Simulation of the LiCAS survey system for the ILC

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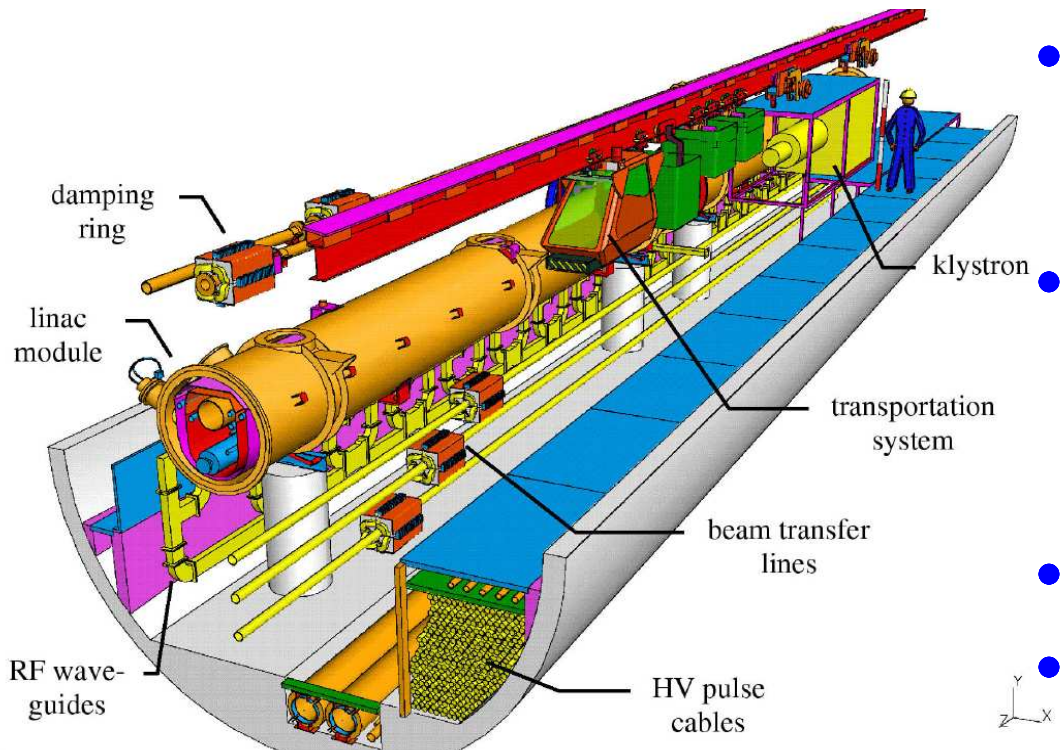
Outlook

- Requirements for the ILC Tunnel Survey and Alignment
- Principles of the LiCAS-RTRS[1] train operation
- Software used in the simulation:
  - Error propagation
  - LiCAS Ray-Tracer and Reconstruction
  - LiCAS Monte Carlo
- Simulation of single train stop ($\sim 20\,m$)
- Train operation along the accelerator tunnel ($\sim 100\,m$)
- Random walk model for the error propagation (extrapolation to $\sim 600\,m$)
- Conclusions

[1] Rapid Tunnel Reference Surveyor

Alignment and survey: basic requirements

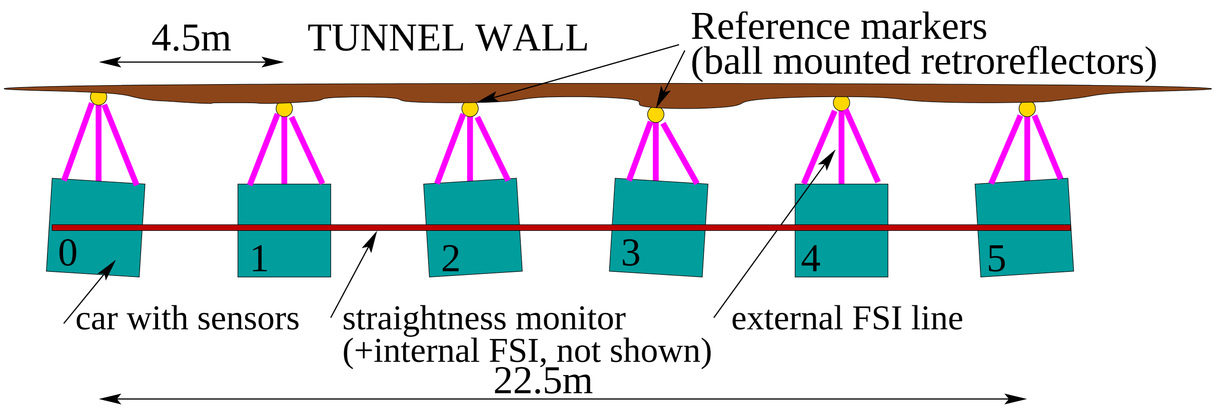


Alignment involves:

1. accelerator component construction accuracy
2. accelerator component fiducialisation
3. reference survey (→ this talk)
4. stake out
5. position adjustment

- ILC will operate at ultra low emittance → alignment of all components will be crucial (cavities, magnets, bpm's, etc.)
- long tunnel ($\sim\ 50\,km$ incl. Damping Rings) to survey: fast, automated measurement needed (realign with minimum shutdown time)
- tight free space ($\approx 1\,m$ wide)
- no long term stable reference monuments (LEP: $100\,\mu m/year$) → survey must be regularly repeated (1-2 times per year)
- biggest problem of open air techniques: refraction

