The LiCAS-RTRS

A Rapid and Cost Efficient Survey System for the ILC

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Linear Collider Alignment & Survey

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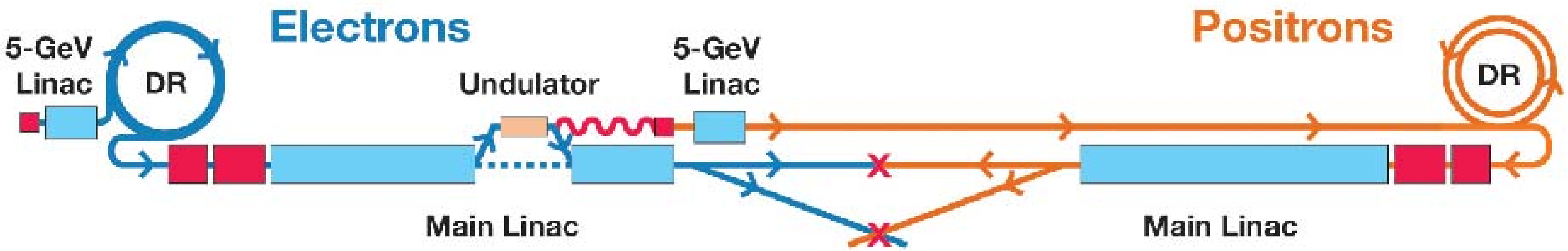
Overview

- Introduction
  - The ILC
  - LiCAS project mission
  - Comparison to traditional techniques
  - The RTRS concept
  - Cost modelling of the RTRS reference survey
- Project Status (news only)
  - Expected performance
  - Sub-systems
    - FSI (skipped)
    - LSM
    - electronics
    - mechanics
  - Installation

International Linear Collider (ILC)



- Total length end to end ~ 30 km
- Total beam lines > 100 km
- E_{cm} adjustable from 200 – 500 GeV (>5*LEP)
- Design peak luminosity 2×10^{34} $cm^{-2}s^{-1}$ (~10,000*SLC)
- Energy stability and precision below 0.1%
- Energy upgradeable to 1 TeV
- Beam height at collision point ~ 5nm

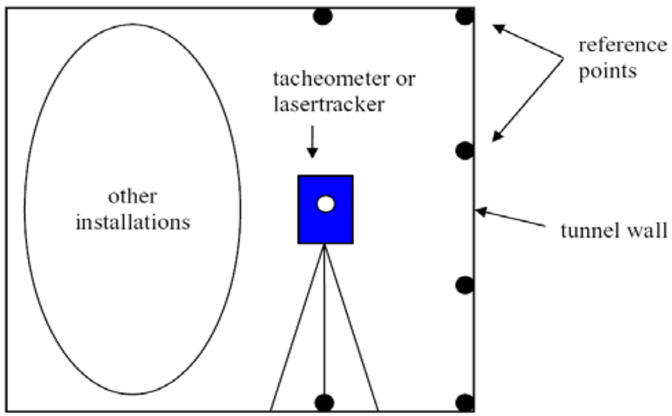
LiCAS Project Mission

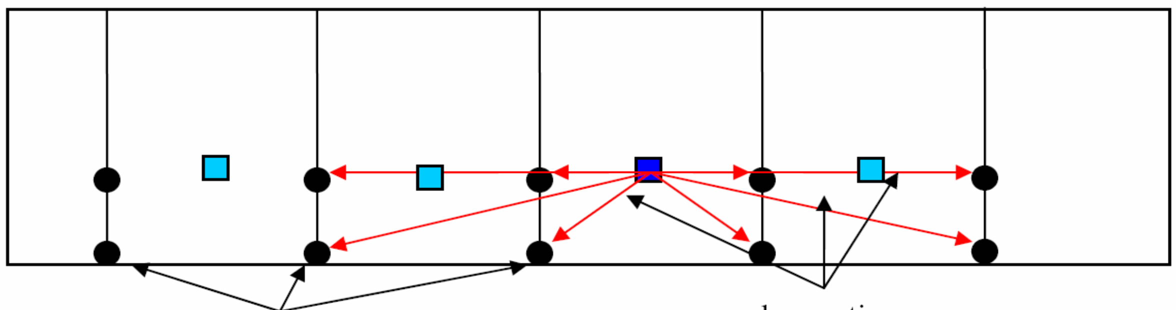
- All ILC elements need to be accurately aligned to produce full luminosity
- Survey = multi step process with single tolerance budget driven by accelerator physics:
  - component construction
  - component fiducialisation
  - **S**urvey ← **LiCAS**
- Reference Network **S**urvey (Linac specs):
  - 200μm vertical = our slice of tolerance budget
  - over 600m = O(betatron) wavelength
- Open air survey too inaccurate (see next slide) due to instrument resolution and refraction and …
- … “somewhat” slow and …
- … “a touch” expensive (see later in this talk)
- Need new technique & instruments

➔ demonstrate Rapid Tunnel Reference Surveyor (RTRS)

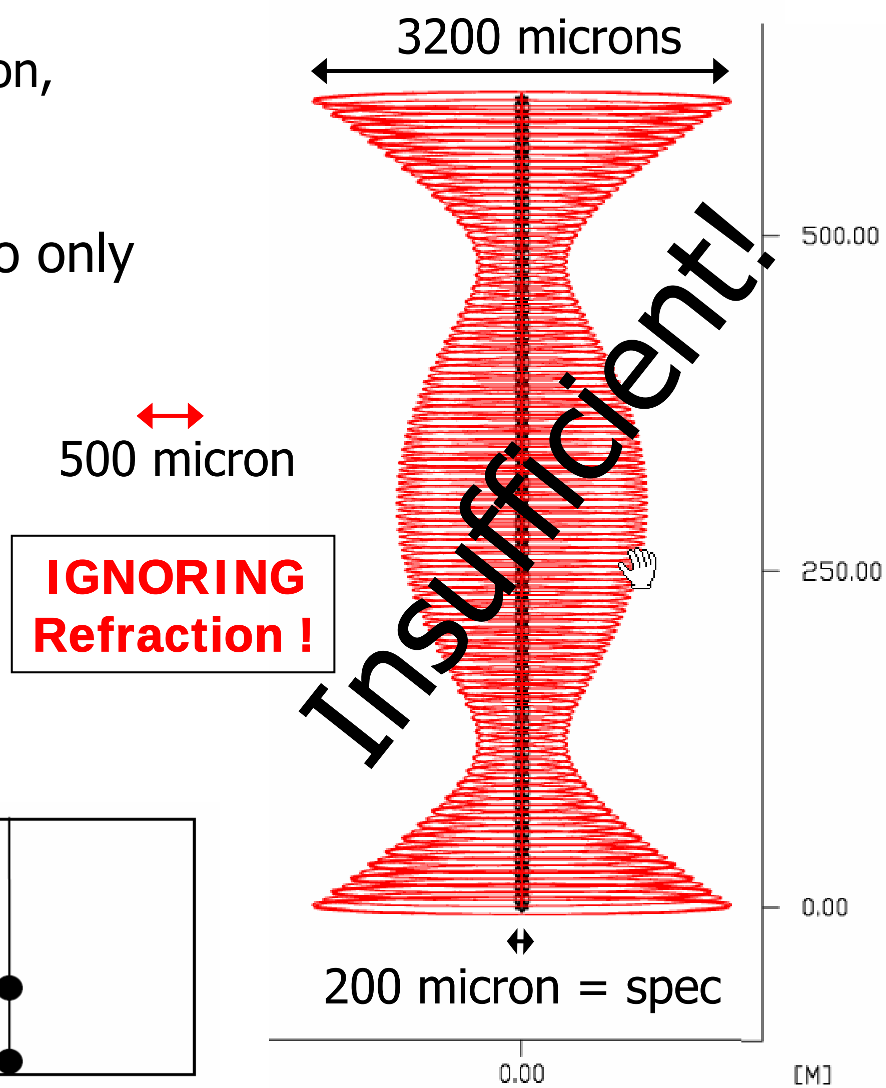
Comparison to traditional survey

- Traditional in this context means:
  - Optical survey in open tunnel air using laser trackers
  - $\sigma_{horizontal}$=0.15mgon, $\sigma_{vertical}$=0.15mgon, $\sigma_{distance}$ =0.015mm
  - Ignoring refraction
- Network geometry assumes access to only one side of the tunnel

