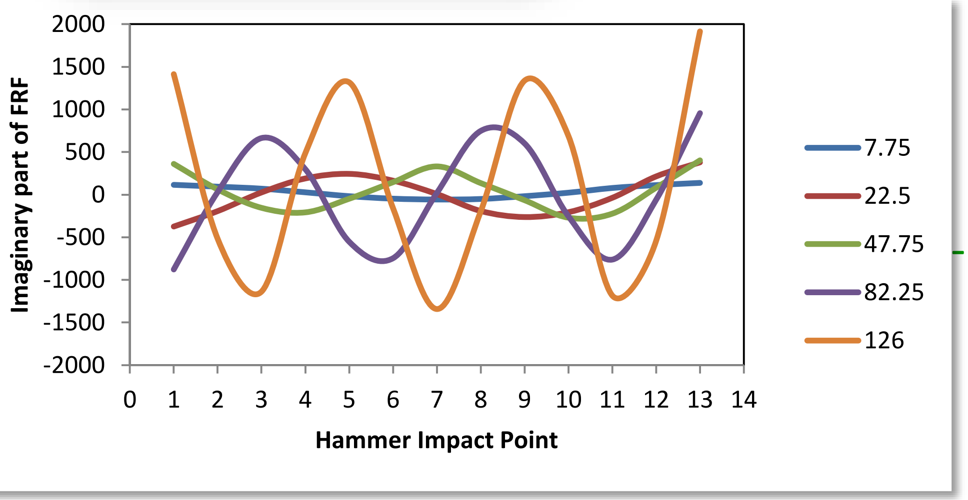


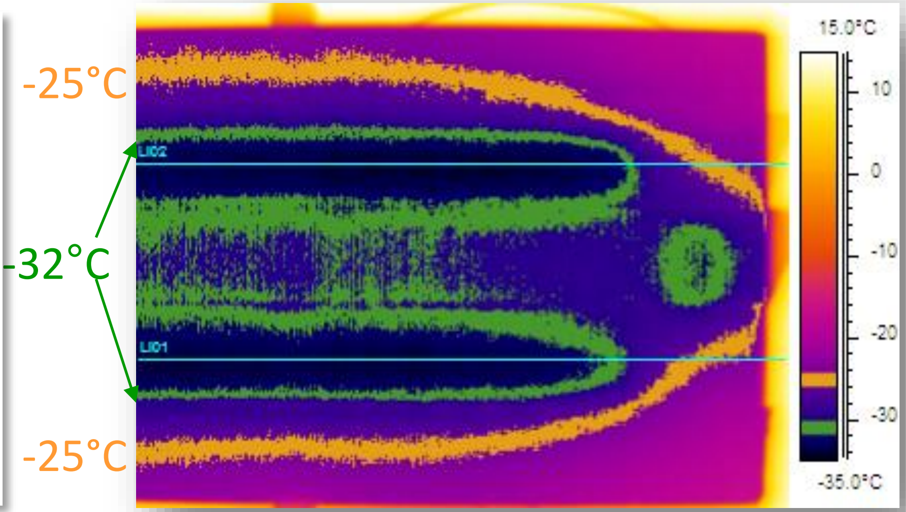
# ATLAS ITk Prototyping

- Pixel ½ cylinder vibration
- Strip Mini-stave assy & test





# $e^+e^-$ Vertex Detector

- Physics Parameters to Hardware Requirements

| Parameter | Value | Hardware Requirement |
|---|---|---|
| Hit resolution | 3µm | • Small pixel size<br>• close to beam-pipe |
| Material budget | < 0.15%X0/layer | • Smart sensors (MAPS, HVCMOS)<br>• thin (50µm) silicon<br>• low (<50mW/cm$^2$) power dissipation |
| Occupancy | < 0.5% | • Small pixel size<br>• Short readout time |
| Radiation tolerance | 1MRad/yr (TID) + $10^{12}$ n-eq/cm$^2$/yr | • Adequate radiation tolerance<br>• Sensible materials choices |

