Simulation of LiCAS error propagation

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Outlook

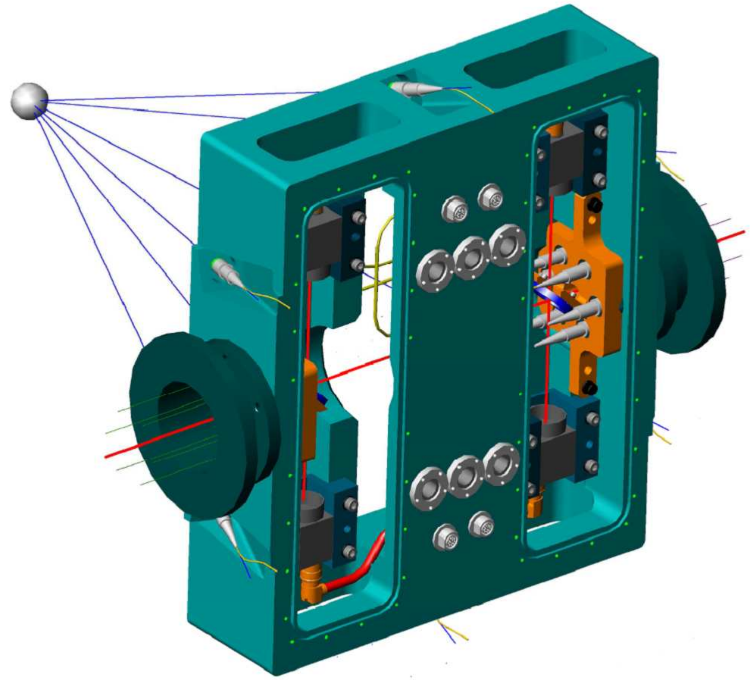
- Concept of the LiCAS-RTRS train
- Opto-geometrical model of the sensing cars
- Idea of the multi-train overlapping measurements
- Simulation and reconstruction software:
  - Analytical (matrix) error propagation
  - LiCAS Ray-Tracer and Reconstruction
  - Monte Carlo approach to error calculations (in progress)
- Single train stop ($\sim 20\,m$) simulation
- Operation along the accelerator tunnel ($\sim 100\,m$)
- Short ruler model (random walk algorithm - extrapolation to $\sim 600\,m$)
- Fourier analysis of alignment trajectories
- Conclusions

