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Advanced mechanics for silicon trackers

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This article discusses design considerations for the mechanical structures of tracking systems currently under construction or being planned. The prime challenges are a high stiffness-to-mass ratio and good thermal conductivity between the heat sources (front-end electronics and sensors) and the local heat sink (coolant). These concepts will be illustrated with a few case studies of tracking systems under construction or in planning.

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1. Introduction

The purpose of the mechanical structures in high-energy physics is the support of the detector elements in space during construction and integration and during operation. In addition, they need to support the services and they often play a critical part in the thermal management of the system, either by providing a thermal path between the on-detector heat sources (front-end electronics and, after irradiation, the sensor) and the local sink (typically a cooling fluid), or, in the case of air cooling, by guiding the air flow.

Material reduction has always been a design driver for tracking systems. Future trackers will push this even further, be it to achieve good resolution for low momenta for example in future lepton colliders, or to maintain good momentum resolutions while keeping the size of the magnets affordable in future hadron machines. While current tracking systems at the LHC typically have a very few percent of a radiation length per layer future systems will require significantly reduced material (order of 0.1% X_0 for vertex layers, 1% X_0 for tracking layers).

Optimization of the detector material needs to take into account the balance between active parts (sensor and electronics) and passive components (structures and services). Currently strong progress is made in developing CMOS technology sensors with integrated Front-End electronics, which promise greatly reduced material because of the elimination of discrete front-end chips and sensor-to-chip bonds. These technologies, while not mature for general use in the current LHC upgrades, will be very likely used for the sensors in future tracking systems. The amount of passive material needs to be reduced accordingly to match the material reduction in the active components.

2. Mechanical performance

2.1 Mechanical requirements

To achieve the full potential of a tracking system the position of its sense elements must be known with an accuracy comparable or better than the single point measurement accuracy (typically a very few μm). In principle one could attempt to achieve this by aiming for such an accuracy of the placement of the sense elements by the support structures. However, this would be very difficult to achieve, in particular on a global scale in a large system. In practice, correcting the actual placement positions using track-based software alignment (TBA) has in a number of large tracking systems proven to be a very powerful tool to provide the necessary accurate sense element position information (see for example [1] or [2]). In this technique high-quality tracks accumulated over a period are used to iteratively find the optimum position of all sense elements by minimizing the residuals of the fits for all these tracks. The length of the period for accumulation is given as a compromise between the number of tracks required to make the convergence robust and the mechanical stability of the sense element positions during and between these periods. Typically the alignment is therefore performed in a hierarchy, where the relative positions of large subsystems, which are often weakly mechanically coupled to each other, are aligned often (potentially down to a scale of days), whereas higher segmentation levels (local supports or individual modules) are aligned much less frequently (typically monthly to yearly). In this way TBA can also track and correct deformations of the system on long time-scales.

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With the precision positioning provided by TBA, the placement accuracy requirements for the structures are greatly relaxed, with the remaining requirements being that clearances required for assembly and HV isolation are satisfied (these are typically of the order of mm), and that overlaps are maintained. These are required for hermeticity (most relevant for large radii) and to allow sense element overlaps for stiff tracks needed for inter-module alignment (most relevant for small radii). To guarantee sufficient overlap for these purposes while minimizing additional material due to placement tolerances typically at the level of a very few hundred μm are required.

The main function of the support structure to support TBA is to provide the necessary stability during the periods over which alignment data is accumulated. This stability must be again significantly better than the point measurement accuracy. To complete the stability requirement one also needs to specify the loads under which this stability needs to be maintained over the required length of time given by the alignment period. Typically, in order of the increasing time-scale, these loads are:

- Vibrations (from external and possibly internal sources)
- Thermal loads
- Seismic events (planned or unplanned changes in the operating conditions which are singular in time, for example magnet ramps, cooling or power system stoppages etc.)
- Humidity variations
- Long-term relaxation effects (creep)

Typically the latter three of these are only relevant on time scales larger than the accumulation periods required by TBA and do therefore not impose major constraints on the support structures.

