Lessons from the ATLAS SCT alignment system for LC detector and MDI alignment

and new technology developments

Armin Reichold for the AMULET collaboration

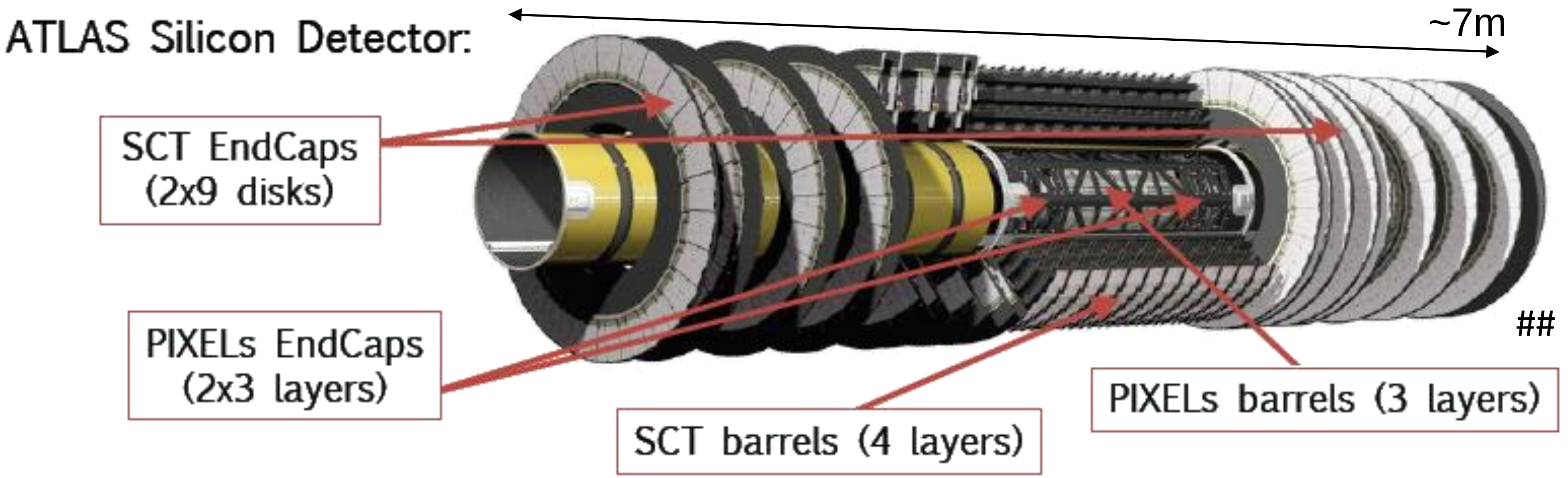
Overview

- ATLAS SCT online FSI alignment (60%)
  - Purpose and Requirements
  - How it works
  - How it was meant to be used
  - How the SCT performed
  - How it is actually used
- Improvements in FSI technology (30%)
  - Dynamic FSI
  - Commercial availability
- Conceptual LC alignment applications & conclusions (10%)

Disclaimer

- I am not a member of the ATLAS collaboration (any more)
- I WAS involved in building the online FSI alignment system for the SCT
- Now working on new FSI technology
- Conclusions concerning ATLAS arise from contact with colleagues (R. Nickerson, S. Gibson, P. Coe), discussions and papers (see list at end of talk)
- ATLAS alignment pictures and graphs largely from: ## = “Rapid precise shape monitoring of the ATLAS silicon tracker”, S. Gibson, see Bibliography

ATLAS SCT online alignment system



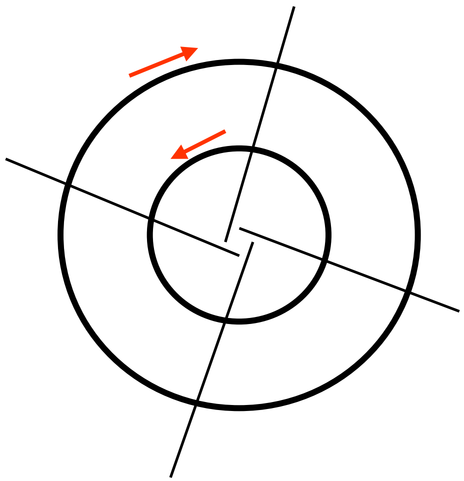
- Purpose:
  - Follow changes of tracking detector shape which are too fast to catch with track-based alignment
    - These were expected due to heat load variations from trigger rate changes and other sources
  - Correct detector positions during such changes
  - Statistical misalignment of tracker elements should not increase statistical error on track parameters by more than 20% at any time
  - Constrain deformation modes that are “weakly” measured by track alignment

ATLAS SCT online alignment system

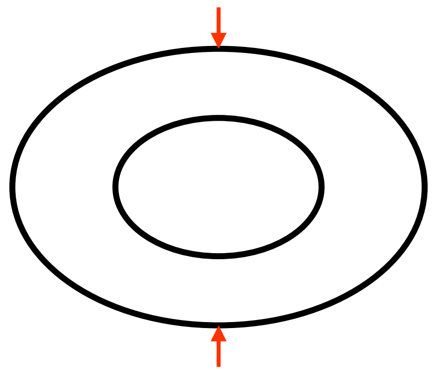
- Resolution requirements
  - ATLAS tracker resolutions are moderate compared to LC plans
    - ATLAS Pixels: $\sigma_{r*\phi}$ = 10 µm , σ_z = 115 µm (LC: 4-7 µm)
    - ATLAS Strips: $\sigma_{r*\phi}$ = 17 µm (LC: 12 µm)
  - Demands on alignment accuracies for ATLAS:
    - Pixels: $\sigma_{align\text{-}r*\phi}$ = 7 µm
    - Strips: $\sigma_{align\text{-}r*\phi}$ = 12 µm

Examples of weakly constrained modes

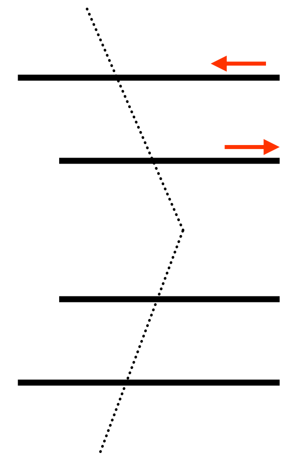
Some types of distortions can leave the tracks helical, but systematically biased



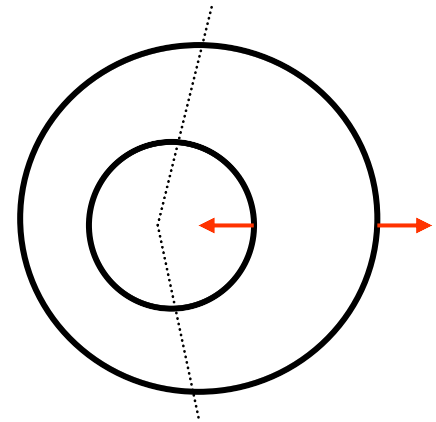
"clocking"
$\delta\phi=\lambda+\beta/R$
(VTX constraint)



radial distortions
(various)



"telescope"
$\delta z \sim R$



ϕ dependent sagitta
$\delta X=a+bR+cR^2$

These need extra handles to measure such as:

- Common vertex for a group of tracks (VTX constraint),
- Constraints on track parameters or vertex position (external tracking (TRT, Muons), calorimetery, resonance mass, etc.)
- Cosmic events (not from vertex)
- External measurements of alignment parameters (hardware alignment systems, mechanical constraints, etc).

[PHYSTAT'05 proceedings]

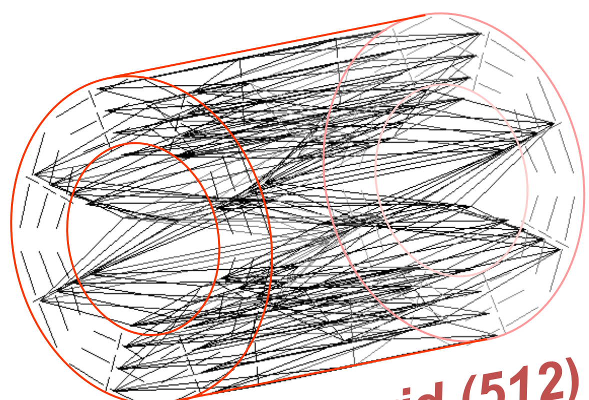
η dependent sagitta
"Global twist"
$\delta\phi=\kappa R\cot(\theta)$

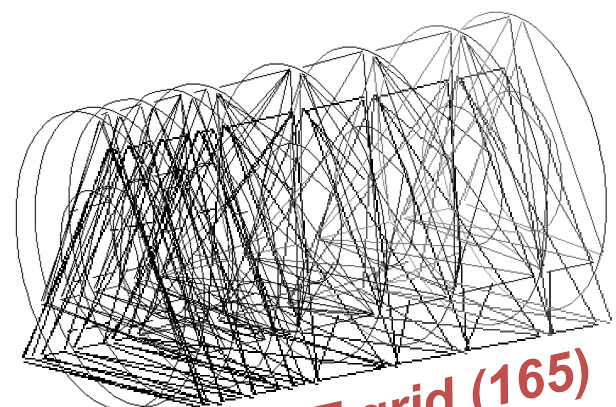
global sagitta
$\delta\phi=\gamma R$

...

