The LiCAS Rapid Tunnel Reference Surveyor

The status after commissioning

Armin Reichold for the LiCAS collaboration.

Warsaw University

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LiCAS

OXFORDphysics

Linear Collider Alignment & Survey

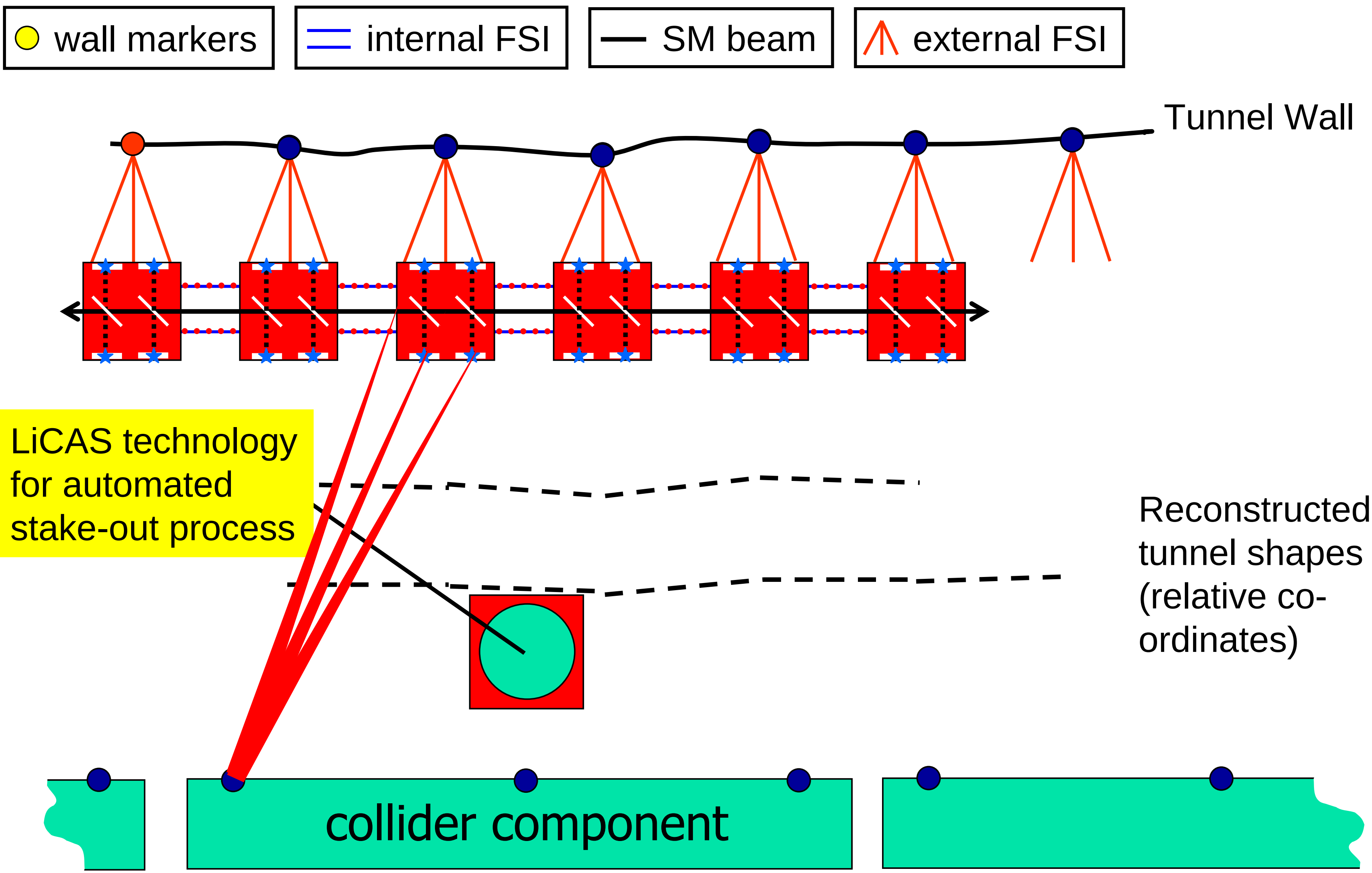
Overview

- Mission statement and design choices
- Purpose of the current RTRS prototype
- Progress and Status
  - construction, installation and commissioning
  - FSI ➔ talk by John Dale
  - LSM ➔ talk by Greg Moss
  - software
  - current prototype functionality
  - analysis and calibration → talk by Grzegorz Grzelak
- Lessons learned
- LiCAS-II
- Plans for the next year

Mission statement (and design choices)

- More than 100km of ILC beamlines need to be accurately aligned to produce ultra high luminosity
- We are developing a method for reference network **S**urvey (LiCA**S**). This method should:
  - address all co-ordinates (vertical is most critical)
  - be highly accurate O(200μm over 600m vertical)
    - use Frequency Scanning Interferometry (FSI)
    - Laser straightness monitors (LSM)
    - both in vacuum
    - these are techniques with high intrinsic resolution avoiding long distance systematic errors from air refraction
  - be cost effective
    - use a fast robotic system which need little manpower and can be remotely operated, reducing cost of staff and off downtime
  - be readily calibrated and show good long term stability
    - have no moving parts in the sensing system (passive sensing unit)
    - capable of in-situ self calibration

RTRS Measurement Concept



Purpose of the RTRS prototype

- Provide an R&D platform with which we can
  - develop methods for robotic tunnel survey.
  - develop methods for in-situ calibration.
  - determine performance of each measurement technique in complex system outside laboratory environment.
  - determine performance of overall RTRS measurement procedure over distances up to 50m (tunnel length limit).
  - learn what minimal & optimised user system should be
- Prototype has functionality beyond that of "user system"

LiCAS Measurement Unit Assembly

- Assembly = VERY hard work for very long time under clean room conditions
- Oxford workshop and students essential (overtime, weekends, long hours, fast turnaround)
- John did 30 days in the clean room with no day off!!