LiCAS-RTRS train: principle of operation

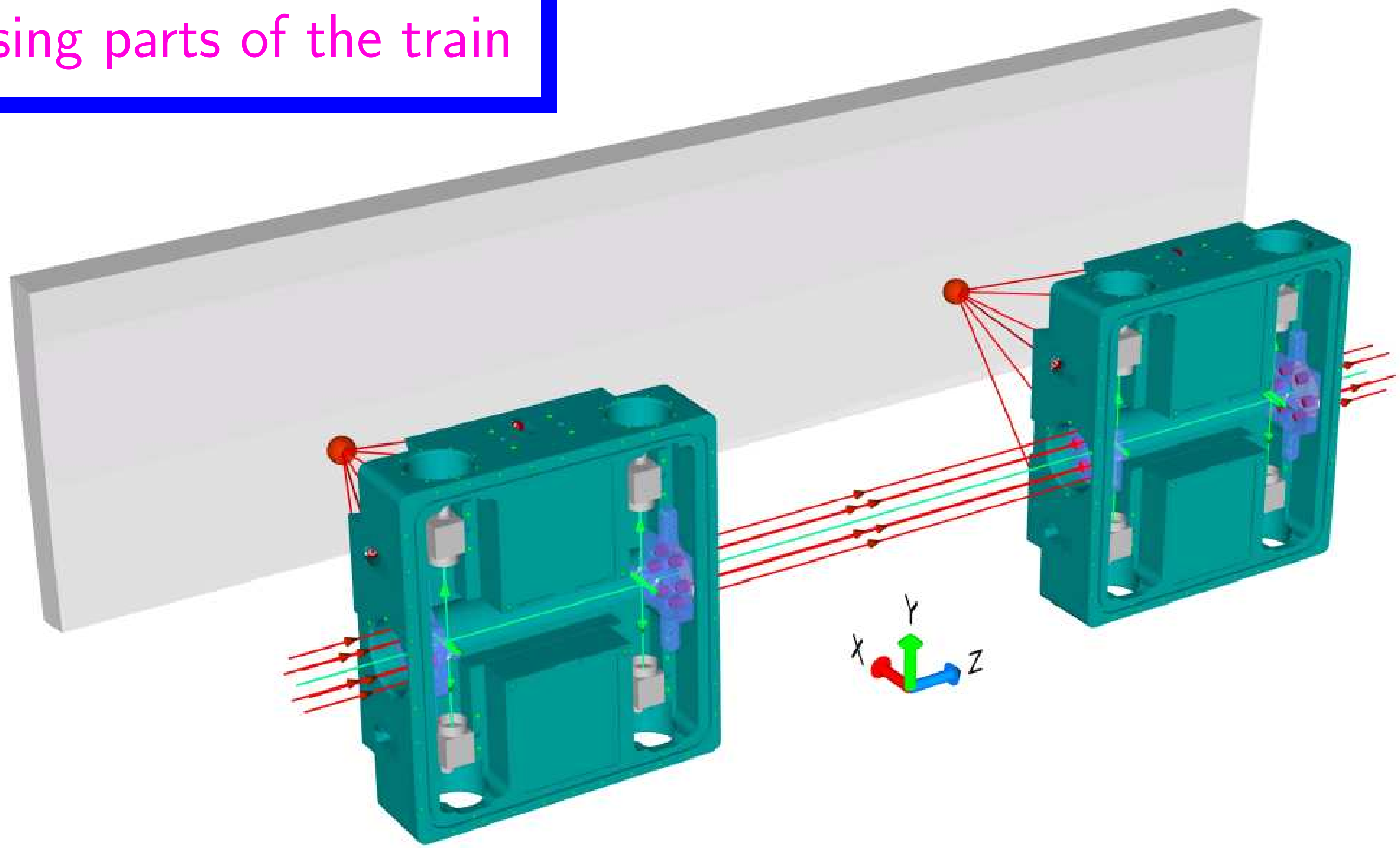


- RTRS: Rapid Tunnel Reference Surveyor - mechanical concept of the survey train developed at DESY for TESLA
- collider alignment at construction stage: $200\,\mu m$ over $600\,m$ in vertical (example TESLA specification)
- LiCAS: Linear Collider and Survey, proposed technology: optical measurements using FSI (Frequency Scanning Interferometry) and Laser Straightness Monitors (LSM) (internal laser beam lines in vacuum)
- More details incl. internal distance measurements on next slide

- automatic train measures reference markers (i.e. defines the reference frame)
- later measure collider position w.r.t. the above co-ordinate system
- internal laser lines in vacuum

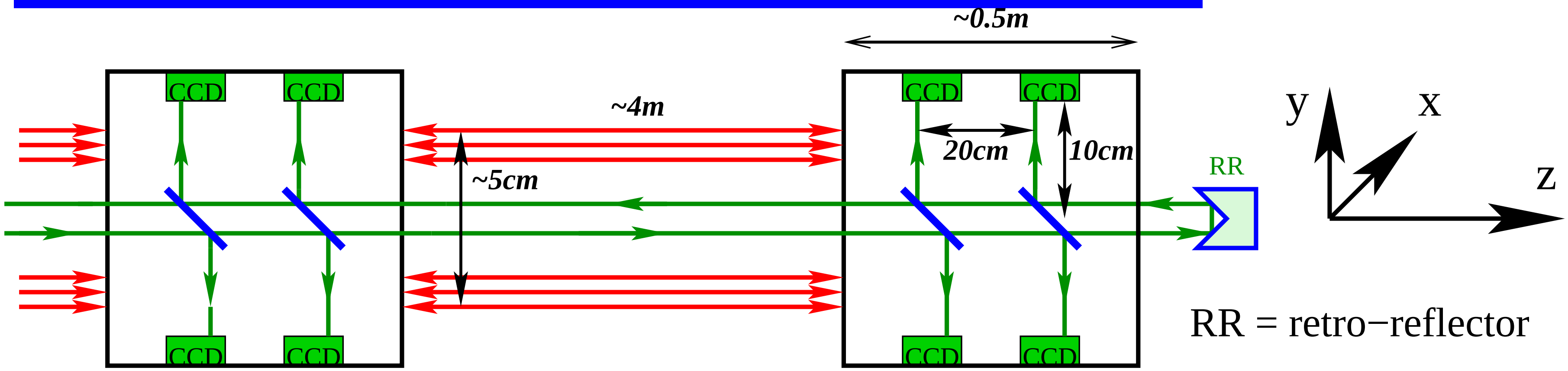
- prototype installation at DESY started in Summer 2006
  → see LiCAS overview talk in this Workshop

Sensing parts of the train



- 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
  - External FSI: 6 laser lines per car, 1 wall marker in front of each car
  - clinometer (not shown) for Rot_z

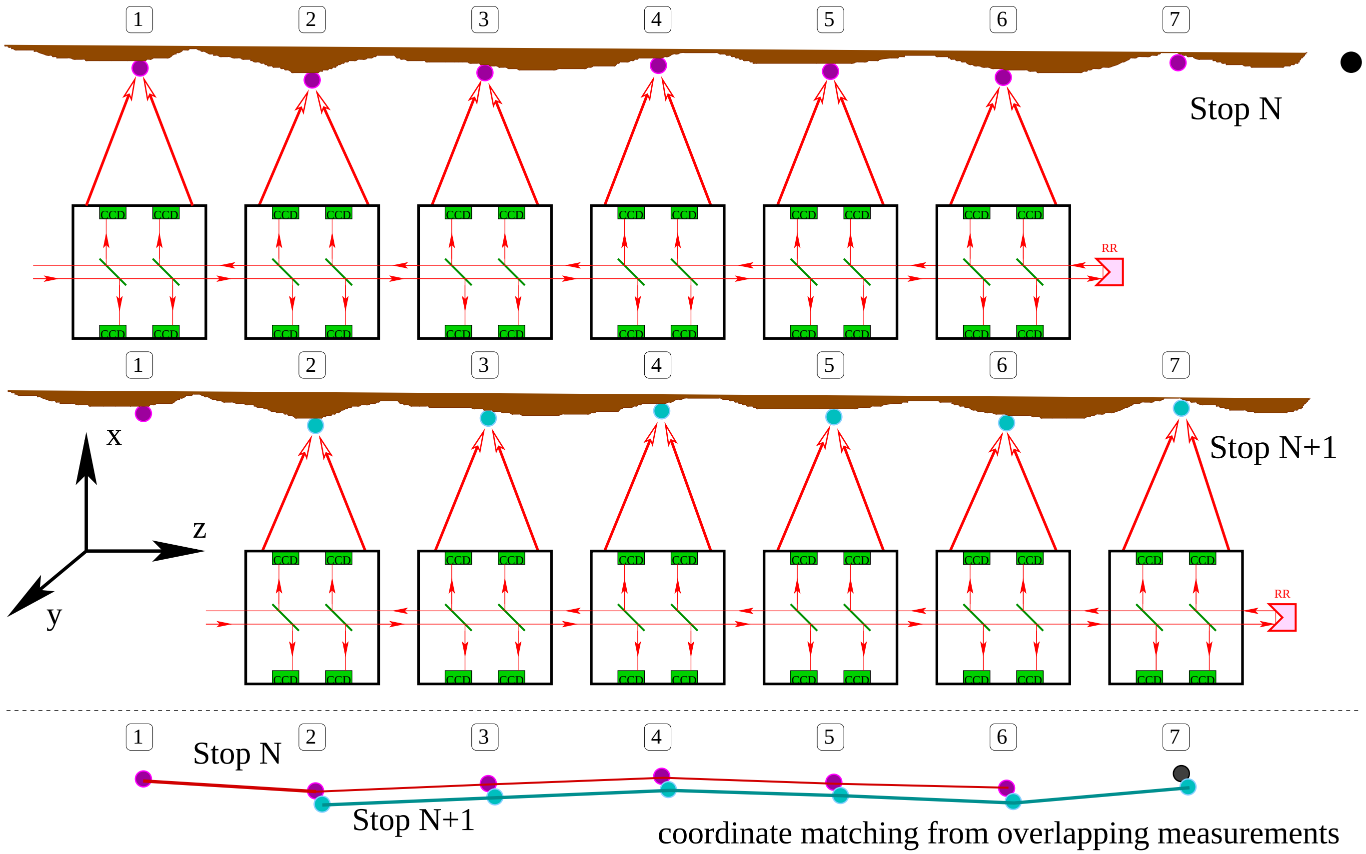
Sensitivity of various internal train subcomponents



