Simulation of the Performance of the LiCAS Train

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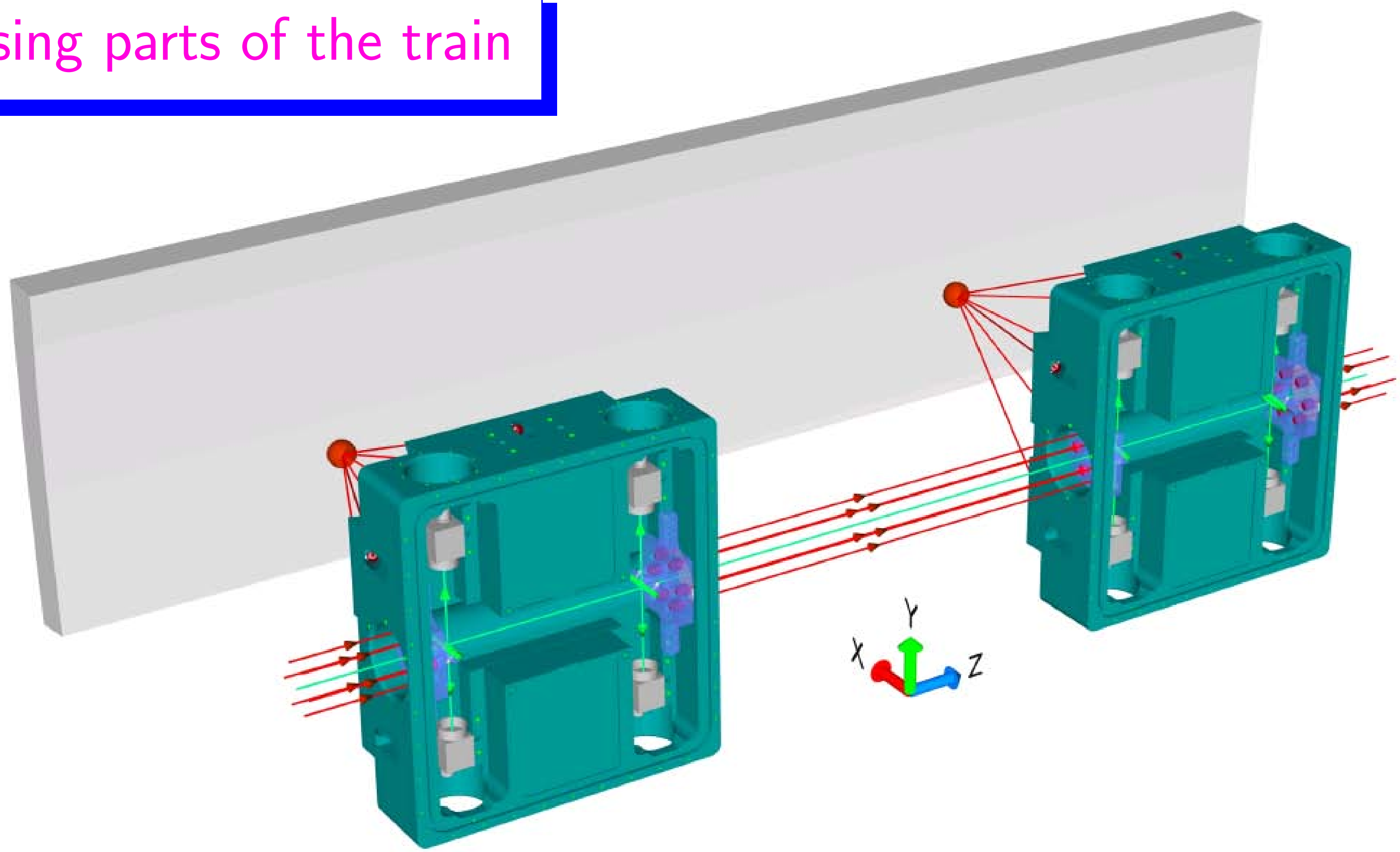
Outlook

- Principles of the train simulation
- Simulation of single train stop
- Train “journey” along the accelerator tunnel
- Random walk model for the error propagation
- Calibration of the train components (LSM)
- Conclusions