Thank you

John

Greg

Mike

Mike

Roy

Mark

Ron

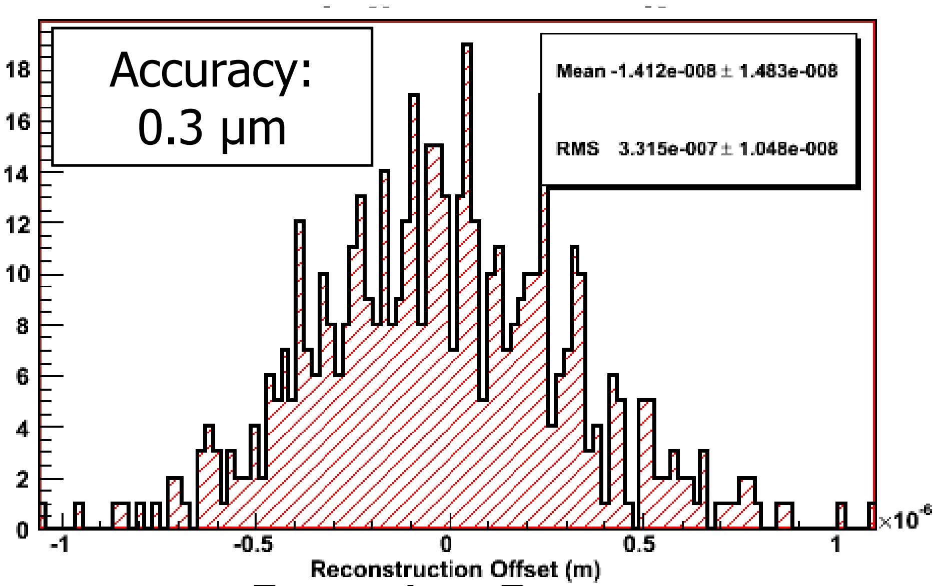
Lee

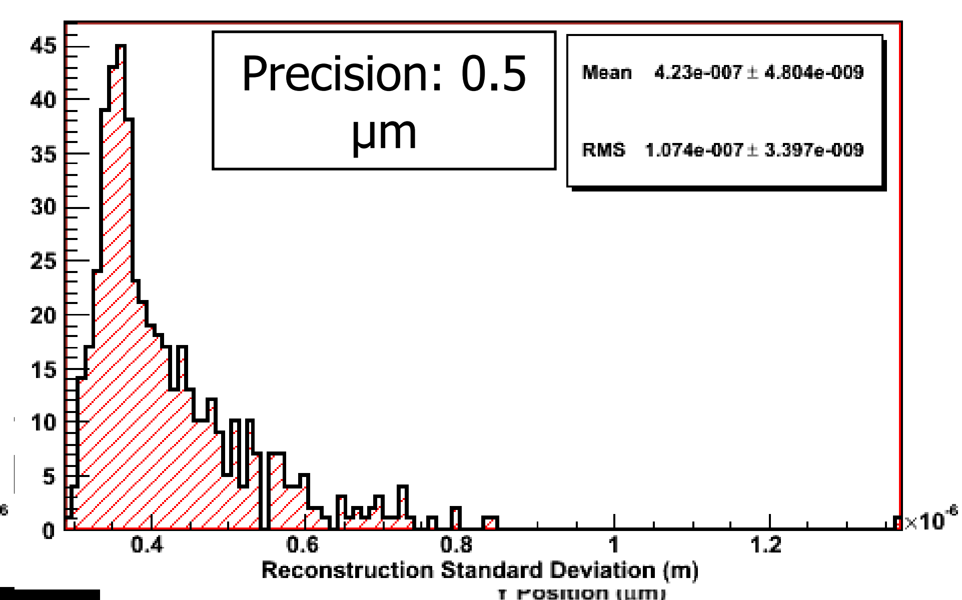
David

Matt

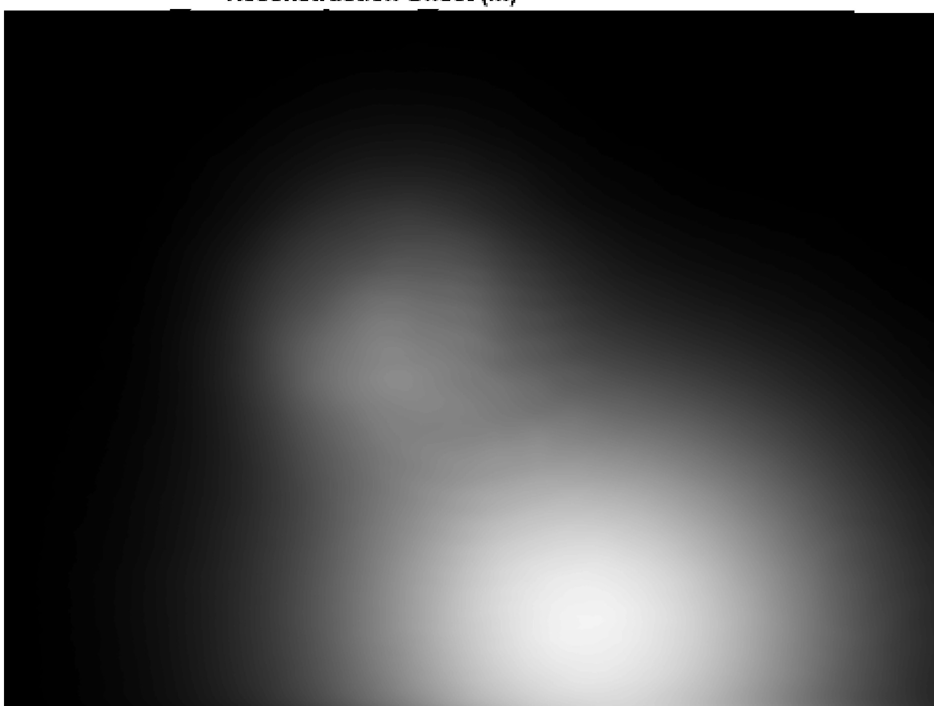
Sigal

Yanmei





ograms of 500 calibrations runs)



s

- Excellent Stability of long FSI lines, <100nm @ 4m over 30h
- World le
  4.4 nm
- Highly r
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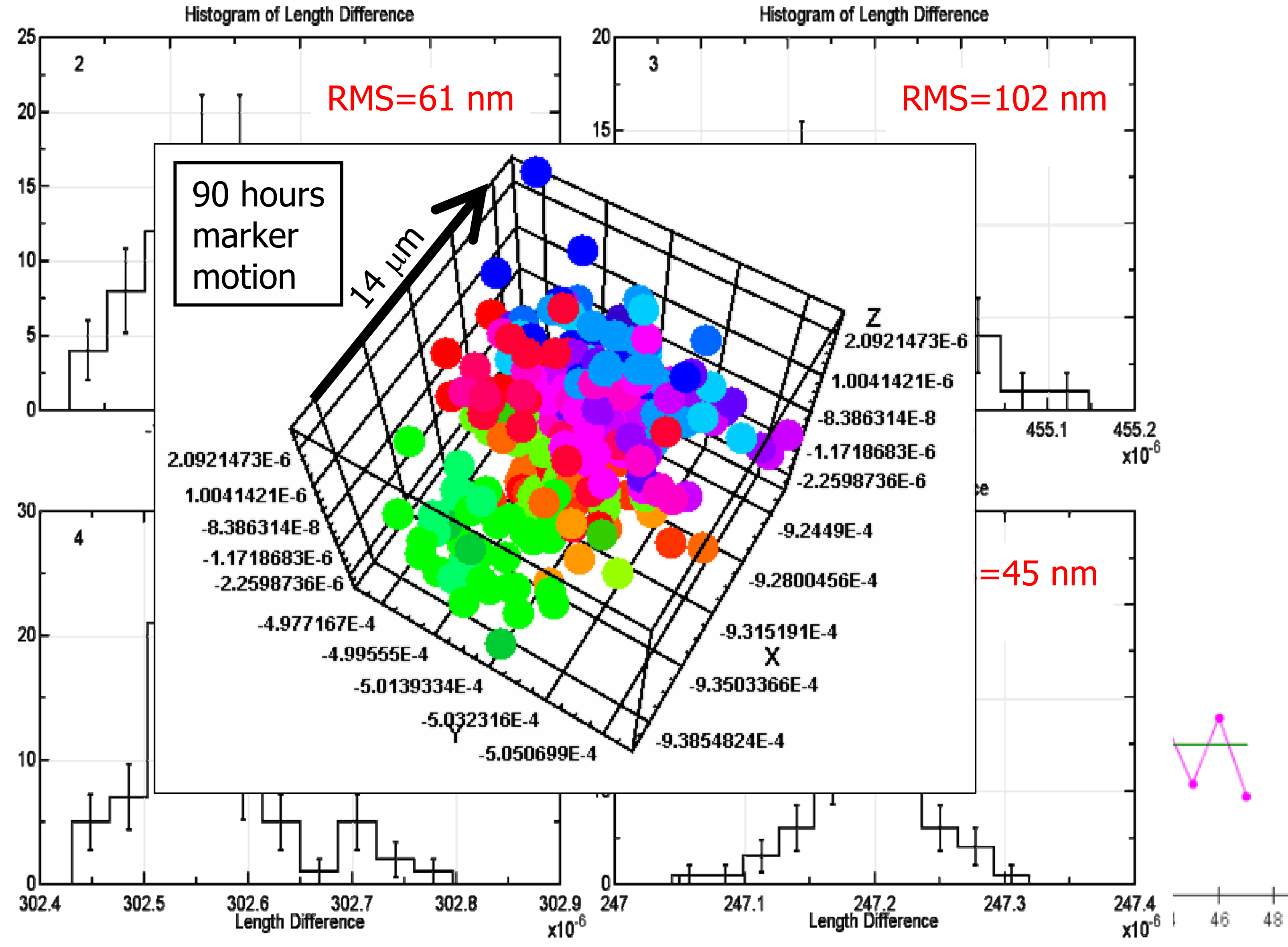