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

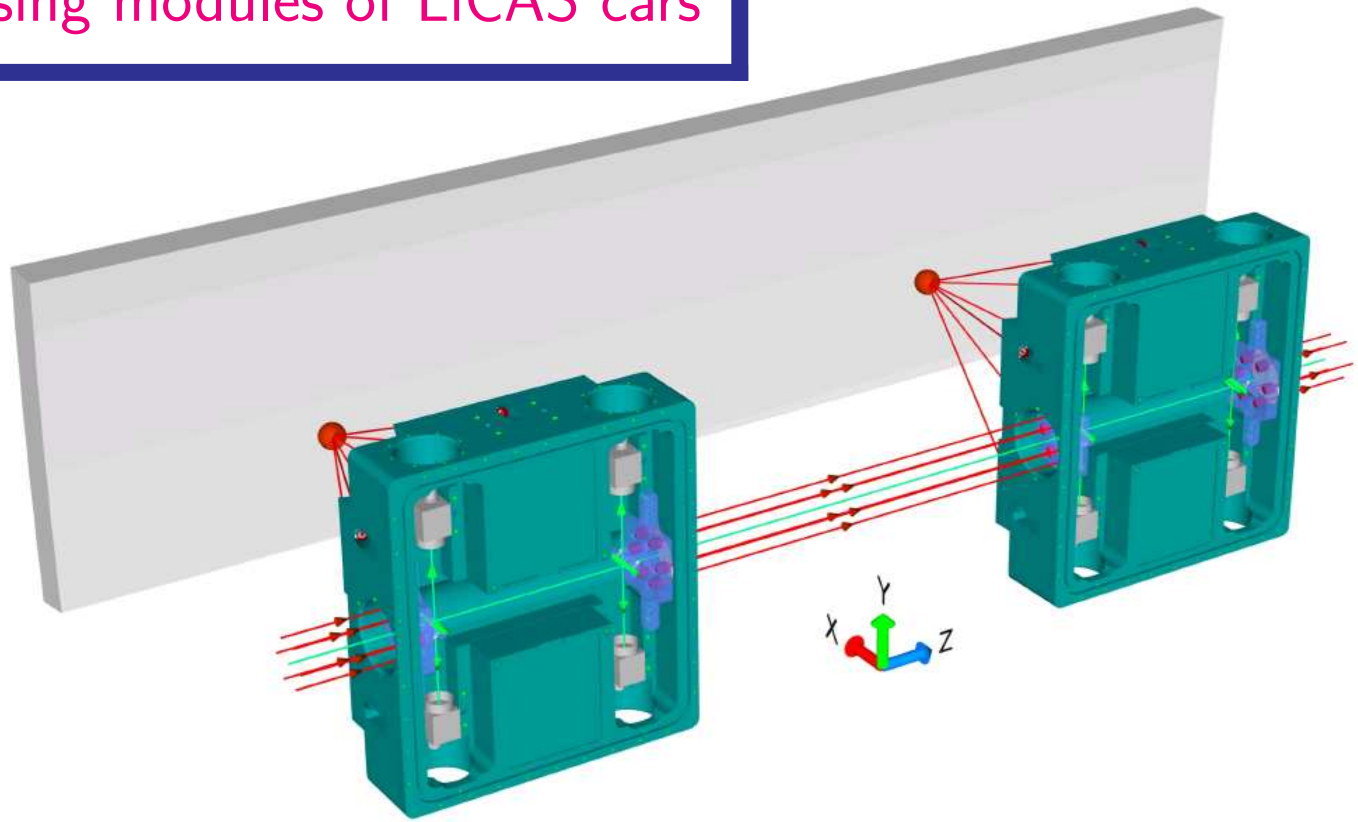
LiCAS Invar sensing body of RTRS car





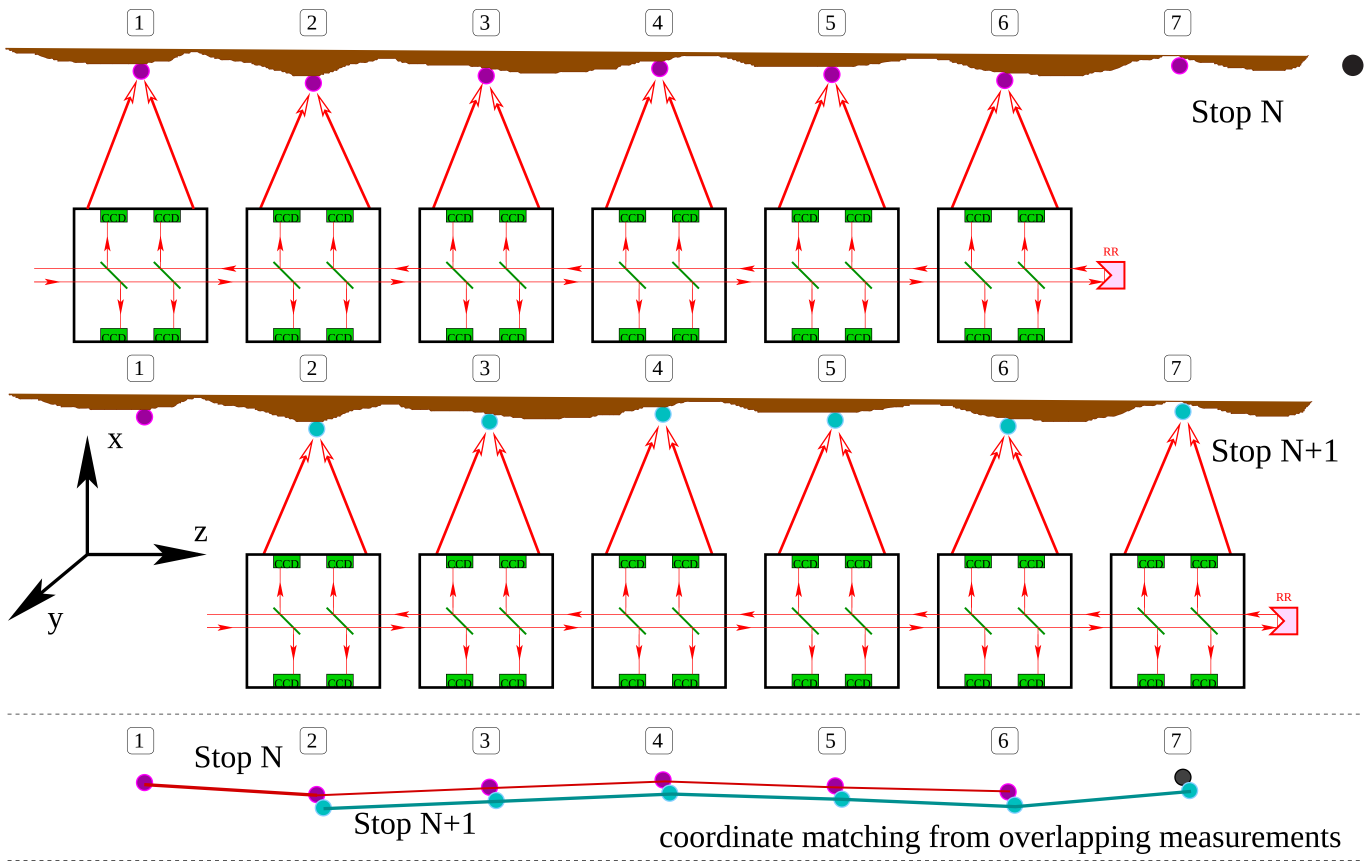
- machining of the LiCAS Invar body for the sensing units
- Invar: alloy of nickel and steel, very small thermal expansion coefficient

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

Multi train overlapping measurement



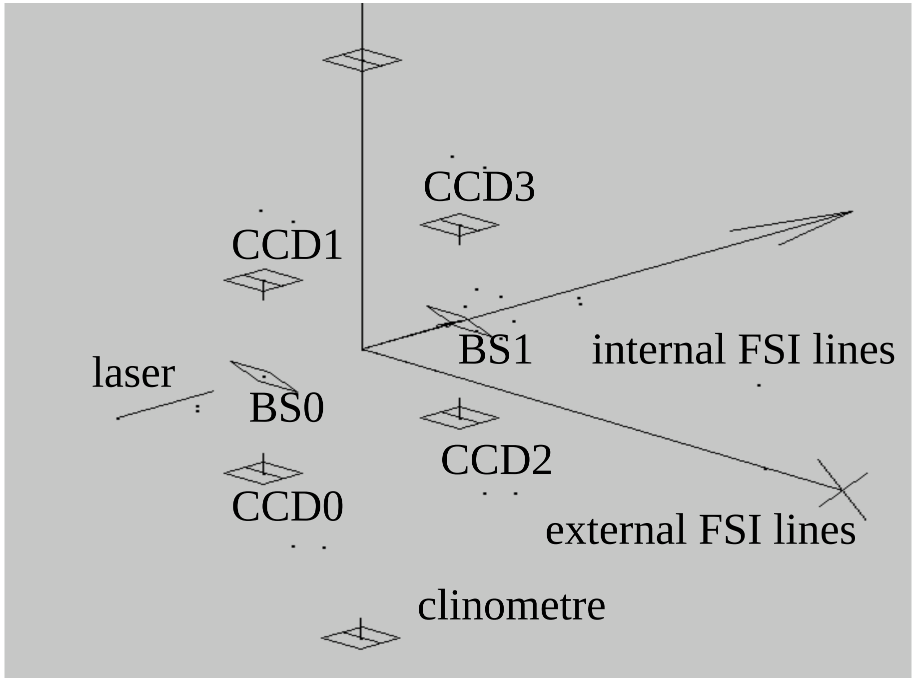
- top view on two train stops along the tunnel wall

- 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)