Accessible DOF:						
$COMP$	Tr_x	Tr_y	Tr_z	Rot_x	Rot_y	Rot_z
LSM	$\surd$	$\surd$		$\surd$	$\surd$	
INT-FSI	$\pm$	$\pm$	$\surd$	$\pm$	$\pm$	
Clinometer				$\surd$(not used)		$\surd$

- LSM: transverse translation ($Tr_{x,y}$, $\sigma \approx 0.3\mu m$) and rotation ($Rot_{x,y}$, $\sigma \approx 3.0\mu rad$)
- INT-FSI: longitudinal distance ($\sigma \approx 1\mu m$) ($\pm$ redundancy for LSM)
- Clinometer: only Rot_z used (insensitive to the geoid shape)

Idea of the overlapping multi train measurement

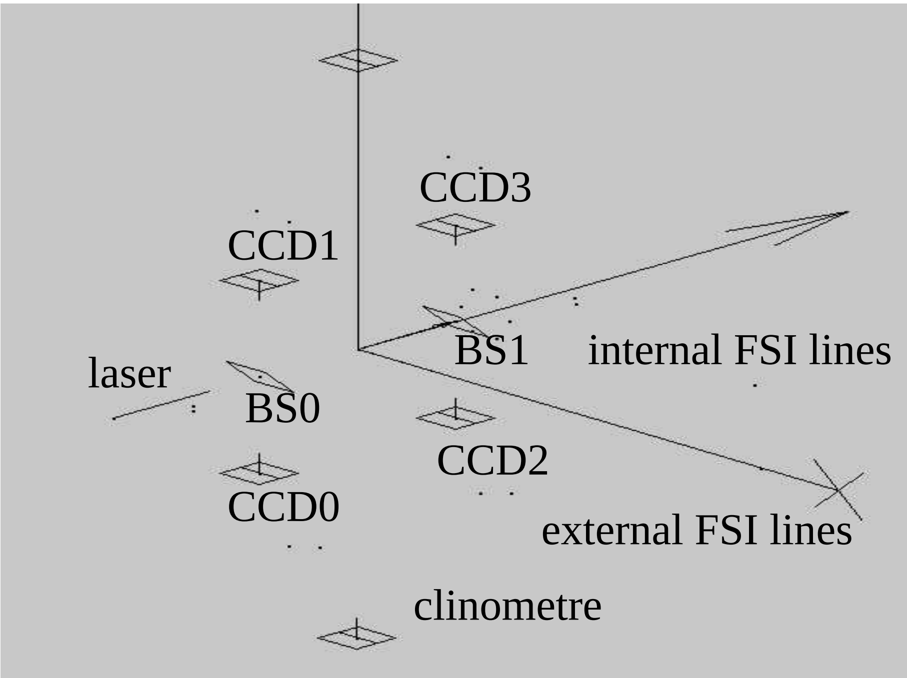


- top view on two train stops along the tunnel wall

- 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)

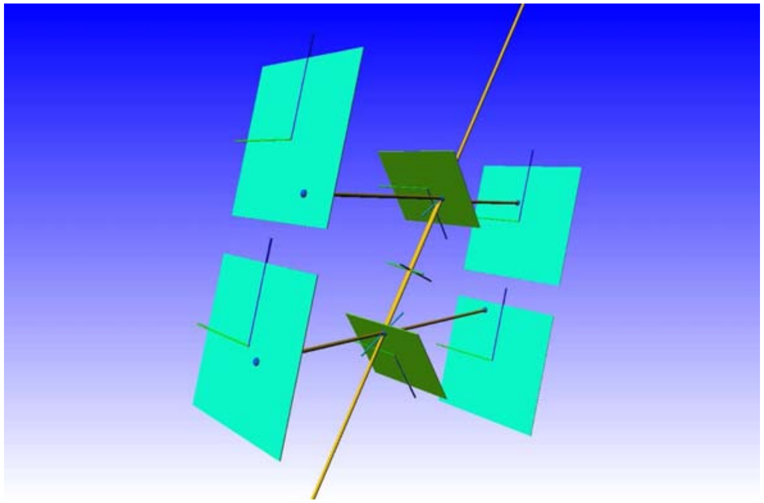
SIMULGEO: Software used in the simulation

- Object oriented script language for description of opto-geometrical systems
- Mechanical correlations between objects grouped in local frames
- ERROR PROPAGATION MODE: Performs full error propagation (N^2 matrix, very CPU consuming)

