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high precision survey and alignment of large linear accelerators

DESY

DESY - The acronym stands for Deutsches Elektronen-Synchrotron - has been established as an independent foundation under civil law in 1959 in Hamburg. It is a research center with 1.500 employees and approximately 3.400 scientists from 280 universities and institutes from 35 countries.

figure 1: DESY facility

Particle Physics at Oxford University

The Subdepartment of Particle Physics is housed in the Denys Wilkinson Building. It is the largest particle physics group in the UK with 23 academics, about 20 post-docs and fellows, 30 graduate students and 40 support staff.

figure 2: The Denys Wilkinson Building

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b) DESY Hamburg, GER, Applied Geodesy Group
* former member of the particular group

Geodetic Tasks

A very high accuracy is demanded for the alignment of all accelerator components to run a linear collider like TESLA successfully. The standard deviation of every component is postulated to be **0.2 mm in lateral and height** over a range of 600 m (alternatively the maximum betatron wavelength). Because of the influence of refraction, this can not be achieved with any open-air optical survey.

Overall Project

The basic network consists of equidistant reference points fixed to the tunnel wall with a separation of approximately 5 m. The alignment of the accelerator is split up in two major steps:

1. The reference points will be surveyed by an automated system (Rapid Tunnel Reference Surveyor, RTRS).
2. The coordinates are transferred to the machine components with a tachoemeter.

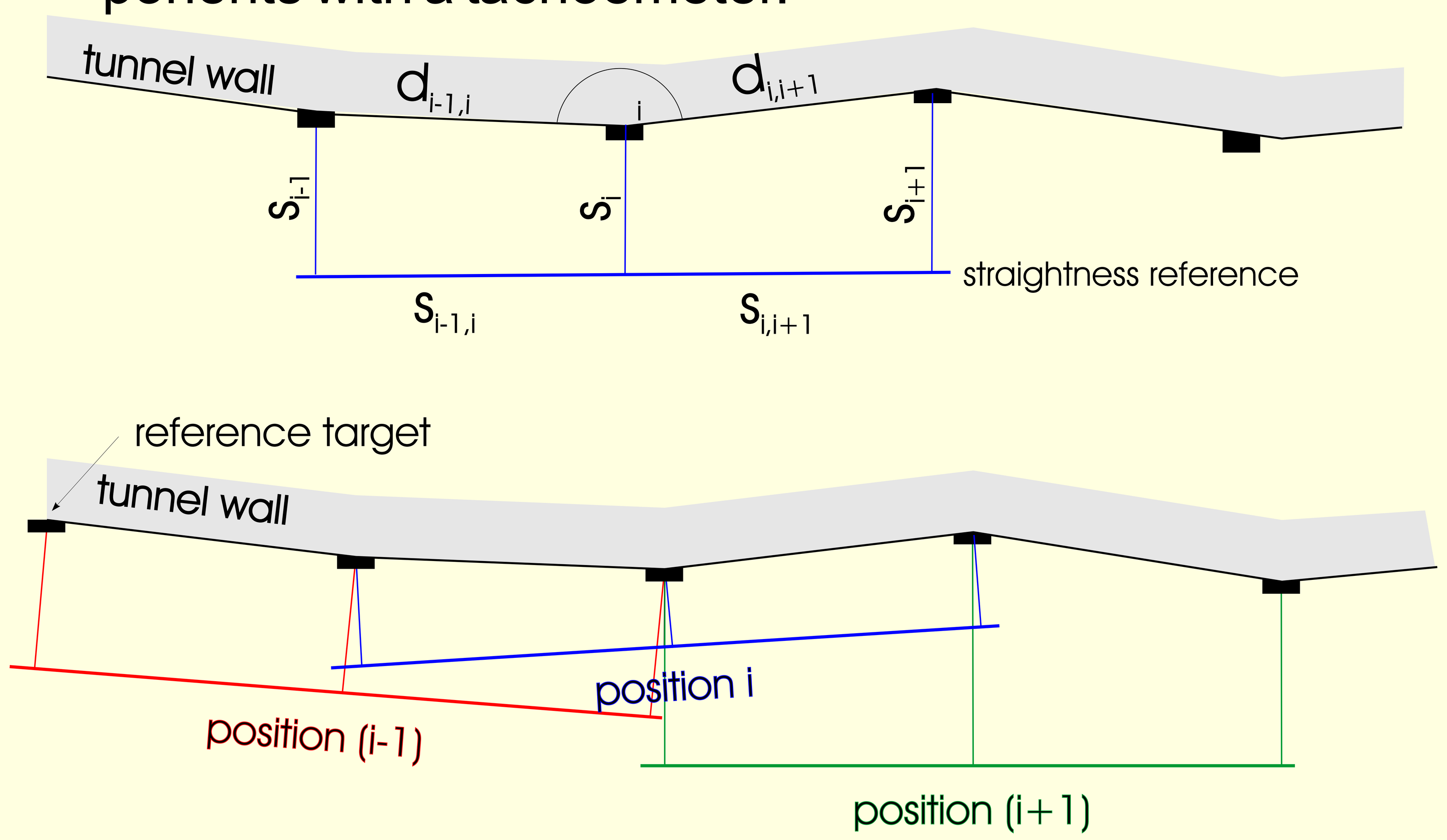

figure 3: concept of geodetic survey (reference network only, simplified 2D)