# Vertex: Support Structures

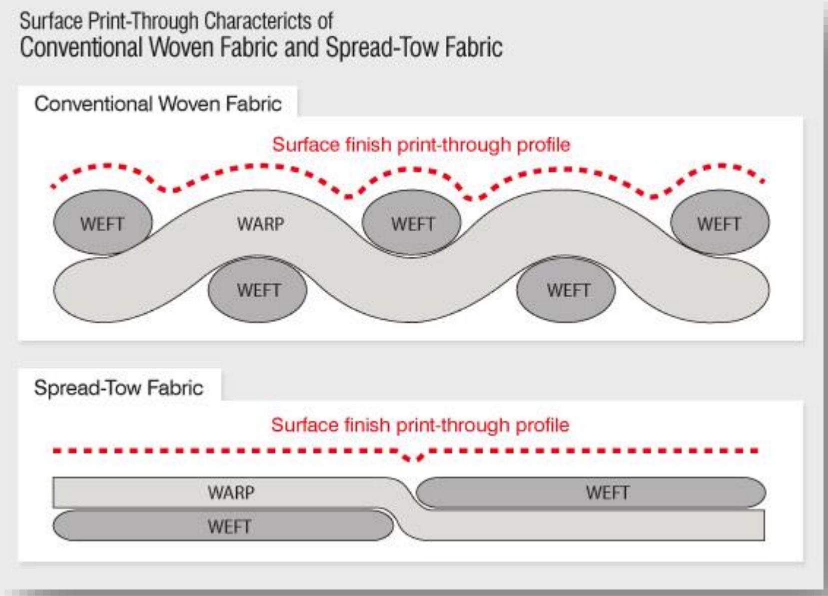
- Most low-mass support structures in PP experiments are made from CFRP.
  - High modulus carbon fibres embedded in a resin matrix
  - Cured under heat (120°C) and pressure (1-7 bar)
  - Laminate built up from several laminae at different angles

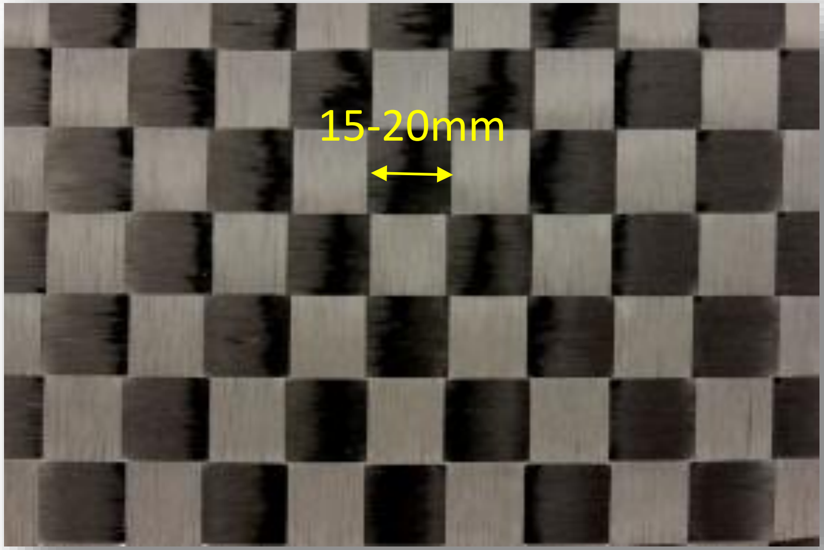
- Primary issue
  - CFRP laminates cured at elevated temperature need to be balanced to avoid distortions
    - Balanced: [0], [0/0], [0/90/0], [0/90/90/0], etc…
    - Increased thickness over mono-layer (eg. Kapton)

- Possible Solution ?
  - Spread-tow laminates

# CFRP Laminates

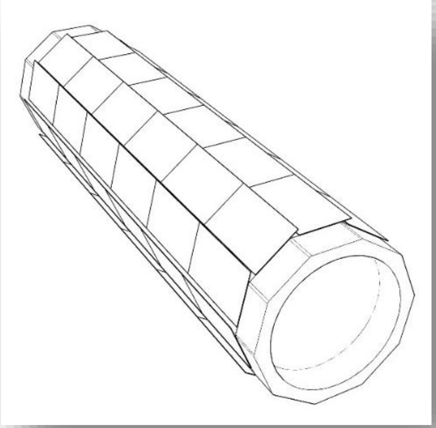
- Laminates either formed of UD layers in different orientations or woven material
- UD laminates need to be symmetric to avoid distortion
  - 3 or more layers
- In Spread-tow pre-preg, the fibre bundles are spread out into strips (typically >15mm wide)
  - Lower areal weight and higher fibre fraction
  - Lower mass for equivalent stiffness
- Laminate is locally asymmetric at short distance scales