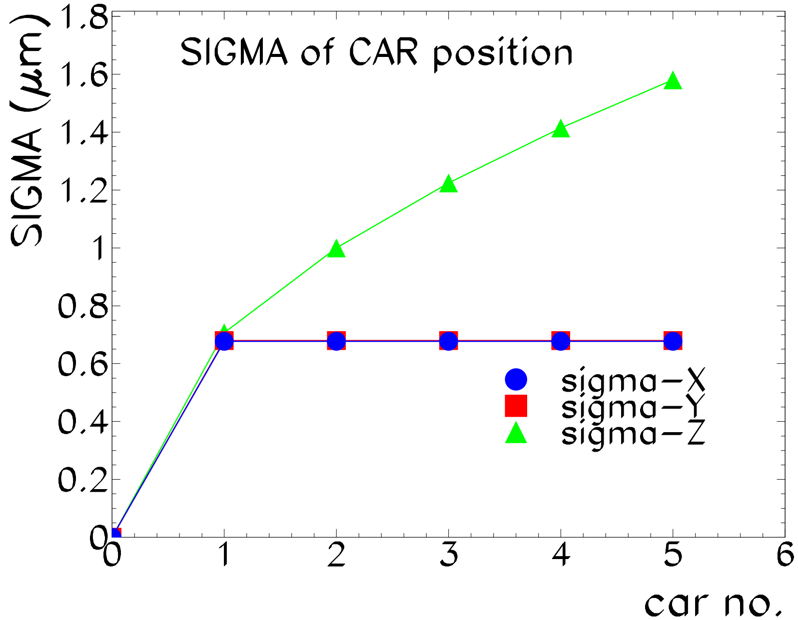


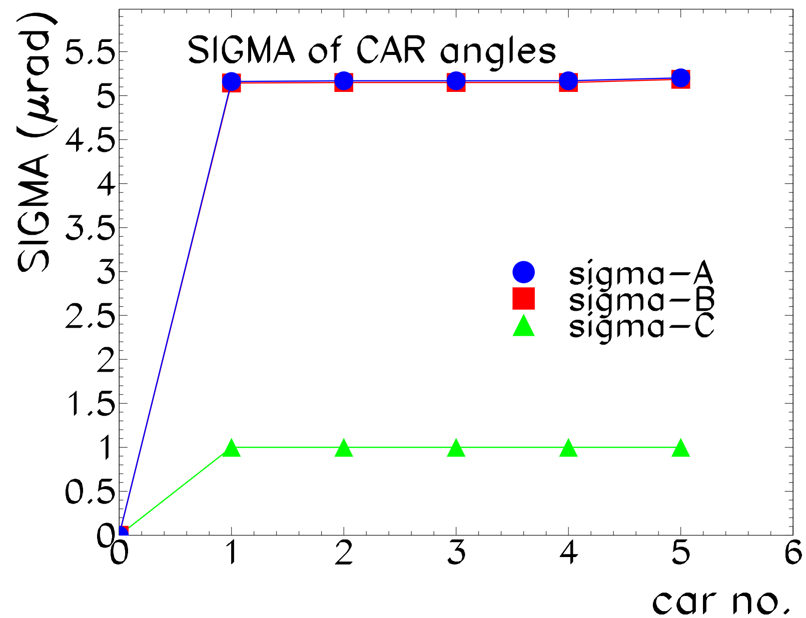
LiCAS Ray-Tracer, Reconstruction and train Monte Carlo

- Ray Tracer: generating (for a given geometry) all CCD, internal and external FSI measurements
- Running SIMULGEO in RECONSTRUCTION MODE.
  Solving the geometry of the system using provided "experimental" measurements. (Input from ray-tracer).
- smearing of the measurements with sensor resolution, running many train journeys in a loop:
  Monte Carlo approach to error propagation (allows also to study error distribution)