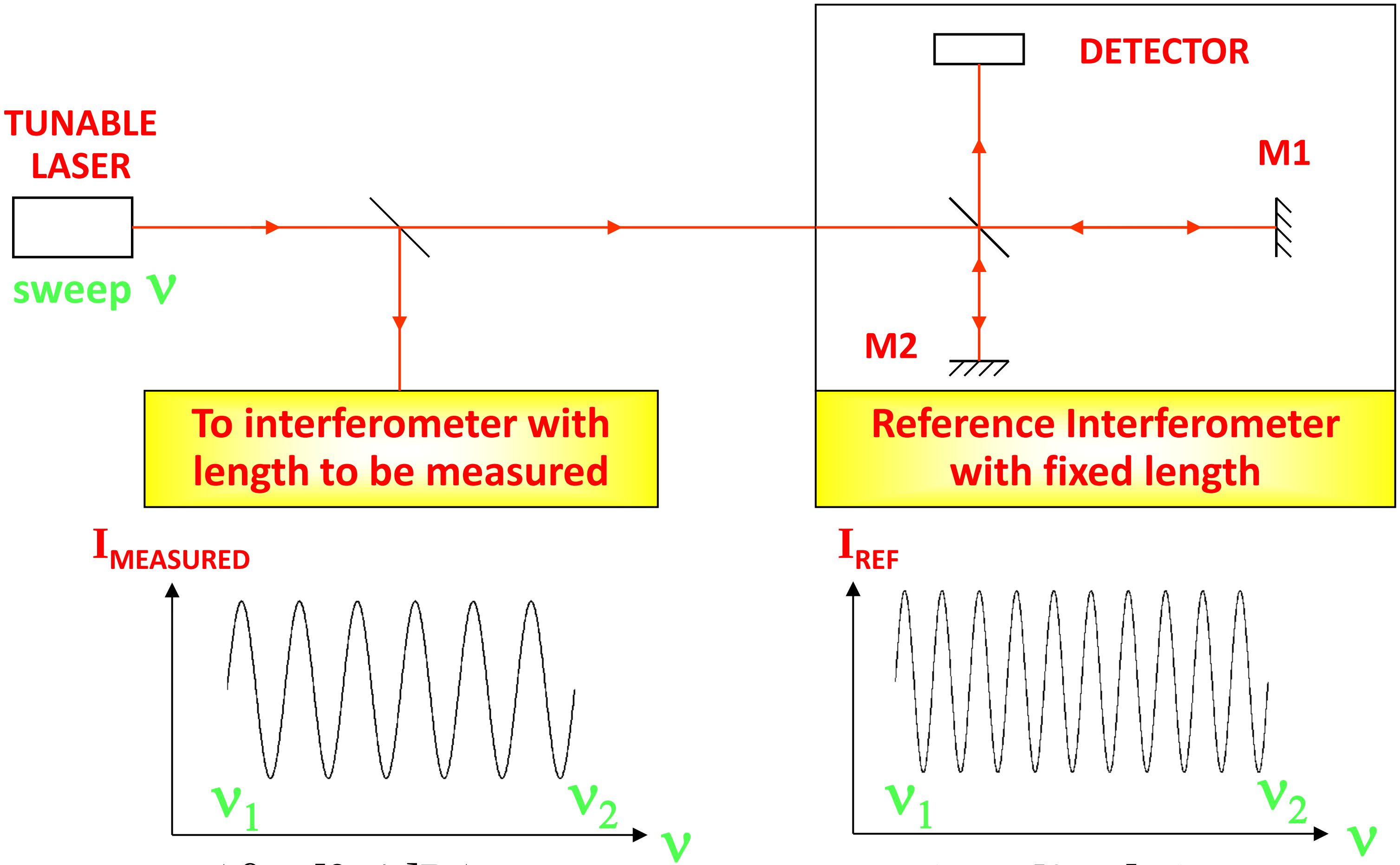
ATLAS SCT online alignment system

- How it works
  - Geodetic grid of length between nodes on support structure
  - Frequency Scanning Interferometry (FSI) designed to measure 842 lengths relative to stable reference interferometer
  - Monitor support structure NOT sensors (too many DOF=34,992)
  - Lengths measured “simultaneously” to a precision of < 1µm.
  - Repeat every 10 min. to track deflections





