Tracker mechanics

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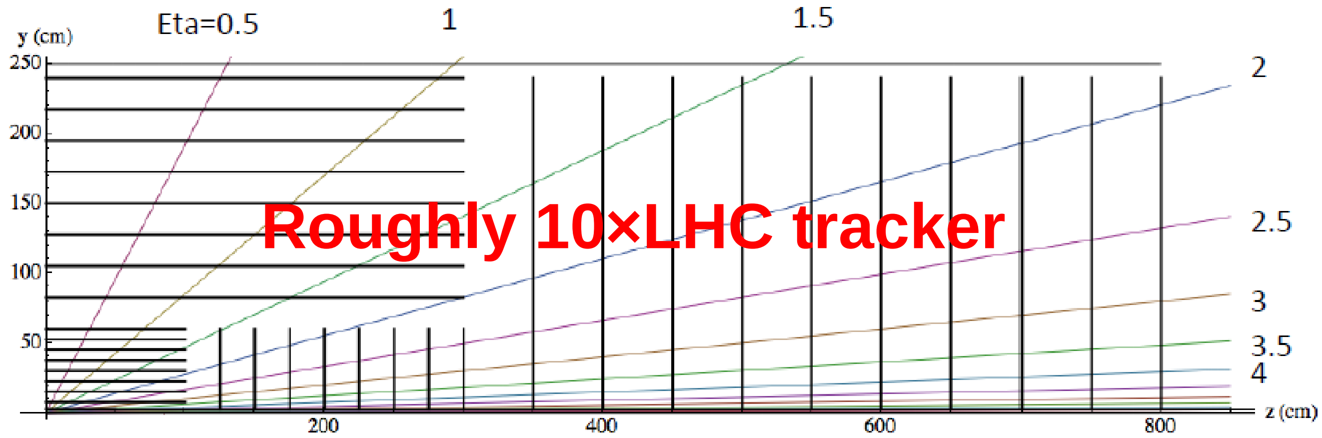
Starting points

- Here:
  - Tracker = tracking + vertexing
  - Mechanics = structures + cooling + services
- I'm a member of the ATLAS collaboration – experiences are ATLAS-biased
  - But from communication with friends in other experiments I think that many of my views are shared
- I will focus on a future hadron experiment
  - Naïve assumption that this will be the most challenging
  - I will not specifically talk about very forward (dipole) tracking

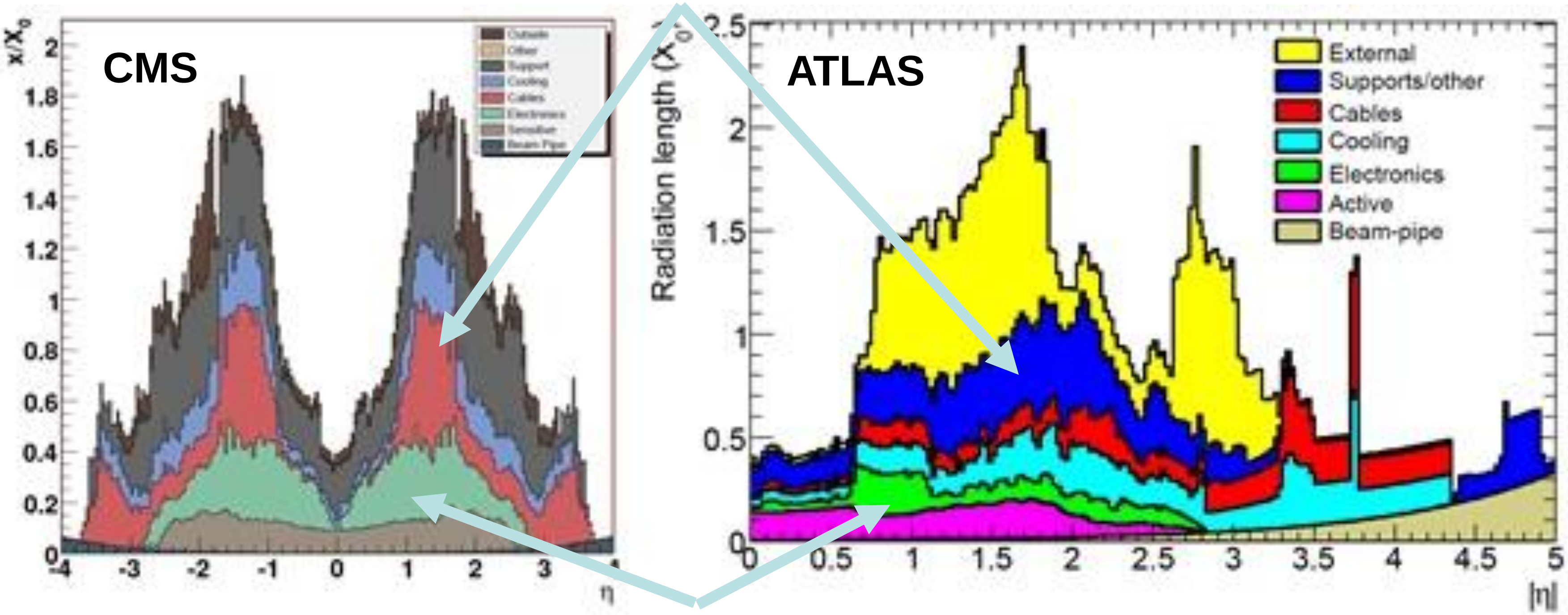
Requirements for a FCC-hadron experiment