Single train simulation: car position and angles, wall markers

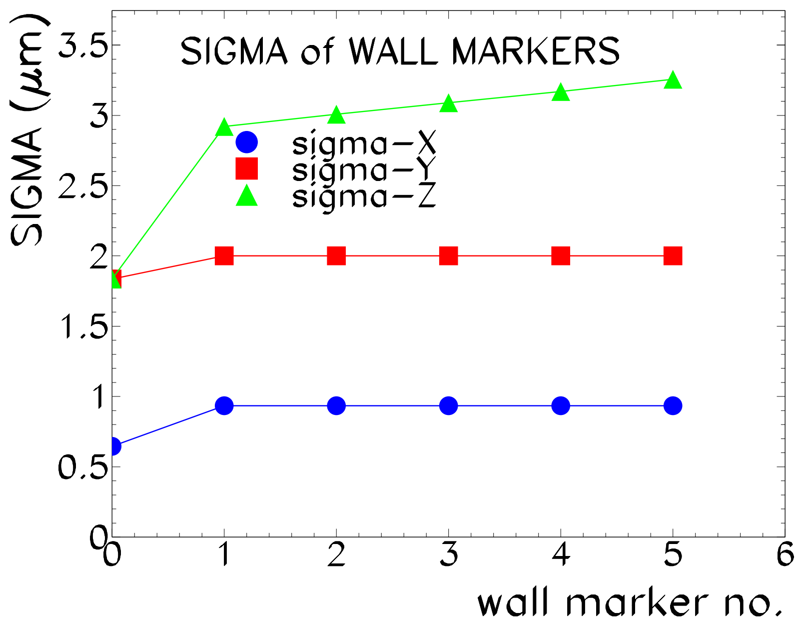




$A = Rot_X$

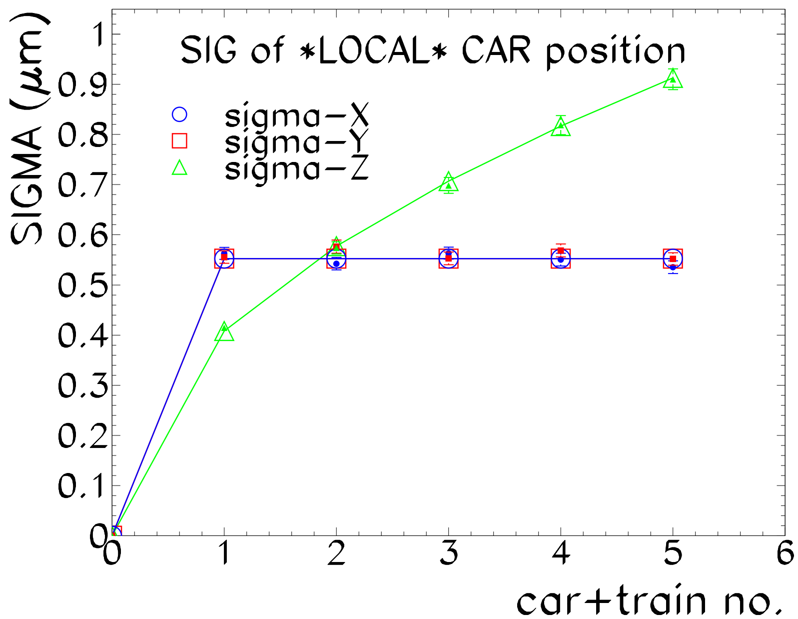
$B = Rot_Y$

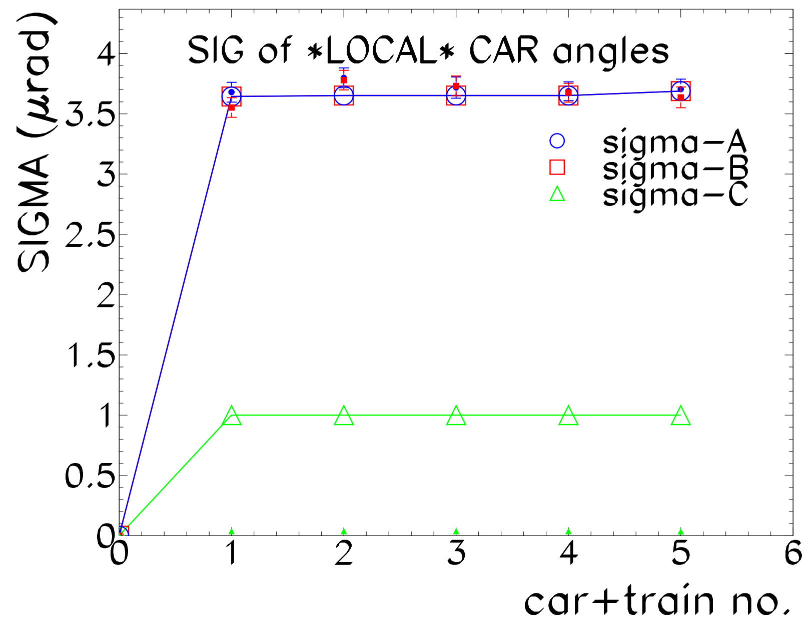
$C = Rot_Z$



- assuming intrinsic resolutions:
  - CCD: $\sigma_{CCD} = 1\,\mu m$
  - FSI: $\sigma_{FSI} = 1\,\mu m$
  - tiltmeter: $\sigma_{tilt} = 1\,\mu rad$
- calib. const.: (INT/EXT-FSI,CCD,BS)
  - $\sigma_{pos} = 1\,\mu m$, $\sigma_{ang} = 1\,\mu rad$

Single train simulation: Monte Carlo approach





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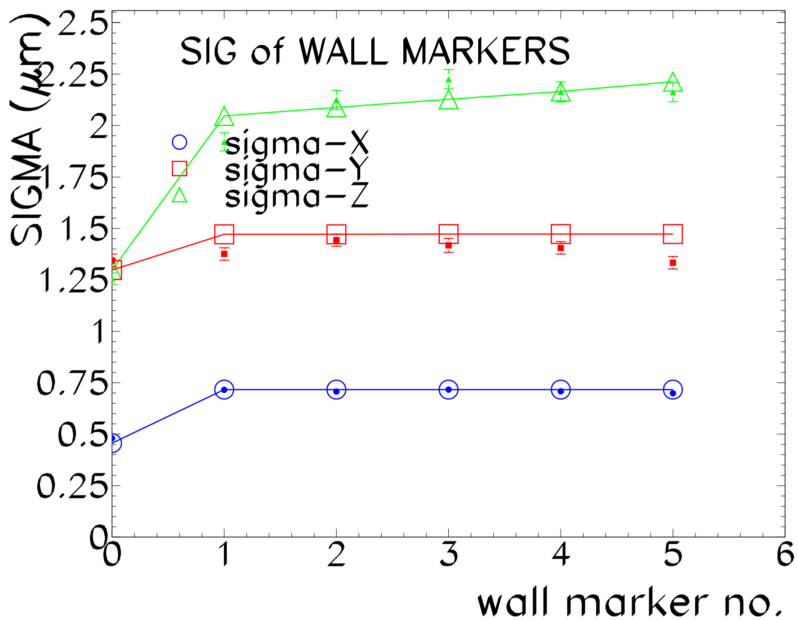
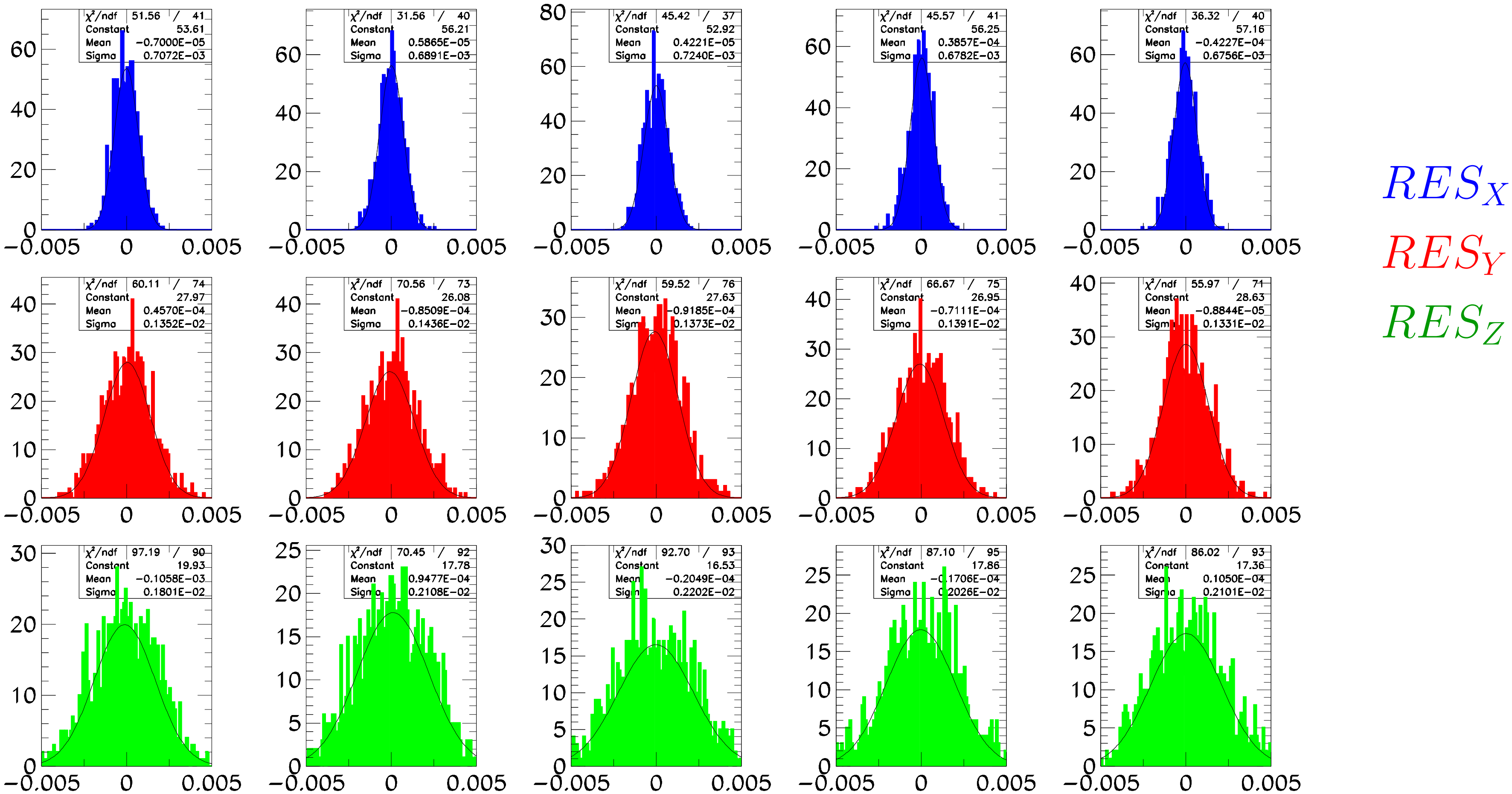


