

Global simulation of the LiCAS/RTRS survey system for the ILC

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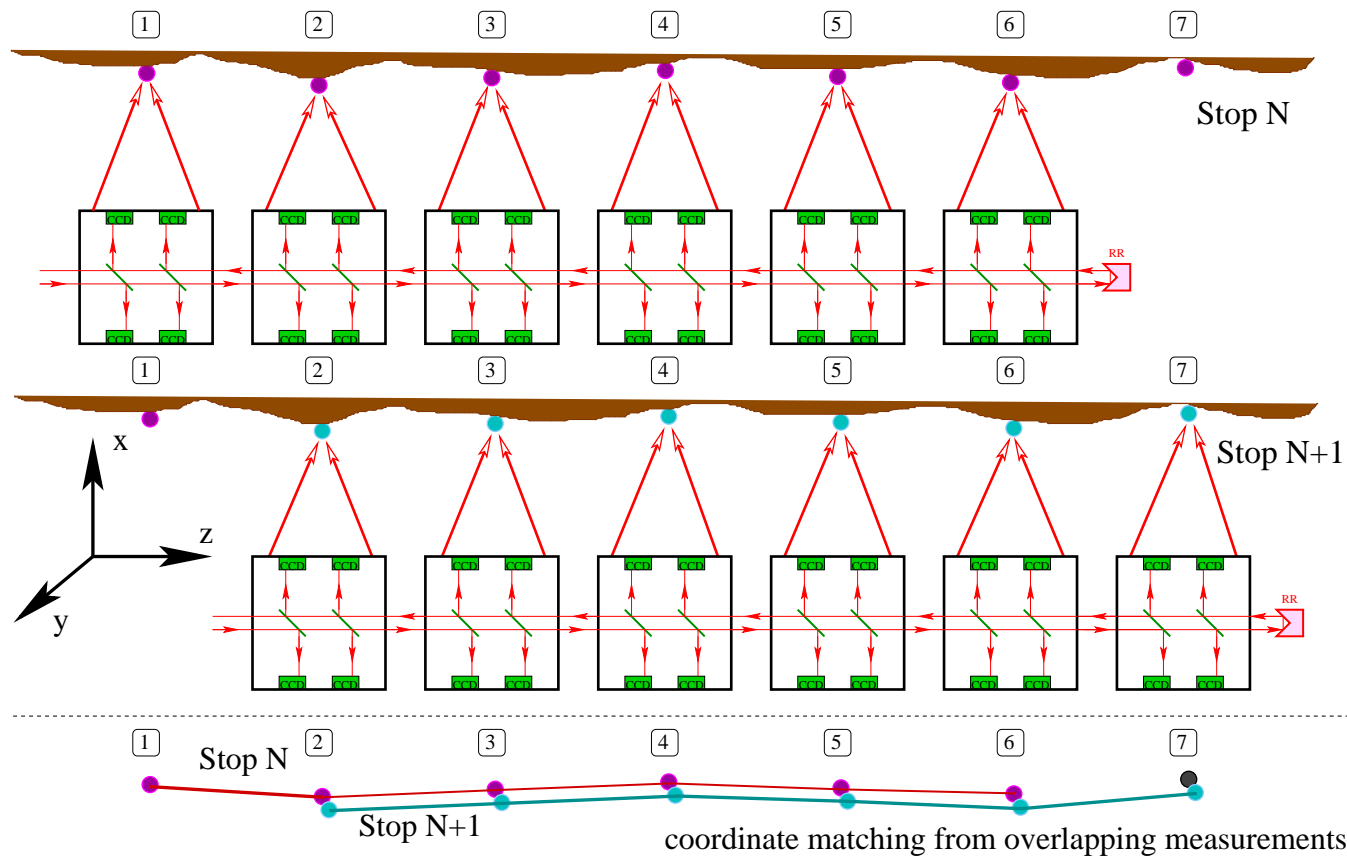


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Outlook

- Idea of the multi-train overlapping measurements
- Opto-geometrical model of the sensing modules
- Simulation and reconstruction software:
 - Analytical (matrix) error propagation
 - Monte Carlo approach to error calculations
- Short ruler model (random walk algorithm)
- Results for statistical errors
- Results for systematic errors
- NOTE: all numerical results for long LiCAS train
(4 cars, 25 m car-to-car distance, operating over 600 m tunnel section = 24 stops)
- Conclusions