- Detector characteristics used in simulations:
  - Material: 3% X/X_0 per layer using a detector 0.43 cm thick composed as: 20% Si, 42% C, 2% Cu, 6% Al, 30% Plastic
  - Sensor thickness: pixels 100 µm, strips 200 µm
    - This is 0.1(0.2)% X_0 – would be clearly mismatched
  - Resolution per layer: 25 µm (rφ)
- Not yet specified
  - Sensor size: Experience shows that (in outer layers) bigger is better, whatever fits on a 200 mm wafer?
  - Little is known about front-end electronics power or leakage power

Material

Cables + cooling + supports



Active + electronics

- Mechanics contributes about half of the material in barrel, and even more in forward
- Future trackers will have significantly less material in active material + electronics
- Naively there appears to be a trade-off material vs size of tracker

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{0.0136}{0.3\,BL(\eta)}\sqrt{\frac{x}{X_0}(\eta)}$$

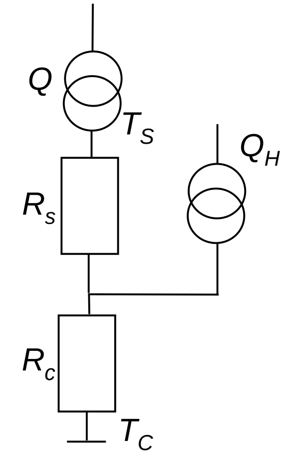
Thermal Management

- Two purposes:
  - Remove heat generated on the detector (→ power)
    - Typically dominated by front-end electronics
    - Defines required coolant power and cooling pipe dimensions
  - Keep detectors cold to limit leakage currents (thermal stability, noise, HV power) (→ temperature)
    - Given by radiation damage (leakage power @ reference temperature), but also thermal impedance between coolant and sensor, and front-end power)
    - Defines required coolant temperature
- Current state-of-the-art in hadron collider experiments is evaporative cooling with CO_2
  - Typical cycle in HEP is 2PACL (2-phase accumulator controlled loop)
    - Evaporation pressure is set in accumulator
    - Coolant is driven through circuit by (sub-cooled) pump
  - Coolant temperature limited by freezing point of CO_2 (-55°C) + temperature margins in the plant + pressure drops in evaporators and return pipes
  - Currently pushing technology to evaporation temperature of -35°C for LHC phase II
  - Lower temperatures might require alternative coolants (N_2O, C_2F_6)
- For low power applications gas cooling is an alternative
  - Key difficulty is design and reliable prediction of performance

What drives the cooling temperature

- Minimal model (Beck&Viehhauser, NIM 618 p.131):
- Simple model assuming isothermal sensor
  - Can be solved analytically
  - Use leakage power scaling

$$Q(T_S) = Q_{ref}\left(\frac{T_S}{T_{ref}}\right)^2 \exp\left(T_A\left(\frac{1}{T_{ref}} - \frac{1}{T_S}\right)\right)$$ with $T_A = 1.2\text{eV}/2k_B$



  - Maximum coolant temperature for thermal stability

$$T_{C,crit} = T_{S,crit}\left(1 - \frac{T_{S,crit}}{T'_A}\right) - R_c Q_H$$ with $$T_{S,crit} \approx \frac{T_{ref}}{1 - \frac{T_{ref}}{T_A}\ln\left(\frac{T_{ref}^2}{(R_S + R_C)Q_{ref}T'_A}\right)}$$

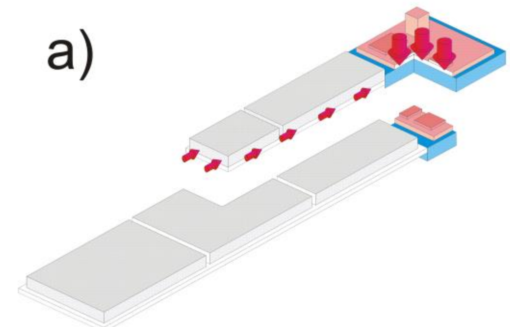
and $T'_A = T_A + 2T \approx T_A + 500K$

- So, keep leakage and electronics power and thermal impedances low

Cooling topologies

- To keep thermal impedance low we need good thermal connection of local sink (coolant) and source (sensors)
- Geometrically this means getting the sink as close as possible to the sensor
- Historically this has led to a developmen from
  - Ladders with cooling at the end, to
  - Cooling pipe along sensor edge(s), to
  - Cooling pipe embedded in structure underneath sensor, to
  - Multiple pipes underneath sensor (microchannels)

a)



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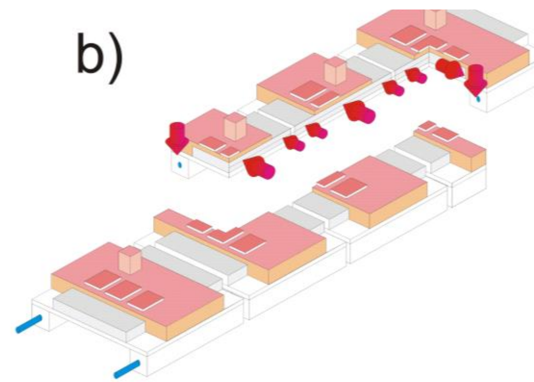

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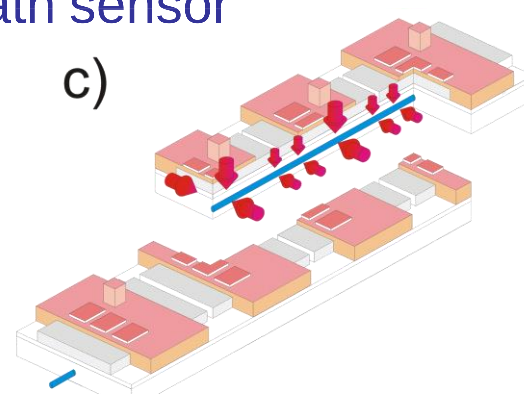