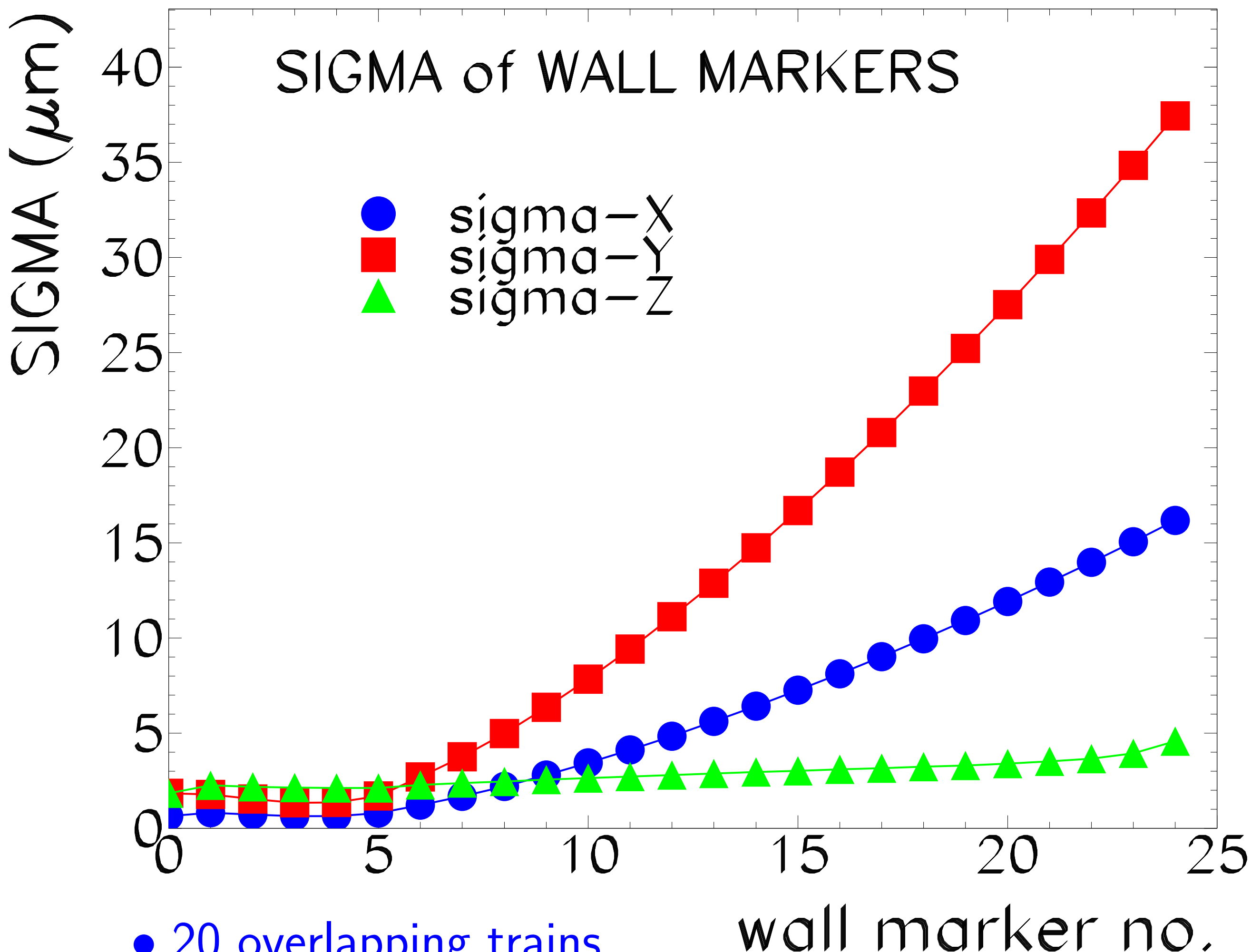
- assuming intrinsic resolutions:
  - CCD: $\sigma_{CCD} = 1\,\mu m$
  - FSI: $\sigma_{FSI} = 1\,\mu m$
- 1000 Simulgeo runs, simplified model, no errors on calib. const. (INT/EXT-FSI,CCD,BS)
- open markers: Matrix calculation (analytic)
  solid markers: Errors from Monte Carlo

Residua distribution (Reconstructed - Generated) for Wall Markers



- 1000 SIMULGEO runs for 1 LiCAS train (smearing only for CCD and FSI)
- Nice Gaussian shapes, no bias on reconstructed mean value (X axis in [mm])
- More study on systematic effects soon

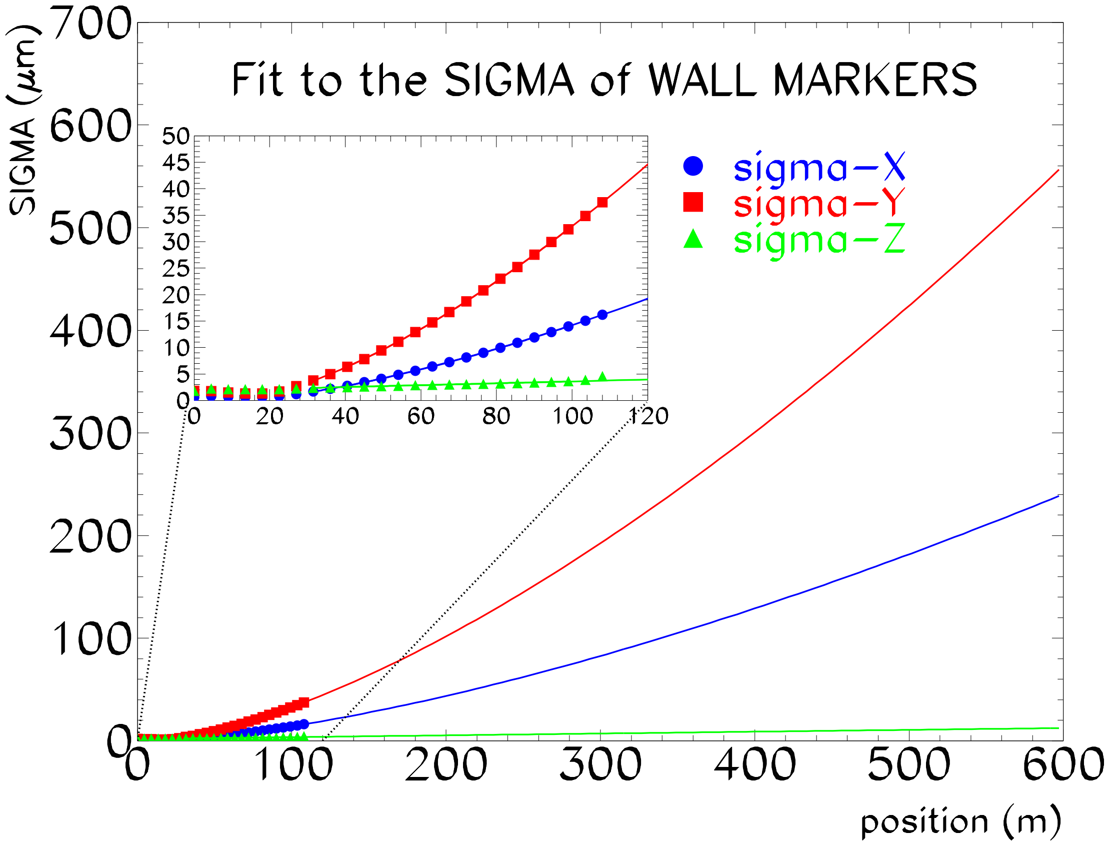
20 train stops ($= 90\,m$ tunnel section)



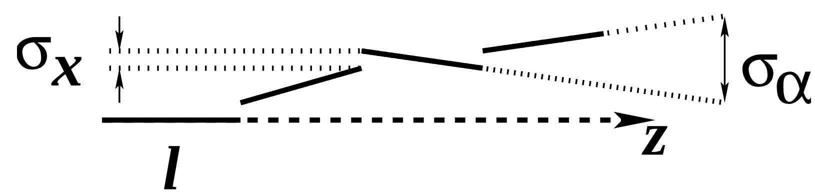
- results of full SIMULGEO simulation (error matrix rank $N^2 \sim 10\,000^2$)
- fast growth of transverse errors !

