Mechanical precision and stability

Georg Viehhauser
University of Oxford

With material taken from S. Marti, A. Morley, C. Kleinwort, C. Gargiulo and probably others. Mistakes are entirely mine.

Introduction

- The question I will discuss: How to set the positioning requirements for a tracking detector?
  - I will not discuss how to achieve them (if you are interested in this see for example C. Gargiulo's talk at the ECFA High Luminosity LHC Experiments Workshop)
- Based on experience in ATLAS
  - From what I know CMS experience is similar
  - It should be noted that the solutions implemented for the LHC experiments were conceived at a time when there was no experience with tracking systems of that size
- My personal background:
  - My main interest are mechanical structures and thermal management
    - I am not a software track-based alignment expert
  - We are going through all this at the moment for the phase II upgrade of the ATLAS tracker
  - Oxford has been the main responsible group for designing, building and operating the FSI alignment system of ATLAS

Positioning requirements

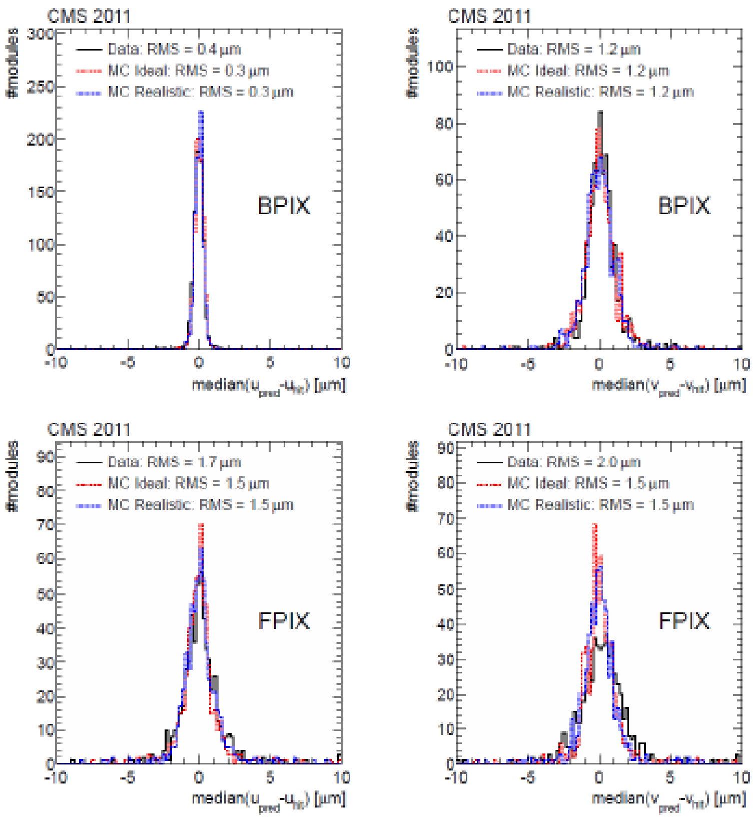
- For a tracking detector (spectrometer or vertexing) we need to know sensor positions in the coordinate system of the tracker
  - Well enough to not significantly degrade performance due to intrinsic resolution
- This is achieved by
  - Placement accuracy
  - Surveys during/after assembly
  - Surveys during operation (hardware alignment system)
  - Offline software track-based alignment (TBA)
- Out of these TBA is the most powerful and important
  - Mechanical engineering needs to support this wherever possible
  - This should drive the positioning requirements for the mechanical engineering

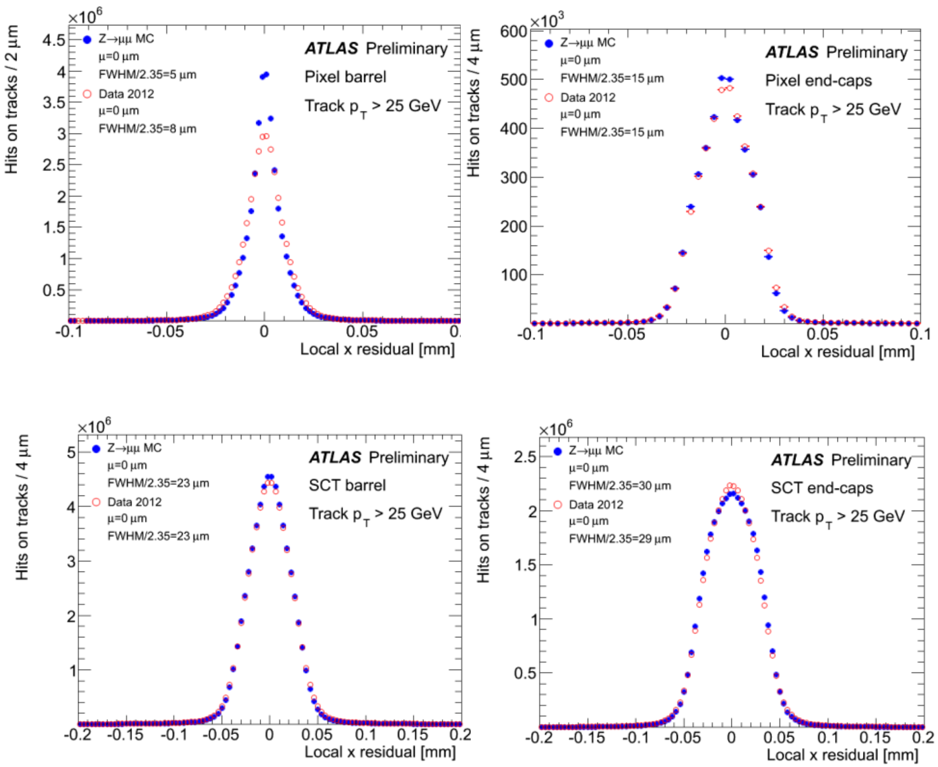
Offline software alignment

- Minimize global χ^2 computed from residuals from high quality tracks
  - Global fit of all track and alignment parameters simultaneously (a few 10^5 parameters)
    - This might seem daunting, but efficient algorithms have been developed for this, which appear strong enough for even larger systems
- To make the software alignment more efficient a hierarchy of alignment structures is used
  - This matches the real mechanical structures
  - In ATLAS:
    - Level 1: subsystems (e.g. pixel barrel)
    - Level 2: disks or barrels
    - Level 3: individual modules (assumed to be internally stable)
  - Experience shows that most movements are at level 1, higher level alignment only needed 2-3 per year
- Track-based alignment by its nature is done for extended periods (alignment cycles)
  - The key demand from the structures is that they are stable over these periods