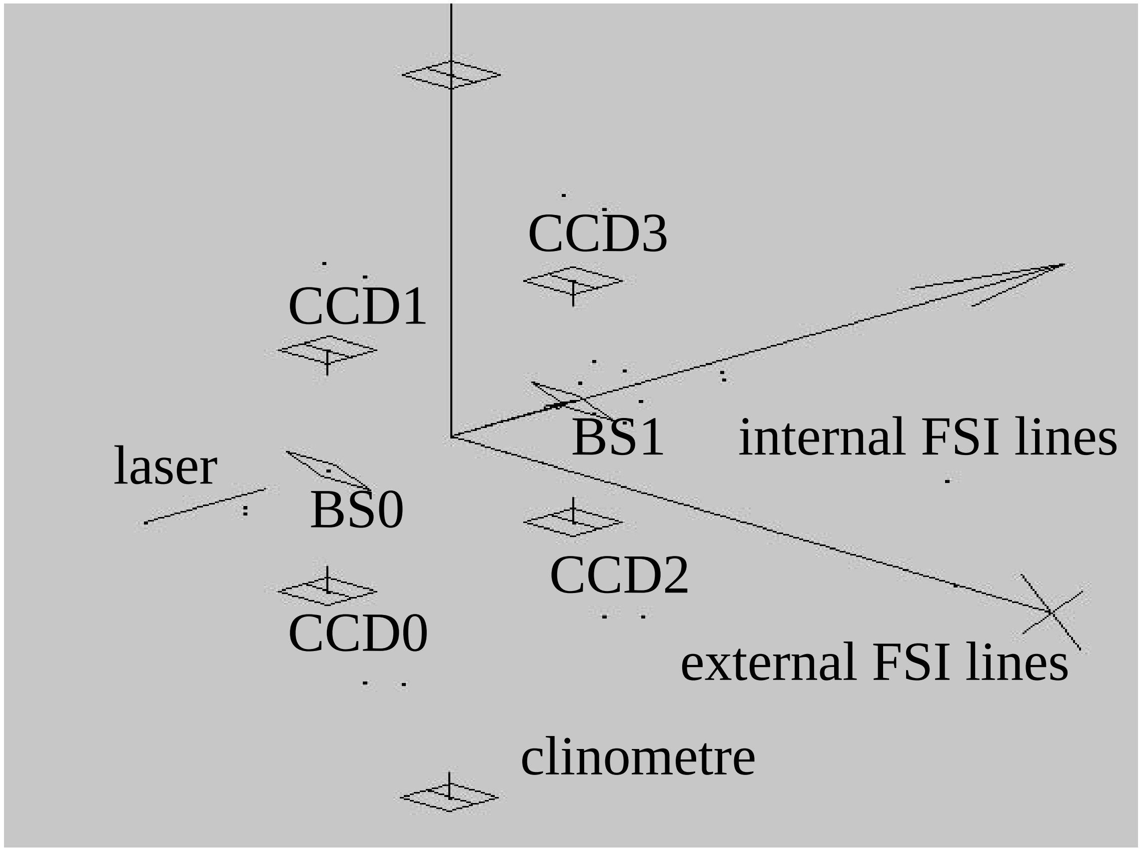
Sensing parts of the train



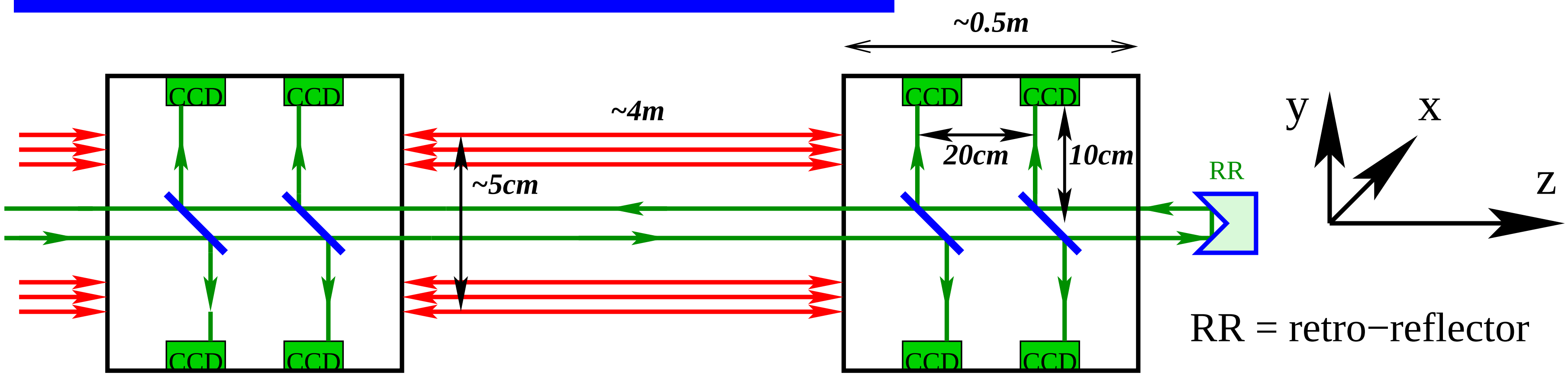
- Important components for the simulation (Laser Straightness Monitor, FSI lines):
  - LSM: 1 laser line per train; 2 beam splitters, 4 CCD cameras per car
  - Internal FSI: 6 laser lines, 6 retro-reflectors per car
  - External FSI: 6 laser lines per car, 1 wall marker in front of each car
  - clinometer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

SIMULGEO: Software used in the simulation

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



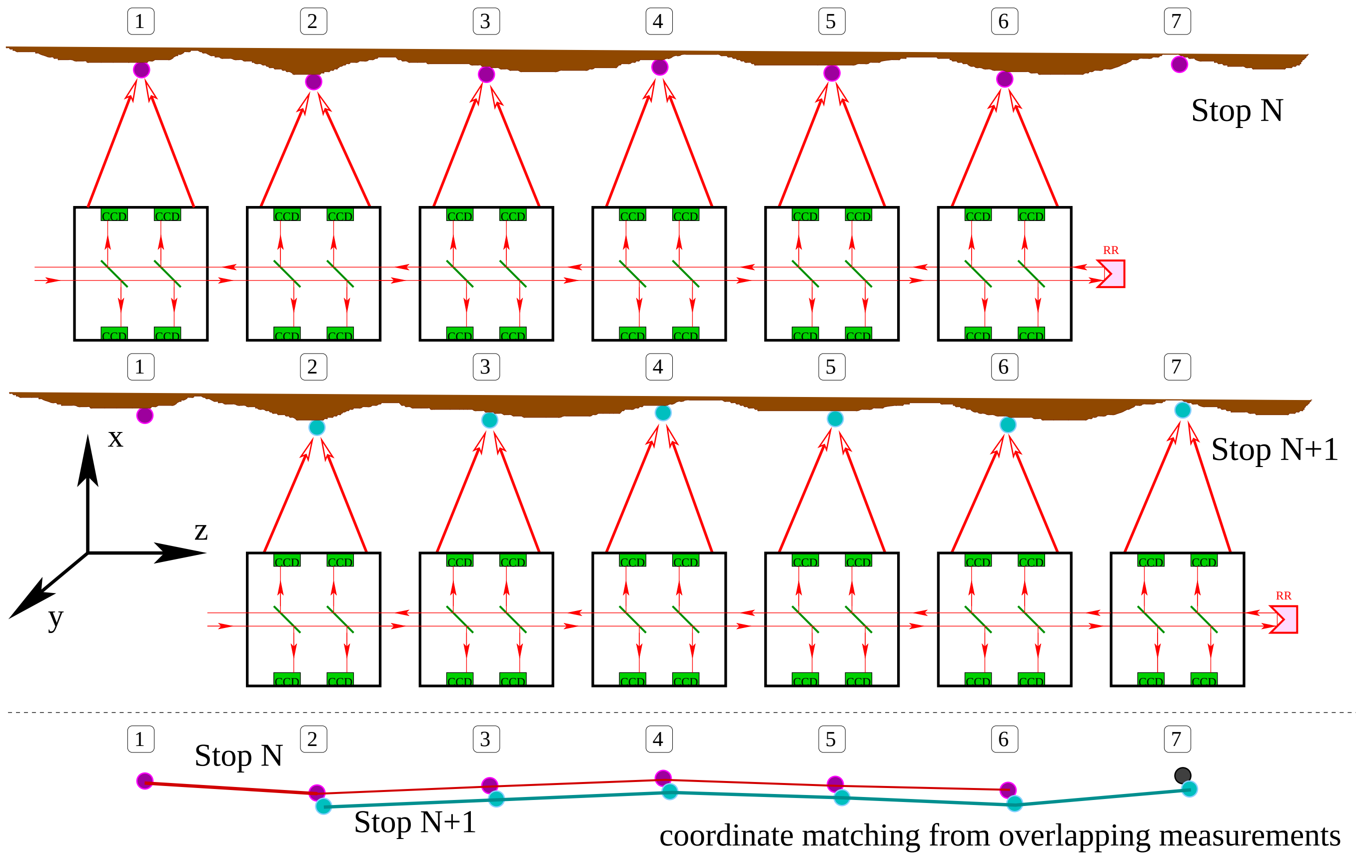
Sensitivity of various subcomponents



Accessible DOF:						
COMP	Tr_x	Tr_y	Tr_z	Rot_x	Rot_y	Rot_z
LSM	√	√		√	√	
INT-FSI	±	±	√	±	±	
Clinometer				√(not used)		√

- LSM: transverse translation ($Tr_{x,y}$) and rotation ($Rot_{x,y}$)
- INT-FSI: longitudinal distance (± some redundancy for LSM)
- Clinometer: only Rot_z used (insensitive to the geoid shape)