Very Basic Principle of FSI

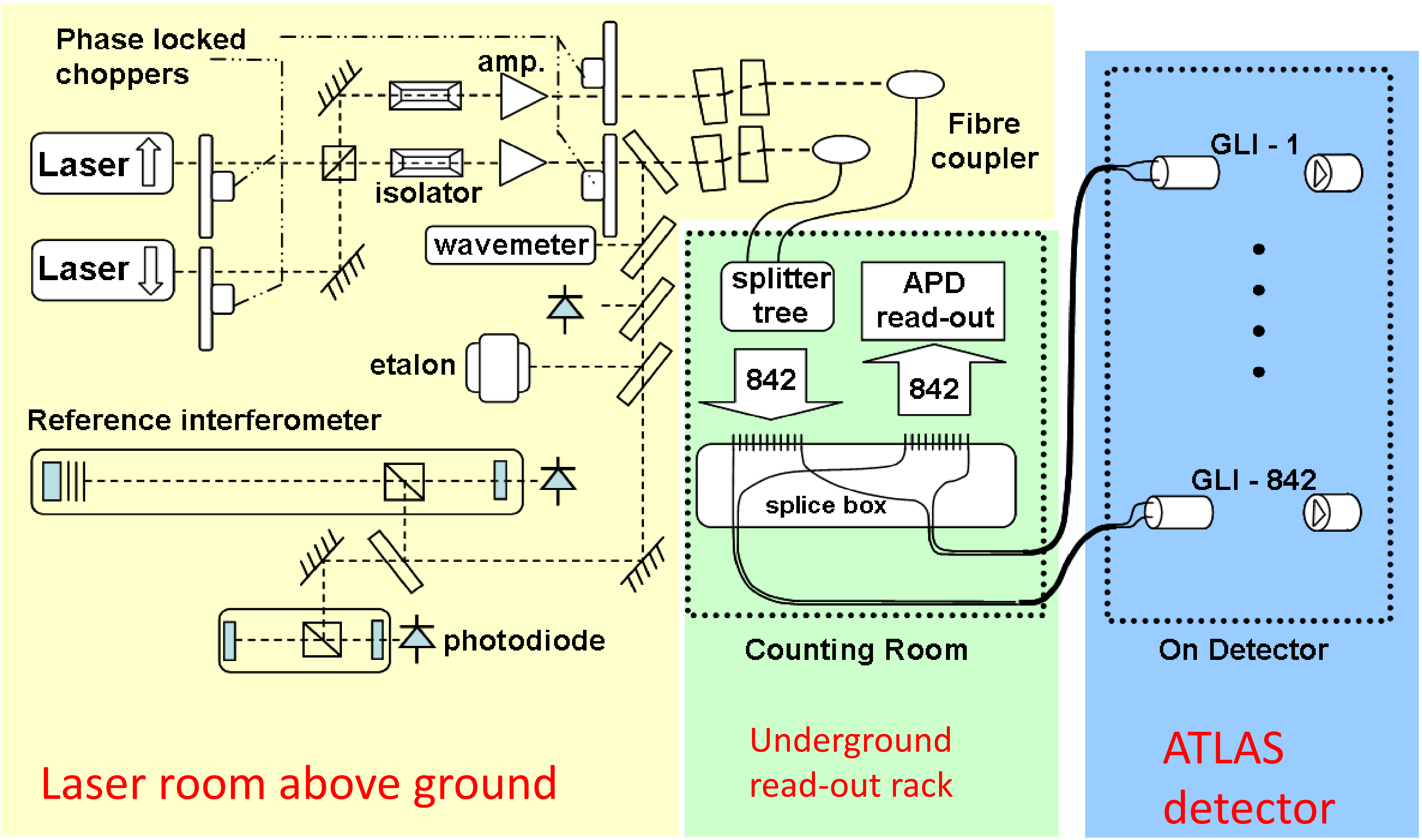


$\Delta\vartheta = [2\pi/c]D\Delta\nu$

$\Delta\Phi = [2\pi/c]L\Delta\nu$

Ratio of phase change = Ratio of lengths

ATLAS SCT online alignment system: System Overview



Tuneable laser amplifier system

Reference Interferometry System

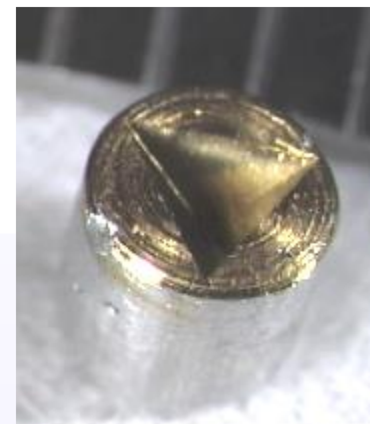
Two

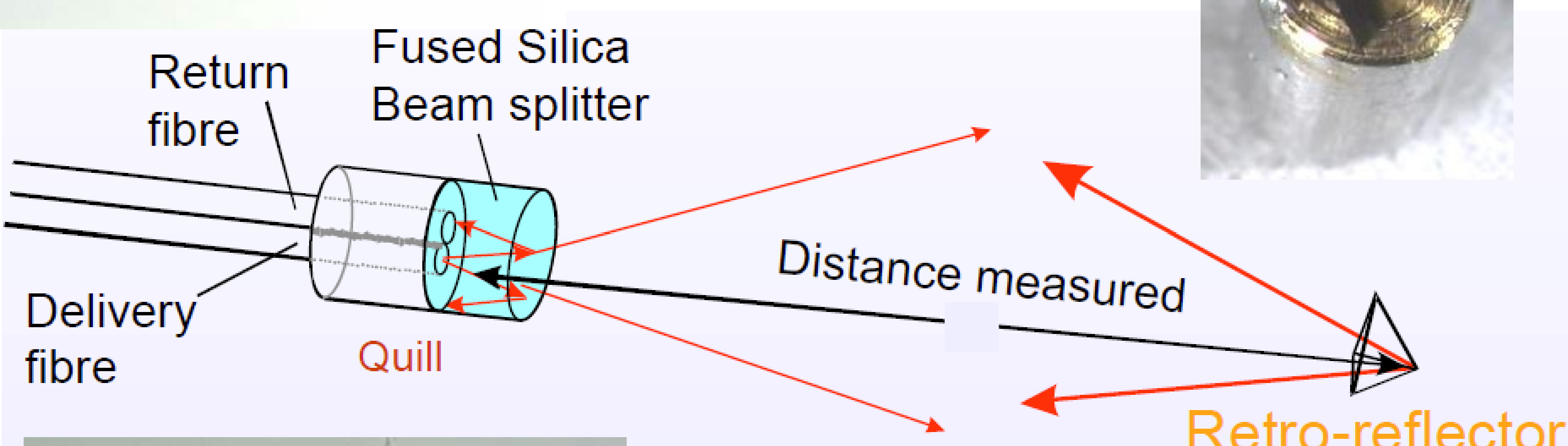
pie

- F
- S
  c
- E
  f
- L

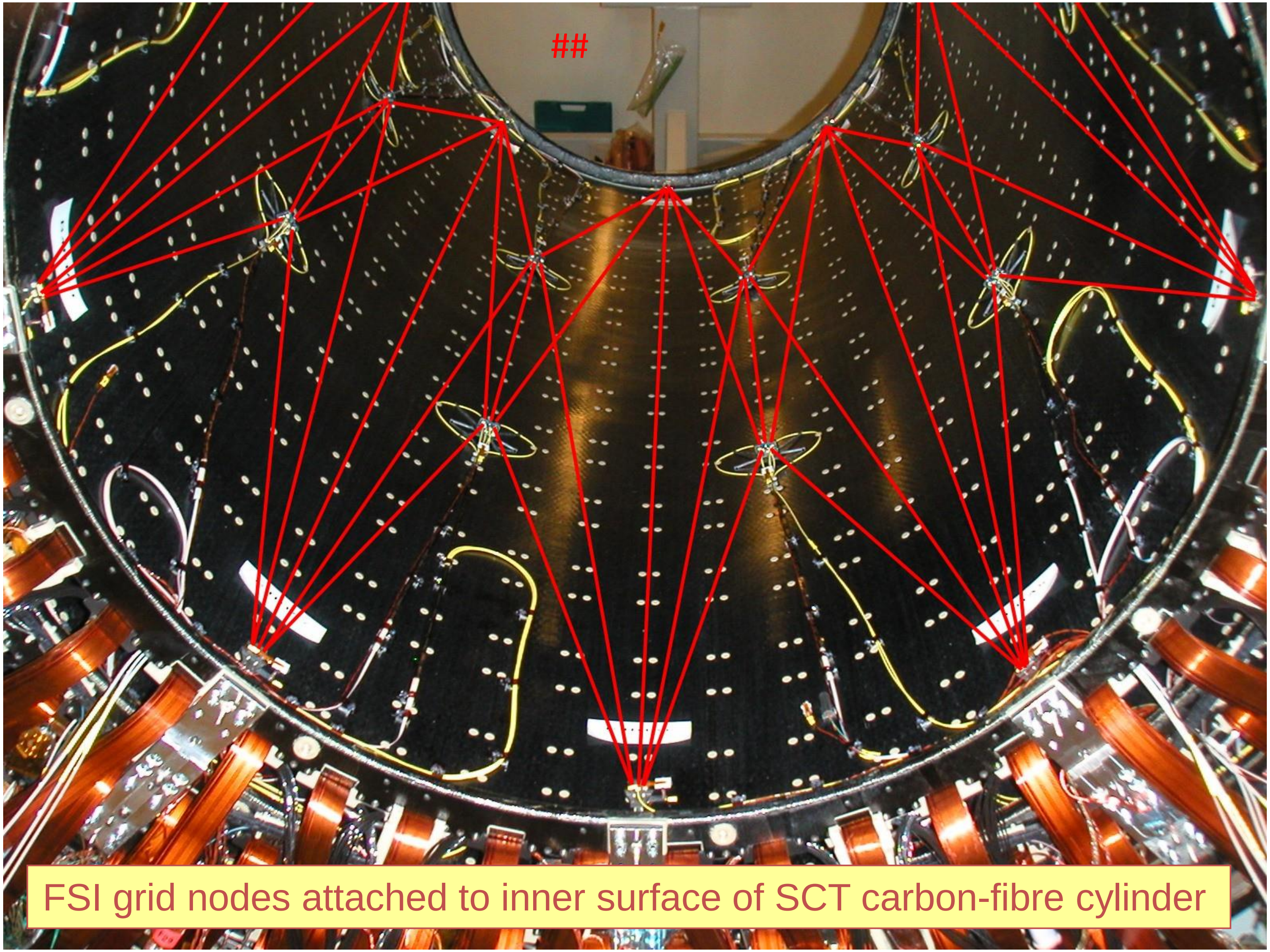
ATLAS SCT online alignment system

- Front-end components of
  - minimal mass
  - high radiation tolerance





ATLAS SCT online alignment system



FSI grid nodes attached to inner surface of SCT carbon-fibre cylinder

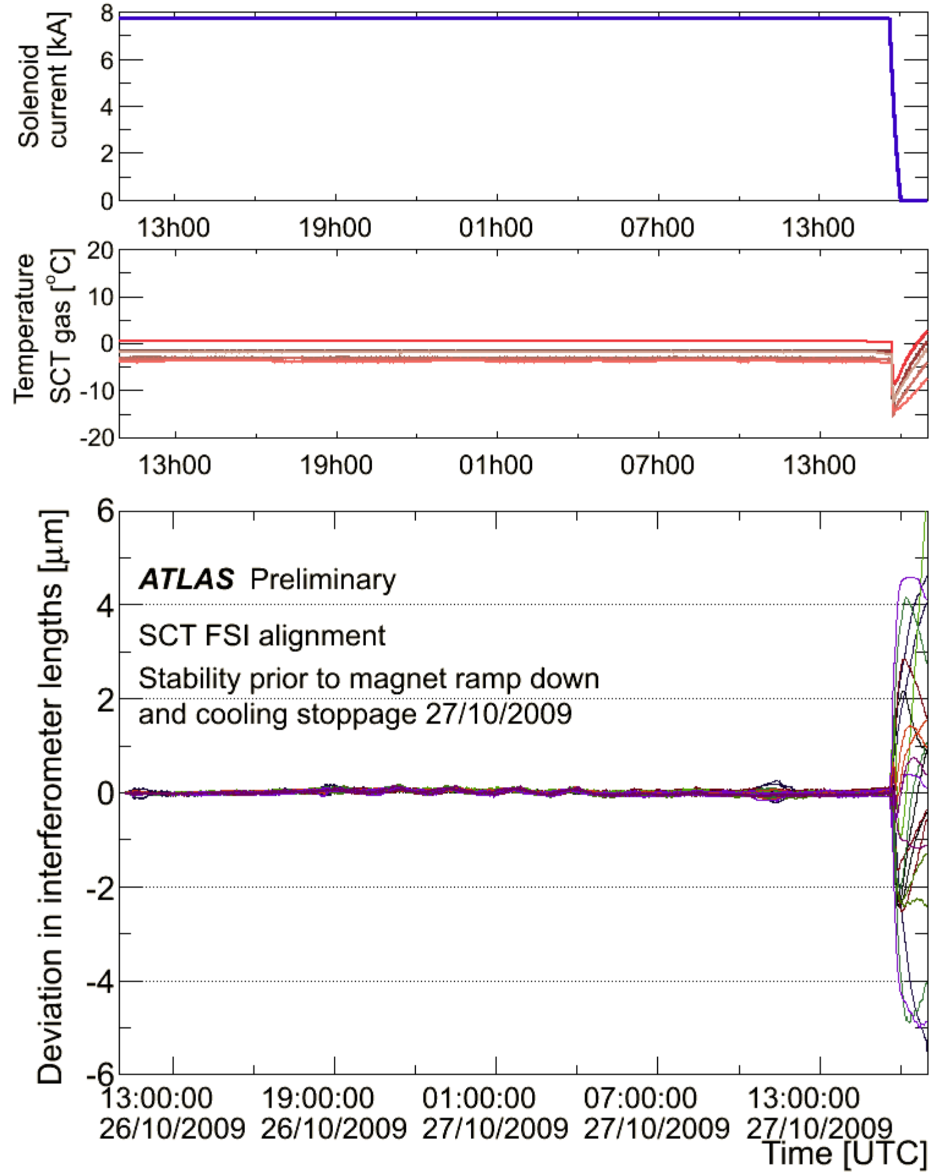
ATLAS SCT online alignment system

How it was **meant to** be used

- Determine approximate FSI network geometry via:
  - Design positions
  - Photogrammetry of end views (64 markers, 20 microns transverse accuracy)
- *Quasi-geodetic* grid needs assumptions to solve ➔ study structure deflections (FEA, ESPI deflection measurements)
- ~~Relate FSI grid shape to detector module positions~~
  - ~~x-ray survey cancelled~~
- FSI monitors support shape changes
  - assume low order deflections (low spatial frequencies) of support from FEA
  - translate these into module position corrections
- Combine
  - FSI module correction every 10 min
  - track alignment of high order deflections (excluding low orders).

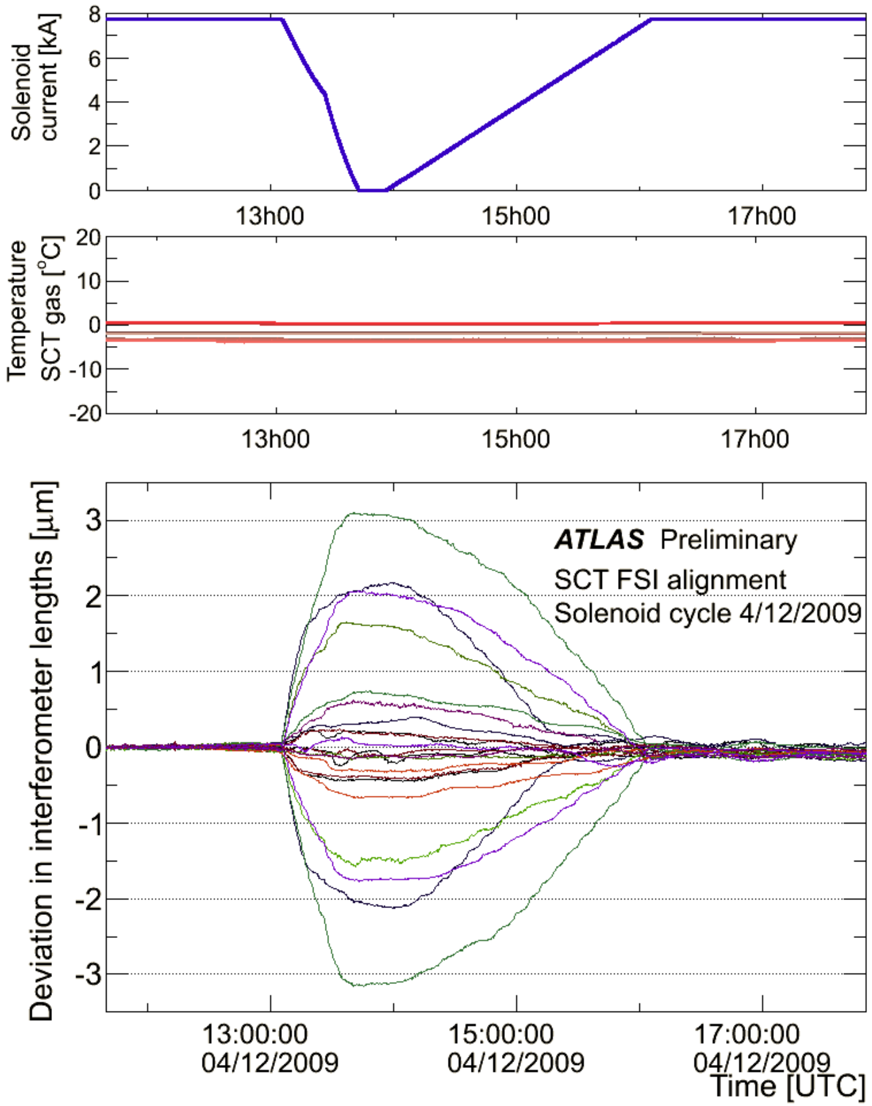
ATLAS SCT online alignment system

- But ....
- SCT is super stable:
  - **stdev ~25 nm** over 2 hours before and after solenoid ramp
  - stdev **< 50nm** over 24 hours
  - Only few barrel interferometers shown



ATLAS SCT online alignment system

- And very repeatable
  - after solenoid ramp
  - return to start values to **stdev ≈ 49nm** around old values
  - only few barrel lines shown
  - **Therefore ➔**



ATLAS SCT online alignment system

How it is **actually** used

- FSI distortion measurements not needed during regular operation (detector too stable)
- Alignment done by tracks alone (no FSI corrections)
- FSI determines periods of stability for track alignment
- What alignment people would have liked instead:
  - FSI system more optimised to measure “weak modes”
  - ATLAS upgrade tracker will be planned with this in mind