Offline software performance

- The current understanding is that this technique is capable of aligning the detector modules to a very few µm
  - Simplest metrics is to look at unbiased residuals
  - I suspect that the achievable precision scales with the space-point accuracy



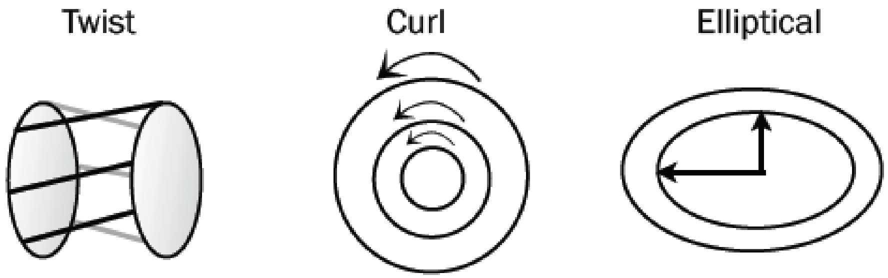


ATLAS-COM-CONF-2014-046, https://cds.cern.ch/record/1708941

Weak modes

- There are classes of deformations (weak modes) which do not alter the X^2 of the alignment fit
  - Coherent deformations, typically internal to one-subsystem (barrel, endcap)
  - Parameters from the fit are completely undefined (floating)
  - Weak mode deformations can be introduced by any high-level alignment
  - They can be introduced by the software alignment (they do not need to be real deformations)
- In current alignment constrained by additional means (cosmics, mass peaks, etc.)
- These are coherent and large-scale internal deformations
  - In principle probably easy to control by mechanics
  - Described by small number of parameters → could probably be controlled by targeted hardware alignment
    - This has not yet been tried

	$\Delta f(r)$	$\Delta f(\varphi)$	$\Delta f(z)$
Δr	radial expansion	elliptical	bowing
$\Delta\varphi$	curl	clamshell	twist
Δz	telescope	skew	z expansion



Placement and surveys during build

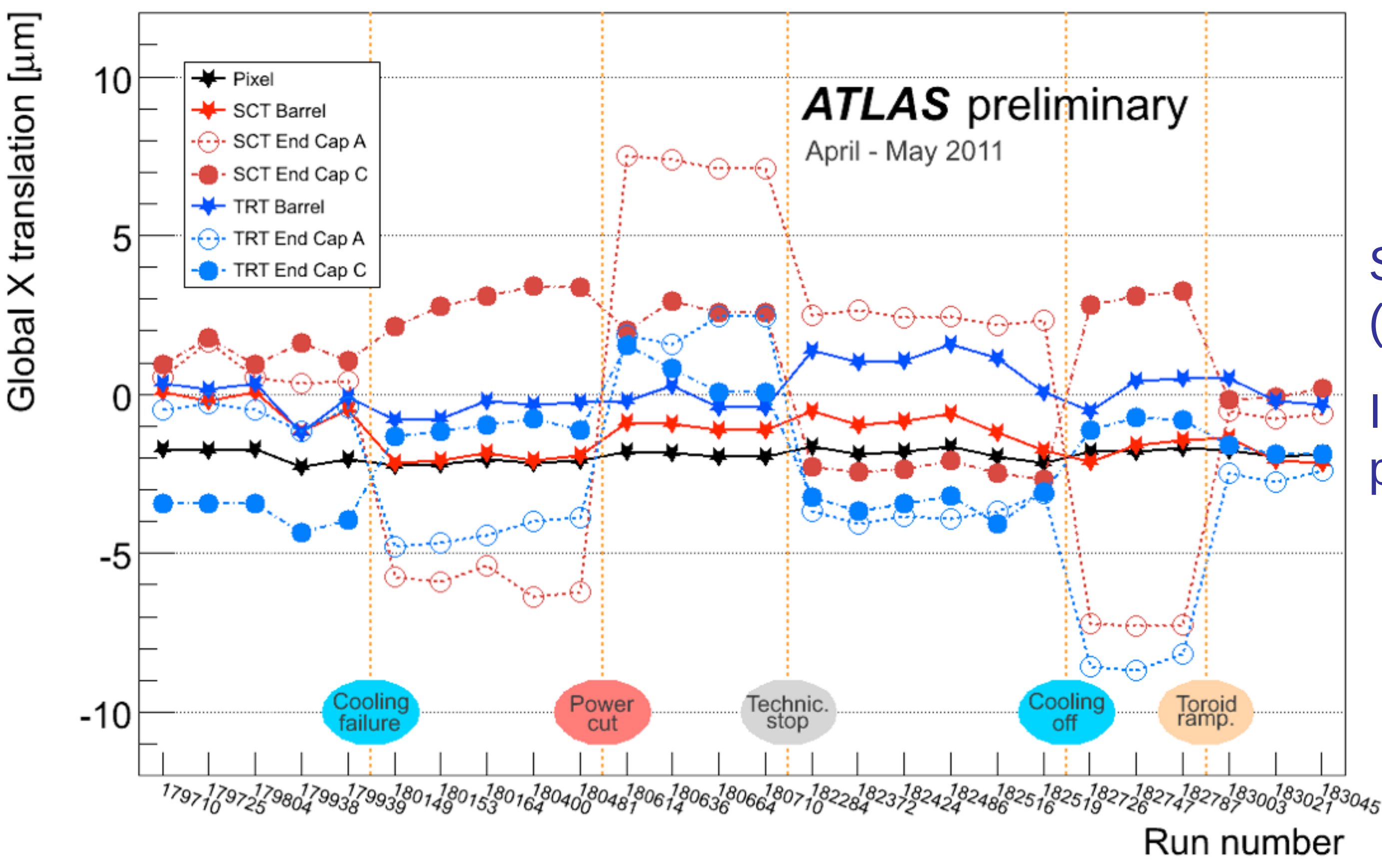
- Because the track-based alignment is so capable placement is not required to extreme levels of accuracy
  - This is something which was – with hindsight – overdone in ATLAS
- Placement only needs to be good enough to
  - Allow everything to fit together
  - Maintain HV isolation clearances
  - Maintain overlaps for coverage and alignment
    - Overlaps provide important constraints for the alignment (in particular circumferential)
      - About 5 detection elements overlap needed (edge + cluster size)
    - Should only be omitted if detection elements are on the same local supports (with some confidence that these are reasonably stable)
- Placement accuracy adds to overlaps
- Knowledge of internal dimensions (by construction or survey) can be useful to reduce parameters at the highest alignment levels
  - In practice this will be only possible locally
- Important caveat: Trigger requirements might supersede the above in future trackers
  - Or the other way round: The trigger needs to not rely on precise placement or needs to be able to accept alignment constants from offline alignment