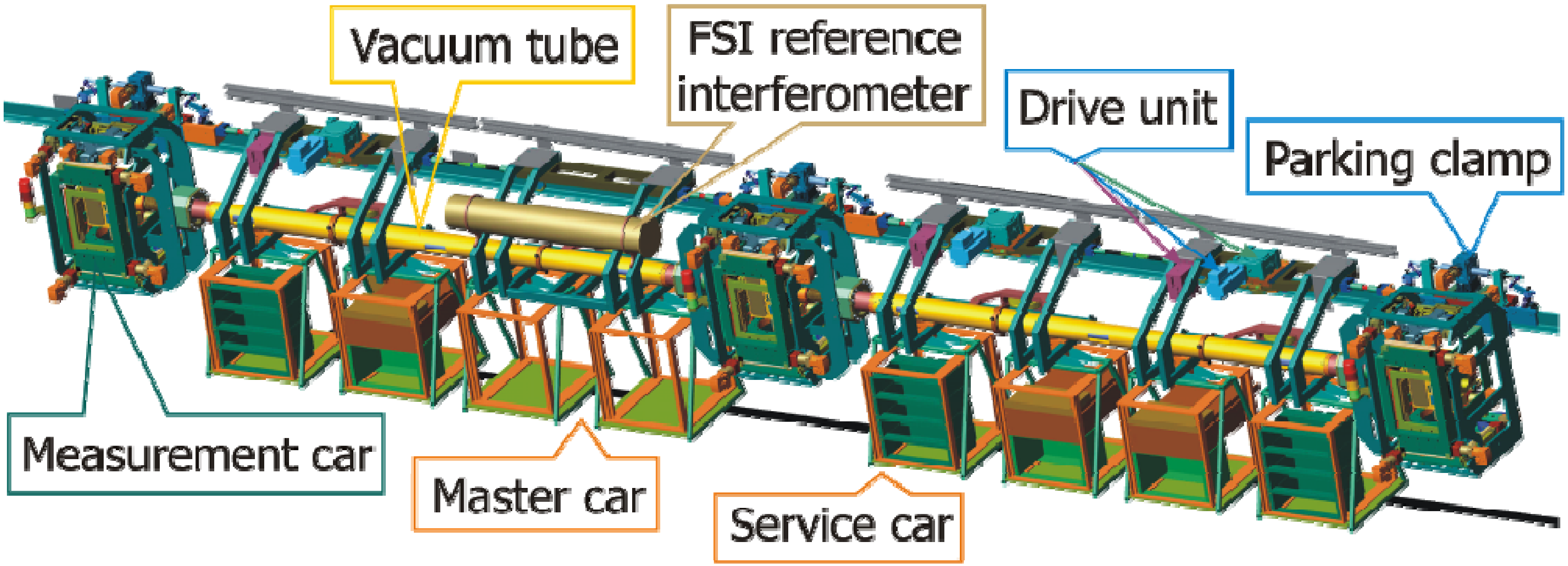




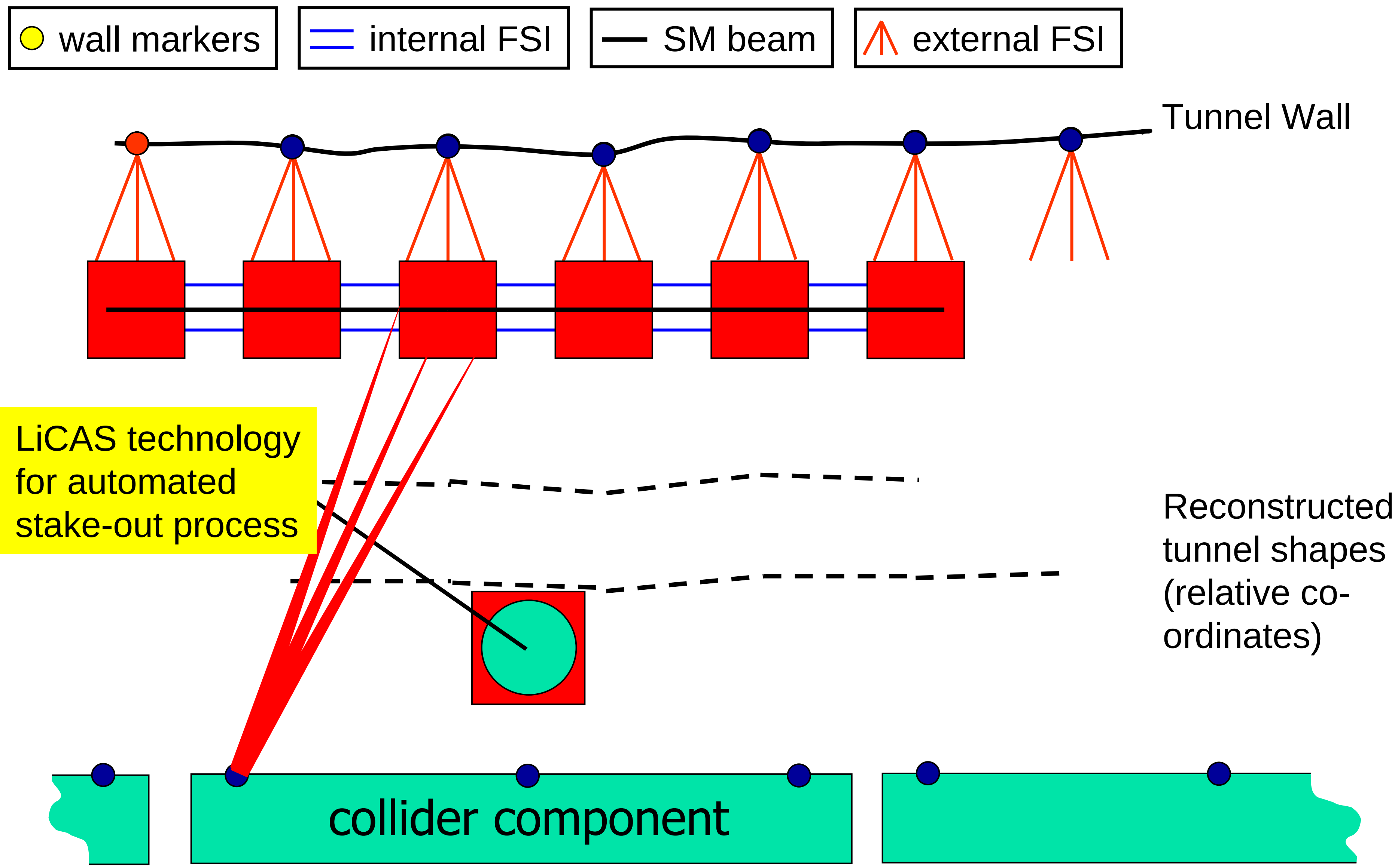
Calculations by M. Schloesser, DESY



RTRS Concept (design overview)

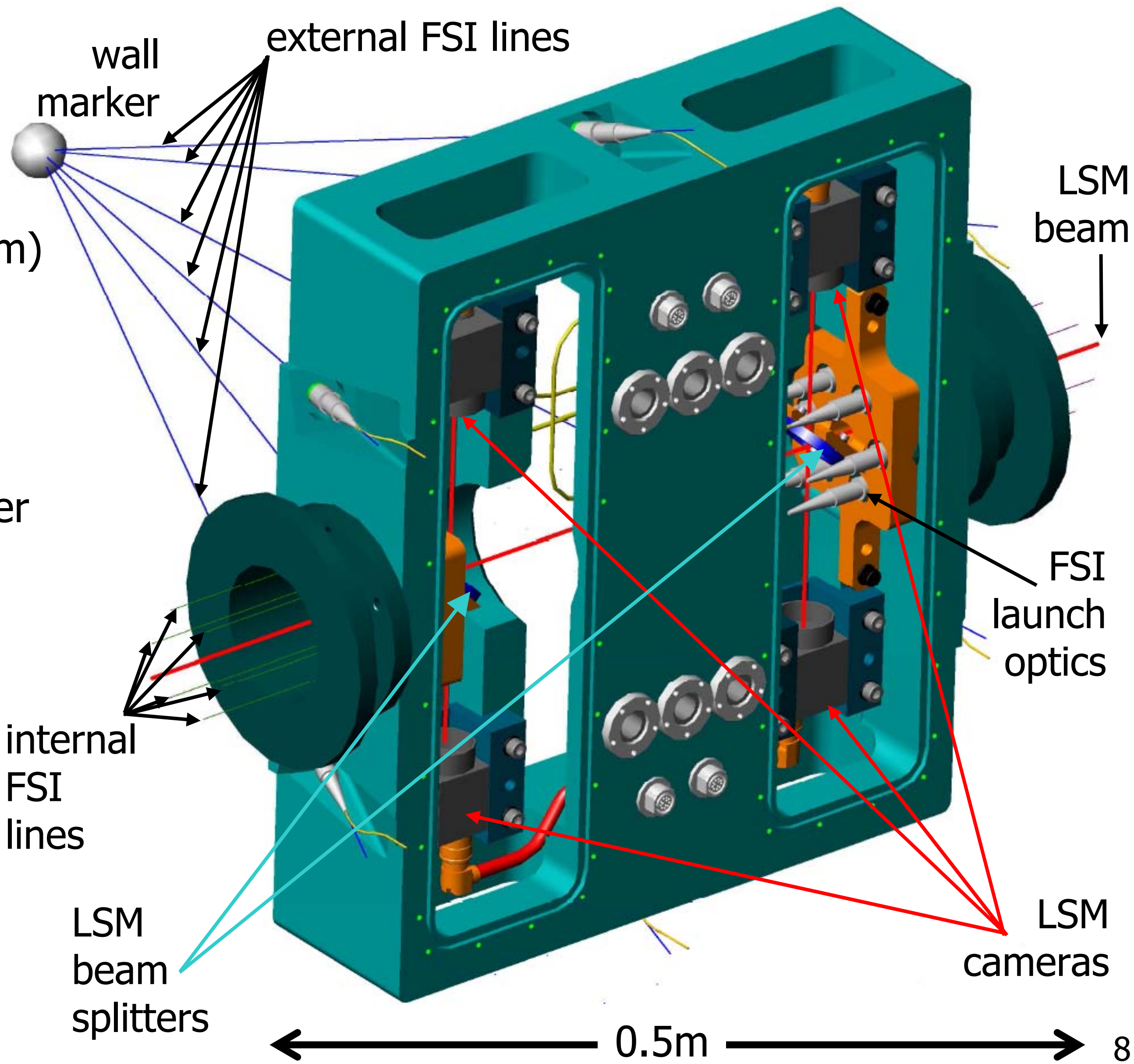


RTRS concept (measurement process)



Measurement Unit (Ox.)

- Machined from single cast of multiple stress relieved Invar
- High precision machining of active element seats O(10 μm)
- CMM survey of the entire unit and sub-assemblies
- Unit under vacuum
- Optimised heat transfer paths from CCD's to surface
- Custom vac. fibre feedthrougs
- Design maxime:
  - Stability of active element positions



- Cost modelling of the reference survey
- $TCO_{Ref} = R_{acc} n_{surv} L_{acc} T_{sd} (k_{sd} + C_{surv}) + I_{surv} + M_{surv}$
  - TCO :Total cost of ownership
  - R_{acc} :Lifetime of accelerator [years]
  - n_{surv} :Number of surveys per year [1/year]
  - L_{acc} :Length of beamline [km]
  - T_{sd} :time required for 1 km survey [days/km]
  - k_{sd} :cost per shutdown time [€/day]
  - C_{surv} :cost of survey team(s) [€/day]
  - I_{surv} :Investment costs for survey system[€]
  - M_{surv} :Maintenance costs for survey instruments[€]

Implications for the ILC

- Global Assumptions
  - R_{acc} = 20 [years]
  - n_{surv} = 1.2 [1/year]
  - L_{acc} = 50 [km]
  - k_{sd} = 800 [k€/day] (HERA operations cost + TESLA investment cost)

- Specific Assumptions

- RTRS (pessimistic)
  - T_{sd}= 0.42 [days/km]
    - 3 min per stop = 1/3 of design speed!
  - C_{surv}= 747 [€/day]
    - (2 per team: design is 1 operator for 4 RTRS)
  - I_{surv}= 500 [k€] per RTRS
    - excluding R&D costs
    - no automated marker placement
  - M_{surv}= 5 [k€] per year per RTRS
    - assume twice as much as a laser tracker

- RTRS (optimistic)
  - T_{sd}= 0.14 [days/km]
    - 1 min per stop = design speed!
  - C_{surv}= 93 [€/day]
    - 1 operator for 4 RTRS
  - I_{surv}= 500 [k€] per RTRS
    - excluding R&D costs
    - including automated marker placement
  - M_{surv}= 2.5 [k€] per year per RTRS
    - same as laser tracker

- Classical
  - T_{sd}= 5 [days/km]
    - 1 team of 3 takes that long
  - C_{surv}= 1120 [€/day]
    - 3 per team at DESY costs
  - I_{surv}= 100 [k€] per tracker
  - M_{surv}= 2.5 [k€] per year per tracker

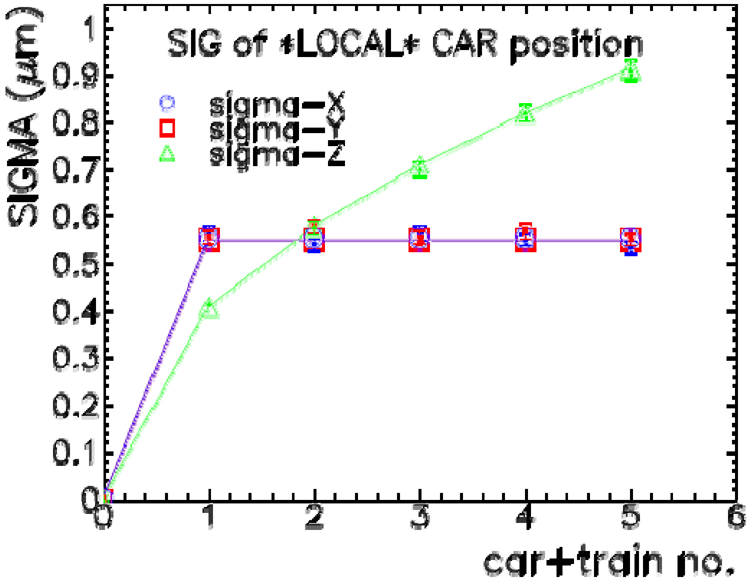
- Cost Comparison (realistic approach, finding minimum in TCO leads to very low down times of a day per year):
  - starting point: 4 RTRS is a practical number

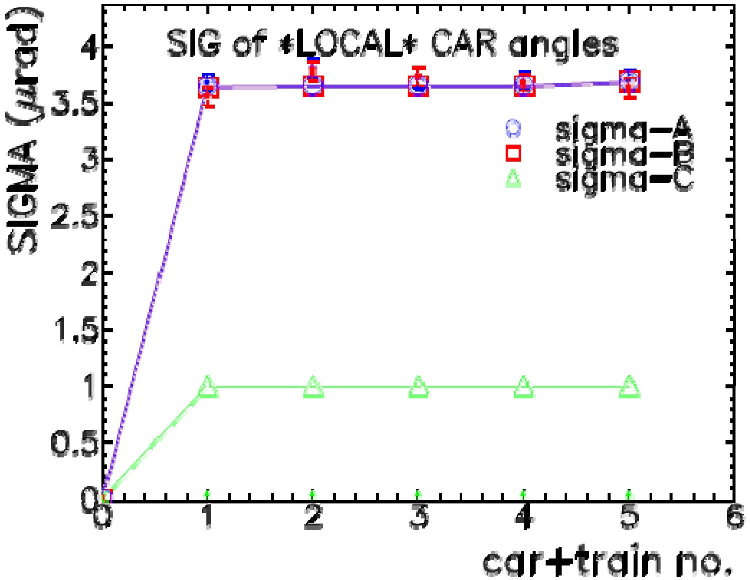
	RTRS pessimistic	Classical matching downtime of RTRS pessimistic	RTRS optimistic	Classical matching downtime of RTRS optimistic
#of teams	**4**	**47**	**4**	**142**
Downtime [days]	**126**	**126**	**42**	**42**
TCO with downtime [k€]	**103,520**	**115,841 (120%)**	**35,797**	**61,804 (173%)**
TCO without down time [k€]	**2,776**	**13,770 (496%)**	**2,216**	**28,020 (1264%)**