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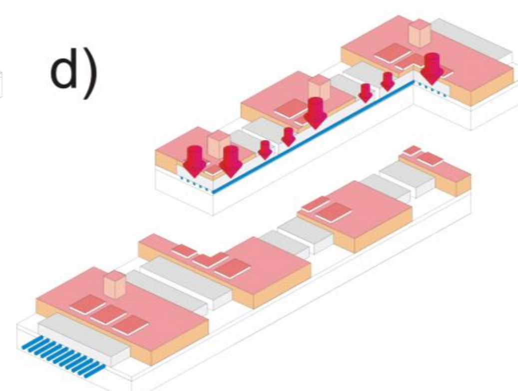
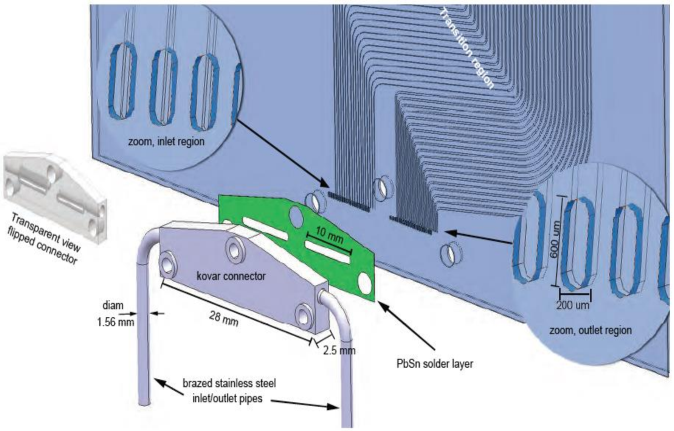
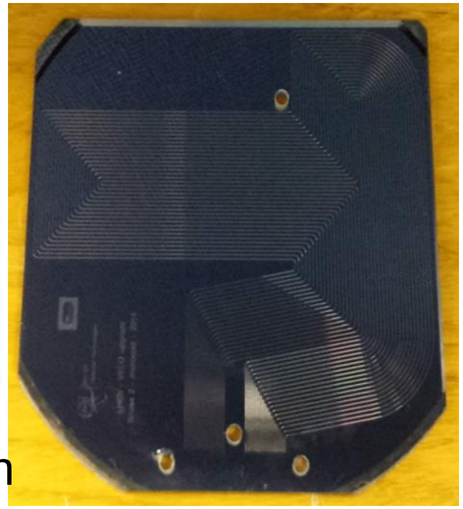


Microchannels

- Very actively investigated for next generation vertex systems
  - Microchannels in Silicon:
    - high strength, small size, same thermal expansion as sensor,
    - but limited in size → large number of interconnects, appears only practical for inner radii
  - PEEK pipes (ID 300 μm)
  - Microchannels in Kapton:
    - can be large area, flexible (can follow non-planar geometries), low material,
    - but probably limited in pressure
- Fluence at the FCC is likely to significantly exceed LHC (phase II) fluences
  - Leakage currents need to be understood, but if they are also larger then the good thermal contact provided by microchannels might be required everywhere

Microchannels

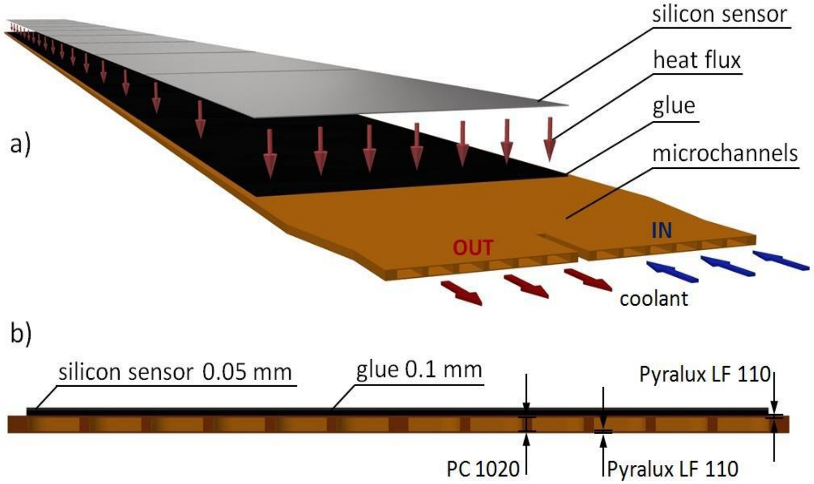




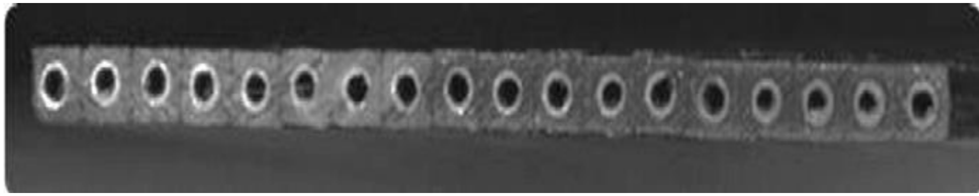
LHCb ‘Snake 2’ prototype - Silicon

ATLAS ITS - Silicon

ATLAS ITS - Kapton



SuperB Vertex detector – PEEK tubes



Structural requirements

- Position of sense elements to be reconstructed by track-based software alignment (TBA)
  - Task of mechanics is to support this as much as possible
- Consequences
  - Placement is uncritical (O(100µm))
    - Maintain clearances and overlaps
  - Knowledge of position (survey, hardware alignment, placement) can be useful to reduce number of degrees of freedom
    - Most practical for local supports
  - Key requirement is stability (O(few µm))
    - Over periods required to accumulate tracks for TBA
    - Definition of stability requires specification of loads