SIMULGEO: Software used in the simulation

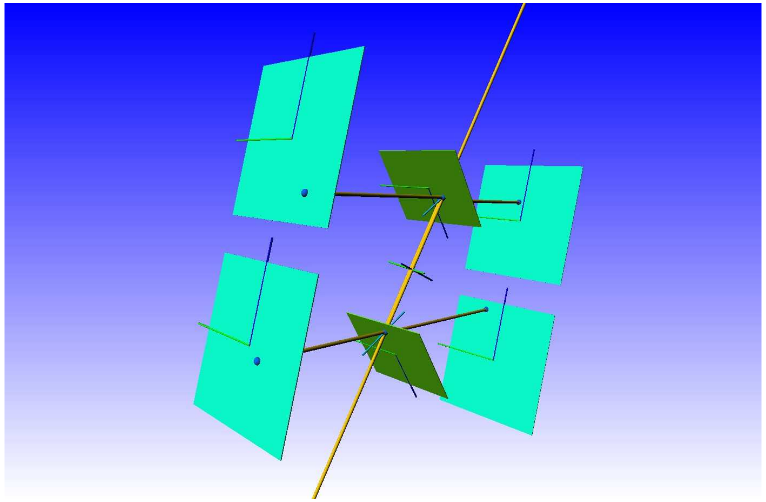
- Script language for description of opto-geometrical systems (light sources, CCD detectors, distancemeters...)
- Mechanical correlations between objects grouped in local frames
- ERROR PROPAGATION MODE:
  Performs full error propagation
  (N^2 matrix, very CPU consuming)

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



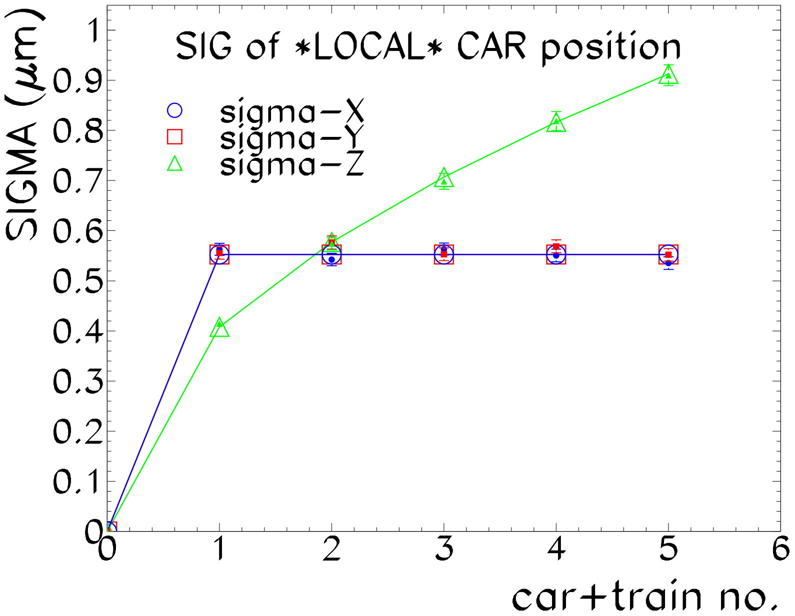
- Optical system (per car): 4 CCDs (4*6 DoF), 6 EXT-FSI (6*3 DoF), 6 INT-FSI (2*6*3 DoF)
- Per train: LSM laser beam (+retro-reflector)
- Extracted: position and rotation of each car (6*6 DoF) and Wall Markers positions (6*3)

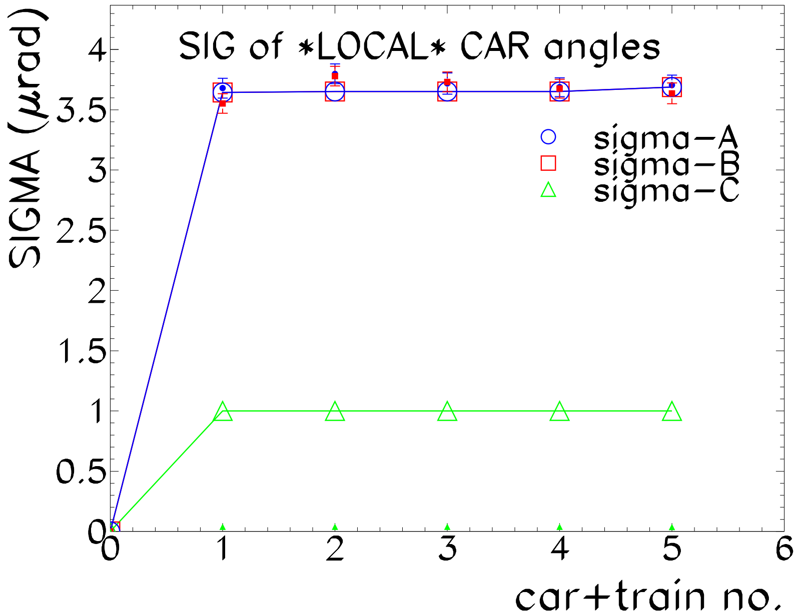
Ray Tracer, Reconstruction and train Monte Carlo



- 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)