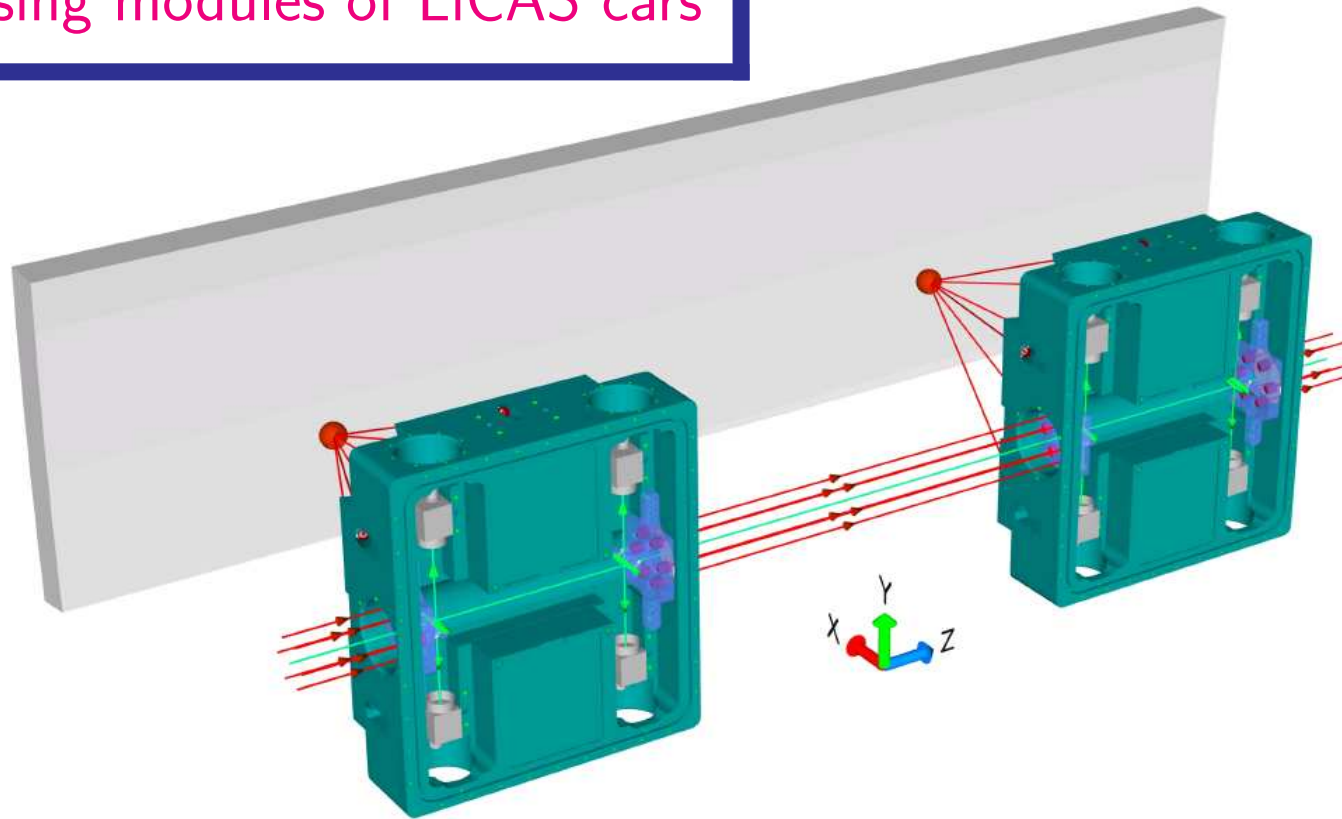
Multi train overlapping measurement



- top view on two train stops along the tunnel wall

- each train stop provides coordinates of N ($=6$) wall markers expressed in the local frame of the train
- overlapping measurements of each wall marker
- local measurements are combined to coincide on the same trajectory in the global tunnel frame (simultaneous fit to all measurements)

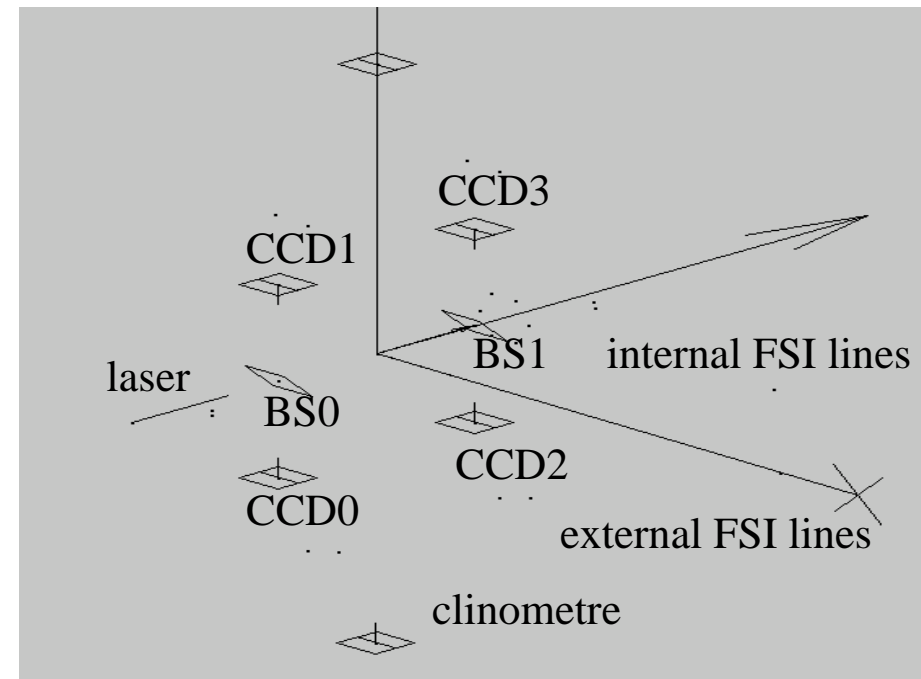
Sensing modules of LiCAS cars



- Important components for the simulation (Laser Straightness Monitor, FSI lines):
 - LSM: 1 laser line per train; 2 beam splitters, 4 CCD cameras per car
 - Internal FSI: 6 laser lines, 6 retro-reflectors per car
(Internal FSI lines and LSM laser operates in vacuum pipe)
 - External FSI: 6 laser lines per car, 1 wall marker in front of each car
 - clinometer (not shown) for Rot_z

SIMULGEO: Software used in the simulation

- Script language for description of opto-geometrical systems (light sources, CCD detectors, distancemeters...)
- Mechanical correlations between objects grouped in local frames
- ERROR PROPAGATION MODE:
Performs full error propagation (N^2 matrix, very CPU consuming)
- RECONSTRUCTION MODE.
Solving the geometry of the system using provided “experimental” measurements. (Input from ray-tracer or real data).



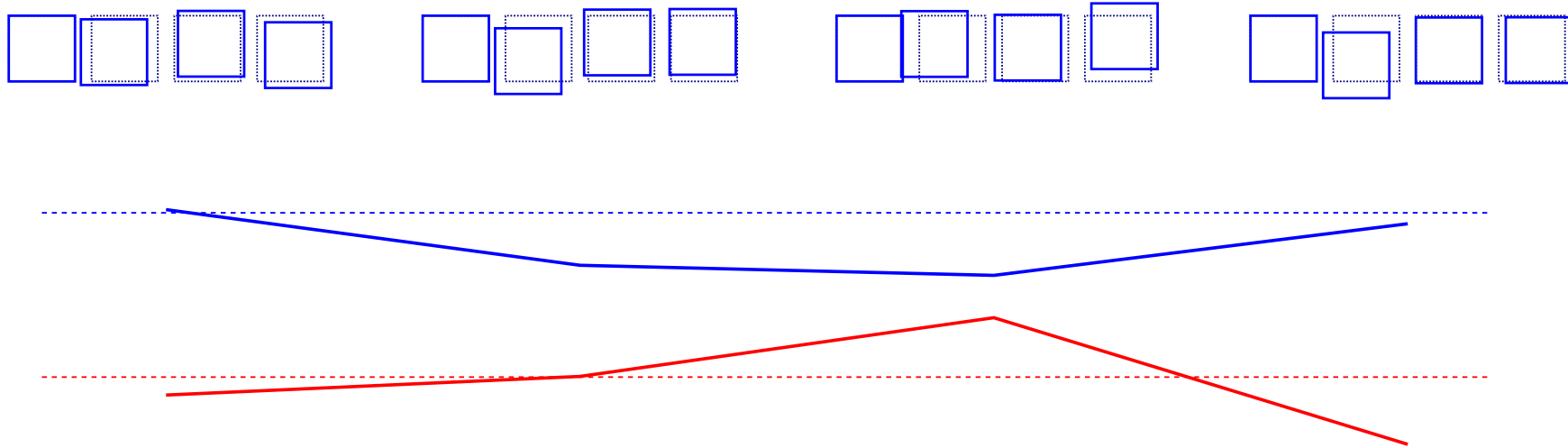
SIMULGEO: developed by L. Brunel at CERN for the alignment of CMS muon chambers

- LIMITATION: Systematic errors (for example miscalibration) are treated in the same way as statistical errors
- SOLUTION: Train MONTE CARLO simulation