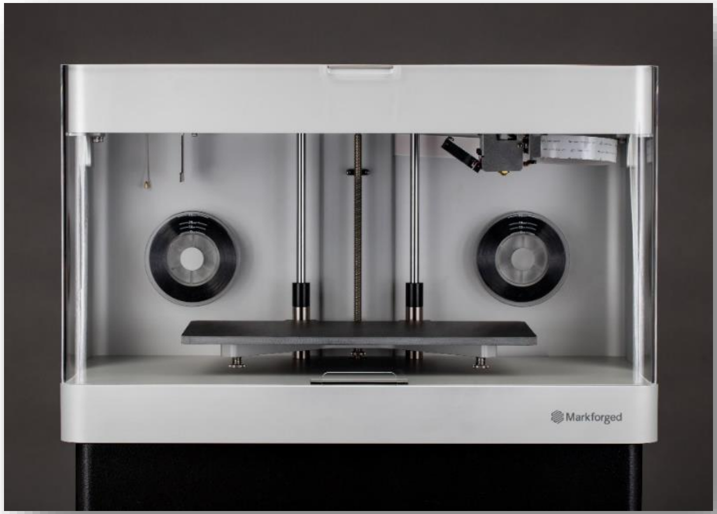
# Straw-man Vertex Layer Support

- Commercial spread-tow weave too large for vertex layer
  - Develop techniques to manufacture custom spread-tow woven pre-preg with weave ~ 5mm
- Single woven layer of K13C2U/EX-1515
  - Thickness ~ 80µm
  - $\%X_0$ ~ 0.03% (1/5 of budget)
- Questions….
  - Does the repeating pattern of alternating asymmetric elements balance the internal stresses out and produce a globally balanced laminate ?
  - Could heat be removed by cooling the end-rings ?

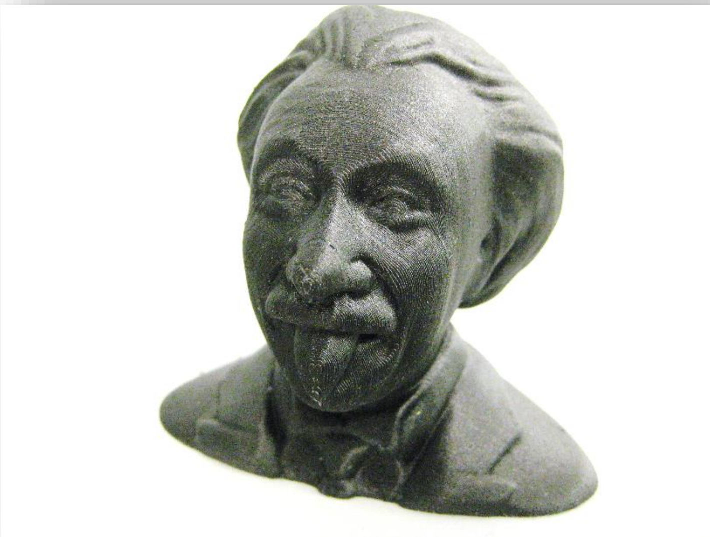



# 3D Printed Tooling

- Markforged Mark-2
  - 320 x 132 x 154
  - Nylon + carbon fibre
  - Onyx™
    - Chopped CF filament
    - HDT 145°C
    - Cover with release film




- Epoxy tooling pre-preg
  - Tencate AmberTool HX42
    - Cure for 8h at 60°C
    - Free-standing post-cure to 190°C
- Cure final part …

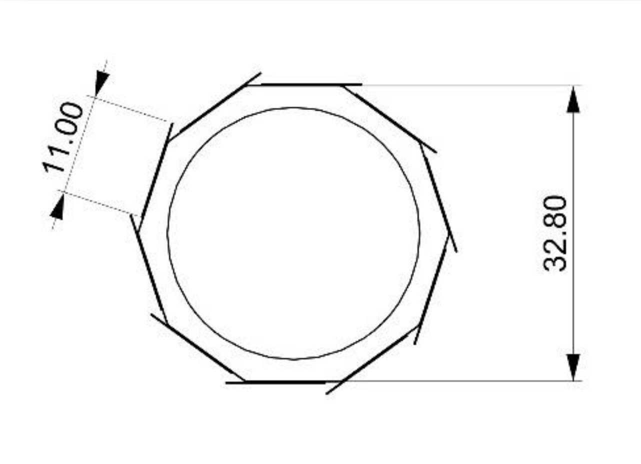


# Spread-tow Vertex Layer Support

- Model the external surface of the support structure, 3D print & polish.

