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

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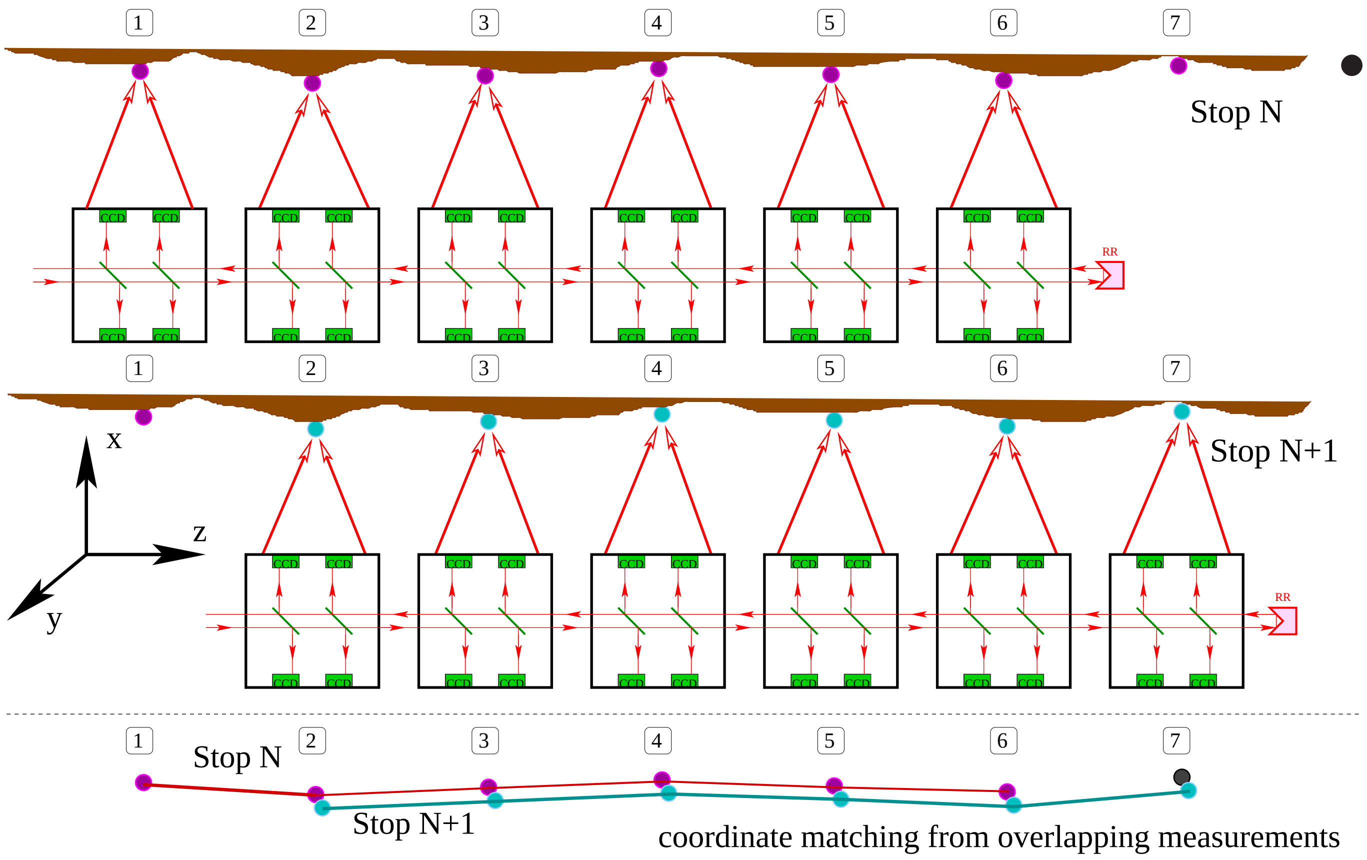
10th INTERNATIONAL WORKSHOP ON ACCELERATOR ALIGNMENT;
KEK, Tsukuba, Japan; February 11-15, 2008.

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
- all numerical results for long LiCAS train
  (4 cars, $25\,m$ car-to-car distance, operting over $600\,m$ tunnel section $= 24$ stops)
- Conclusions

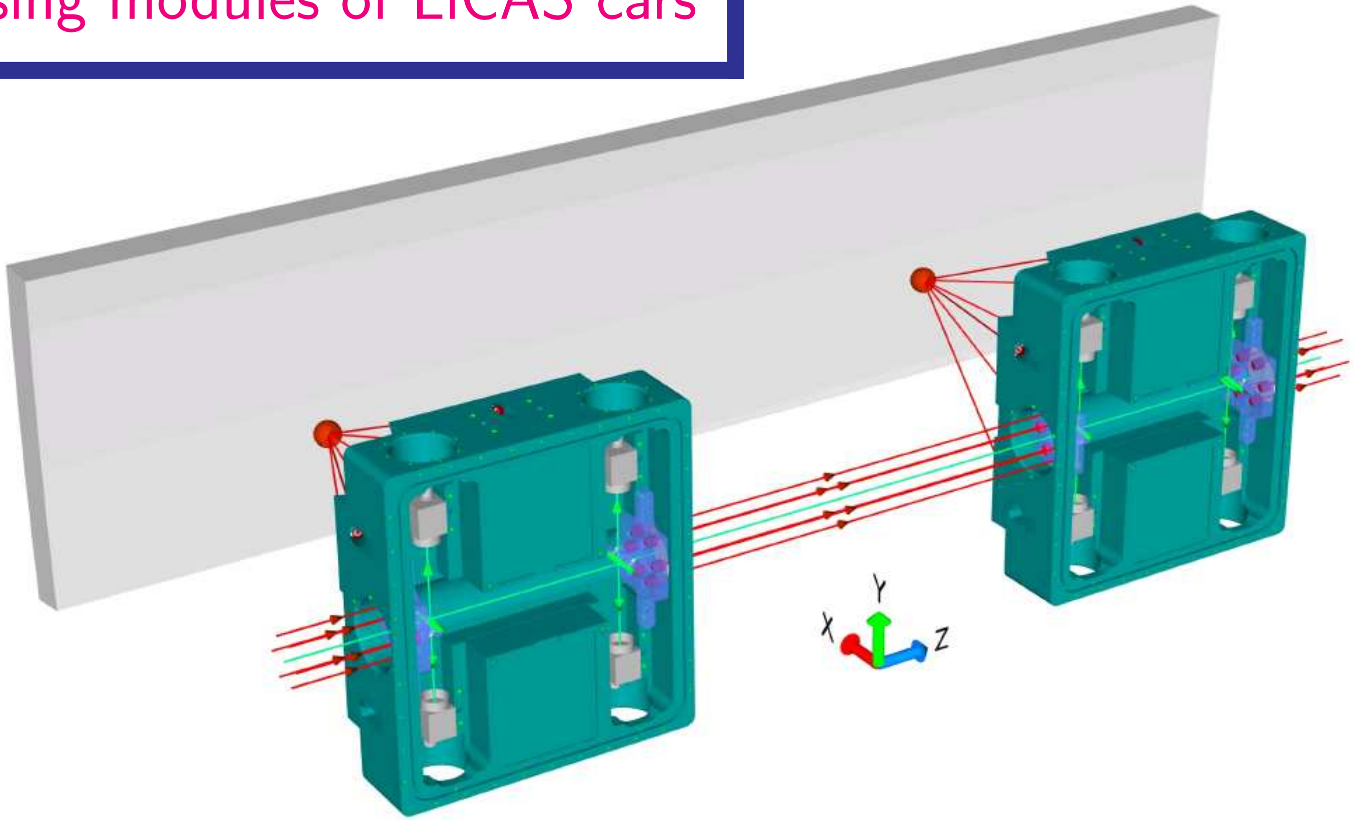
Multi train overlapping measurement



- 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)

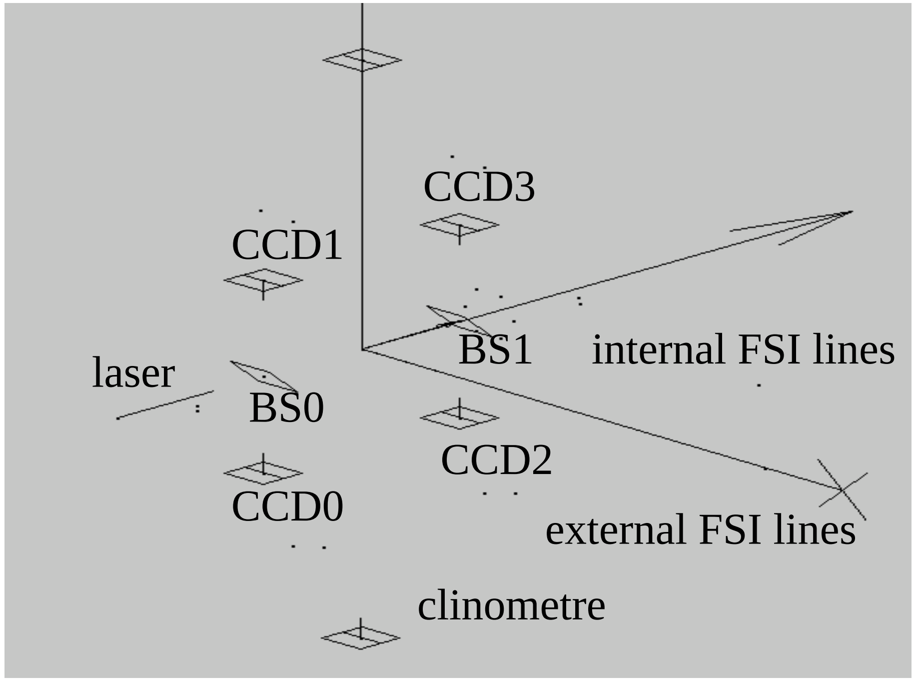
Sensing modules of LiCAS cars



- 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 $\sigma = 10\, mm$ 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

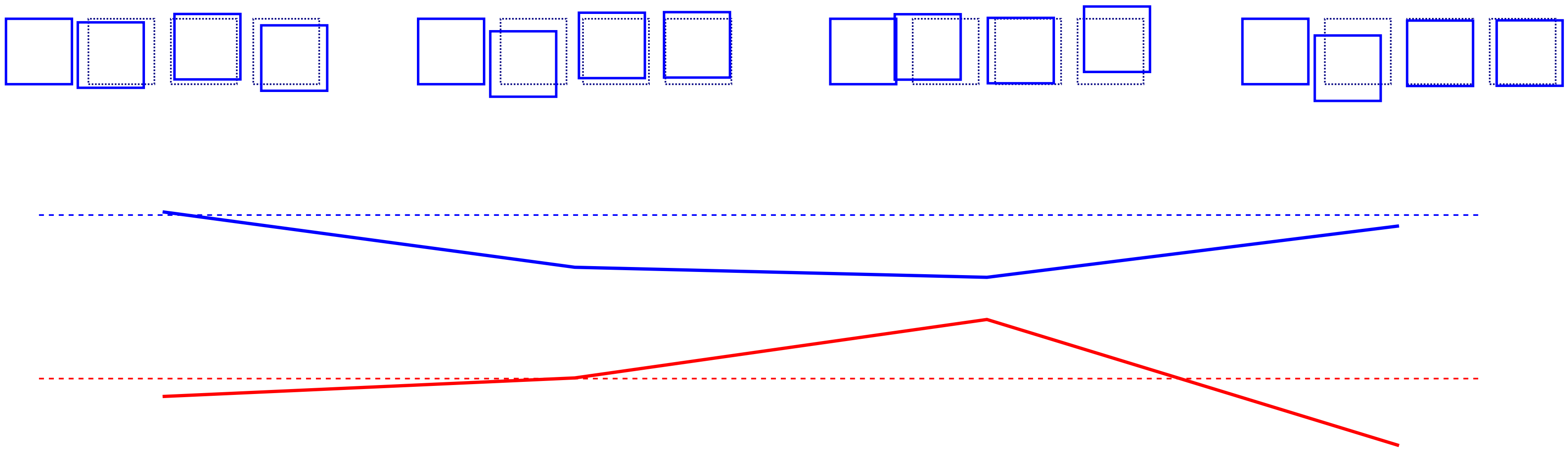
   3a. LOOP over cars in the train

   - generate car stops in front of wall markers
     (smeared by $\sigma = 10\, mm\, (pos)\, , \sigma = 10\, mrad\, (ang)$)
   - 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 $\sigma = 1\, \mu m$)