Train Monte Carlo: the algorithm

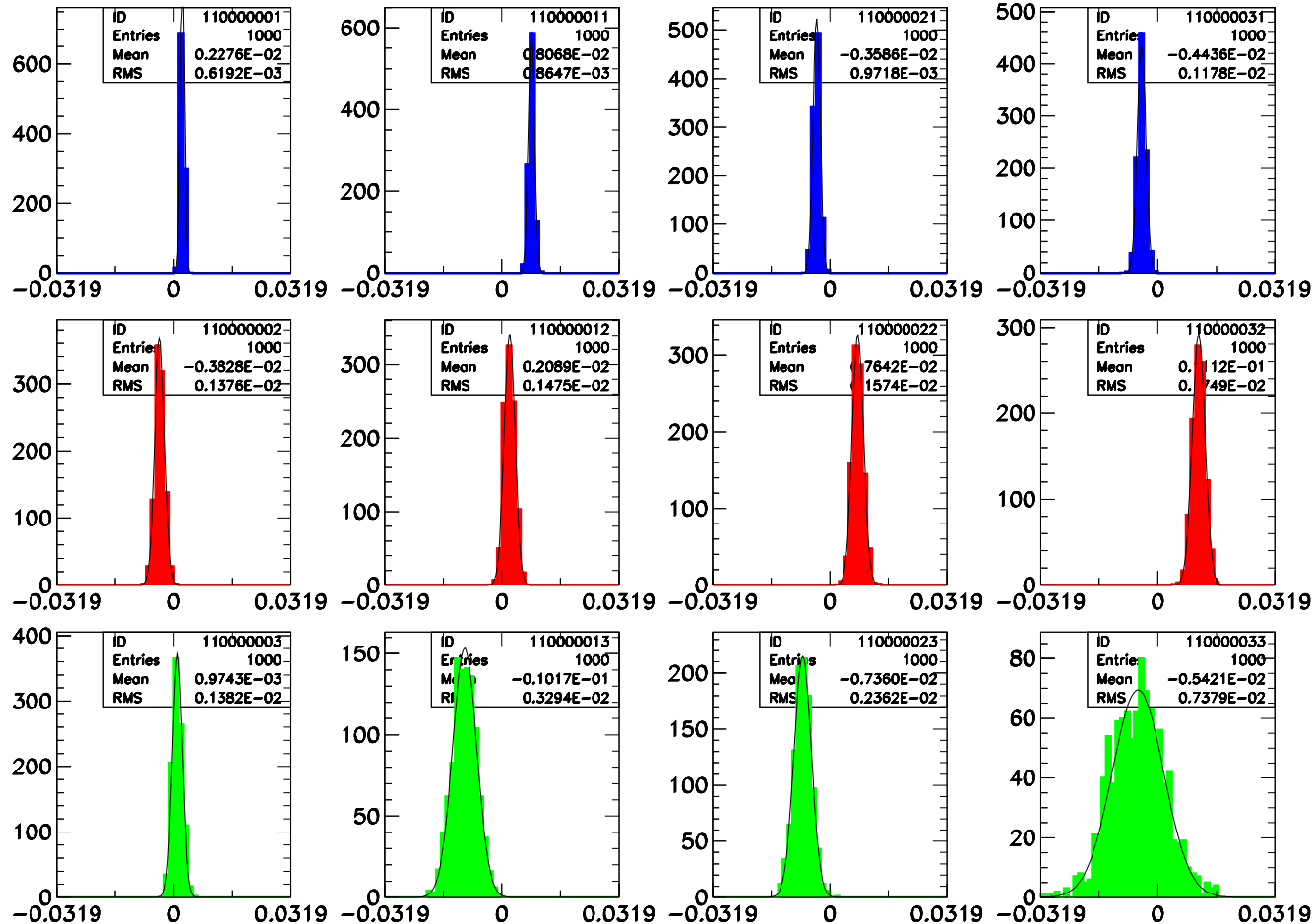
1. generate **TRUE** wall markers positions along the tunnel
(nominal values smeared by $\sigma = 10 \text{ mm}$ in X, Y, Z direction)
2. generate train “miscalibration pattern” for CCDs/FSI on each car
3. LOOP over “runs” (train journeys) along the tunnel
 - 3a. LOOP over cars in the train
 - generate car stops in front of wall markers
(smeared by $\sigma = 10 \text{ mm}$ (pos), $\sigma = 10 \text{ mrad}$ (ang))
 - transfer all coordinates of CCDs/FSI to the global (tunnel) frame
 - generate measurements of sensing units using **Ray Tracer** and **TRUE geometry on input**
(CCDs,FSI measurements smeared by resolution of $\sigma = 1 \mu\text{m}$)
4. **RECONSTRUCT** the system w.r.t. the unknown position/angles of cars and wall markers using **MISCALIBRATED geometry** and **smeared measurements**
5. collect histograms, calculate statistics for **RECONSTRUCTED-TRUE** variables