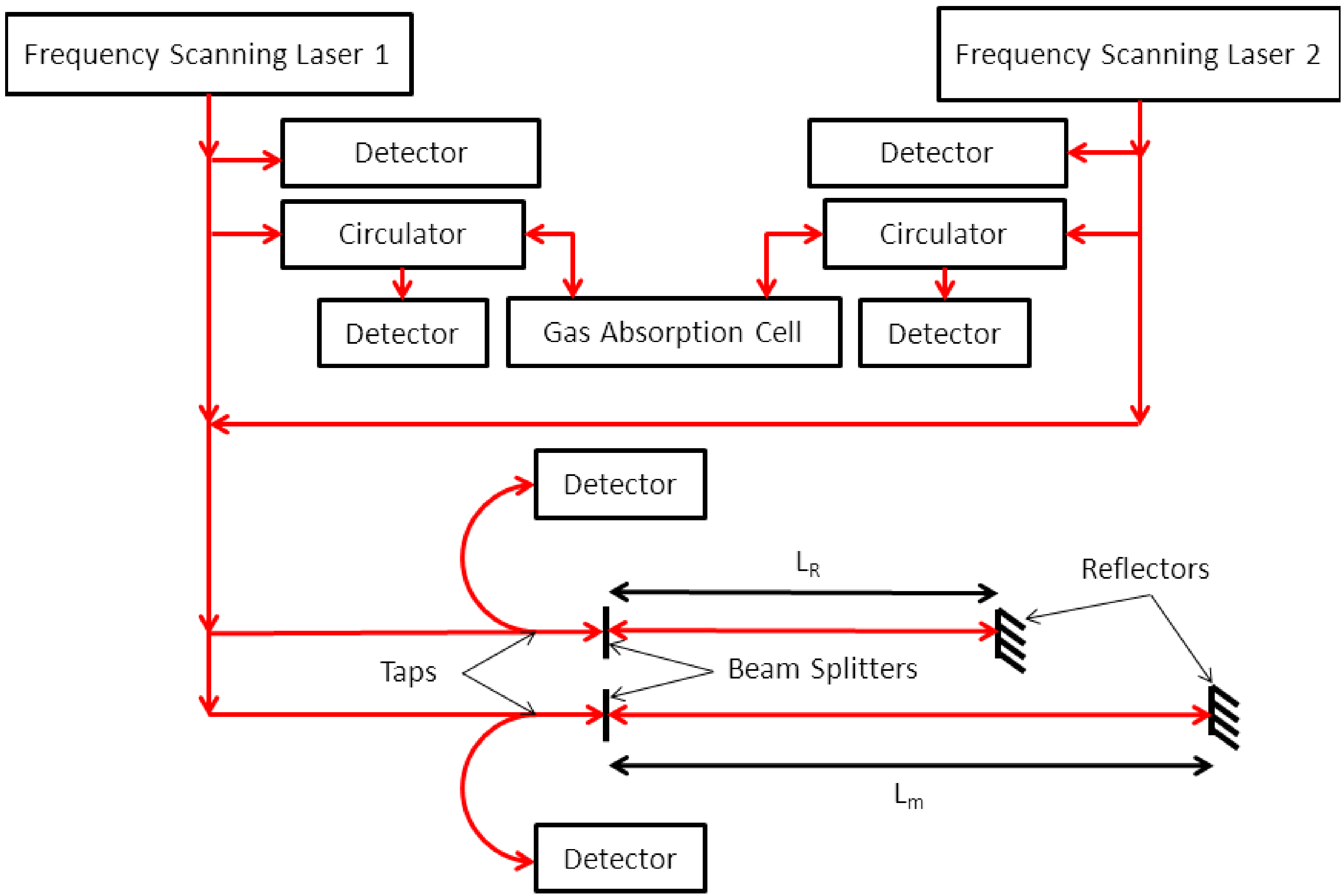
ATLAS SCT online alignment system

- By now this is “old” technology
  - lasers: λ=835nm (not telecoms)
  - Slow mode hop free tuning
  - small tuning range
  - external beam splitters
  - metal reflectors
  - two fibres for each line
  - reference interferometer defines the length scale
  - but this has improved …

New FSI technology

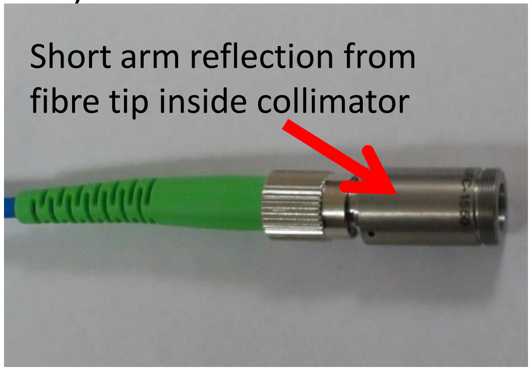
- FSI development continued after ATLAS
- Initially work aimed at LC applications
  - LiCAS = ILC main linac alignment
  - AMULET = FF stabilisation
  - Ended abruptly when STFC withdrew UK support for ILC
- Later work aimed at commercialisation
  - Projects: AMULET, Comet
  - new funding via EPSRC, ETALON AG, NPL
  - Aims:
    - Measure absolute length in meters traceable to SI definition
    - Measure varying length $L(t)$ not only tolerate changes and average
    - Higher measurement frequency
    - Lower cost
    - Improve practicability (speed, analysis, handling, etc.)
    - Make it into a toolkit for metrology applications

Dynamic FSI: Schematic (Patented)



Dynamic FSI: hardware changes

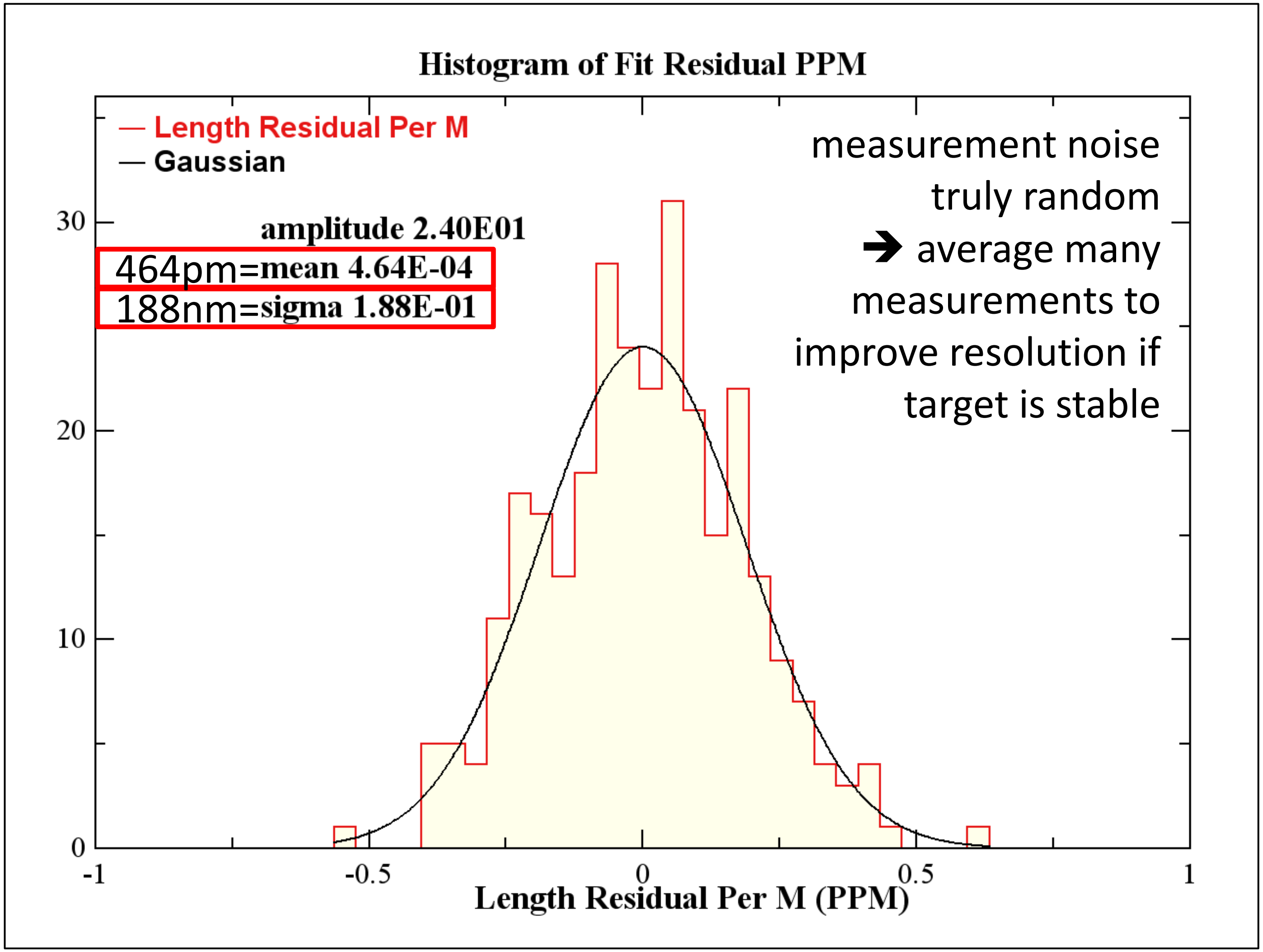
- Moved to telecoms wavelength 1550nm
  - wide tuning range O(100nm)
  - fast tuning O(1000nm/s)
  - cheap lasers and other components
  - cheap extra power due to EDFA
  - Easier to be eye safe
- Both lasers present in all interferometers simultaneously (no multiplexing or chopping)
- Gas absorption cells provide length scale via physically fixed absorption features
  - naturally long term stable
  - minimal influence from environment (pressure shifts)
  - traceable to SI meter via frequency comparison
  - much cheaper & simpler than invar reference
- Fibre reference interferometers
  - stability required over O(1 sec)
  - length measured each "shot"
  - compact, cheap, coiled fibre interferometer
- Single fibre for delivery and readout
- No external beam splitter (fibre end = beam splitter)
- Use collimated beams up to 50m



Dynamic FSI: new capabilities

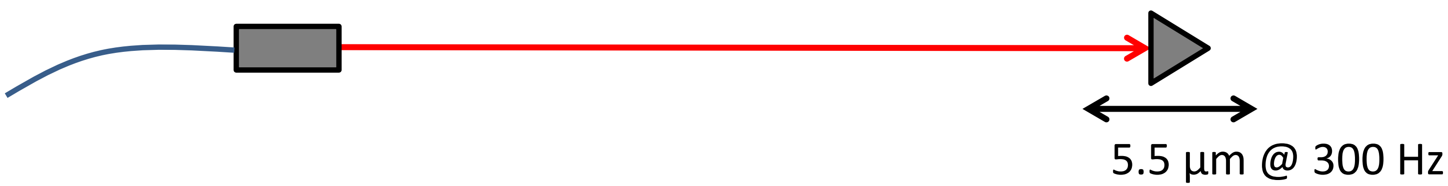
- Measure changing (< 19 mm/s) ABSOLUTE distances time resolved at 2.77 MHz inside each scan
- Scan resolution better than ± 0.1μm
- Scan repetition rates 0.1 to 10 Hz
- Absolute measurement uncertainty <±0.5 μm/m (at 95% CL) over life time