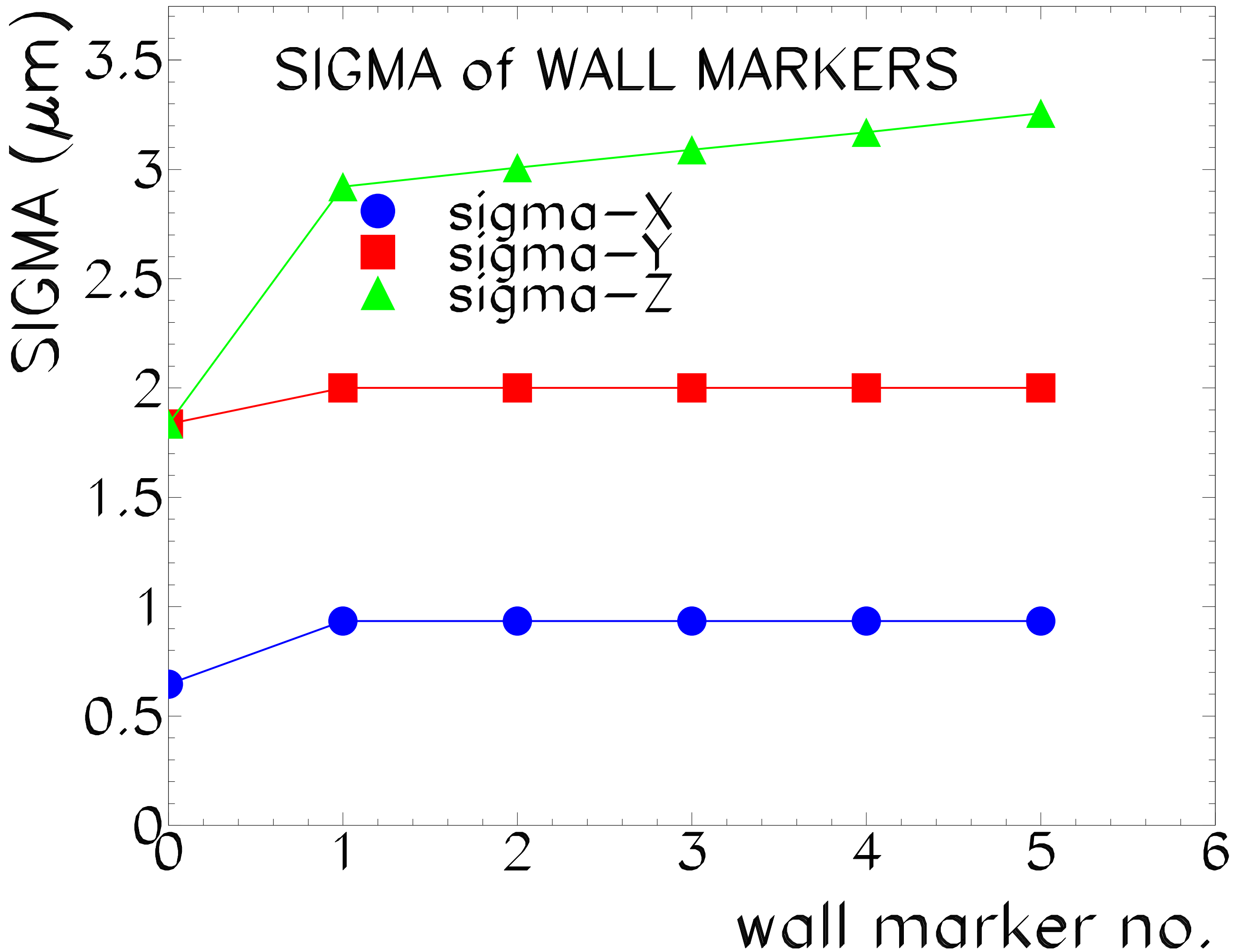
Idea of the multi train measurement



- top view on two train stops along the tunnel wall
- details of the wall structure are magnified

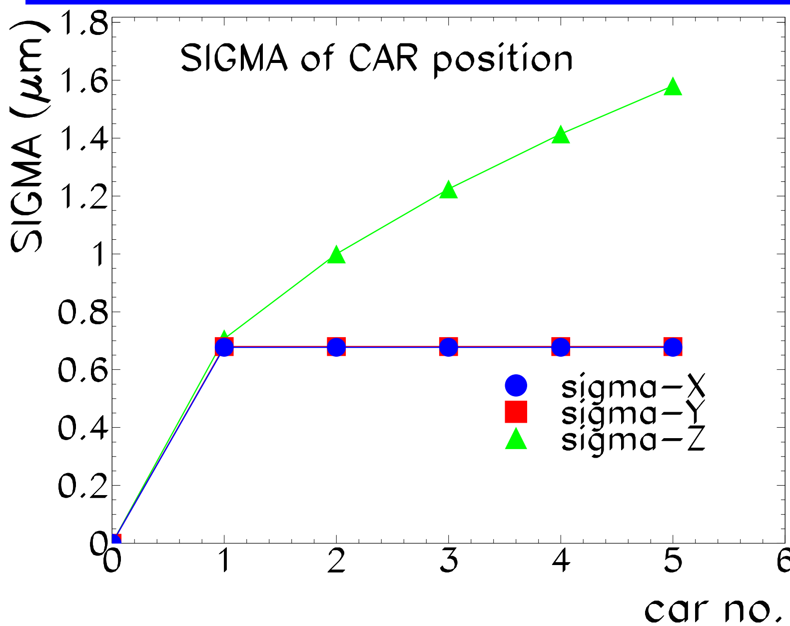
- N overlapping measurements of each wall marker
- each measurement provides coordinates of N points expressed in the local frame of the train
- local measurements are combined to coincide on the same trajectory in the global tunnel frame

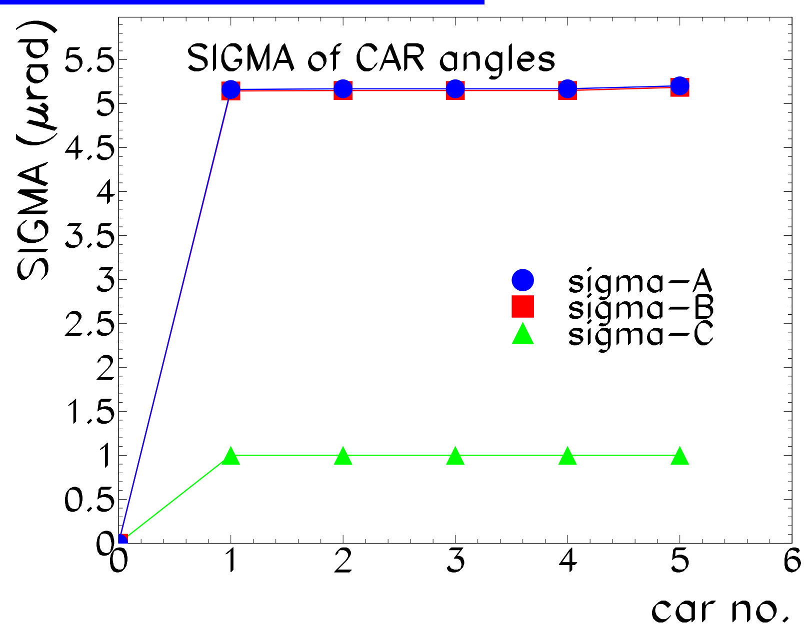
Single train simulation: resolution for reference markers



