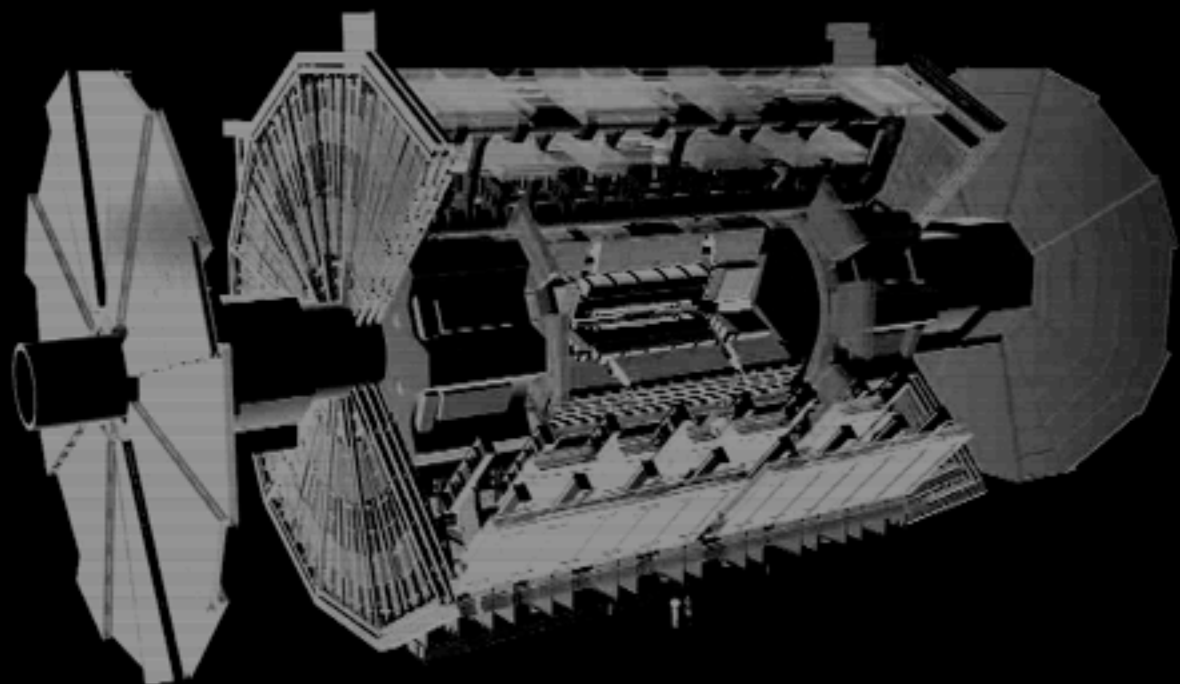
Alignment of the ATLAS Inner Detector



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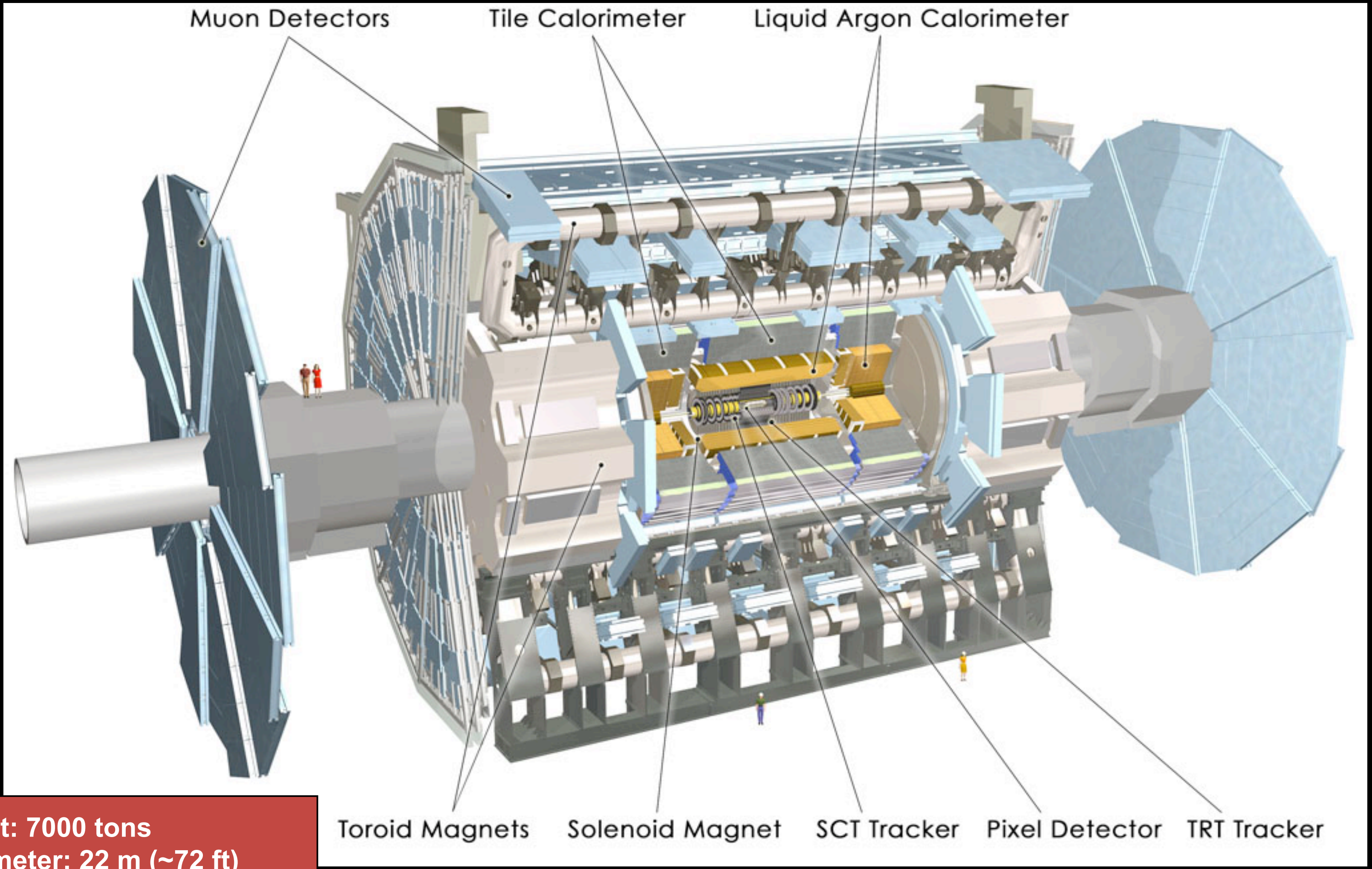
The University of Melbourne
On behalf of the ATLAS Inner Detector Alignment Group