4. RECONSTRUCT the system w.r.t. the unknown position/angles of cars and
   wall markers using MISCALIBRATED geometry and smeared measurements

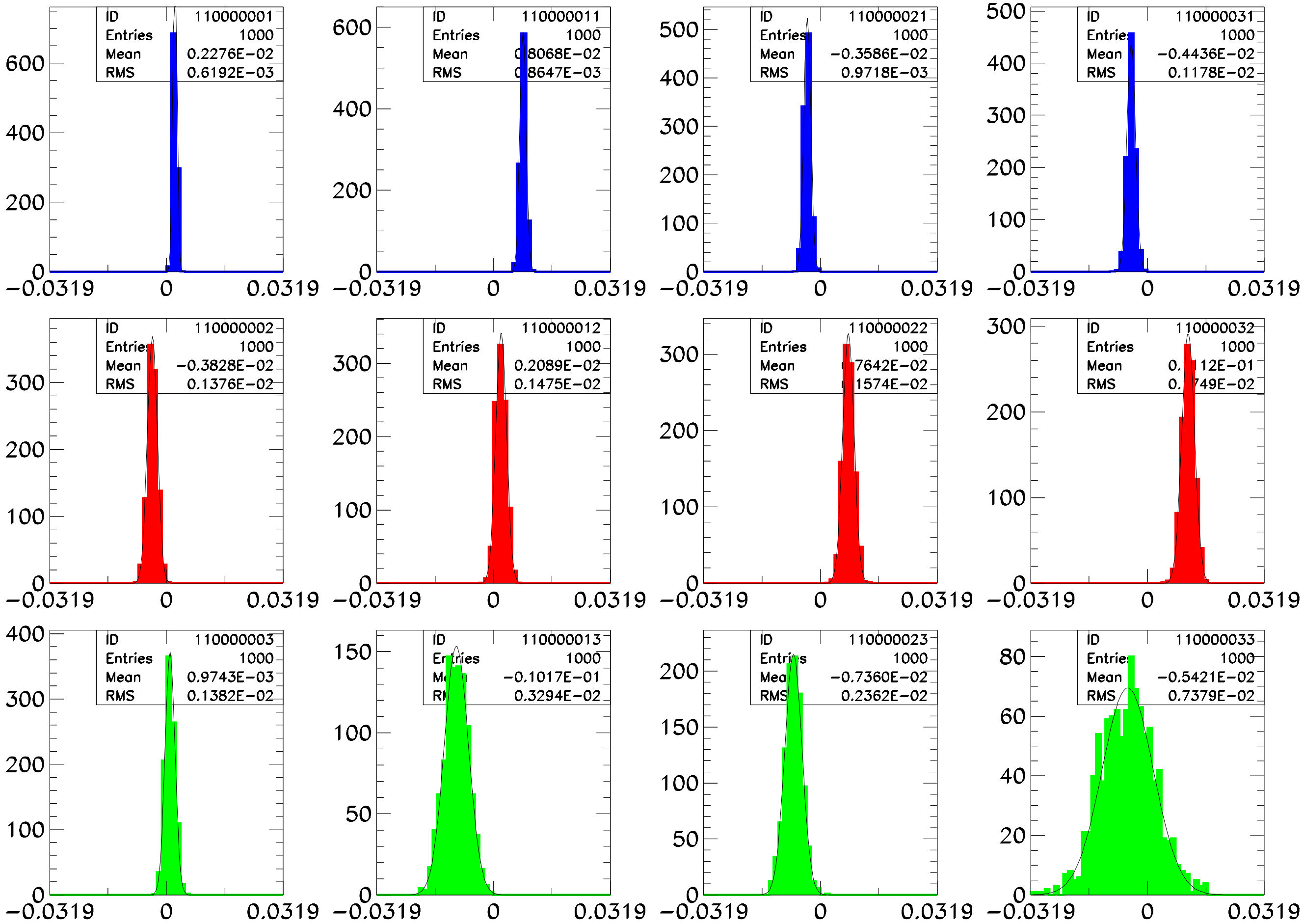
5. collect histograms, calculate statistics for RECONSTRUCTED-TRUE variables

Miscalibrated train: egxample of "miscalibration pattern" for CCDs



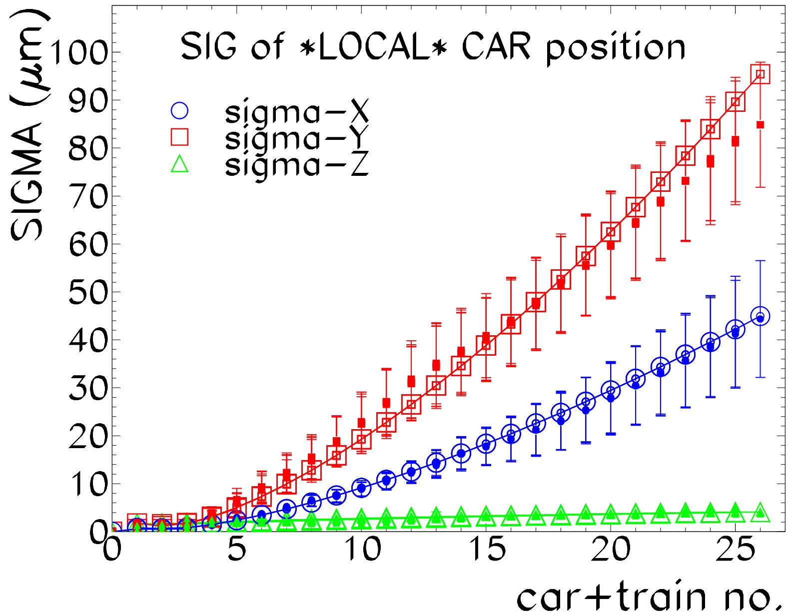
- CCD positions/angles and FSI retro-reflectors/launch points miscalibrated with Gaussian smearing
- example of CCD "miscalibration pattern" shown for $\sigma = 1\mu m\,(pos)$ (schematic view of 4 cars, 4 CCDs per car; nominal and distorted CCDs shown)
- as a result LSM (Laser Straightness Monitor) is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

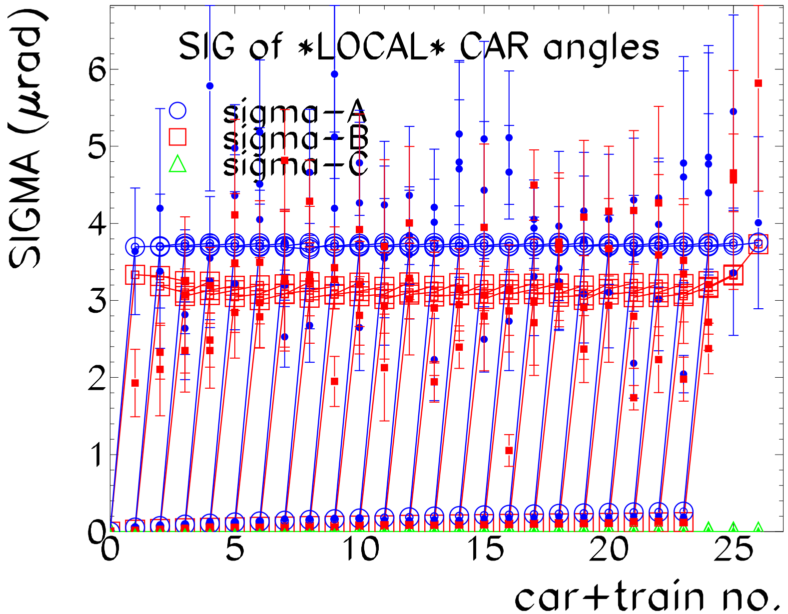
Train Monte Carlo: Wall Markers positions: REC-TRUE distribution



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

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

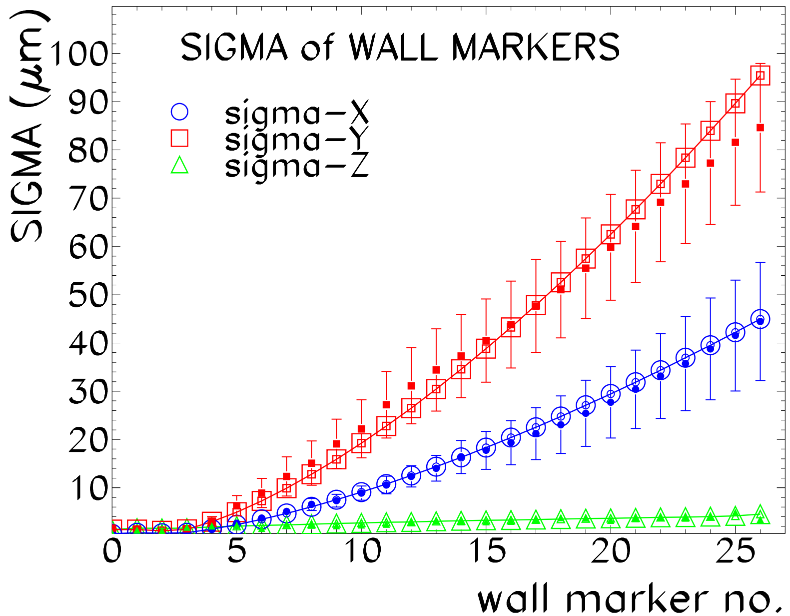




$A = Rot_X$

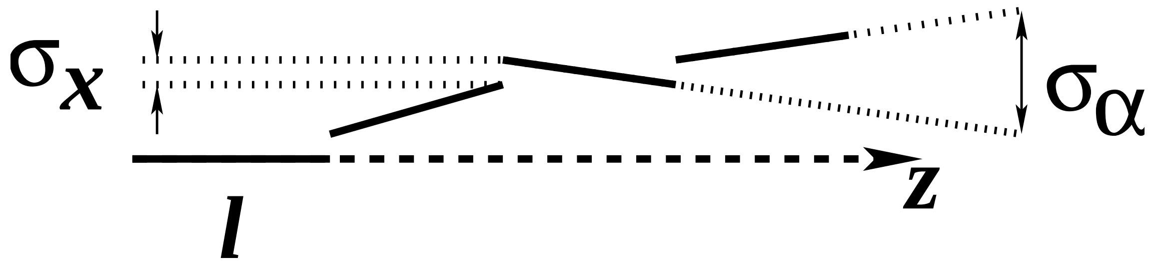
$B = Rot_Y$

$C = Rot_Z$



- assuming intrinsic resolutions:
  - CCD: $\sigma_{CCD} = 1\,\mu m$
  - FSI: $\sigma_{FSI} = 1\,\mu m$
- 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

Short ruler model (or random walk along the tunnel)