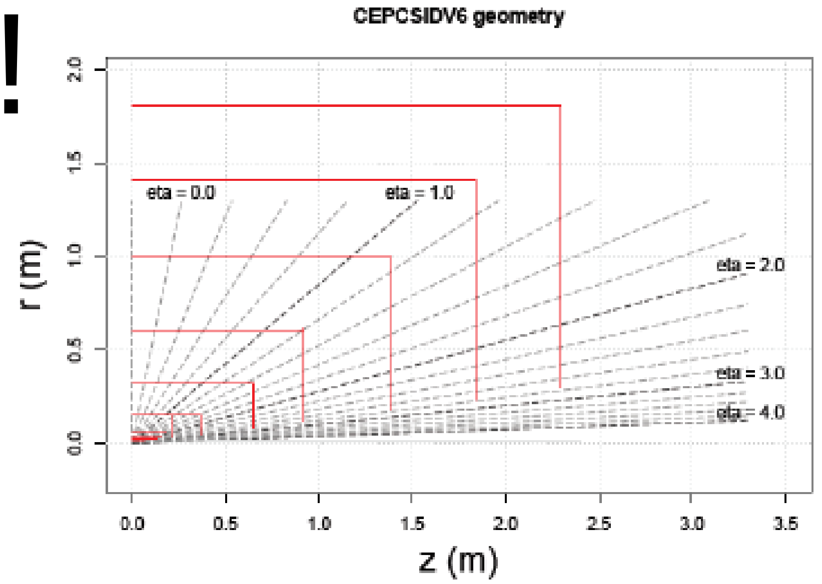
- Manufacture mould from model using low temperature curing tooling pre-preg.
  - Stand-alone post-cure at ~190°C

- Manufacture spread-tow support shell from CFRP moulds
  - 5mm spread-tow pre-preg using K13C2U/EX-1515
  - Vacuum bag cure




# All-Silicon Outer Tracker

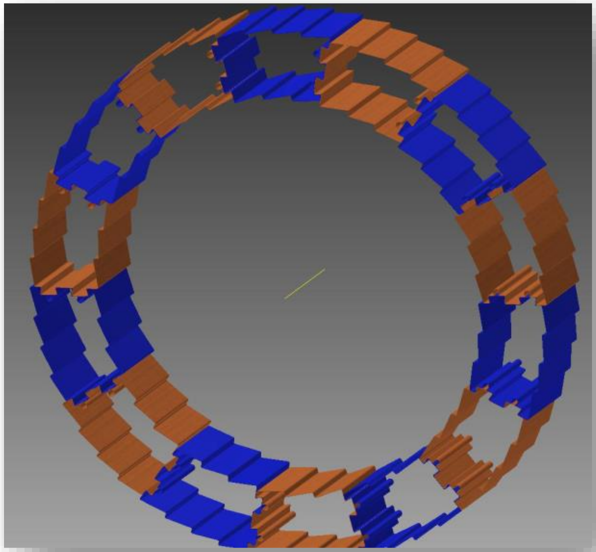
- Main issue is sCALE !
  - eg Barrel: 112m$^2$
  - Outer radius ~ 1.8m