Dynamic FSI: verification 0.2 to 20m

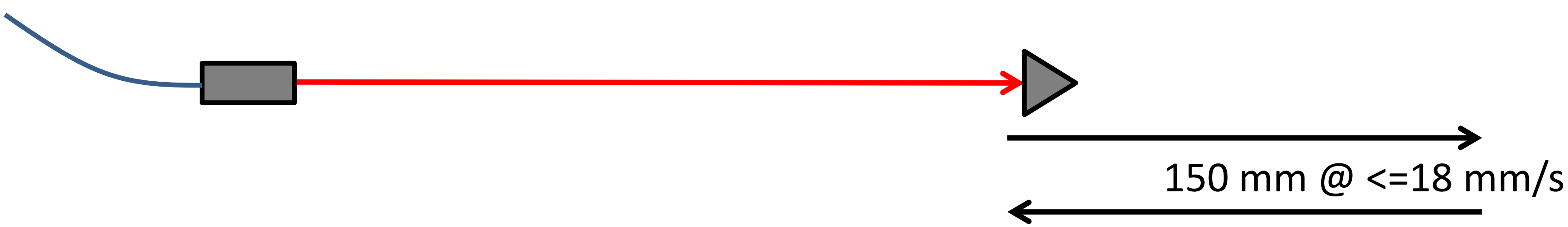


Dynamic FSI: Measurement Results with commercial Multiline™ system

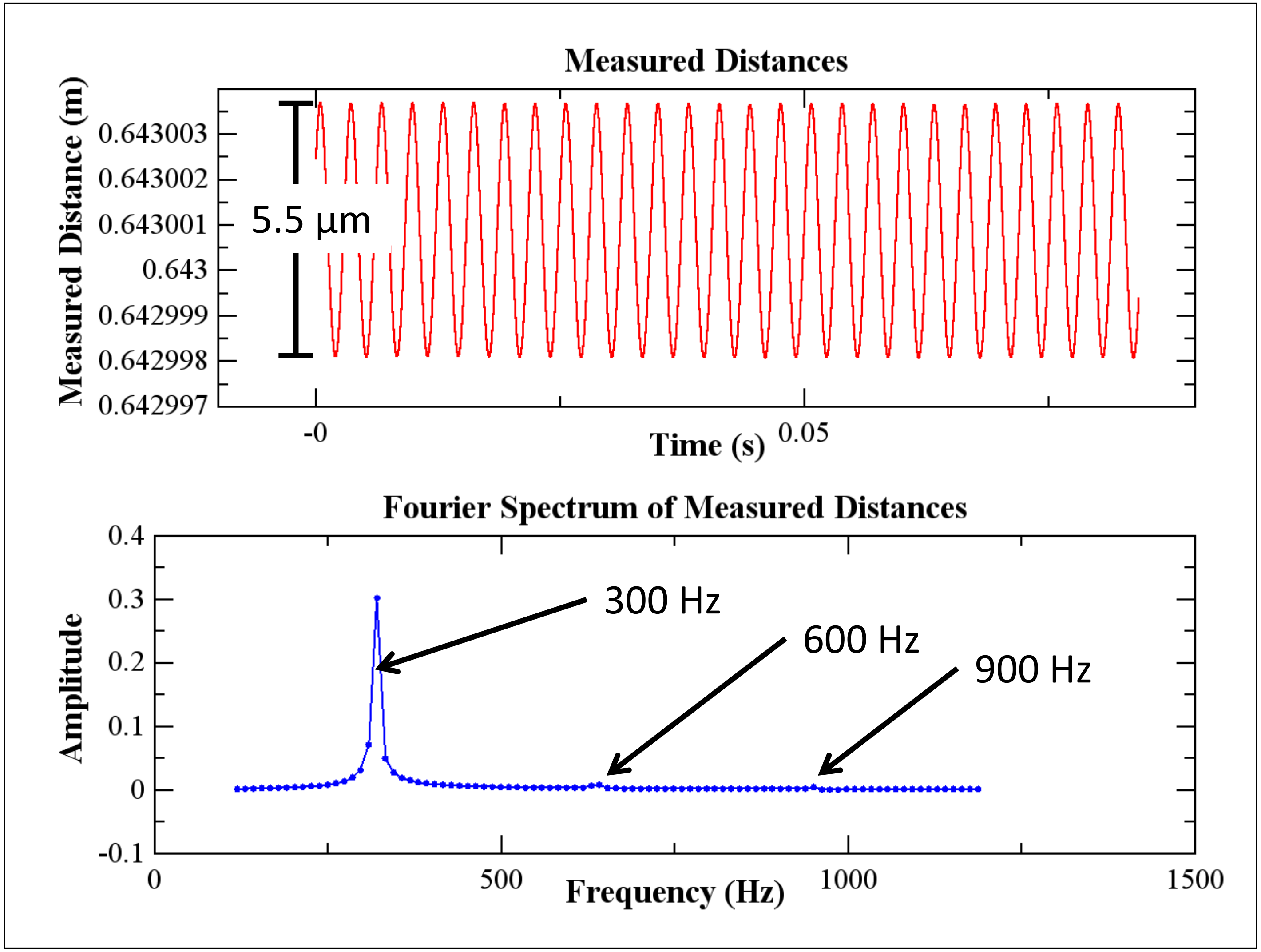
– One line monitor piezo-driven vibrating target 60 cm away



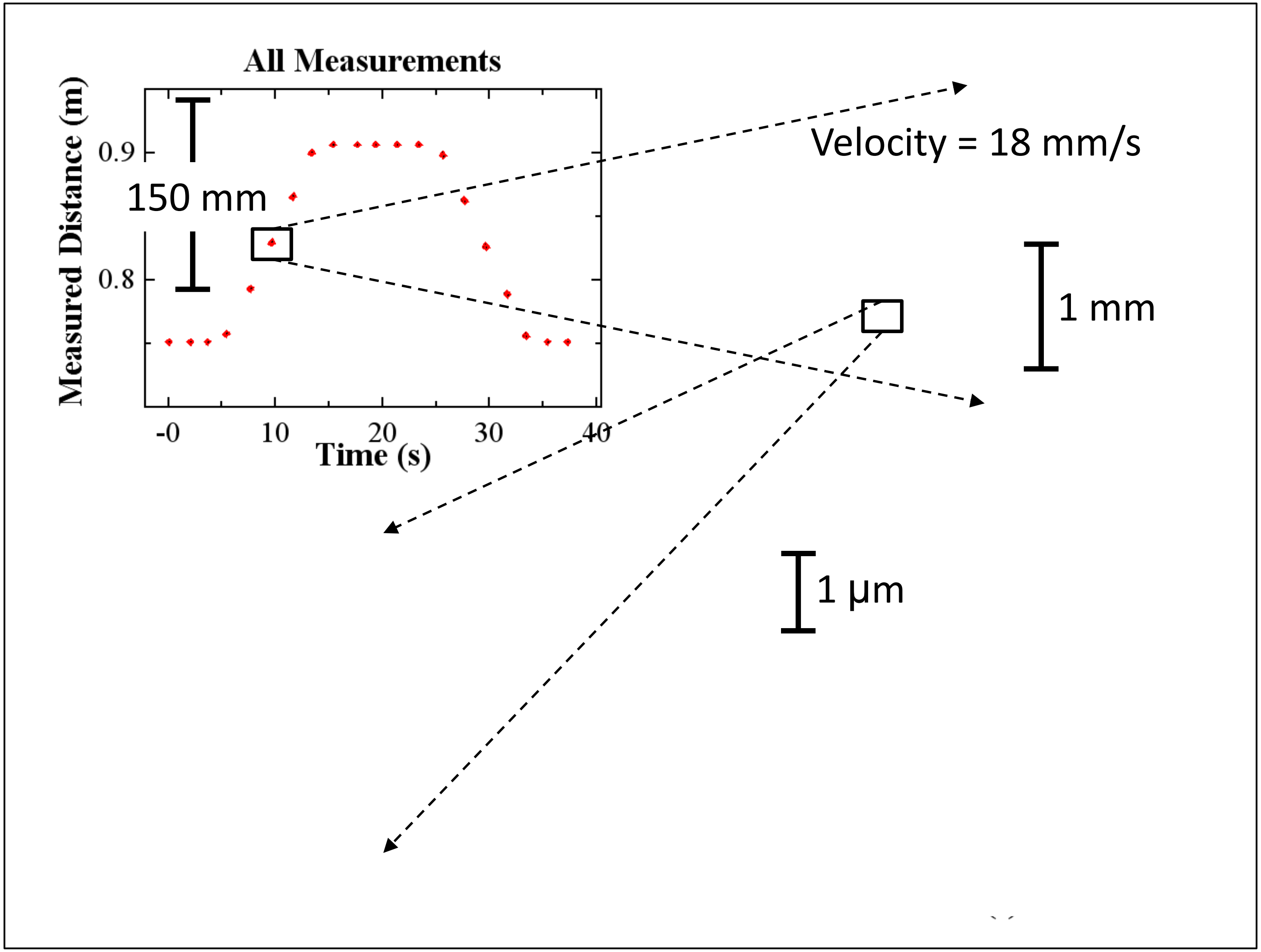
– One line monitors linear motion of target on stepper motor stage 75-90 cm away



Monitoring of a vibrating target



Monitoring of a slowly moving target



Dynamic FSI:

Commercial Multiline™ system from ATAON AG

www.etalon-ag.com/index.php/en/products/multiline

- 24 measurement lines
- Up to 88 lines with extra DAQ cards in current DAQ crate
- Laser system can power up to 200 lines
- With EDFA practically no limit on number of lines
- Extra DAQ crates attached via USB
- Fully calibrated and traceable
- Entire system in single *smaller rack*
- CERN and SLAC will buy

What do we need to align for LC

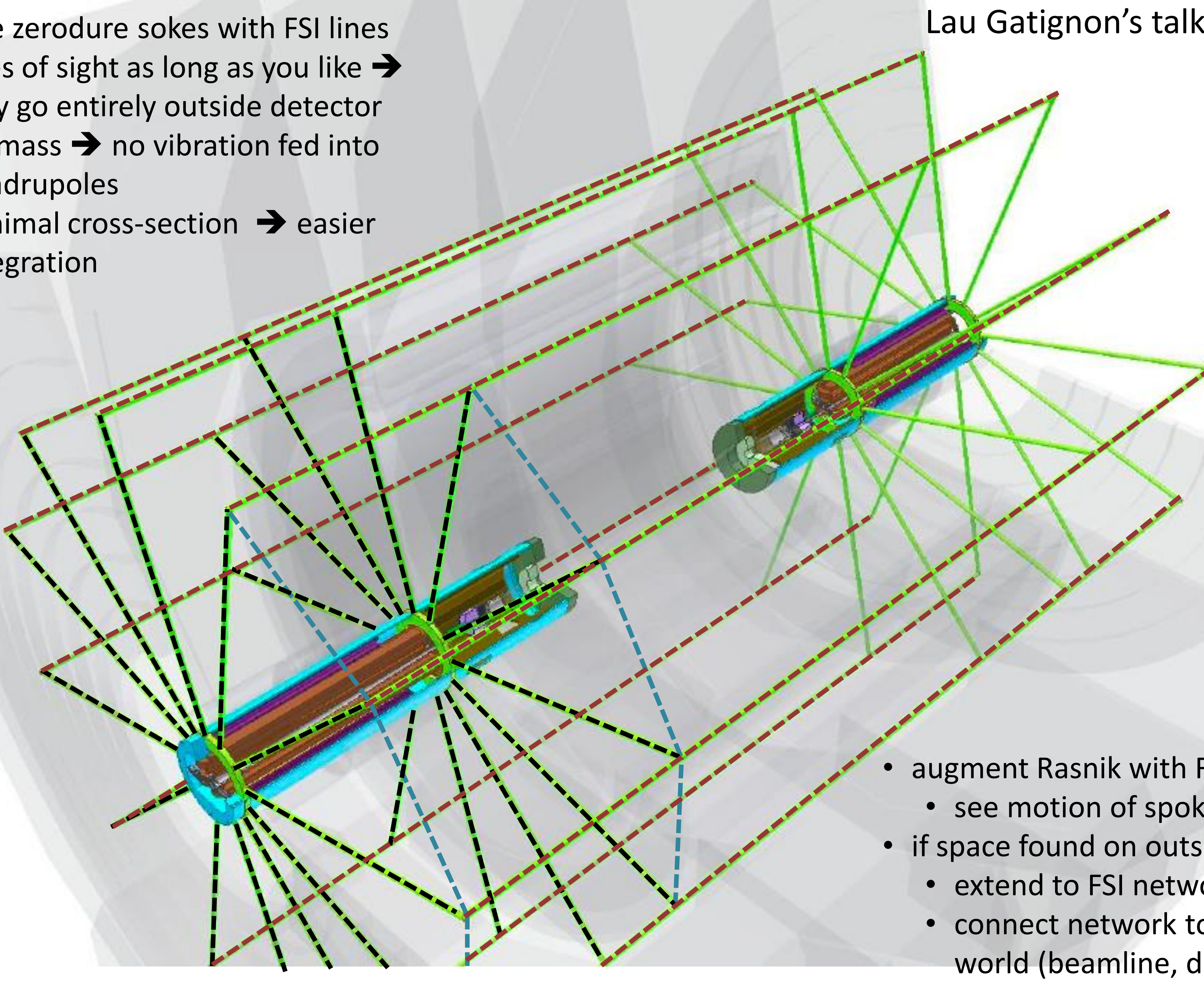
- Track and Vertex detectors
  - Higher resolution compared to ATLAS wants better alignment
  - Lower mass (LC vertex det = few 0.1% X0, ATLAS pixels few % X0) will make distortions bigger
  - Push-Pull makes distortions more frequent and likely
  - tracker needs to be aligned to other non-tracking detectors as well (cannot be done with track alignment)
- Entire detector needs to be aligned to beam line after push pull
- MDI elements
  - hard to reach inside detector
  - Push pull will move them around
  - see next slide for some concepts