Concept

With the technique of **multipoint alignment** the effects of refraction can be eliminated or reduced if a mechanical structure or a laser beam in vacuum is used as straightness reference. Multipoint alignment in this context means that the lateral distances s_{i-1}, s_i and s_{i+1} (fig. 3) between the straightness reference and several reference points are measured. Together with the distances $s_{i-1,i}$ and $s_{i,i+1}$ the angle and the distances d can be calculated (here simplified to 2D). With and d for all positions i a traverse is used to estimate the coordinates.

Rapid Tunnel Reference Surveyor, RTRS

A train with six measurement cars (blue) will overdetermine the multipoint-alignment problem and provide enough redundancy to get sufficient accuracy and reliability for the reference measurement. For electronics and drives additional service cars (grey) are needed. The RTRS train acts autonomously and runs through the tunnel without user interaction.

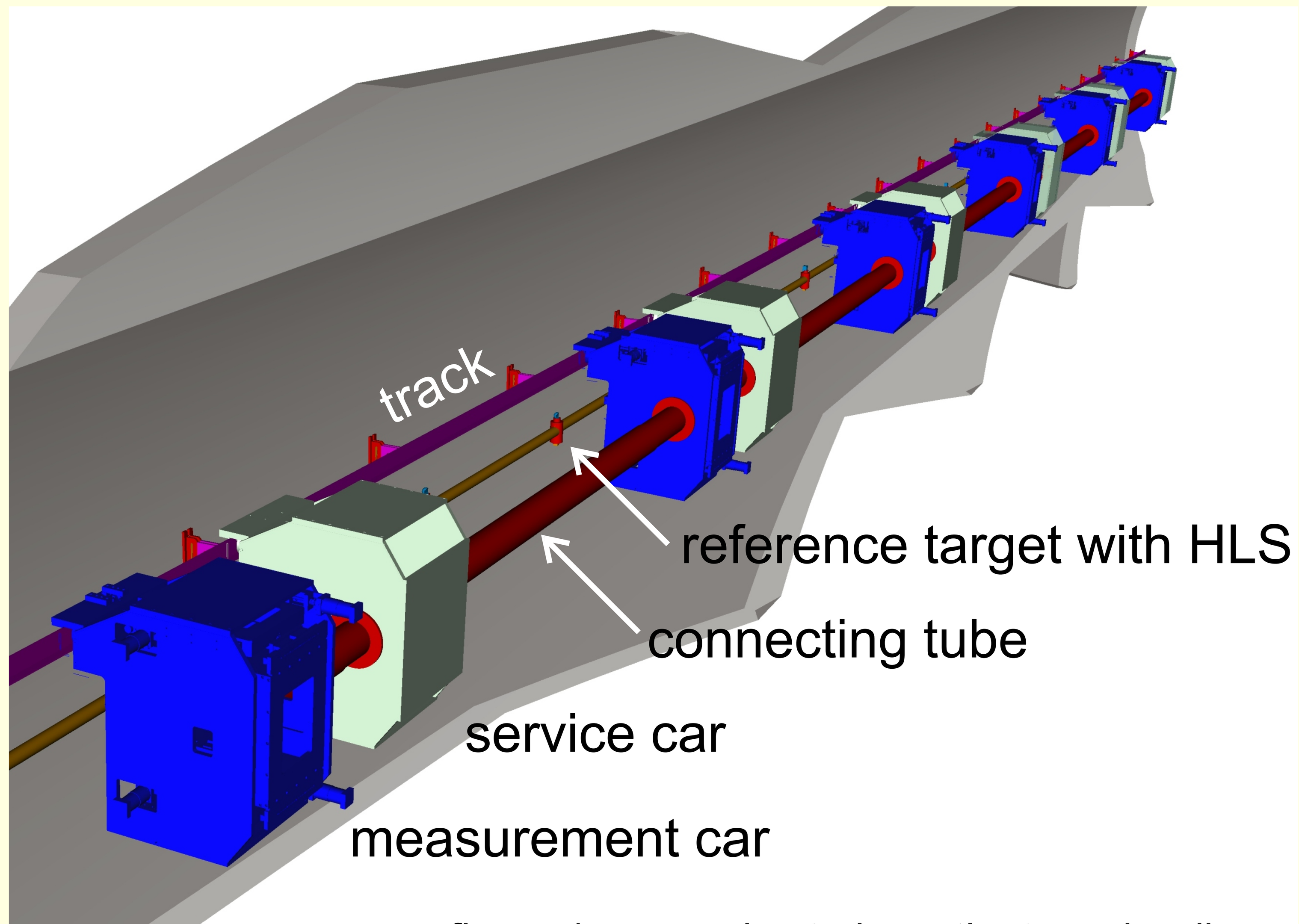

figure 4: measuring train on the tunnel wall

Setting out the Beamlines

A tachoemeter on a movable car is estimating its position doing a free-station survey. Afterwards the beam line components can be adjusted from this free station.