Software

Software Package		lines of code
Firmware	:	13008
Simulgeo and simulations	:	30894
Drive motor control	:	625
LSM reconstruction & calib	:	86328
FSI reconstruction & calib	:	47322
Global reconstruction & calib	:	1125
Temperature calibration	:	6000
FSI file I/O	:	1897
Stepper motor control	:	4615
DAQ	:	72107
GIACoNDE and binary java I/O	:	17604

Total	:	281525

- That is 3.60 times "The lord of the rings" but provides a slightly less thrilling reading experience

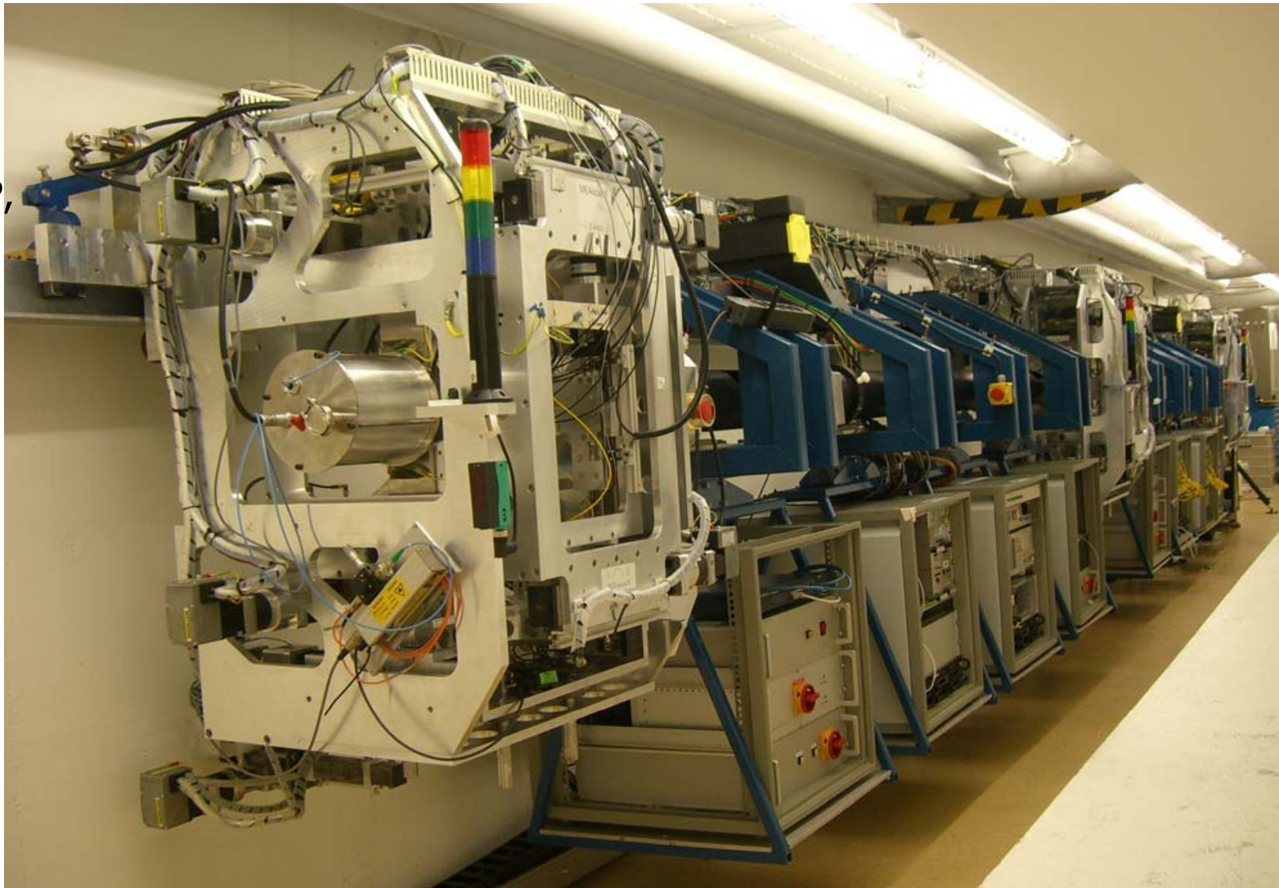
Major sub-projects

- LSM software (Greg Moss)
  - was written over 3 years
  - 86,000 lines of code
  - in excess of 200 classes and global functions
  - ray tracing
  - multiple beam fitting
  - reconstruction
  - classical and self calibration
  - Monte-Carlo evaluation software
  - results presentation
- Reference interferometer calibration (John Dale)
  - during one year
  - took 700 GB of raw data
  - in 22,000 data runs
  - with major improvement to mechanics