- distance between wall markers: $4.5\,m$

Single train simulation: car position and angles

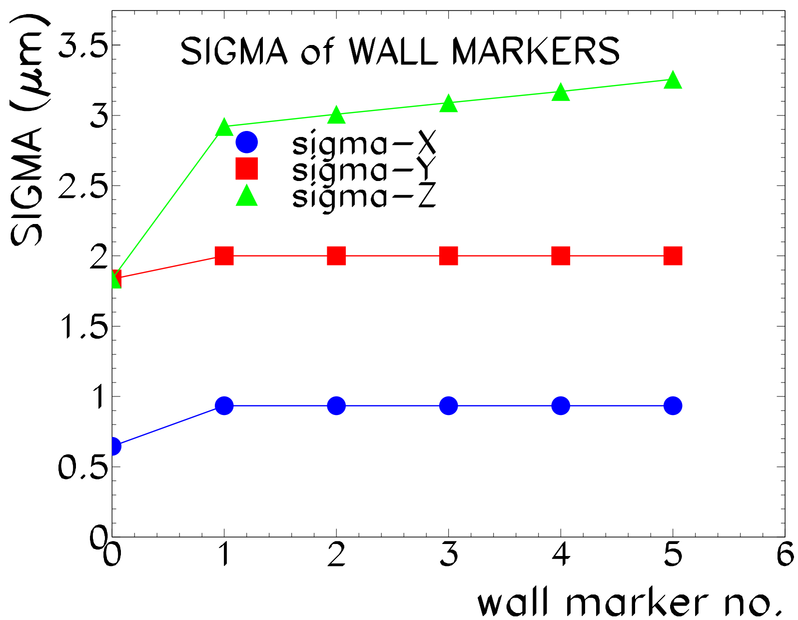




$A = Rot_X$

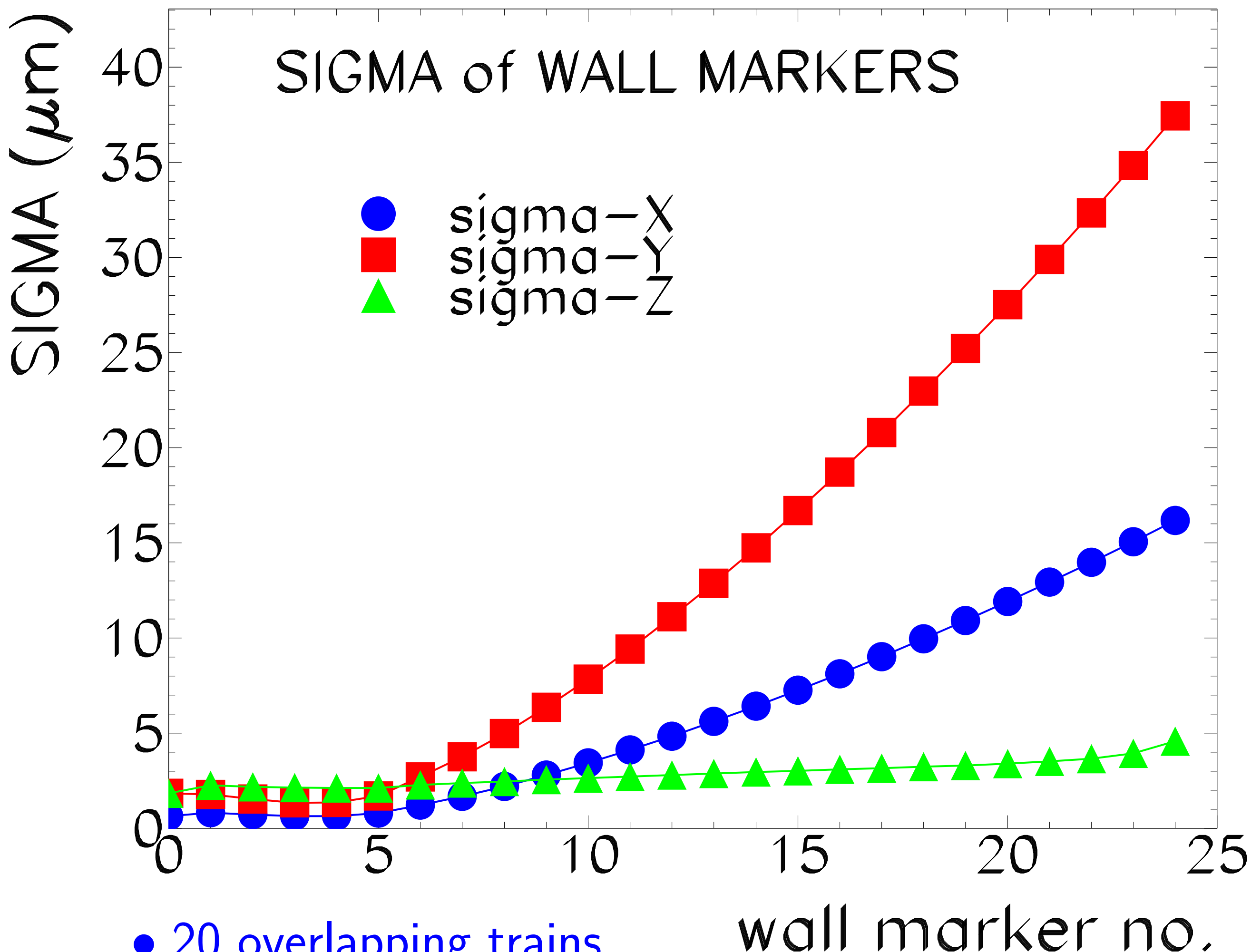
$B = Rot_Y$

$C = Rot_Z$



- 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)
  - $\sigma_{pos} = 1\,\mu m$, $\sigma_{ang} = 1\,\mu rad$

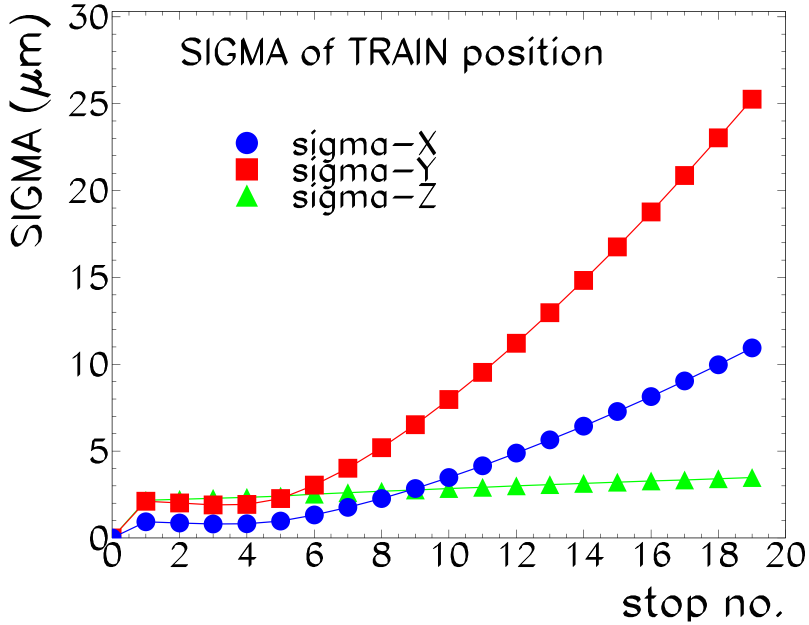
20 train stops ($= 90\,m$ tunnel section)

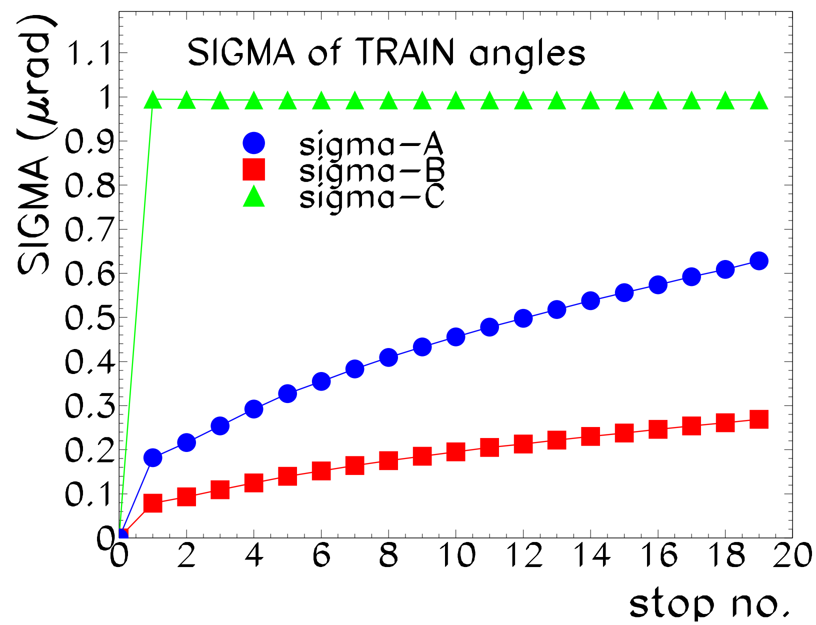


- fast growth of transverse errors !