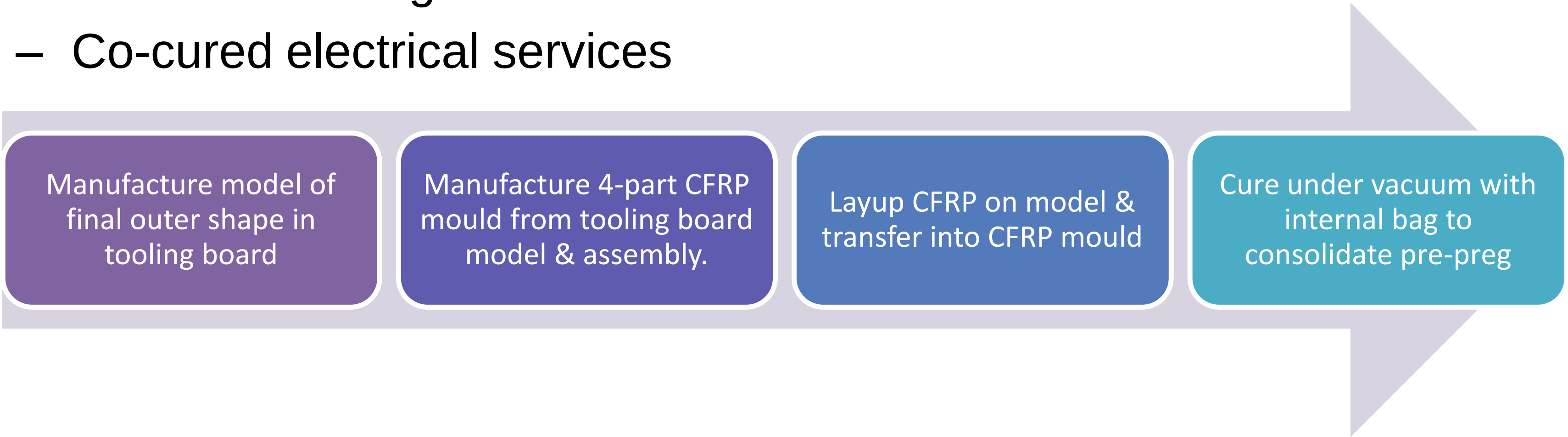

- ATLAS ITk barrel
  - 392 staves x 1.4m x 0.1m x 2 = 110m$^2$
  - Stave (Local Support) concept
    - Thermo-mechanical support structure
    - SS modules *glued* on both sides
    - Stand-alone 'system'

# Interlocking Super-module

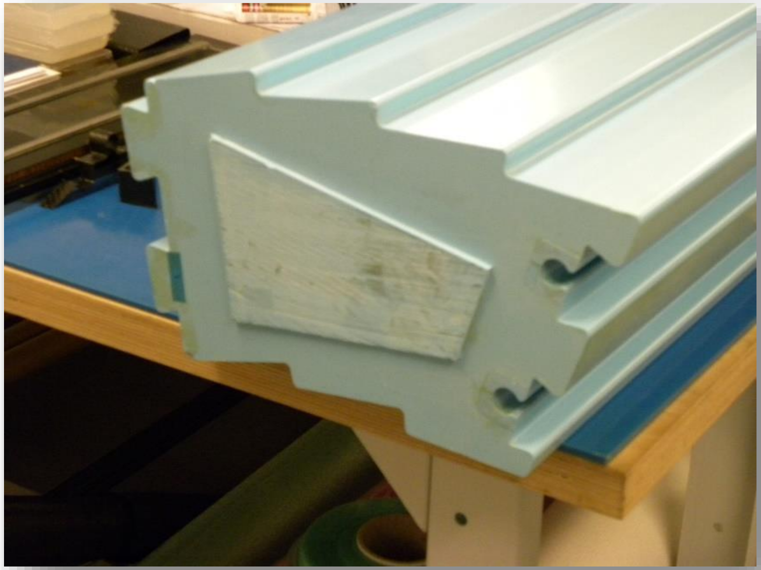
- One complete double-layer formed from 14 interlocking super-modules in phi
- Homogeneous structure to maximize stiffness & minimize material
- Each super-module combines local and global supports for 7 ladders together in single structure.
  - Gaseous cooling
  - Co-cured electrical services