Single train simulation: Monte Carlo approach

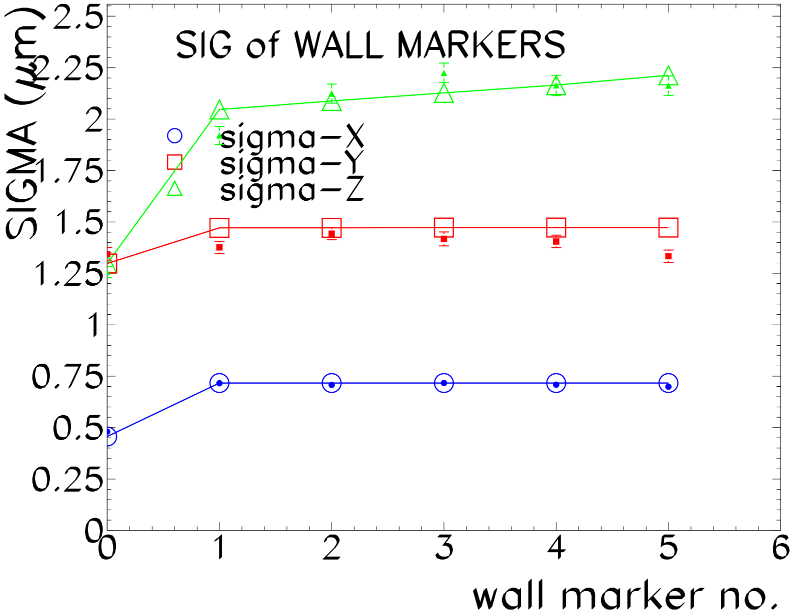




$A = Rot_X$

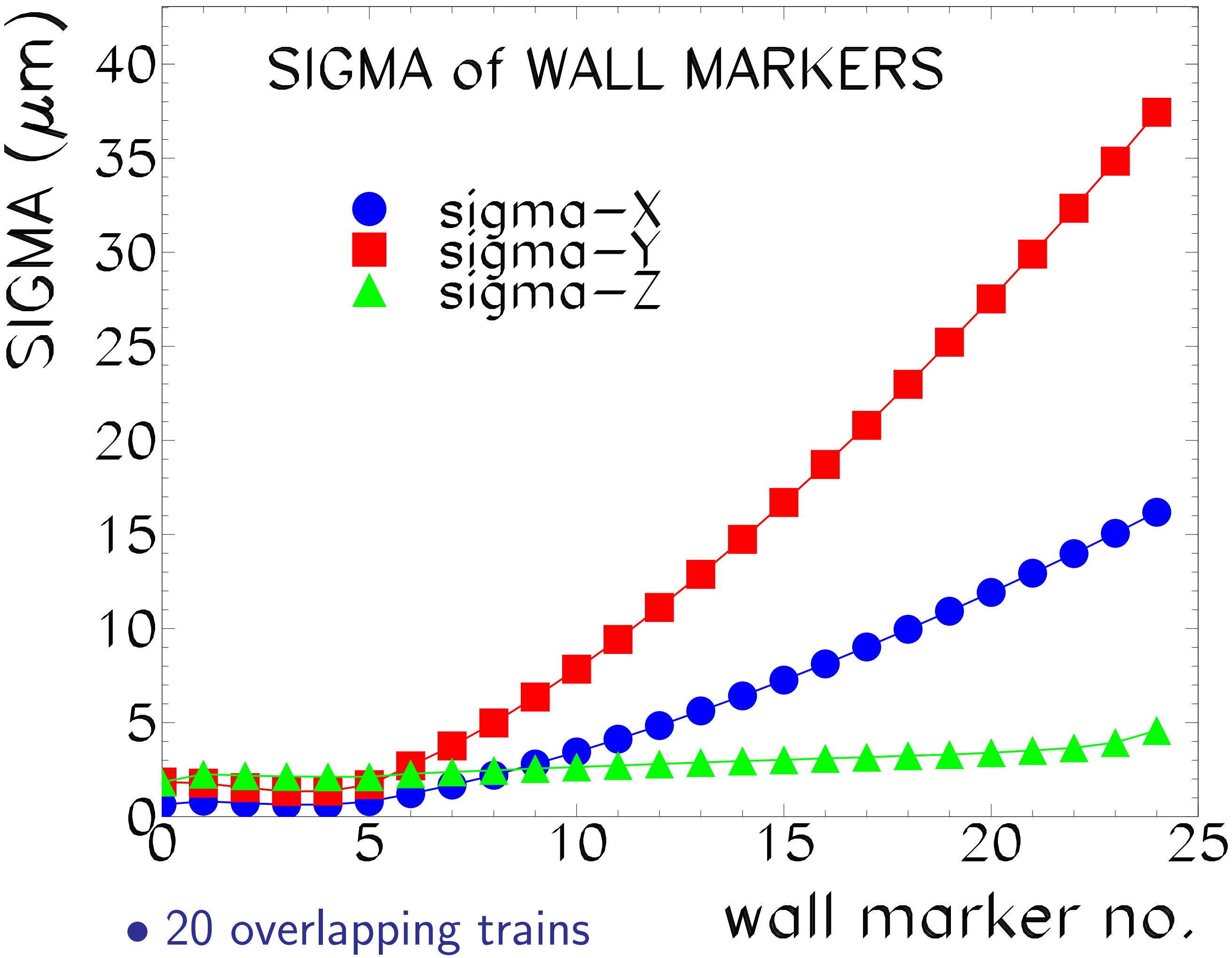
$B = Rot_Y$

$C = Rot_Z$



- 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

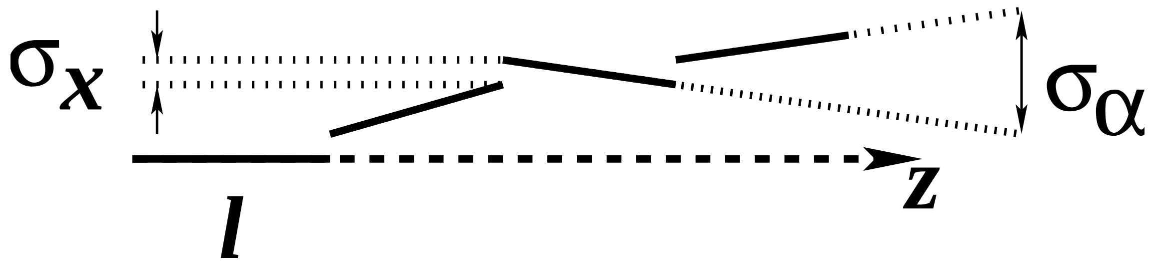
20 train stops ($= 90\,m$ tunnel section)



- 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

Short ruler model (or random walk along the tunnel)