2.2 Vibrational loads

The external vibration can be characterized by the acceleration spectral density (ASD), given in g_{N}^2/Hz. Typical vibration levels measured in HEP tracking environments are at the level of $10^{-7}\ g_{\mathrm{N}}^2$/Hz and below (see for example figure 1). For an accurate prediction of the stability under this load a detailed FEA or measurement of representative prototypes (the latter being challenging for large structures) can be used with such a spectrum as input, but a reasonable simple estimate of the RMS displacement can be obtained from Miles' equation [3]

$$\delta_{\mathrm{RMS}} = \frac{a_{\mathrm{RMS}}}{(2\pi f_0)^2} = \sqrt{\frac{ASD \cdot Q}{32\pi^3 f_0^3}},$$

where f_0 is the frequency of the first mode, ASD the value of the acceleration spectral density and Q the quality factor of the structure ($Q = 1/2\zeta$ with the damping factor ζ). This equation is derived under the assumption of a constant ASD and for a 1D oscillator, but still can be used to obtain a reasonable estimate of the RMS deformation of a 3D structure. Figure 2 gives an example for results from Miles' equation. For the assumed value of $Q = 10$ an RMS displacement of 1 μm can be achieved for an ASD of $10^{-7}\ g_{\mathrm{N}}^2$/Hz with a structure with a first mode frequency of 50 Hz.

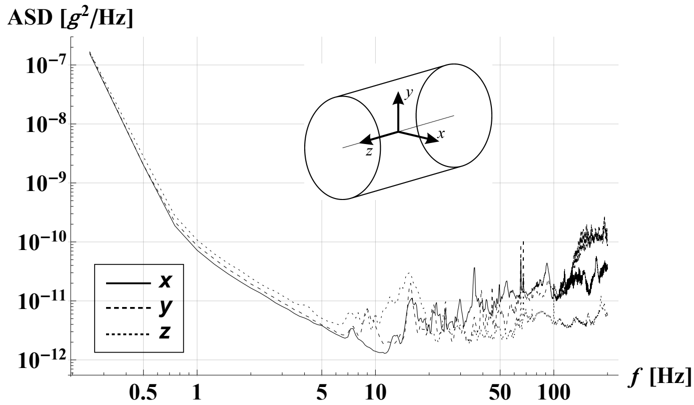

Figure 1: Long-term average ASD measured on the ATLAS ID supports.

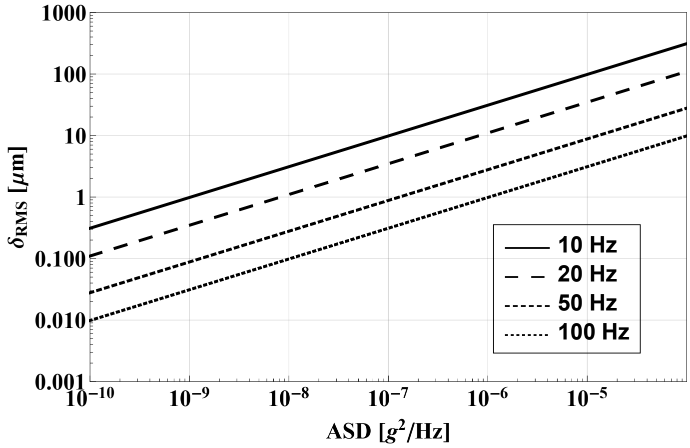

Figure 2: RMS displacement response as a function of a white base vibration ASD from Miles' equation ($Q = 10$).

Vibrations from internal sources are usually also small, with the possible exception of air flow cooling systems. These are very difficult to predict (as is the general performance of such systems) due to the effects of local turbulent perturbations. A controlled assessment of these effects in the design phase can only be achieved for airflows which are carefully contained and channelled.

2.3 Thermal loads

Thermal loads can affect the structural stability if they change during the alignment periods. The first approach to minimizing such deformations must therefore be to keep the thermal loads in the system constant on any timescale which is larger than the thermal response time of the system, $\tau = RC$, where R is the thermal impedance of the system to a temperature-stable local cold sink (typically a cooling fluid) and C the heat capacity. The thermal response time is typically several seconds. The primary constraints on the heat load stability are on the on-detector front-end electronics to equalize power consumption (for example as a function of the trigger rate) and the cooling system, which needs to maintain a stable sink temperature. The latter is achieved in an evaporative cooling system by a stable feed and return pressure, and in a monophase system (including air cooling) by a stable input temperature and flow rate. Any variation of the heat load will usually also change the temperature of the system, both by changing the sink temperature, but also by changing the temperature gradient of the conductive heat path between the heat sources and the sink.

In the mechanical design deformations due to variations of the thermal load are most likely to be introduced by high-shear-strength bonding of materials with dissimilar coefficients of thermal expansion. If such bonds are required deformations can be reduced by symmetric designs.