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

20 train stops ($90\,m$): train position and angles





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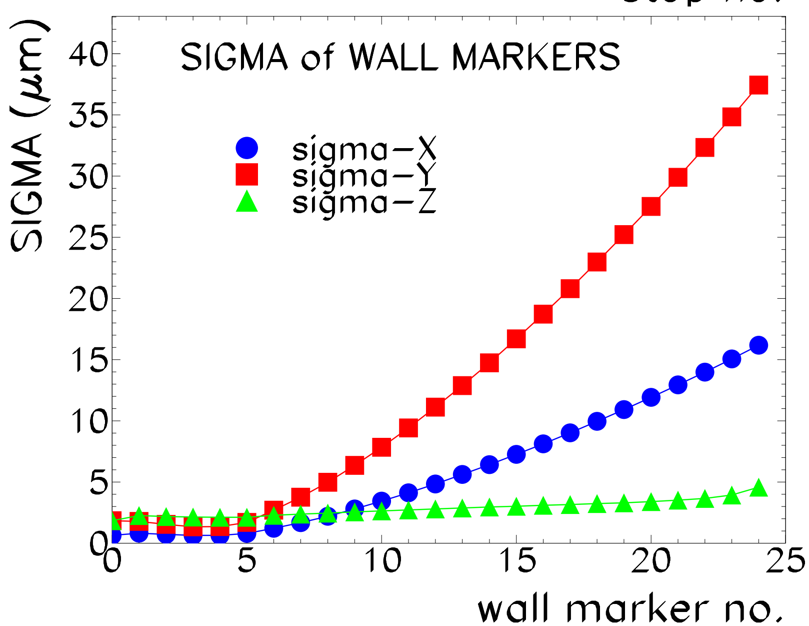
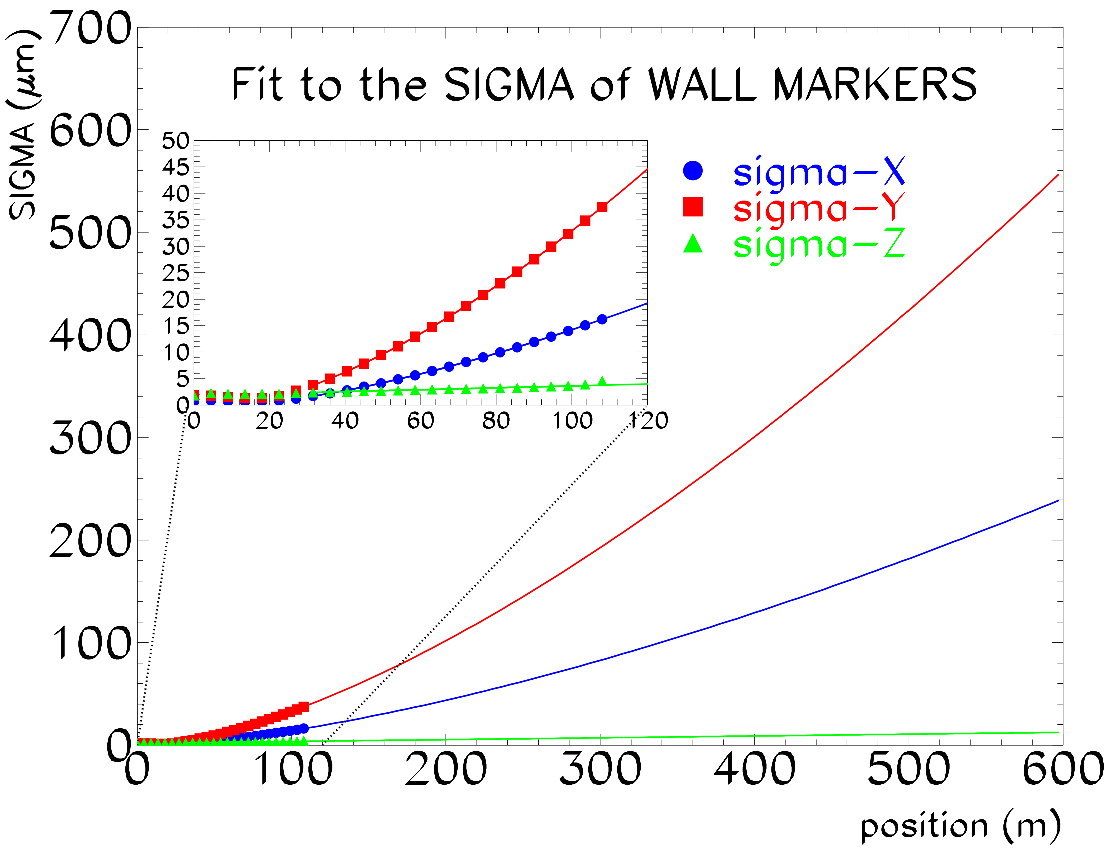
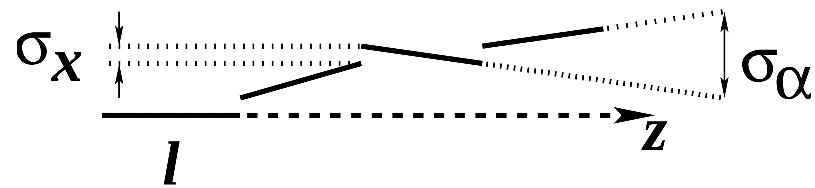


- intrinsic resolutions and calibration constants as for single train simulation (all $\sigma = 1\,\mu m\,; 1\,\mu rad$)
- very CPU and memory consuming ! (10000^2 matrix) for 20 stops $1.0\,GB$ RAM and $34\,h$ CPU time @$2\,GHz$

Extrapolation to $600\,m$ tunnel section



- extrapolation using random walk model:



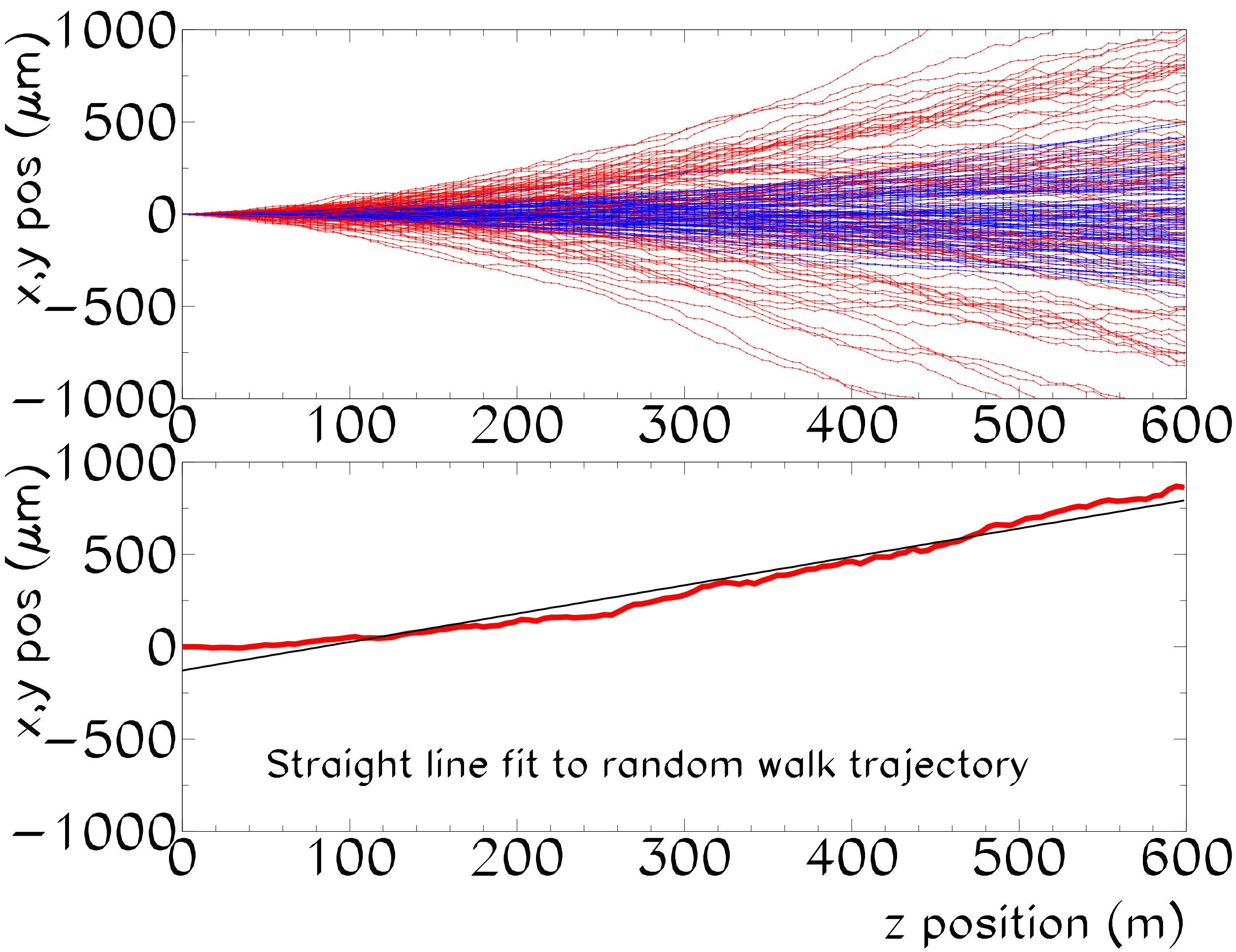
- off-sets and angles are relative to the previous "ruler"
- asymptotic behaviour:

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

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

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

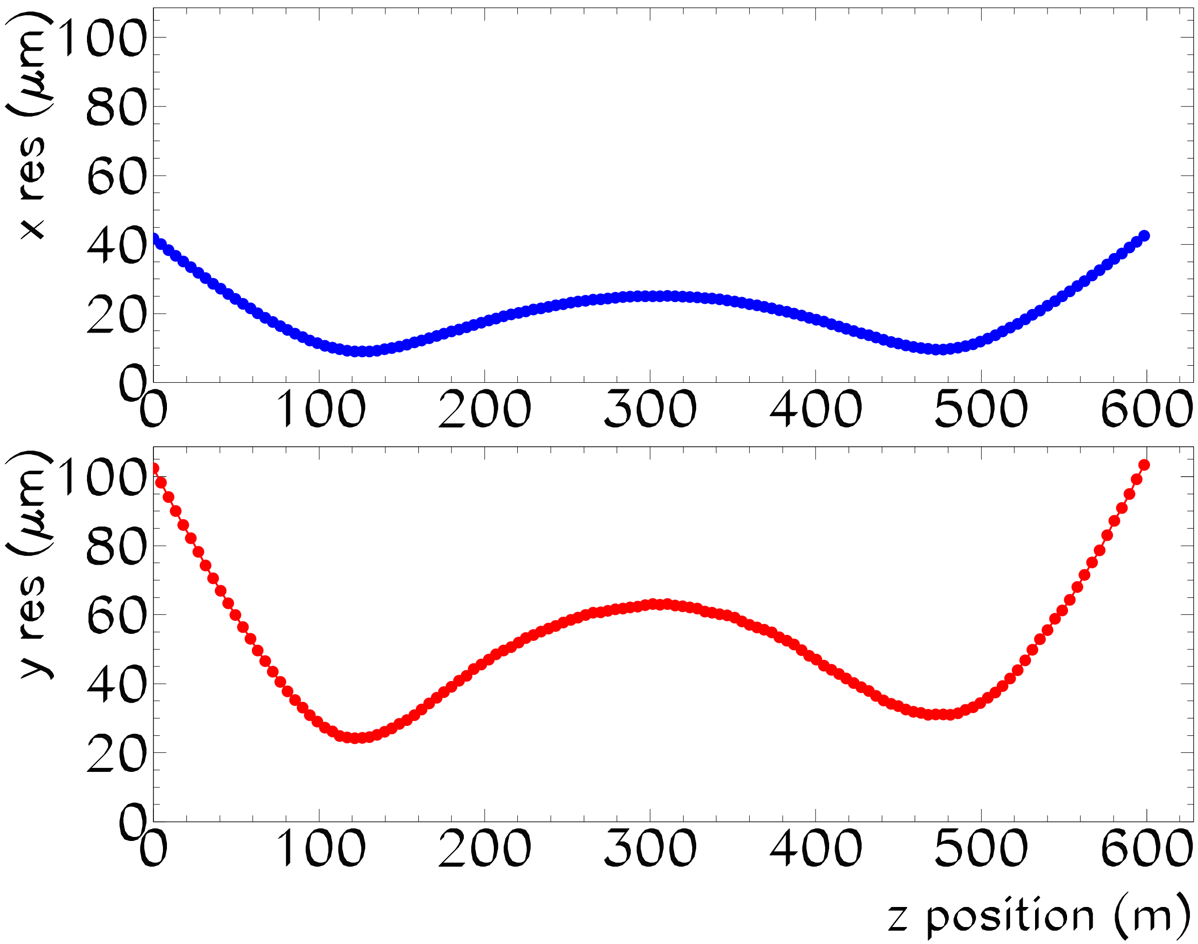


- trajectories generated from Random Walk Monte Carlo using parameters from the fit to SIMULGEO points (X, Y) direction

- straight line fits to the Random Walk paths for $600\,m$ tunnel section

- repeating this procedure for many "numerical experiments"...

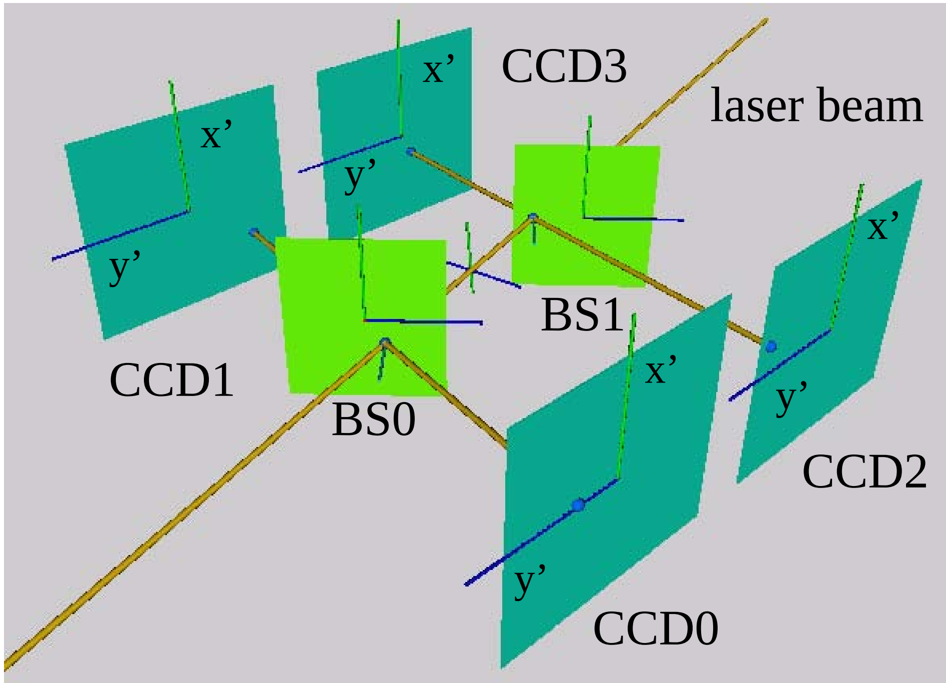
Random Walk Monte Carlo: residua

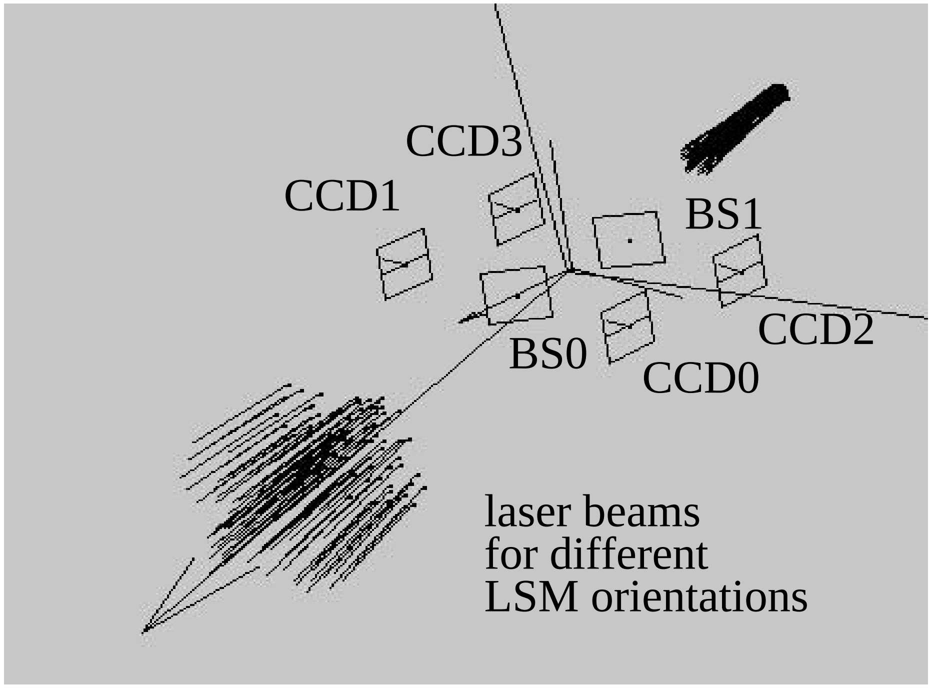


- mean deviation from straight line fits (X, Y) direction
- realistic input to the simulations of beam dynamics

- well below specification: $\sigma_x = 500\mu m$, $\sigma_y = 200\mu m$
- however: only statistical errors included

