Position stability and monitoring in ATLAS

Georg Viehhauser with input from Steve McMahon, Anthony Morley, Pawel Bruckman, Andreas Salzburger, Eric Anderssen and others (errors are entirely mine)

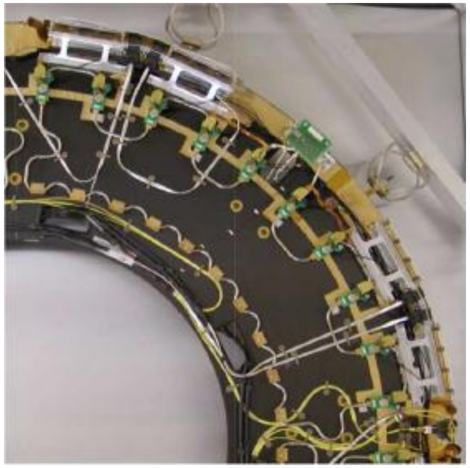
What this talk is about

- How do we know where things are?
- What contribution to this knowledge comes from hardware?
  - Build tolerances
  - Structural stiffness
  - Alignment systems
- How do the physicists (tracking and track-based alignment community) convey their needs to the mechanical engineering community
- All in the context of ATLAS silicon detectors– what has been done and achieved in the past, and what we plan to do in the future

Structures of the ATLAS silicon detectors

Barrel strips:

- Individual modules
- mounted with CF brackets
- on XN50A/RS3 & Ultracor UCF-83-1/4-3.0 sandwich cylinders (one per layer)

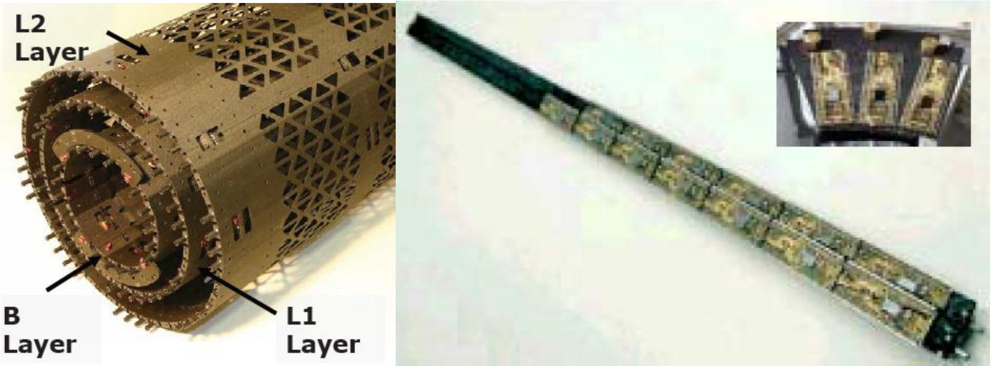


EC strips:

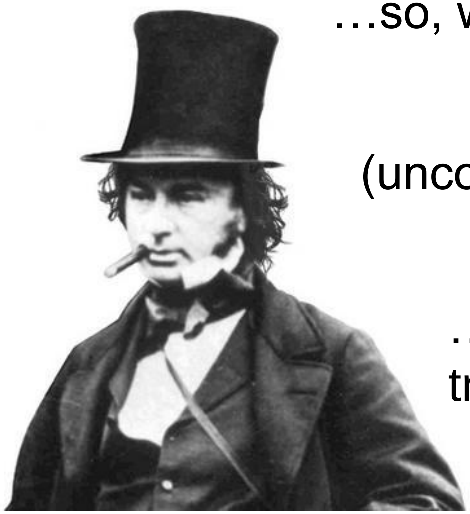
- Individual modules
- mounted on carbon-carbon cooling blocks
- on YSH-50A/RS3 & Korex sandwich disks

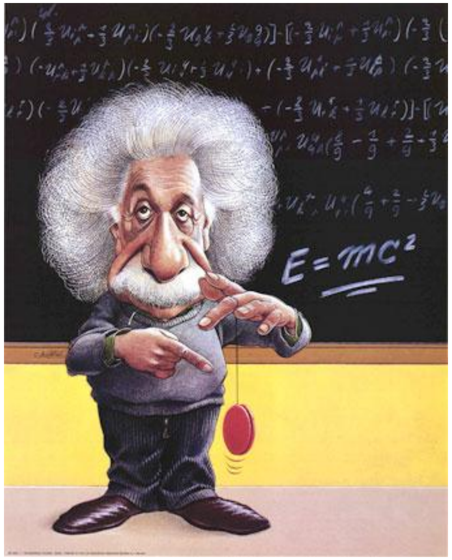
Pixel system:

- Local supports (bi-staves and sectors) made of UHM CF
- On CF cylinders (YS80/EX1515)



Does this sound familiar?...


Isambard Kingdom Brunel



…so, what stiffness should our structure have?...

…well, make it as stiff as possible.

(unconvinced)…ok…

… and use as little material as possible…

…Duh…so how do I know how to
trade off one against the other?

… Hmm, just design it so that the
resonance frequency is above 50Hz…

Why?...

…because this is line frequency…

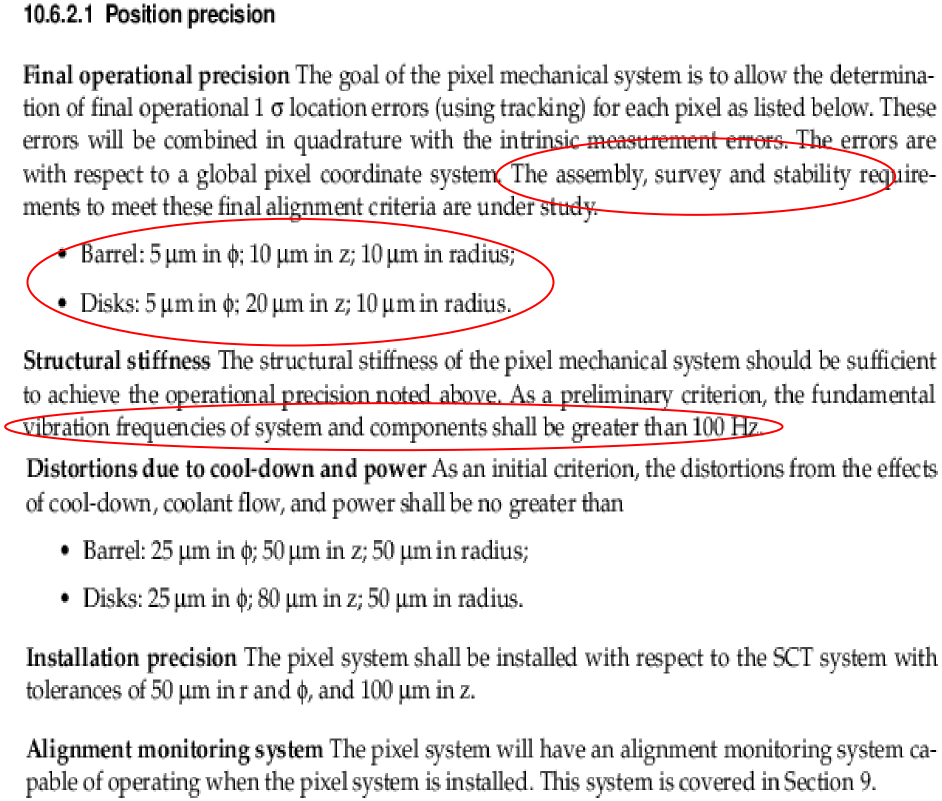
(goes away, grumbling something about) …proper specifications…

Detailed stability definitions did exist in the case of ATLAS (although not everybody seems to have been aware of them)

What was specified

From the ATLAS Inner Detector TDR:

Pixel:



10.6.2.1 Position precision

Final operational precision The goal of the pixel mechanical system is to allow the determination of final operational 1 σ location errors (using tracking) for each pixel as listed below. These errors will be combined in quadrature with the intrinsic measurement errors. The errors are with respect to a global pixel coordinate system. The assembly, survey and stability requirements to meet these final alignment criteria are under study.