Stability requirements

- Stability is the most critical requirement for the mechanical engineering of precision tracking systems
- A definition of stability needs the definition of the timescales and the loads for which the system has to be stable
  - Timescales can (should) match timescales of alignment cycles at different alignment levels
  - These definitions should be used throughout the project
    - Can affect requirements for e.g. cooling, front-end electronics etc.
- In principle the response of the system to these loads can be predicted from FEA and verified by prototypes
  - In practice this task might be made easier by allocating a stability budget for different levels of the mechanical structures (because understanding smaller structures is easier)

Stability experience

- Very high stability has been achieved
  - Main perturbations are from external sources (magnet ramps, power supply switch, cooling stops etc.)
  - Between these stability is at the level of a very few µm

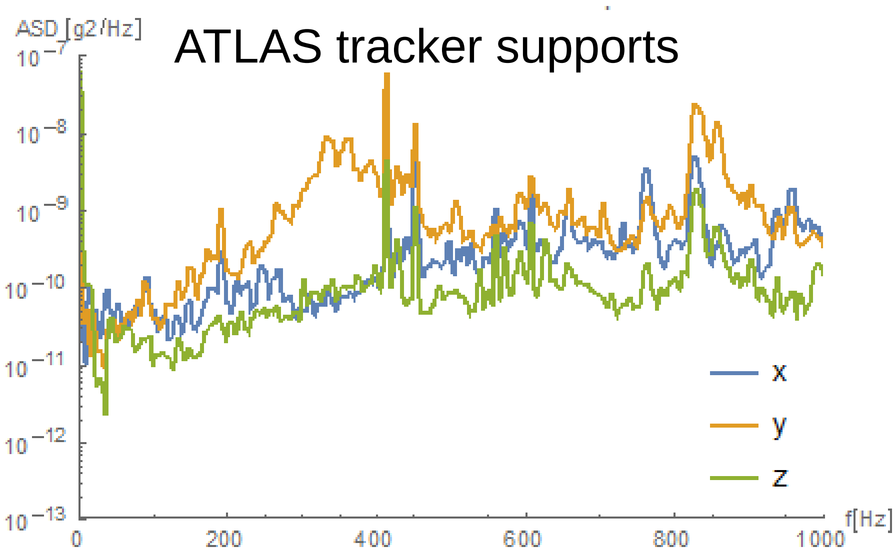


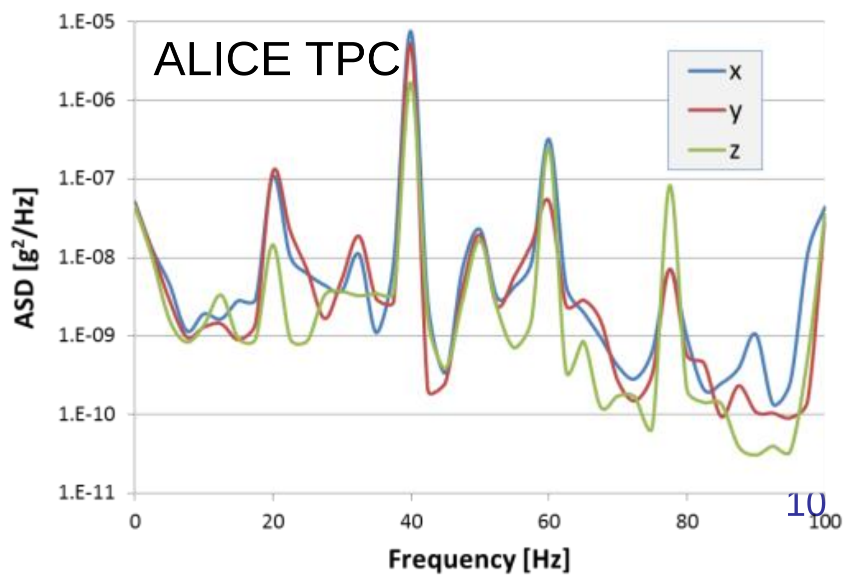
Stability at level 1 (large sub-structures)

Internal stability probably better

Short term loads: Vibrations

- External vibrations can be characterized by a power spectral density (typically acceleration spectral density – ASD)
  - Given by ground vibrations + vibration sources from the rest of the experiment
  - Typical ASDs in particle physics experiments are low (10^{-7} g^2/Hz or lower)
  - Other sources of internal vibrations (e.g. cooling) should be avoided by design
- The displacement response can then be calculated from FEA
- Simple estimates can be found using Miles' equation
  - 1µm RMS displacement for a resonance frequency of 50 Hz at an ASD of 10^{-7} g^2/Hz (Q=12.5)





Other loads

- Short timescales (≤1d):
  - Thermo-mechanical loads: result from changes of the temperatures of the structures, in particular
    - If the temperatures change locally and/or
    - Different parts of the structure have different thermal expansion coefficients (CTEs)
  - Heat load power changes cause temperature changes in two ways:
    - Local temperatures change according to thermal impedance to local sink
    - Sink temperature can change as well
  - Difficult to predict, preferred strategy is to design constant heat loads
- Medium timescales (≤1mo):
  - External ('seismic') events: Cooling system stops, magnet ramps etc.
  - Increased temperature and humidity variations
- Long timescales
  - Creep and relaxation due to static loads
  - Requirements similar to original placement requirements

Alignment to other systems

- Tracker alignment to the magnetic field
  - Rotations
    - These can be seen as a weak mode: again reconstruct and correct mass peak dependence on η and Φ
    - Requires quite a lot of data
  - No real handle on translations
- Tracker alignment to other sub-detectors
  - This is less critical because of resolutions and intermediate material
  - Typically undemanding because lots of tracks available for relative alignment