Structural loads

Load type		Control
Vibrations	External	Typically low ($<10^{-7}$ g^2/Hz)
	Internal (e.g. cooling flow)	Load should be kept small by design of cooling
Thermo-mechanical loads	Electrical power fluctuations	Load should be kept small by design of electronics
	Cooling system T variations	Load should be kept small by design of cooling
Seismic shocks	Magnet ramps, power cuts etc.	Start new alignment period
Humidity variations		Low and slow in controlled environment
Long-term relaxation and creep		Slow

- External loads are usually low or can be isolated/dampened
- Internal loads should be kept small by design
- Resulting stiffness requirements should be moderate (significantly less than first mode frequency of 50 Hz)
  - Potential to aggressively optimize material against stiffness

How to achieve stiffness

- Beam eigenfrequencies:

$$f_n = \frac{1}{2\pi}\omega_n = \frac{\kappa_n^2}{\pi^2}\sqrt{\frac{EI}{\lambda}}$$

- RMS deflection under external vibration

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

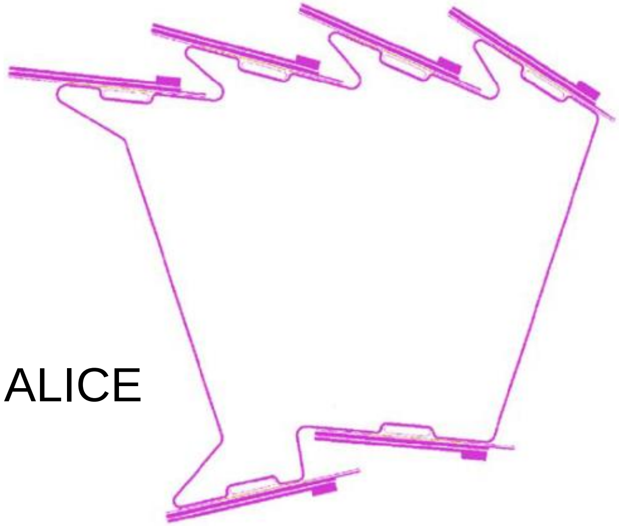
Miles' equation

κ_n	of order unity (depending on boundary (support) conditions)
λ	mass per unit length
E	Young's modulus
I	Moment of inertia
ASD	Acceleration spectral density of vibration
Q	Quality (reciprocal of damping)

- Traditional ladder/stave geometry has poor moment of inertia
- Cylindrical support structures are good but
  - Stiffness limited by hoop stiffness (can be addressed by local stiffeners)
  - For outer layers become very large objects – unwieldy in integration
- Recently local support geometries are being developed which try to achieve a compromise
  - High moment of inertia + compact size
  - Currently only for vertex systems