- Barrel: 5 µm in ϕ; 10 µm in z; 10 µm in radius;
- Disks: 5 µm in ϕ; 20 µm in z; 10 µm in radius.

Structural stiffness The structural stiffness of the pixel mechanical system should be sufficient to achieve the operational precision noted above. As a preliminary criterion, the fundamental vibration frequencies of system and components shall be greater than 100 Hz.

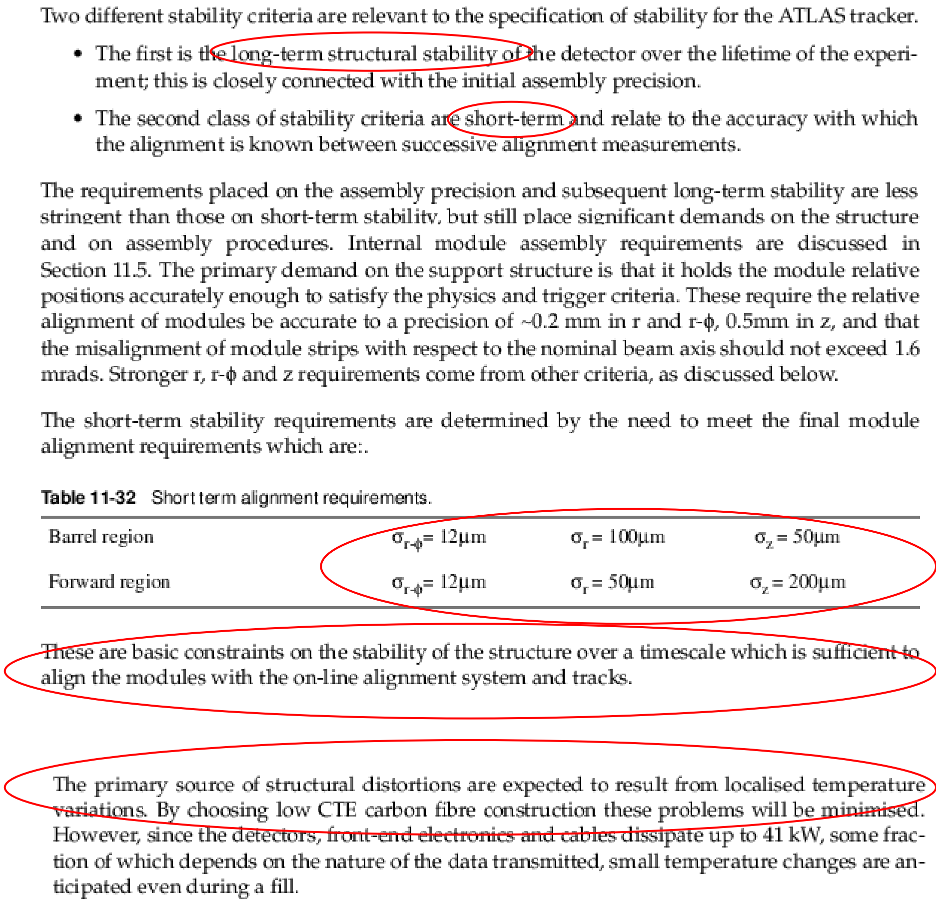
Distortions due to cool-down and power As an initial criterion, the distortions from the effects of cool-down, coolant flow, and power shall be no greater than

- Barrel: 25 µm in ϕ; 50 µm in z; 50 µm in radius;
- Disks: 25 µm in ϕ; 80 µm in z; 50 µm in radius.

Installation precision The pixel system shall be installed with respect to the SCT system with tolerances of 50 µm in r and ϕ, and 100 µm in z.

Alignment monitoring system The pixel system will have an alignment monitoring system capable of operating when the pixel system is installed. This system is covered in Section 9.

Strips:



Two different stability criteria are relevant to the specification of stability for the ATLAS tracker.

- The first is the long-term structural stability of the detector over the lifetime of the experiment; this is closely connected with the initial assembly precision.
- The second class of stability criteria are short-term and relate to the accuracy with which the alignment is known between successive alignment measurements.

The requirements placed on the assembly precision and subsequent long-term stability are less stringent than those on short-term stability, but still place significant demands on the structure and on assembly procedures. Internal module assembly requirements are discussed in Section 11.5. The primary demand on the support structure is that it holds the module relative positions accurately enough to satisfy the physics and trigger criteria. These require the relative alignment of modules be accurate to a precision of ~0.2 mm in r and r-ϕ, 0.5mm in z, and that the misalignment of module strips with respect to the nominal beam axis should not exceed 1.6 mrads. Stronger r, r-ϕ and z requirements come from other criteria, as discussed below.

The short-term stability requirements are determined by the need to meet the final module alignment requirements which are:.

Table 11-32 Short term alignment requirements.

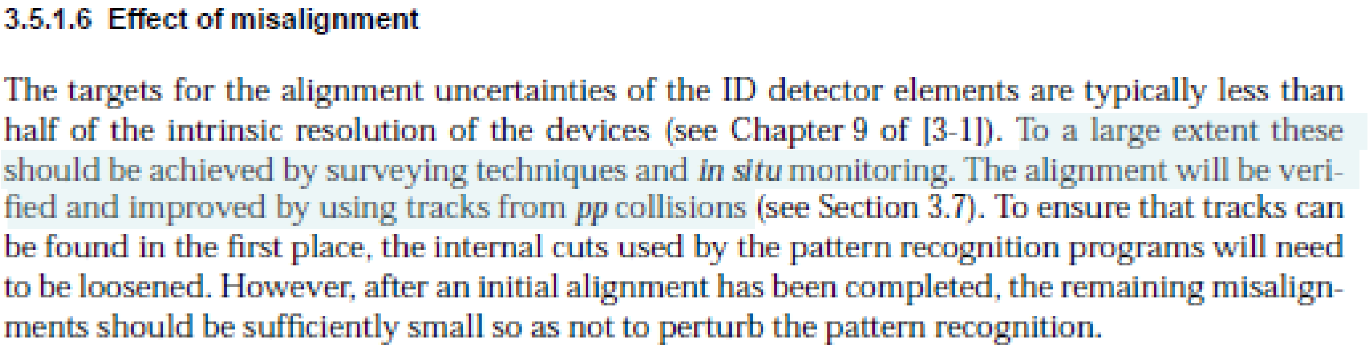
Barrel region	$\sigma_{r-\phi}$= 12µm	σ_r = 100µm	σ_z = 50µm
Forward region	$\sigma_{r-\phi}$= 12µm	σ_r = 50µm	σ_z = 200µm

These are basic constraints on the stability of the structure over a timescale which is sufficient to align the modules with the on-line alignment system and tracks.

The primary source of structural distortions are expected to result from localised temperature variations. By choosing low CTE carbon fibre construction these problems will be minimised. However, since the detectors, front-end electronics and cables dissipate up to 41 kW, some fraction of which depends on the nature of the data transmitted, small temperature changes are anticipated even during a fill.