Miscalibrated train: egxample of “miscalibration pattern” for CCDs



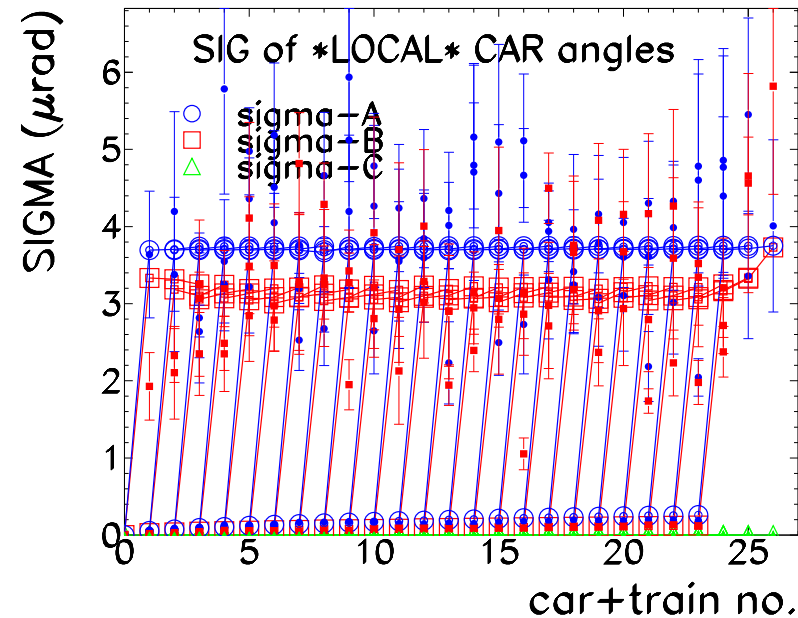
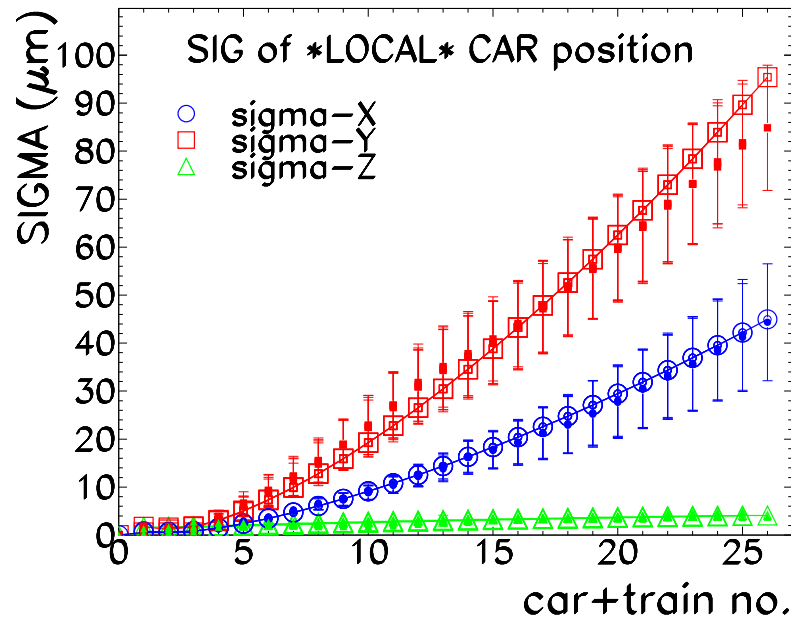
- CCD positions/angles and FSI retro-reflectors/launch points miscalibrated with Gaussian smearing
- example of CCD “miscalibration pattern” shown for $\sigma = 1\mu m$ (*pos*) (schematic view of 4 cars, 4 CCDs per car; nominal and distorted CCDs shown)
- as a result LSM (Laser Straightness Monitor) is no longer straight (!)
- ruler becomes “zigzag” (**X direction**, **Y direction**) with some mean curvature

Train Monte Carlo: Wall Markers positions: REC-TRUE distribution



- distribution of (REC-TRUE) position for X, Y, Z co-ord. for 4 wall markers
- symmetric Gaussian shapes: RMS \rightarrow statistical errors
- MEAN value shifted: \rightarrow systematic errors (RESIDUA)

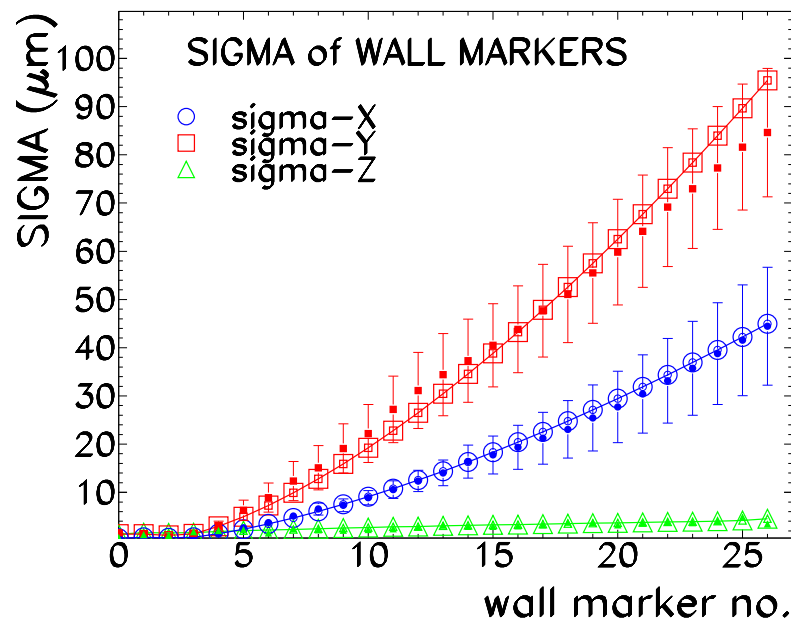
Train Monte Carlo: Statistical errors: RMS of (REC-TRUE)



$A = Rot_X$

$B = Rot_Y$

$C = Rot_Z$



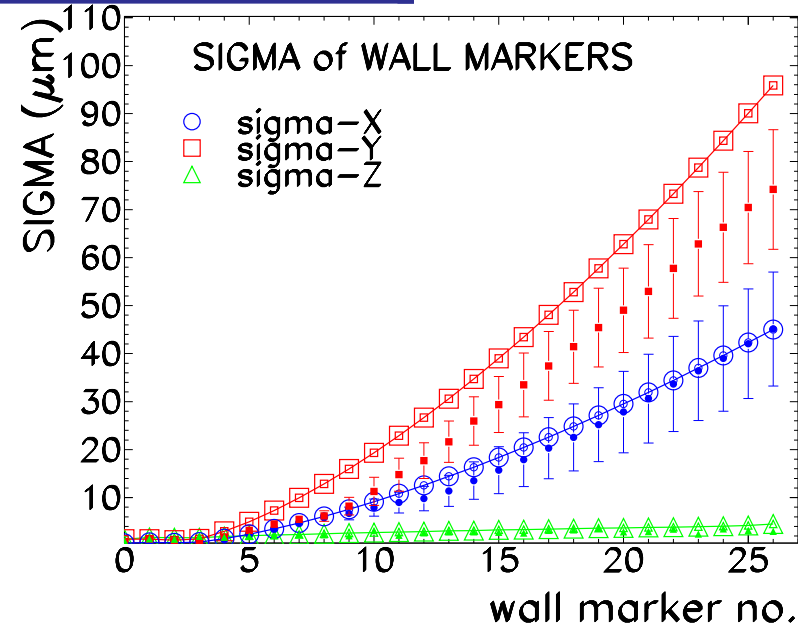
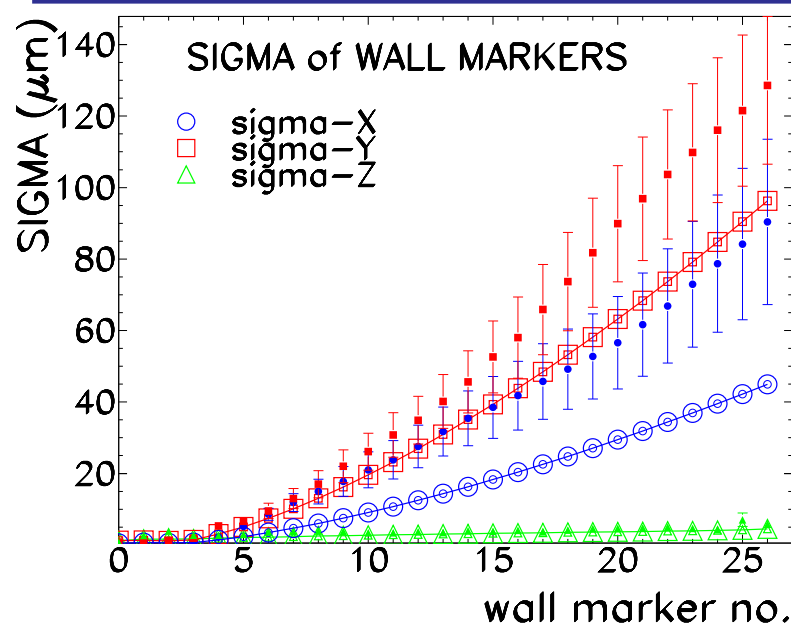
- assuming intrinsic resolutions:

– CCD: $\sigma_{CCD} = 1 \mu\text{m}$

– FSI: $\sigma_{FSI} = 1 \mu\text{m}$

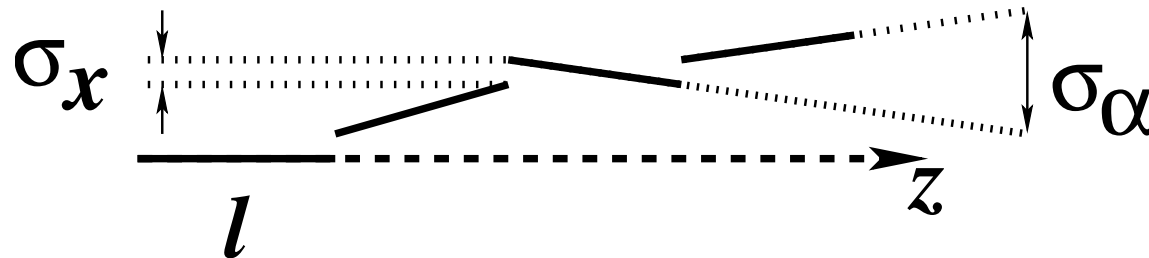
- 10 Simulgeo runs, 4 cars, 25 m car-to-car distance
growth of transverse errors: $\sim n^{3/2}$
- open markers: Matrix calculation (analytic)
solid markers: Errors from Monte Carlo

Train Monte Carlo: Statistical errors (cont.)



- open markers: Matrix calculation (analytic)
solid markers: Errors from Monte Carlo
- disagreement sometime observed for particular “miscalibration patterns”
and/or size of the cars position/angles randomisation
- artefact of the numerical methods used (?)
- effect under investigation but much smaller then the systematic errors (see next pages)

Short ruler model (or random walk along the tunnel)



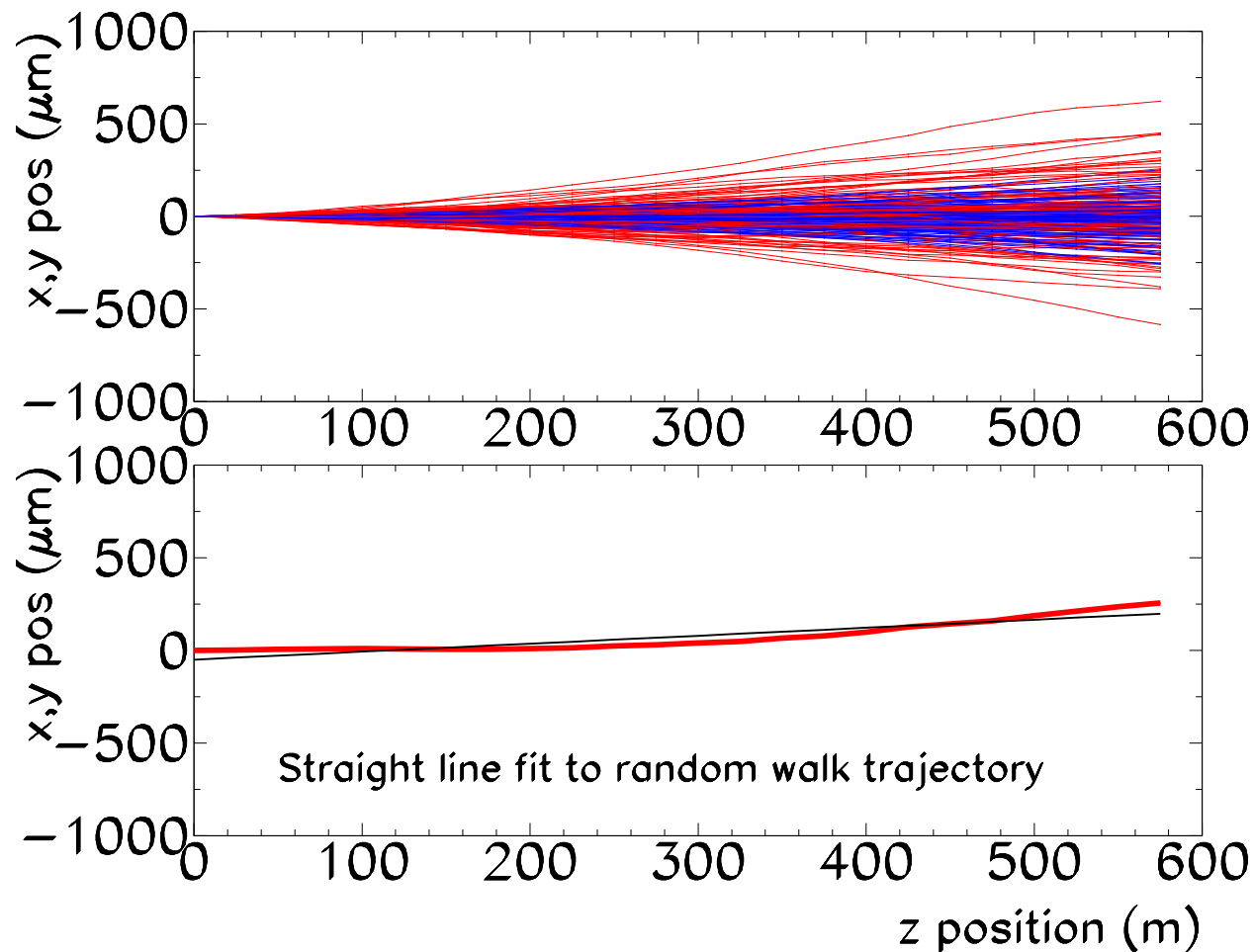
- two sources of errors (2D case): position (off-set) and direction (angle)
- off-sets and angles are **relative** to the previous “ruler”

$$\sigma_{xy,n} = \sqrt{l^2 \sigma_\alpha^2 \frac{n(n+1)(2n+1)}{6} + \sigma_{xy}^2 \frac{n(n+1)}{2}}, \quad \sigma_{z,n} = \sqrt{\sigma_z^2 \frac{n(n+1)}{2}}$$

n – wall marker number, l – effective length of the ruler (here: distance between cars), errors: σ_α – angular, σ_{xy} – transverse, σ_z – longitudinal