Current prototype functionality

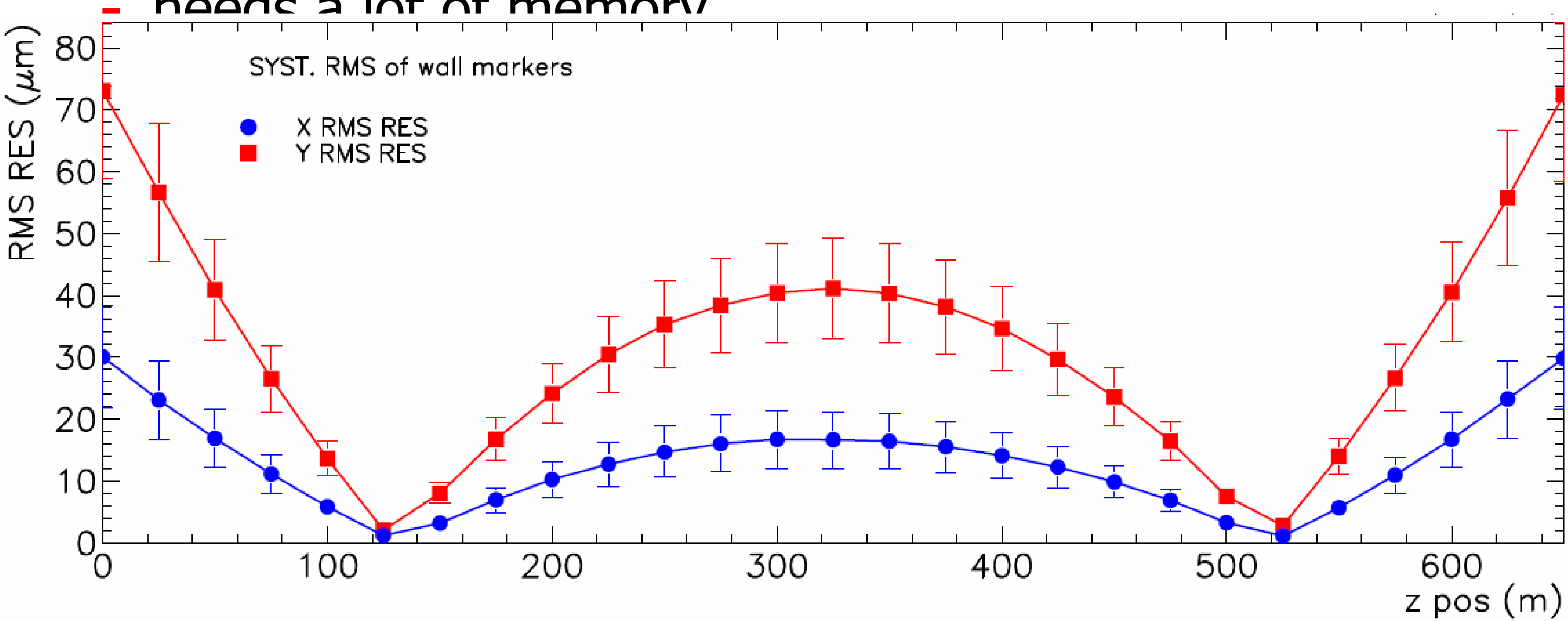
- RTRS = Large scale robotic sensing system
  - Robotics:
    - 1 ton moving mass
    - each measurement unit moves in 6D
    - 25 axis of motion
    - 39 CAN bus controlled stepper motors
    - 6 network controlled picco motors
    - 3 drive motors with 6 kW total power
    - 82 limit and proximity switches
- DAQ
  - 204 MB data per stop
  - 4 servers with 1.2 TB storage take data via:
  - CAN, USB-II, RS485, TCP-IP, PCI
- Pre-Calibration
  - all sensing elements measured with CMM and smart scope
- Mechanics
  - vacuum system with > 100 accesses, joints and feedthroughs, many custom

- Sensing systems (data source rate):
  - 38 FSI interferometers (210 MB/sec)
  - 12 LSM cameras (298 MB/sec)
  - 3 wall marker cameras (78 MB/sec)
  - 96 calibrated temperature sensors
  - 3 computer controlled lasers
  - 12 axis of gravity reference tilt sensors



Analysis & Calibration

- So far high level reconstruction uses Simulgeo
- Simulgeo = flexible general purpose tool but
  - lacks some features needed to describe proper calibration experiments (can't move an object) *)
  - needs a lot of memory



*) Simulgeo is still a good tool to check calibration constants and measure systematic errors. See talk by G. Grzelak

Analysis & Calibration

- We follow the Canadian and German schools (owls to athens)
  - D.E. Wells & Edward J. Krakiwsky
  - Hans Pelzer
  - Charles L. Lawson & Richard J. Hanson
- Brief reminder of the basic idea:
  - Measure observables F (FSI lengths, CCD co-ordinates, tilt angles)
  - F depend on unknowns X through non linear function F=F(X)
  - X consist of
    - internal unknowns X_i (calibration constants)
    - external unknowns X_e (wall marker co-ordinates)
  - We seek those $X_{optimal}$ which describe our measurements best

$$\sum_{i=all\ measurements} \left[F_{i,computed}(X_{optimal}) - F_{i,observed} \right]^2 = \min$$

  - We find them iteratively using a linearised Gauss Markov model *)

$F = A \cdot (X - X_0) + F_0$ where $A = \partial F / \partial X$ +) is called the design matrix

  - We can now analytically compute elements of the design matrix

*) Gauss Markov is the best linear estimator but there can be better non-linear estimators ➔ Greg's Ray tracer + non-linear fit

+) ignore $\partial^2 F / \partial X^2$ although trying to find minimum

Analysis & Calibration

- The LSM design matrix for self calibration
  - move one car to different positions measuring at each position

first position | second position

X_e = external unknowns

X_i = internal unknowns (calibration parameters)

xternal unknowns

car position

x,y,Rx,Ry

Measure-ments (knowns)

Unknowns

[redacted]