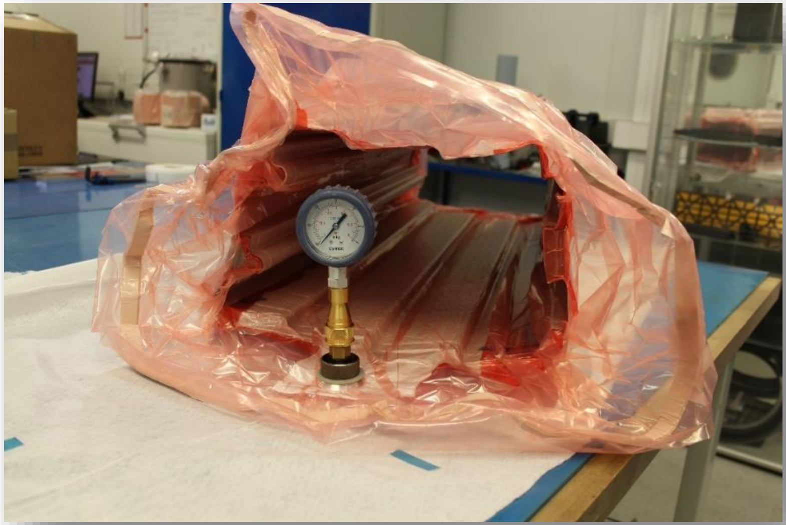
Co-development with Oxford University



# Interlocking Super-module



Model made from tooling board

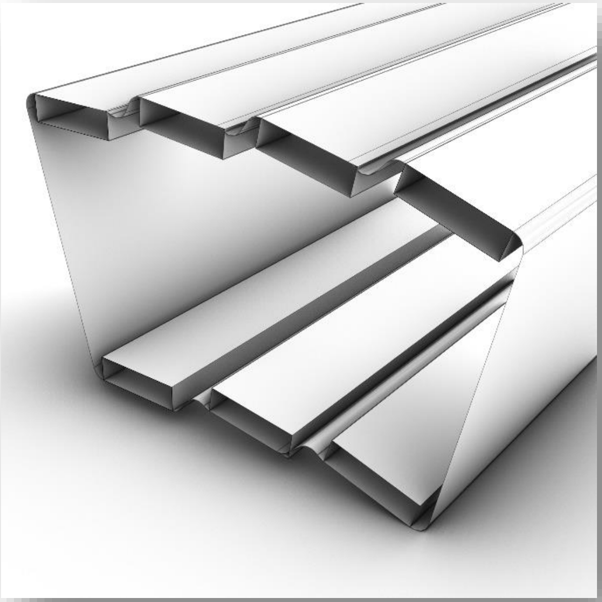


Vacuum Bagging

Mould tool sections made from model

Final component

# Next Steps

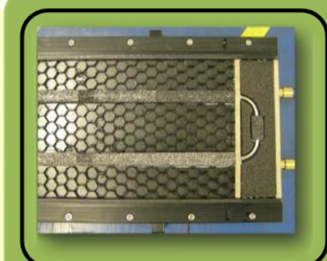


- Cooling
  - Air directed through box channels integrated into structure
    - New mould tool just received
    - 3D printed inlet manifold
- Thermal Test
  - Attach 10x10 heater pads
  - Vary power & air flow
  - Use IR to measure surface temperatures

# Liverpool Advanced Materials Lab

## Materials & Processing Technology

- Carbon fibre, resin systems, nano-particles
- CFRP pre-preg, resin infusion
- Spread-tow pre-preg



## Structures

- High-performance, low-mass support structures for tracking detectors
- Composite components for CTA, Formula Student, etc..

## Performance Verification

- Component geometry
- Mechanical properties of CFRP laminates
- Deformation of structures

# AML – Facilities & Expertise

- Production Facilities
  - 1.7m x 0.8m Autoclave
  - 3m x 2m x 2m oven
  - Pattern cutter
  - Markforged Mark 2 3D printer
- Expertise
  - Epoxy & cyanate ester resin systems
  - UD and woven material
  - Resin infusion
  - RTM
  - Out-of-Autoclave processing
- Materials Testing
  - 5 & 30ktonne materials tester
  - DSC (adhesives)
  - Modal Analysis
  - Deformation
  - Laminate QC
- Outreach

Formula Student

HPV record bid

# Summary

- HL-LHC
  - Support structures for HL-LHC trackers rely on using aerospace-grade CFRP
    - High modulus, high thermal conductivity, low areal weight fibres
    - Cyanate Ester resins (low CME & radiation-hard)
  - Radiation damage to silicon requires low temperature operation using bi-phase $CO_2$
    - Optimize for zero-CTE, dew-point ~ -50°C
    - Thermal runaway requires efficient cooling (low $\Delta T$) motivating bi-phase $CO_2$ and high performance, low density, carbon foams & laminates
- e+e-
  - $\%X_o$ and scale (both large and small!) are main challenges
  - Warm operation and allowing a large $\Delta T$ - but check junction temperatures !
  - Avoid ‘clumpiness’ (tubes, brackets, fixings, etc)
    - Use homogeneous layers of CFRP (eg spread tow) and interlocking systems for large area tracking
  - Limit ‘weak modes’ by intimately connecting large structures together over large areas to minimise differential motion
- Status
  - Manufacturing techniques for ‘proof-of-principle’ structures being developed.
  - Mass build-up, metrology, stiffness, cooling performance, etc.. to come!

Next Forum on Tracking Detector Mechanics, Valencia, 25-27$^{th}$ June