Expected Performance

- Two independent methods to predict the performance of the RTRS (for details see: Grzelak, Simulation of the LiCAS Survey System for the ILC, IWAA 2006, TH007)
  - Analytical error propagation (old)
    - describe an opto geometrical model of the measurement process using SIMULGEO, representing all statistical errors across multiple RTRS stops
    - Use Simulgeo in error progagation mode
    - produces average wall maker errors, no distributions, only statistical errors
  - Monte Carlo simulations (new)
    - Simulate many measurement campaigns of a known tunnel geometry using a custom ray tracer (generates measurements with statistical and systematic errors)
    - perform full reconstruction of marker positions using Simulgeo Model in reconstruction mode
    - produces error distributions, access to systematics and calibrations by varying RTRS geometry parameters between ray-tracer and Simulgeo Model

- Both techniques agree well (only short distance simulated so far)

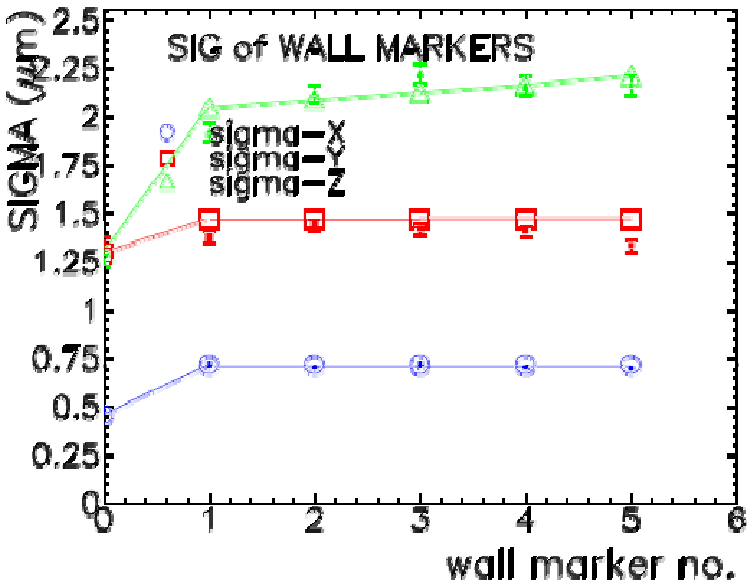




$A = Rot_X$

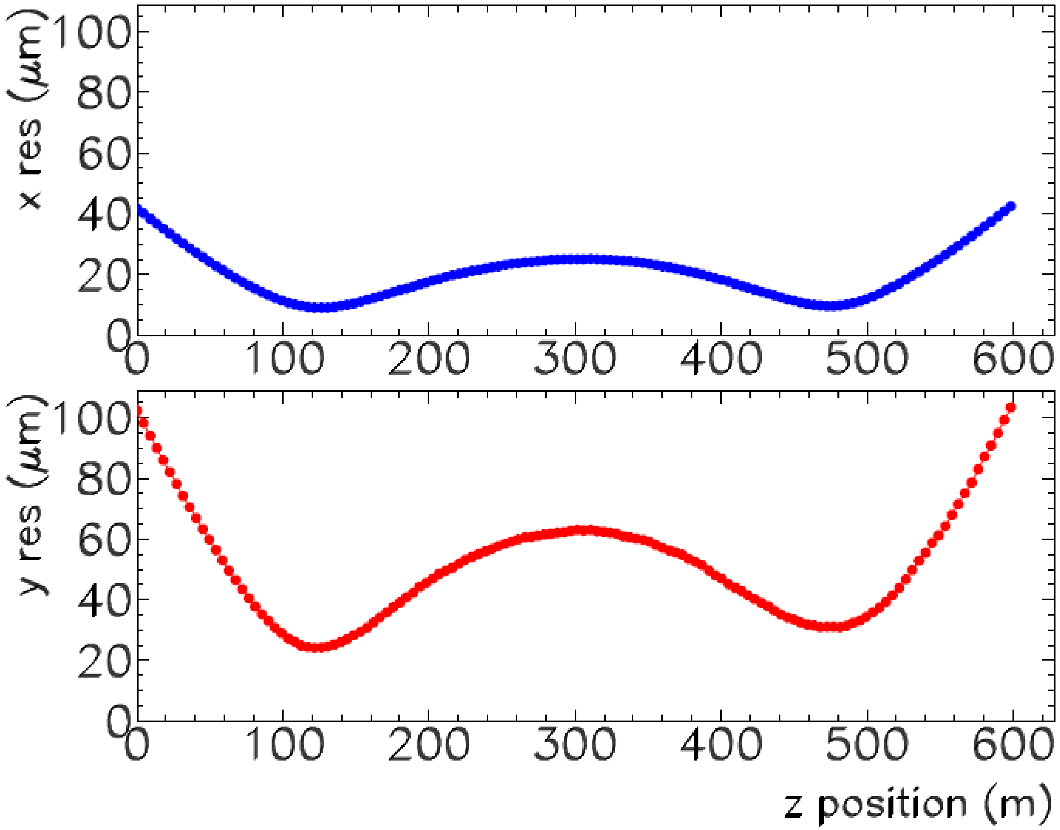
$B = Rot_Y$

$C = Rot_Z$



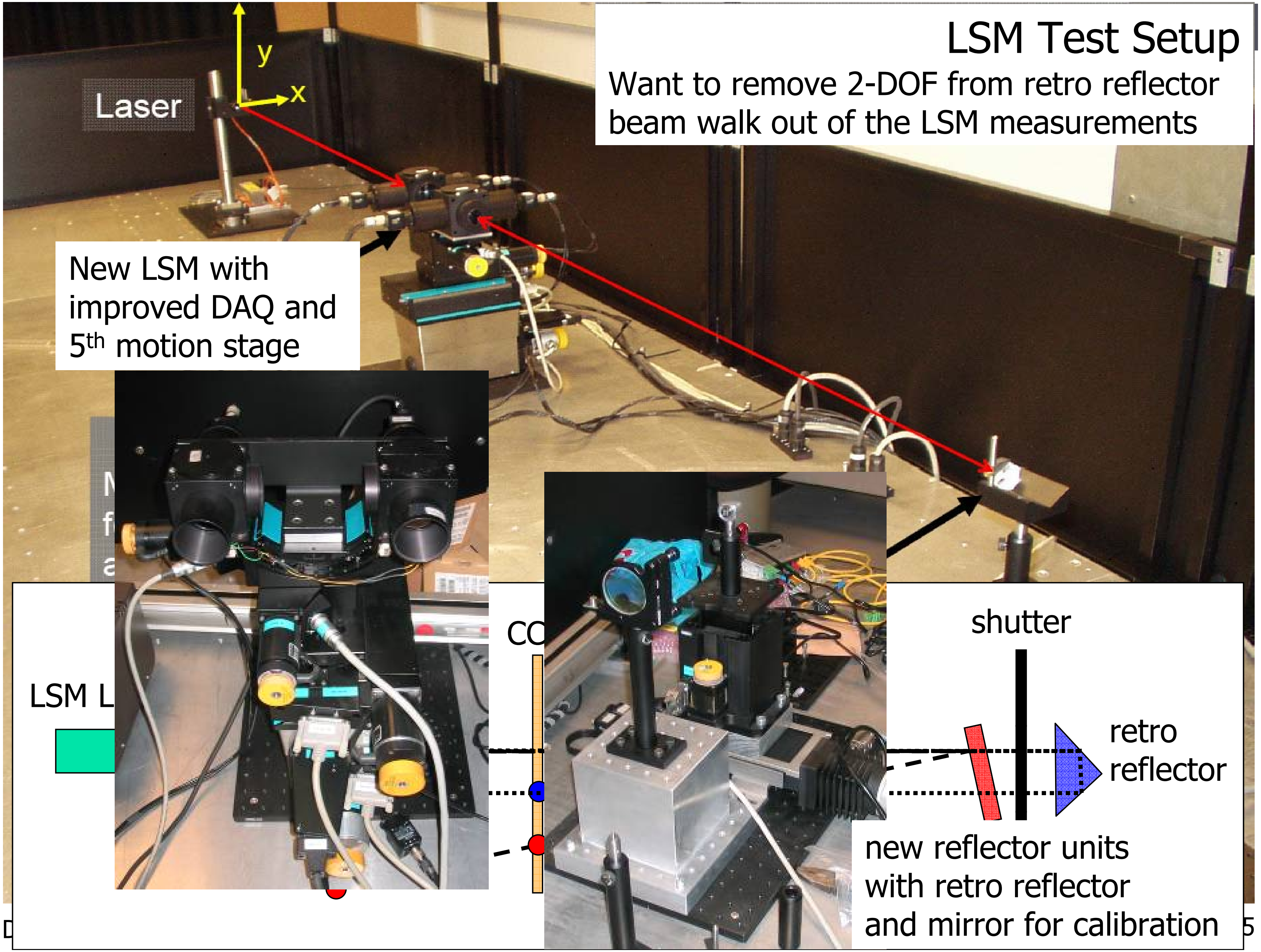
- assuming intrinsic resolutions:
  - CCD: $\sigma_{CCD} = 1\ \mu m$
  - FSI: $\sigma_{FSI} = 1\ \mu m$
- 1000 Simulgeo runs, simplified model, no errors on calib. const. (INT/EXT-FSI,CCD,BS)
- open markers: Matrix calculation (analytic)
  solid markers: Errors from Monte Carlo

- Long distance results:

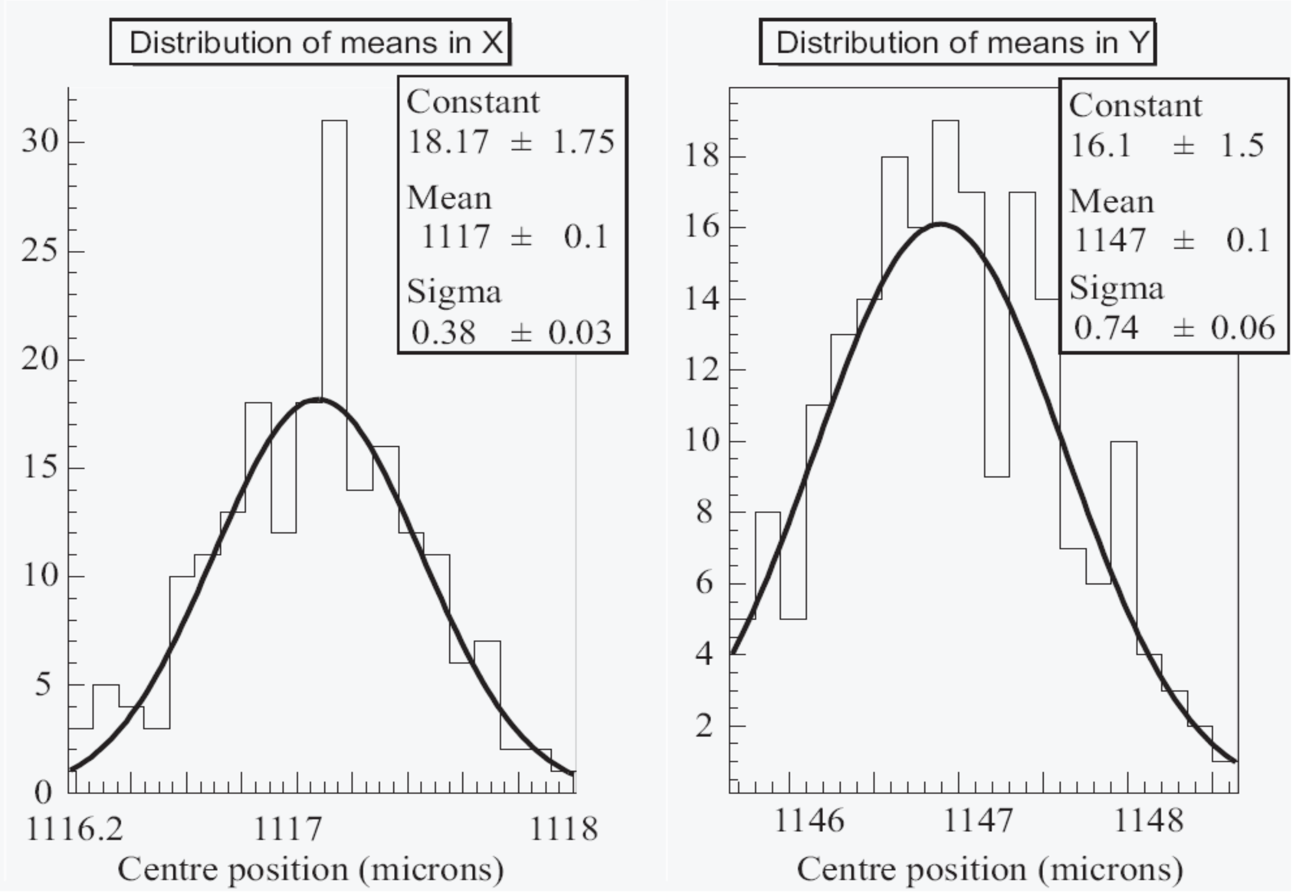


- mean deviation from straight line fits (X, Y) direction
- realistic input to the simulations of beam dynamics

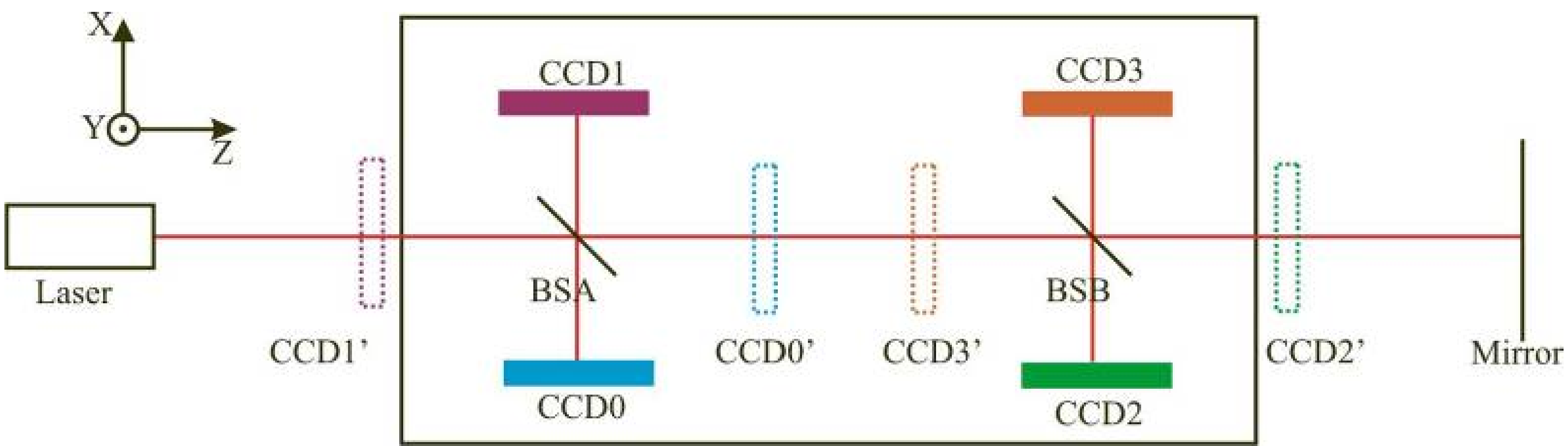
- well below specification: $\sigma_x = 500 \mu m$, $\sigma_y = 200 \mu m$
- however: only statistical errors included
- precision between X – Y can be swapped by changing the marker location (horizontal to vertical position)


LSM Test Setup
Want to remove 2-DOF from retro reflector beam walk out of the LSM measurements
Laser
y
x
New LSM with improved DAQ and 5th motion stage
shutter
retro reflector
new reflector units with retro reflector and mirror for calibration
LSM L

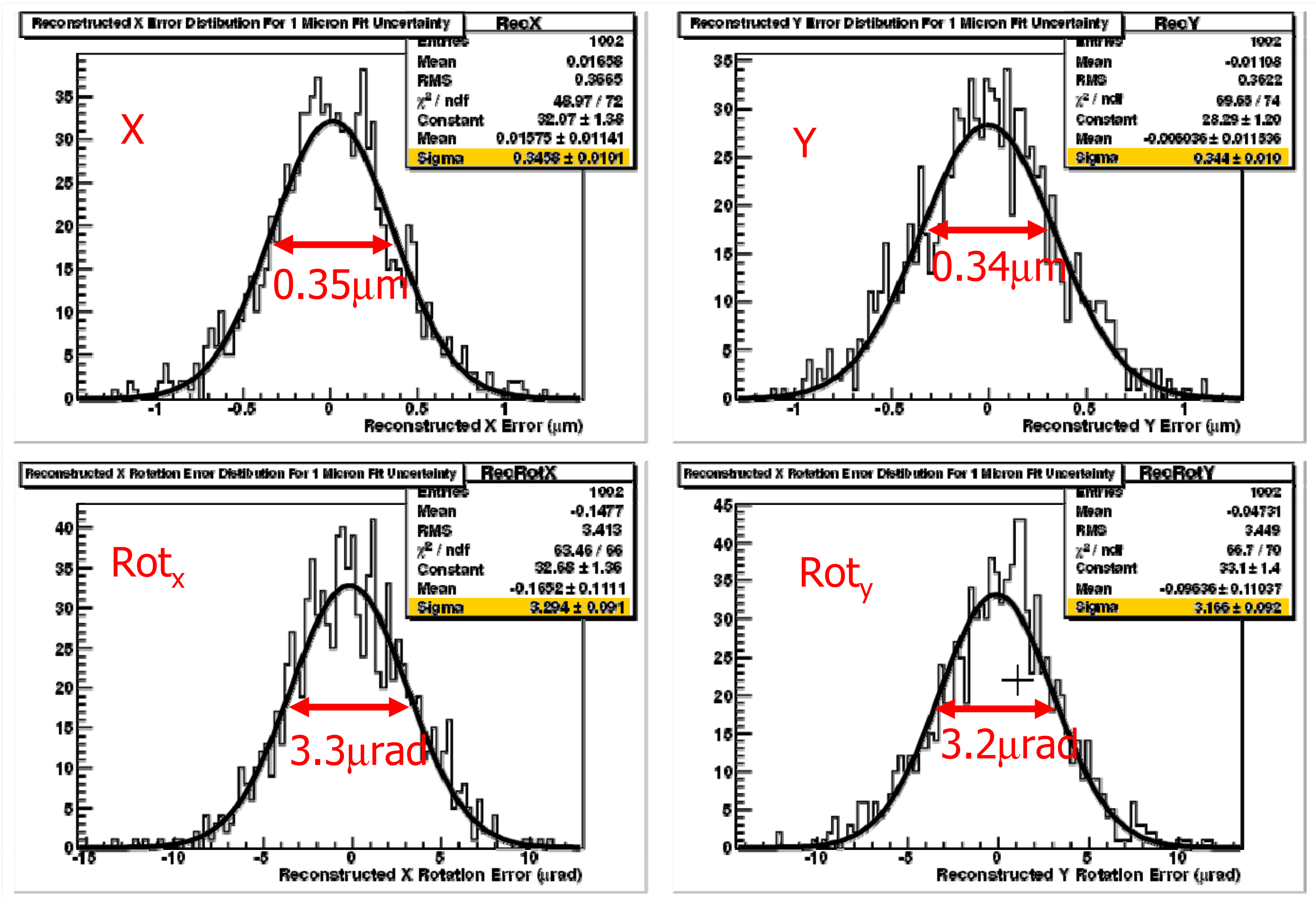
- Spot position fitting in open air (2m)
  - Fourier filtering
  - 2D Gaussian fitting
  - resolutions well below 1 micron
  - most likely limited by refraction effects in current set-up
  - Measurements in a long vacuum (RTRS) will soon be available



- Reconstruct co-ordinates in LSM frame using only LSM readout (independent of SIMULGEO reconstruction)
- Independent of non-LSM calibration constants
- Based on linearised model (small angles, small calibration constants, small deviations from symmetry)
- Very fast as it is analytical
- Can be used inside motion feedback loops to keep LSM on beam or to find beam
- Used to verify Simulgeo reconstruction code



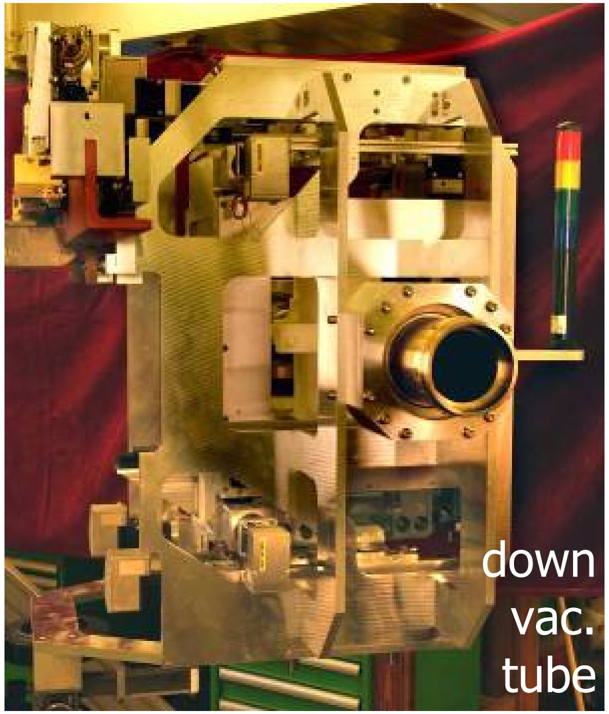
- Sensitivity study, no calibration errors, only 1 micron spot position errors, fast linearised reconstruction