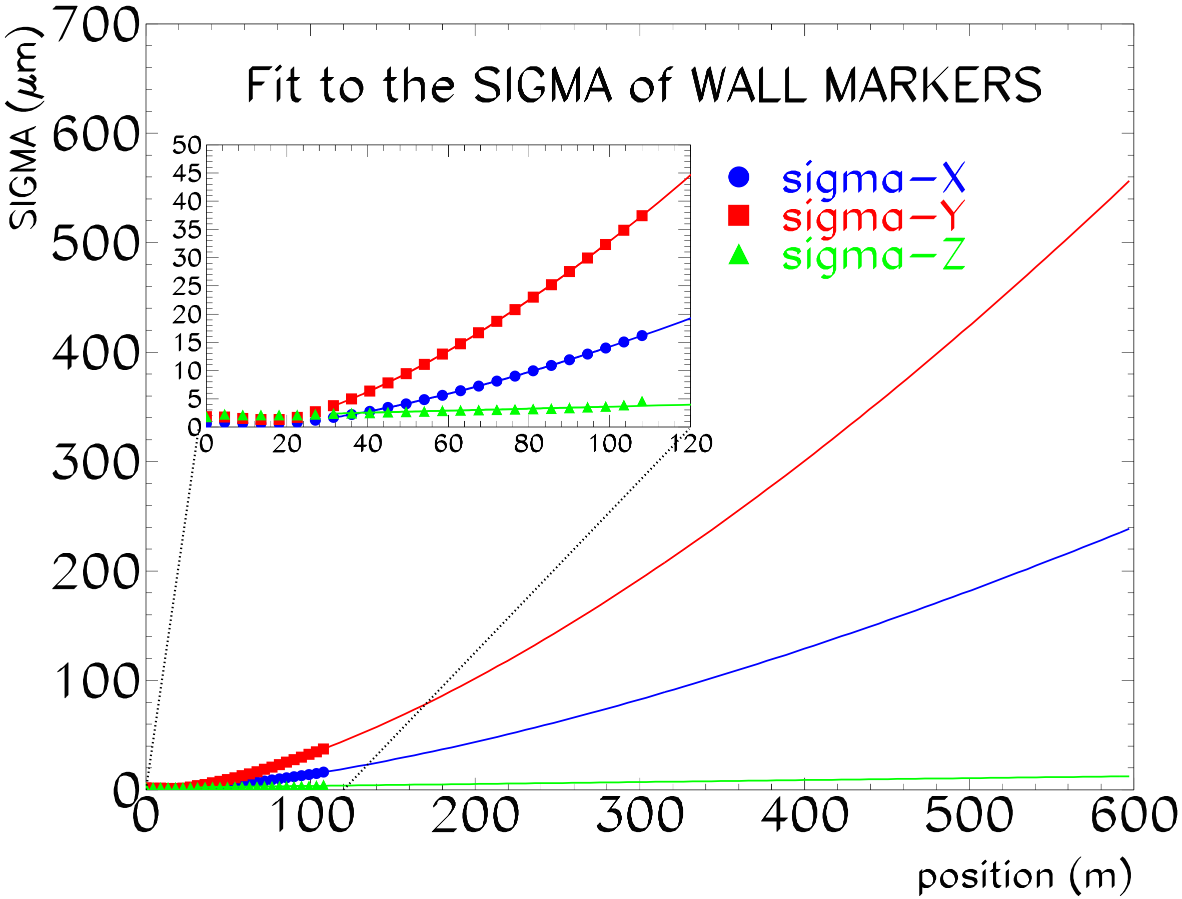


- two sources of errors (2D case): position (off-set) and direction (angle)
- off-sets and angles are relative to the previous "ruler"

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

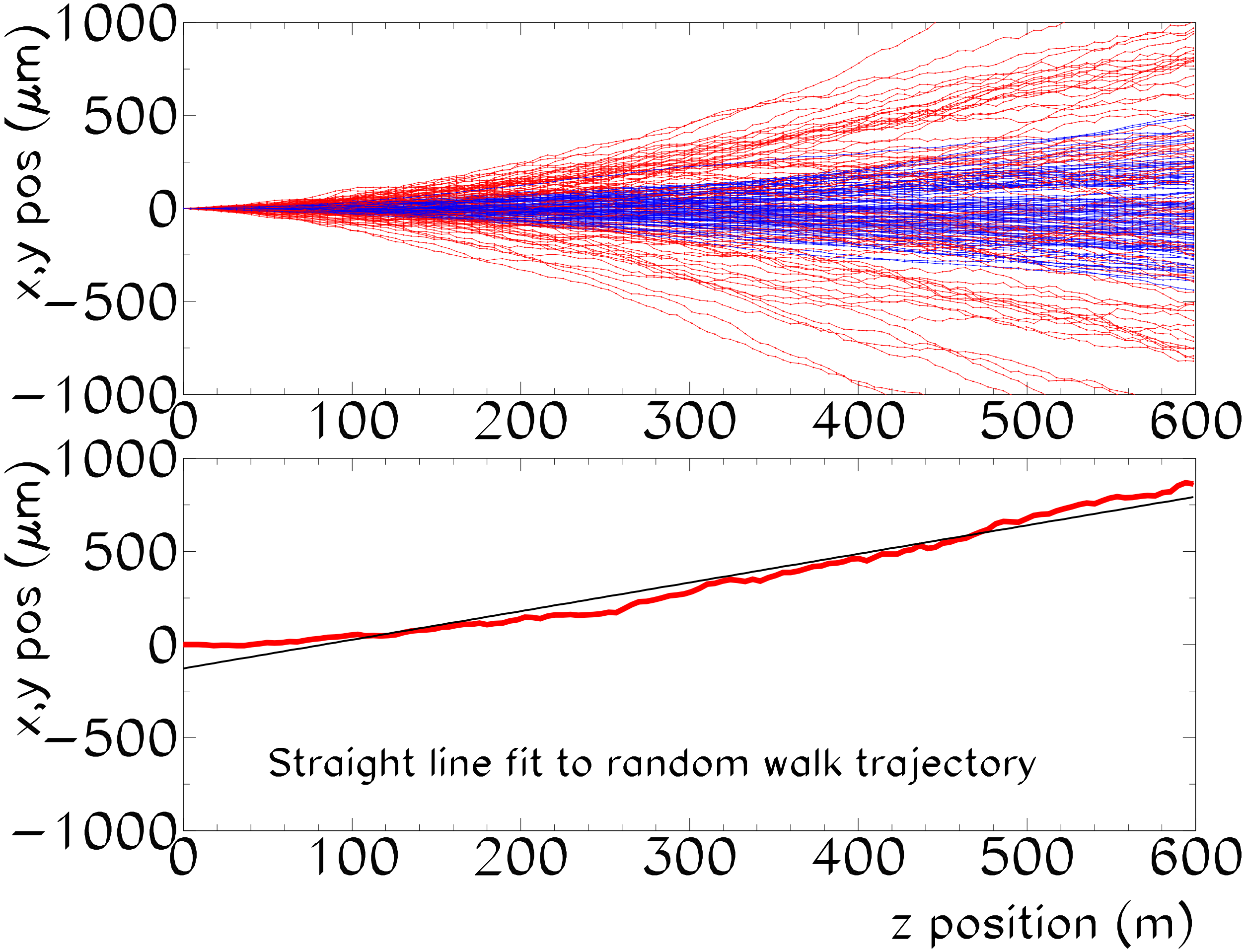
n – wall marker number, l – effective length of the ruler (here: distance between cars), errors: σ_α – angular $(\sim 0.1\,\mu rad)$, σ_{xy} – transverse $(\sim 0.5\,\mu m)$, σ_z – longitudinal $(\sim 0.1\,\mu m)$