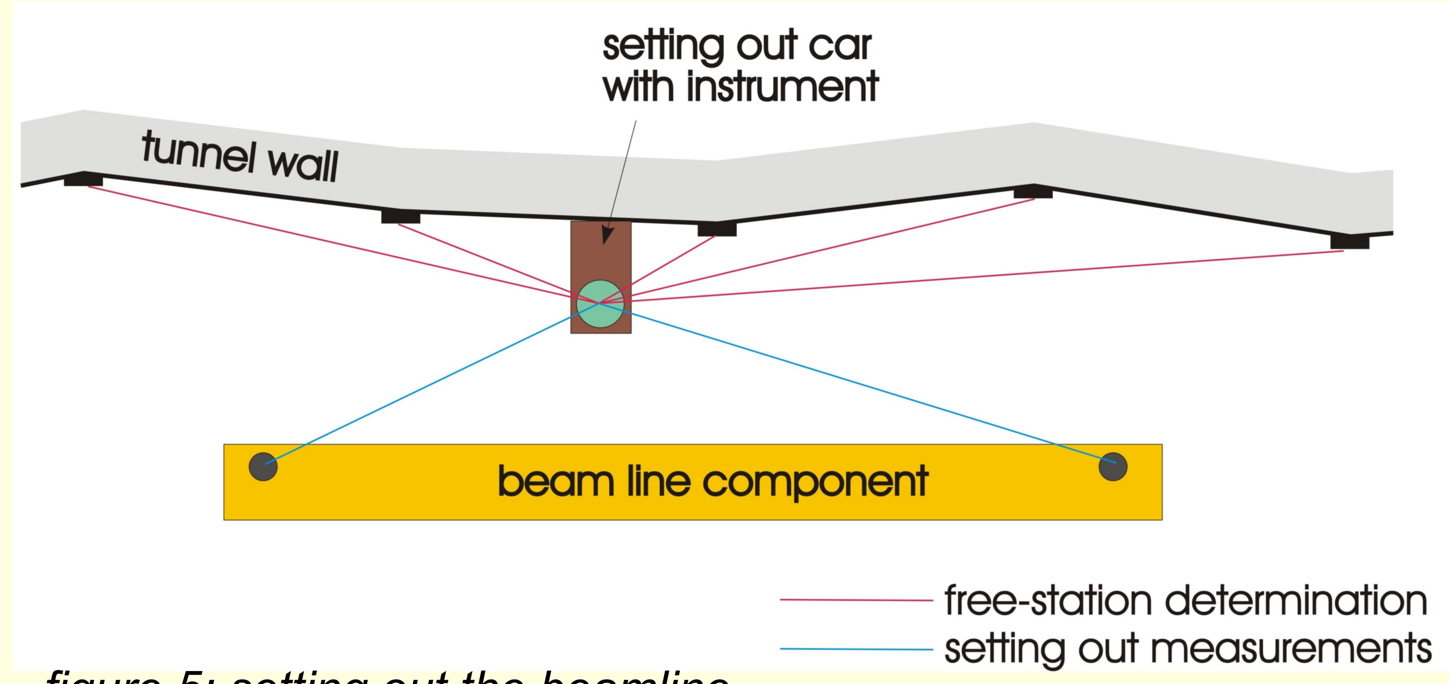

figure 5: setting out the beamline

Curvature of the Earth

If the accelerator follows the curvature of the earth, height measurements can be done differently from the other two dimensions - a Hydrostatic Levelling System (HLS) is used for the height determination in this case.

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THE GELIS-TRAIN - AN APPROACH TO A RAPID TUNNEL REFERENCE SURVEYOR

HORIZONTAL PLANE DETERMINATION

A stretched wire is used as straightness reference in the GeLiS-Train. This wire runs through the whole train in a closed tube to prevent influences from external forces. It is fixed in the front and rear of the train only and thus gives a straight line between the first and the last car, when projected onto the horizontal plane.
In every single car the distance between the reference target (A) and the wire (C) is measured with two optical 3D-sensors (B, D) and two incremental length gauges (E , F). The cameras (H) are used for rough positioning. (G) is the measuring vessel of the HLS.