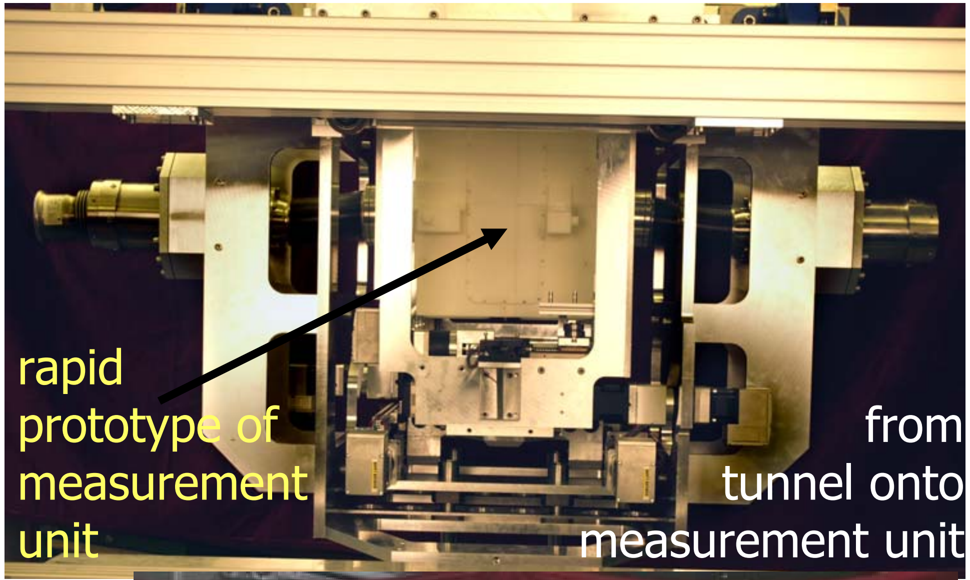


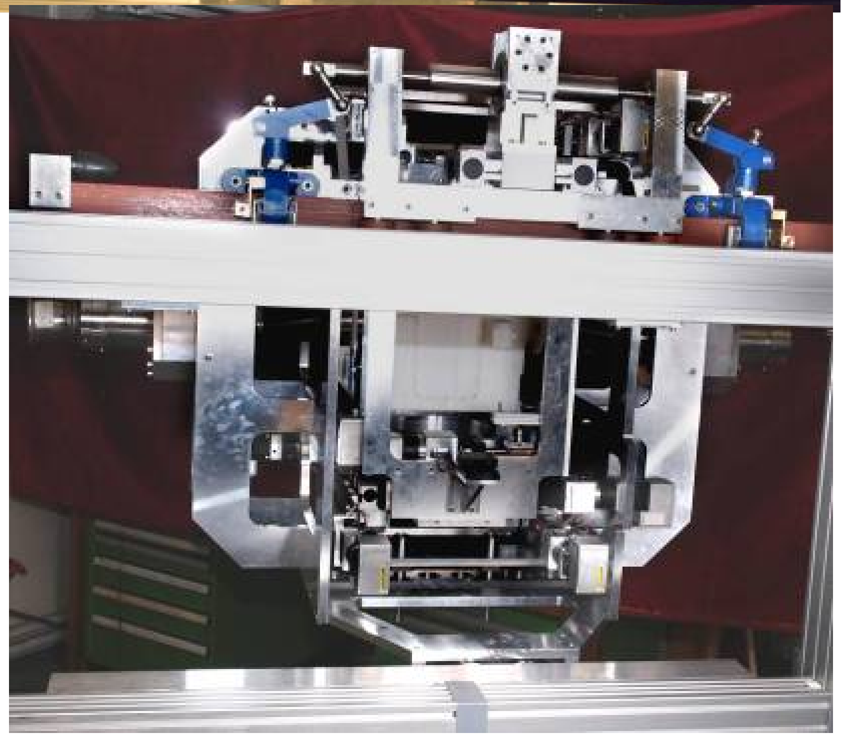
Measurement Cars (DESY)

- 3 Units built at DESY (finished)
- 6 DOF for position of measurement unit to:
  - Adjust to wall marker
  - Adjust to neighbouring cars
- Total of 12 stepper motors and stages controlled via CAN-bus
- Extremely rigid frame for:
  - Position repeatability
  - Vibration stability
- Mechanical decoupling from noise in service car
- Clamps to rail while measuring

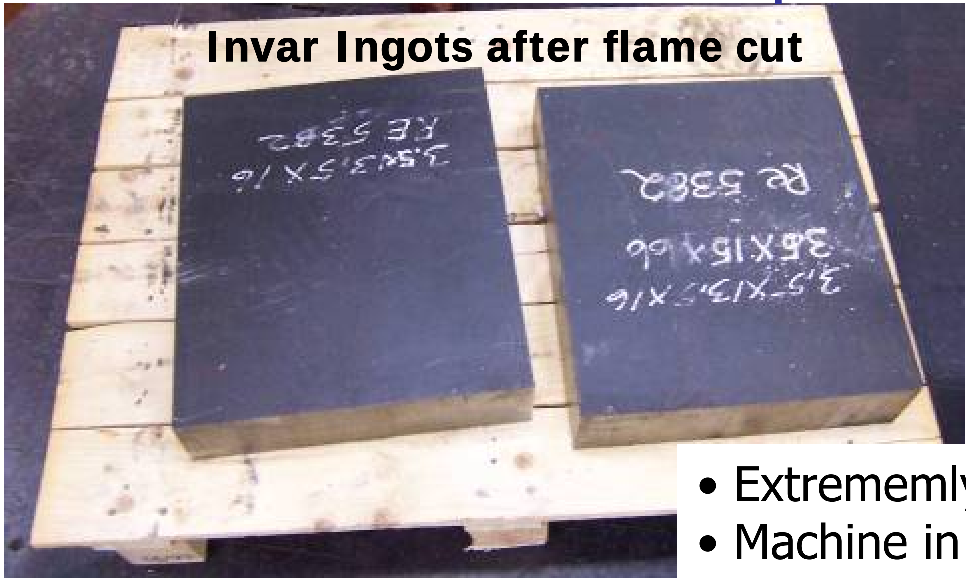
Measurement Cars



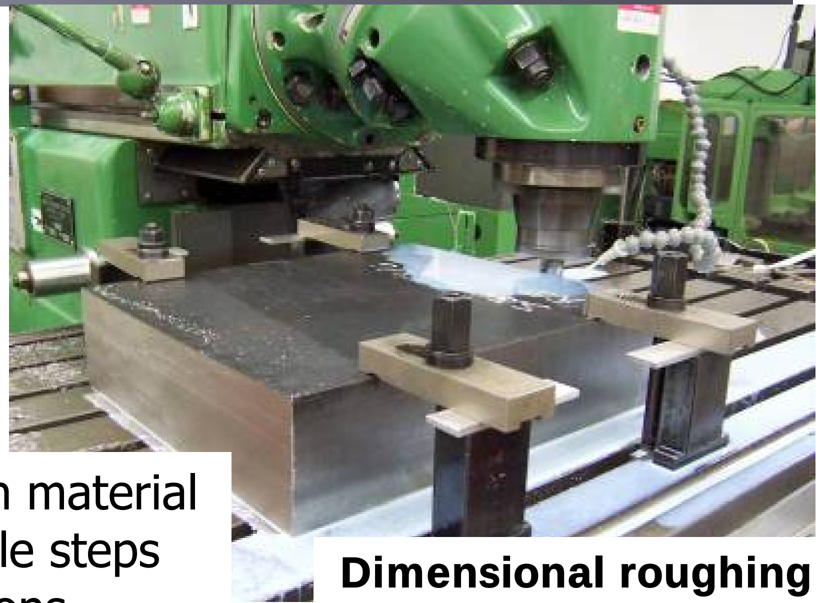




Measurement Unit production

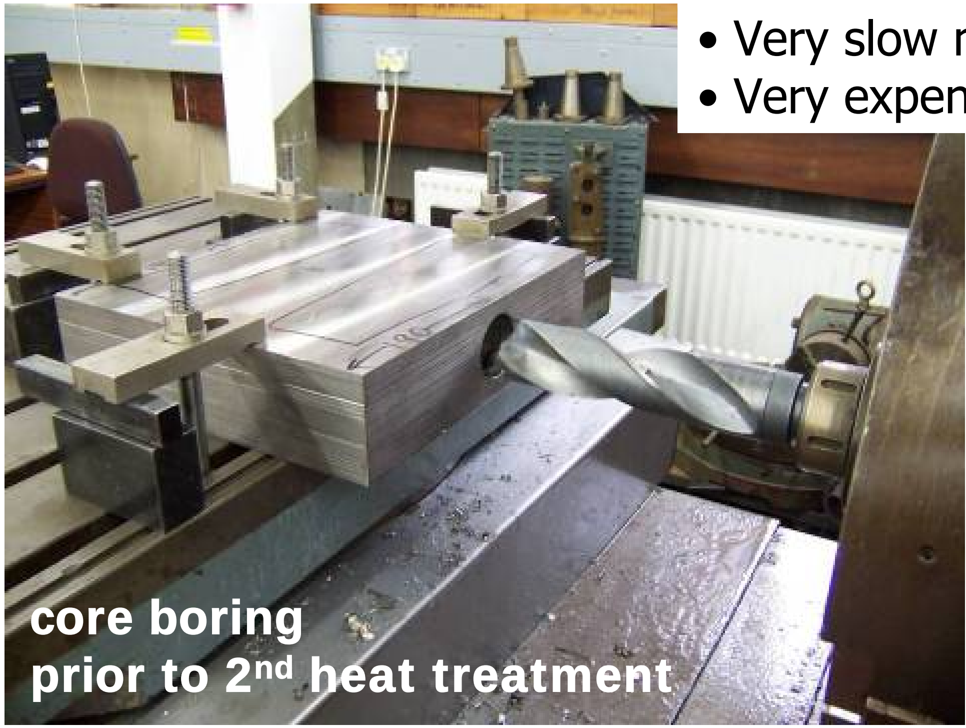


Invar Ingots after flame cut



Dimensional roughing

- Extrememly tough material
- Machine in multiple steps to minimise distortions
- Very slow machining speed
- Very expensive tooling