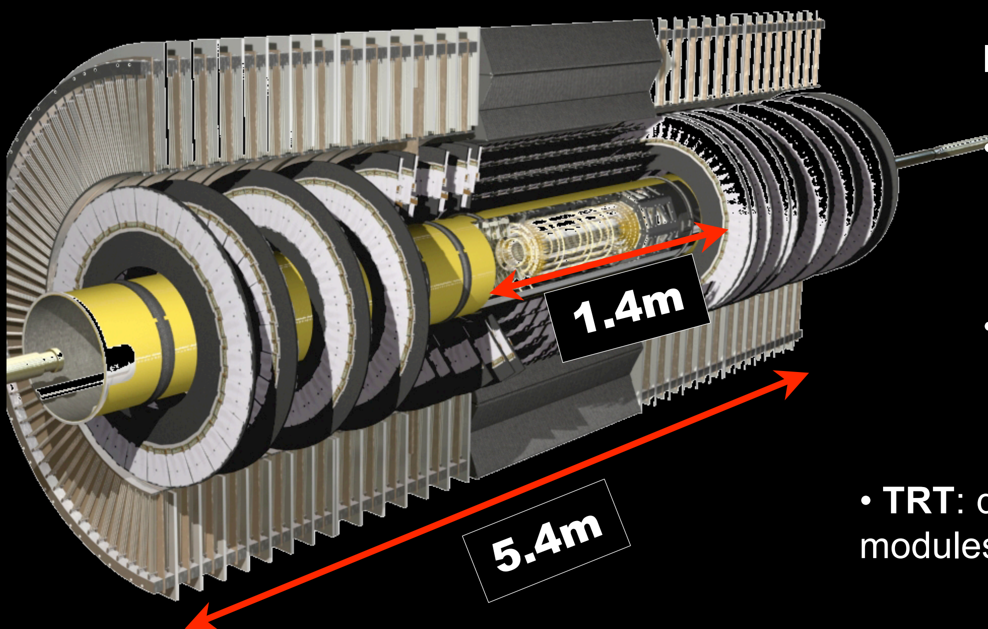
FD07 27-29 June 2007 Florence, Italy

ATLAS



- Total Weight: 7000 tons
- Overall Diameter: 22 m (~72 ft)
- Overall Length: 45 m (~148 ft)
- Magnetic field (solenoid): 2 Tesla

ATLAS Inner Detector



Inner Detector:

- **PIXEL:** Silicon pixel detectors
  Pixel size 50x400µm
  Intrinsic Resolution:
  Local X ~14 µm
  Local Y ~115 µm

- **SCT**: Silicon strip detectors
  80µm strip pitch,
  40mrad stereo angle
  Intrinsic Resolution:
  Local X ~23 µm
  Local Y ~580 µm

- **TRT**: drift-tube system. Limited granularity (barrel modules, end cap disks)

Current Alignment Strategy:

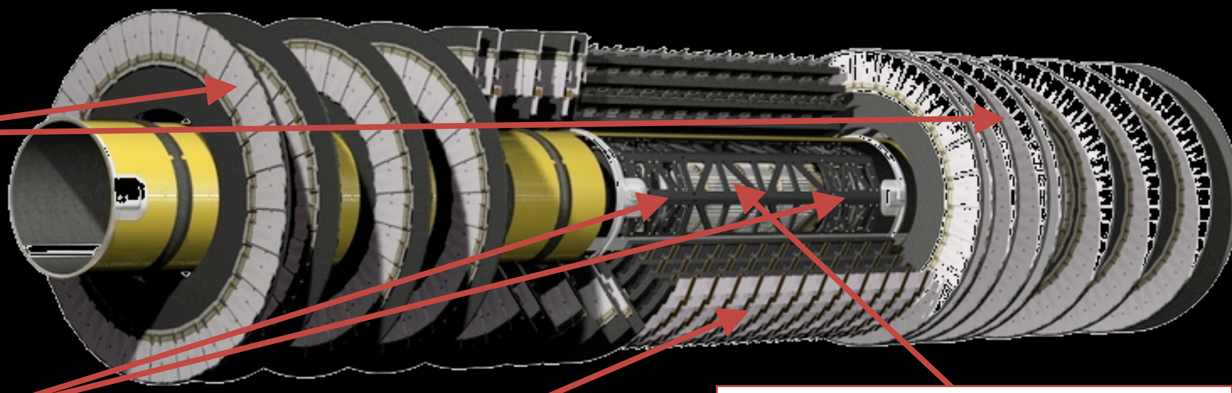
1. Perform full alignment of the silicon
2. Align TRT modules using tracks from the newly aligned silicon

Alternative (under consideration):

1. Do a combined simultaneous alignment of both subsystems (TRT can help to constrain momentum)

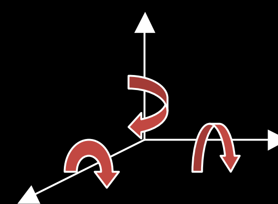
The ATLAS Silicon Detector

ATLAS Silicon Detector:



	Barrel		End Cap	
Detector	PIXELs	SCT	PIXELs	SCT
Layers/disks	3	4	2x3	2x9
Modules	1456	2112	2x144	2x988
Subtotal	3568		2264	
Total	**5832**			

3 translations
& 3 rotations
of each module



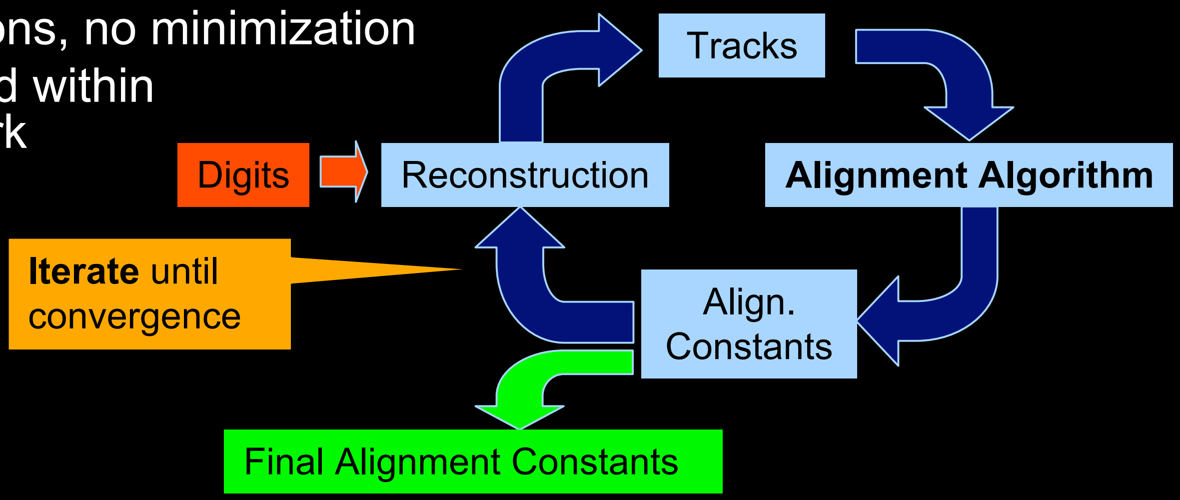
In total we have to deal with 34,992 DOF!
The challenge is to align the detector daily to ensure we have accurate results