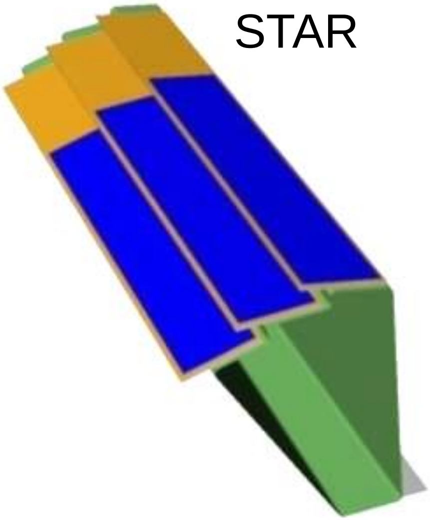
High-moment-of-inertia local supports

ALICE



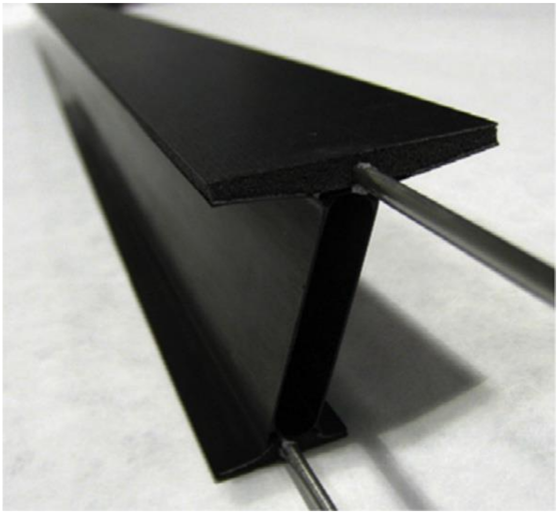
doi:10.1016/j.nima.2006.04.093

STAR



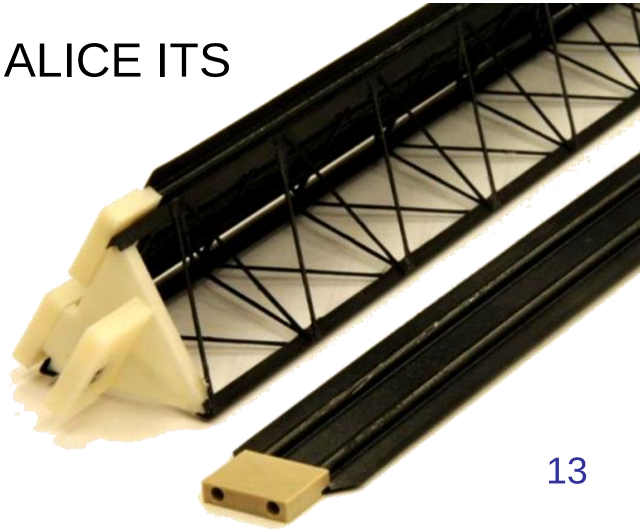
doi:10.1016/j.nima.2010.12.006

ATLAS upgrade



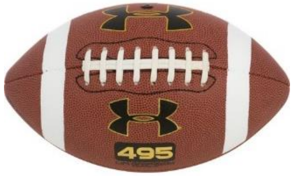
doi:10.1016/j.nima.2013.07.005

ALICE ITS



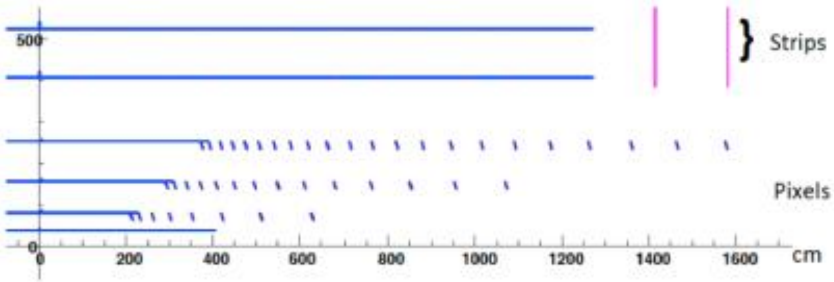
Minimal area geometries

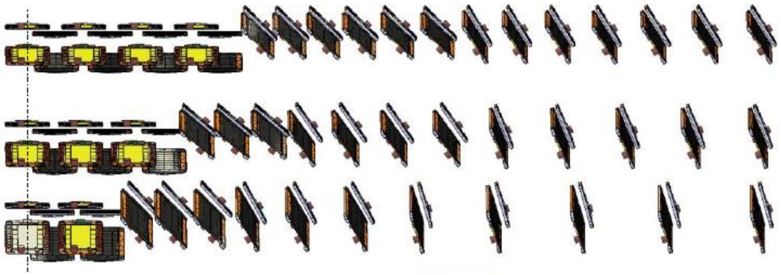
- Traditionally tracker layout consist of cylindrical barrels and disk-shaped endcap
- In terms of material the optimal shape for full coverage would be a football
  - Smaller area → less material (perpendicular incidence), less power, lower costs

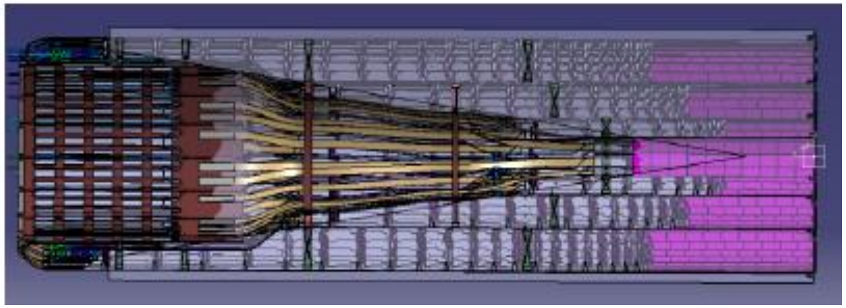


  (Note that this also would be an ideal shape in terms of stiffness)
- Recently designs are being developed for inclined sensor geometries
  - Both, on linear and ring geometries
  - One of the biggest challenges in these geometries is service connection, in particular the cooling contact
- Note that this leads to either
  - Moulded 3d CF structures
  - Spaceframes
  - Where the latter probably has the potential for less mass, but becomes joint-limited
- Currently one of the limitations for the optimization of these geometries appears to be rigid detector simulation codes