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)

Random Walk Monte Carlo: trajectories, fits

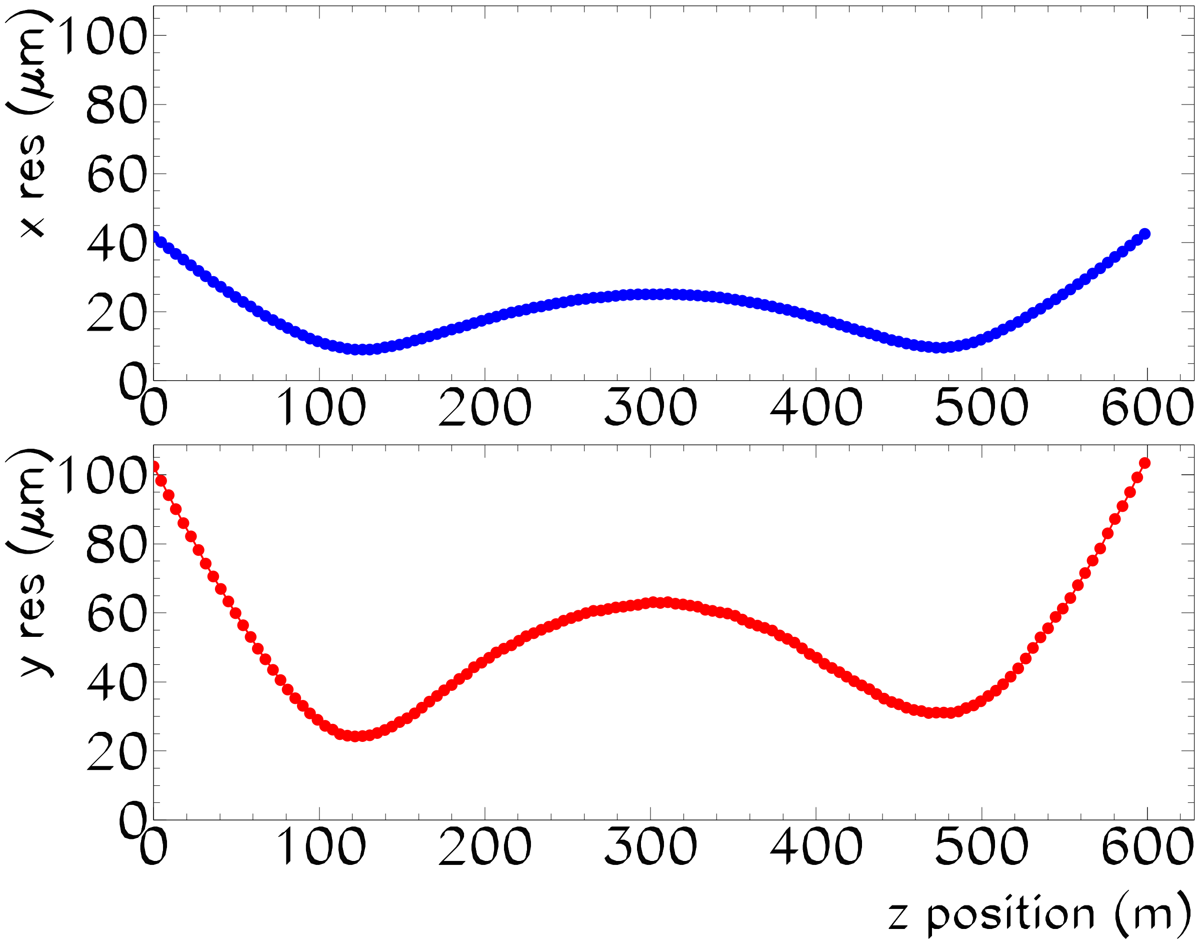


- trajectories generated from Random Walk Monte Carlo using parameters from the fit to SIMULGEO points (X, Y) direction

  - 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"...