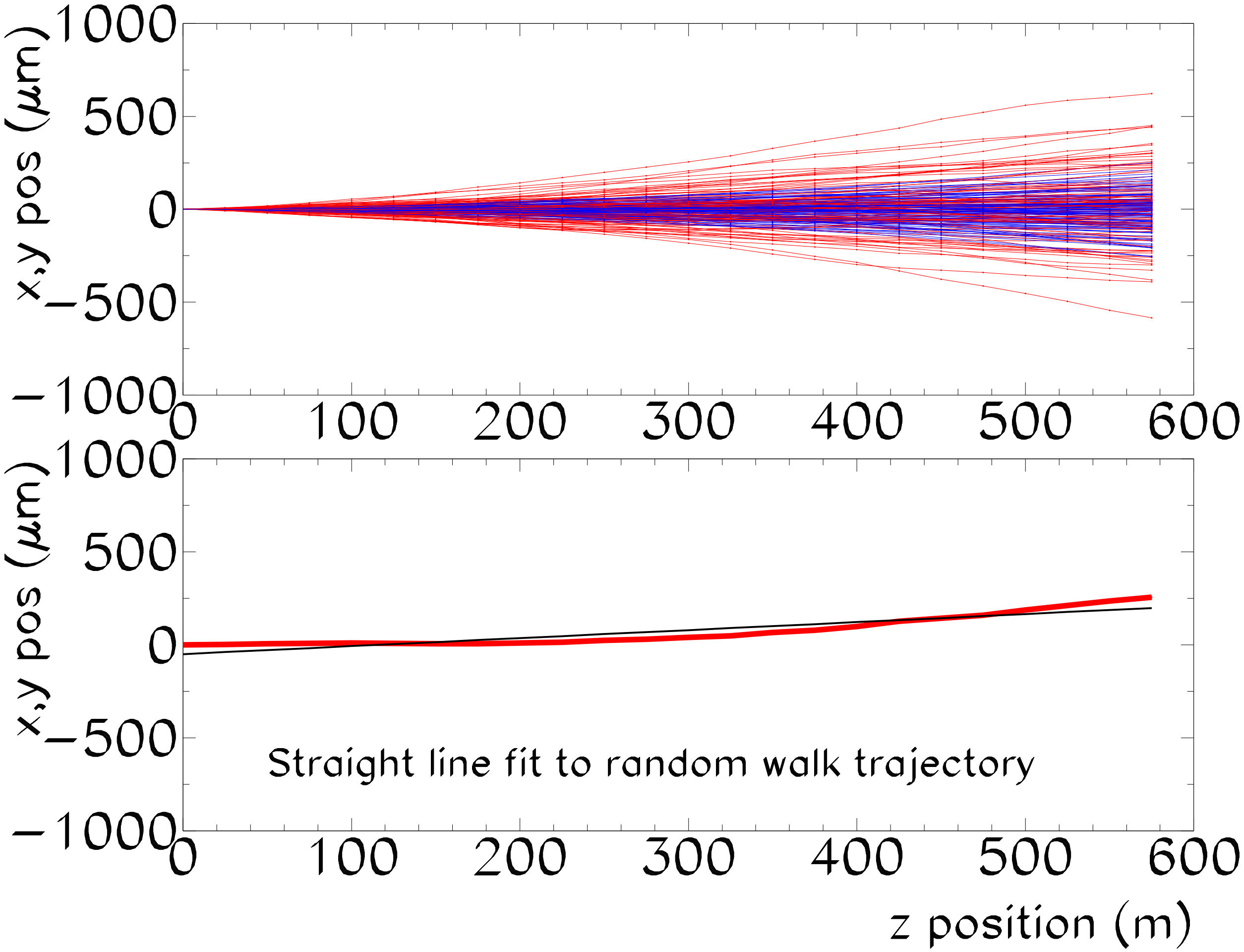
- two sources of errors (2D case): position (off-set) and direction (angle)
- off-sets and angles are relative to the previous “ruler”

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

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

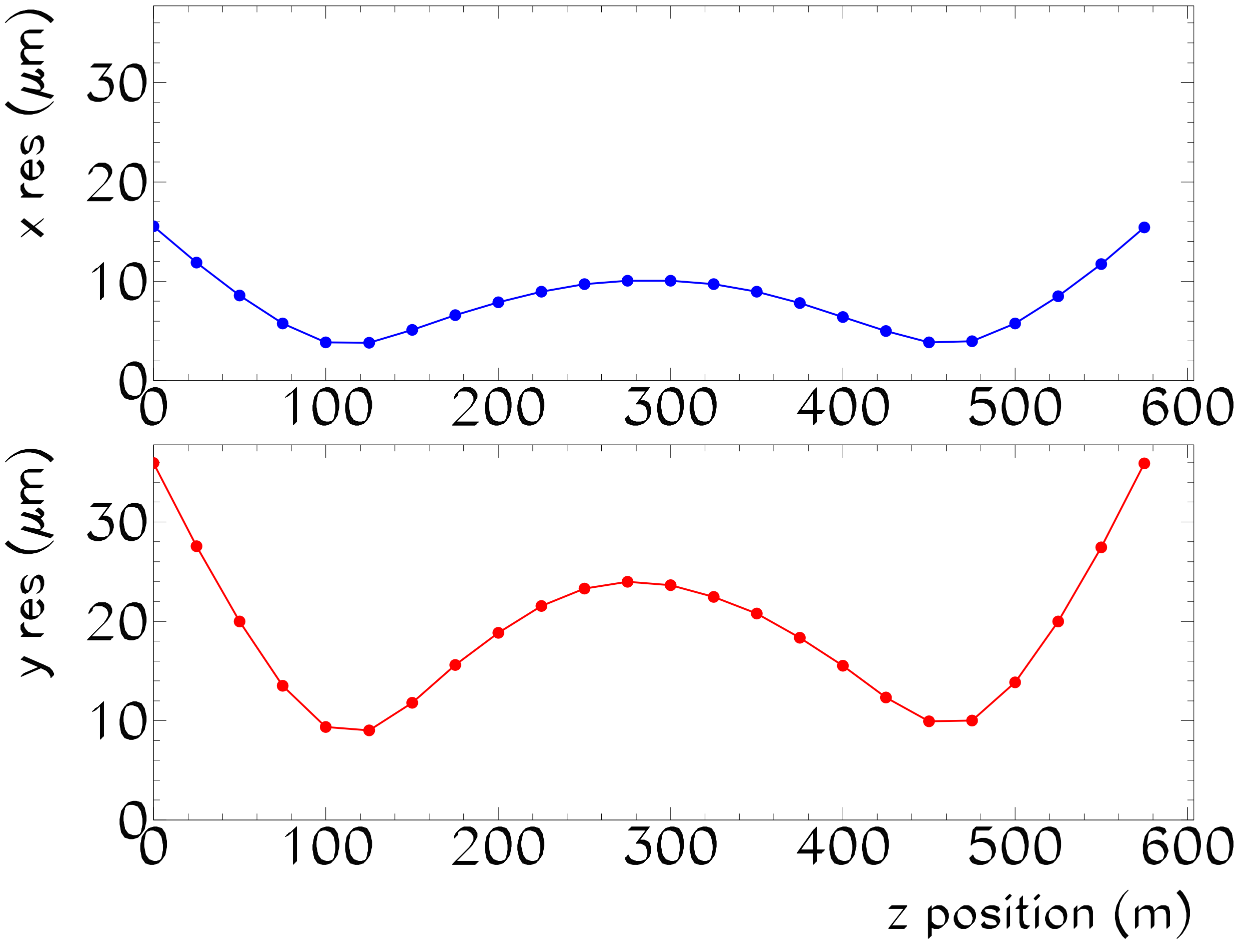


- trajectories generated for Random Walk model using parameters from the fit to SIMULGEO points (X, Y) direction

- 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"...

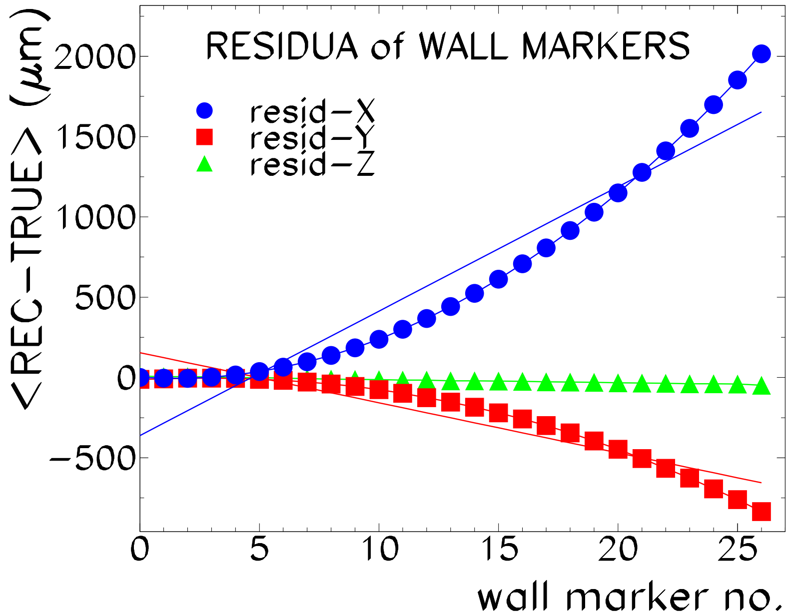
Random Walk Monte Carlo: residua of stat. errors

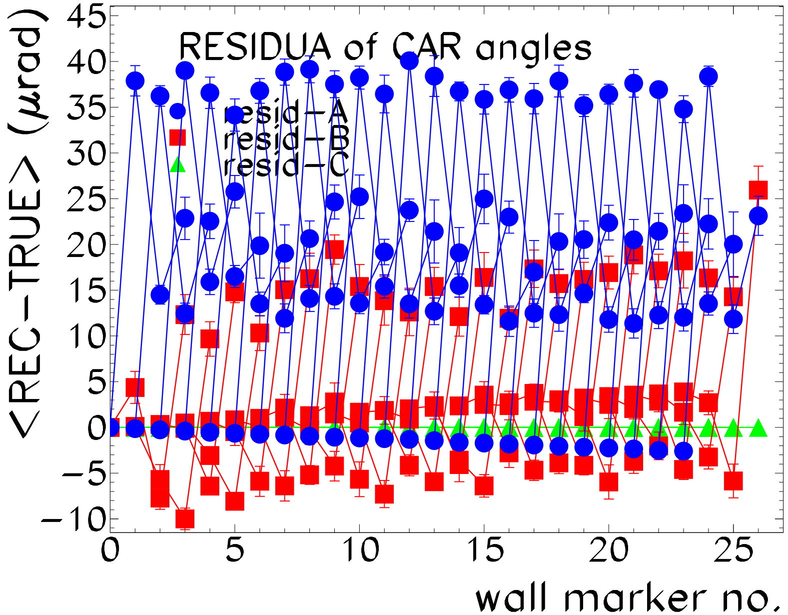


- mean deviation from straight line fits (X, Y) direction

- 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)





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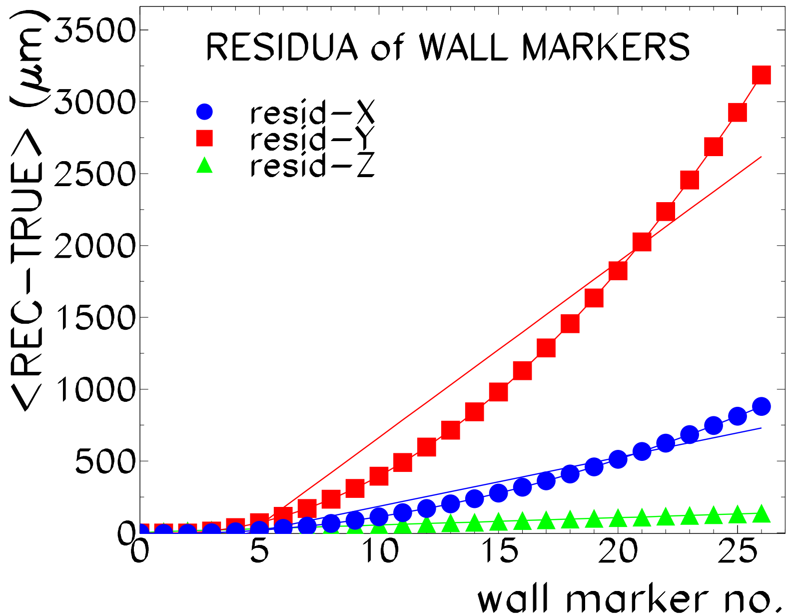
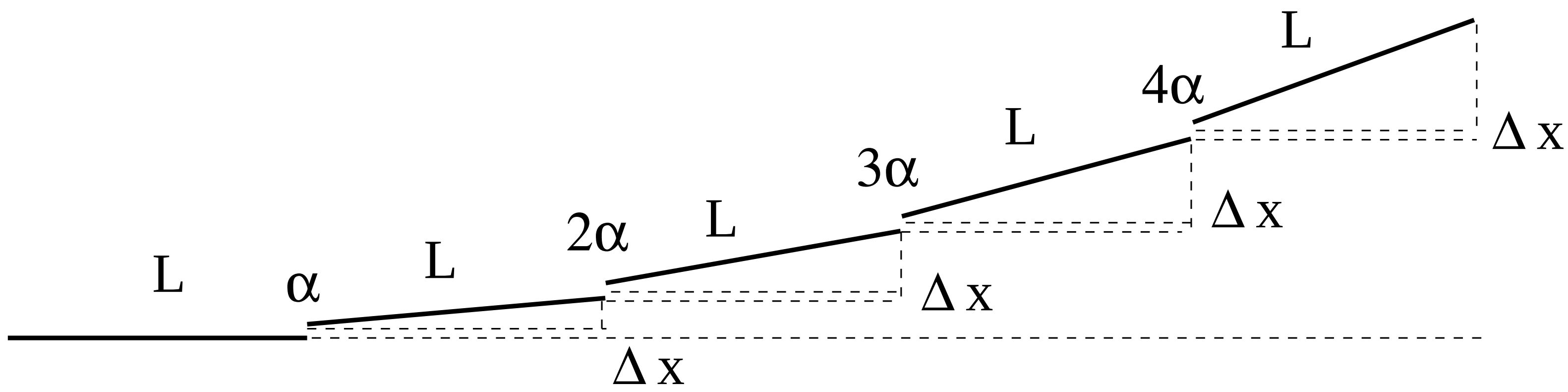