And how it ties together

From overall ATLAS TDR:

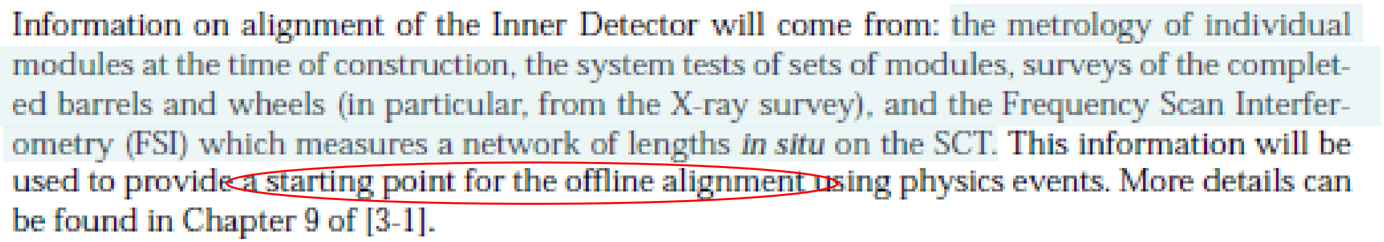


3.5.1.6 Effect of misalignment

The targets for the alignment uncertainties of the ID detector elements are typically less than half of the intrinsic resolution of the devices (see Chapter 9 of [3-1]). To a large extent these should be achieved by surveying techniques and *in situ* monitoring. The alignment will be verified and improved by using tracks from *pp* collisions (see Section 3.7). To ensure that tracks can be found in the first place, the internal cuts used by the pattern recognition programs will need to be loosened. However, after an initial alignment has been completed, the remaining misalignments should be sufficiently small so as not to perturb the pattern recognition.

Emphasis on hardware alignment
Tracks provide correction

Hardware alignment is starting point for track-based alignment



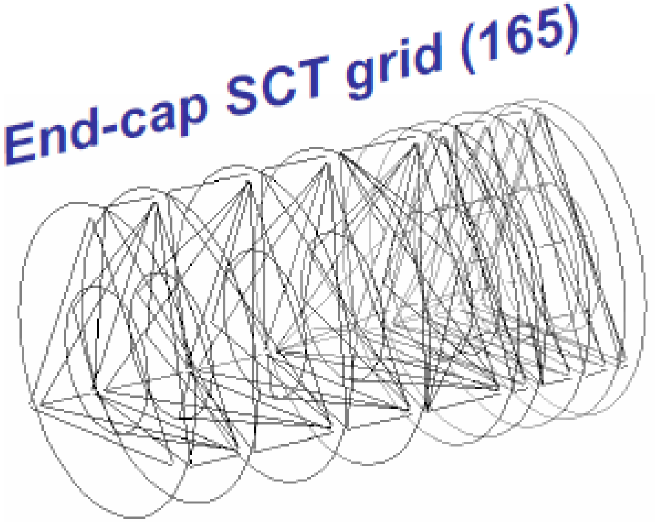
Information on alignment of the Inner Detector will come from: the metrology of individual modules at the time of construction, the system tests of sets of modules, surveys of the completed barrels and wheels (in particular, from the X-ray survey), and the Frequency Scan Interferometry (FSI) which measures a network of lengths *in situ* on the SCT. This information will be used to provide a starting point for the offline alignment using physics events. More details can be found in Chapter 9 of [3-1].

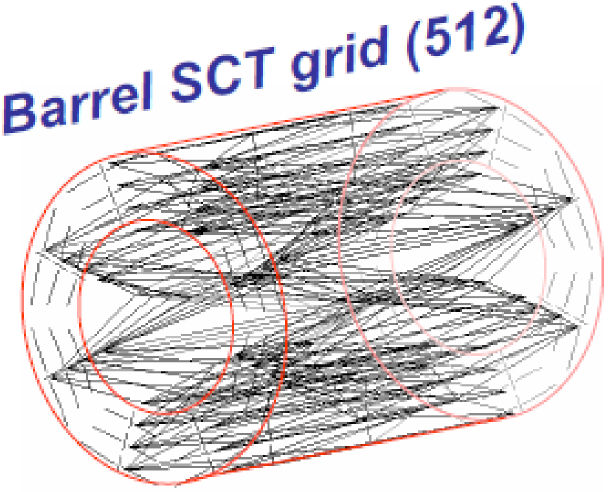
So, there was a sequence outlined:

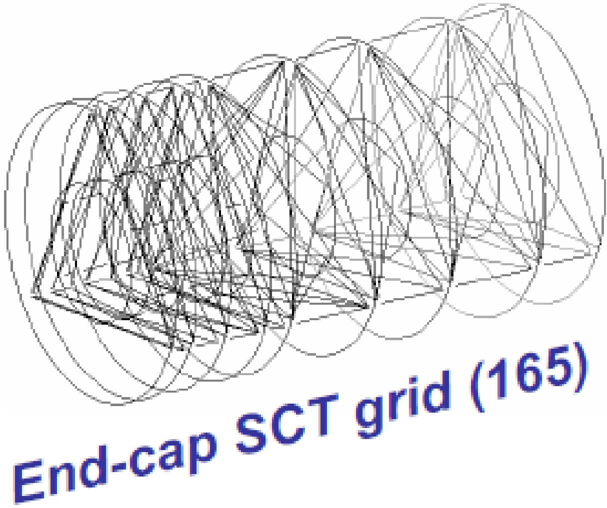
1. Placement
2. Metrology during build at various levels
3. X-ray survey (shoot X-rays as straight lines through the tracker)
4. Frequency Scanning Interferometry (FSI) system for online deformation monitoring
5. And then: track-based alignment

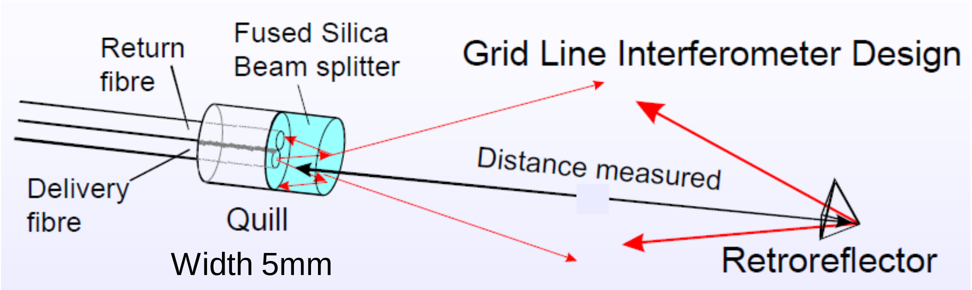
ATLAS FSI system

- 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)







