Interlocking Super Modules for Future Large Area Tracking Systems

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Goal

• Build a structure for a large \((r \geq 1 \text{ m}, l \geq 3 \text{ m})\) with very low mass \((<1\%X_0)\) for the next collider detector (LC, CLIC, FCC,…)

• Structural performance similar to current LHC systems (on a possible larger scale)
  • In particular sense element positioning stability \((\text{RMS}) \leq 1-2 \mu\text{m} \) perpendicular to strips (driven by needs of track-based alignment, proven to work at LHC)
  • Positioning accuracy \(O(100 \mu\text{m})\) (to maintain clearances and overlaps)

• In terms of structural performance and material the requirements will be independent of exact nature of next collider detector

• Expected to be different: thermal management
  • Linear collider:
    • Low (pulsed) FE power,
    • Prime goal to remove (modest amount of) heat with minimal mass, air cooling possible
    • Prime challenge for structure: internal vibrations
  • Hadron machine:
    • High FE power,
    • Prime goal control of leakage and thermal stability, likely evaporative cooling (CO\(_2\)?)
    • Prime challenge for structure: minimize thermal impedance, thermo-mechanical loads from temperature gradients
  • Keep both options open
Strategy

- Stiffness of a (beam) structure is given by $EI$ (Moment of inertia (shape))
  - Modulus (material)

- In terms of material choice little room of improvement
  - The use of K13C/D2U (UD) and CN60 or similar (woven) is now pretty much standard – no stiffer commercial fibres

- Significant improvements only by improving ratio of moment of inertia over mass
  - Effectively this means opening up the structures (possibly coupling adjacent layers of tracker)
  - Approach has been pioneered by LBNL for vertex systems

- Move to open structures has to be done with an eye on (local) buckling stiffness, which will become the limiting parameter
  - Again to be addressed by shape

- Other considerations:
  - Material-optimal layouts are not linear (axial or radial), but have inclined modules, so that module plane is particular to track from vertex – exploit shapeability of composites
  - Services should be integrated into the structure (possibly by co-curing) to simplify construction and minimize mass, but differential thermal expansion needs to be watched
  - Modularity (hierarchical assembly of contained units with simple interfaces) should be optimized to give units which are good compromise of value (small enough that it is limited) and functionality (big enough that [aggressive] testing is meaningful) – also facilitates distributed manufacture reducing project risk
Disclaimer: What you are seeing now does not officially exist

• There is no funded future detector effort in the UK
• What we have achieved is therefore entirely the result of the enthusiasm of the involved people, and limited by the non-existence of funds and our obligations to our (official) affiliations
• We would have liked to have more things to show here, but we just didn’t get to it...
Box channel design

• Couple two adjacent layers (here at radius 640 mm and 885 mm with 4 and 3 rows of 10 cm wide modules each)
  • This already gives very high bending stiffness
• Investigate further increase of stiffness by locking box channels to cylinder using tongue-and-groove mechanics
  • Not clear whether this can be done with required precision and/or whether this improves overall stiffness
• Current status: Several 1 m long prototypes produced
  • So far only suboptimal fibre used
    • Mostly for visualization of design and demonstration of manufacturing
    • Structural performance not yet studied
  • Investigate different types of cooling (air-cooling ducts or co-cured Kapton pipes (like ALICE)
    • Cooling not yet functionally tested
Box channel manufacture

- Original mould from chemical tooling board, smoothed with 1200 grit wet and dry, sealed with Monocote sealer, then treated with Monocote HP7 release fluid
- This is used to make CF mould (in four sections) using Tencate HX42 Tooling prepreg (postcured to 135°C)
- CF (Tencate 8020 2 x 2 Twill 45% Resin) bagged from the inside to the mould → good control of external dimension
Box channel manufactured
Air-cooling channels

Original mould
Carbon fibre mould
Fabricated final part
Integrated low-mass cooling tubes

- Follow a concept developed by ALICE: co-cured Kapton tubes
  - Commercial off-the-shelf item used in medical industry
  - Here: Goodfellow 1.105mm OD, 1.00mm ID, wall thickness 50 μm, length 1000 mm
    - Have not investigated, but it seems likely that we can get longer lengths
  - So far only small lengths trialled (100-300 mm) – but plan to use in box channel
  - Not yet pressure tested - no optimization of lay-up

- Ladder: 280 x 20mm with co-cured kapton tube 1mm ID x 300mm long.
- Lay-up of fibres - 90, 0(longitudinal), 90. The tube centralised and a .85mm wire inserted, three layers of fibre 280 x 10 covering tube. Vac bagged, cured with pressure.
- Total mass 2gms ( = 36mg/cm²)
Integrated electrical services