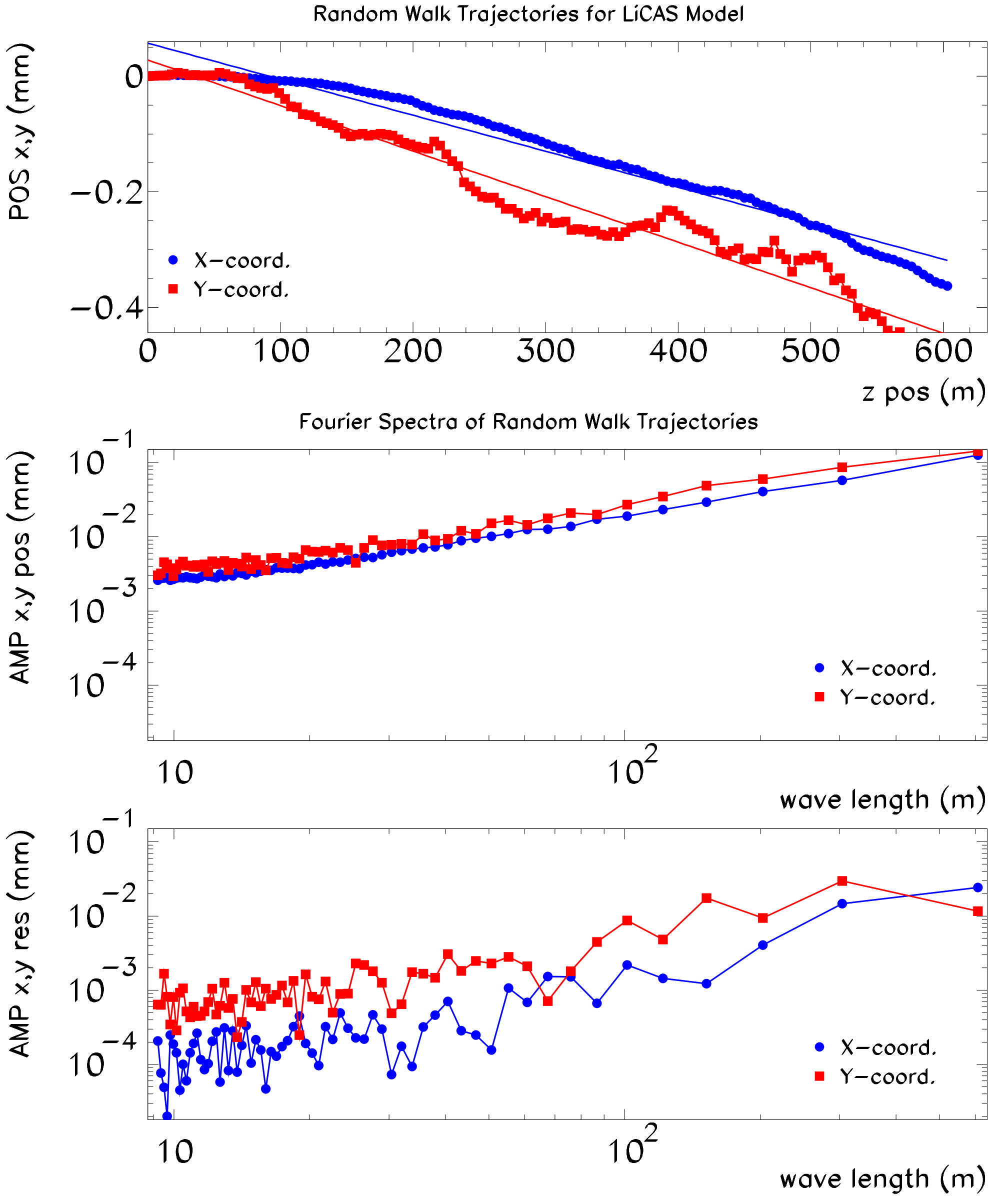
Random Walk Monte Carlo: residua



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

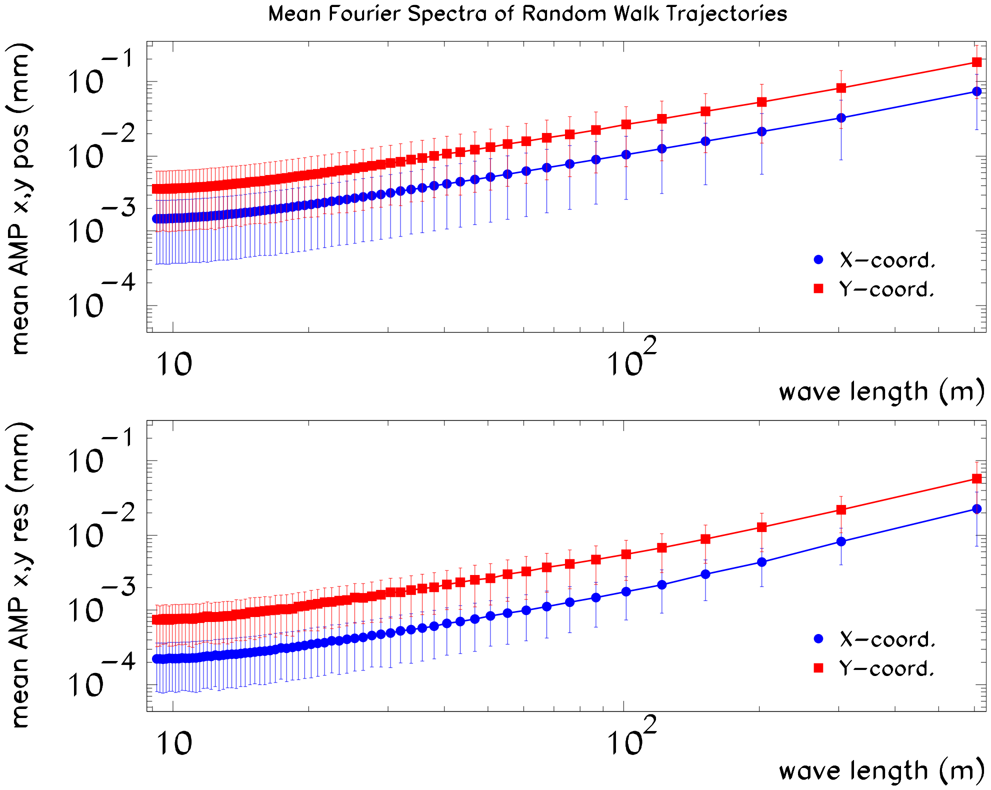
- well below specification: $\sigma_x = 500\mu m$, $\sigma_y = 200\mu m$
- however: only statistical errors included so far
- precision between X – Y can be swapped by changing the marker location (horizontal to vertical position)