ATLAS ID Alignment

- Alignment is determination of the position and orientation of the detector components.
  - Initially required due to finite accuracy of the detector assembly
  - Also required to account for detector deformation due to temperature, magnetic field, material load
- Sources of knowledge for alignment
  - Assembly knowledge: construction precision and surveys, for initial position corrections and errors (~100μm SCT, ~30μm Pixel)
  - Online monitoring and alignment: lasers, cameras, before and during runs
  - Offline track-based alignment: using physics and track residual information (~10um, below the intrinsic resolution of the detector)
  - Offline monitoring: using physics, track and particle ID parameters
- The use of all possible sources of information is vital to ensure the alignment of your detector is optimal

ATLAS ID Track-based Alignment

- Intrinsic alignment of Silicon and TRT, Si+TRT, all rely on minimizing residuals
- Global χ^2:
  - minimization of χ^2 fit to track and alignment parameters
  - 6 DoF, correlations managed, small number of iterations
  - Inherent challenge of large matrix handling and solving
- Local χ^2 :
  - similar to global χ^2 , but inversion of 6x6 matrix/module
  - 6 DoF, no inter-module or MCS correlations
  - large number of iterations
- Robust Alignment:
  - Centre residuals and overlap residuals
  - 2-3 DoF, many iterations, no minimization
- All algorithms implemented within ATLAS software framework and share common tools
- Able to add constraints from physics & external data



The Global χ^2 Approach

Method consists of minimizing a giant χ^2 resulting from a simultaneous fit of all particle trajectories and alignment parameters:

$$\chi^2 = \sum_{tracks} r^T V^{-1} r$$

$$r(\pi, a, m)$$

r = residuals
V = covariance matrix
π = track parameters
a = alignment parameters
m = measurement

Use the linear expansion (assume all second order derivatives negligible).

$$\frac{d\chi^2}{d\pi} = 0 \rightarrow \quad \pi = \pi_0 + \delta\pi = \pi_0 - \left(\frac{\partial e^T}{\partial \pi_0} V^{-1} \frac{\partial e}{\partial \pi_0} \right)^{-1} \frac{\partial e^T}{\partial \pi_0} V^{-1} r(\pi_0, a)$$

$$\frac{d\chi^2}{da} = 0 \rightarrow \quad \left(\sum_{tracks} \frac{dr^T}{da_0} V^{-1} \frac{dr}{da_0} \right) \delta a + \sum_{tracks} \frac{dr^T}{da_0} V^{-1} r(\pi_0, a_0) = 0$$

Key relation!

$$\frac{dr}{da} = \frac{\partial r}{\partial a} + \frac{\partial r}{\partial \pi} \frac{d\pi}{da}$$

Alignment Parameters are given by:

$$\delta a = - \underbrace{\left(\sum_{tracks} \frac{\partial r^T}{\partial a_0} W \frac{\partial r}{\partial a_0} \right)^{-1}}_{\mathcal{M}} \underbrace{\sum_{tracks} \frac{\partial r^T}{\partial a_0} W r(\pi_0, a_0)}_{\mathcal{V}}$$

Where

$$W \equiv V^{-1} \hat{W} \equiv V^{-1} - V^{-1} E (E^T V^{-1} E)^{-1} E^T V^{-1}$$

$$E = \frac{dr}{d\pi_0}$$

Similar approach to Millipede at CMS

χ^2 Invariant Modes

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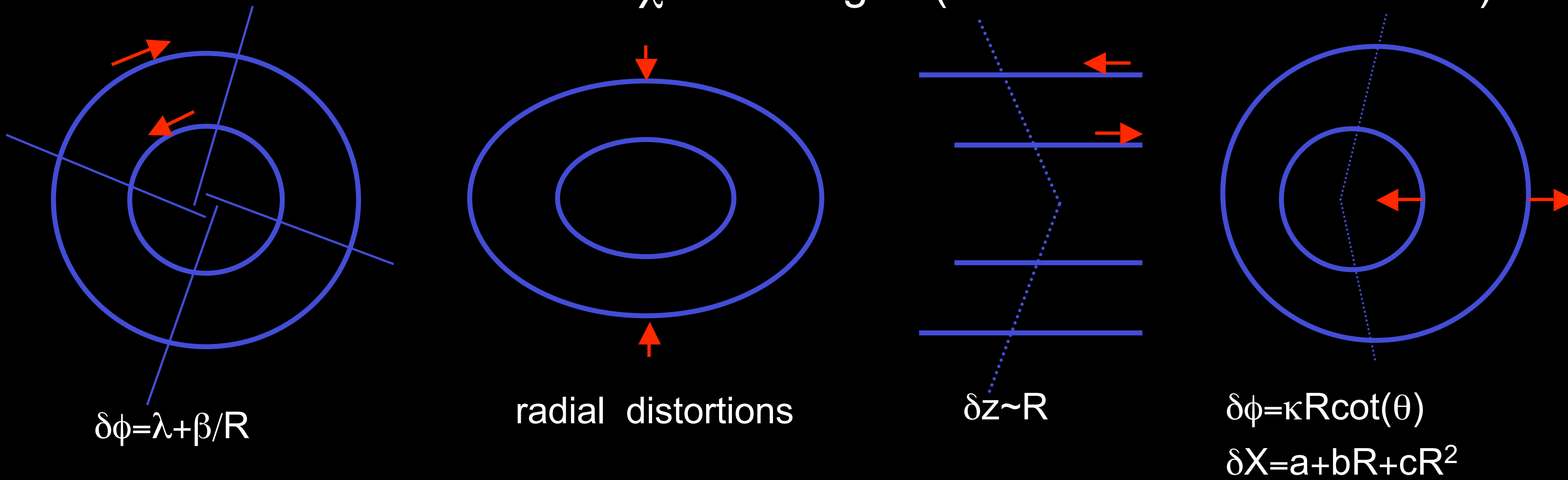
Certain transformations leave χ^2 unchanged (the so called weak modes).