Hardware alignment systems

- Both, ATLAS and CMS, have hardware alignment systems in strip sections
  - ATLAS: Frequency Scanning Interferometry (FSI) system
    - Grid line array of 842 lines between Barrel and EC
    - Independent of sensors (mechanically and in terms of readout)
    - FSI can in principle provide sub-micron absolute distance information
  - CMS: Laser alignment system
    - 434 modules (3%) are illuminated by laser beams
    - Read out together with regular data taking (100Hz in orbit gap)
- Prime motivation for such systems at the time was unknown environment of a detector of unprecedented size
- Currently both systems are not used in the alignment other than to provide independent quick monitoring of perturbations which require start of a new alignment cycle
  - The fact that they are not used reflects the fact that the anticipated need for these systems did not materialize
  - The systems have not had to demonstrate their ability to provide useful alignment constants for the reconstruction
  - These systems are still the only systems which allow the study of fast deformations

Other requirements for the mechanical engineering

- Positioning requirements are not the only requirements needed for mechanical engineering
- Other requirements
  - Multiple scattering material
    - This is most in tension with positioning requirements
  - Radiation hardness
  - Thermal management
    - Integration of heat paths into the mechanical design
  - Integration requirements
    - Size and shape of mechanical structures will be driven by the need to achieve a fast, robust construction of the system (including QC)
  - Installation and access scenarios
    - In particular if activation of the detector and environment is a concern
    - These will define separations, interfaces and clearances
  - Cost
    - Not only cost of materials, but including prototyping, manufacturing, yields, repairs etc.

So what are the numbers we are discussing in ATLAS?...

- These numbers are all under discussion
- Stability

Table 1: Summary of stability requirements in $r\varphi$. Stability requirements in other directions are ten times higher.

	Timescale	Requirement	Comment
Short	1d	2µm	
Medium	1m	5µm	Always within sub-systems, on a global scale only between seismic events
Long	Several month to years	as assembly placement accuracy	

Based on performance we think we achieved in Run I

- Hermeticity for 1 GeV/c tracks, 5 strip/pixel overlap for straight tracks (1-2 edge, 3 for cluster), vertex within 1 mm radius of tracker center
  - Placement accuracy on top of this not defined, to be chosen by pixel/strip projects, which will involve optimization for integration and material
- Other constraints

Table 1: Constraints on dimensions which are difficult to track for track-based alignment (Difference between true positions and known positions after placement and surveys).

	Limit
Δr	10µm (pixel barrels) 100µm (strip barrels)
Δz	20µm (pixel disks) 100µm (strip disks)

This is the most demanding/controversial requirement
It tries to support TBA by constraining the dimension in which it is weak

How to approach this for the LC

- I think it is necessary to form a team of mechanical engineers + software alignment experts
- They should develop from the beginning a system which is optimized for alignment
- Part of this would be to develop mutual understanding
- From engineers to software alignment:
  - Input for simulation what are possible deformations? What are reasonable limits on what can be achieved?
  - We can offer to target certain deformations by either stiffening them through design, or tracking them with dedicated hardware alignment. Is this useful?
- From software alignment to engineers:
  - Requirements for mechanical performance, layout, need for hardware alignment

Summary

- The LHC experience:
  - Track-based alignment is the most powerful alignment tool
    - Alignment at the level of a very few µm has been achieved. It can even find sensors shape parameters
    - Mechanical engineering should support this as much as possible
    - The critical requirement for the structures is stability
    - High stability is achievable because loads are small or can be made small
  - Placement accuracy is only required to maintain overlaps and clearances
  - (Local) surveys can be useful, but are not essential
  - Hardware alignment systems have very little use for the actual detector alignment
- Future experiments:
  - I expect all these conclusions to apply for any future tracker
  - My advice is to form from early on a strong collaboration of mechanical engineers and software alignment experts to develop good understanding of each other and a common strategy from the beginning
    - This will allow to specify useful positioning requirements for the mechanical structures

Further Material

How Alignment Works (for CMS)

- Basic principle of track based alignment : minimise global χ^2 computed from track-hit residuals
- If we change the alignment parameters → track parameters change as well → huge coupled system
- To treat all correlations properly, perform global fit of all track parameters and all alignment parameters simultaneously

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{measurements}} \left(\frac{m_{ij} - f_{ij}(\mathbf{p},\mathbf{q}_j)}{\sigma_{ij}} \right)^2$$

m_{ij}: measurement
σ_{ij}: uncertainty
f_{ij}: track prediction
$\mathbf{p}$: alignment param.
$\mathbf{q}_j$: track parameters

- With linearisation of prediction at initial track and alignment parameter leeds to huge linear equation system:

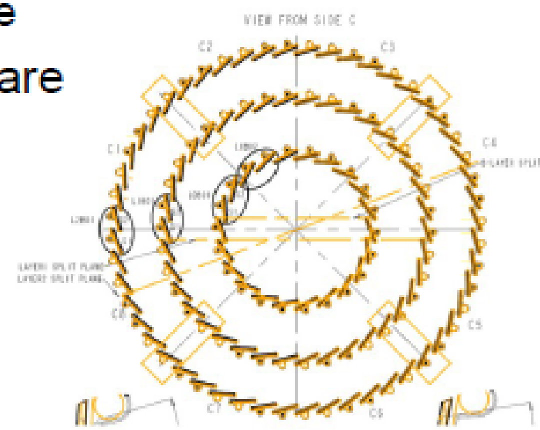
$$f_{ij}(\mathbf{p},\mathbf{q}_j) \approx f_{ij}(\mathbf{p}_0,\mathbf{q}_{j,0}) + \Delta\mathbf{p}\frac{\partial f_{ij}}{\partial \mathbf{p}} + \Delta\mathbf{q}_j\frac{\partial f_{ij}}{\partial \mathbf{q}_j}, \quad \mathbf{C}\cdot(\Delta\mathbf{p},\ldots,\Delta\mathbf{q}_j,\ldots) = \mathbf{b}$$

- Can be reduced with block matrix algebra to system for global parameter corrections:

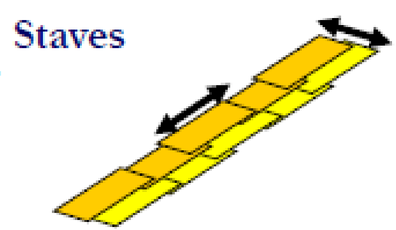
$$\mathbf{C}'\cdot\Delta\mathbf{p} = \mathbf{b}'$$