- 20 overlapping trains
- train stops are coupled to each other via the (previously measured) wall markers

Extrapolation to $600\,m$ tunnel section



- extrapolation using random walk model:



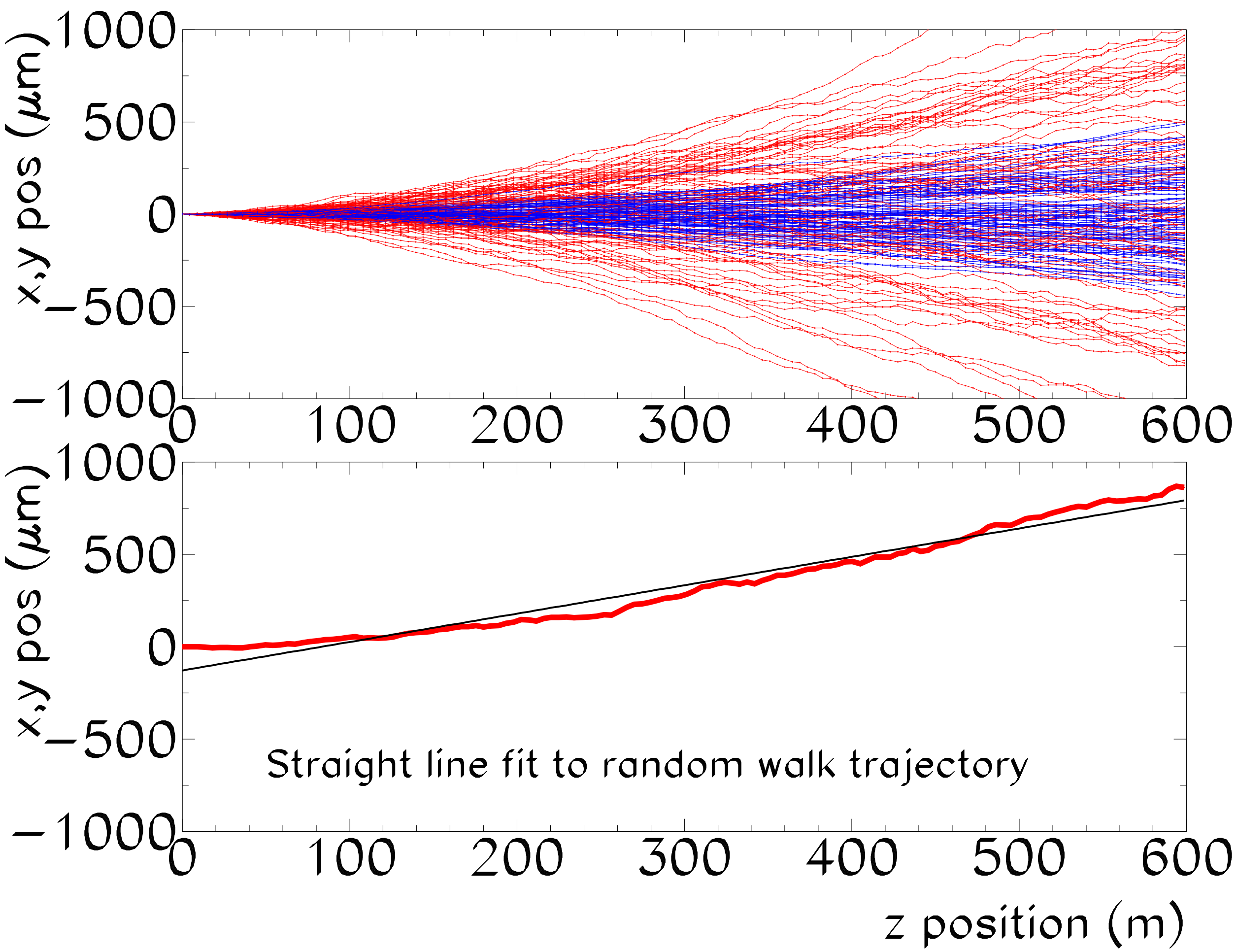
- off-sets and angles are relative to the previous "ruler"
- asymptotic behaviour:

$$\sigma_{xy,n} \sim n^{\frac{3}{2}}, \quad \sigma_{z,n} \sim n$$

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

n – wall marker number, l – effective length of the ruler (here: distance between cars),
errors: σ_α – angular $(\sim 0.1\,\mu rad)$, σ_{xy} – transverse $(\sim 0.5\,\mu m)$, σ_z – longitudinal $(\sim 0.1\,\mu m)$