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



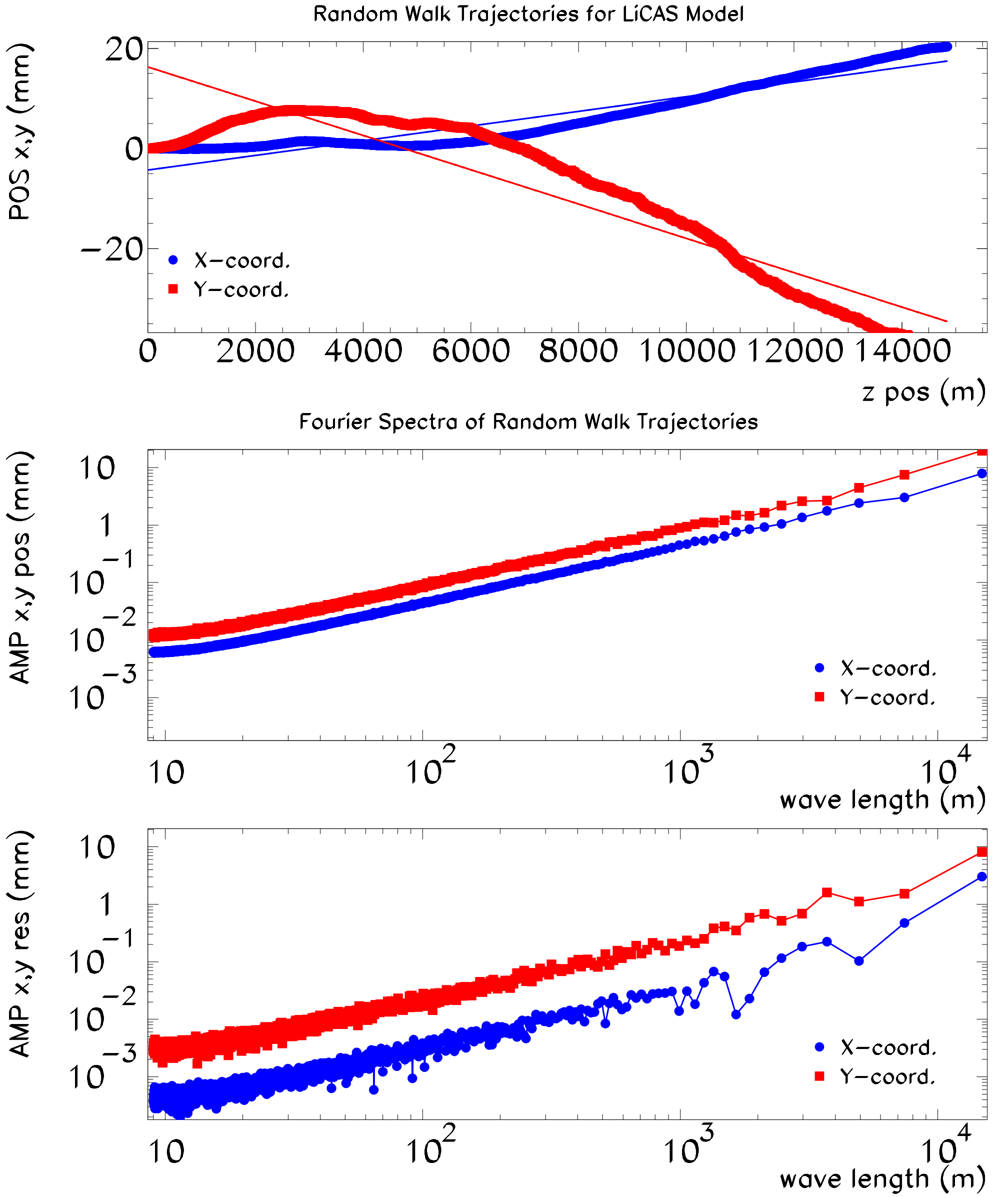
- typical example of x,y MC trajectories
- FFT spectra of x,y positions
- FFT spectra of x,y residua

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



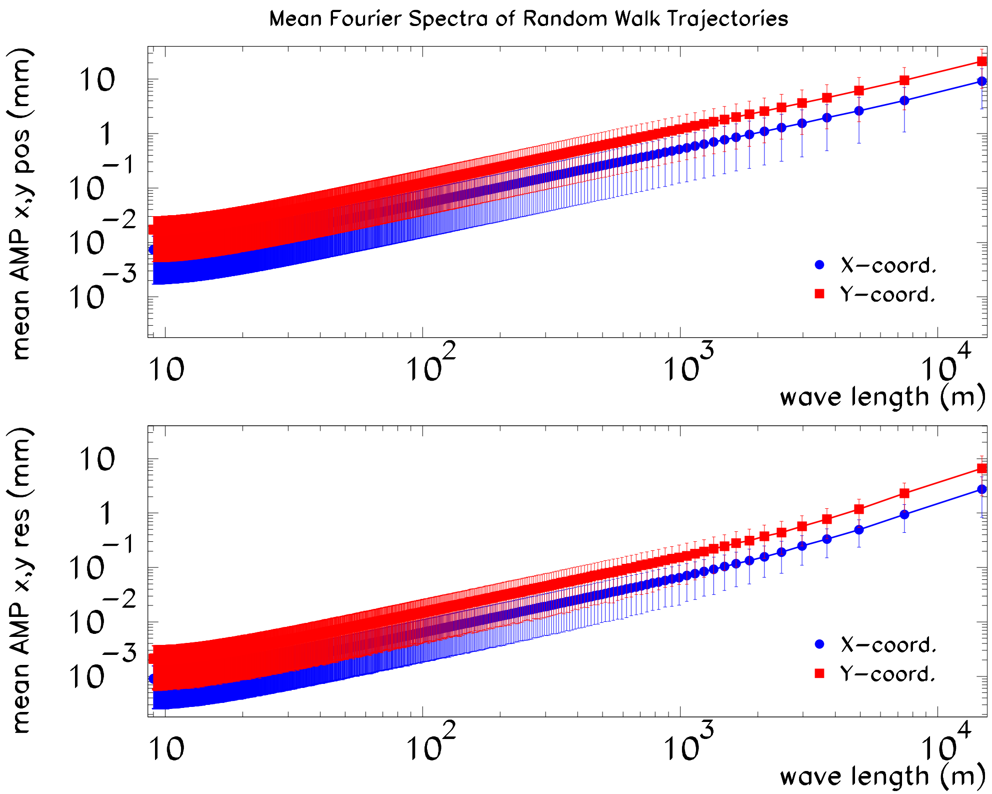
- mean FFT spectra of x,y positions
  $< Amp > @600\,m \sim 200\,\mu m$
- mean FFT spectra of x,y residua
  $< Amp > @600\,m \sim 50\,\mu m$

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
  $< Amp > @15\,km \sim 5\,mm$

Summary/Plans

- 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
- Spectral analysis of alignment trajectories performed $\longrightarrow$ no high frequency oscillations
- Next plans: study systematics errors using Monte Carlo approach
- Demonstrate the train performance in the test tunnel
- Start to work on the next generation of RTRS for XFEL tunnel