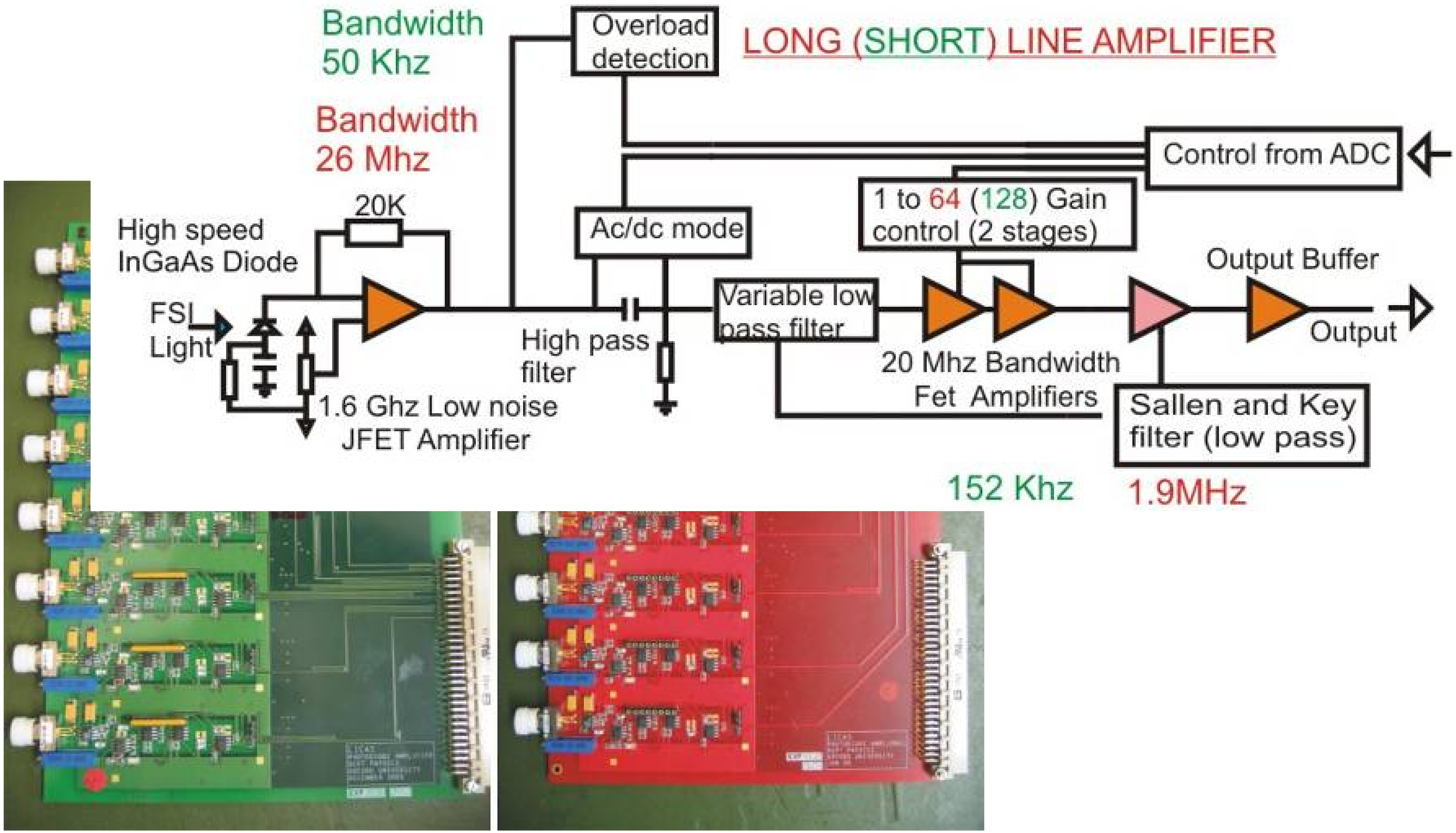
core boring
prior to 2nd heat treatment

Top and bottom precision ground 80 % of features machined

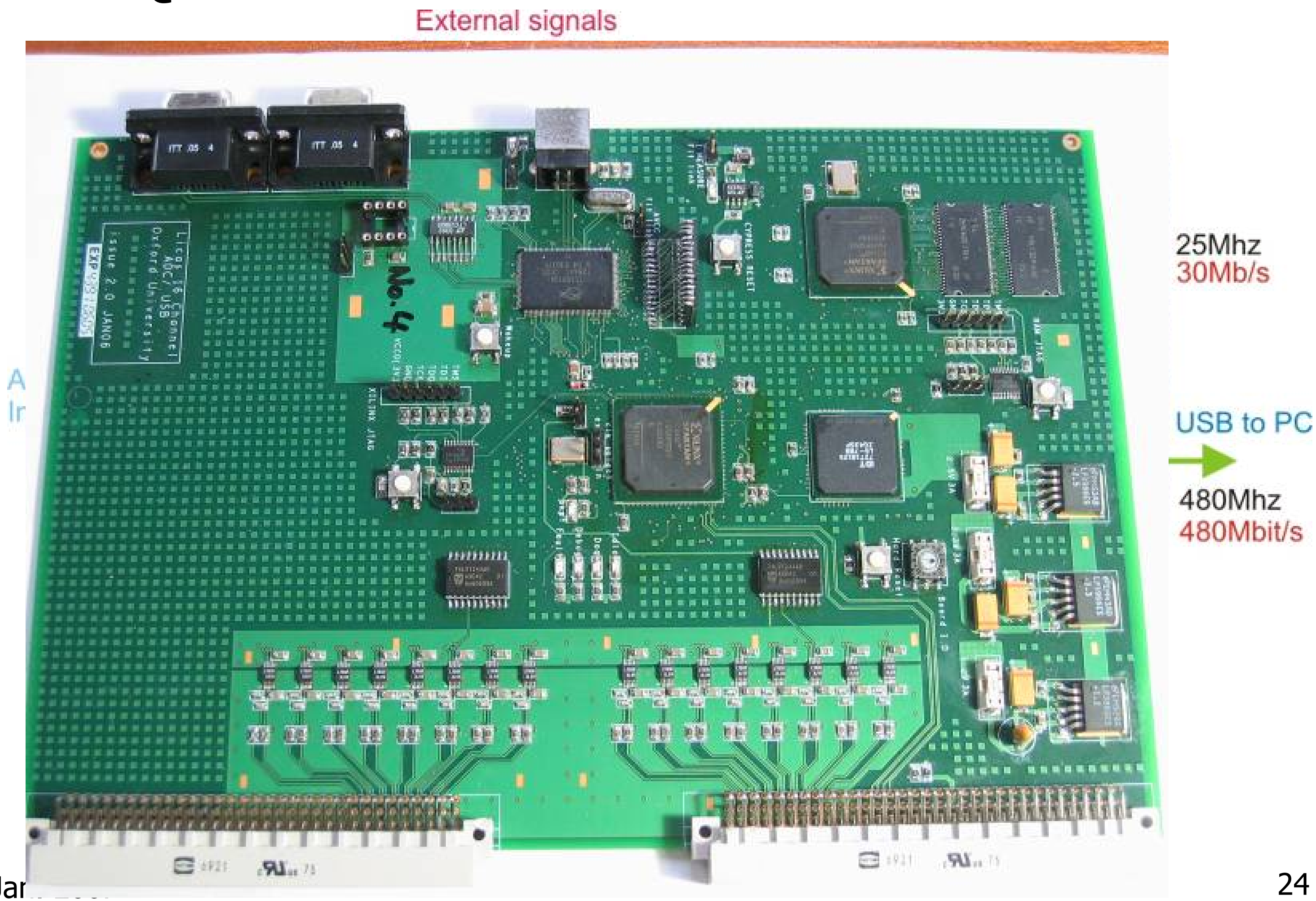
Electronics Subsystems

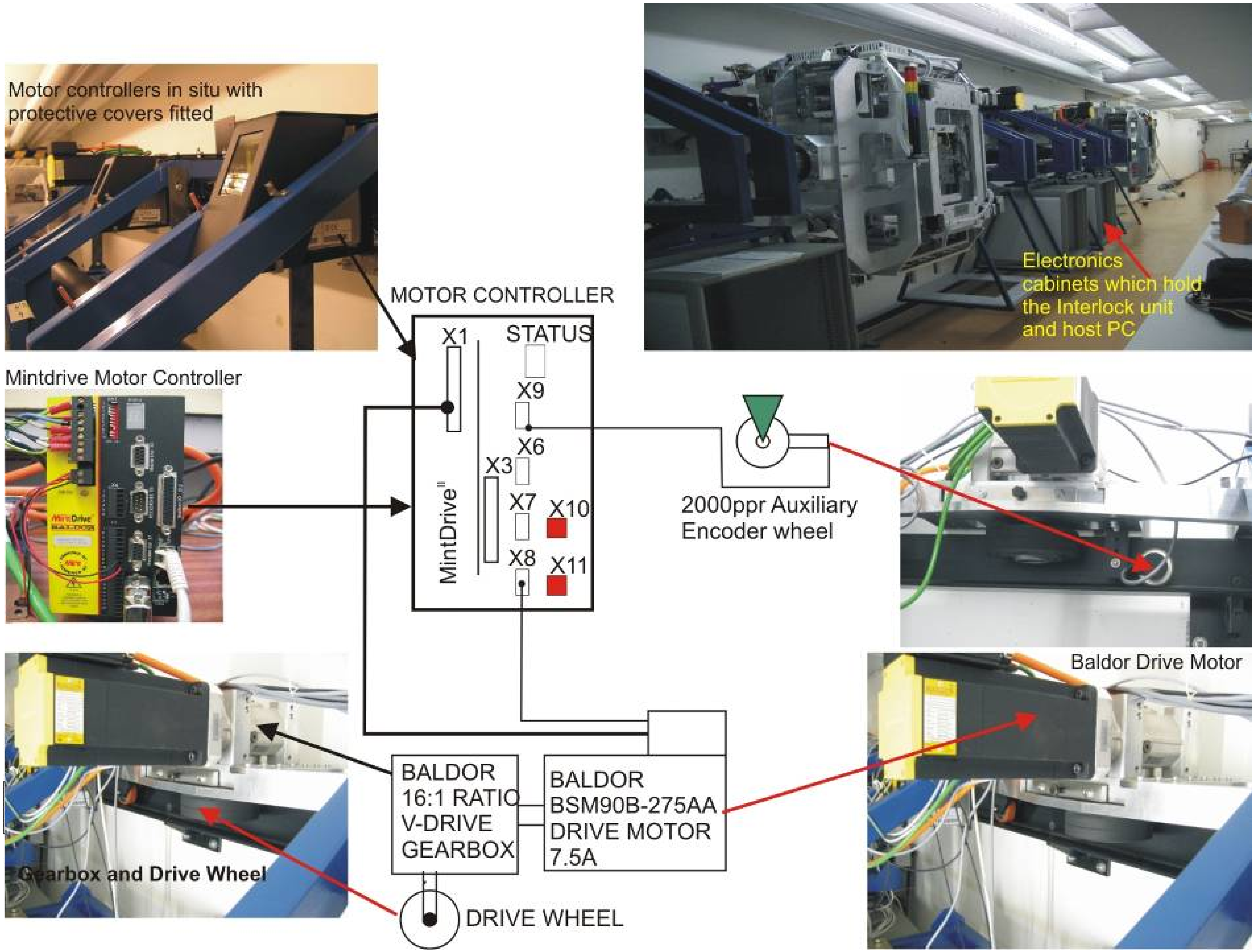
- Drive Control System
- Custom DAQ for FSI
- Commercial DAQ for LSM-CCDs
- ELMBs (Embedded Local Monitoring Boards, ATLAS) via CAN bus for auxiliaries
  - temperature
  - pressure
  - digital I/O (limit switches)
- Trigger and Clock distribution ($\Delta t < 100$ ns)
- Dual CPU, server based control computers
  - 3*service car reading all sensors (Frame grabbers, USB, CAN)
  - 1*master car controlling FSI and LSM laser systems, propulsion and safety and collating data from service cars for reconstruction (CAN, GPIB, RS485)

FSI DAQ: Photo Amplifiers



- FSI DAQ: USB ADC board




Motor controllers in situ with protective covers fitted
MOTOR CONTROLLER
Electronics cabinets which hold the Interlock unit and host PC
Mintdrive Motor Controller
X1
STATUS
X9
X6
X3
X7
X10
X8
X11
MintDrive
2000ppr Auxiliary Encoder wheel
Baldor Drive Motor
BALDOR 16:1 RATIO V-DRIVE GEARBOX
BALDOR BSM90B-275AA DRIVE MOTOR 7.5A
Gearbox and Drive Wheel
DRIVE WHEEL

RTRS Installation at DESY

- Service, measurement and master car joined into one RTRS
- Drive system installed and operational
- Power and interlocks installed
- Motion stage systems in measurement cars operational
- Parking brakes operational

- Vacuum system 95% installed
- Infra structure complete
  - air conditioning
  - interlocks
  - networks
  - rail

- Carefull, now it moves!

forwards…

…and backwards!

Summary

- A LiCAS RTRS prototype is being built to try and meet the survey requirements of the ILC
- The LiCAS project is well advanced
  - Have simulated effects of random errors on resolution
  - Are now simulating systematic errors
  - Majority of the RTRS now installed at DESY
  - Completion of the invar measurement units is the main outstanding construction task
  - Expect improvements to FSI from new reference interferometers
  - Custom DAQ system has been built (backup slides)
  - Can predict the effect of survey accuracy on ILC Linac performance (backup slides)
- Calibration and determination of residual systematic errors is the main goal of the next year
  - FSI reference length to be traced to frequency standard
  - system calibration to be achieved by
    - as built measurements using CMM and Smart-Scope
    - in-situ consistency fits to monitored differential motion
- Estimates of the reference survey cost strongly favour the RTRS over classical survey methods