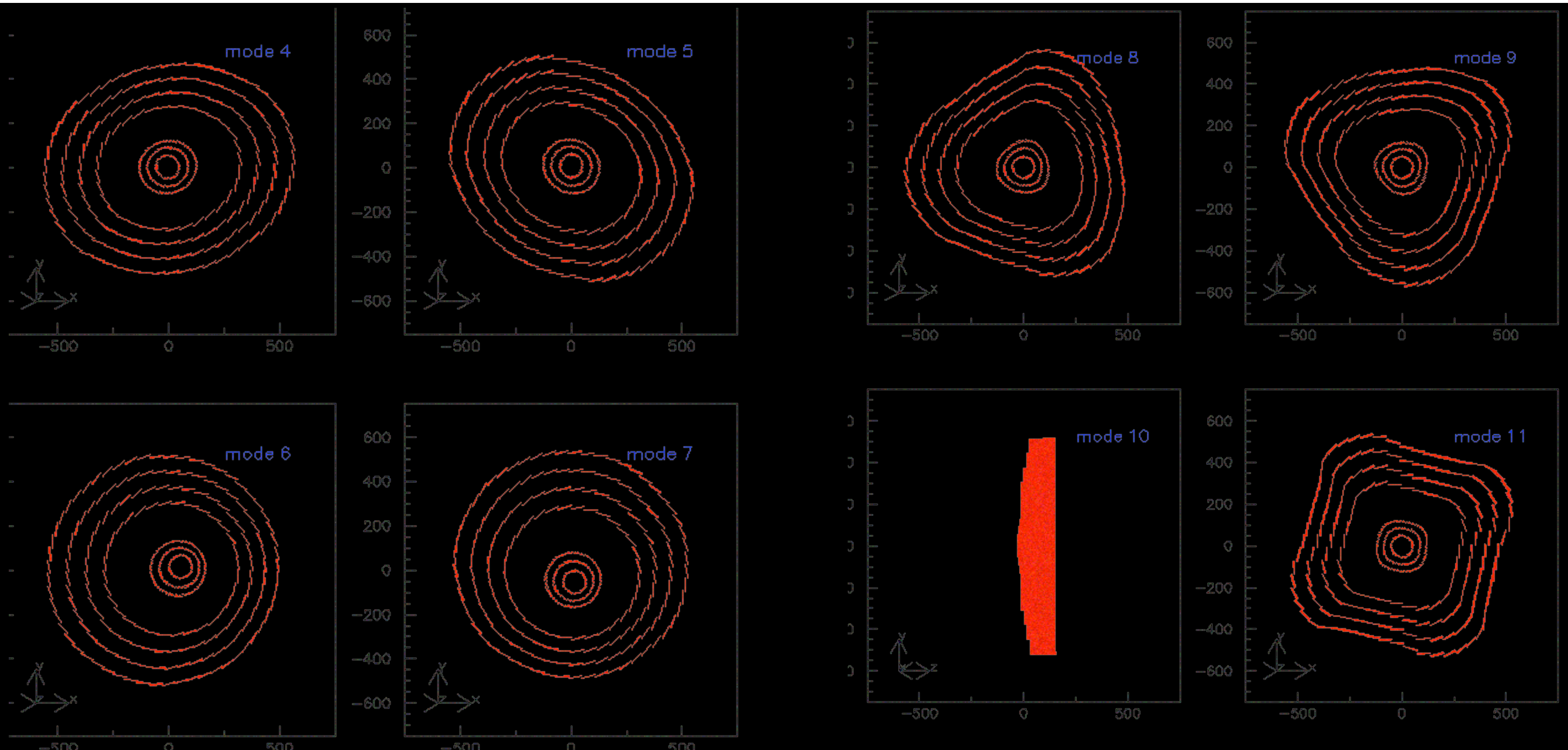


Need tools to tackle these such as:

- Requirement of a common vertex (VTX constraint),
- Constraints on track parameters or vertex position (external tracking, calorimeters, resonant mass, ...)
- Off-beam axis tracks (cosmic tracks, beam halo)
- External constraints (hardware systems, mechanical constraints, …).

Easily incorporated in the algorithms (for ex, global χ^2)

More on Weak Modes



- Weak modes contribute to the lowest part of the eigenspectrum.
- These deformations lead directly to biases in physics (systematic effects).
- Understanding these effects is of the utmost importance

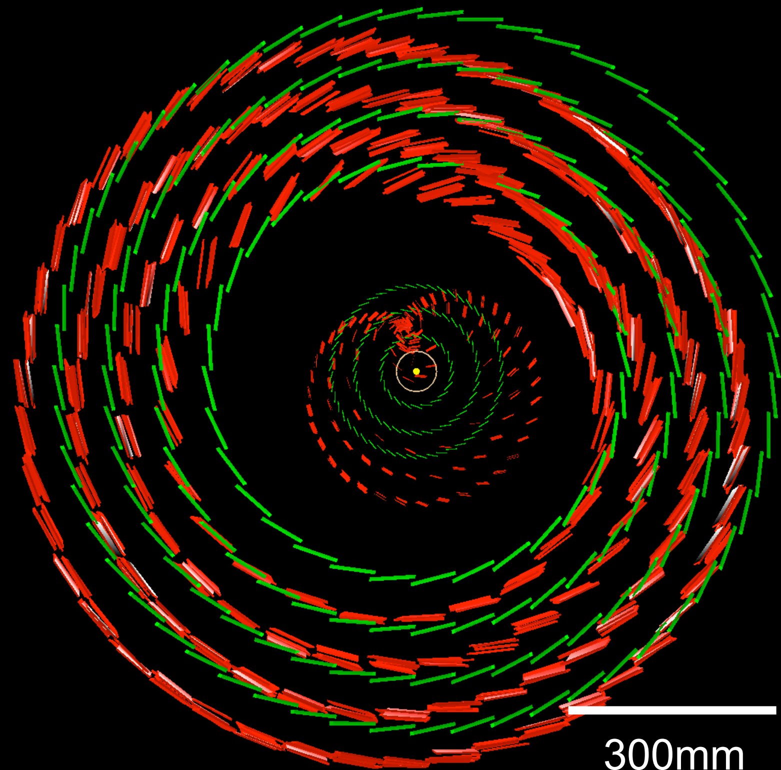
Solving Large Degrees of Freedom

- ATLAS Inner Detector has a large system to solve (35k DoF)
- Limiting factors:
  - **Size:** Full ID needs ~8GB for handling the alignment matrices
  - **Precision:** Matrices can have large condition numbers
  - **Execution time:** Single-CPU machines with non-optimized libraries take days
- Currently solving using
  - 64-bit parallel computing
    - Solving full pixel subsystem (12.5k DoF) on 16 nodes takes only 10mins (~7hrs on a single cpu,diagonalisation)
  - Single CPU solutions possible
    - already implemented MA27 in Athena: takes 24 sec for 12.4k DoF and for the full 35k DoF less than 10mins,
    - Other techniques tested …. Many solvers produce similar results