first position

CCD-0 x Y

CCD-1 x Y

CCD-2 x Y

CCD-3 x Y

second position

CCD-0 x Y

CCD-1 x Y

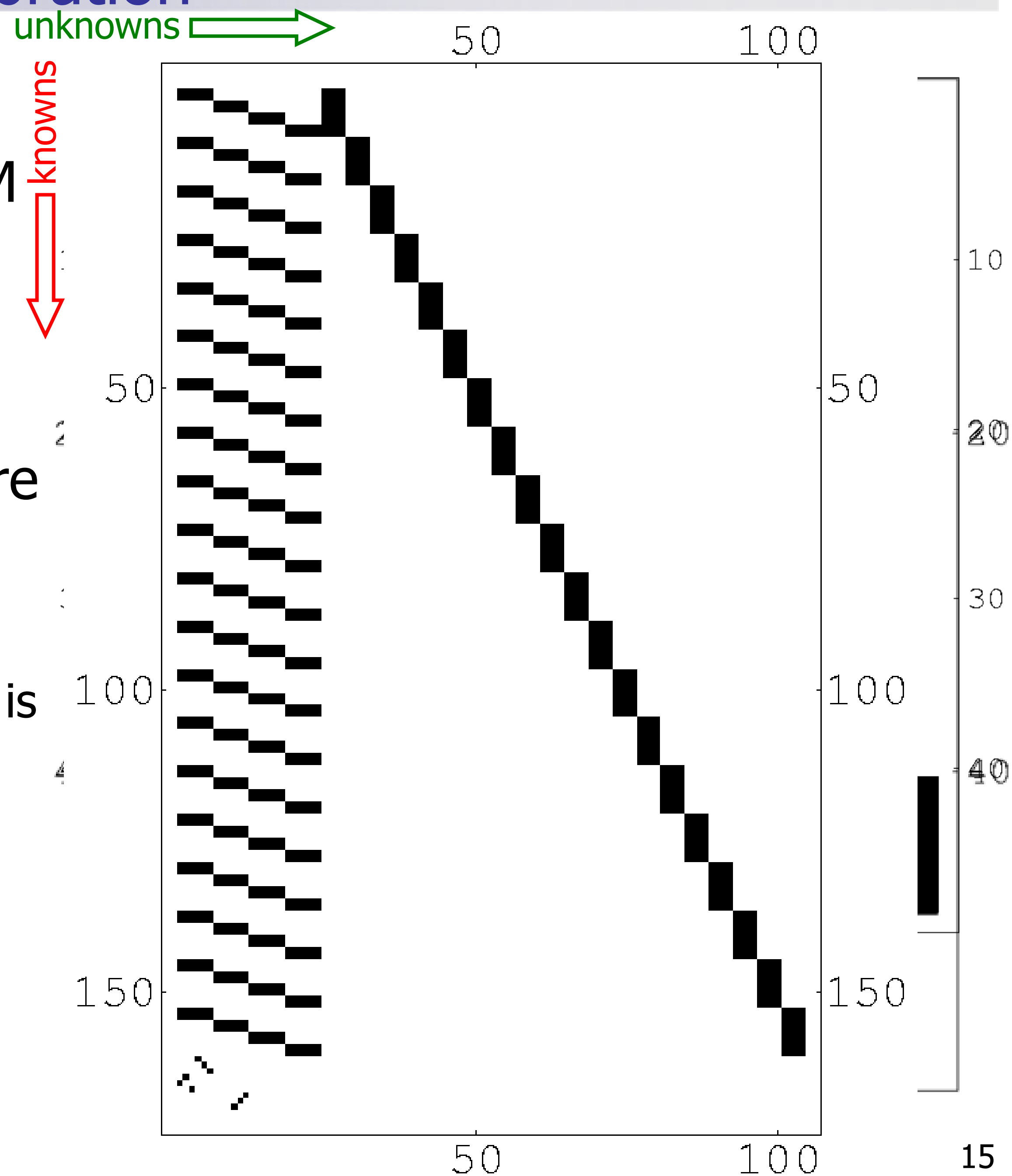
CCD-2 x Y

CCD-3 x Y

1
2
3
4
5
6
7
8

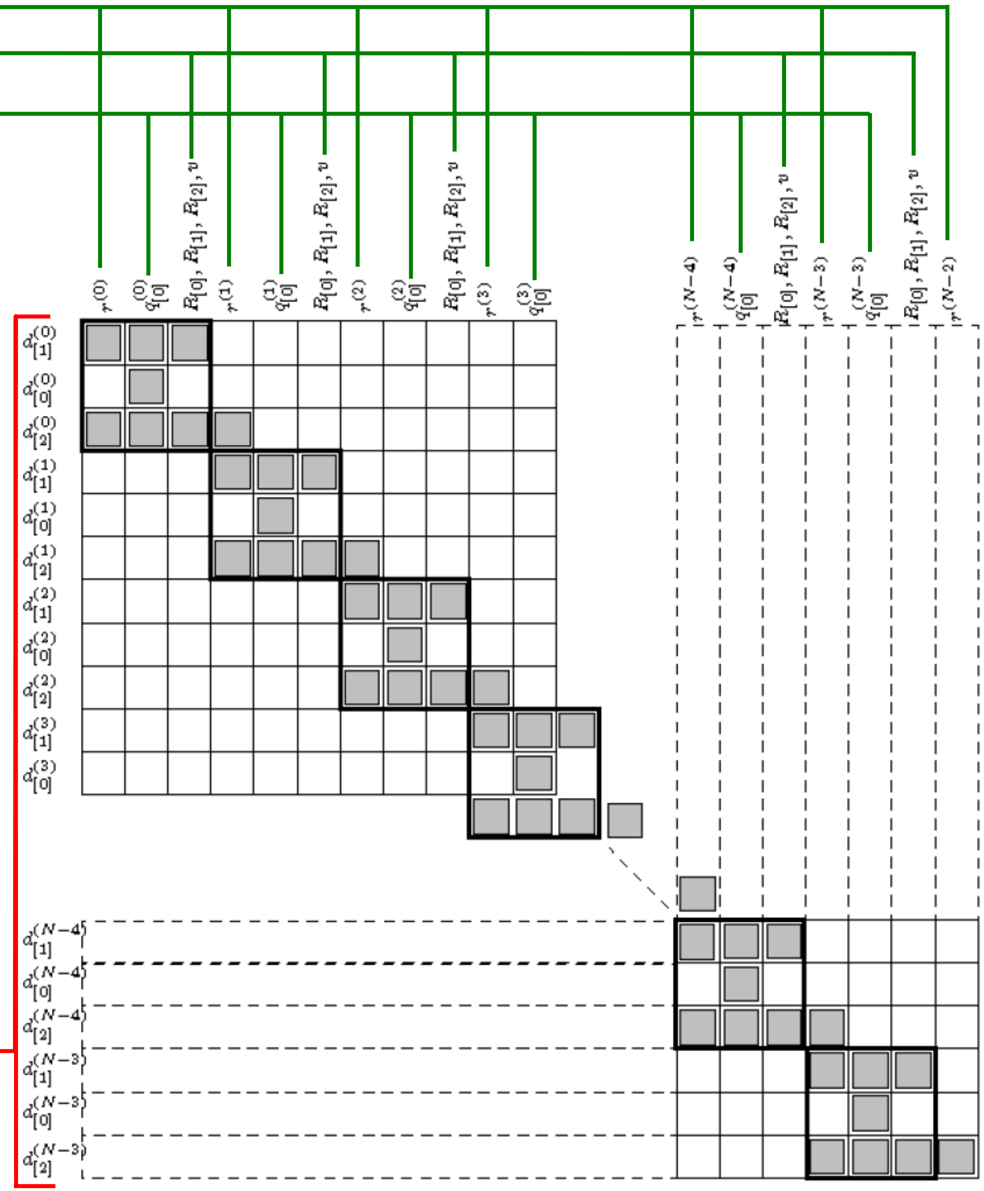
Analysis & Calibration

- Need at least 6 positions to solve LSM calibration
  - now A is square
- Also need to properly constrain it
- Now need to add more measurements to get decent accuracy (20 positions)
  - analytical form of this is ~1500 pages A4
  - numerical inversion is not too difficult



Simplified design matrix for tunnel survey (3-car train)