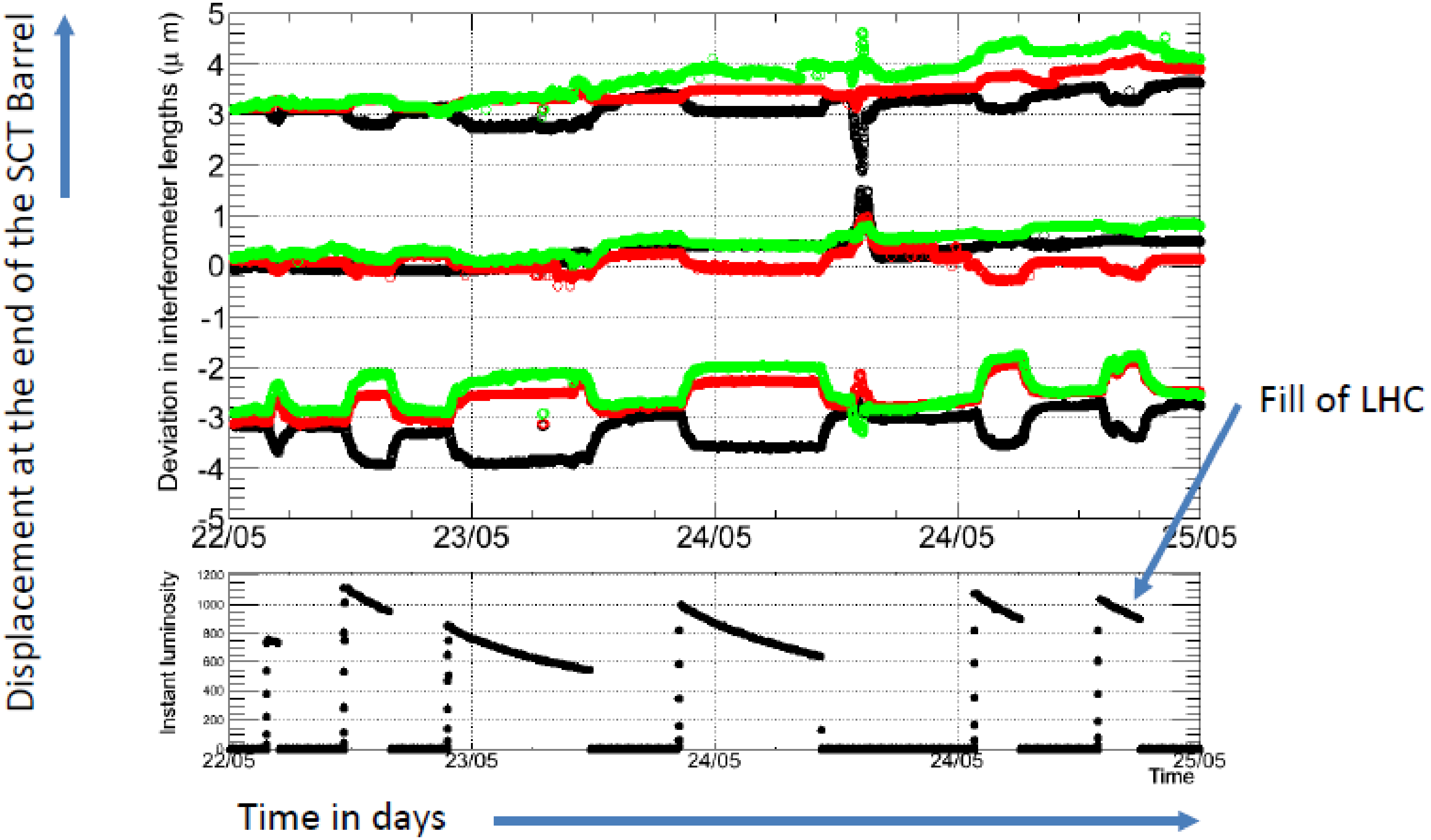


Width 5mm
Height 2.5mm
Length 9mm

Diameter 2.5mm

What has been achieved in ATLAS (short term?)

This is measured with the Frequency Scanning Interferometer (>800 grid lines) that is built into the detector. The period covers 3 days/6 LHC fills. It shows what is realizable in a large detector

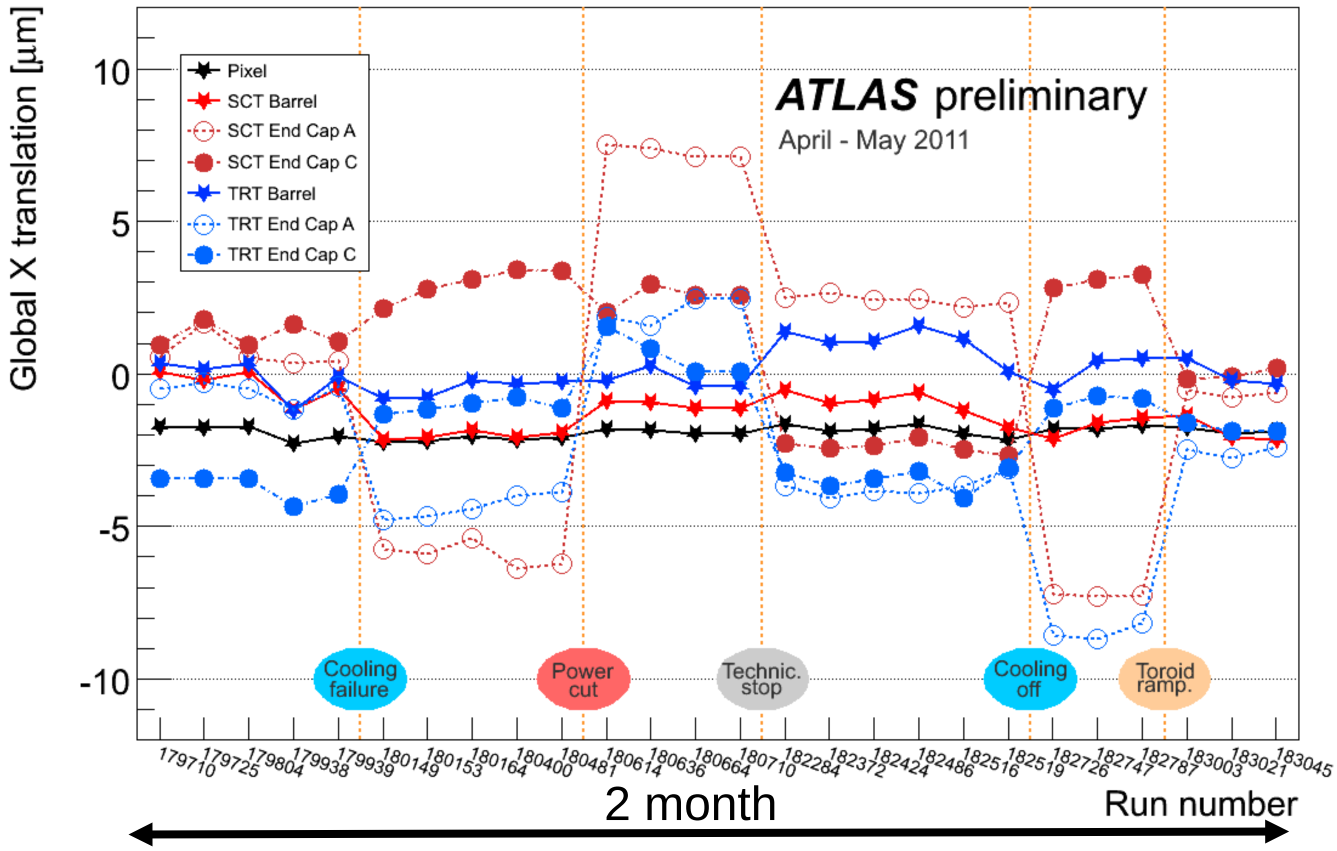


Displacement at the end of the SCT Barrel

Fill of LHC

Time in days

What have we achieved (medium timescale)?



This is driven by ‘seismic events’

- Cooling system stops, magnet quenches, power outages, etc…
- For example: 19 cooling system stops (16 unscheduled) in 2011

What we really did

Sequence defined in the TDR:

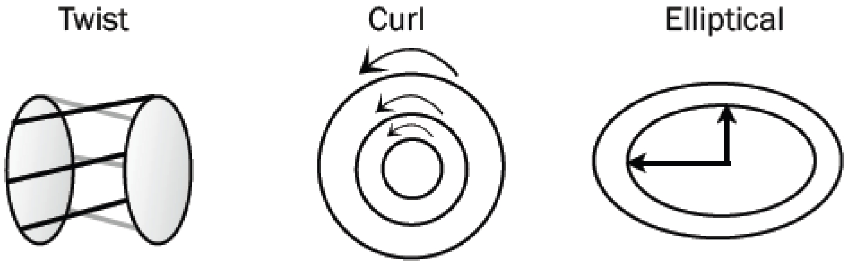
1. Placement
   - Significant efforts were spent to place components accurately (for example µm precision in the placement of sensors in strip modules)
   - It is now commonly understood that a high level of placement accuracy is not required
2. Metrology during build at various levels
   - Was done for some components (pixels) but not for others (strips)
3. X-ray survey (shoot X-rays as straight lines through the tracker)
   - Cancelled due to time pressure during integration
4. Frequency Scanning Interferometry (FSI) system for online deformation monitoring
   - This is installed and running beautifully, however
   - It's information is not used actively in the alignment (just used for cross-checks and monitoring of stability)
5. And then: track-based alignment
   - This is the main alignment method and has proven to be very powerful
   - But there are classes of deformations which are more difficult to address than others ('weak modes')

The most important reason for this change of tack is the excellent stability, which exceeds the levels outlined in the TDR

Weak deformation modes

- Deformations which do not result in a significantly increased χ^2 of a track fit, but affect other physics-relevant measurement parameters (e.g. vertex position).
- Typically these are coherent deformations of larger sections of the tracker.