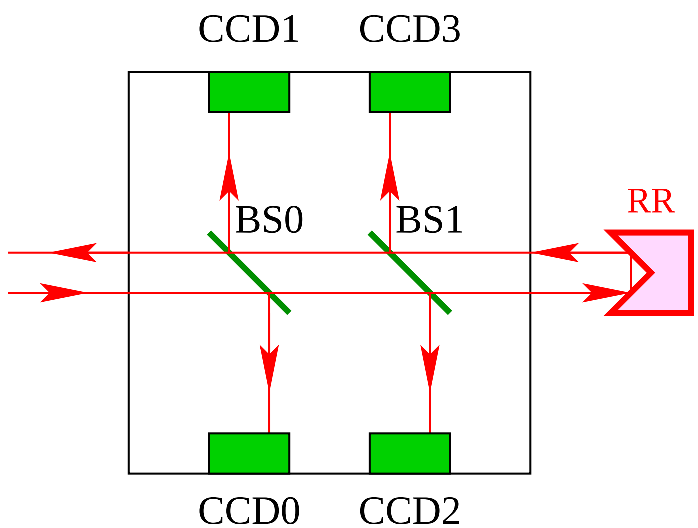
Calibration of the Straightness Monitor

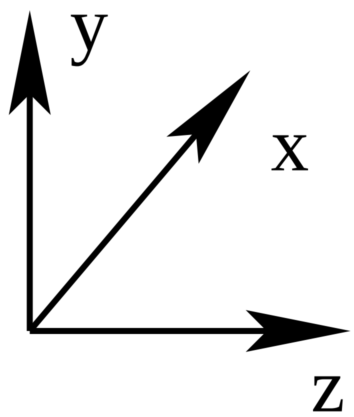




- Main Idea: multi dimensional parameter scan
- Simulation (proof of principle): ray tracing data as an input to the SIMULGEO
- Whole mechanical frame of LSM rotated and translated as a rigid body
- Overconstrained fit to extract the calibration constants
  (positions and rotations of the CCD cameras and beam splitters)

LSM: precision on calibration constants

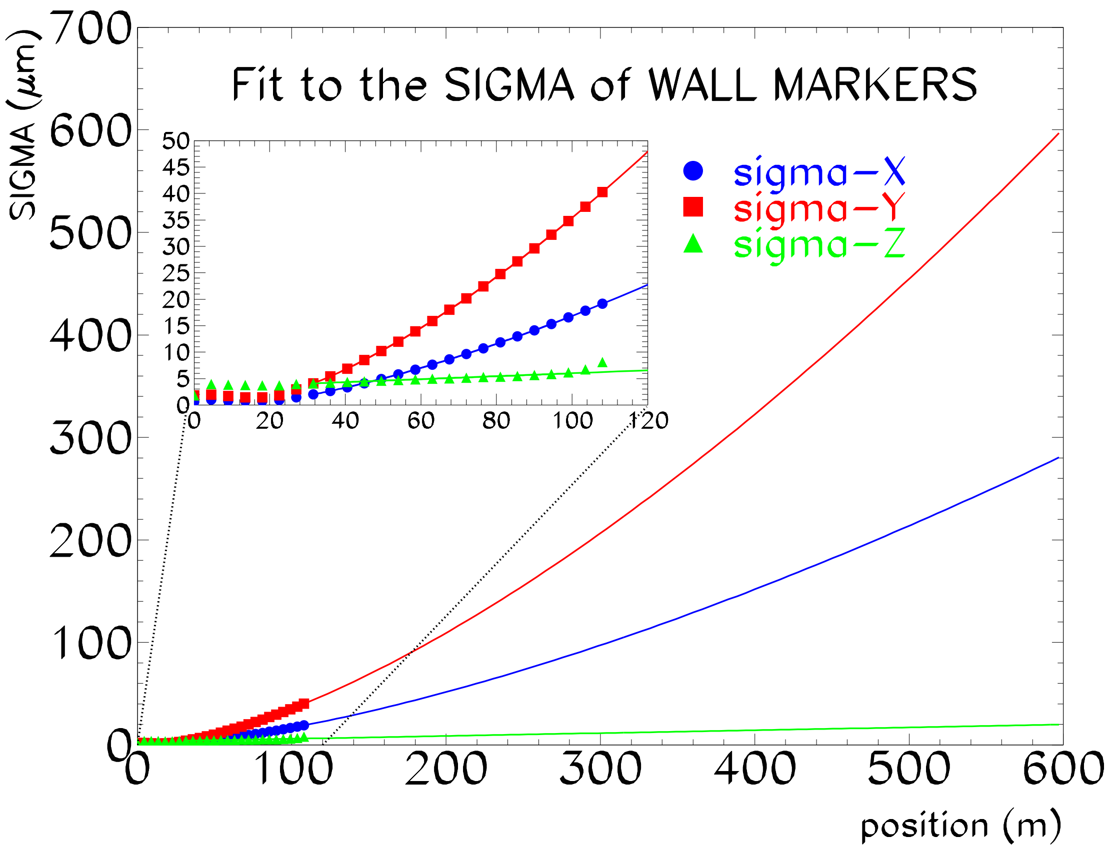




- estimated precisions on calibration constants:
  - BS0: $Rot_x = 4.6\,\mu rad$
  - CCDn: $pos_x = 3.7\,\mu m$
  - CCDn: $pos_y = 2.4\,\mu m$
  - CCDn: $pos_z = 3.7\,\mu m$
  - CCDn: $Rot_x = 68.2\,\mu rad$
  - CCDn: $Rot_y = 63.2\,\mu rad$
  - CCDn: $Rot_z = 9.6\,\mu rad$

- CCD0 defines the local reference frame of the car
- motion stage precision: $\sigma_{X,Y} = 0.05\,\mu m$ $\sigma_{A,B} = 1.7\,\mu rad$ $(10^{-4}\,deg)$

$600\,m$ tunnel section using calibration constants for LSM

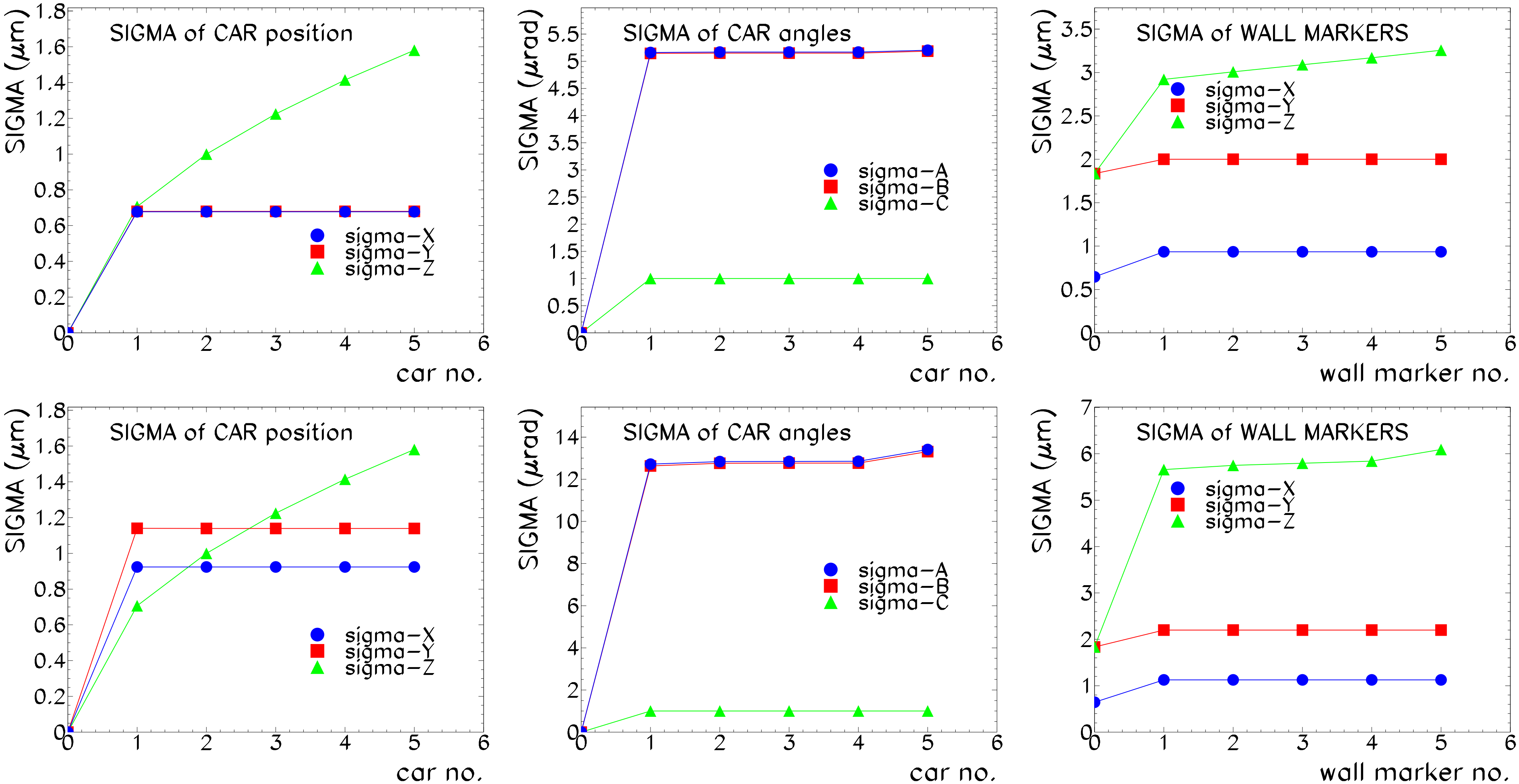


- week dependence on CCD orientation
  (short lever arm for Rot_Y, $\sim cos()$ like dependency for Rot_X and Rot_Z)
- very overconstrained measurement of wall markers