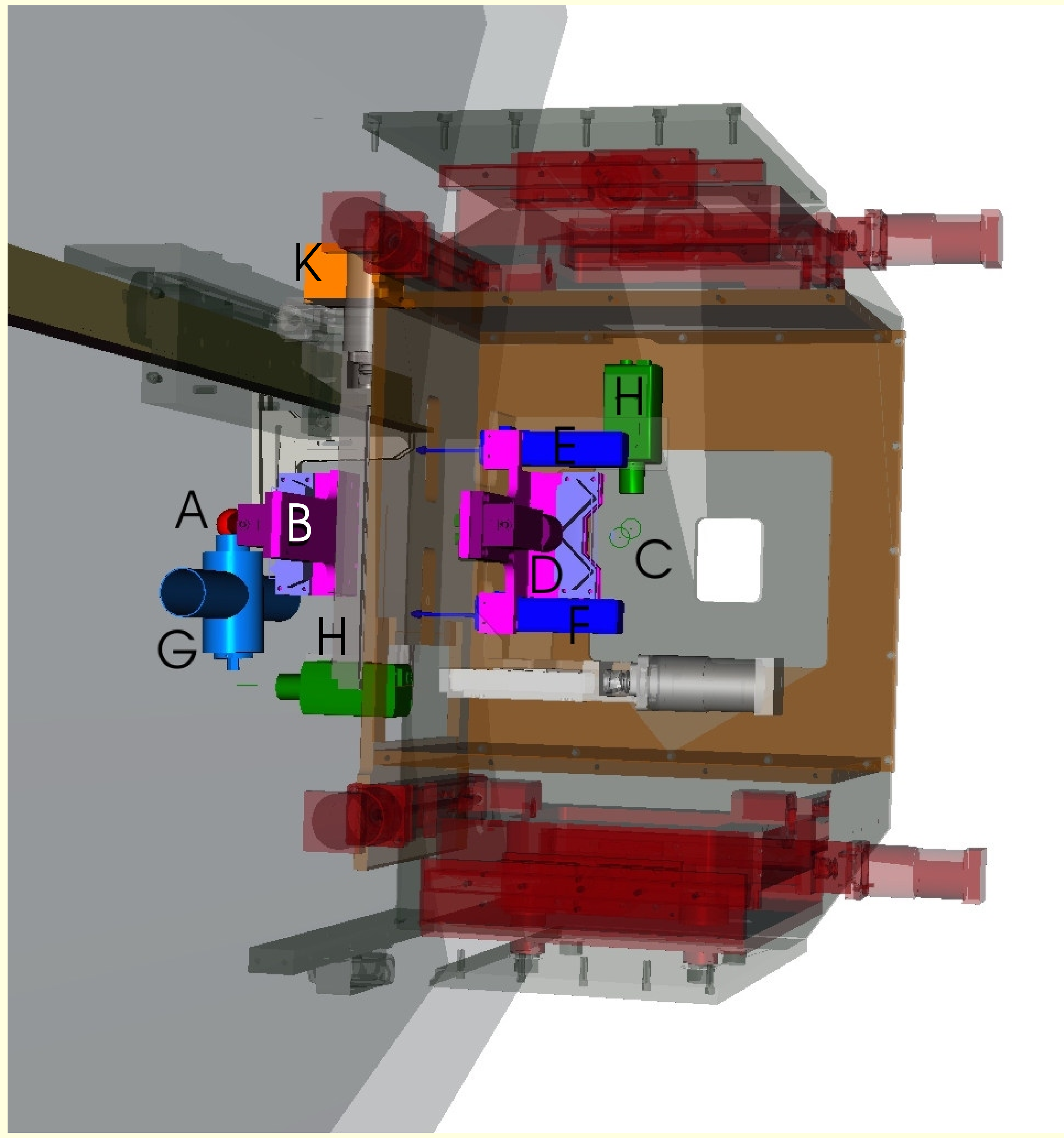

figure 6: a GeLiS car in the tunnel

Because the measuring range of the 3D-Sensor is only a few millimeters the sensors have to be placed on movable stages so that they can compensate for the tunnel tolerance of several centimeters. Furthermore the tilt of the inner block is measured by a biaxial tilt sensor (K) and adjusted to zero with the stages.

The distance between the reference target and the stretched wire is measured with an accuracy of better than 3µm.

OPTICAL 3D-SENSOR

For the contactless distance determination an optical sensor consisting of a digital camera and a split-image prism is used.