Overlaps

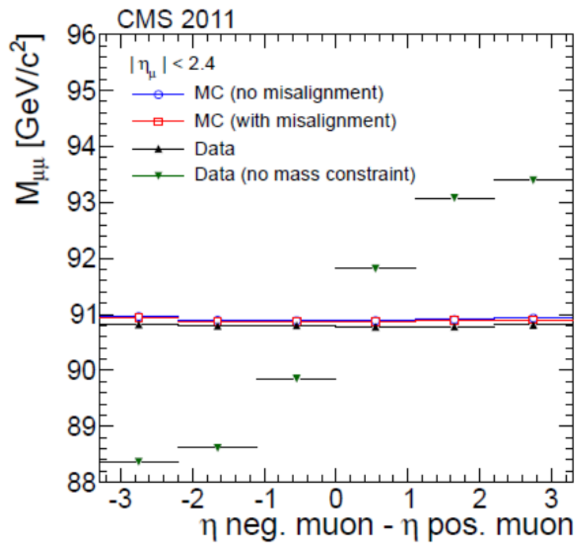
- *Rφ* module overlaps are of great importance as they produce a constraint on circumference (2π boundary)
  - Correlate in a natural manner the position (alignment) of neighbour modules
  - Put strong limits on the circumference and radius of the circle modules form
    - Otherwise, track based alignment almost blind to these
  - The usefulness of overlaps depend on how big they are
  - Still not trouble free as edge effects may spoil them
    - Module distortions
  - It is important that the distance between overlapping modules to be small
    - Minimize Multiple Coulomb Scattering effects



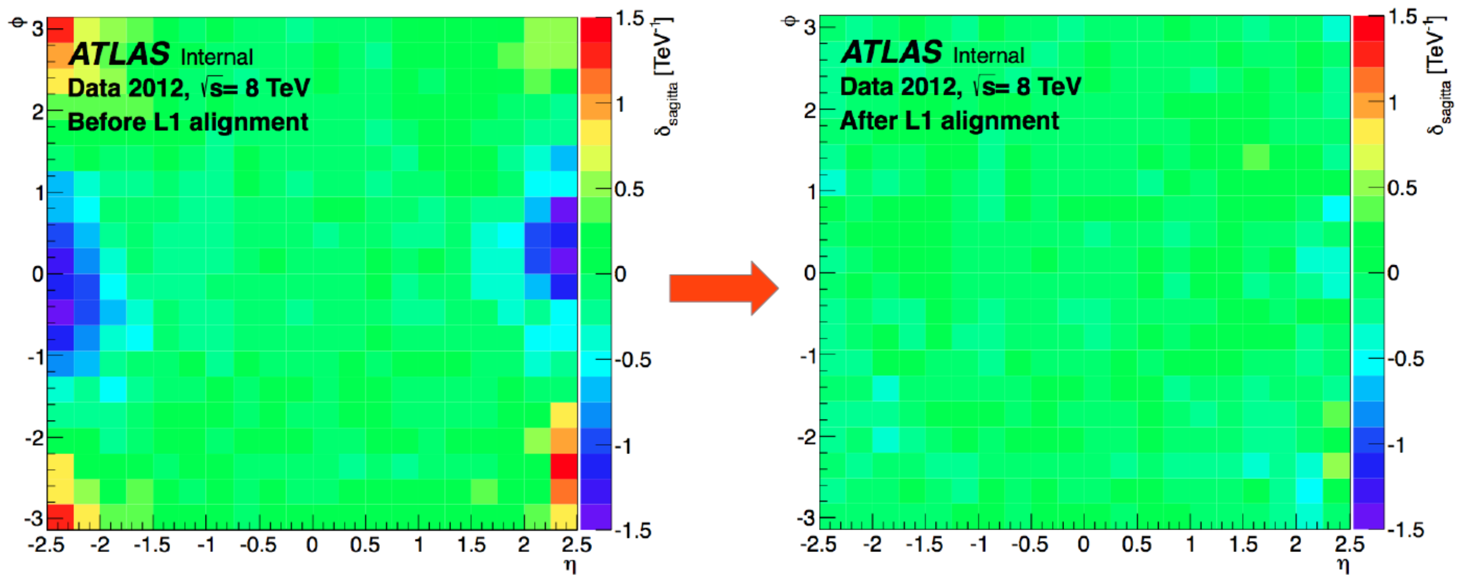
- Z overlaps have a smaller impact as the system is not closed in Z
  - Still correlate the position (alignment) of neighbour modules
  - They may be useful within a stave to keep the size ~constant.



Examples of weak mode alignment

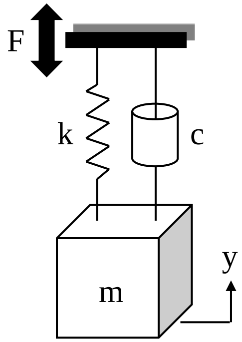


$Z \rightarrow \mu^+\mu^-$



Miles' equation

- For a 1dim harmonic oscillator under gravity



Frequency of first fundamental mode: $f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}}$ ← sag

- Response to uniform vibration spectrum described by Miles' equation

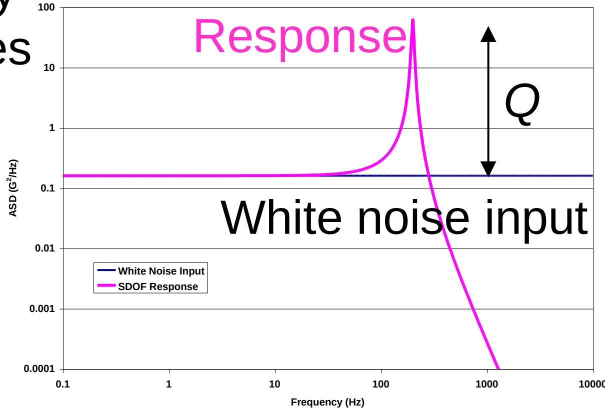
$$a_{RMS} = \sqrt{\frac{\pi}{2} ASD \cdot f_0 \cdot Q}$$

← Quality factor, typically ~12.5 for CF structures

↑ Acceleration Spectral Density (typically in g^2/Hz, FT of time-based acceleration measurement)