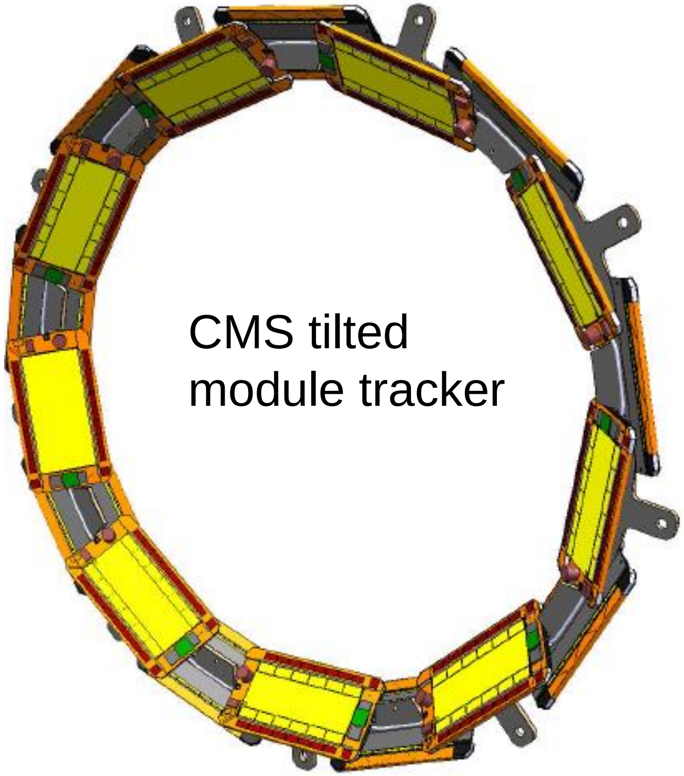
Tilted module supports



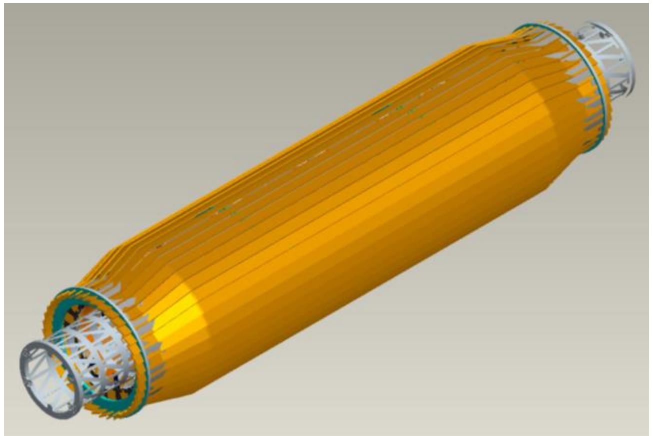




ATLAS Alpine pixels



CMS tilted module tracker



ATLAS I-beams with tilted ends

Services

- Integration of services into support structures can save material and increase compactness
  - Kapton/Cu or Kapton/Al flex circuits co-cured with CF sheets
  - Cables enclosed in hollow structural elements
  - Cooling pipes as structural elements
    - Carbon fibre pipes
    - Metal 3d printing
- It should be noted that optical conversion on the detector will be excluded by dose levels
  - Need to develop low-mass high-speed data links and work on their integration

Modularity

- To limit time needed for integration and access modularity must be designed into the system from the beginning
- Modularity here means
  - Each component needs to be contained, with simple interfaces to the rest of the system
  - 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 – sub-systems - tracker etc.

Conclusions

- The optimal tracker mechanics will depend on various inputs – close communication with other aspects of the project are essential

Input	Interaction with
Installation and access scenarios	
Layout (using inclined sensor geometries)	Tracking performance community
Material of sensor and electronics	Sensor and electronics community
Power (electronics and leakage)	
Stability requirements from track-based alignment	Alignment community

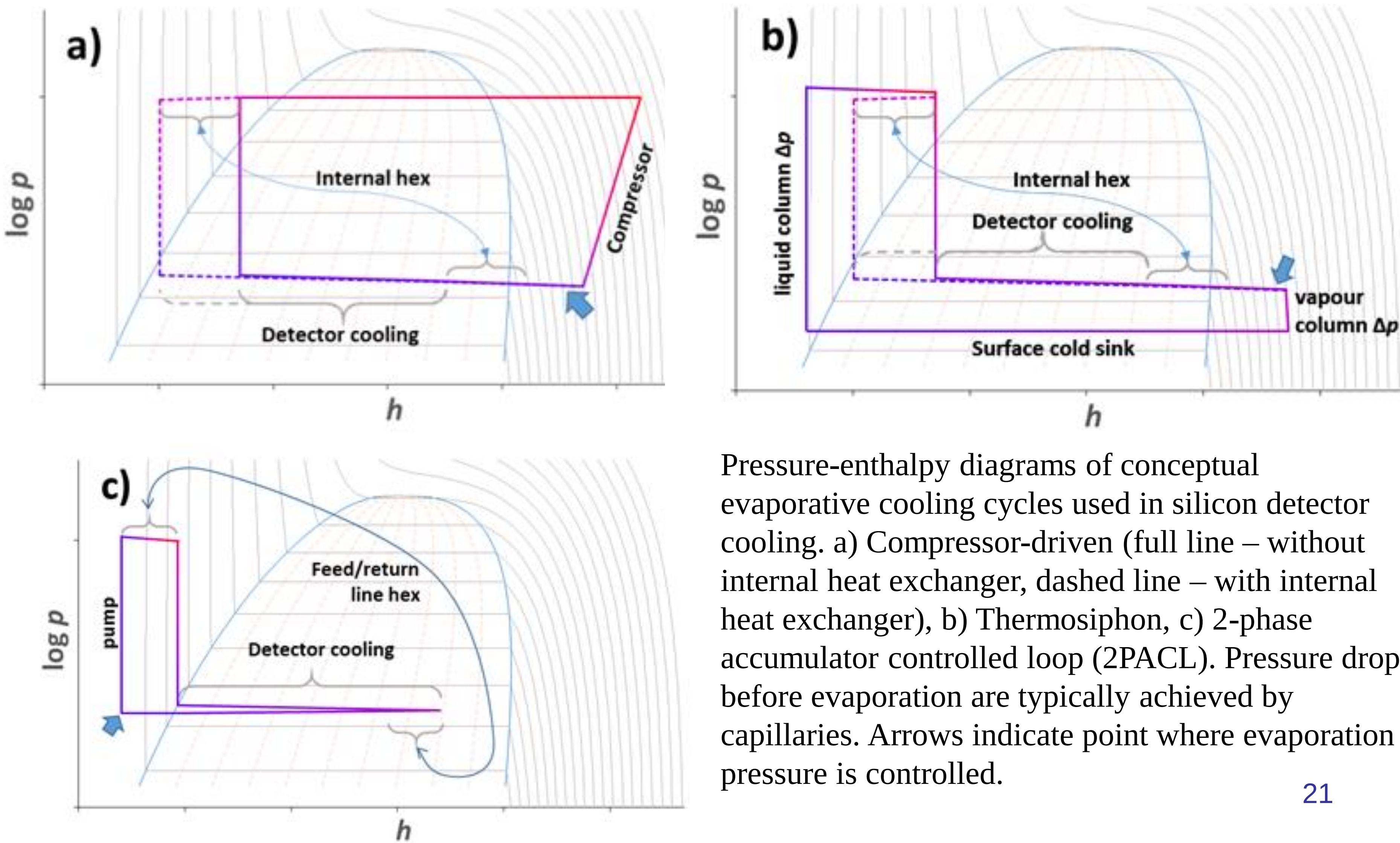
  – It should be noted that the communication needs to be two-way, i.e. tracker mechanics also needs to provide guidance/limitations for other aspects
- The goal must be to aggressively reduce tracker material compared to current and imminent tracker designs
  – I think there is a lot of potential for doing this