2.4 Limitations of track-based alignment

TBA has two areas of weakness: The first is that certain deformations of the overall systems are poorly constrained. These are typically twists, scaling or telescoping modes in a cylindrical geometry around the origin of the tracks used for the alignment. Because of the weak constraint such deformations are not only likely to be overlooked if they exist in reality, but they can also be artificially introduced when TBA is run at a fine segmentation level. Deformations of this type are called 'weak modes'. In practice weak modes are controlled by considering additional constraints, either by using tracks from other sources (e.g. cosmics), or by reconstructing the invariant mass of well-known physics channels.

The second challenge for TBA is to find correct positions of the sense elements in the direction out of the plane of accurate measurements. The limited angular variation of the good quality, and therefore stiff, tracks used in TBA puts only a weak constraint on this dimension and additional constraints from mechanical means can be helpful (if these provide information at the level of 10 to 100 μm), but are very difficult to achieve in practice.

Other useful mechanical inputs to the alignment which are more likely to be achieved can be local survey data or build precision, and parametric models of deformations, which all can help to reduce the number of alignment parameters which need to be found by the TBA and thus can reduce processing times and improve robustness.

2.5 Structure shape and tracker layout

With stability being the main requirement for the tracker support structures a high stiffness-to-mass ratio for these structures becomes the main design target. To understand the relevant design parameters it is instructive to investigate the behaviour of simple beams. A standard treatment of simple beams is the Euler-Bernoulli equation

$$\lambda \frac{\partial^2 y}{\partial t^2} + c \frac{\partial y}{\partial t} + EI \frac{\partial^4 y}{\partial x^4} = \phi(x,t),$$

where λ is the longitudinal density, c a damping factor and $\phi(x,t)$ a driving function. The parameter governing the stiffness of the beam is the product EI, which is referred to as the bending stiffness. It consists of the elastic modulus E, which is a material property and the moment of inertia I, which is a geometrical property. Carbon fibre composites are now routinely used as the structural material for tracking detector support structures. In this group of materials uni-directional ultra-high modulus (UHM) fibre has the highest modulus. A UHM fibre commonly used in tracking detectors is K13C/D2U, with a tensile modulus of more than 900 GPa. The modulus of this material is already at the upper end of the range for commercially available carbon fibre and further improvement of the stiffness-to-mass ratio by the use of higher modulus material is unlikely. Rather more promising are designs which increase the moment of inertia, essentially the cross-section, of the support structures, while maintaining the same amount of material. This leads to more open structures which rely on the possibility to mould the carbon fibre into sophisticated 3D shapes like I-beams or box or wedge shaped geometries, or to concentrate the fibre into the members of a truss structure.

Another push to exploit the shapeability of carbon fibre composite structures is coming from advanced layout concepts, which minimize tracker material by inclining the detector modules as the polar angle approaches the forward direction. In this way tracks cross each sensor close to perpendicularly, thus minimizing the module material per solid angle. While carbon fibre structures can easily be shaped to provide this geometrical freedom the challenge is to maintain good thermal contact with the typically linear cooling structures.

3. Thermal performance

3.1 Thermal requirements

A secondary function of tracker support structures is often that they are a part of the thermal management. Silicon detectors must be cooled for several reasons:

- Heat from the FE electronics and radiation-damaged sensors needs to removed from the detector volume,
- Detrimental annealing needs to be limited by keeping the detector cold,
- Good thermal contact to a sufficiently cold local heat sink is required to maintain thermal stability after radiation damage, i.e. to prevent ‘thermal runaway’.

The local heat sink (typically a coolant) is often embedded into the structure and the relevant structural property contributing to the thermal performance is the thermal impedance[1] between sources and sink (coolant). Dimensionally this is the temperature difference between the two divided by the heat (power) transferred. The thermal impedance must be low enough to achieve the requirements outlined above.

3.2 Thermal modelling

Usually the heat path has a complex geometry and in principle the temperatures of the system could be predicted from 3D FEA. However, this becomes a time-consuming task once the temperature-dependence of the leakage current is to be included (to verify thermal stability), and prohibitively difficult if there are other temperature-dependent heat sources in the system (e.g. damage mechanisms or efficiencies in the front-end electronics). In that case useful approximations can be derived from thermal network models [4], [5]. These can be solved analytically in simple cases or with little effort numerically for more complicated cases. These models can include many inputs (sensor and electronics parameters), but the key input from the mechanics is the

[1]Sometimes the term ‘thermal figure of merit’ is used, which is the inverse of the thermal impedance, but it also includes a normalization factor for area. The latter has little justification and tends to obscure the physical meaning of this parameter.

thermal impedance, which can be obtained from FEA or measurements, and can the be used in the calculation.