John W Miles

1d oscillator response

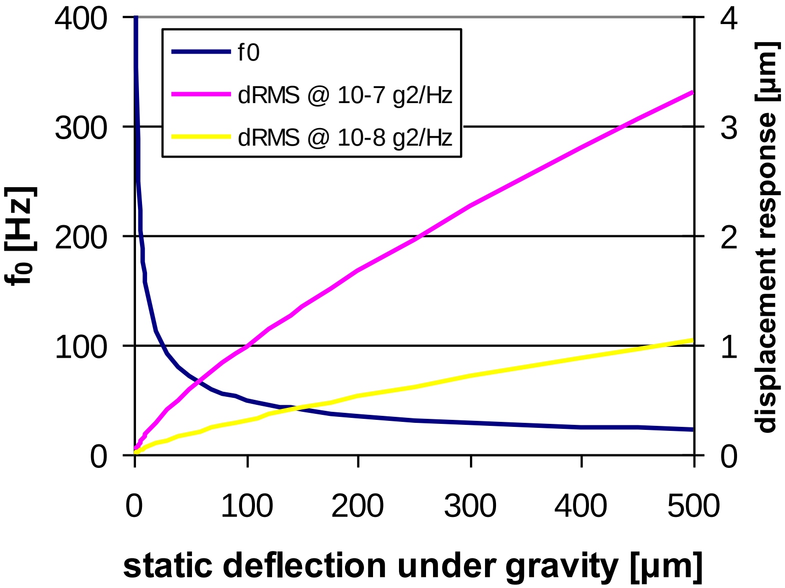


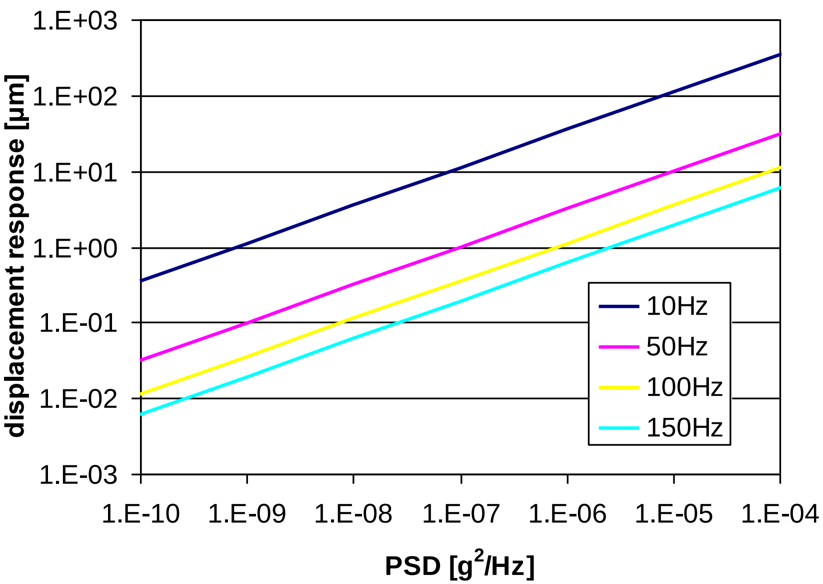
- For purposes of order of magnitude estimates this will also apply for 3d objects, although one needs to watch out for coincidences of structural resonances and peaks in the ASD spectrum

Displacement response to vibration

Displacement response

$$\delta_{RMS} = \left(\frac{1}{2\pi f_0}\right)^2 a_{RMS} = \sqrt{\frac{ASD \cdot Q}{32\pi^3 f_0^{\,3}}} = \frac{\sqrt{ASD \cdot Q}}{2}\left(\frac{\delta_{grav}}{g}\right)^{3/4}$$





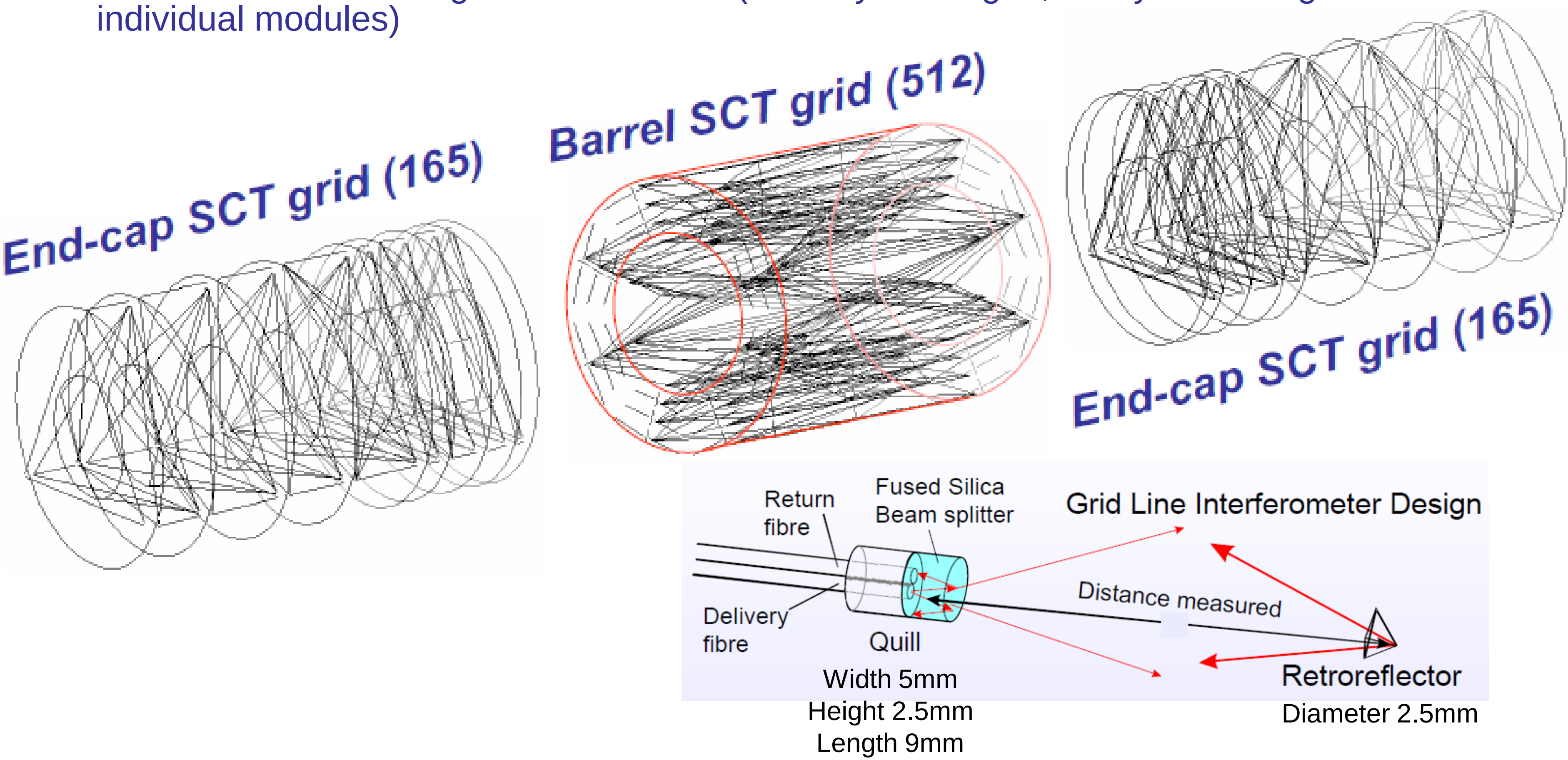
- To maintain a displacement response of 1 µm for an ASD of 10^{-7} g^2/Hz the first mode needs to be at 50 Hz (assuming Q=12.5)
  - This would be equivalent for a static gravitational sag of about 100µm (1d)