Harry van der Graaf / NIKHEF

(CLIC solution for FF pre-alignment from Lau Gatignon's talk, Tue. am)

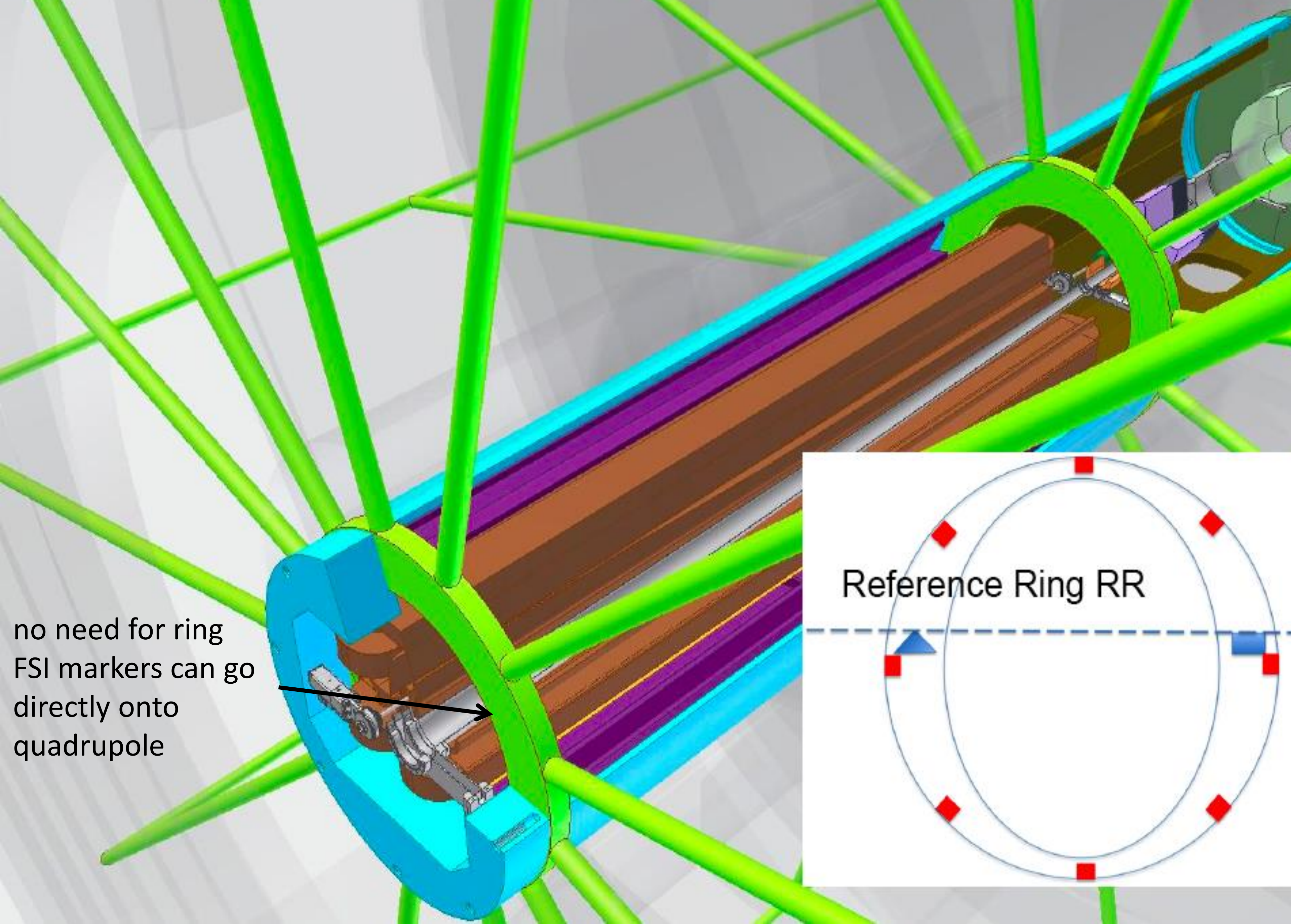
replace zerodure sokes with FSI lines

- lines of sight as long as you like ➔ may go entirely outside detector
- no mass ➔ no vibration fed into quadrupoles
- minimal cross-section ➔ easier integration



- augment Rasnik with FSI
  - see motion of spoke ends
- if space found on outside:
  - extend to FSI network
  - connect network to outside world (beamline, detector)

(CLIC solution for QD0 pre-alignment from Lau Gatignon's talk, Tue. am)



Conclusions

- FSI technology matured and commercially available
- FSI can be a powerful tool for various alignment systems
- It is Pointless to hardware align DOF that either:
  - are readily determined by track alignment → must know track alignment capabilities
  - or do not vary significantly during operation → design of hardware alignment is also integral to design of support structure
- Weak modes can eventually be aligned with tracks but:
  - needs special constraints (invariant masses, common vertex, external tracking, calorimetry, cosmics)
  - therefore takes a lot of data over a long time
  - hardware alignment can track weak modes over long times and enable track alignment data to be used over long times
- **→ Hardware and track alignment must be designed together with tracking mechanics**
- ATLAS upgrade projects are now starting to go through this process
- ATLAS expertise grown over first run is "available and willing to help"
- Sorry: All LC alignment specific technical work unfunded in UK
- But: There is hope and there is interest ;@)

Thanks to

- The AMULET collaboration:
  - John Dale[1], Ben Hughes[2], Andrew Lancaster[3], Andrew Lewis[2], Armin Reichold[3], Heinrich Schwenke[4], Matt Warden[1]

    1: DESY, 2:NPL, 3:Oxford JAI, 4:ETALON AG
- The ATLAS SCT alignment team
- The audience for all that patience

BACKUP SLIDES AND REPEATS FOR PDF PRINTS

Bibliography of ATLAS stuff

- Rapid precise shape monitoring of the ATLAS silicon tracker. S. Gibson
  - http://indico.cern.ch/materialDisplay.py?contribId=29&sessionId=1&materialId=slides&confId=13681
- Alignment of the ATLAS Inner Detector Tracking System with 2010 LHC proton-proton collisions at $\sqrt{s} = 7$ TeV
  - ATLAS-CONF-2011-012
- First data from the ATLAS Inner Detector FSI Alignment System
  - http://www-conf.kek.jp/past/iwaa08/papers/FR002.pdf
  - http://www-conf.kek.jp/past/iwaa08/presents/FR002_talk.pdf
- Study of alignment-related systematic effects on the ATLAS Inner Detector track reconstruction,
  - http://inspirehep.net/record/1204342/files/ATLAS-CONF-2012-141.pdf
- A NOVEL METHOD FOR ATLAS FSI ALIGNMENT BASED ON RAPID, DIRECT PHASE MONITORING,
  - http://cds.cern.ch/record/1305878/files/ATL-INDET-PROC-2010-037.pdf
  - http://cds.cern.ch/record/1291618/files/

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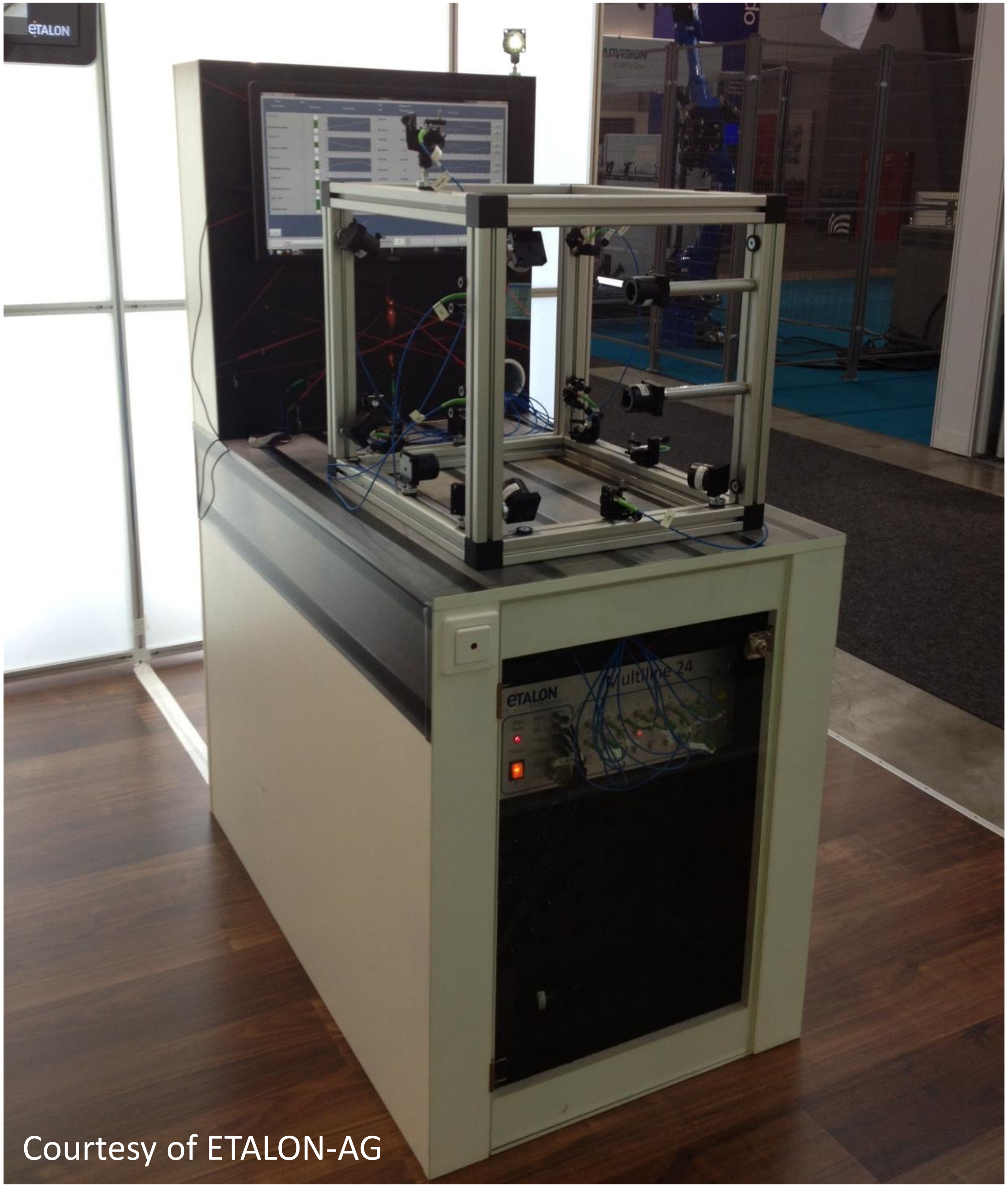