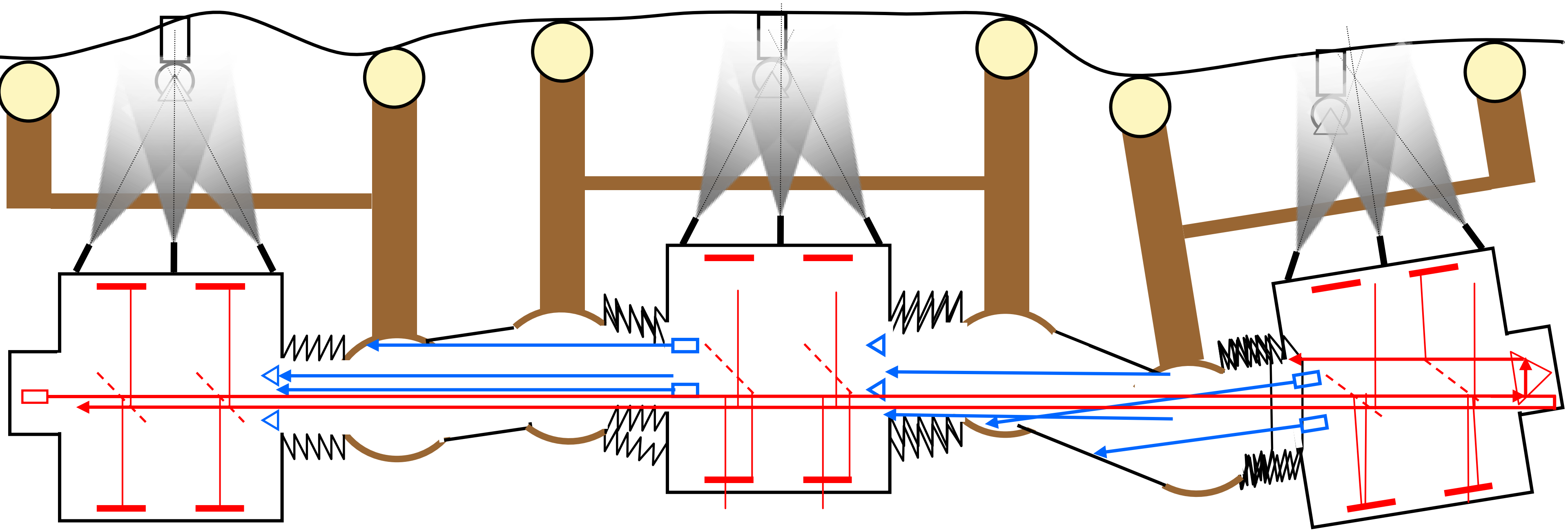
- ignore for this example :
  - left band of calibration constants
  - all but external FSI measurements
- now X_e are
  - vectors from one wall marker to the next $\boldsymbol{r}^{(n)}$
  - car positions v } wrt. first car
  - car angles $R_{[n]}$ } wrt. first car
  - marker position wrt "its" car $q^{(m)}_{[n]}$ (m) train stop number, [n] car number
- only measurements shown:
  - length $\boldsymbol{d}$ of external FSI lines $d^{(m)}_{[n]}$ (m) train stop number, [n] car number
  - $(A^T PA)$ is tri-diagonal!



Lessons learned

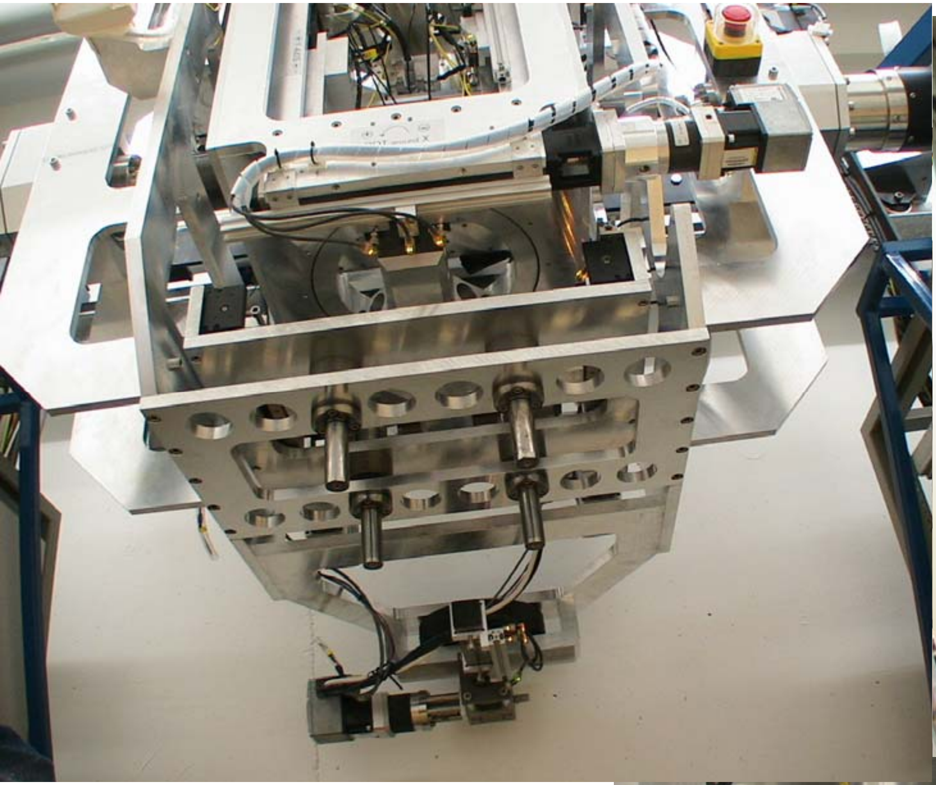
- RTRS
  - LSM sees vibrations → need more rigid support and have to use image averaging
  - Weight of unit, mover system and vacuum system is large and leads to vibration problems and low Eigenfrequencies ➔ bootstrap our "diet" with a Carbon Fibre Unit
- LSM
  - Multiple reflections in cameras are relevant → next time remove cover plates from CCD chips
- FSI
  - internal and external FSI perform above expectations
    - internal RMS=O(100-200nm)
    - external RMS=O(2-3 μm)
  - reference interferometer design must account for calibration process
- We are more sensitive to calibration errors than expected (yes JP., you were right. We are slow learners but we DO learn.)
  - Systematic errors scale with $length^2$ (statistical error scales only with $L^{3/2}$)
  - want longer train via large car separation to be less sensitive to errors. (4 cars with 25m car separation appears very safe)
  - want methods for cancellation of errors (up & over a'la laser tracker, see later)