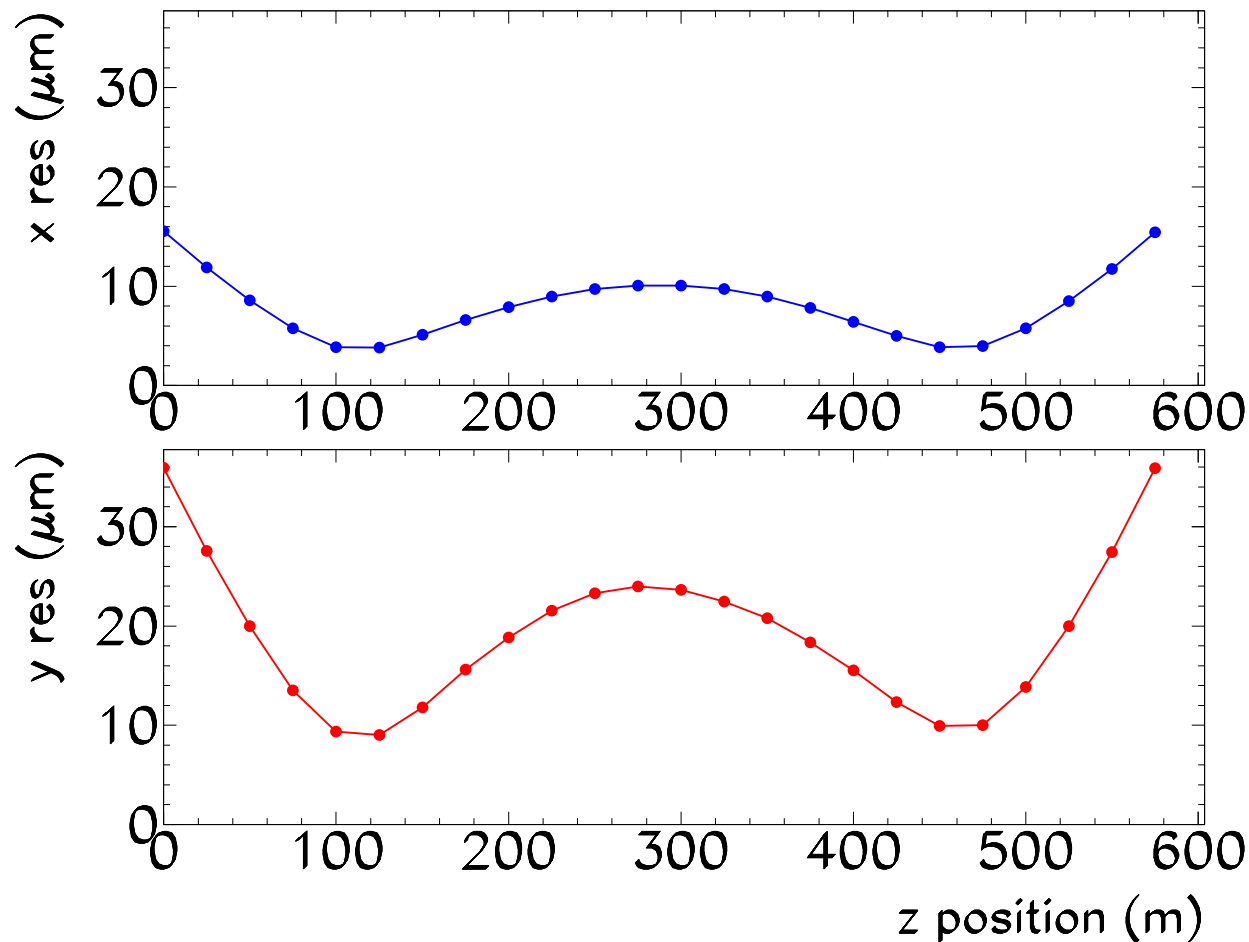
- asymptotic behaviour of transverse errors: $\sim n^{3/2}$

Random Walk model: trajectories, straight line fits



- trajectories generated for Random Walk model using parameters from the fit to SIMULGEO points (X , Y) direction
 - points along trajectories are very correlated (ie.: small 'oscillations' observed)
 - straight line fits to the Random Walk paths for 600 m tunnel section
- repeating this procedure for many “numerical experiments” ...

Random Walk Monte Carlo: residua of stat. errors

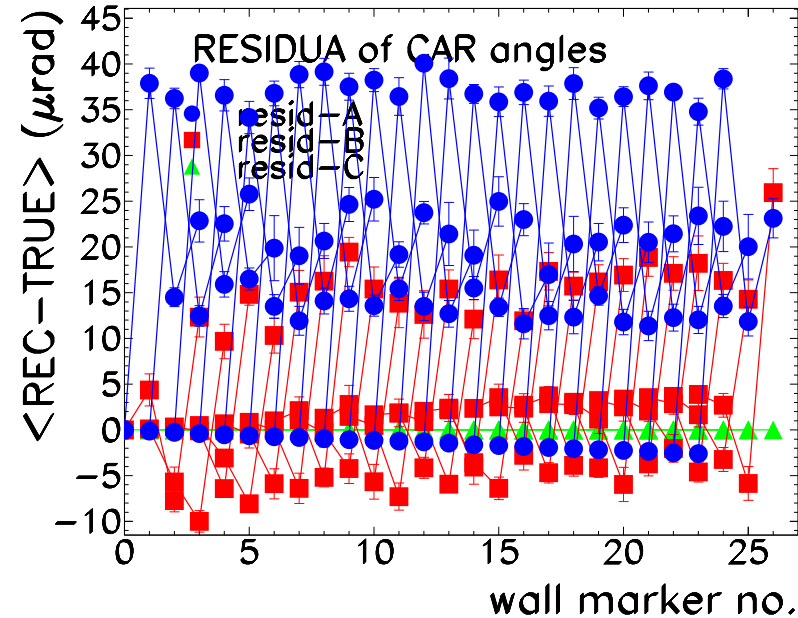
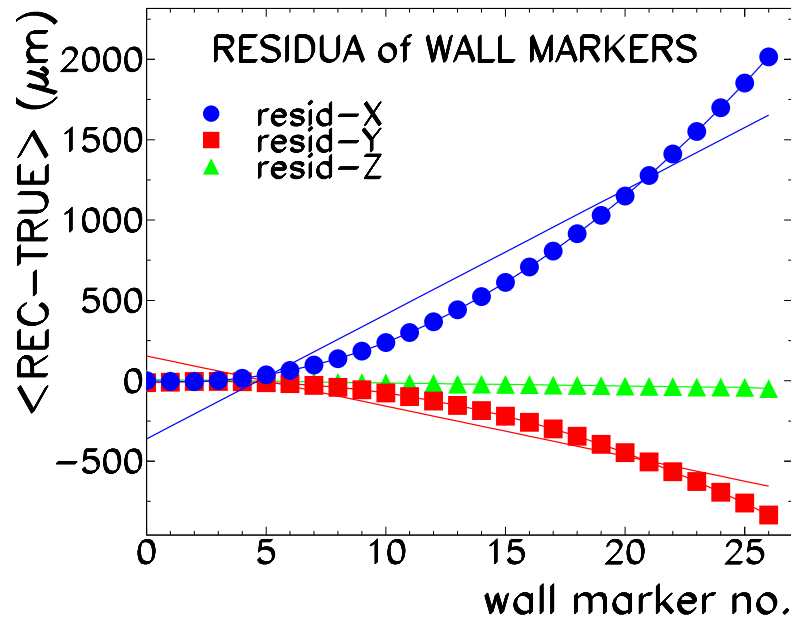