ATLAS CSC Challenge

- Misalign the whole detector quite badly
- Assuming no knowledge of the misalignments try to align your detector
- Aim to test performance and understand needs for real data conditions

LEVEL 1 TRANSFORMS						
System	X	Y	Z	Alpha	Beta	Gamma
Pixel detector	-0.60	+1.05	+1.15	-0.10	+0.25	+0.65
SCT Barrel	-0.70	+1.20	+1.30	+0.10	+0.05	+0.80
SCT Endcap A	-2.10	-0.80	+1.80	-0.25	0	-0.50
SCT Endcap C	-1.90	+2.00	-3.10	-0.10	+0.05	+0.40



Nominal Detector

Misaligned Detector (Distortions x50)

Level of applied misalignments:

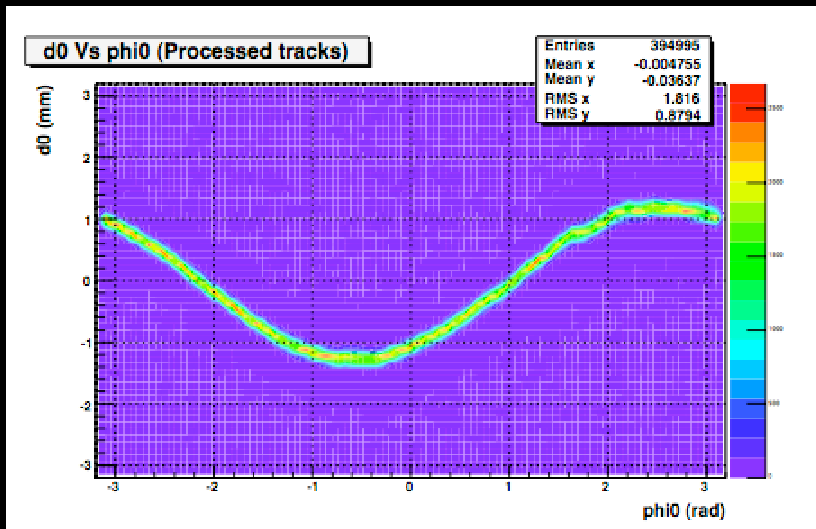
- Modules = Level 3
- Layers = Level 2 (barrel layers or disks)
- Subdetectors = Level 1 (whole barrel or EC)

From detector assembling and installation:

Misalignments largest on L1 and smallest on L3

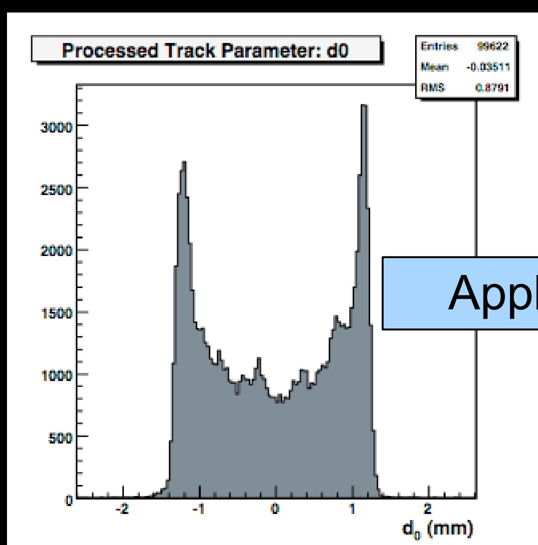
⇒ Alignment strategy: L1 ⇒ L2 ⇒ L3

A taste of the CSC

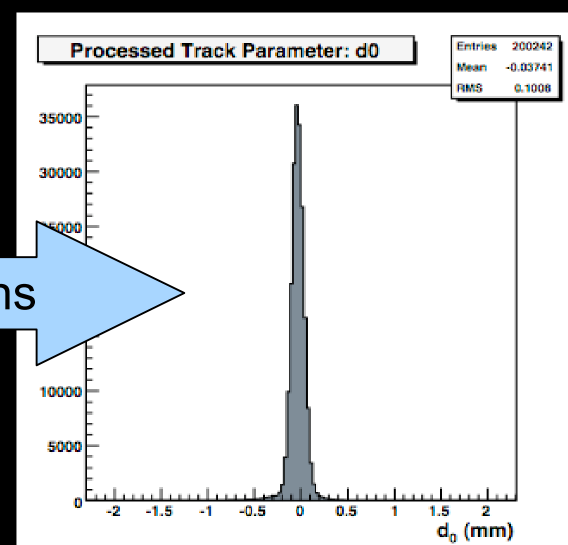


$$d_0 = x_0 sin\phi_0 - y_0 cos\phi_0$$

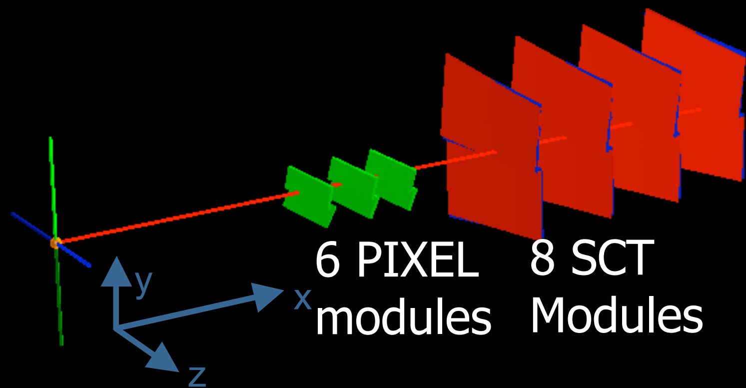
	Fit (mm)	Pixel CSC level 1 (mm)
x0	0.660	0.60
y0	1.042	1.05