LHC tracker mechanics

Future tracker mechanics

Further Material

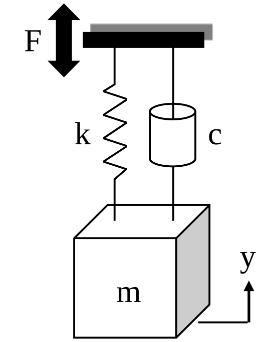
Cooling cycles in HEP



Pressure-enthalpy diagrams of conceptual evaporative cooling cycles used in silicon detector cooling. a) Compressor-driven (full line – without internal heat exchanger, dashed line – with internal heat exchanger), b) Thermosiphon, c) 2-phase accumulator controlled loop (2PACL). Pressure drops before evaporation are typically achieved by capillaries. Arrows indicate point where evaporation pressure is controlled.

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

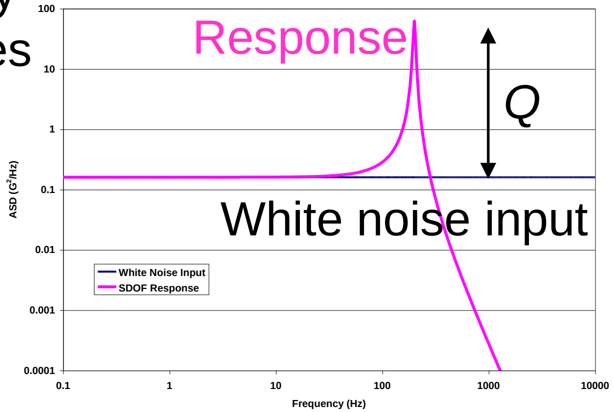
$$a_{RMS} = \sqrt{\frac{\pi}{2} ASD \cdot f_0 \cdot Q}$$

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

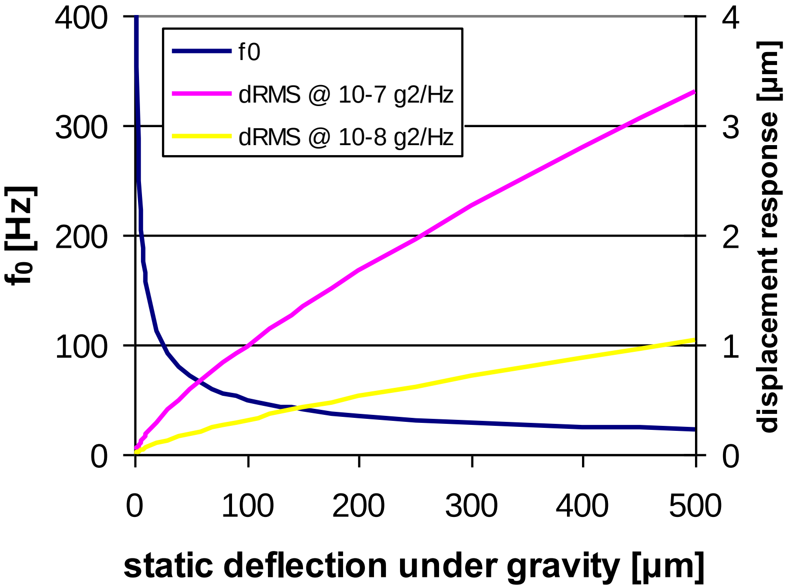
1d oscillator response

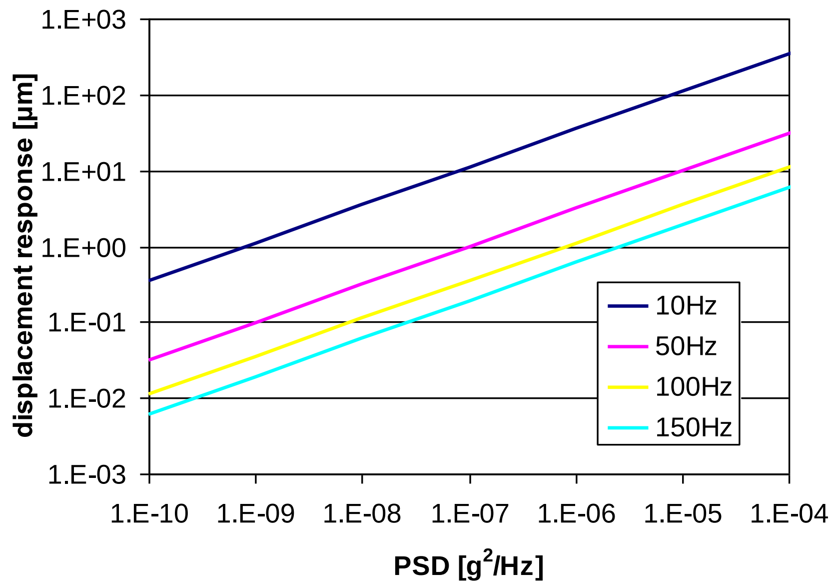


- For purposes of order of magnitude estimates this will also apply for 3d objects, although one needs to watch out for coincidences of structural resonances and peaks in the ASD spectrum