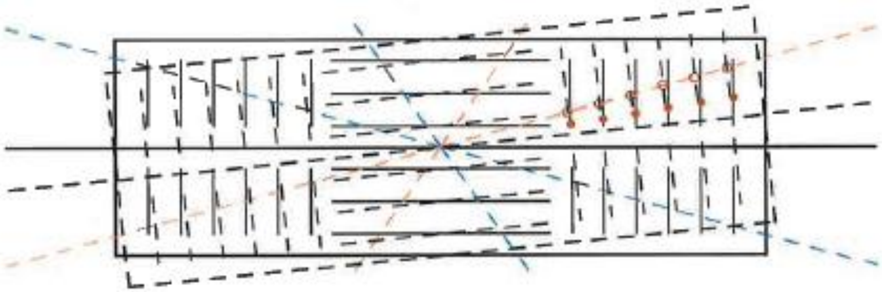
	$\Delta f(r)$	$\Delta f(\varphi)$	$\Delta f(z)$
Δr	radial expansion	elliptical	bowing
$\Delta\varphi$	curl	clamshell	twist
Δz	telescope	skew	z expansion



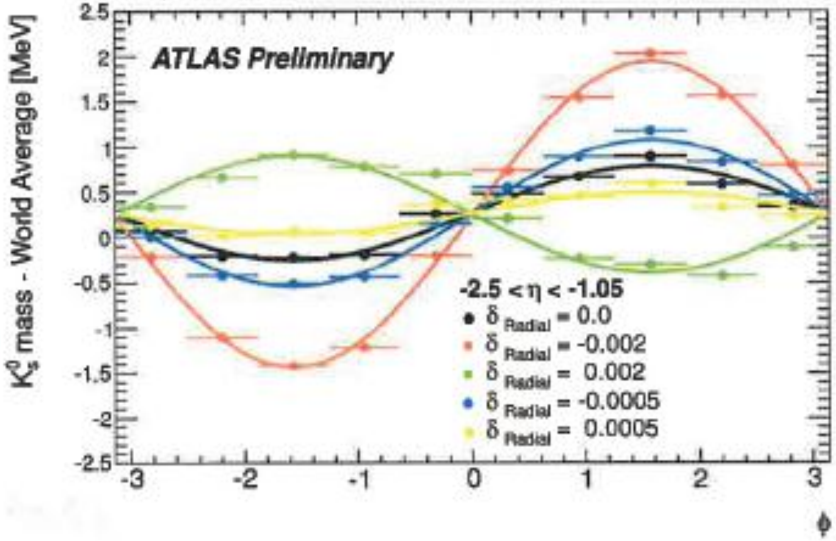
- In track alignment some of these movements can be constrained from
  - module overlaps (in particular in r due to the closed loop constraint),
  - with cosmics,
  - or from higher-order reconstruction (e.g. reconstruction of invariant mass-peaks
- Weak modes shifting the positions in φ (in particular curls and twists) have strongest impact on reconstructed momentum
- But: weak mode misalignments creep in for any track-based alignment

Example for weak mode deformation

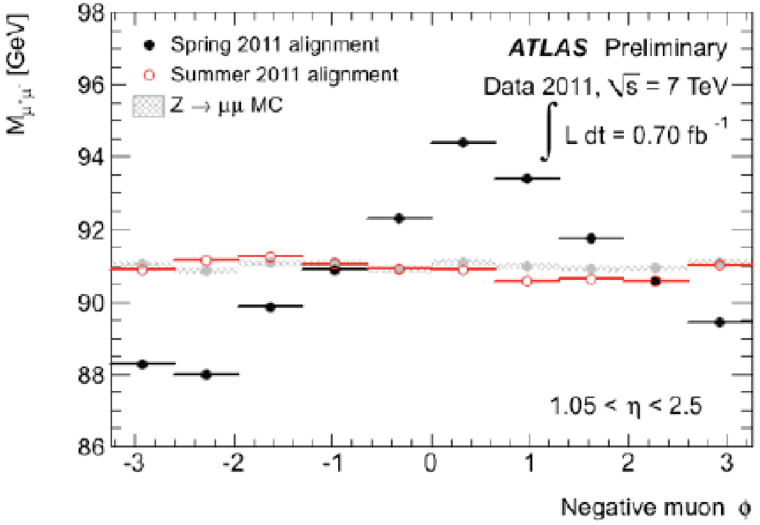
Tracker tilt:



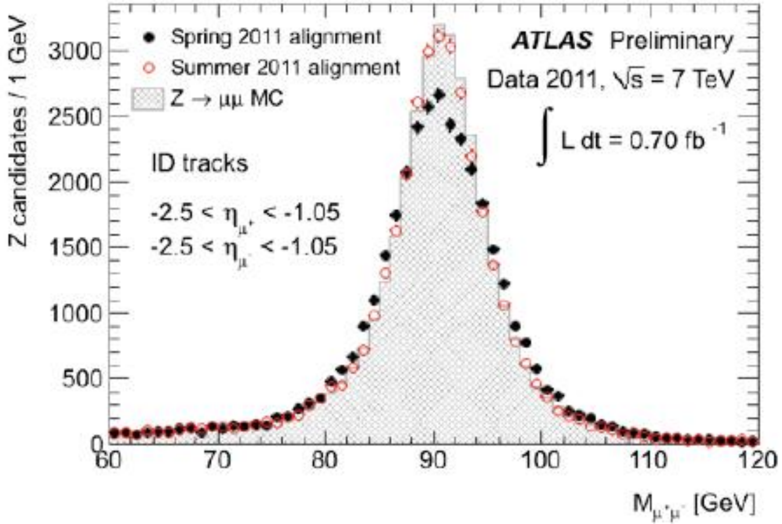
K_s mass reconstruction



Z mass reconstruction



Z mass peak



Our approach for the future

As a starting point for the design of the HL-LHC ATLAS tracker structures want to define positioning requirements

- This clearly is based on experience from current tracker
- Input from tracking and track-based alignment communities

Stability requirements for phase II

- Short timescale:
  - No major disturbing events from external causes (magnet ramps, intended or unintended cooling system stops etc.)
  - From ATLAS experience: ~24h. Corresponds to the timescale of a track-based alignment cycle.
  - Typical load variations during this timescale are
    - External vibration (relevant at time scales of up to 1s),
    - Power fluctuations of the front-end electronics of about 10%,
    - Temperature variations at any given position of ±1°C.
  - In present tracker typically a stability of 1µm was achieved during these periods (in rφ)
  - For future tracker we require the same performance over this timescale.
- Medium timescale:
  - Timescale over which we currently gather enough data to constrain the weak modes (~1 month)
  - During these periods there are changes of
    - Temperature variations at any given position of ±3°C,
    - Relative humidity variations between 10% and 50% at the operating temperature.
  - In addition (relatively infrequent) external perturbations ('seismic events') can occur, which include
    - Magnet ramps,
    - Cooling system cycles,
    - Power and HV cycles,
  - In the present tracker typically a stability of order of 10µm was achieved during these periods.
  - For future tracker we require a stability of 5µm everywhere between seismic events, and internal to subsystems at all times
- Long timescale:
  - Stability against relaxation caused by creep, possibly accelerated by irradiation.
  - The timescale is months to years.
  - Require that the detector positions satisfy the same criteria as in the original placement requirements