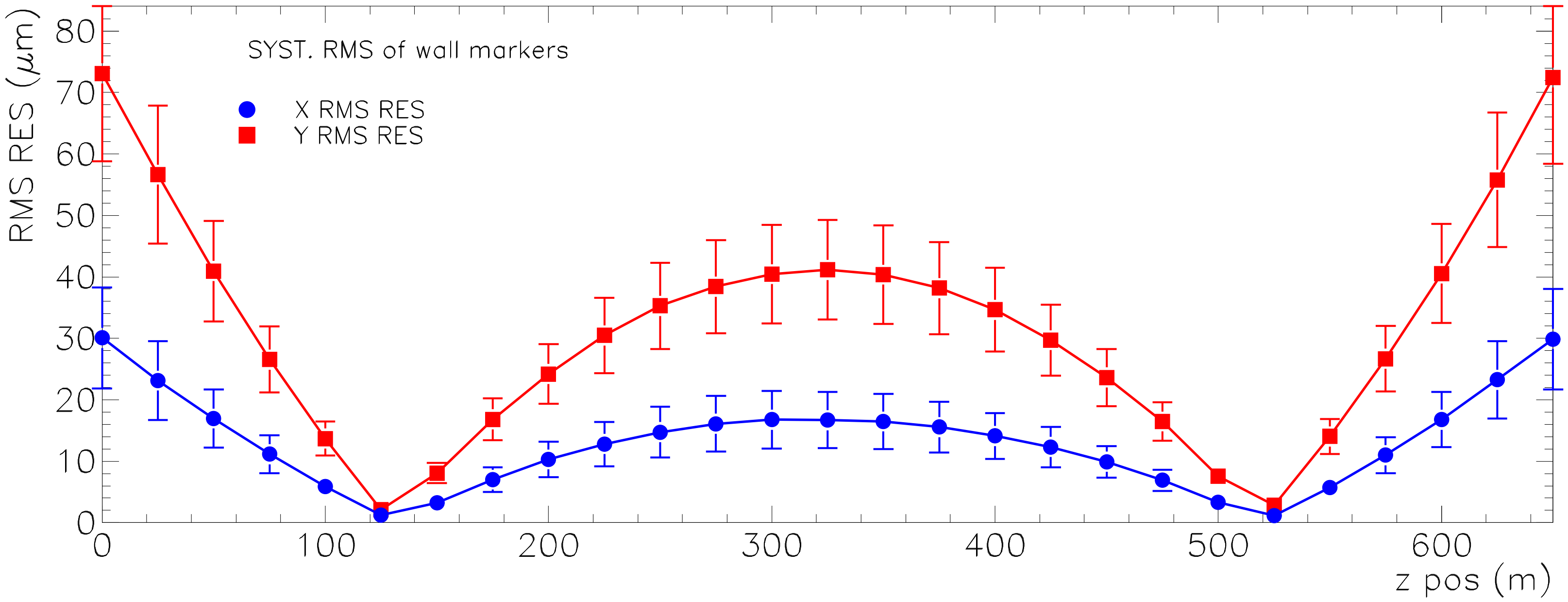
- assuming calibration precision:
  - CCD: $\sigma_{CCD} = 5\,\mu m$
  - FSI: $\sigma_{FSI} = 5\,\mu m$
- linear $(\sim n)$ growth of angular errors
  quadratic $(\sim n^2)$ growth of transverse errors
- examples of straight line fits for
  two "miscalibration patterns"

Model of systematic errors for LiCAS train



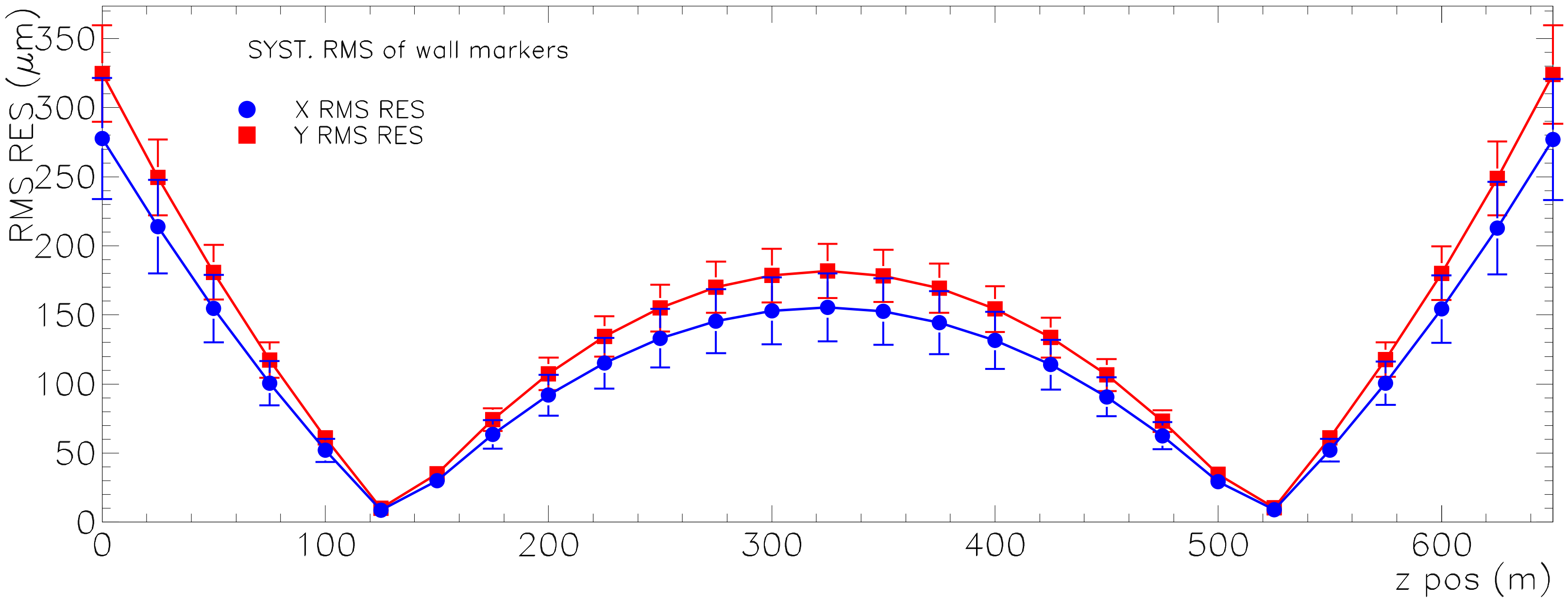
- angular term:
  $\sigma_{ang}^{syst} = L\sin(\alpha) + L\sin(2\alpha) + L\sin(3\alpha) + ... + L\sin(n\alpha)$
  $\sigma_{ang}^{syst} \simeq L\alpha(1+2+3+...+n) = L\alpha n(n+1)/2 \longrightarrow n^2$ (quadratic !!)
- translation term:
  $\sigma_{tr}^{syst} = n\Delta x$ (linear)
- full formulae:
  $\sigma_{tot}^{syst} = L\alpha n(n+1)/2 + n\Delta x$
  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: $\sigma_{CCD} = 1\,\mu m$; FSI: $\sigma_{FSI} = 1\,\mu m$
- well below 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: $\sigma_{CCD} = 5\,\mu m$; FSI: $\sigma_{FSI} = 5\,\mu m$
- reaching specification: $\sigma_x = 500\mu m$, $\sigma_y = 200\mu m$

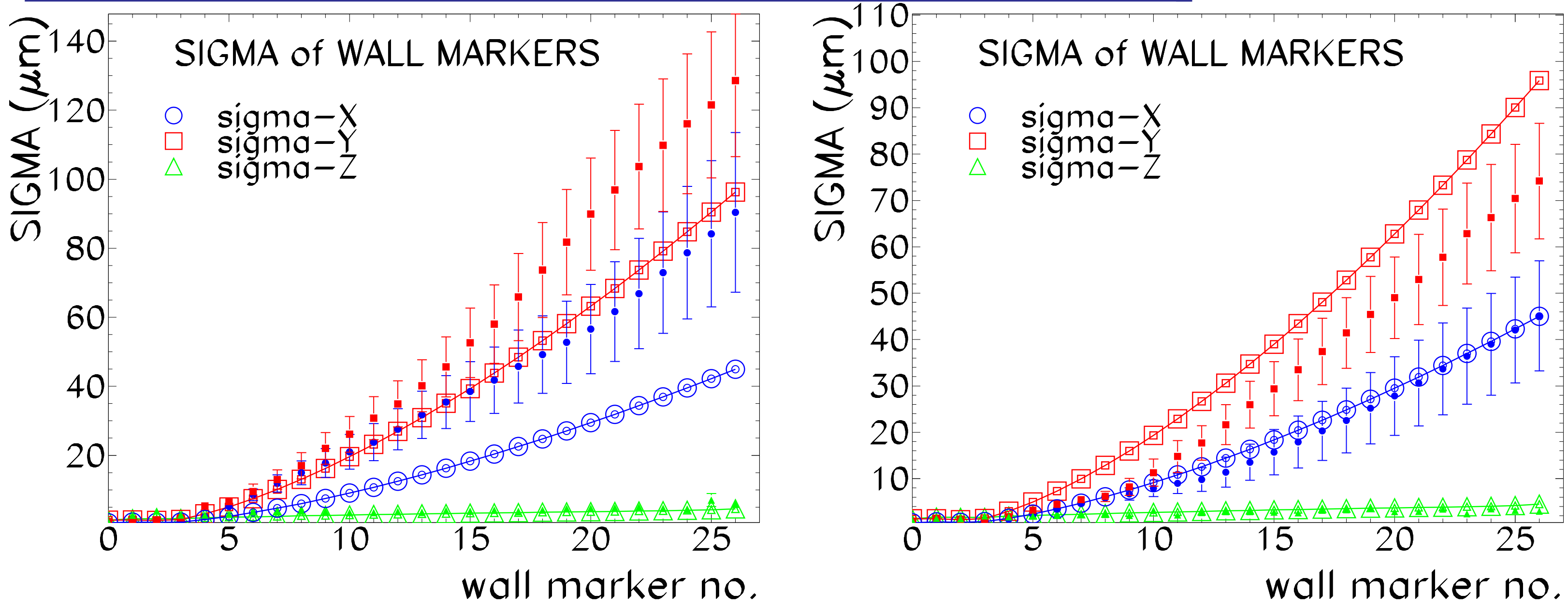
Conclusions/Plans

- 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, $\longrightarrow$ 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