Displacement response to vibration

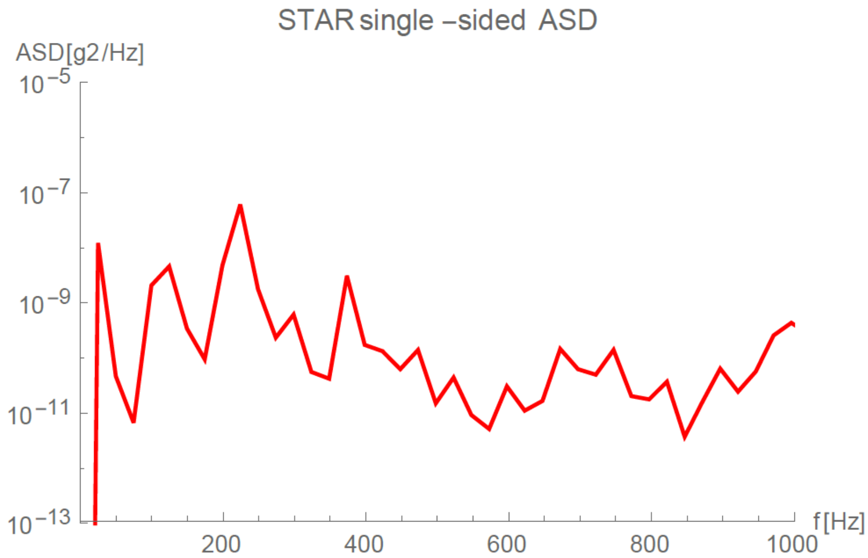
Displacement response $$\delta_{RMS} = \left(\frac{1}{2\pi f_0}\right)^2 a_{RMS} = \sqrt{\frac{ASD \cdot Q}{32\pi^3 f_0^{\ 3}}} = \frac{\sqrt{ASD \cdot Q}}{2}\left(\frac{\delta_{grav}}{g}\right)^{3/4}$$

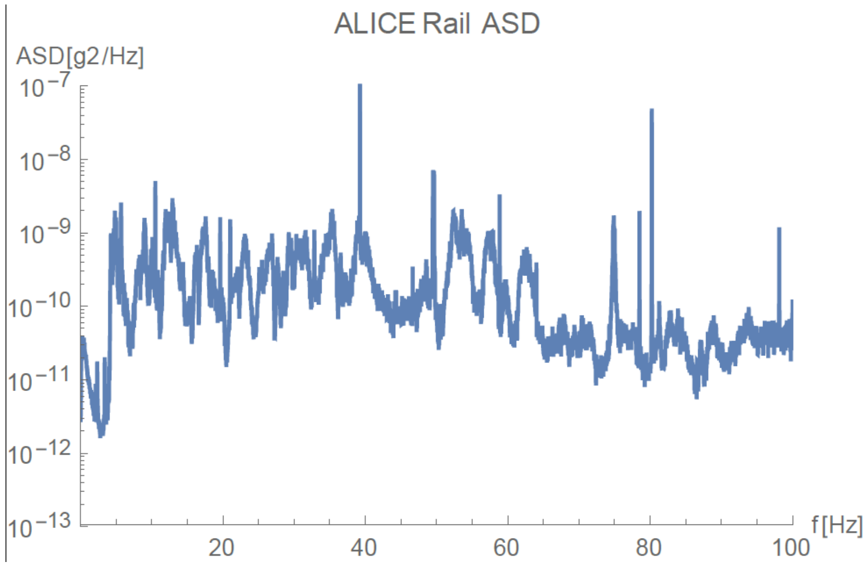


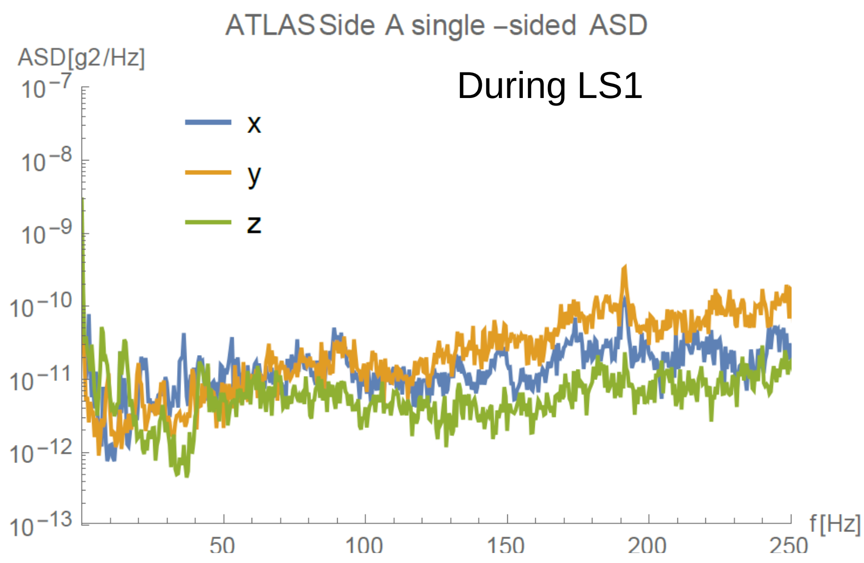


- To maintain a displacement response of 1 µm for an ASD of 10^{-7} g^2/Hz the first mode needs to be at 50 Hz (assuming Q=12.5)
  - This would be equivalent for a static gravitational sag of about 100µm (1d)

Vibration spectra in experiments







- Currently installing continuous readout of 2×3 accelerometers in ATLAS
  - Should give us large statistics as well as accelerations due to seismic shocks

Further reading

- Talks at the Forum for Tracking Detector Mechanics – 2015 - 2014 – 2013 – 2012
- P. Petagna, *Past Experiences and Future Trends on Vertex Detector Cooling at LHC*, PoS(Vertex 2013)037
- G. Viehhauser, Thermal management and mechanical structures for silicon detector systems, 2015 *JINST* **10** P09001