3.3 Thermal geometries and cooling integration

The thermal impedance of the heat path is given by the geometry (cross-section and length of thermal path), and the thermal conductivities of the employed materials. The optimization of these factors has driven the development of cooling geometries in tracking systems over the past 30 years, during which the heat sinks were progressively brought closer to the heat sources. The current state-of-the-art geometry for liquid coolants are microchannels, which provide a planar sink in direct contact with the sensor. The most widely used carrier material for the microchannels is silicon, which offers good pressure retention and thermal properties which are similar to the sensor, but this technology is difficult to scale to the size of a tracking system, because of the limited size of the substrate requiring a large number of interconnects and large area microchannel technologies in polymers will need to be developed.

4. Service integration

An elegant widely used solution for low-mass electrical services are Kapton/copper or Kapton/aluminium flex circuits. These can be co-cured with the carbon fibre structure to save fixture material or glue. The connection to modules is then typically done by wire or tap bonding. Bonding of services to structures by gluing or co-curing can cause differential thermal expansion issues and it is therefore desirable to design symmetric sandwiches. A further consideration for the use of large flex circuits is the poor thermal conductivity of the electrical insulation layers which can create a thermal barrier.

5. Modularity

To limit time needed for integration and access modularity should be designed into the system at all levels. Modularity here means that each component is contained, with simple interfaces to the rest of the system. It does not require that there are large numbers of a specific modular item. The modular components should link together in a hierarchy with progressively larger units. During integration only fully tested modular units are being added, so that for each new integration step only the success of only this step needs to be verified. This modularity should be employed at all levels throughout the tracker (Detector modules - local supports - services - global supports - sub-systems - tracker etc.). The hierarchy should be designed with enough levels to allow for early and vigorous QA, and so that the incremental change introduced by each integration step remains small. Modular designs for all components also facilitate parallel and distributed production.

6. Case studies

In the following sections we will illustrate the concepts outlined above with a few case studies.

6.1 ALICE ITS OB

In this design ([6], [7]) the detector ladders (figure 3) obtain a large moment of inertia through truss structure made of filament-wound carbon fibre (M55J, 540 GPa) with a resulting sag of 40 to 110 μm (depending on support conditions) over a length of up to 1.5 m. The first mode is at 50 Hz (spring-supported). Good thermal connection is achieved by a cold plate made of UHM CF (K13D2U) with embedded polyimide tubes (2.67 mm inner diameter, 64 μm wall), and the electrical services are provided by a polyimide/aluminium Flexible Printed Circuit, which is connected to the chips by laser soldering.

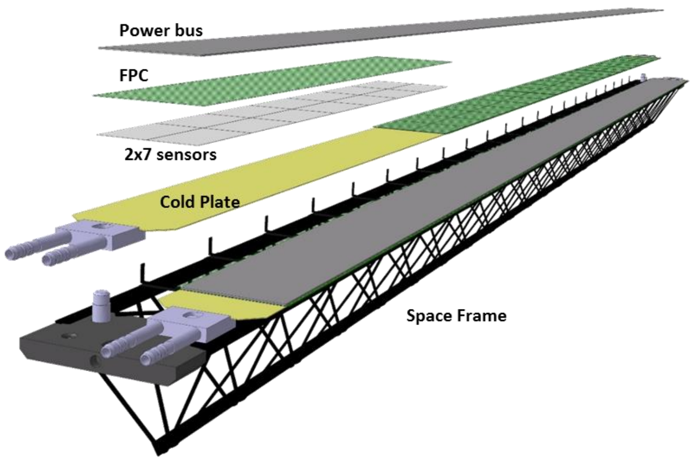

Figure 3: Exploded view of ALICE OB stave [6].

6.2 Mu3e

Ultra-low mass (0.1%X_0/layer) is achieved in this design (figure 4) by a support structure made from 15 μm thick Kapton [8]. Again a high moment of inertia is achieved, here by V-shaped Kapton channels glued to the ladders. The electrical services are again Kapton/aluminium High Density Interconnects, connected by tab bonding in this case.