Stability under vibration – Miles’ equation


John W Miles

- The acceleration response of a 1dim dampened oscillator for constant ASD can be found from Miles’ equation

$$a_{RMS} = \sqrt{\int_0^\infty \frac{ASD \cdot f_0^{\;4}}{\left(f_0^{\;2} - f^{\,2}\right)^2 + 4\zeta^2 f^{\,2} f_0^{\,2}} df} = \sqrt{\frac{\pi}{2} \cdot ASD \cdot f_0 \cdot Q}$$

Quality factor

Acceleration spectral density

- The displacement response is

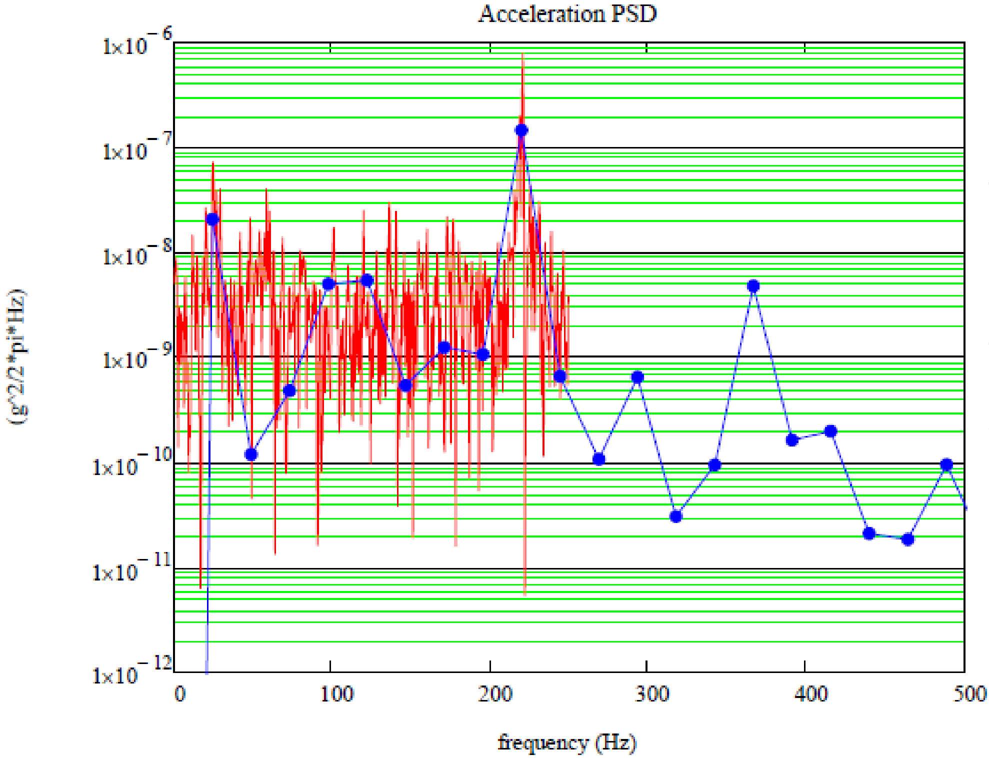
$$\delta_{RMS} = \frac{a_{RMS}}{(2\pi f_0)^2} = \sqrt{\frac{ASD \cdot Q}{32\pi^3 f_0^{\;3}}}$$

- And, using the deflection under gravity

$$\delta_{RMS} = \frac{\sqrt{ASD \cdot Q}}{2}\left(\frac{\delta_g}{g}\right)^{3/4}$$

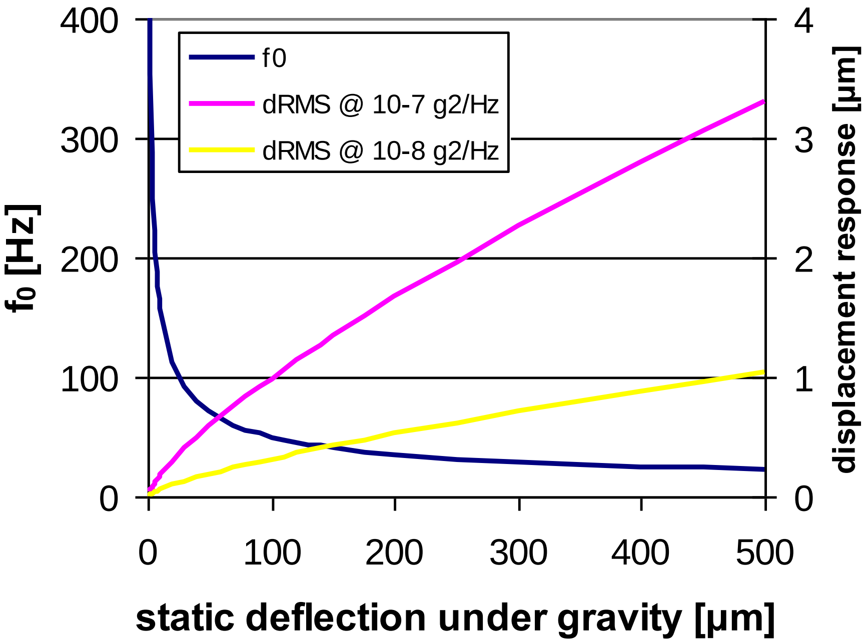
Acceleration spectrum in particle physics experiments

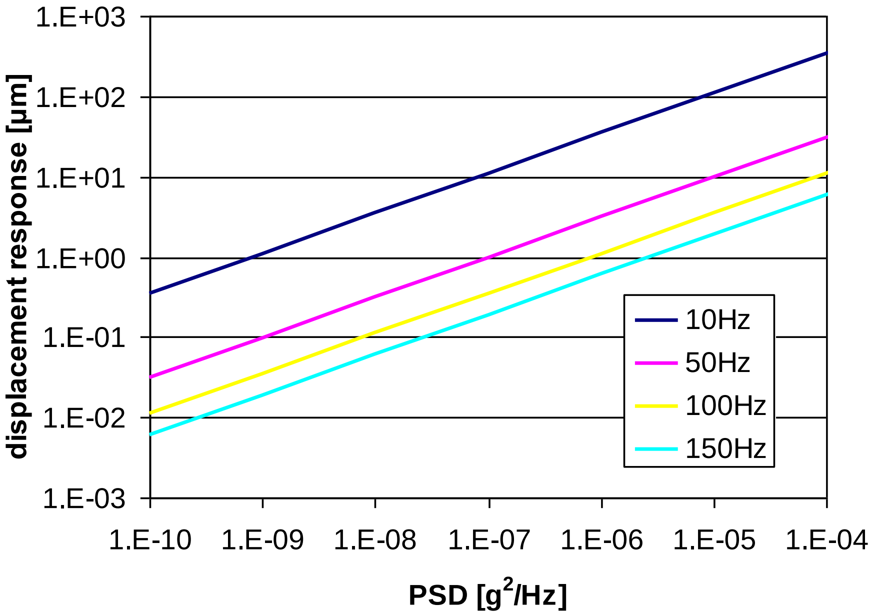
- Unfortunately we don’t have a measurement of the ASD in ATLAS yet
- This will be done during and after the shutdown next year
- But we have a measurement of ASD in STAR, for illustration
- This is at $10^{-8}g^2$/Hz with a single peak at $10^{-7}g^2$/Hz at about 240 Hz, no indication of line frequency being a particular problem
- This is representative for light industrial environment (typically 10^{-7} to 10^{-8} g^2/Hz)



Courtesy of E. Anderssen, H. Wieman

Displacement response for 1d oscillator





- Assumes *Q* = 12.5
- At $10^{-7}g^2$/Hz resonance frequency must be 50Hz for an RMS displacement of 1μm
  - And about 25 Hz at $10^{-8}g^2$/Hz
- Does this also apply to 3d object?