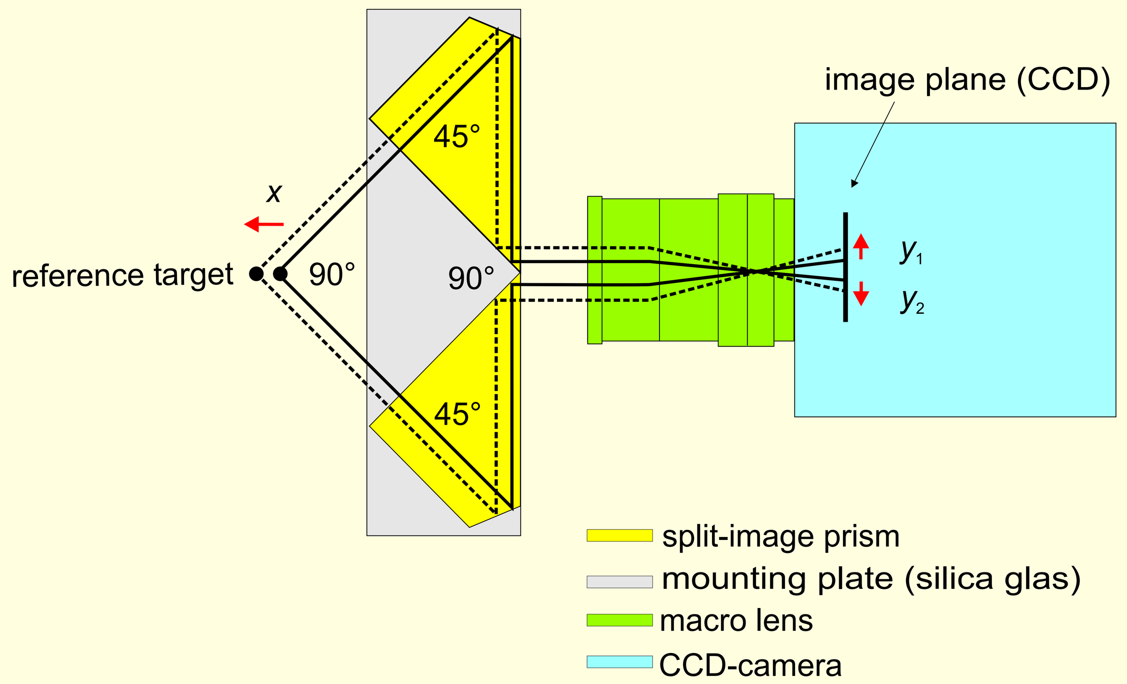

figure 7: optical 3D-sensor

The main advantage compared to a two-camera solution is that there is no special stability requirement for the relative positions of the cameras. There is only a stability requirement for the prism itself, which is much easier to achieve.

VERTICAL MEASUREMENT

Since the accelerator may follow the curvature of the earth and a wire has limitations as a height reference due to its sag, a drift-free hydrostatic levelling system (HLS) was developed. To eliminate the effect of temperature differences a system with a free surface is used. The surface is sampled with an ultrasonic system, the distances R_1, R_2 and OF are measured simultaneously. Combined with the calibrated distances D_1 and D_2 a calibrated measurement of H_P is possible.