Damping

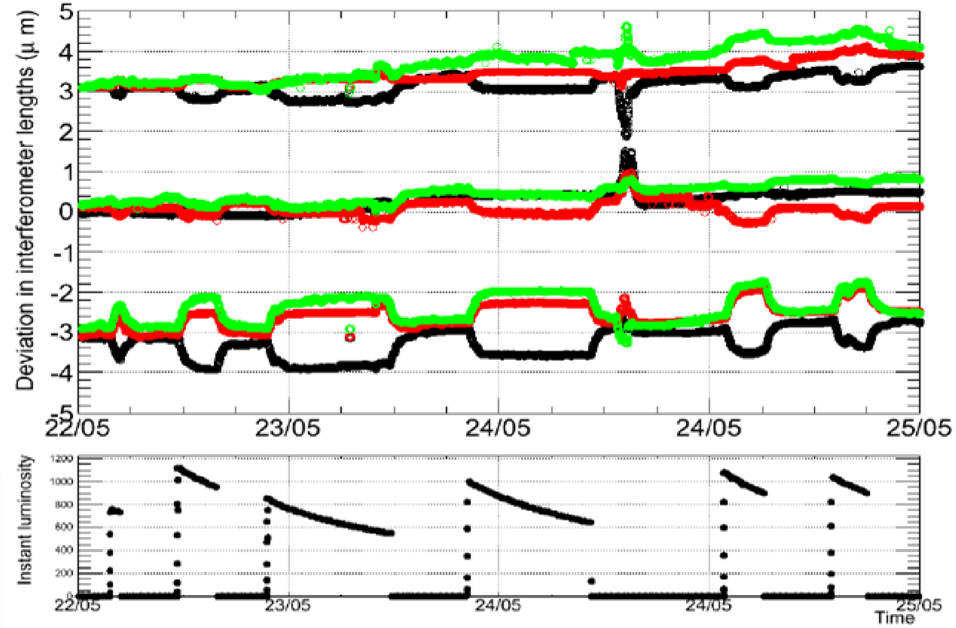
- Damping is to a large extent driven by the materials
- In CF composite structures it’s dominated by the matrix material and the fibre orientation
- Typical values in literature for damping in high-modulus CF structures are between ~1-5%, where the lower number is along unidirectional fibres and the upper for larger angles. More complex lay-ups somewhere in between
- This results in $Q \sim 1/2\zeta$ between 10 and 100
- Larger structures will probably be much stronger damped due to parasitic (non-support) connections (e.g. services)

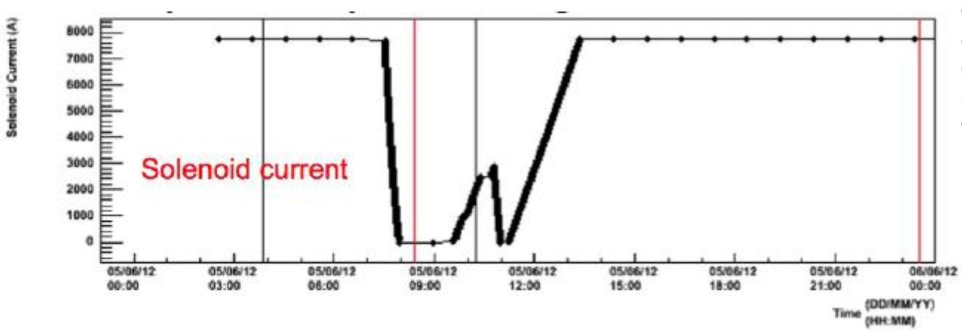
ATLAS FSI system

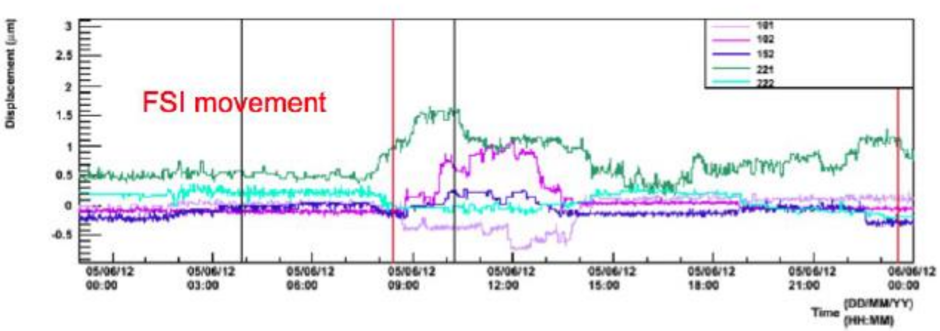
- A geodetic grid of length measurements between nodes attached to the SCT support structure
- All 842 grid line lengths are measured simultaneously using FSI to a precision of <1µm
- Only small and passive components within tracker
- Allows an absolute length measurement (but only of the grid, tells you nothing about individual modules)