Multi-modal systems

- Displacement for multi-modal system

Modal participation factor

Modal amplitude (normalized)

$$y(x,f)=\frac{\varphi(f)}{\lambda}\sum_{n=1}^{\infty}\frac{\Gamma_n X_n(x)}{\left(f^2-f_n^{\,2}\right)+2i\zeta f f_n}$$

Acceleration density

Damping (assumed independent of mode)

- Modal participation factors

$$\Gamma_n=\int_0^l \lambda X_n(x)dx \quad \text{and} \quad m_n=\Gamma_n^{\,2}=\left(\int_0^l \lambda X_n(x)dx\right)^2 \quad \text{with} \quad m=\lambda l=\sum_{n=1}^{\infty} m_n$$

(This assumes uniform base vibration)

Modal masses

- Modal participation factors and mode shapes can be obtained from FEA (or for simple systems analytically)

Example: Euler-Bernoulli beams

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

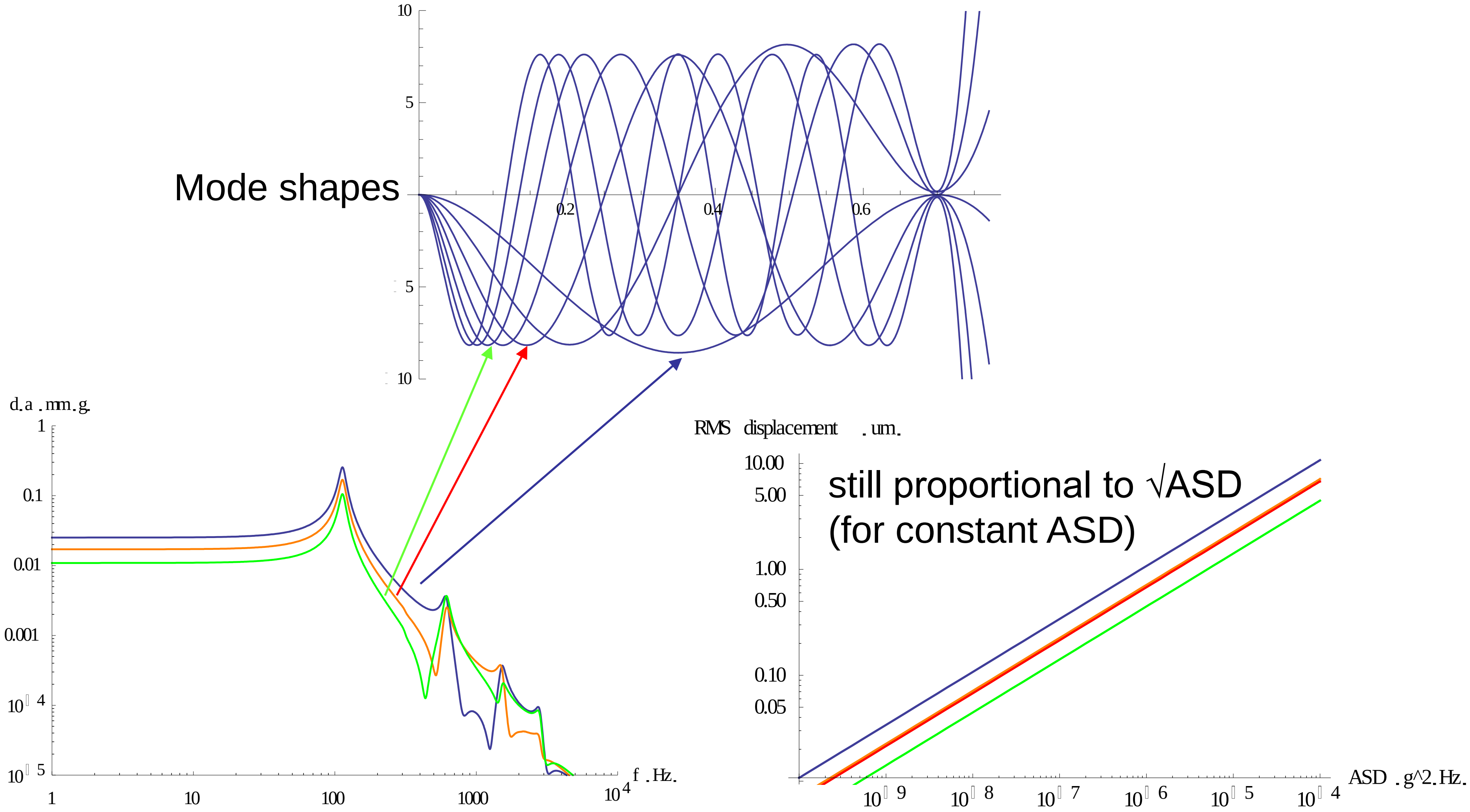
- Solutions for resonance frequencies

$$f_n = \frac{1}{2\pi}\omega_n = \frac{\kappa_n^{\,2}}{\pi^2}\sqrt{\frac{EI}{\lambda}} \quad \text{with} \quad \begin{cases} \cos(\kappa_n l)\cosh(\kappa_n l) = 1, \text{fixed - fixed} \\ \sin(\kappa_n l) = 0, \text{simply supported} \\ \cos(\kappa_n l)\cosh(\kappa_n l) = -1, \text{fixed - free} \end{cases}$$

Simple CF/foam sandwich like outer pixel stave
$EI = 13.4\mathrm{Pam}^4$,
$\lambda = 0.055\mathrm{kg/m}$,
$l = 0.7\mathrm{m}$

Mode	Fixed-fixed			Both ends simply supported			Fixed-free		
	$\kappa_n l$	f_n [Hz]	m_n/m	$\kappa_n l$	f_n [Hz]	m_n/m	$\kappa_n l$	f_n [Hz]	m_n/m
1	4.730	113	69.0%		50	81.1%	1.875	18	61.3%
2	7.853	313	0		200	0	4.694	112	18.8%
3	10.996	613	13.3%		450	9.0%	7.855	313	6.5%
4	14.137	1013	0	$n\pi$	801	0	10.996	613	3.3%
5		1514	5.4%		1251	3.2%	14.137	1013	2.0%
6	$\approx\frac{(2n+1)\pi}{2}$	2114	0		1801	0	$\approx\frac{(2n-1)\pi}{2}$	1514	1.3%
7		2815	2.9%		2451	1.7%		2114	1.0%
Gravitational sag	δ_{grav} = 25μm (x = 0.5l)			δ_{grav} = 126μm (x = 0.5l)			δ_{grav} = 1226 μm (x = l)		

Example: fixed-fixed beam



Mode shapes

still proportional to √ASD
(for constant ASD)

Displacement response at different locations

Comparison to Miles' equation

- Compare analytical multi-modal analysis with Miles' equation (taking f_0 (1dim) = f_1 (multi-modal))

	$x = x_1$		$x = x_2$		$x = x_3$		Longitudinal RMS
	x/l	d/d_{1D}	x/l	d/d_{1D}	x/l	d/d_{1D}	
Fixed-fixed	0.5	132.0%	0.71	87.5%	0.79	54.7%	83.1%
Both ends simply supported	0.5	127.3%	0.75	90.0%	0.83	63.7%	90.0%
Fixed-free	1	156.6%	0.47	48.1%	0.69	91.0%	78.3%

- Miles' equation underpredicts maximum RMS displacement along beam, but overpredicts everywhere else (including RMS along beam by up to 20%)
- Ratios are independent of beam parameters, only depend on BCs
- → Miles' equation still appears to predict beam reasonably well

Depends on environment

$$d_{RMS} \approx \sqrt{\frac{\pi^3}{32}\frac{1}{\kappa_1{}^3}}\left(\frac{\lambda}{EI}\right)^{\frac{3}{4}}\sqrt{Q \cdot ASD}$$

Depends on BC

Depends on beam properties

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)