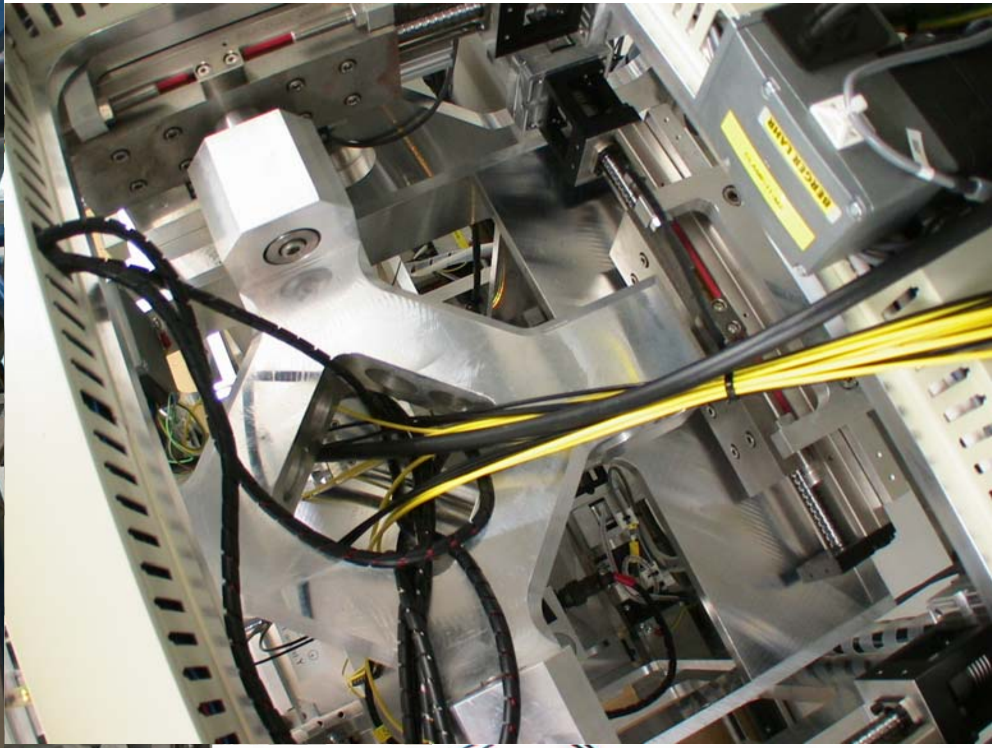
Lessons learned (6D motion)

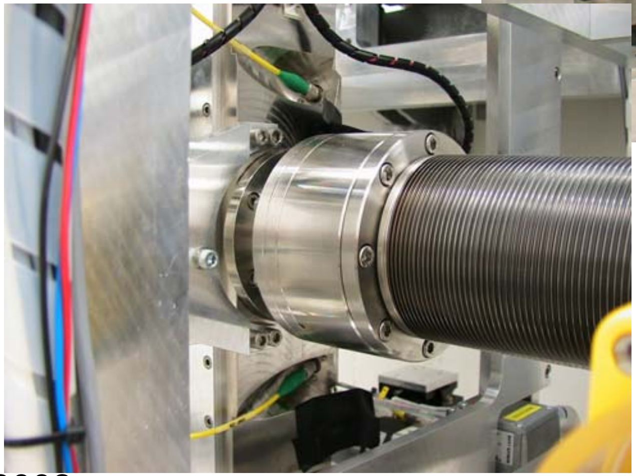


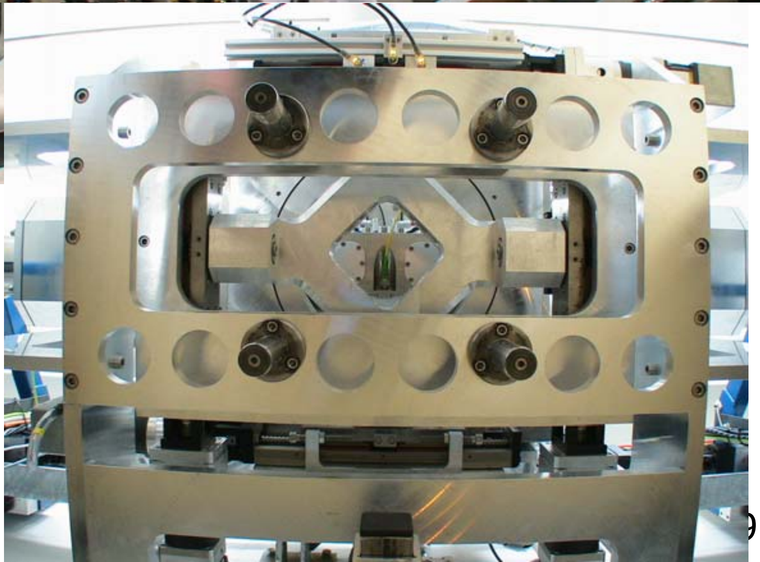
- The 6D motion system
  - used to stay inside the dynamic range of internal and external sensors against the non-straightness of the rail
  - most complex system in RTRS
  - complex motor control software needed
  - major cost driver