ATLAS FSI examples



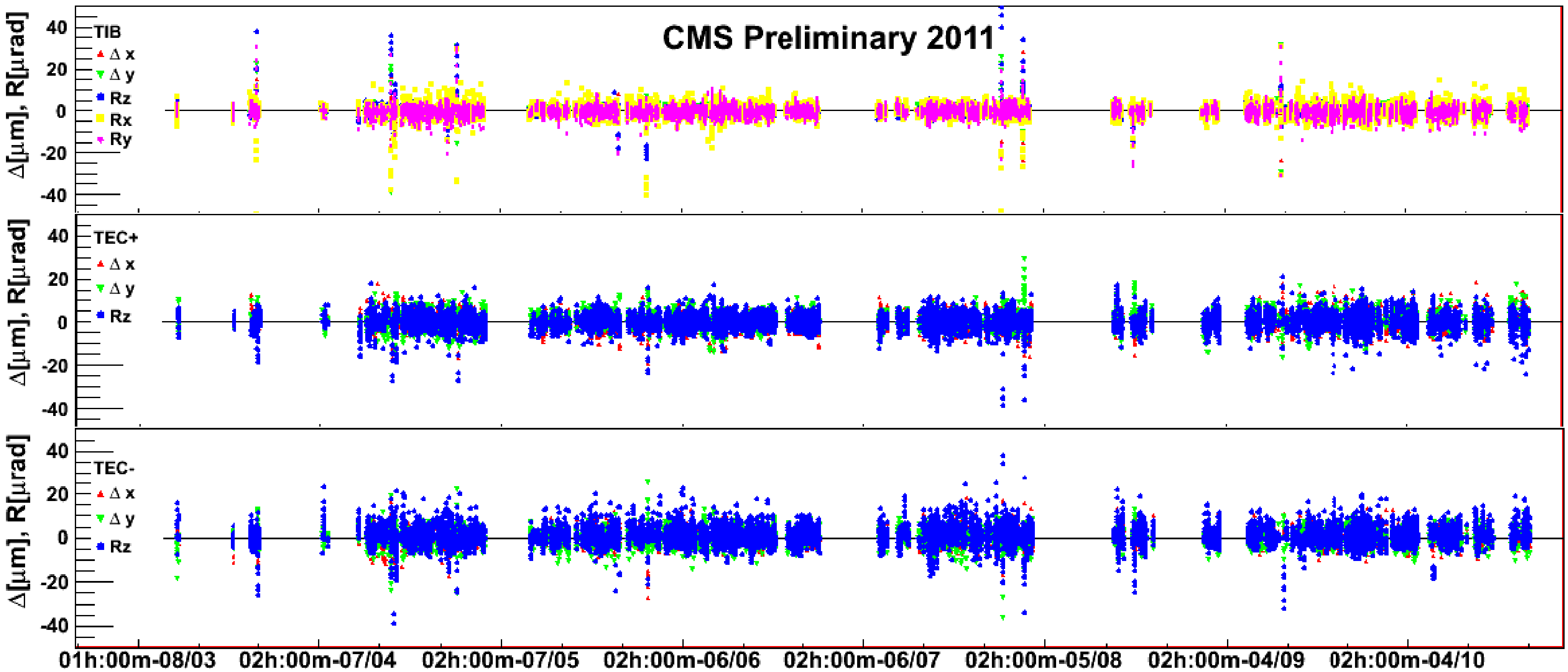




Note that these are timescales which are inaccessible to TBA

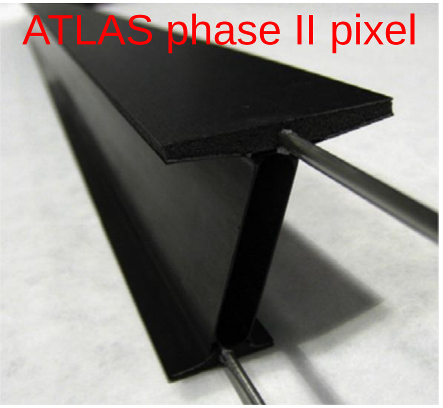
(days and below)

CMS laser alignment example

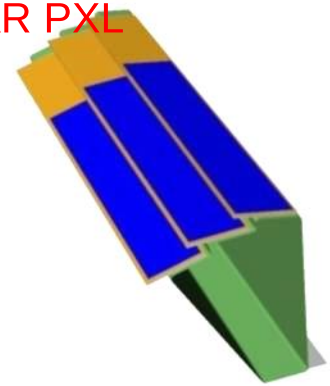


How can we achieve stiffness?

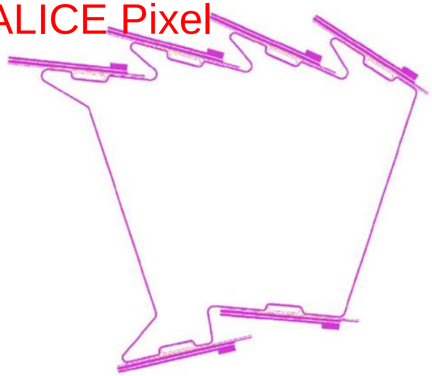
- The key is **design for large moment of inertia** (together with high modulus)
  - Ladders are poor
  - Large cylinders are better
    - But: hoop stiffness is now the challenge
    - Also: integration of large cylinders has many disadvantages
      - Large, valuable objects – difficult to move/transport
      - Technologies get challenged late in the integration
- Can one make smaller units which are clever structurally?
  - Yes, exploit the mouldability of CF (and Kapton-based service elements)!
  - Examples exist for vertex/pixel systems, need to scale by 10 in size



doi:10.1016/j.nima.2013.07.005



doi:10.1016/j.nima.2010.12.006



doi:10.1016/j.nima.2006.04.093

- And, with 50μm sensors, the structures do not need to be flat…

Further reading

- ATLAS collaboration, *Alignment of the ATLAS inner detector and its performance in 2012*, ATLAS-COM-CONF-2014-046 (2014).
- CMS collaboration, *Alignment of the CMS tracker with LHC and cosmic ray data*, 2014 JINST 9 P06009; doi:10.1088/1748-0221/9/06/P06009.
- S.M. Gibson et al., *A novel method for ATLAS FSI alignment based on rapid, direct phase monitoring, 11th International Workshop on Accelerator Alignment*, DESY (2010), ATL-INDET-PROC-2010-037.
- B. Wittmer et al., *The laser alignment system for the CMS silicon microstrip tracker*, Nucl. Instr. Meth. A581 (2007), pp. 351-355; doi:10.1016/j.nima.2007.08.002.
- C. Kleinwort, F. Meier, *Alignment of the CMS silicon tracker – and how to improve detectors in the future*, Nucl. Instr. Meth. A650 (2011), pp. 240–244; doi:10.1016/j.nima.2010.11.187.
- M. Gersabeck, *Alignment of the LHCb vertex locator*, Nucl. Instr. Meth. A598 (2009), pp. 71–74; doi:10.1016/j.nima.2008.08.112.