Advanced mechanics for silicon tracker

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The purpose of tracker mechanics

• Support detector elements in space
  • During operation
  • During production and integration

• Support services

• (Often:) provide a thermal path from local heat sources to a sink
  (typically a cooling pipe)

• But: The most powerful tool to obtain knowledge of the sense element positions (on the scale of a tracker) is track-based alignment (TBA)
  • Hardware alignment systems are challenging and not capable of providing position information for (all) the sense elements at the required level
    (typically µm)
  • Structure design must facilitate and support TBA – this drives many requirements
Requirements

• Mechanical Requirements:
  • Positioning
    • Includes deformation under static loads (loads that are reproducible – gravity, but also power etc.)
  • Stability:
    • This is the critical requirement
  • Timescales:
    • TBA is done with data taken within a period (depending on the size of the structure to be aligned)
    • ATLAS/CMS: Large structures can be aligned often (daily), individual modules 1-2 times per year
    • This defines stability timescales
  • Loads:
    • Vibrations (external and internal)
    • Variations in on-detector heat loads and temperatures (electronics and cooling)
    • Seismic events (major disruptions of detector status – cooling system on/off, magnet quench, etc.)
    • Humidity variations
    • Long-time response to static loads (‘creep’)

• Strength
  • Usually (apart from space experiments) less demanding - mostly during transport and integration

• Thermal requirements:
  • Geometry and materials for thermal path
Material

• Current systems (ATLAS/CMS are typically $O(1\%X_0)$ per layer)

• Future detectors, independent of the exact machine topology (lepton linear or hadron circular) will demand significantly less material
  • Lepton collider: reduce material to achieve good resolution at low momenta
  • Hadron collider: reduce material to keep magnet size manageable while maintaining momentum resolution

• Contributions from sensor & FE electronics and structure & services
  • Structure material must match sensor material
  • Future tracker will be HV-CMOS with integrated FE, possibly thinned down
    • This will greatly reduce material – challenging to match
    • Will only achieve this with composites and integrated services
Mechanical requirements - placement

• Placement accuracy usually not critical
  • TBA will find generally find initial displacements very quickly

• What is required?
  • It needs to go together (clearances are typically in order of mm)
  • Need to maintain overlaps
    • Hermeticity for physics (typically down to a give momentum) – defining for large radii (trackers)
    • Overlaps of a few sense elements per module needed for TBA (typically stiff tracks) – defining for small radii (vertex detectors)
    • Placement accuracies (typically a very few 100µm) need to be added – result in more material/constrained space

• Knowledge of out-of-plane position to better than 10-100 µm is useful
  • This is where TBA is weak
  • This can be achieved by placement (build accuracy), survey, or hardware alignment
    • All very difficult at this level

• What can be useful and is achievable are
  • Local survey data or build precision
  • Parametric models of deformations

• If you are working on structures: Speak to your alignment people!
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

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

• 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 \( \tau > \frac{RC}{RC} \) 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
Structure shape and tracker layout

- Stiffness is a function of modulus and cross-section
  - For example: Euler-Bernoulli beam
    \[ \lambda \frac{\partial^2 y}{\partial t^2} + c \frac{\partial y}{\partial t} + EI \frac{\partial^4 y}{\partial x^4} = \phi(x, t) \]
  - 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)

- Material-optimal layouts are inclined
  - Difficult to reconcile with linear cooling structures
- Move from longitudinal and flat structures to true 3d structures

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ATLAS upgrade alpine layout T.Todorov et al.
ATL-UPGRADE-PUB-2013-009
Thermal requirements

• Detectors must be cooled to
  • Remove heat from the FE and radiation-damaged sensors
  • Prevent detrimental annealing effects (less relevant for n-in-p as used in strip systems for LHC phase II upgrades)
  • Maintain thermal stability after radiation damage (prevent “thermal runaway”)

• The relevant structural property contributing to the thermal performance is the thermal impedance between sources and sink (coolant)
  • Dimensionally this is the temperature difference divided by the heat transferred (a power)
  • Widely used is the term ‘thermal figure of merit’
    • This is the inverse, but also includes a normalization factor for area which has little meaning
    • This term tends to obscure the physical meaning of this parameter
Thermal modelling

• Prediction of temperatures is in principle possible (using 3D FEA) but is a tedious job once different conditions need to be explored
  • In particular if there are more temperature-dependent parameters in the system (e.g. electronics damage mechanisms (TID effect) or efficiencies)

• Simple network models can be useful approximations
  • In simple cases these can be solved analytically
  • In more complex cases they still provide a tool to develop parametric models which can be solved numerically in short time

• These models can include many inputs (sensor and electronics parameters)
  • The key input from mechanics is thermal impedance – this can be obtained from FEA and measurements
Thermal modelling examples

**Simple network model**

\[ T_{S,crit} \approx \frac{T_{ref}}{1 - \frac{T_{ref}}{T_A} \ln \left( \frac{T_{ref}^2}{R_a T_A} T_A \right)} \]

\[ T_{0,crit} = T_{S,crit} \left( 1 - \frac{R_c Q}{T_{S,crit}} \right) \]

\[ T_{C,crit} = T_{0,crit} - \frac{R_c Q}{T_{S,crit}} \]

**Complex network model (ATLAS phase II strips)**

- **Thermal part**
  - Includes temperature-dependent TID bump and converter efficiency