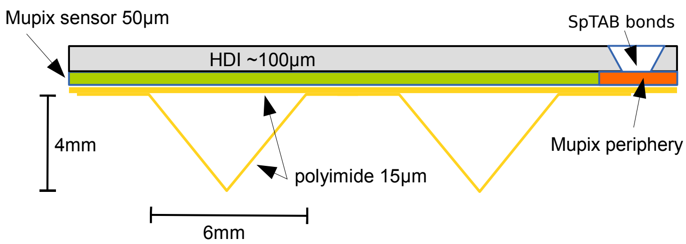

Figure 4: Cross-section through a Mu3e detector ladder [8].

6.3 Inclined rings

Inclined rings are considered in several experiments (see for example figure 5) to optimize material in barrel/endcap transition regions. In such layouts cylindrical modularity is retained by placing the inclined rings at same radius as barrels. A challenge for these layouts is that inclined layouts are difficult to realize with axial structures (in particular the thermal management is challenging) and some of the gain in module material is offset by increased service material (in particular cooling).

Figure 5: Inclined rings for the CMS Phase 2 Outer Tracker Central Barrel Upgrade [9]. Active elements in quadrant of overall tracker layout with flat barrel and inclined regions (left). Ring with PS modules (right).

6.4 STAR PXL

This system ([10], [11]) achieves $0.4\% X_0$/layer with a structure consisting of cantilevered sector tubes (figure 6). A large moment of inertia is achieved by combining the supports for two consecutive layers. Cooling is achieved by air-flow through the sector tubes. Due to the high modulus of inertia, low mass and small size the structure is extremely stiff with a sector first mode of 230 Hz (measured). Still, the air flow of 9 m/s introduces significant deformations with a displacement of 25 to 30 μm and an RMS of 5 μm at full flow.

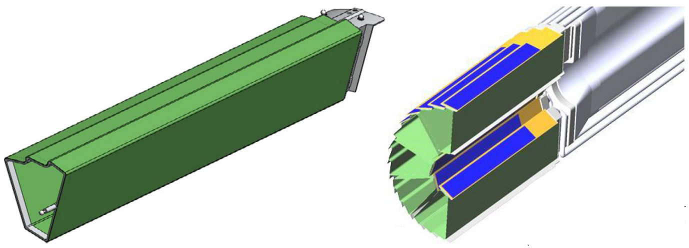

Figure 6: STAR PXL. Sector (left) and detector-half (right) [10], [11]. On each sector three rows of detectors are mounted on the top (outer radius) and one on the bottom (inner radius).

In the design for this system it was assumed that TBA would not be used for the alignment of the detector modules. Therefore significant efforts were made to achieve high build accuracy and all sensor positions on a half-detector were surveyed by CMM using feather probes. However, in the final analysis TBA was still employed to improve the alignment of the detector modules.

6.5 Box channels

The idea of high moment of inertia structures by linking consecutive layers is developed further in this design study for a large tracker for future colliders. This design also studies the possibility to link this box channels circumferentially to achieve an even higher moment of inertia (figure 7).

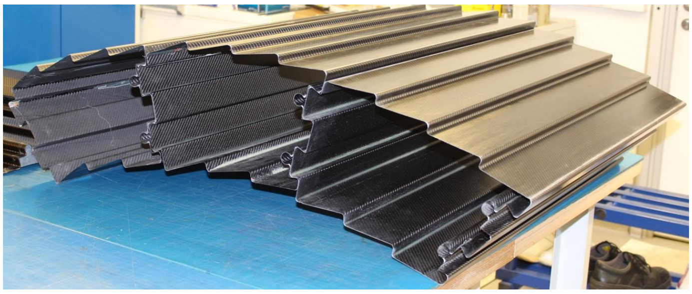

Figure 7: Box channel design study (courtesy Liverpool University).

7. Summary

New sensor technologies and performance requirements for future experiments demand significant reduction in structure material to $0.1\%X_0/1\%X_0$ per vertex/tracking layer. The mechanical properties of the structures in these experiments will be driven by the needs of track-based alignment, for which the key requirement is stability. The mechanical loads (vibrations) under which this stability has to be achieved are typically low with the possible exception of internal vibrations from air flow in air cooling system. Thermo-mechanical loads can be more demanding and should be addressed by levelling power and cooling temperatures, and symmetric mechanical designs. The optimization of stiffness and material will drive development of more open, non-linear structures for the mechanics of future tracking systems.

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