BACKUP Polts

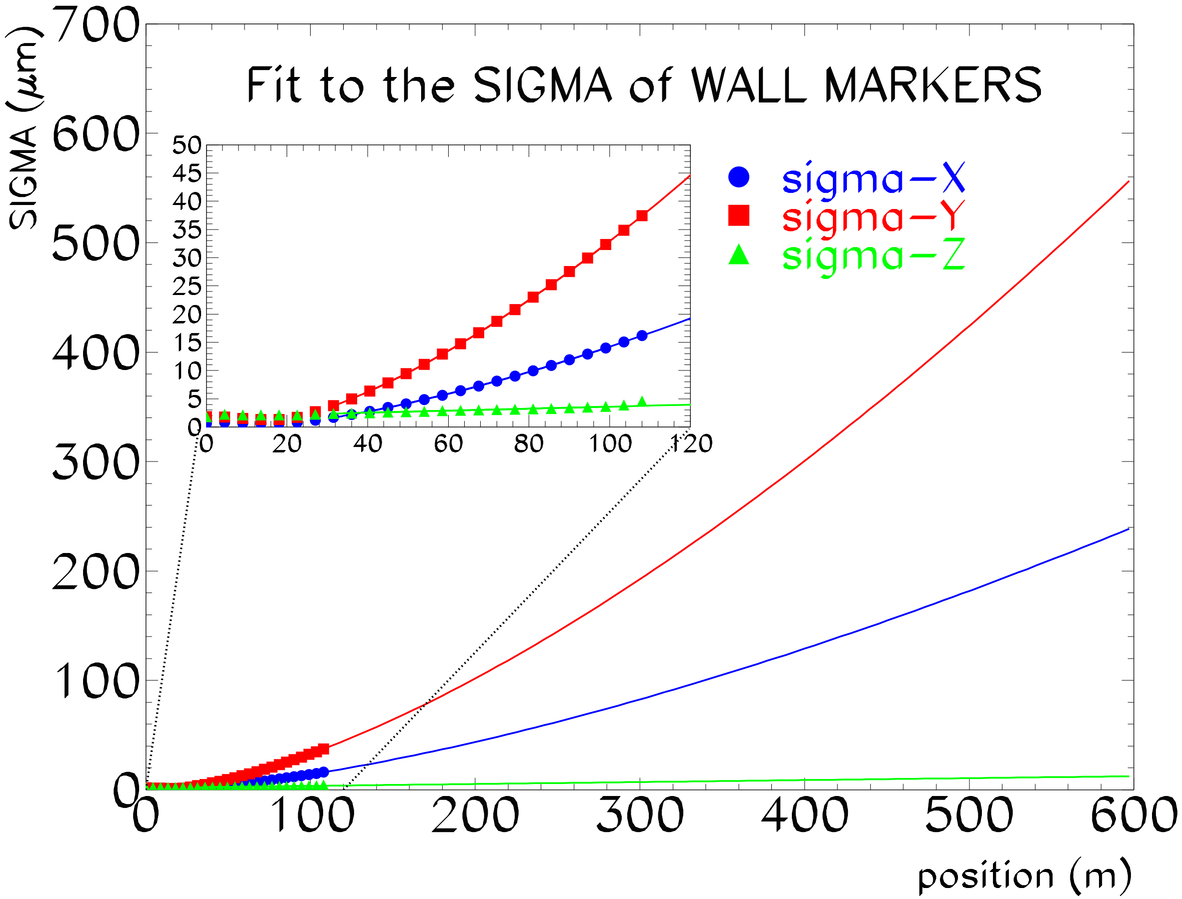
- Backup plots ...

Train Monte Carlo: Statistical errors (cont.)



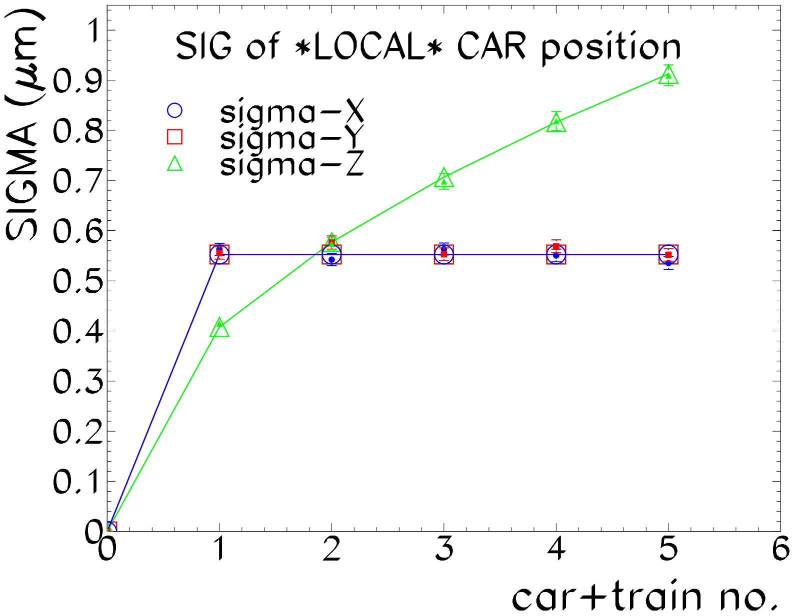
- open markers: Matrix calculation (analytic)
  solid markers: Errors from Monte Carlo
- disagreement sometime observed for particular "miscalibration patterns" and/or size of the cars position/angles randomisation
- artefact of the numerical methods used (?)
- effect under investigation but much smaller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

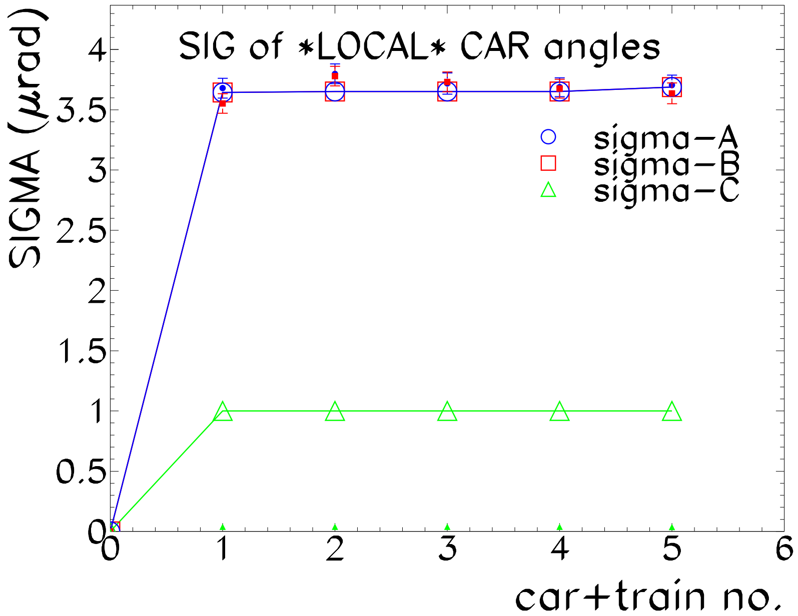
Extrapolation to $600\,m$ tunnel section (TESLA betatron wavelength)



- extrapolation using random walk model, asymptotic behaviour: $\sigma_{xy,n} \sim n^{\frac{3}{2}}, \;\; \sigma_{z,n} \sim n$
- longitudinal precision promising for dumping rings ($\sim 0.2\,mm/10\,km$, stat. errors only)

Single train simulation: Monte Carlo approach





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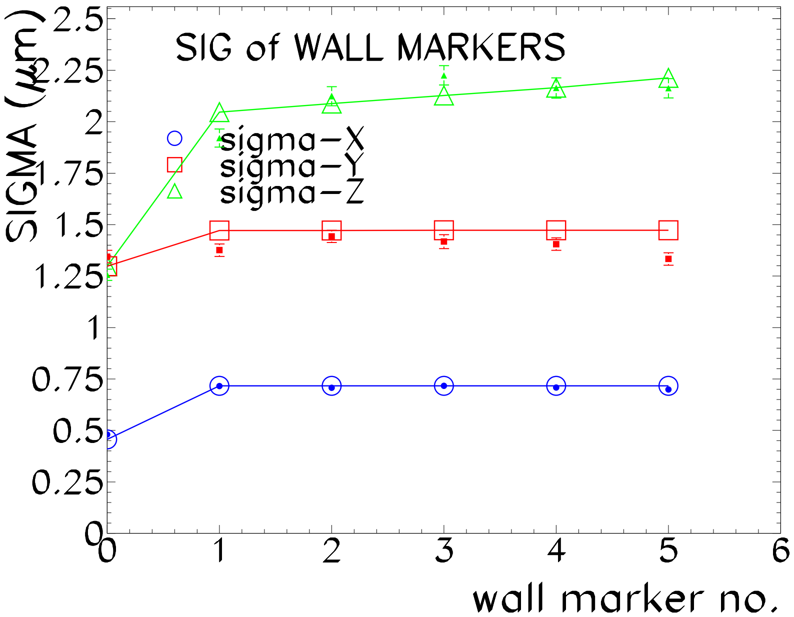
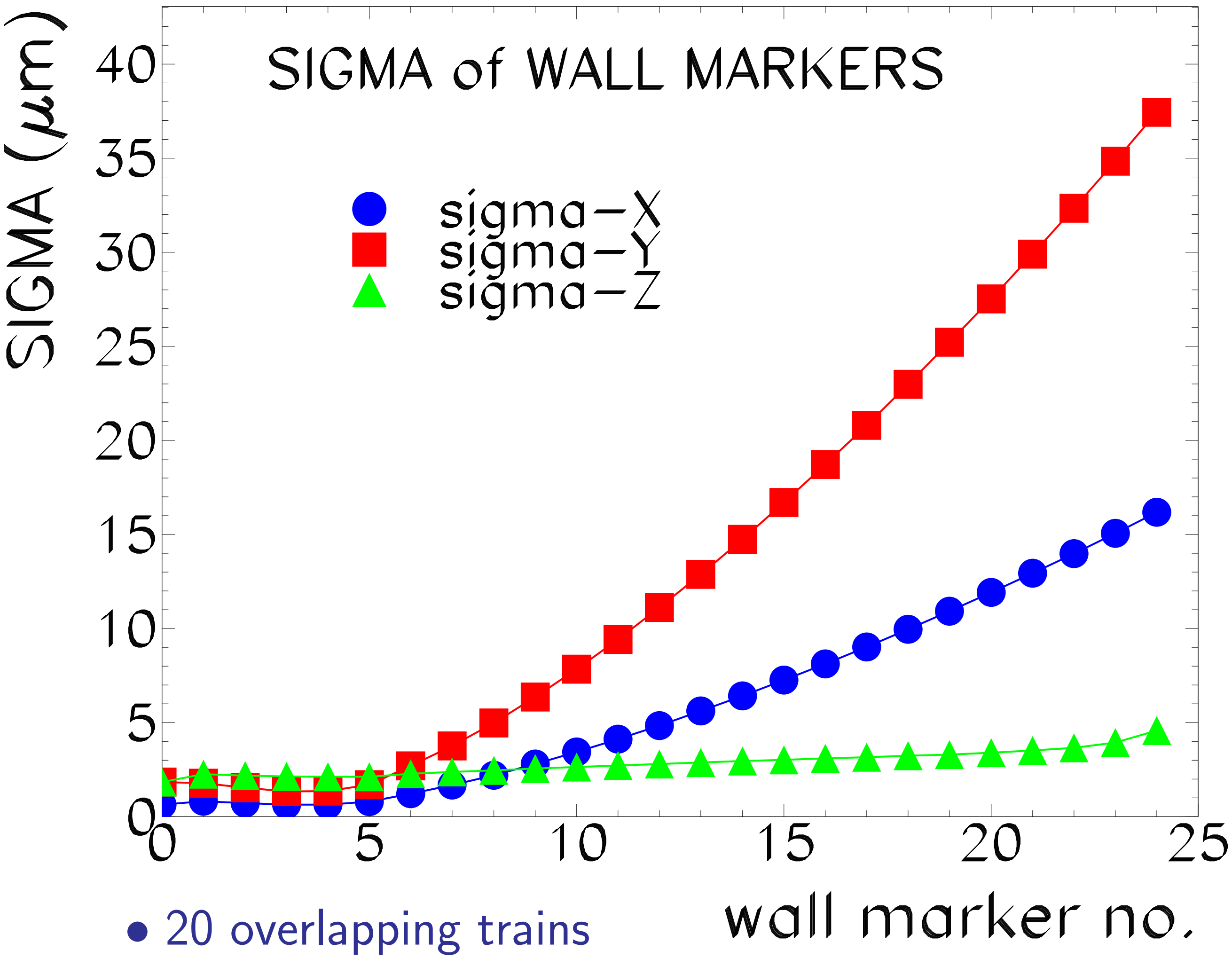


- assuming intrinsic resolutions:
  - CCD: $\sigma_{CCD} = 1\,\mu m$
  - FSI: $\sigma_{FSI} = 1\,\mu m$
- 1000 Simulgeo runs, simplified model, no errors on calib. const. (INT/EXT-FSI,CCD,BS)
- open markers: Matrix calculation (analytic)
  solid markers: Errors from Monte Carlo

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

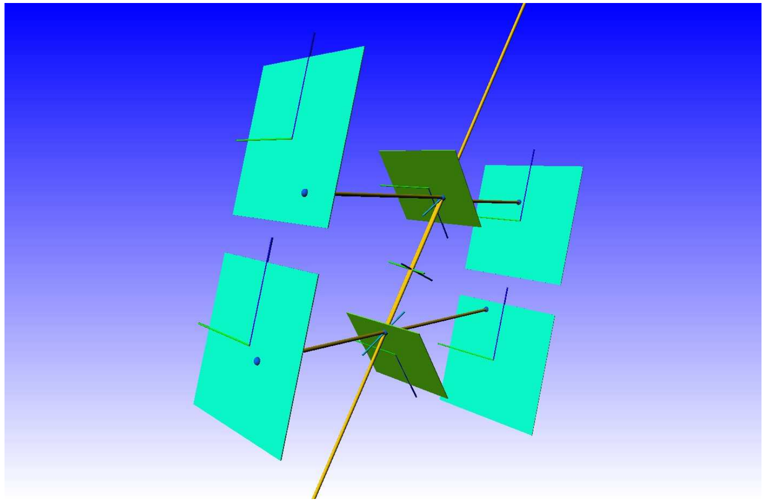


- results of full SIMULGEO simulation (error matrix rank $N^2 \sim 10\,000^2$)
- very CPU consuming !
- fast growth of transverse errors !