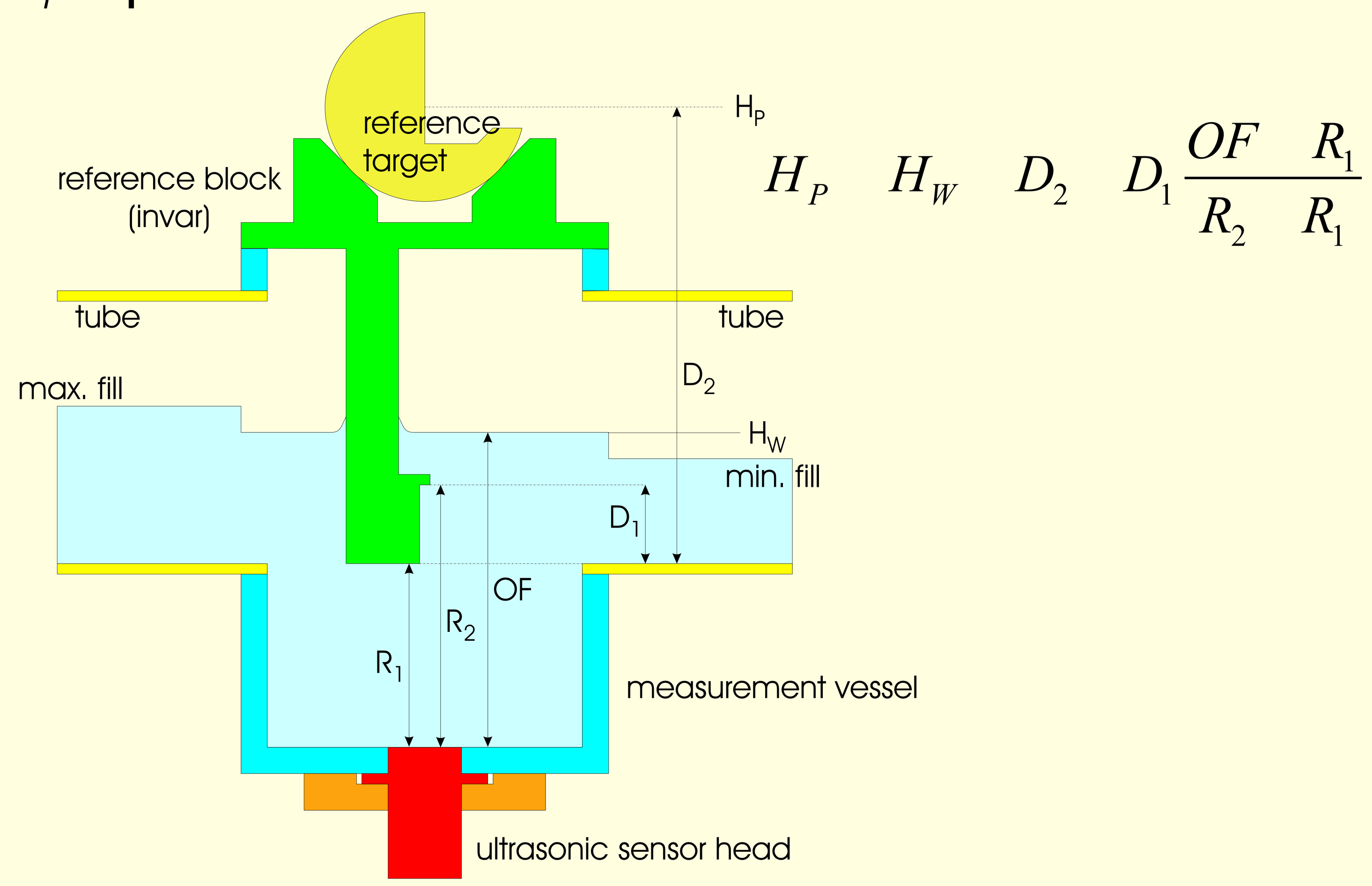

figure 8: ultrasonic measurement system

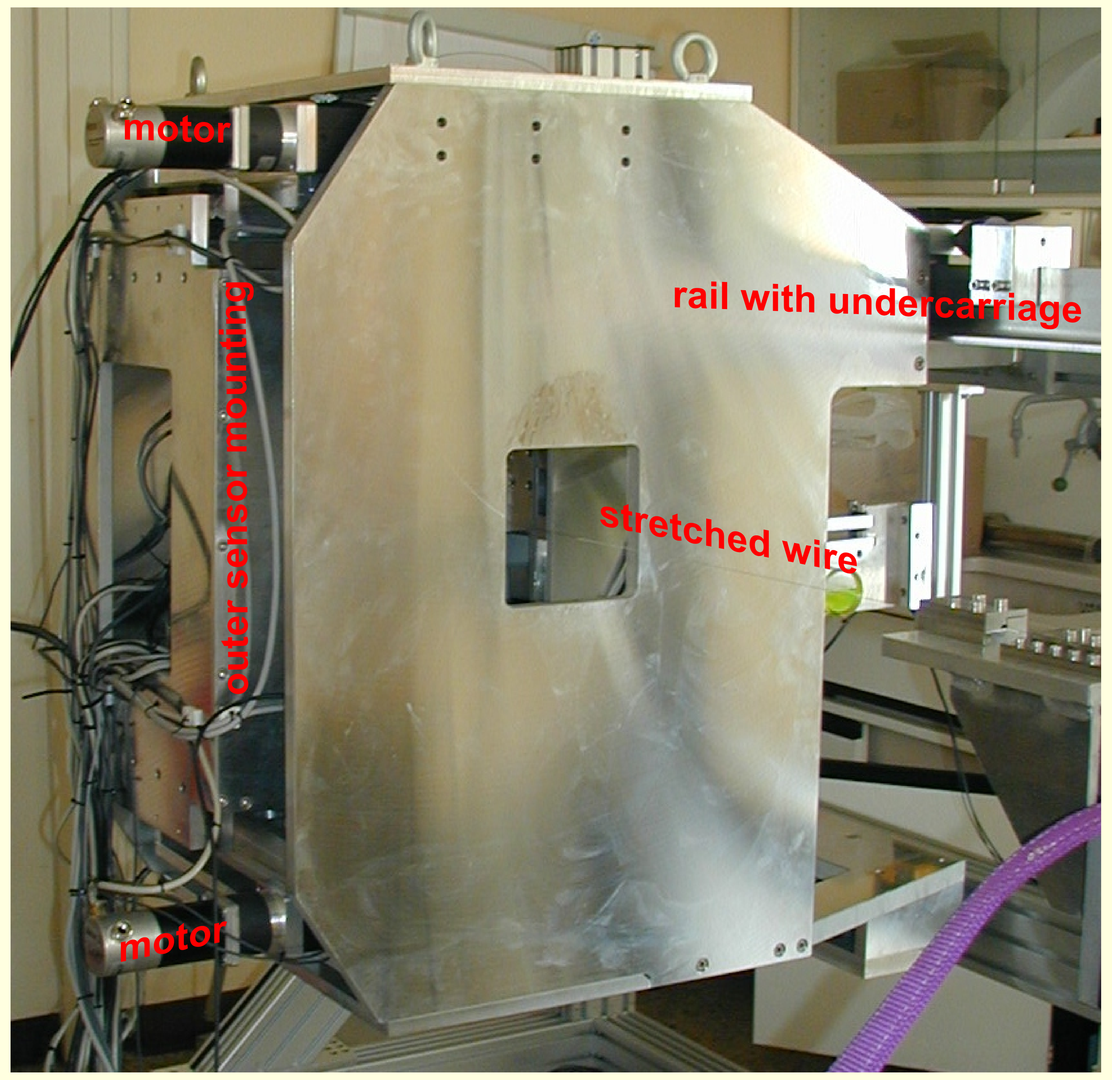

figure 9: Prototype, view towards the tunnel wall

GELIS PROTOTYPE

To date a one car GeLiS prototype has been built. Tests of functionality and repeatability are in progress. Software is being developed and improved.
At the same time we work on improvements of the mechanical structure and the electronics, mainly on shrinking the data processing units, is progressing.
The continuation of the GeLiS version of the RTRS project is doubtful due to serious cuts in its budget.