Apply Corrections



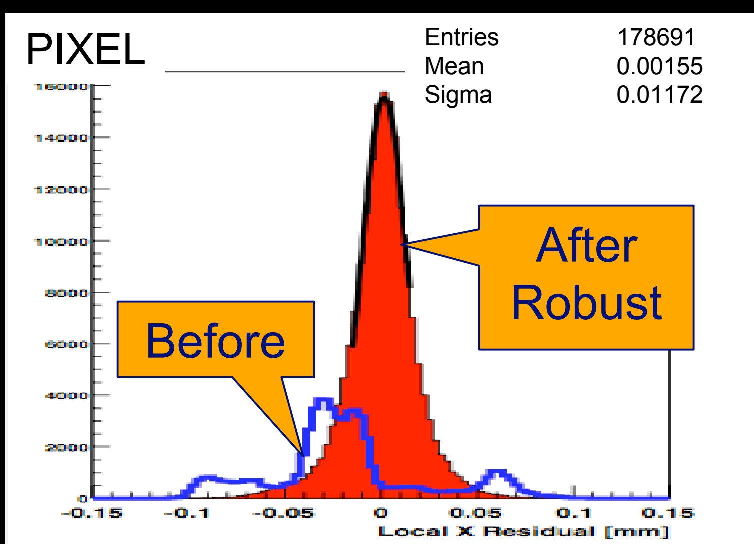
ATLAS ID Alignment: CTB Performance

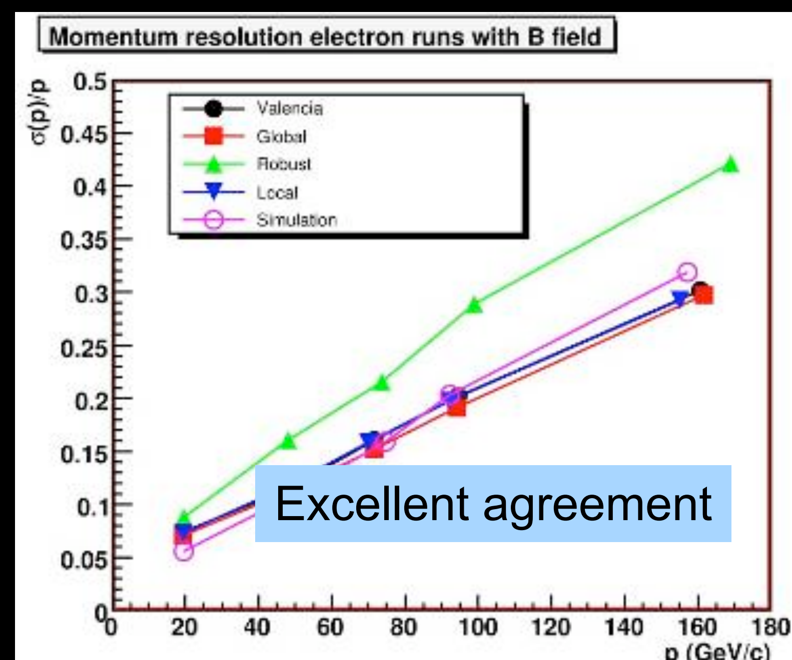


First real data from ID at H8 beam in 2004

- Large statistics of e^+/e^- and π (2-180 GeV)
- B-field on-off runs
- Results from various algorithms have been combined: reached an alignment precision sensitive to effects of a few microns!

Overall residual resolution obtained:
Pixel residual sigma ~10μm,
SCT ~ 20μm





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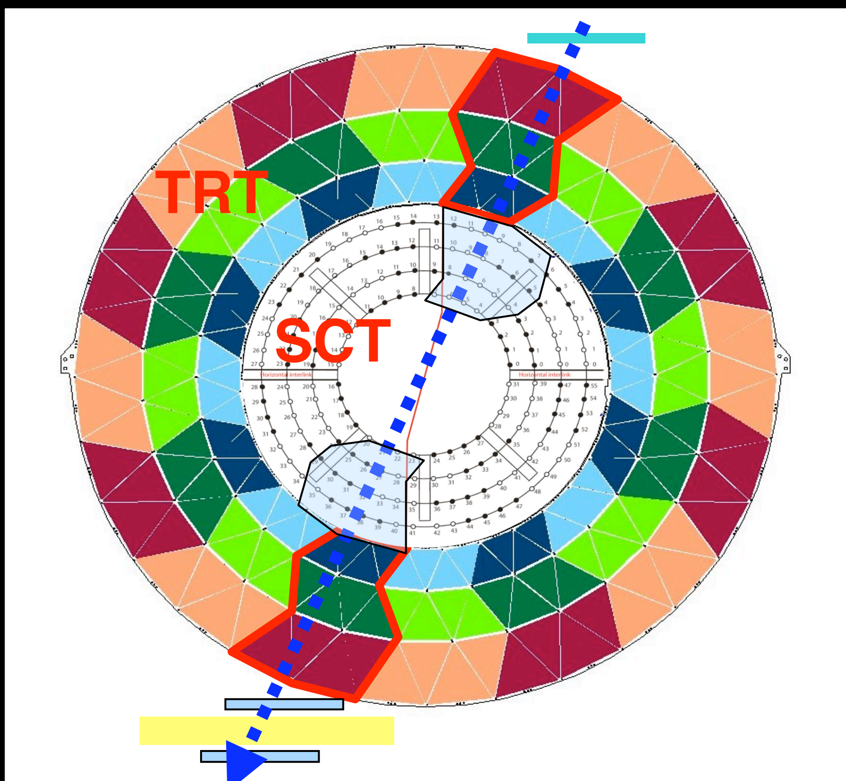
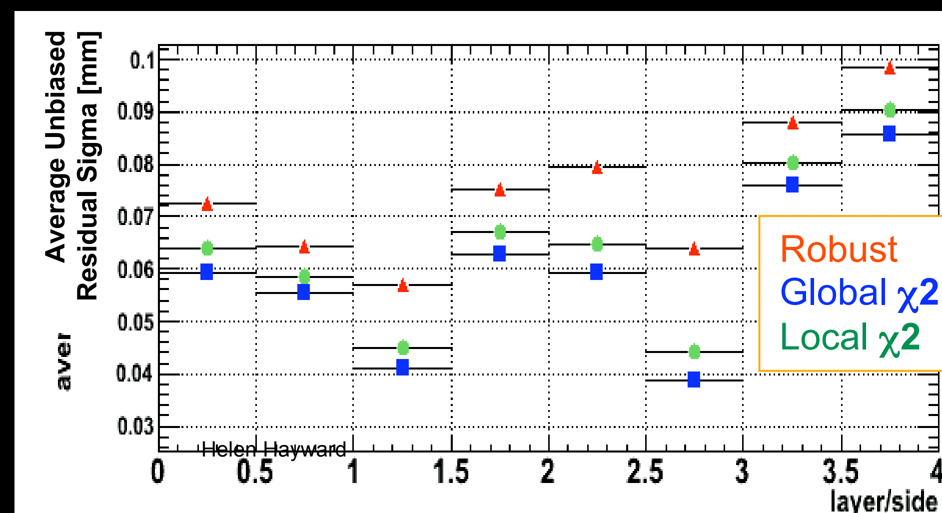
ATLAS ID Alignment: SR1 Cosmics Performance