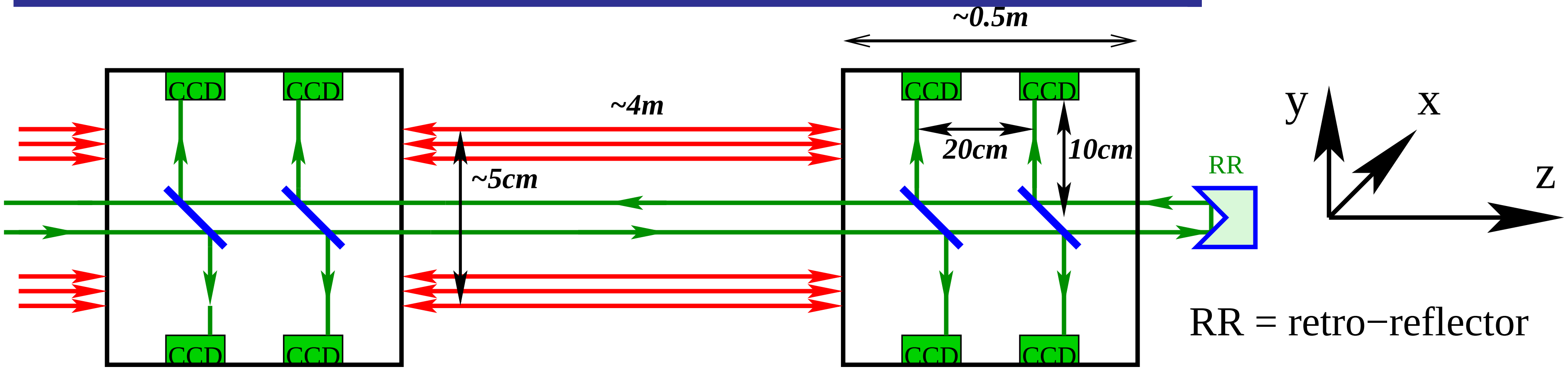
- 20 overlapping trains
- train stops are coupled to each other via the (previously measured) wall markers

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 CCD/FSI resolution, running many train "journeys" in a loop:
  Monte Carlo approach to the propagation of stat. errors
  (next plans: use it to study systematics)



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)		$\surd$

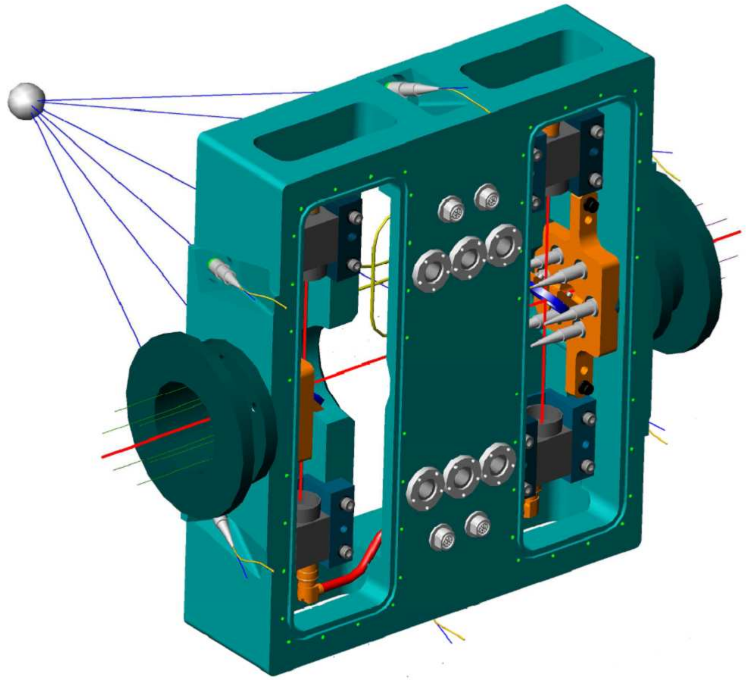
- LSM: transverse translation ($Tr_{x,y}$, $\sigma \approx 0.3\mu m$) and rotation ($Rot_{x,y}$, $\sigma \approx 3.0\mu rad$)
- INT-FSI: longitudinal distance ($\sigma \approx 1\mu m$) ($\pm$ redundancy for LSM)
- Clinometer: only Rot_z used (insensitive to the geoid shape)

RTRS: Rapid Tunnel Reference Surveyor in DESY "red-green" tunnel

- Tunnel infrastructure ready (tunnel length $60\,m$)
- Mechanics (propulsion, control, etc.) of RTRS ready
- Waiting for Invar sensing modules

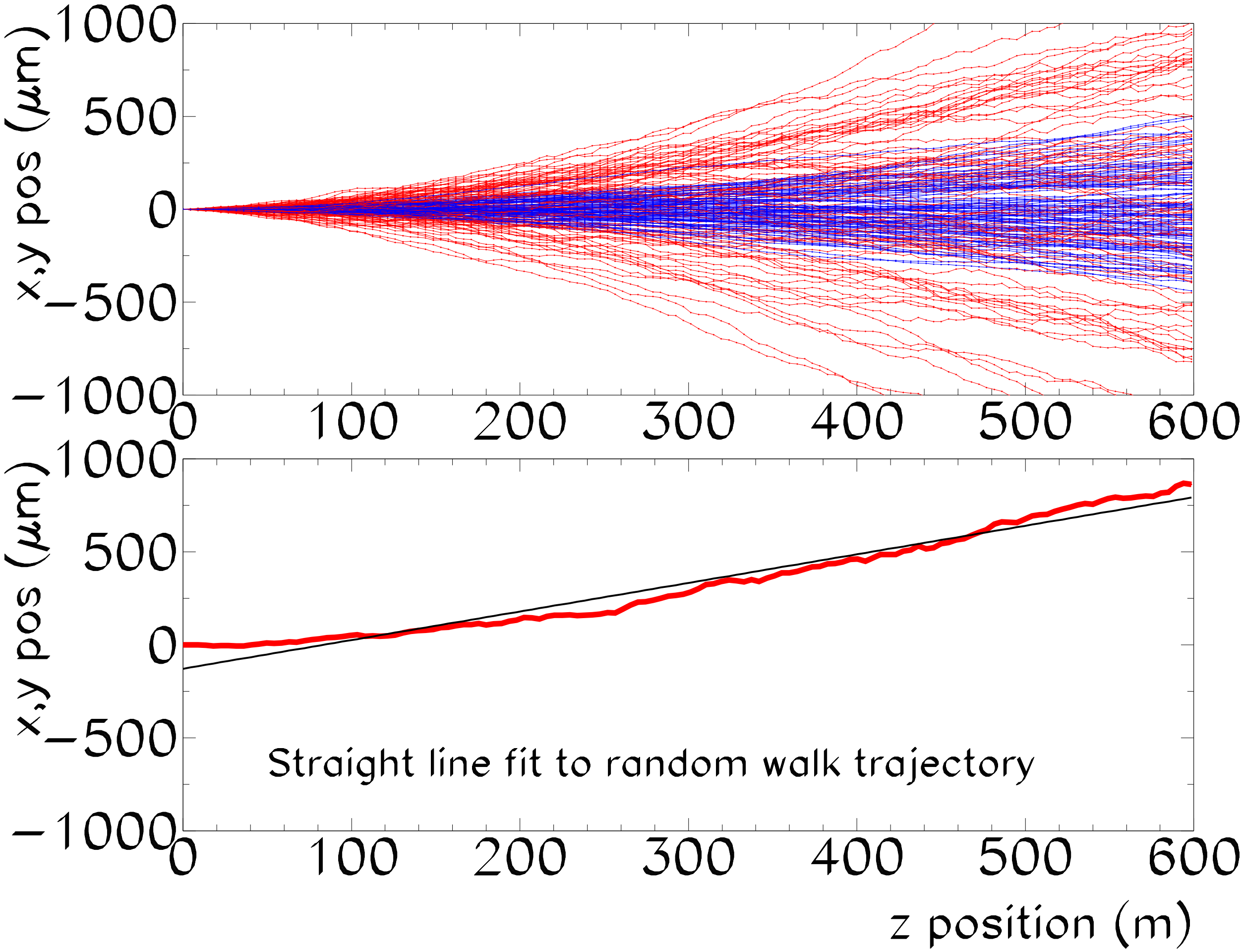
LiCAS Invar sensing body of RTRS car





- machining of the LiCAS Invar body for the sensing units
- Invar: alloy of nickel and steel, very small thermal expansion coefficient

Random Walk Monte Carlo: trajectories, fits

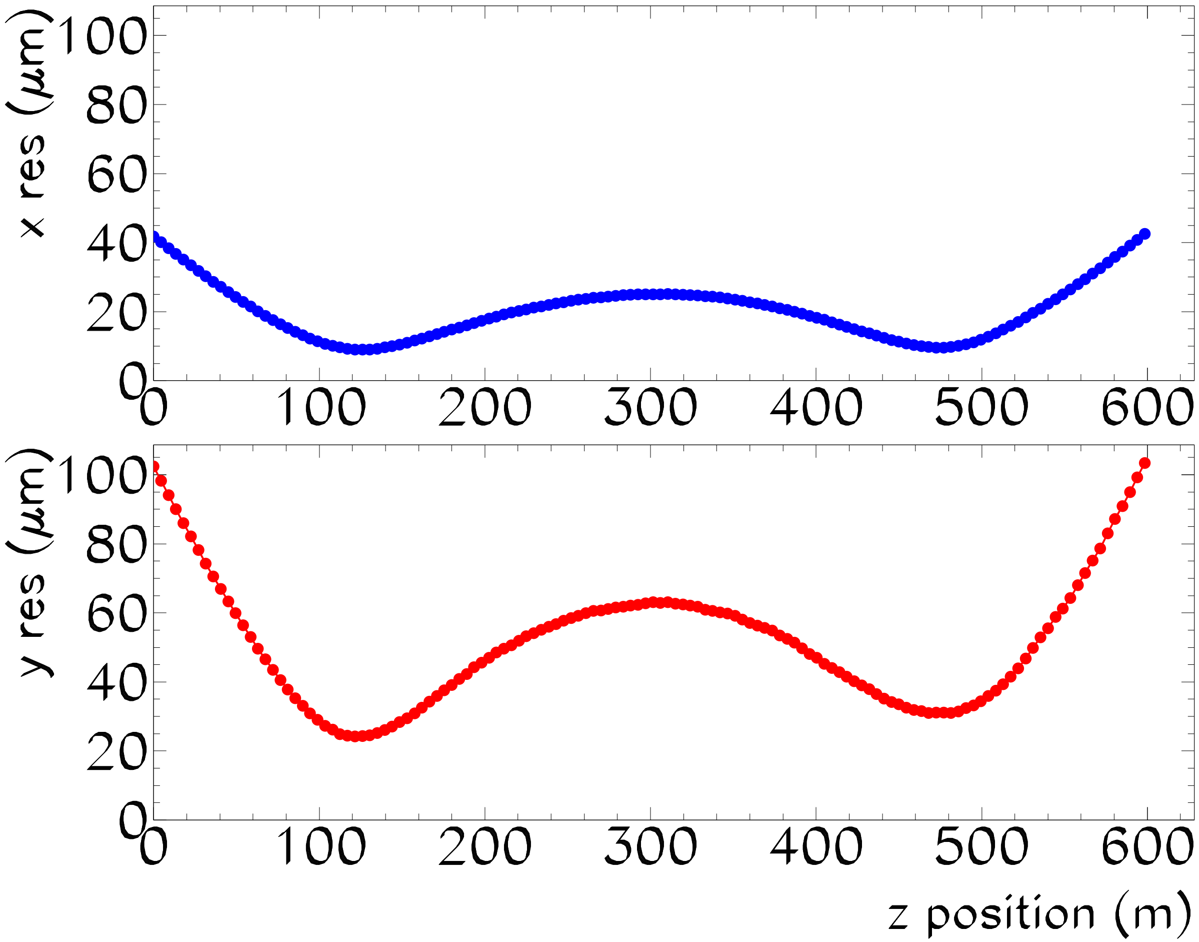


- trajectories generated from Random Walk Monte Carlo using parameters from the fit to SIMULGEO points (X, Y) direction

- 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"...