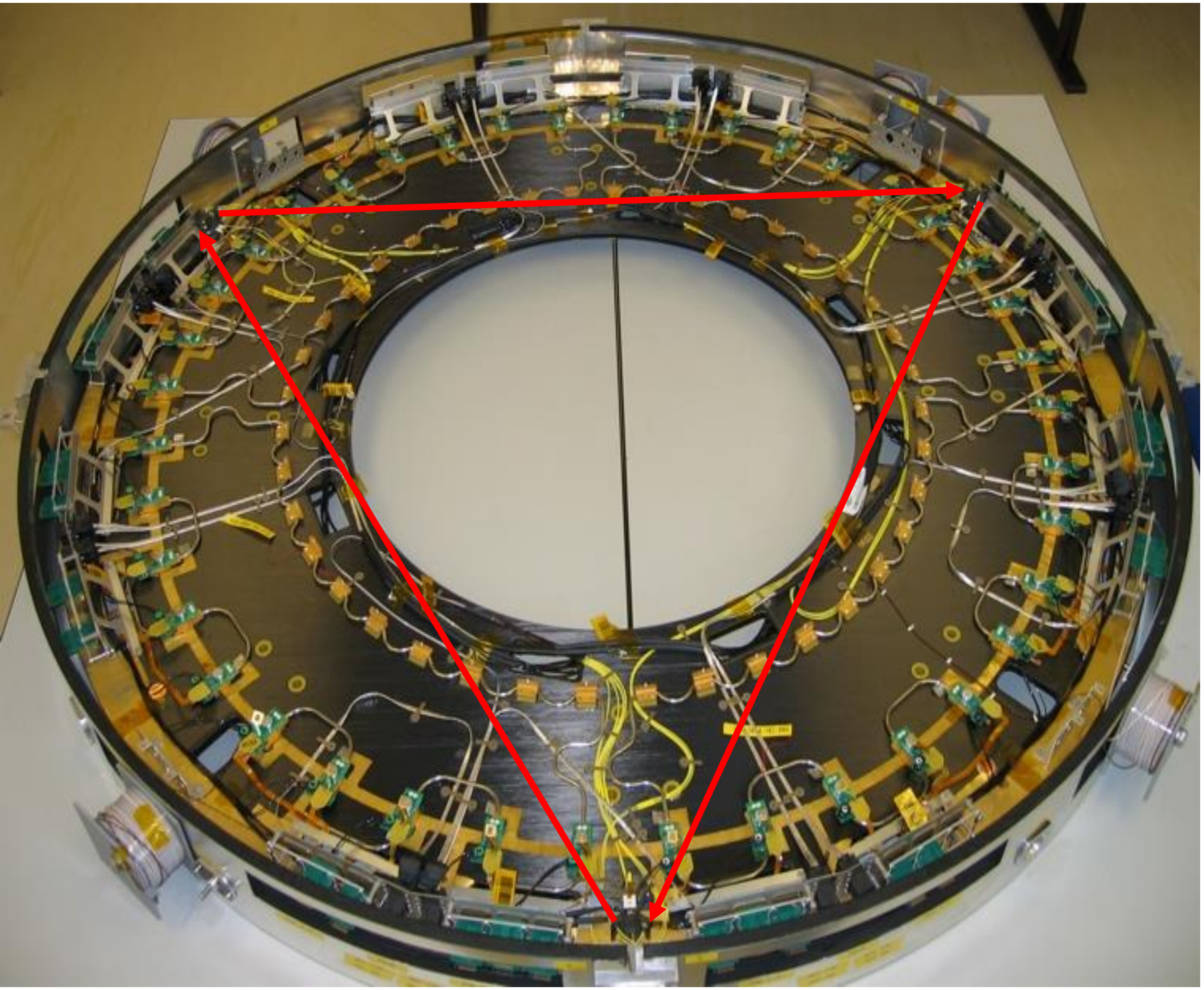
Courtesy of ETALON-AG

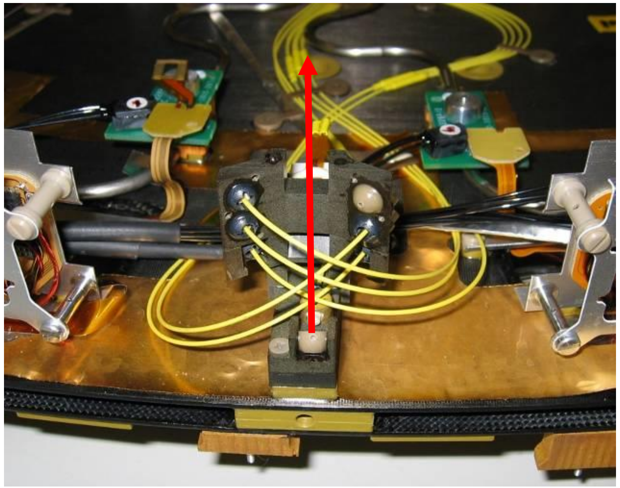
What do we need to align for LC

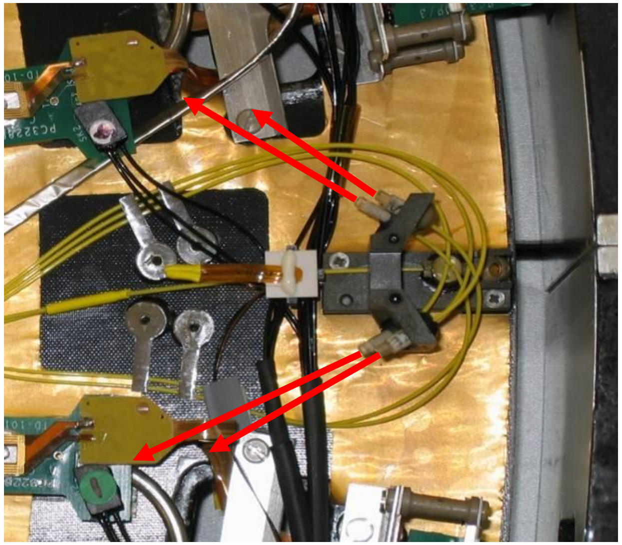
- A word on FF stabilisation
  - Continuous dynamic FSI exists (thesis A. Lancaster)
  - Higher resolutions are coming available (thesis A. Lancaster)
  - Combinations with classical interferometry are being tested ➔ nm resolutions are the aim
- Sorry: All LC alignment specific technical work currently unfunded
- But: There is hope and there is interest ;@)

End-cap FSI (1/18)

##





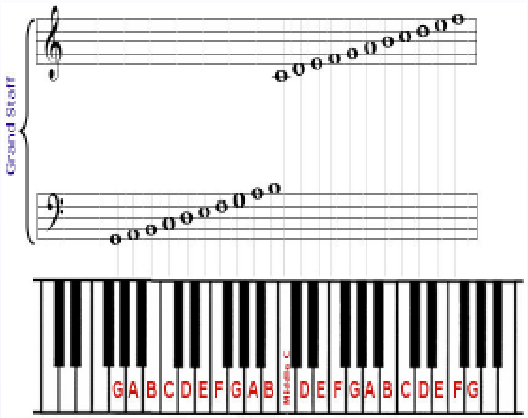


ATLAS SCT online alignment system

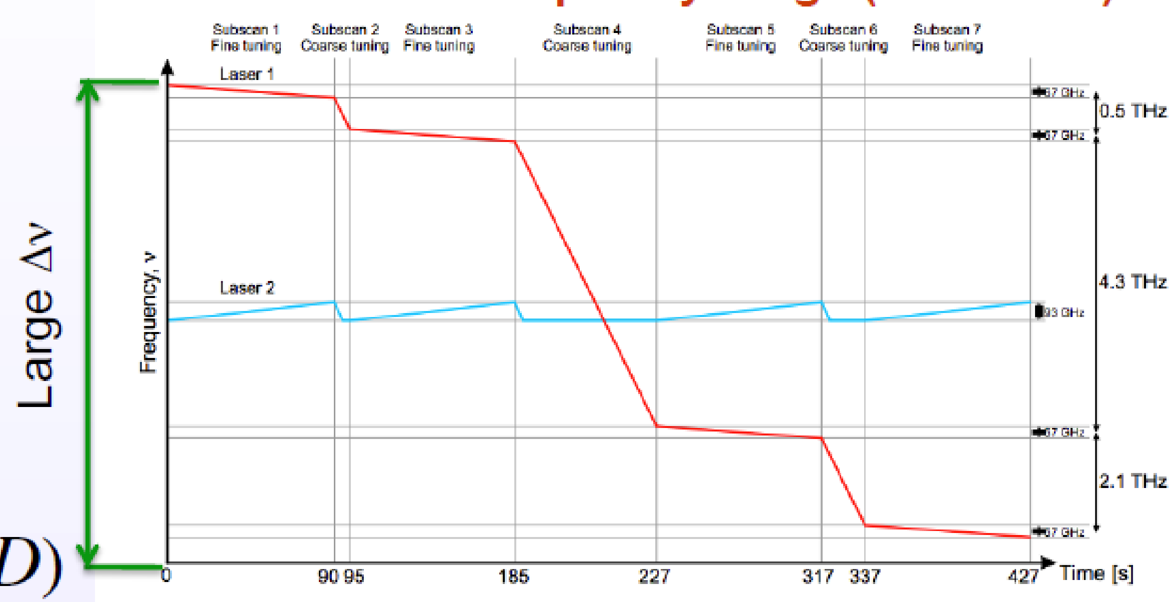
- ATLAS FSI operation methods
  - “Absolute mode”:
    - Measure OPD ratio of unknown interferometer to stabilised, evacuated reference interferometer
    - one length measurement every frequency scan O(once per 8 minutes)
    - sub-micron sensitivity (varies with signal to noise)
  - “Vibrato mode”:
    - Relative change of measurement interferometer length
    - Once every 8 seconds
    - 50nm sensitivity

Conventional FSI for absolute distance measurement

Like a long musical scale



Scan a LARGE frequency range (Δν~10THz):



$$\Delta\theta_{GLI} = \frac{2\pi}{c}(D\Delta\nu + \nu\Delta D)$$

- Measure absolute length D every 8 minutes. (wrt reference)
- νΔD term is cancelled using two lasers and a wavemeter.

Pros:

- Precise absolute measurement, D.
- Can power cycle laser without loss of precision.
- Excellent for long term monitoring.

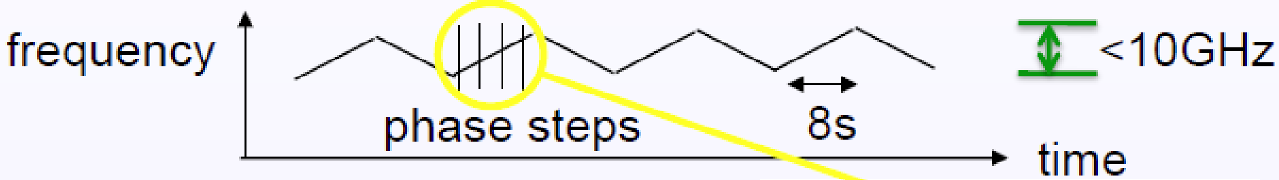
Cons:

- Need large Δν & two lasers to reduce systematic errors arising from ΔD.
- Slow, about 8 minutes per measurement.
- Remaining errors are largest when the components are moving: limits resolution during interesting rapid events.