Thermal load changes

- Changes in front-end electronics power consumption
  - Rate-dependent
    - In ATLAS reduced by L1 levelling
  - Different run types (calibrations etc.)?
- In ATLAS SCT front-end power constant within 10% (expected to be similar for phase II)
  - Local variation of front end power changes local temperature according to thermal impedance between source (ASIC) and sink (coolant)
  - But: in evaporative cooling system a change of load will result in a change of output vapour quality
    - This will result in a different pressure drop in the return pipework
    - Typically in evaporative systems the pressure is defined by a remote backpressure regulator or accumulator
    - So, the evaporation temperature will change on the detector
    - Any short-term coolant flow variation will have a similar effect

ATLAS phase II positioning requirements

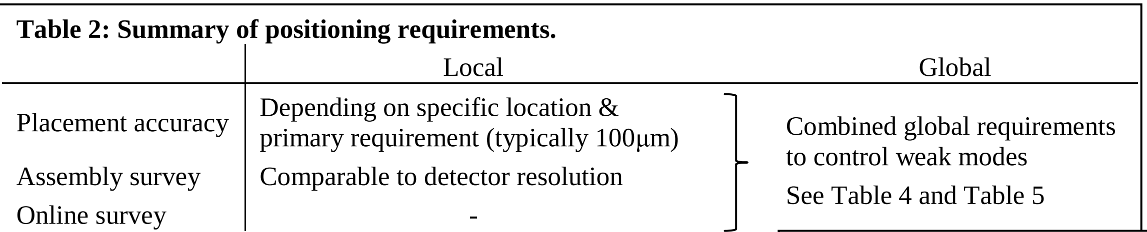


Table 2: Summary of positioning requirements.

	Local	Global
Placement accuracy	Depending on specific location & primary requirement (typically 100µm)	Combined global requirements to control weak modes See Table 4 and Table 5
Assembly survey	Comparable to detector resolution	
Online survey	-	

Stabililty

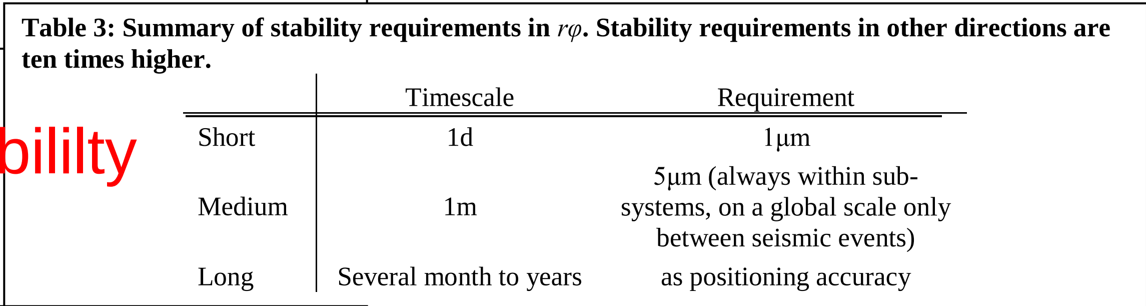


Table 3: Summary of stability requirements in $r\varphi$. Stability requirements in other directions are ten times higher.

	Timescale	Requirement
Short	1d	1µm
Medium	1m	5µm (always within sub-systems, on a global scale only between seismic events)
Long	Several month to years	as positioning accuracy

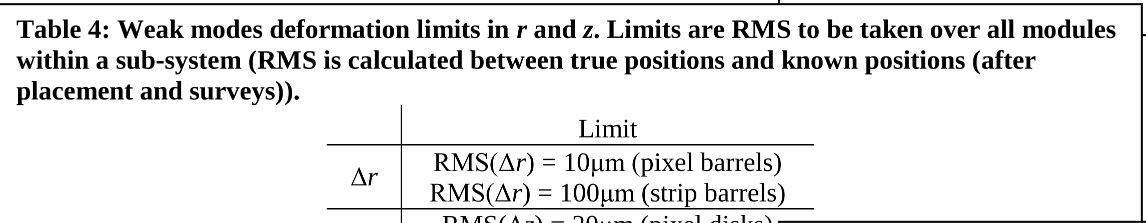


Table 4: Weak modes deformation limits in *r* and *z*. Limits are RMS to be taken over all modules within a sub-system (RMS is calculated between true positions and known positions (after placement and surveys)).

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

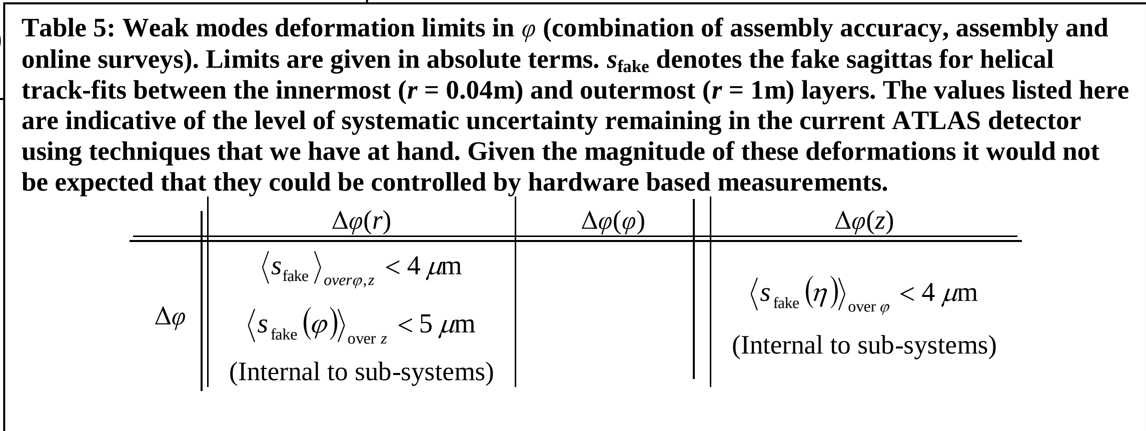


Table 5: Weak modes deformation limits in φ (combination of assembly accuracy, assembly and online surveys). Limits are given in absolute terms. s_{fake} denotes the fake sagittas for helical track-fits between the innermost (r = 0.04m) and outermost (r = 1m) layers. The values listed here are indicative of the level of systematic uncertainty remaining in the current ATLAS detector using techniques that we have at hand. Given the magnitude of these deformations it would not be expected that they could be controlled by hardware based measurements.

	$\Delta\varphi(r)$	$\Delta\varphi(\varphi)$	$\Delta\varphi(z)$
$\Delta\varphi$	$\langle s_{\text{fake}} \rangle_{over\varphi,z} < 4\ \mu\text{m}$ $\langle s_{\text{fake}}(\varphi)\rangle_{\text{over } z} < 5\ \mu\text{m}$ (Internal to sub-systems)		$\langle s_{\text{fake}}(\eta)\rangle_{\text{over } \varphi} < 4\ \mu\text{m}$ (Internal to sub-systems)

Constraints on position knowledge {placement and surveys) which alignment community thinks will help constraining weak modes

Summary

- The main tool for alignment in ATLAS is track-based alignment
  - Mechanical engineering should support it
  - Understanding between these communities is sometimes difficult
- The main requirement for track-based alignment is stability
  - Placement accuracy and assembly surveys are not critical
  - Our experience from ATLAS is that excellent stability is achievable (particularly short-term)
  - The dominant disturbances to stability on short timescales are vibrations and thermal load variations
    - Vibrations are not particularly critical as particle physics experiments are not particularly noisy environments
    - For an acceleration spectral density of 10-7 g2/Hz the first resonance frequency needs to be above 50 Hz to achieve a stability of 1µm (but not because it's line frequency…)
    - Deformations due to thermal load variations should be addressed at the source
      - Equalize front-end power consumption
      - Build stable cooling system