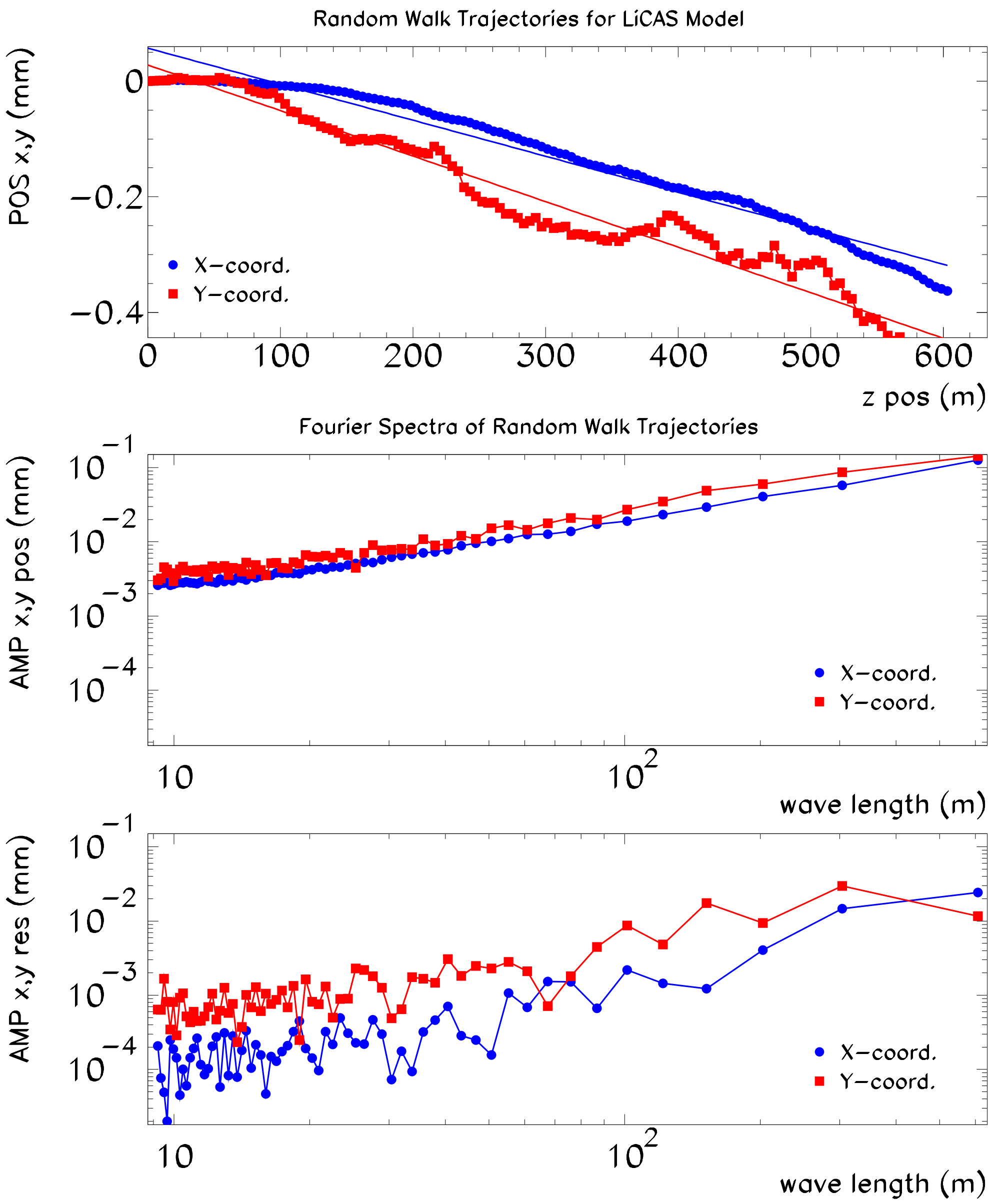
Random Walk Monte Carlo: residua



- mean deviation from straight line fits (X, Y) direction
- realistic input to simulations of beam dynamics (`licas_sim`) $\longrightarrow$ LiCAS Random Walk Simulation

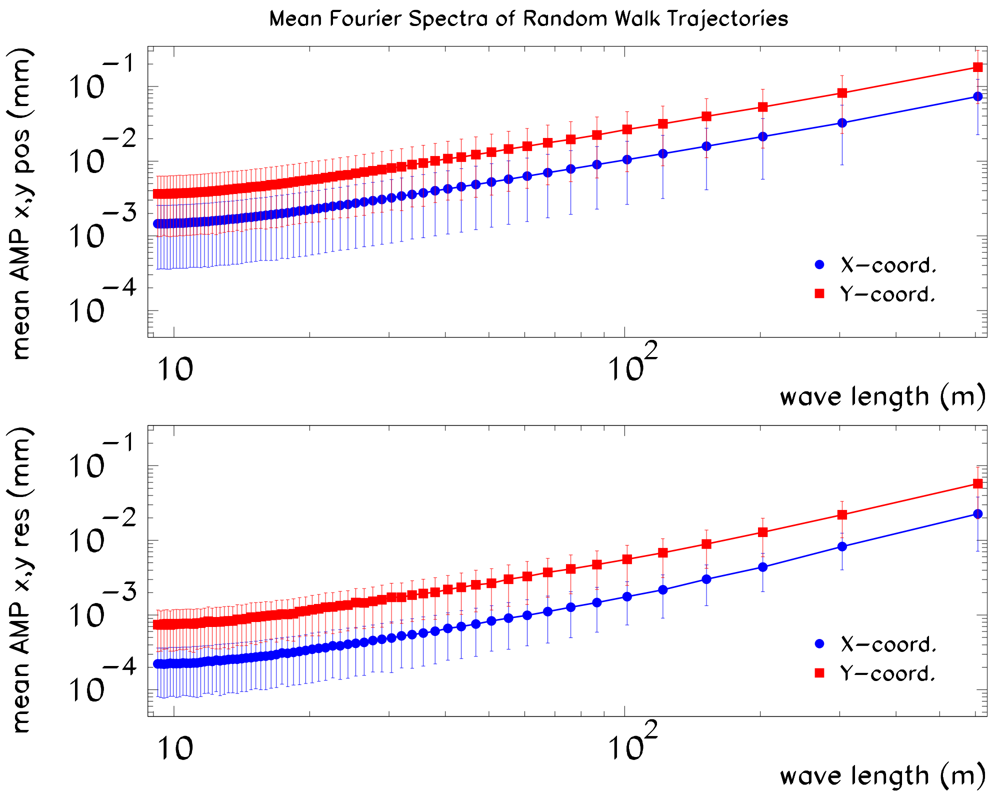
- well below specification: $\sigma_x = 500\mu m$, $\sigma_y = 200\mu m$
- however: only statistical errors included so far
- precision between X – Y can be swapped by changing the marker location (horizontal to vertical position)

Fourier analysis of MC LiCAS trajectories: $600\,m$ tunnel section



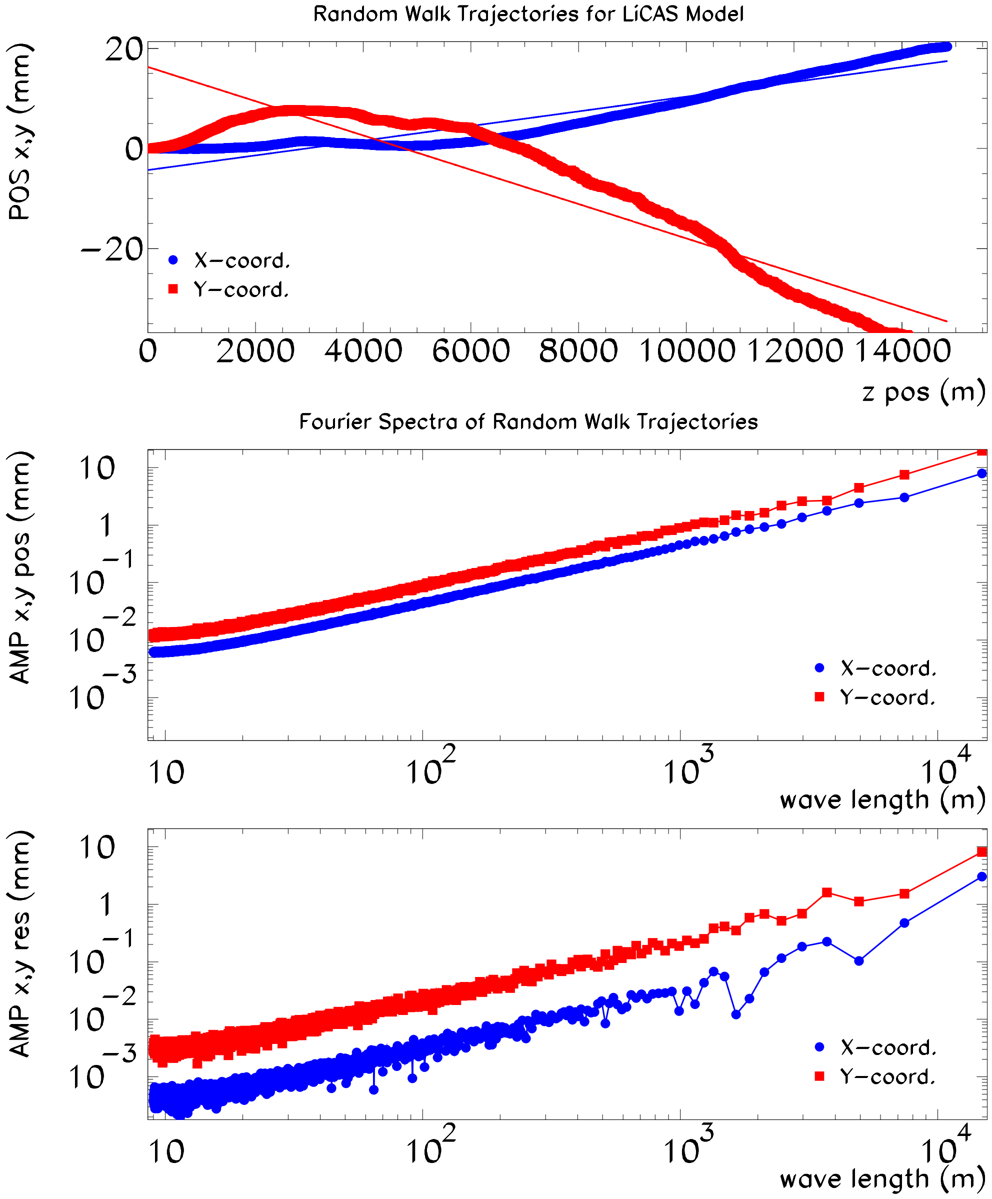
- typical example of x,y MC trajectories
- FFT spectra of x,y positions
- FFT spectra of x,y residua