Random Walk Monte Carlo: trajectories, fits

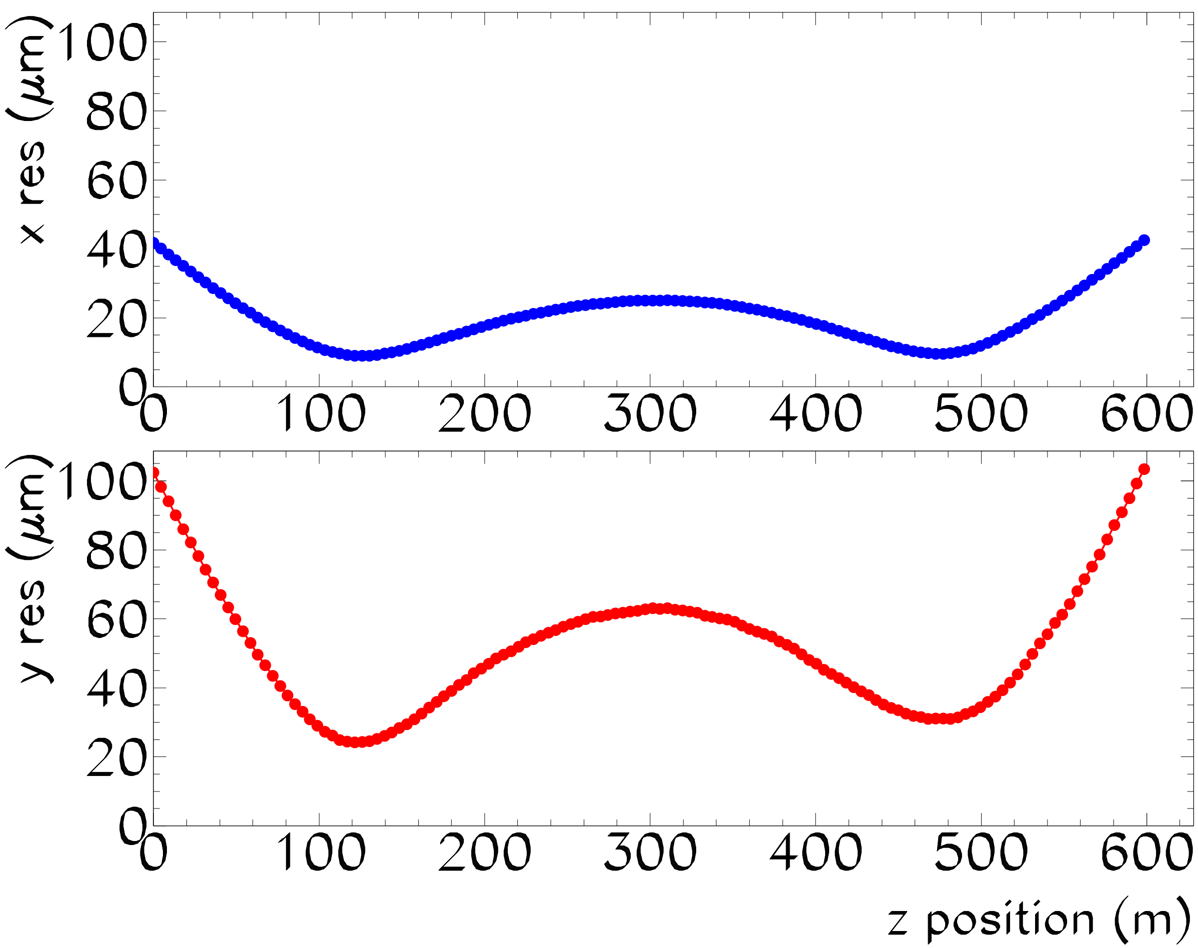


- trajectories generated from Random Walk Monte Carlo using parameters from the fit to SIMULGEO points (X, Y) direction

- good news: points along trajectories are strongly 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"...

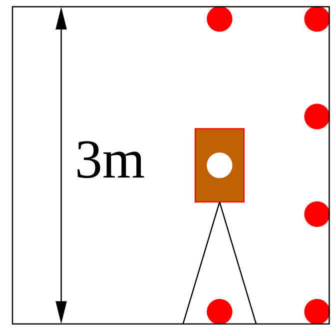
Random Walk Monte Carlo: residua

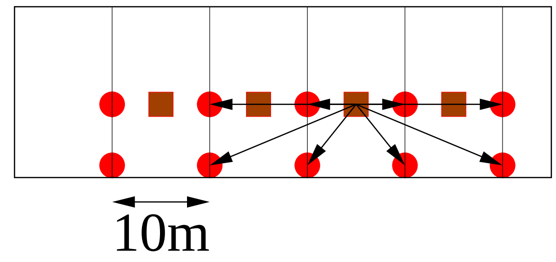


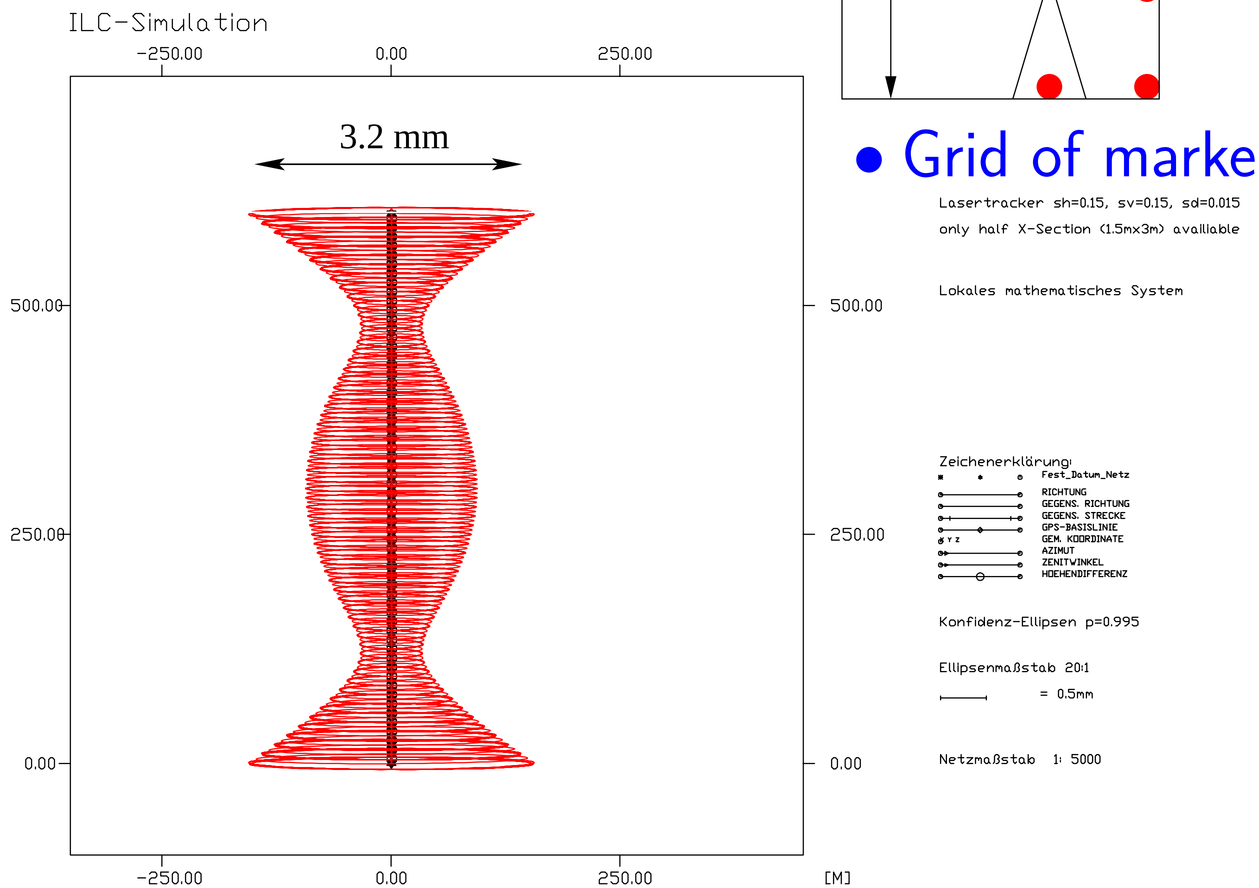
- mean deviation from straight line fits (X, Y) direction
- realistic input to the simulations of beam dynamics

- 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)

Classical metrology result







- Grid of markers used in simulation

- using Lasertracker ($\sigma_h = 0.15\,mgon$, $\sigma_v = 0.15\,mgon$, $\sigma_d = 0.015\,mm$)
- Neglecting refraction in air !

Summary

- LiCAS technology is capable of surveying the ILC tunnel to desired accuracy: $\mathcal{O}(200)\,\mu m$ over $600\,m$ tunnel section
- Reconstruction procedure for wall markers positions using CCD and FSI readout for single and many train stops was developed
- Systematics errors under study (using Monte Carlo approach)
- Work in progress on the train calibration procedure (LSM,FSI,...) $\longrightarrow$ next plans:
  - determine sensitivity to different calibration parameters
  - find method of $in\ situ$ calibration