- Plan to use similar techniques to ATLAS barrel stave manufacture
  - There: 1400×120 mm² Cu/Kapton tapes co-cured with 3 layers of K13C2U/EX1515 0/90/0
  - Cured against a flat or curved jig of Al or CF
  - Connection to hybrids by wire-bonding
    - Do-able for flat ATLAS structures, but probably interesting for 3D box-channels
    - Either develop 3D wire bonders, or find different joining technique
    - This depends a little on module/hybrid design (number of connections required, etc.)
A goal for an RD collaboration: spin-out

• I think one of the goals for an R&D collaboration is to develop technologies with the potential for spin-outs
  • Always a soft spot for funding agencies
  • And maybe there is real potential…

• I can imagine that composite structures with integrated cooling/electrical services could be interesting for aviation, space and/or (racing) car industries

• An RD collaboration could provide the framework and effort required to get in touch with industry
Next steps

• Use better material (CN60 on the way)
• Verify dimensions
• Study stiffness under various loads (static, vibration, thermal etc.)
• Verify air-cooling performance
• Build full-scale box channel with Kapton tubes and test liquid cooling
• Build full-scale box channel with co-cured electrical tape
• Further design issues
  • End flanges (including cooling connections)
  • How to increase length? (make it longer or join sections)
  • Inclined modules?
... and other activities in Oxford

Possibly pertinent to the discussion here
As part of AIDA2020 we have established a facility to characterize support structures under various loads at Oxford

- Several setups for different loads (vibrations, air flow, climate chamber) and survey technologies (capacitive, laser, photogrammetry, FSI)
- We have performed first measurements for first two customers (Bristol and Valencia)
CTE measurement of CF

- CF links (18cm)
- FSI lines for distance measurement

Aluminium
20 ppm/ °C

Carbon Fibre
1.1 ppm/ °C

Photogrammetry survey of large CF structure

Air flow cooling system

Difference between two sets of measurements

25 μm
Future collaborations

• The AIDA facility is open for customers
  • If you have a structure you want to study get in touch (no fees)
  • We are currently discussing the next version of AIDA, if you want to become a collaborator, get in touch
    • This would particular apply if you want to develop new structural technologies, which we then would characterize in the facility

• If you want to participate in further development of the box channel, get in touch
  • Currently this would be informal
  • But this is what we would bring into an RD collaboration
Further material
Mechanical requirements – stability under vibration

• External vibrations are tiny (ASD<<10^{-7} \text{ g}^2/\text{Hz})
• Exact response of structures requires FEA and measurement, but a simple estimate can be obtained from Miles’ equation

\[ \delta_{\text{RMS}} = \frac{a_{\text{RMS}}}{(2\pi f_0)^2} = \sqrt{\frac{\text{ASD} \cdot Q}{32\pi^3 f_0^3}} \]

• Response of a 1D oscillator (to a flat ASD), but still a meaningful estimator for 3D geometries (with \( f_0 \) frequency of first mode)

• Internal vibrations are usually tiny
  • Possible exception is air flow in air cooling systems
    • Very difficult to predict (as is the cooling performance in these systems), as it depends on local perturbations
    • Strive to use channelled air flow

• Generally: Vibrations can be easily controlled
Mechanical requirements – stability under thermal loads

• The first approach to thermal loads must always be to make them constant
  • On time scales which are longer than the thermal response time of the system $\tau > RC$ with $R$ the thermal impedance (definition later), and $C$ the heat capacity of the system
    • Typically several seconds
  • This should be a design requirement for the FE…
    • If the electronics power is varying (for example with the trigger rate), then a programmable shunt can be used to compensate for these variations
  • …and the cooling system
    • In an evaporative cooling system this is achieved by stable feed and return pressures (and constant heat loads)
    • In monophase system (including air cooling) that’s stable input temperature and flow rates

• For the mechanical design: Be careful with bonding dissimilar materials with differential thermal expansion
  • Best approach: strive for symmetry
Beam stiffness

• Stiffness is a function of modulus and cross-section
  • For example: Euler-Bernoulli beam
    \[ \frac{\partial^2 y}{\partial t^2} + c \frac{\partial y}{\partial t} + EI \frac{\partial^4 y}{\partial x^4} = \phi(x, t) \]
  • The relevant structural performance parameter is the bending stiffness \( EI \)
    • \( E \): elastic modulus
      • For flat geometries unidirectional UHM fibres ( fibre \( E > 800 \text{GPa} \) ), widely used is K13C/D2U – little room for improvement
      • For sharp corners and woven material lower modulus is required
    • \( I \): moment of inertia
      • Increase cross-section
  • To prevent local buckling: increase local stiffness (again best by 3D shaping)