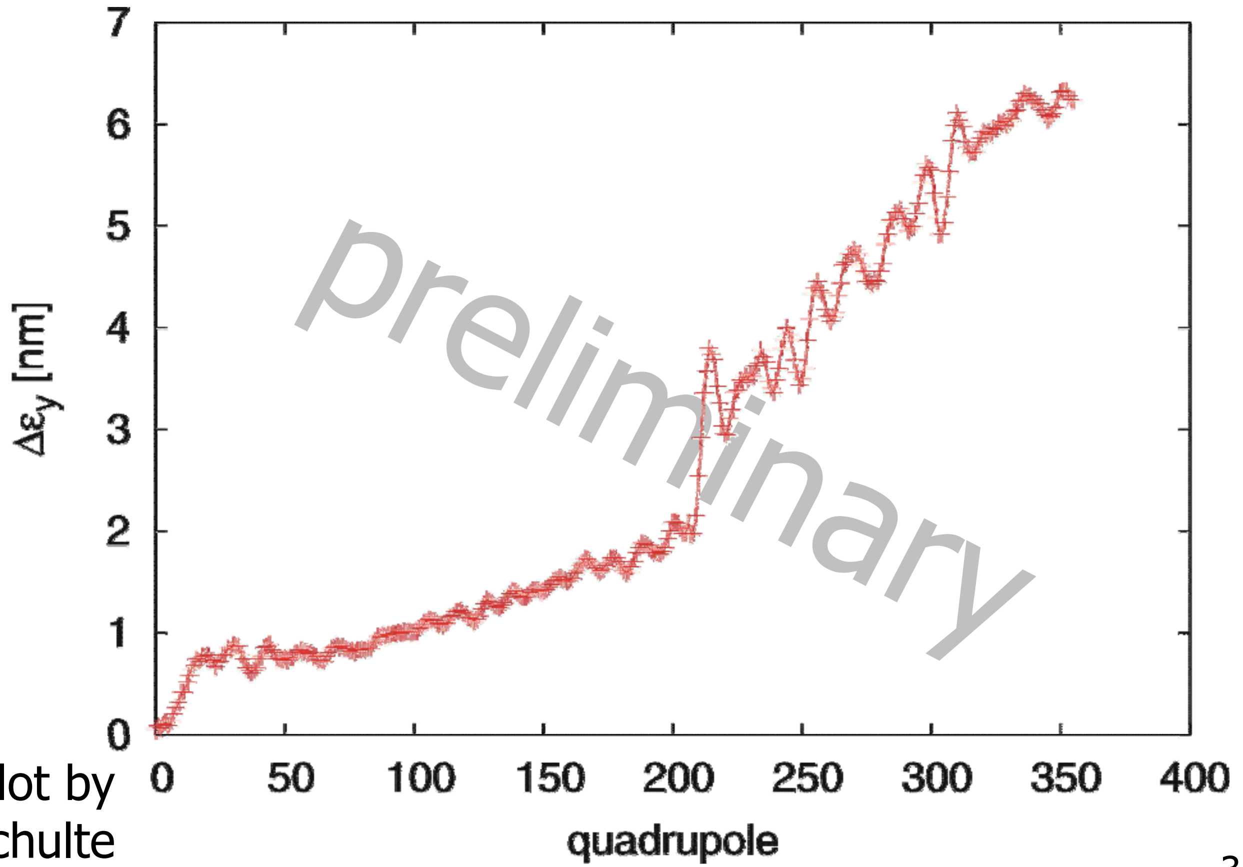
The End

Thank you for your attention

Backup Slides

- Interface from performance simulations to PLACET (RWALK_licas_sim)
- Simulate positions of all accelerator components as expected after LiCAS survey
- Feed this back into PLACET to study emmitance growth

- Emittance growth vs. Quadrupole number
- Long range Licas survey errors only
- ongoing study



plot by
D. Schulte

FSI Reference calibration

- Do we need to know the reference interferometer OPD OPD_{ref} on an absolute scale?
  - Yes, because
    - we want to use comparisons with other systems for system calibration
    - we want to be able to maintain the scale over the ILC project life time O(20-30 years)
    - Note: OPD_{ref} is aproximately 10m
- How accurately do we need to know L_{ref} ?
  - More accurate than the resolution of the technique (better then 1 μm, say 0.5 μm)
  - Accurate enough to be able to use a single phase measurement at a reference wavelength to fine tune the length, i.e. we know the order number (much better then 1.5 μm, say 0.1 μm)
  - Accurate enough to be able to see creep or drift over reasonably short time scales (say 50 nm)

FSI Reference calibration

- Saturated acetylene absorption cell (NPL) can define $\Delta\lambda/\lambda$ to O(10^{-10}) for many lines in the 1.5 μm region if scanned slowly
- Build passively stabilised etalon with
  - high finesse of few 10^3 and
  - FSR $\approx$ O(10) GHZ and
  - peak(s) close to absorption feature(s)
- At few GHz/s (slow) scan laser linearly through etalon and absorbtion cell
  - ➔ measure FSR to O(10^{-9})
- Directly afterwards (within passive stabilisation time) perform fast FSI scan through reference interferometer and etalon simultaneously
  - ➔ measure the frequency change $\Delta\nu_{FSI}$ across part of FSI scan to O(10^{-8})
- Determine total phase advance $\Delta\Phi_{ref}$ generated by reference interferometer during $\Delta\nu_{FSI}$ by phase extraction methods to O(10^{-8})
- From knowledge of $\Delta\nu_{FSI}$ and $\Delta\Phi_{ref}$ obtain OPD_{ref} to O(few 10^{-8}) corresponding to few 0.1 mm.

- If OPD_{ref} is known to O(0.1 micron)
- and comparison to a wavelength standard can be made regular enough for drift not to destroy knowledge of the order number
- then a very short scan (AOM) around any well known single wavelength can reveal the phase and thus OPD_{ref}
- A variety of derivatives of the above method are possible
- We are looking for advice on this.

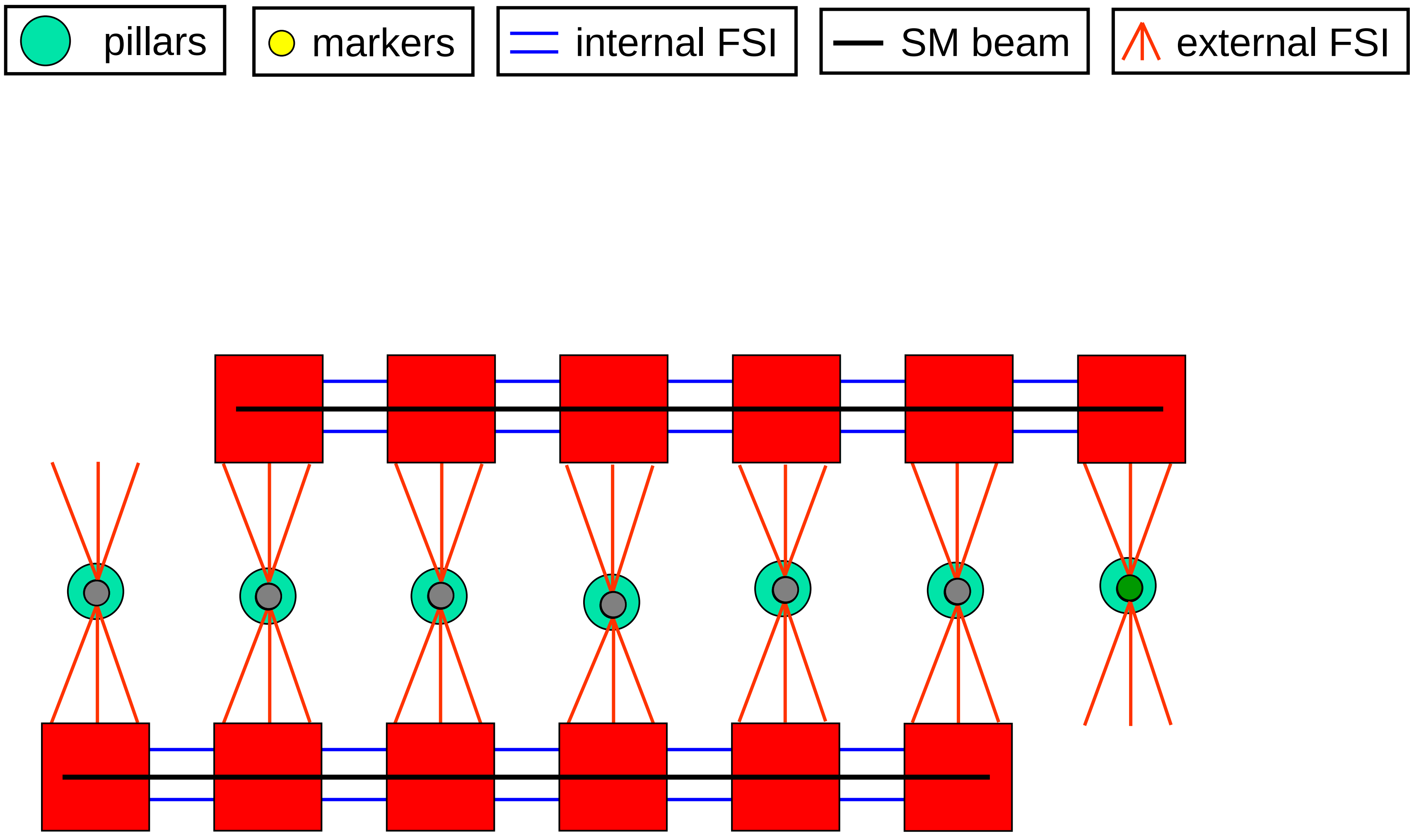
- Reconstruction of wall marker positions depends on the geometry of the measurement units
- This problem partially factorises into
  1. geometry of LSM to get
     - unit's transverse offsets and
     - transverse angles (pitch, yaw) wrt. LSM beam
  2. geometry of internal FSI system to get
     - distance between units and
     - relative transverse angles
     - shared problem between two units, one for launch other for reflectors
  3. geometry of external FSI system to
     - measure 3D co-ordinates of wall markers wrt. unit's external FSI system
  4. orientation of tilt sensors to determine roll
  5. relative co-ordinates of the 4 sub-systems

- As built measurements:
  - perform highly accurate CNC production to reduce size of calibration constants to O(10 μm)
  - verify built at all stages with CMM and Smart-Scope (for CCD location) to obtain approximately 5 μm 3D co-ordinates to final assembly
  - sub-assemblies (i.e. cameras with holders, pellicle holders, etc.) are measured before and after insertion to unit

System Calibration

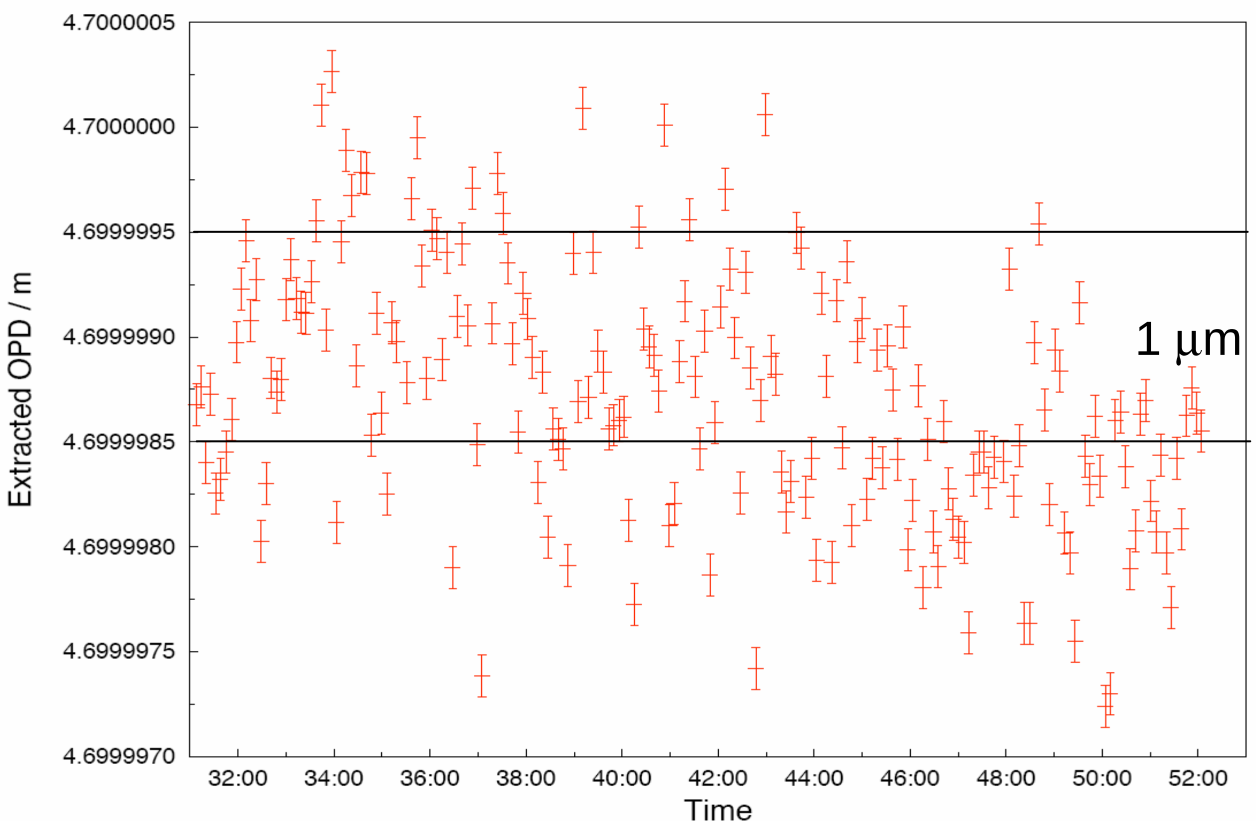
- In-situ geometry calibration:
  - fully assemble RTRS to operational state
  - during one measurement stop (all elements inside dynamic range, all measurements active)
  - move one measurement unit in many steps across its dynamic range keeping roll close to zero of tilt sensor
  - monitor differential 6D motion with as many laser trackers (maybe 3D-arm, slow?) as possible
  - reconstruct the motion using the RTRS assuming
    - wall markers do not move
    - two other cars do not move
  - vary the calibration constants of each subsystem until the reconstructed moves fit best to the monitored ones
    - this can give entire relative geometry of LSM
    - and entire external FSI system relative geometry
    - and partial relative geometry of the internal FSI system
  - repeat the above for all units
  - change units into all possible different locations and repeat again
  - rotate units by 180 degrees in pitch and repeat again