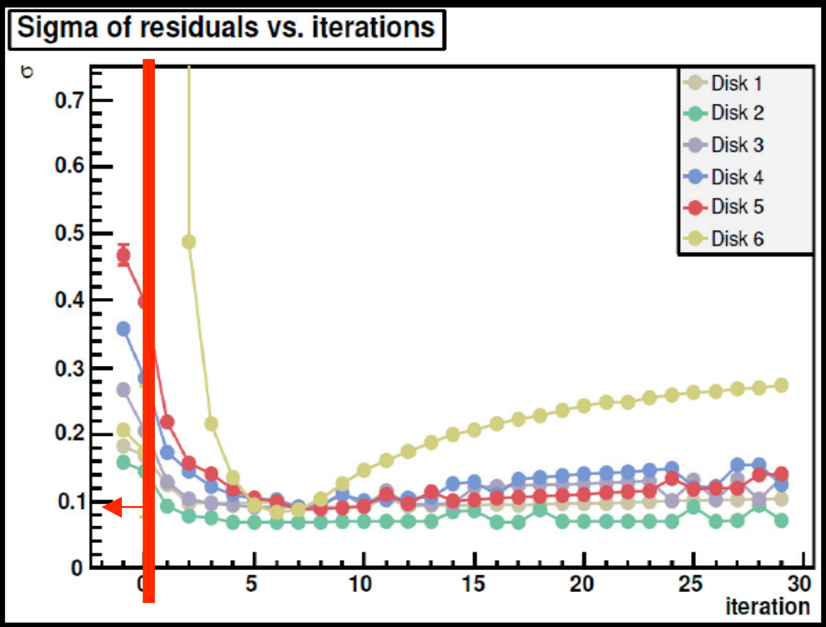


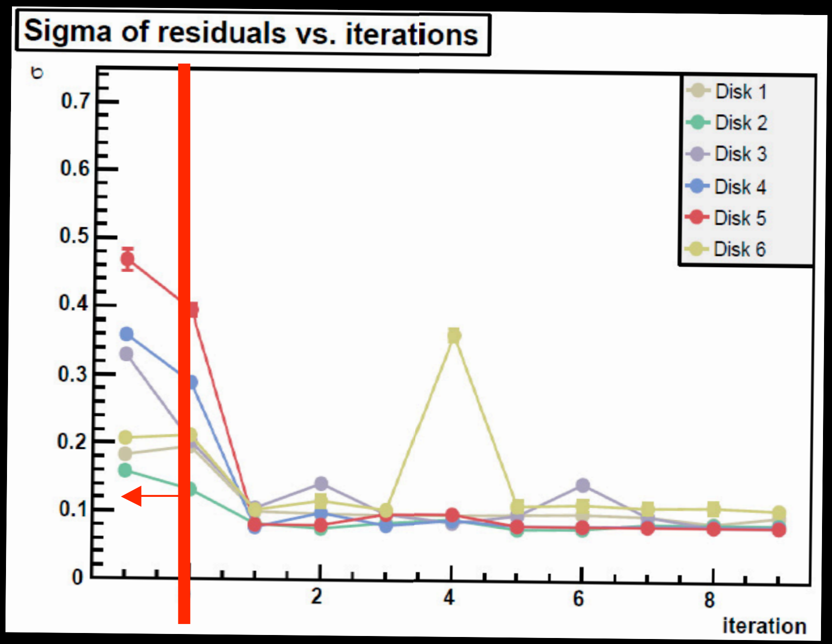
- Surface runs in spring 2006: ~400k Barrel cosmics recorded (22% of SCT, 13% of TRT detector used)
- No B-field! No momentum measurement! MCS important ~<10 GeV, need to deal with larger residuals than CTB



ATLAS ID Alignment: SR1 Cosmics Performance

Detector End Caps





Survey Information

Survey Information

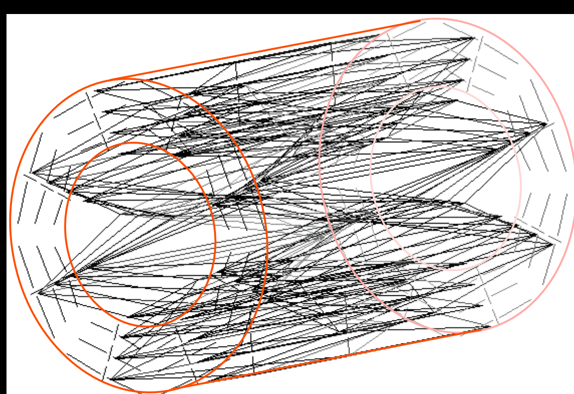
Local χ^2

Global χ^2

ATLAS ID optical alignment (FSI)

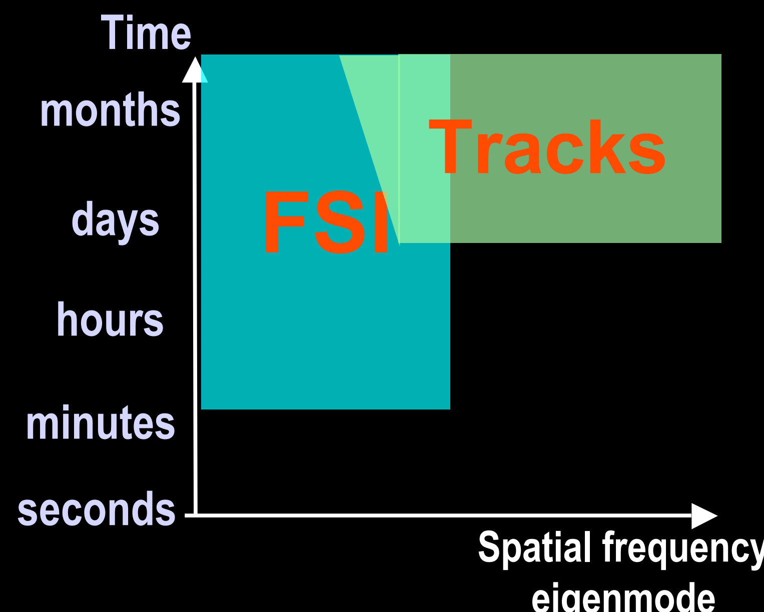
- Frequency Scanning Interferometer: Geodetic grid of 842 simultaneous length measurements (precision <1μm) between nodes on SCT support structure.
- Grid shape changes determined to < 10μm in 3D.
- Time + spatial frequency sensitivity of FSI complements track based alignment:
  - Track alignment average over ~24hrs+.
    high spatial frequency eigenmodes, “long” timescales.
  - FSI timescale (~10mins)
    low spatial frequency distortion eigenmodes -> weak global modes!
- Software principles already studied, implementation to be finalized!