- mean deviation from straight line fits (X, Y) direction

- statistical component of error budget well below specification:

$$\sigma_x = 500\mu m, \sigma_y = 200\mu m$$

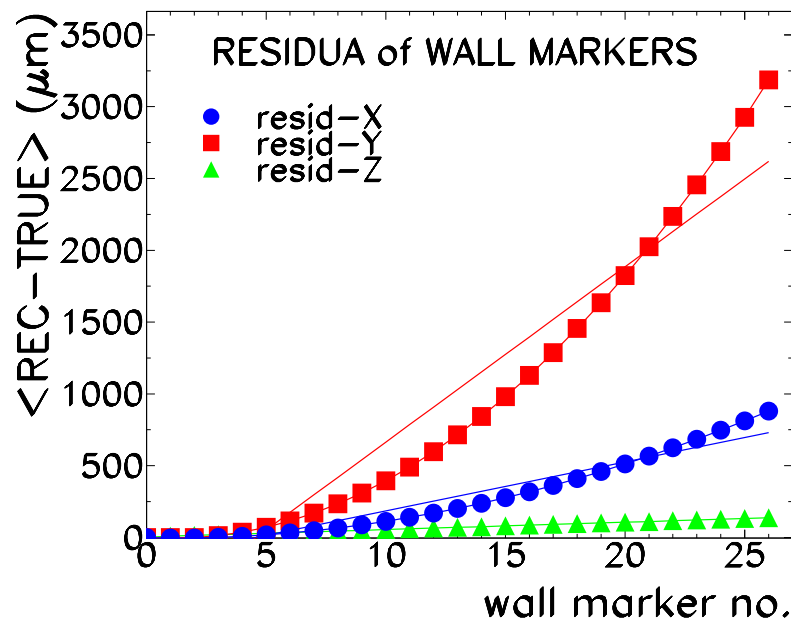
Train Monte Carlo: systematic errors (MEAN of REC-TRUE)



$A = \text{Rot}_X$

$B = \text{Rot}_Y$

$C = \text{Rot}_Z$



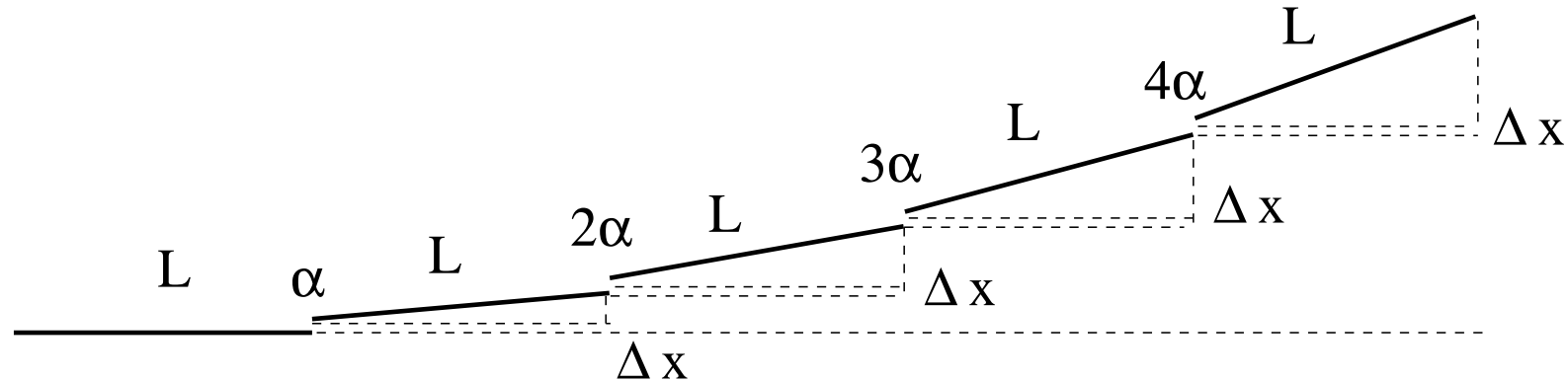
- assuming calibration precision:

- CCD: $\sigma_{\text{CCD}} = 5 \mu\text{m}$

- FSI: $\sigma_{\text{FSI}} = 5 \mu\text{m}$

- linear ($\sim n$) growth of angular errors
- quadratic ($\sim n^2$) growth of transverse errors
- examples of straight line fits for two “miscalibration patterns”

Model of systematic errors for LiCAS train



- angular term:

$$\sigma_{ang}^{sys} = L \sin(\alpha) + L \sin(2\alpha) + L \sin(3\alpha) + \dots + L \sin(n\alpha)$$

$$\sigma_{ang}^{sys} \simeq L\alpha(1 + 2 + 3 + \dots + n) = L\alpha n(n + 1)/2 \rightarrow n^2 \text{ (quadratic !!)}$$

- translation term:

$$\sigma_{tr}^{sys} = n\Delta x \text{ (linear)}$$

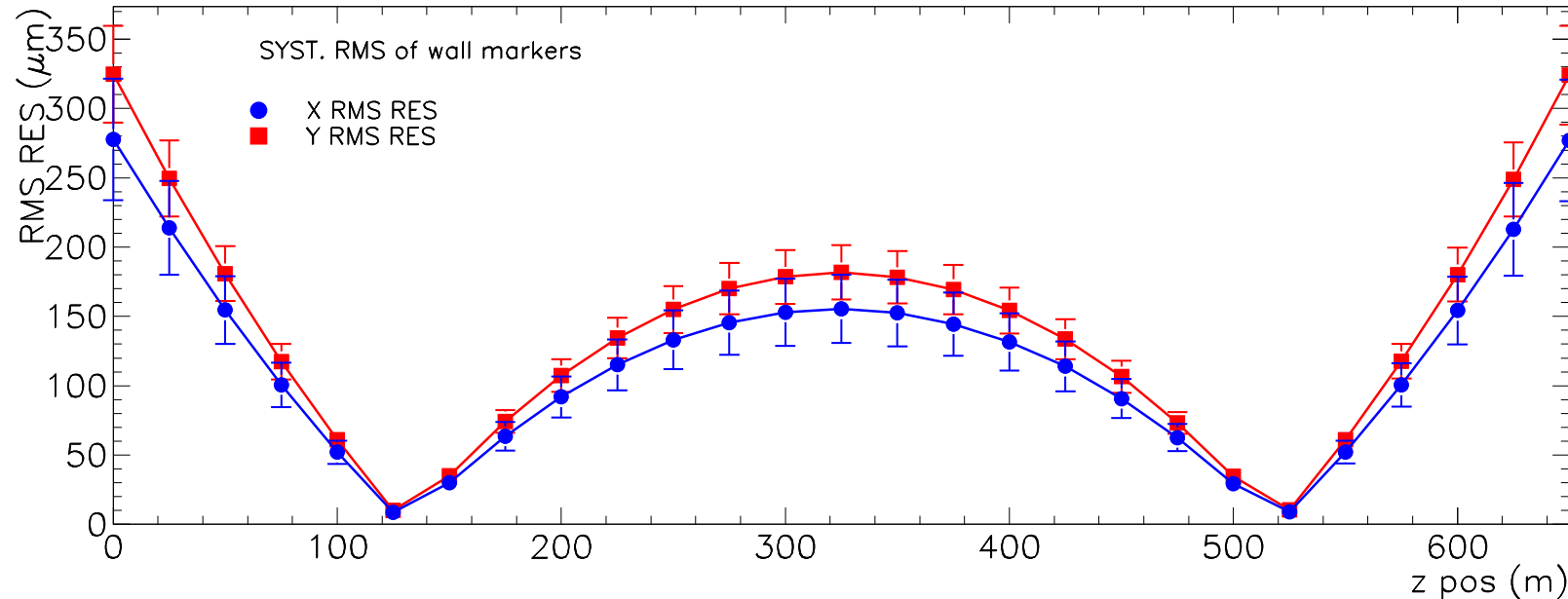
- full formulae:

$$\sigma_{tot}^{sys} = L\alpha n(n + 1)/2 + n\Delta x$$

where L is the “effective” ruler length (car-to-car distance)

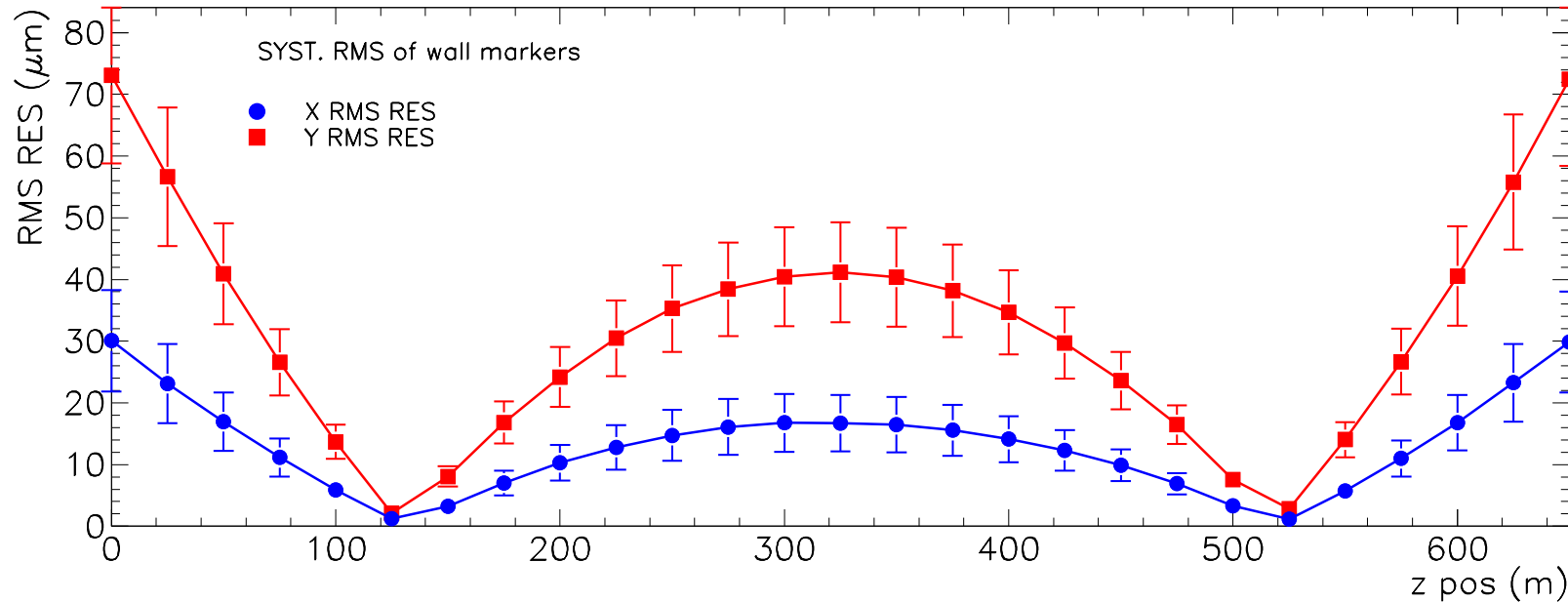
α and Δx should be extracted from the full SIMULGEO model

Train Monte Carlo: systematic errors: RMS of RESIDUA



- RMS of residua distribution for 10 different “miscalibration patterns”
- calibration precision: CCD: $\sigma_{CCD} = 5 \mu m$; FSI: $\sigma_{FSI} = 5 \mu m$
- reaching specification: $\sigma_x = 500 \mu m$, $\sigma_y = 200 \mu m$

Train Monte Carlo: systematic errors: RMS of RESIDUA



- RMS of residua distribution for 10 different “miscalibration patterns”
- calibration precision: CCD: $\sigma_{CCD} = 1 \mu m$; FSI: $\sigma_{FSI} = 1 \mu m$
- well below specification: $\sigma_x = 500 \mu m$, $\sigma_y = 200 \mu m$

Conclusions/Plans

- LiCAS technology is capable of surveying the ILC tunnel to desired accuracy: $\mathcal{O}(200) \mu m$ over $600 m$ tunnel section
- Realistic model of error propagation for LiCAS train was developed (both statistical and systematic errors)
- Simulation and reconstruction software using above model is ready, → can be used to test/validate different train concepts
- LiCAS train base line design has changed from 6 cars $4.5 m$ car-to-car distance to 4 cars $25 m$ car-to-car distance
- Next plans:
 - incorporate the systematic errors to the `licas_sim` package generating the input for the ILC beam dynamics simulations
 - test the reconstruction software on real data from the LiCAS train prototype operating now at DESY