6D Motion System





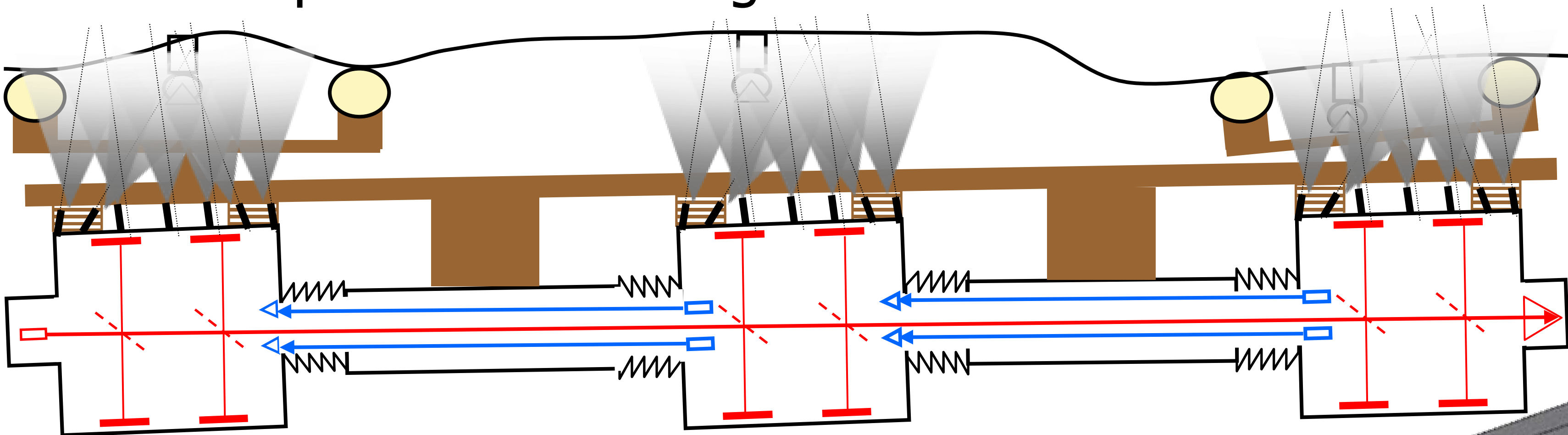


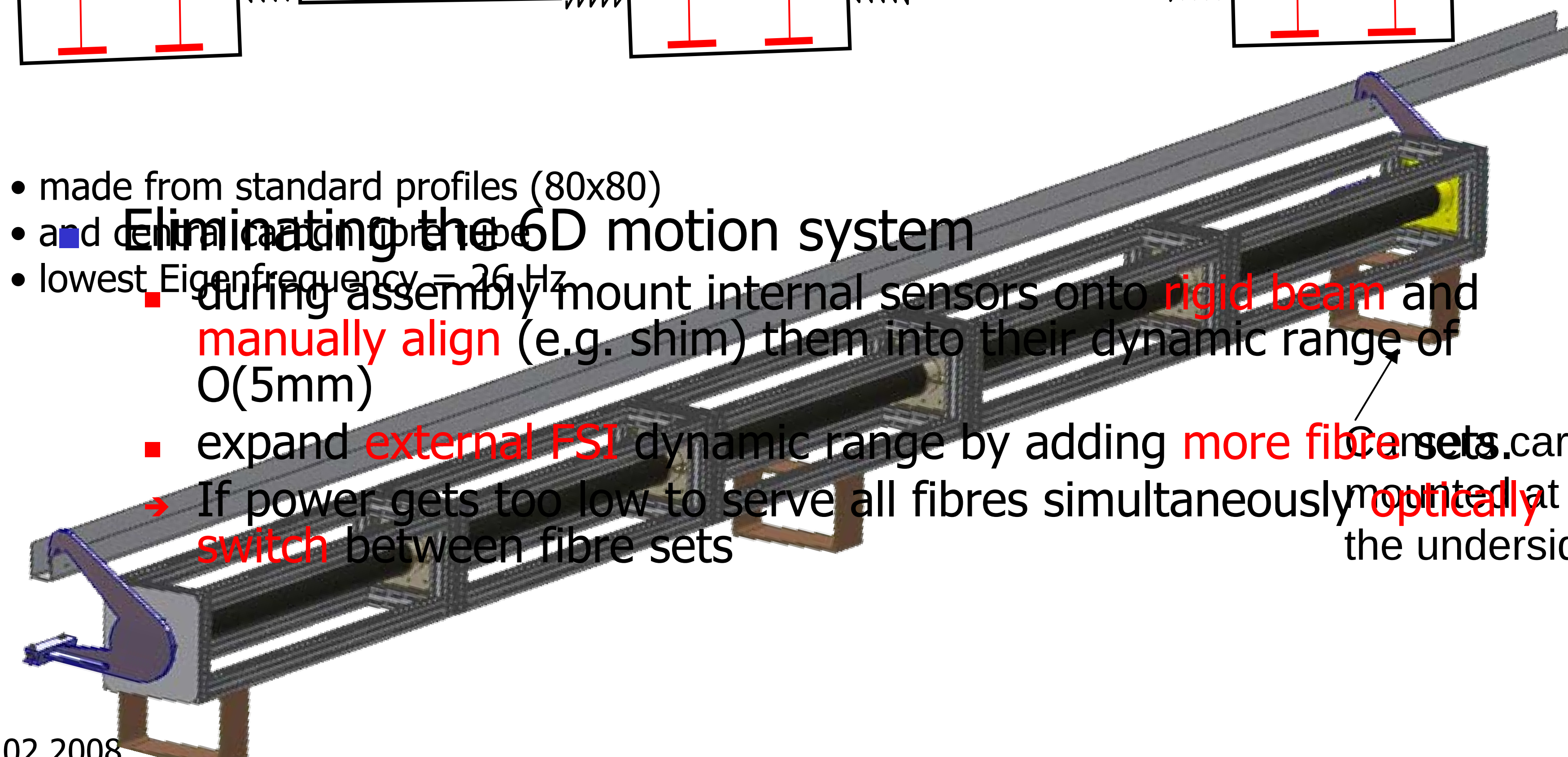


Lessons learned & LiCAS-II-a

- Can we improve 6D motion system
  - hexapod movers
  - more rigid:
    - ν_{res}=90 Hz (horz.)
    - ν_{res}=500 Hz (vert.)
  - high load: 200 (50) kg vert. (horiz.)
  - fewer motors: 6 instead of 10
  - smaller: ∅=350 mm, H=330 mm
  - lighter: m=17 Kg
  - huge travel:
    - ±50mm (horz.) ± 25 mm (vert.)
    - $\pm 15^{o}$ (θ_x, θ_y) $\pm 30^{o}$ (θ_z)
  - They are not exactly cheap though

Conceptual sketch of rigid beam mechanics for LiCAS-II





- made from standard profiles (80x80)
- and central carbon fibre tube
- lowest Eigenfrequency = 26 Hz

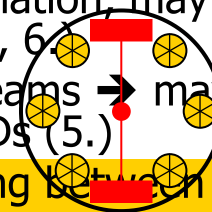
Camera cars mounted at the underside

Eliminating the 6D motion system

- during assembly mount internal sensors onto rigid beam and manually align (e.g. shim) them into their dynamic range of O(5mm)
- expand external FSI dynamic range by adding more fibre sets.
- ➔ If power gets too low to serve all fibres simultaneously optically switch between fibre sets

LiCAS-II Changes

- LiCAS-II changes
  1. a) rigid-beam mechanics or
     b) hexapod movers
  2. dual laser scanning
  3. Carbon Fibre measurement units
  4. Fold cameras into cylindrical envelope
  5. new reference interferometers *)
  6. increased spacing between cars
  7. >3 cars, preferably 6
- Pros
  - no [improved] 6D unit adjustment system (1.a [1.b])
  - smaller (1.a, 1.b, 4.)
  - lighter (1.a, 1.b, 3., 4.)
  - easier to install (1.a, 1.b)
  - more resistant to vibration (1.a, 1.b, 2.)
  - less systematic errors (5., 4., 2.)
  - higher resolution (2., 5.)
  - vacuum system needs very little flexibility (1.a)
  - no time needed for pre-alignment of train (1.a)
  - cheaper (1.a)
- Cons
  - Carbon Fibre is more complex to engineer (3.)
  - dual lasers need faster DAQ (expected ready for test in June, 2.)
  - needs better LSM collimation, may use Poisson-line instead (5., 6.)
  - longer LSM ➔ wider beams ➔ may need slightly larger CCDs (5.)
  - may need fibre switching between parts of external FSI (1.)
    - either less synchronous data
    - or search for the best external area first then take synchronous data
  - Hard to scale to long length (1.)



*)
- 4-fibre readout measures instantaneous phase (see talk by P. Coe)
- more beam folding ➔ shorter external dimensions
- liquid cooled/heated for ease of calibration
- both ends openable
- compensation length adjustable while in vacuum
- material CTE measured before construction ➔ need less dynamic range in tuning mechanism

Plans for next year

- Operation of current prototype at DESY until Aug08
  - run calibration experiments
  - improve vibration isolation
  - perform multiple full tunnel surveys
    - use various RTRS configurations (swap units, rotate units)
    - use variable fraction of measurements in analysis to test redundancy
    - check systematics against laser trackers
  - operation with Helium instead of vacuum
  - study of different analysis and calibration methods (linear algebra)
- Build dual laser scanning FSI DAQ and test it on the RTRS
- Build new reference interferometers and compare them to old ones
- **CANNOT** build a second RTRS due to termination of ILC program in the UK ➔ This is our last IWAA

Thanks for your attention