Barrel SCT



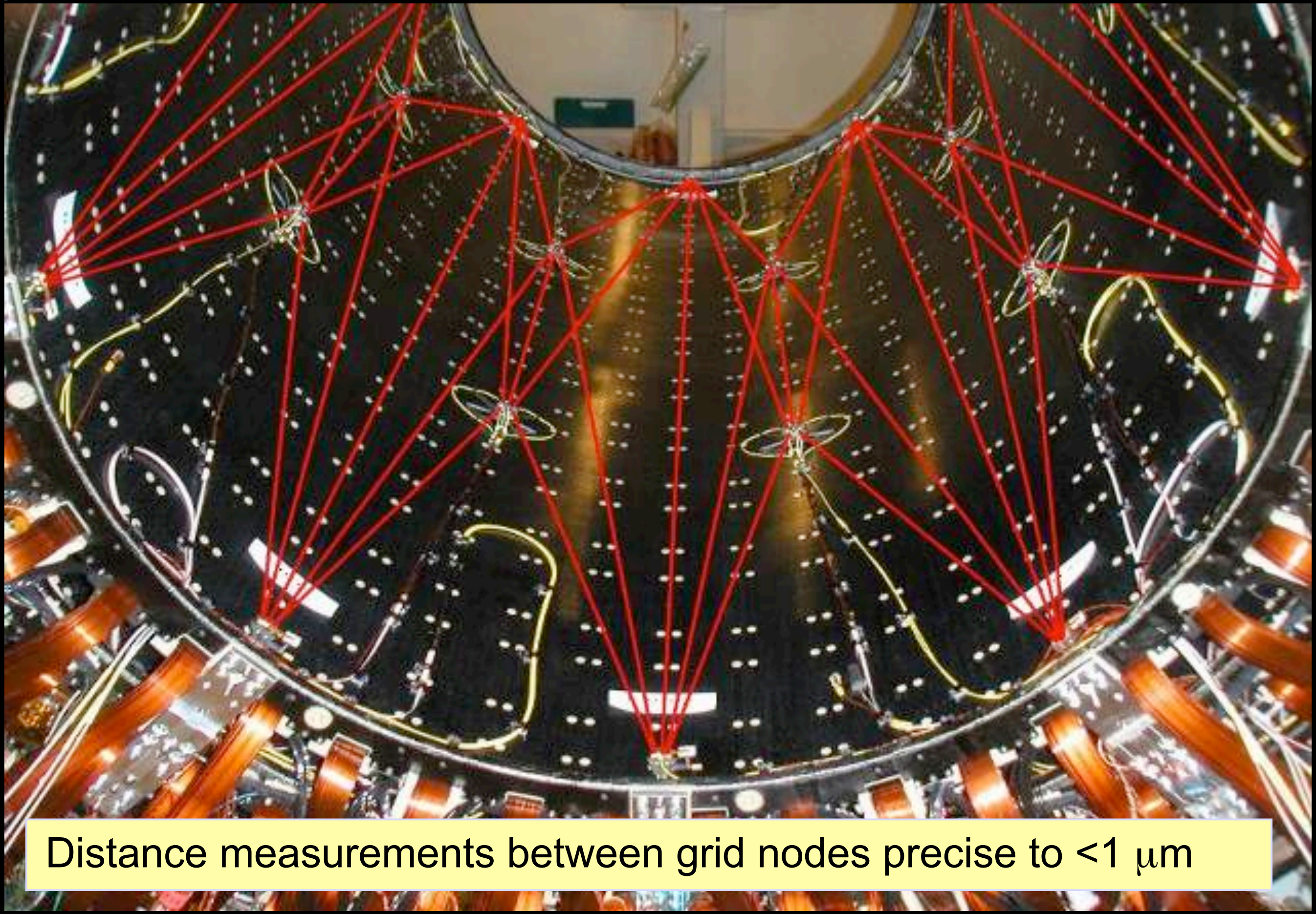
80+(3x[80+16])+(2x72)=512

End-cap SCT 165x2=330



ATLAS FSI on detector

FSI will be used intensively before and during the early runs and the track-based alignment and FSI interplay will be tested. Stability of the detector will indicate how frequently data needs taken during normal operation.



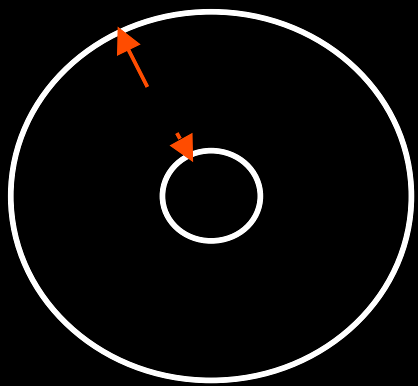
Distance measurements between grid nodes precise to <1 μm

Conclusion

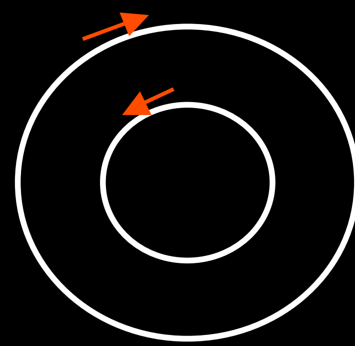
- Three track based alignment algorithms have been successfully developed
- Tests on simulated and real data have given positive results
- A lot has been learned, fixed, improved, but there is still more to do
- FSI is getting ready to monitor SCT stability during commissioning with cosmics and early accelerator data
- A variety of source of information will be required to align the ATLAS Inner Detector
- We will be ready for real data taking

Backup Slides

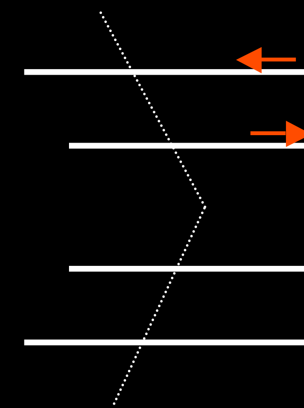
What happens if we don’t have correct alignment



Radial Expansion



Curl



Telescope

	ΔR	Δϕ	ΔZ
R	Radial expansion (distance scale)	Curl (charge asymmetry)	Telescope (COM boost)
ϕ	Elliptical (vertex mass)	Clamshell (vertex displacement)	Skew (COM energy)
Z	Bowing (COM energy)	Twist (CP violation)	Z expansion (distance scale)

Constraining the System

- A number of mathematical techniques can be used to help constrain the system
  - Lagrange multipliers can be used to restrict global rotations however they increase the size of matrix.
  - Additional bilinear terms can be used to give each parameter an error, unfortunately this will make the matrix dense.
- Constraints on track parameters or vertex position (external tracking (TRT, Muons), calorimetry, resonant mass, etc.)
- Cosmic events
- External constraints on alignment parameters (hardware systems, mechanical constraints, etc).