- **Electrical part**

**ATLAS SCT**

**Sensor T**

**Sensor I**

**Runaway**

NIM A 618 (2010) 131–138

Kurt Brendlinger, Forum Tracking Detector Mechanics 2018
Thermal geometries and cooling integration

• Thermal impedance is given by
  • Thermal conductivities (materials)
  • Cross-section and length of thermal path

• This optimization has driven the development of cooling geometries over the past 30 years
  • Heat sink moves progressively closer to sources

• The current state of the art are planar microchannels
  • In Silicon: Good pressure retention, thermal properties similar to sensor
  • But difficult to scale to tracker size – Need to investigate flexible microchannel technologies
Service integration – electrical

• An elegant widely used solution for low-mass services are Kapton/metal flex circuits
  • Kapton/Cu is straightforward, Kapton/Al needs careful manufacture and choice of connection techniques to avoid cracking
  • Can be co-cured with the carbon fibre structure to save fixture material or glue
  • Typical connection to modules by wire bonding
    • Interesting challenge how to do bonding in non-flat geometries

• Issues:
  • Bonding of services to structures causes differential thermal expansion issues
    • Design symmetric sandwiches
  • Electrical insulation layers also have poor thermal conductivity – can create a thermal barrier

Done (e.g. ATLAS strips) Not yet

Kapton/Cu co-cured with 3 layers of K13C2U/EX1515 0/90/0

ATLAS barrel strips

1400 mm

100 mm
Modularity

• To limit time needed for integration and access modularity must be designed into the system from the beginning

• Modularity here means
  • Each component is contained, with simple interfaces to the rest of the system
    • Does not necessarily mean that there are large numbers of a specific modular item
  • Modular components link together in a hierarchy
    • During integration only fully tested modules are being added, so for each new integration step only the success of only this step needs to be verified
  • Wherever applicable modules can be produced in parallel

• Modularity for all components of the tracker at all levels
  • Detector modules – local supports – services – global supports – sub systems – tracker etc.
  • Build in enough levels into this hierarchy to allow for early and vigorous QA, and so that incremental change for each integration step remains small
Case studies: ALICE ITS OB

- Moment of inertia through truss structure
  - Filament-wound carbon fibre (M55J, 540 GPa)
  - Sag 40-110 µm (depending on support conditions), 50 Hz spring-supported
- Thermal conductivity through cold plate
  - Unidirectional UHM CF (K13D2U) with polyimide tubes (64 µm wall)
- Flexible Printed Circuit: Polyimide/aluminium
  - Connect to chip by laser soldering

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Case studies: Mu3e

Ultra–low mass (0.1%$X_0$/layer) achieved by

• Support structure made from Kapton
• Kapton/Al High Density Interconnect with tab bonding

Frank Meier, Forum Tracking Detector Mechanics 2018 and Kirk Arndt private communication
Case studies: Inclined rings

- Inclined rings to optimize material in barrel/endcap transition regions
  - Inclined layouts are difficult to realize with axial structures (in particular the thermal management is challenging)
  - To allow cylindrical modularity inclined rings at same radius as barrels
  - Some of the gain in module material is offset by increased service material (in particular cooling)

ATLAS outer barrel pixels

CMS TBPS

600 mm
Case Studies: STAR PXL

- 0.4% $X_0$/layer
- Mechanics optimized for quick installation/de-installation
  - Structure consists of cantilevered sector tubes
- Air flow cooling through sector tube (9 m/s)
  - Sector first mode: 230 Hz (measured)
  - Sensor vibration at full flow: 5 µm RMS
  - Sensor displacement at full flow: 25-30 µm
- No TBA assumed for design
  - All sensor positions surveyed on a half-detector
  - But TBA was used in the analysis

Deformation under air flow
Sensor survey
Case studies: Box channel

- Design study for future tracker
- Scale vertex detector sector tube geometries to tracker dimensions
  - Includes air cooling channels
  - Next step is to co-cure Kapton/metal flex circuits
- Study possibility to link channels circumferentially
  - This would further increase moment
- Still a linear object
  - Is it possible to shape surface for inclined modules?
Advanced mechanics summary

• Mechanical properties are driven by needs of TBA
  • The key requirement is stability
    • Stiffness under external vibrations is not a concern as the load levels are typically very low
    • A possible source for internal vibrations is air flow in air cooling system – ideally to be addressed by channelling the flow
    • Thermo-mechanical loads should be addressed by levelling power and cooling temperatures, and symmetric designs

• Thermal properties are driven by radiation damage issue
  • Most prominent requirement is thermal stability
  • Reduce thermal impedance from sources to local sink by bringing cooling as close to heat sources as possible

• New sensor technologies and requirements for future experiments (to $0.1X_0/1X_0$ per layer) demand significant reduction in structure material
  • Stiffness/material ratio can only be improved by increased moment of inertia
  • Material-optimized layouts do require tilted module geometries
  • Services must be tightly integrated into structures
  • Stiffness optimization and material optimization will drive development of more open, non-linear structures
Further Material
Linear model verification

Normal modules

ATLAS barrel strips - FEA and linear model

End-of-stave modules

Average temperature of this sensor
(Note ~15° across sensor)

Dots: FEA
Line: Linear model

FEA Results (LS17_5_RAT)

Long Strip EoL \( \Delta T \) (sensor mean T rise above Tevap) vs Tevap for fluence (SF=1.5) at innermost of 4 barrels.