Novel method for precise displacement measurement

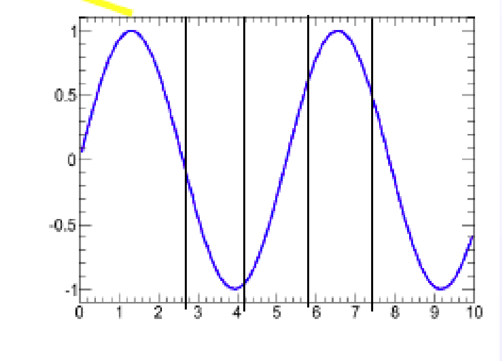
Like a vibrato note!

- **Rapidly oscillate laser frequency over small range (<10 GHz).**



- Use 4 phase steps to directly measure interferometer phase every 8 seconds.

$$\Delta\theta_{GLI} = \frac{2\pi}{c}(D\Delta\nu + \nu\Delta D)$$



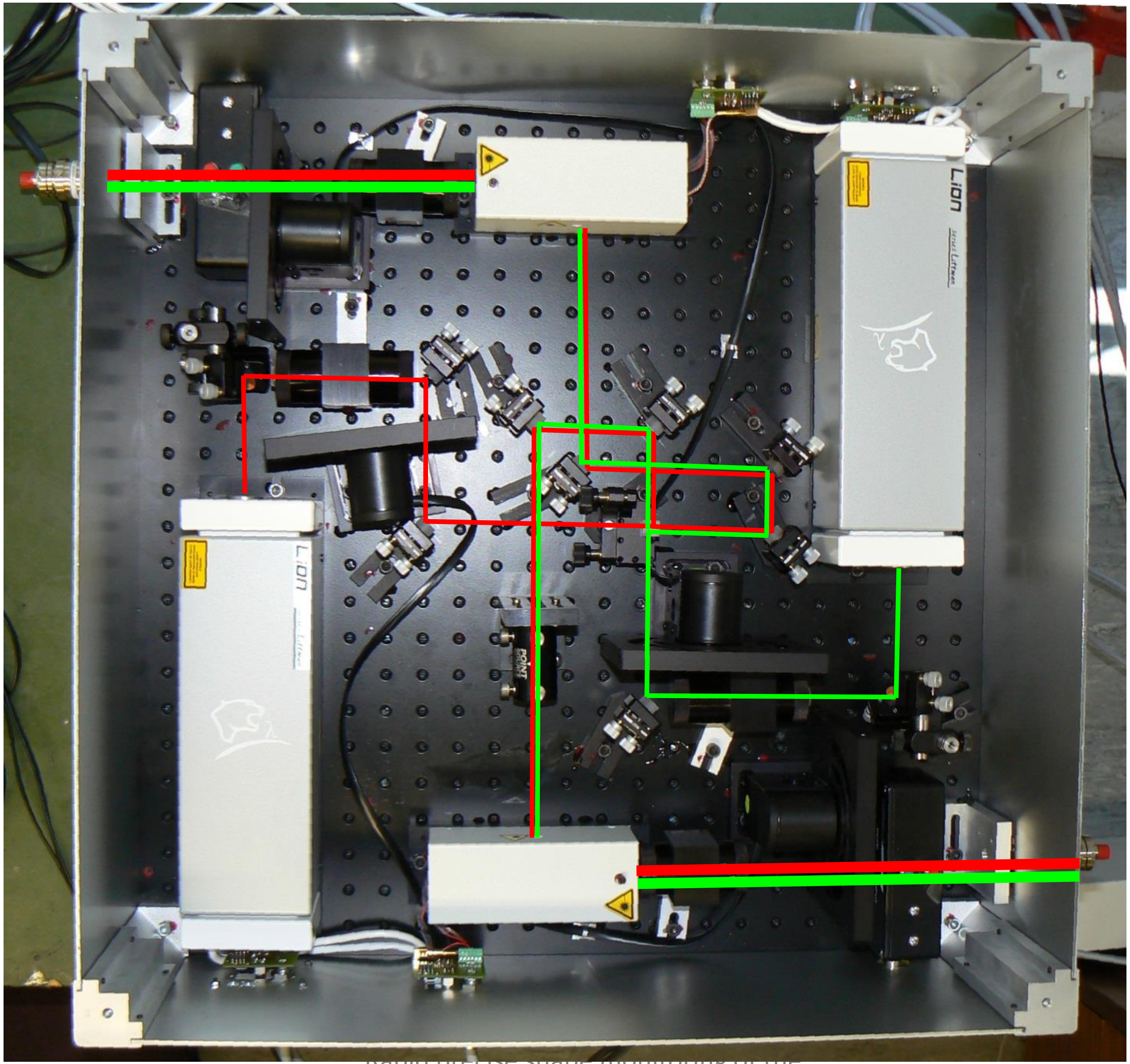
- Measure relative displacement ΔD every 8 seconds.
- DΔν term is corrected using reference interferometer system.

Pros:
- Rapid, relative measurement, ΔD.
- Sensitive to length changes at a fraction of wavelength (typ.< 50 nanometers)
- Excellent for ultra-precise short term monitoring.
- Simplified setup (single laser, small Δν)

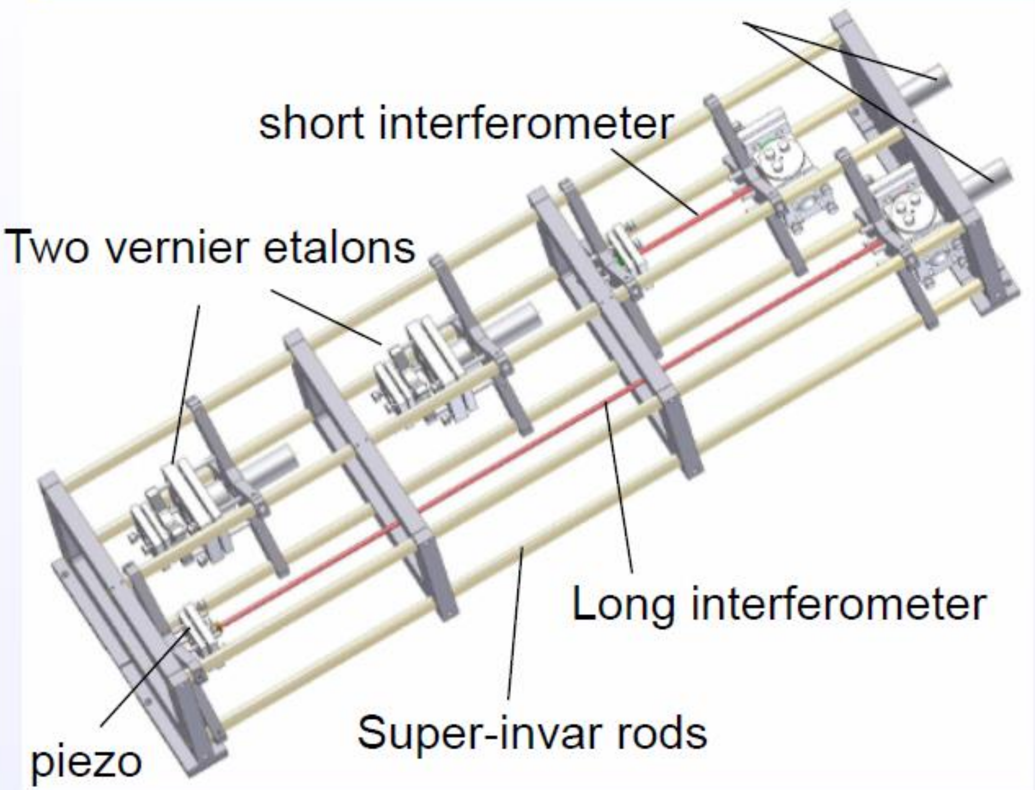
Cons:
- Lasers must run continuously, otherwise reference point it lost.
- May miscount fringes in rare case movements are extremely rapid (>λ/2 over 8s sampling time).

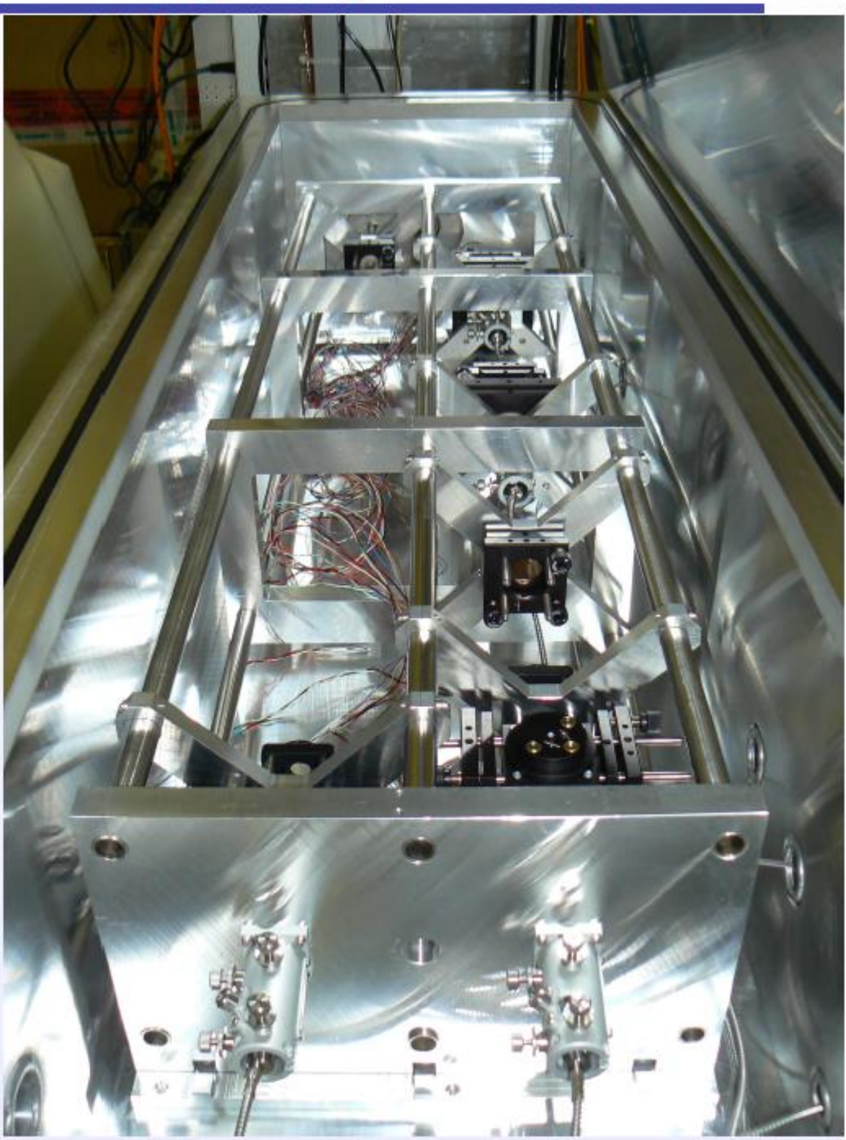
Two colour laser amplifier system

Two colour laser amplifier system



Reference Interferometry System





- Fibre collimators provides low M^2 beam.
- Super-invar / steel thermally compensating design to balance CTEs. $\Delta T(C_1L_1 - C_2L_2) = 0$.
- Both interferometers have four-fibre read-out for instantaneous phase measurement.
- Long reference has piezo for phase stepping.