Summary

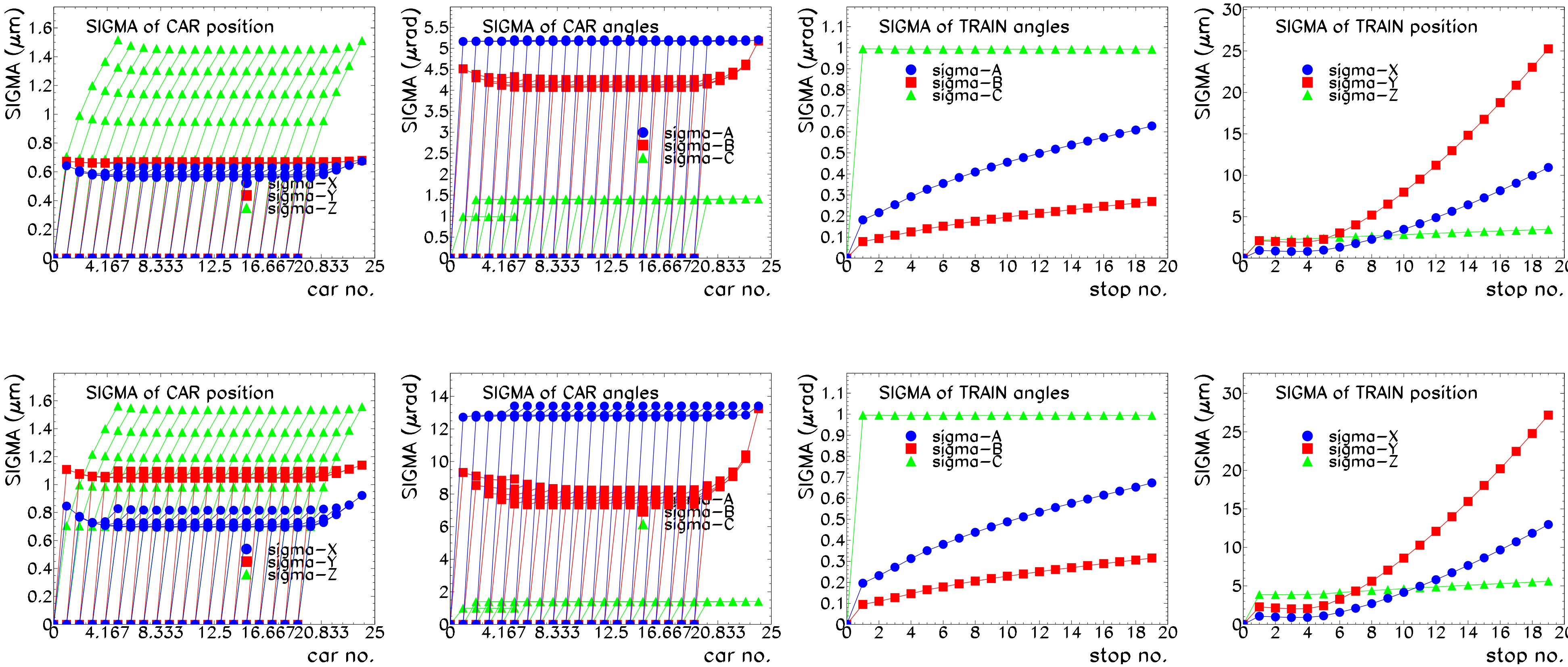
- LiCAS technology is capable of surveying the LC tunnel to desired accuracy ($\mathcal{O}(200)\,\mu m$ over $600\,m$ tunnel section)
- Work in progress on the train calibration procedure (LSM,FSI,...)
- First successful attempt to design LSM calibration
- Simplified models for reconstruction software needed (how this influences the overall precision ?)

Single train simulation: car position and angles



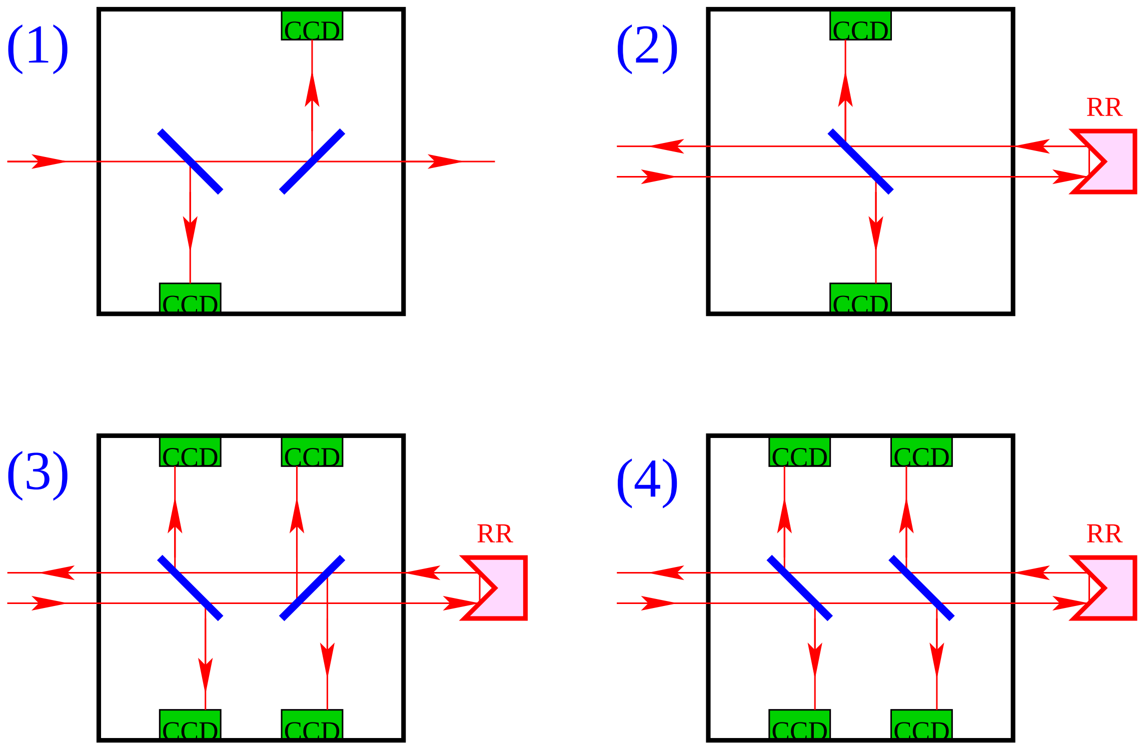
- single train simulation with $1\,\mu m/1\,\mu rad$ and “realistic” calibration

20 train stops $(90\,m)$: train position and angles



- resolution on local positions and angles of cars inside the train frame

Configurations of the Straightness Monitor



- (1) single beam pass, but... in 3D not a SM at all !!
- (2) OK, but no redundancy required for RR "walk" (offset) fit
- (3) OK but no profits from extra measurements
- (4) optimal configuration, high redundancy (4 pairs of LSM !)