FFT mean spectra: $600\,m$ tunnel section



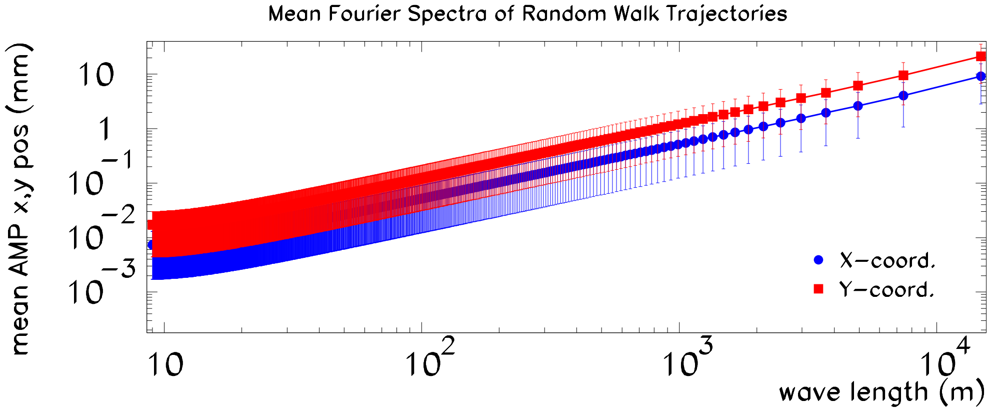
- mean FFT spectra of x,y positions
  $< Amp > @600\,m \sim 200\,\mu m$
- mean FFT spectra of x,y residua
  $< Amp > @600\,m \sim 50\,\mu m$

Fourier analysis of MC LiCAS trajectories: $15\,km$ tunnel section

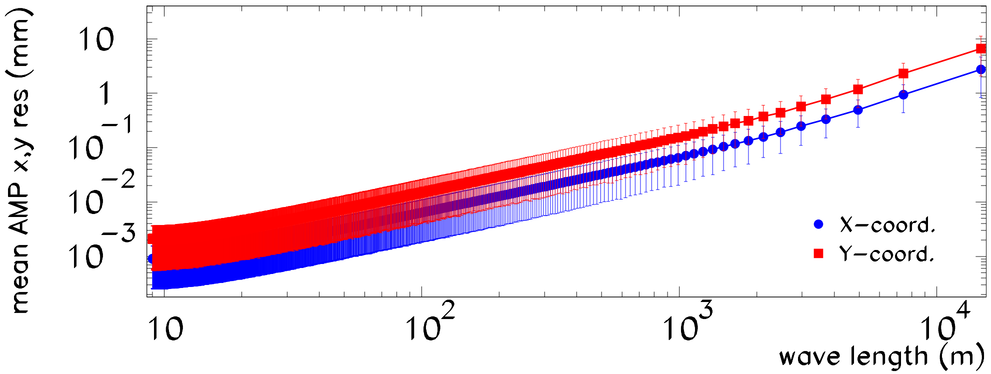


- typical example of x,y MC trajectories
- FFT spectra of x,y positions
- FFT spectra of x,y residua

FFT mean spectra: $15\,km$ tunnel section

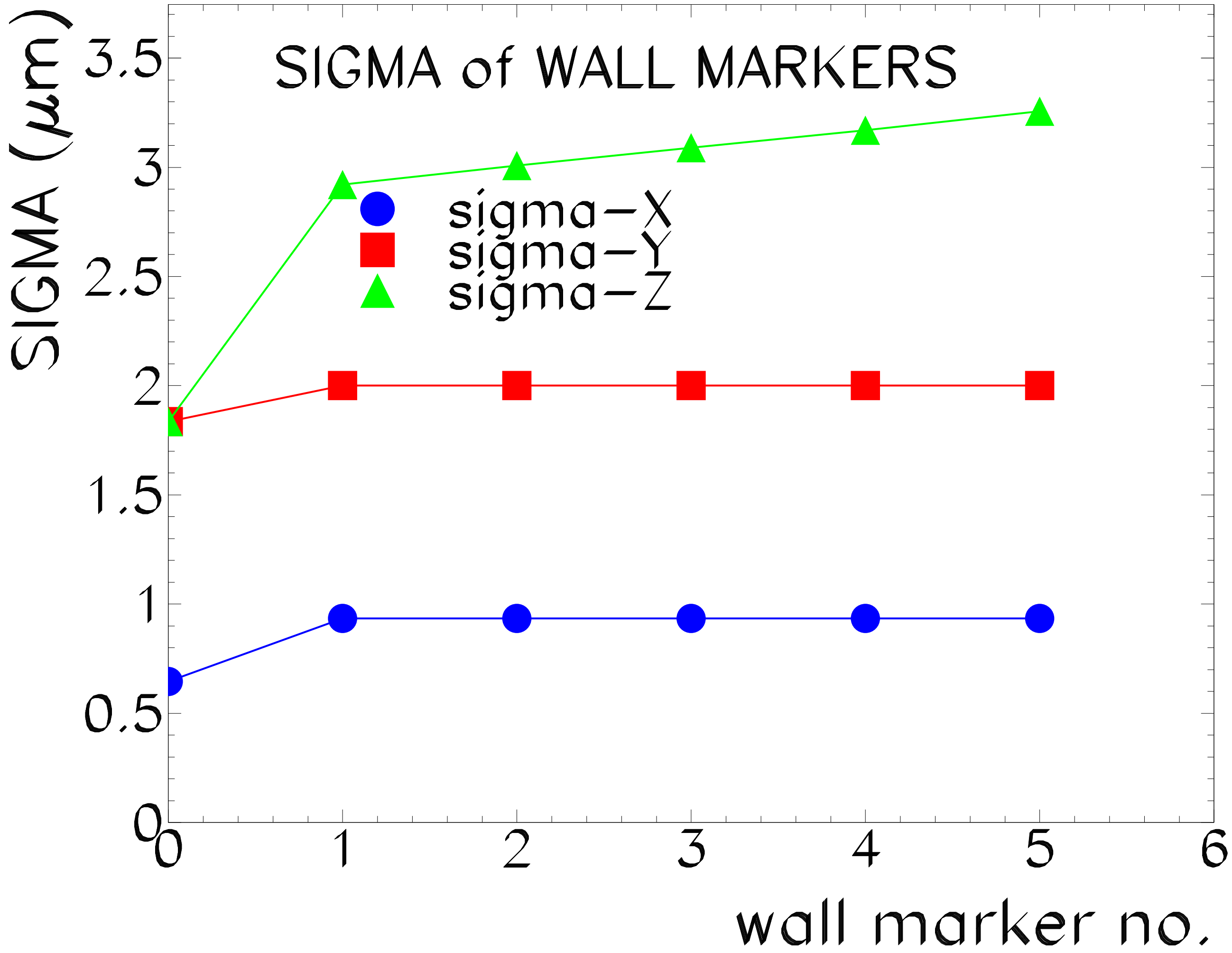


- mean FFT spectra of x,y positions $< Amp > @15\,km \sim 20\,mm$



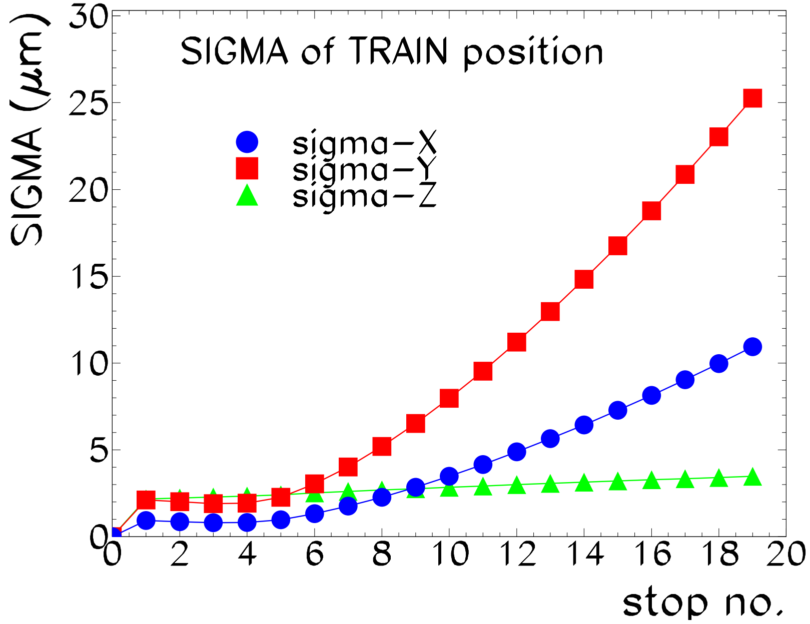
- mean FFT spectra of x,y residua $< Amp > @15\,km \sim 5\,mm$

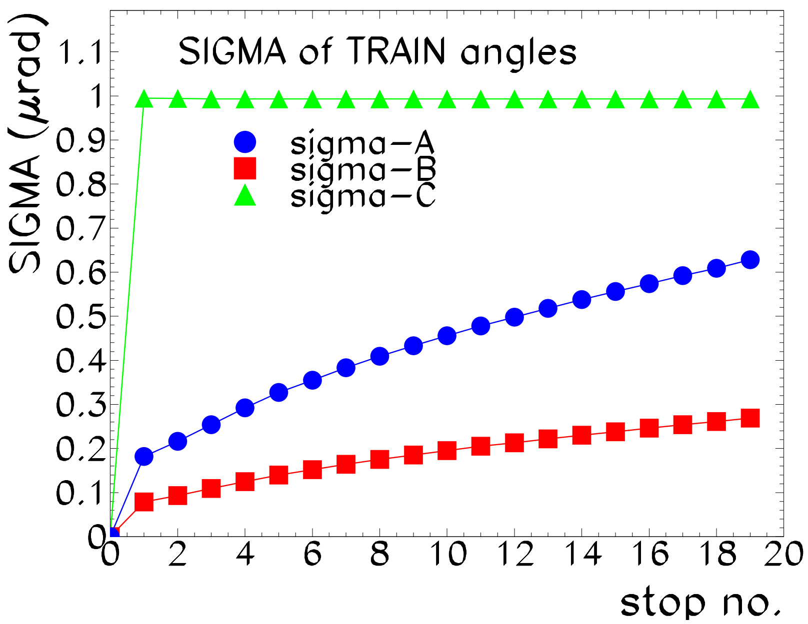
Single train simulation: resolution for reference markers



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

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





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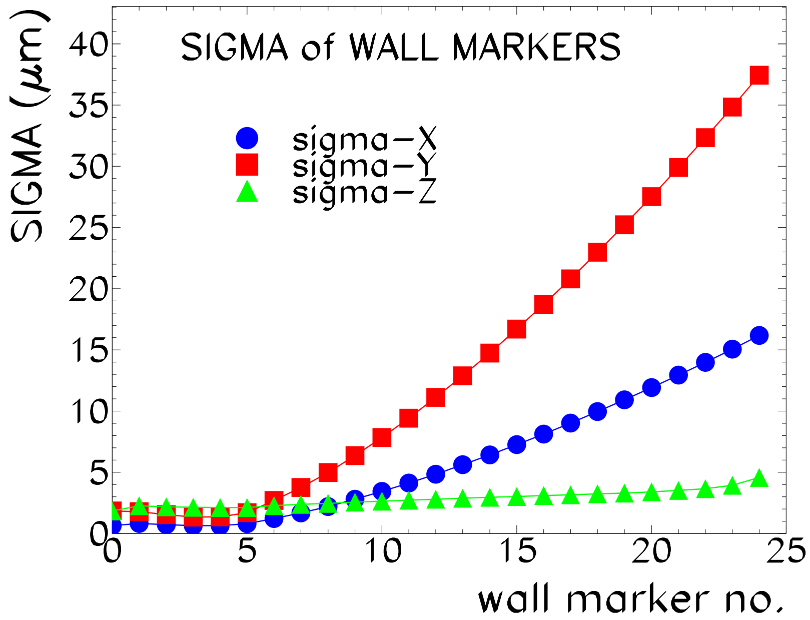

- intrinsic resolutions and calibration constants as for single train simulation (all $\sigma = 1\,\mu m\,;1\,\mu rad$)
- very CPU and memory consuming ! (10000^2 matrix) for 20 stops $1.0\,GB$ RAM and $34\,h$ CPU time @$2\,GHz$