System Calibration

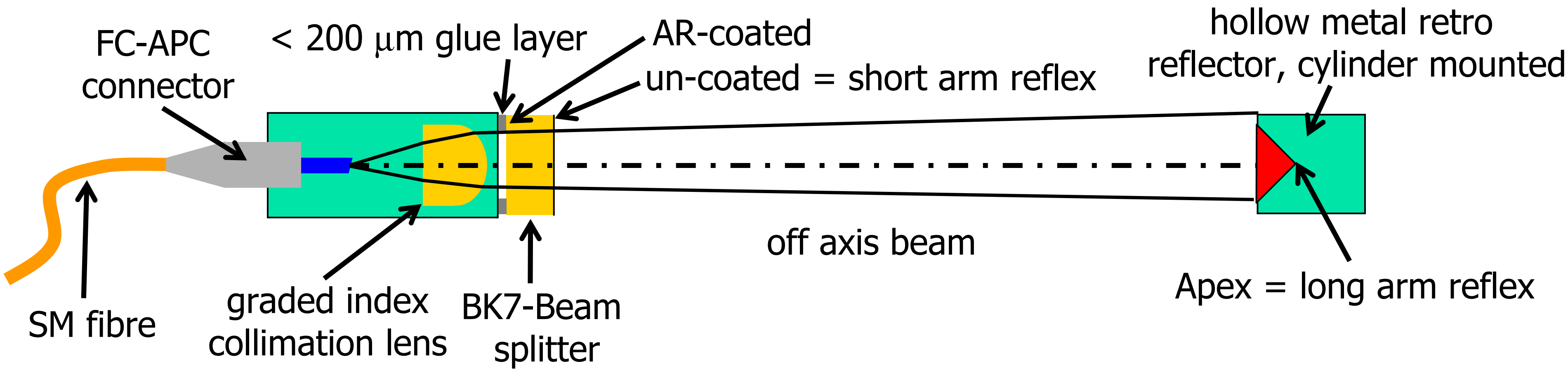


FSI results (long lines)

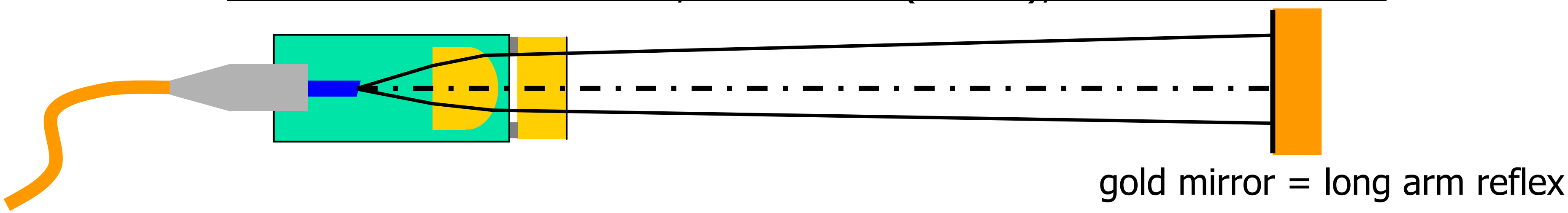
- Using old Michelson style reference interferometer
- Passive thermal shield, operates in air, no expansion compensation, steel table
- Expect large improvements from new ref. & evac measurement interferometer
- OPD measured over 25 min
- No offline corrections for thermal expansion
- OPD = 4.6999989 ± 5.94×10^{-7} m



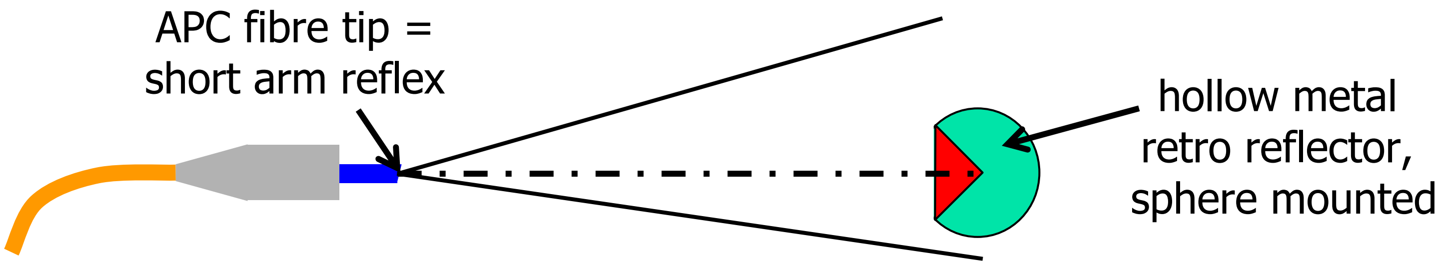
Long line measurement interferometer, OPD ≈ 5m, surface to point



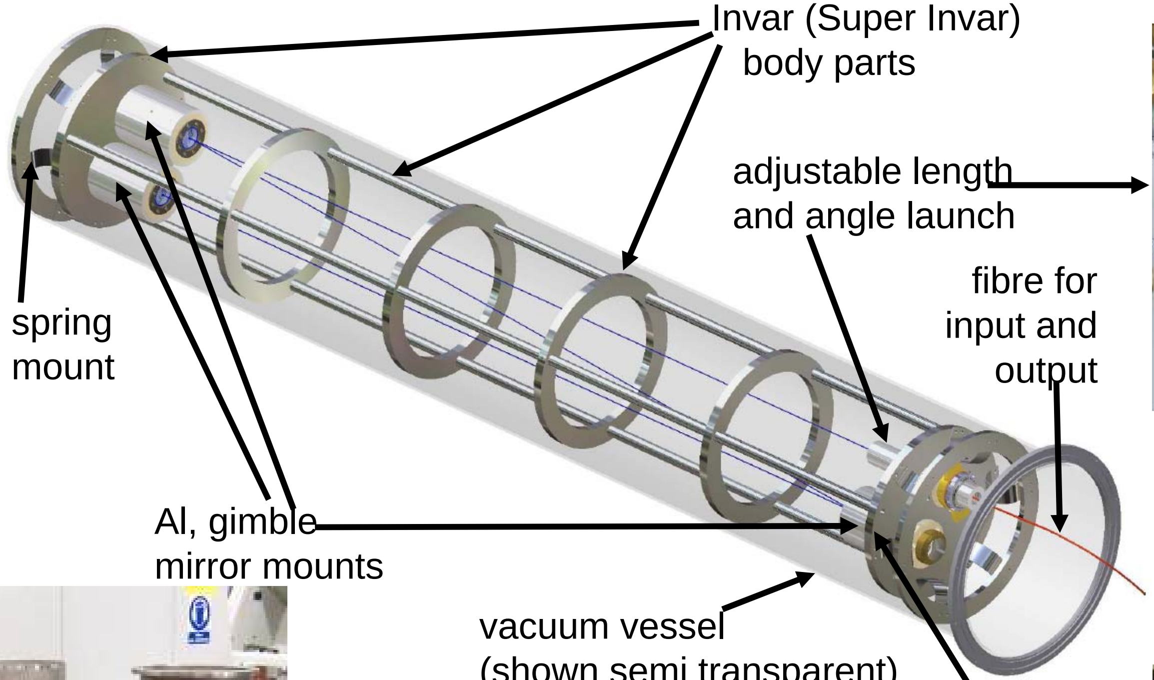
Reference interferometer, OPD=10m (folded), surface to surface



Short line measurement interferometer, OPD ≈ 0.5m, point to point

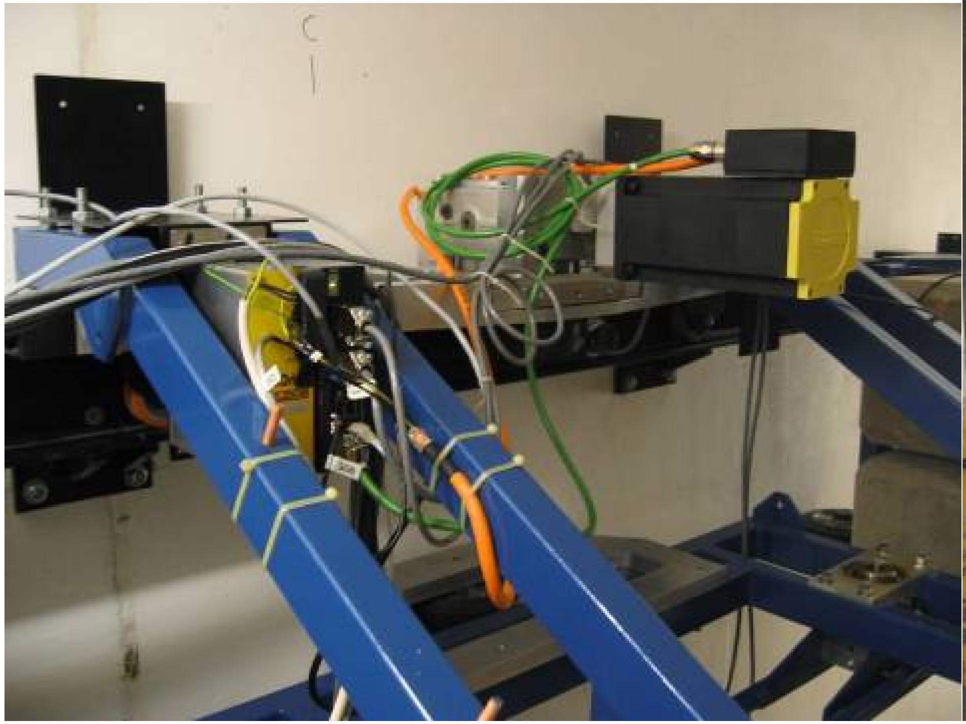


Reference Interferometers



RTRS drive tests at Oxford

- Oxford drive tests on 25m rail test stand
- 3 service + 1 master car + 3 “dummy” measurement cars as loading
- Developed torque synchronisation software
- Three schemes tested
- Finishing touches to be done when operational at DESY



- Cost Comparison (brute force cost minimisation):
  - starting point: find minimum of TCO with downtime

	RTRS pessimistic, min TCO (with down time cost)	**Classical** matching downtime of RTRS pessimistic	**Classical** min TCO (with down time cost)	**RTRS** optimistic, min TCO (with down time cost)	**Classical** matching downtime of RTRS optimistic	**Classical** min TCO (with down time cost)
#of teams	**26**	**308**	**179**	**16**	**522**	**179**
Downtime [days]	**19**	**19**	**34**	**11**	**11**	**34**
TCO with downtime [k€]	**41,375**	**68,496 (166%)**	**60,371 (146%)**	**17,211**	**94,210 (547%)**	**60,371 (351%)**
TCO without down time [k€]	**15,976**	**52,920 (331%)**	**33,570 (210%)**	**8,816**	**85,020 (964%)**	**33,570 (381%)**

- Downtime too low (<parasitically available downtime)