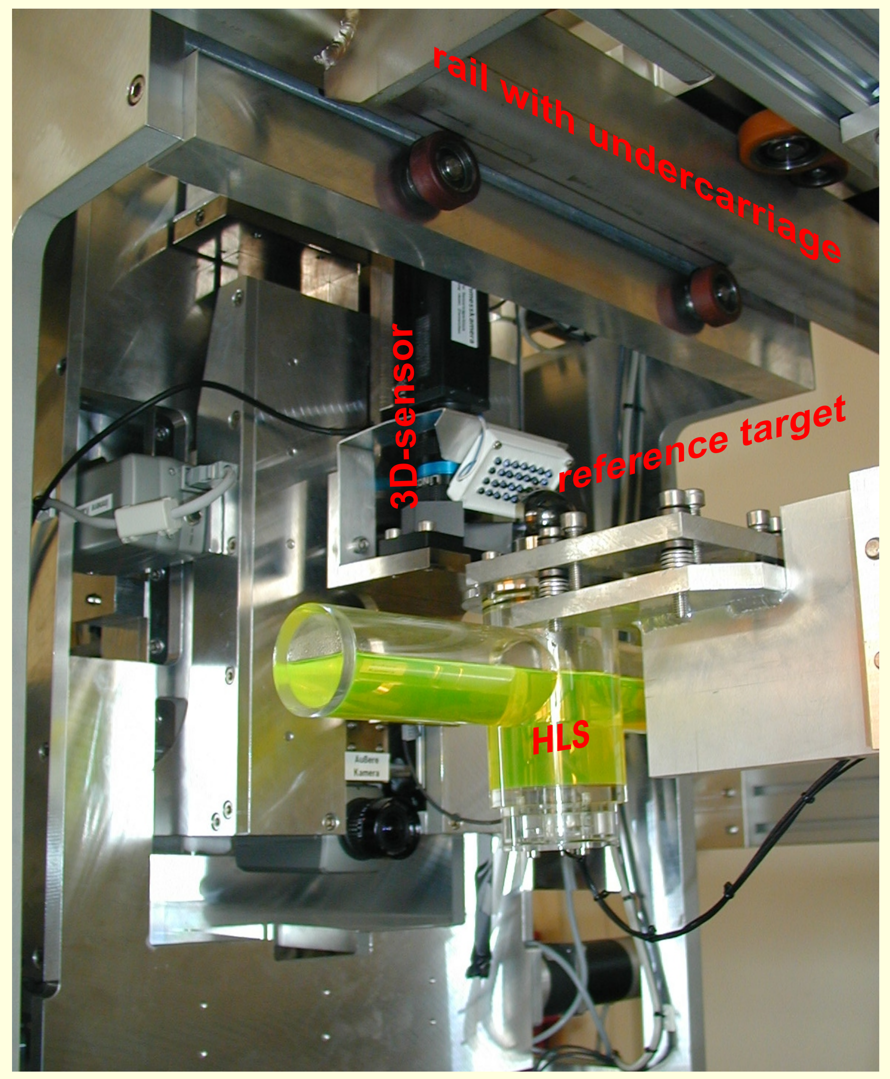

figure 10: view from the tunnel wall

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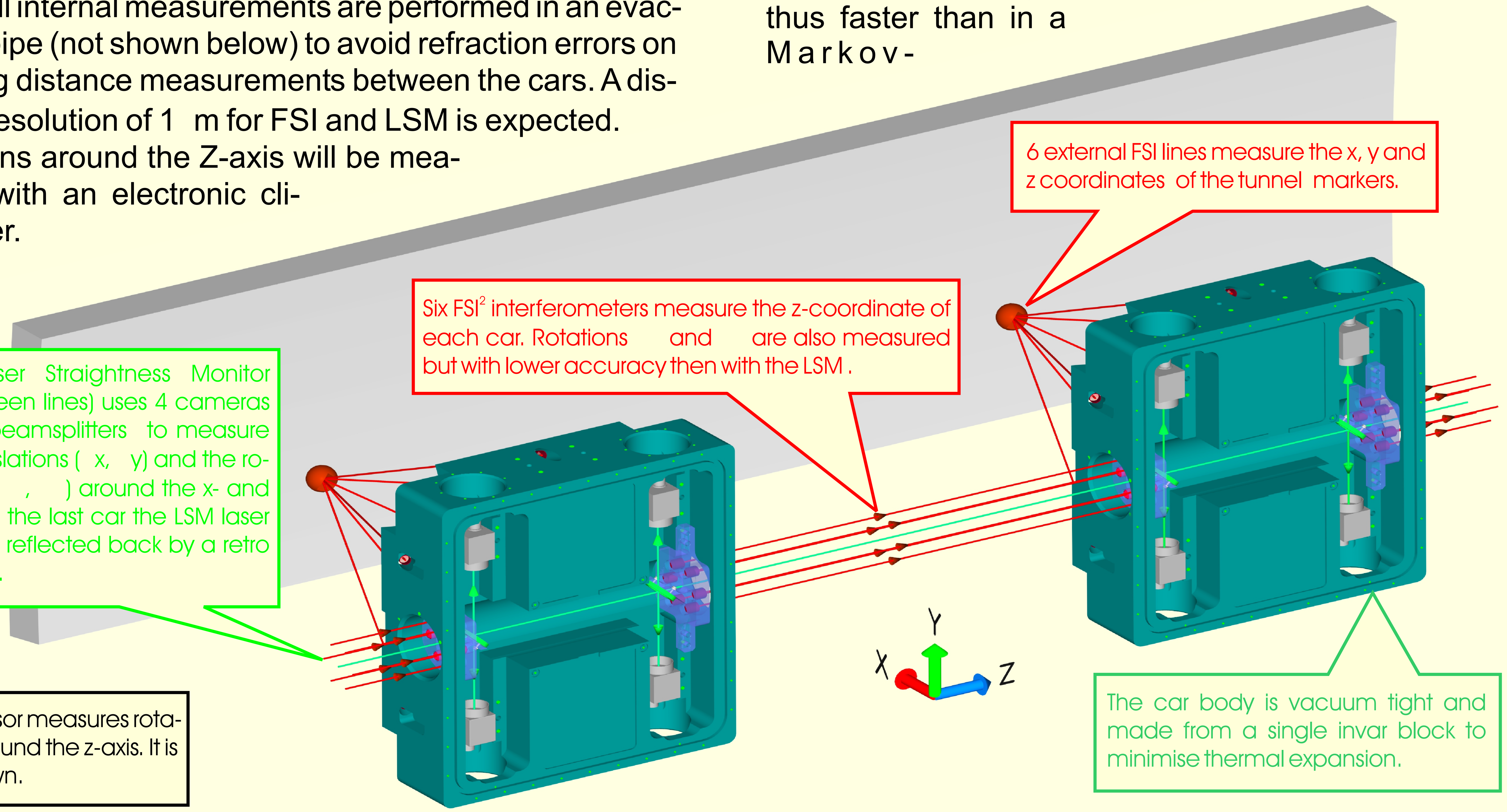
LiCAS-RTRS Survey System for Ultra High Accuracy Tunnel Networks

Measurement Principle of the LiCAS-RTRS[0]

Each LiCAS car is capable of measuring its own 6 DOF as well as the 3 coordinates of the corresponding tunnel marker. The Laser Straightness Monitor (LSM[1]) uses two pairs of cameras to measure the transverse offsets (x, y) and the rotations around the X- and Y-axis with respect to the incoming and returning laser beam. The distance between cars is measured with 6 FSI[2]-interferometers. The position of the tunnel marker is measured in an over determined way by 6 short external FSI lines. All internal measurements are performed in an evacuated pipe (not shown below) to avoid refraction errors on the long distance measurements between the cars. A distance resolution of 1 m for FSI and LSM is expected. Rotations around the Z-axis will be measured with an electronic clinometer.

Simulation of the measurement process

Measurement errors are initially determined with the optogeometric simulation program SIMULGEO[3]. Results for a single train stop are shown in Figure 11. Due to the huge computational effort this is only practical up to 15 train stops (80m). Longer distances are simulated with a random walk model. The parameters of the model[4] are determined with a fit to the SIMULGEO results (Fig. 12). The errors of the tunnel marker positions after n steps can be computed analytically (see right). The errors grow asymptotically with $n^{3/2}$ and thus faster than in a Markov-process. This is due to the angular correlations between steps. Figure 13 shows random-walk Monte-Carlo Simulations over 600m and the average residuals against a straight line fit from many random walks. The deviation remains below 100 m over 600m and thus stays well withing the required tolerances for the TESLA collider. It should be noted that these simulations have been intensively used to optimise the LiCAS design.



$$\sigma_n = \sqrt{l^2\sigma_\alpha^2\frac{n(n+1)(2n+1)}{6} + \sigma_x^2 n}$$

n: number of tunnel marker
l: Distance between cars of the RTRS
: modelparameter for the angular error around x-axis
x: modelparameter for translation error along x-axis
n: error of n. tunnel marker along x-axis
The formula for errors in y is completely analogous

fig 11: SIMULGEO error propagation for a single RTRS

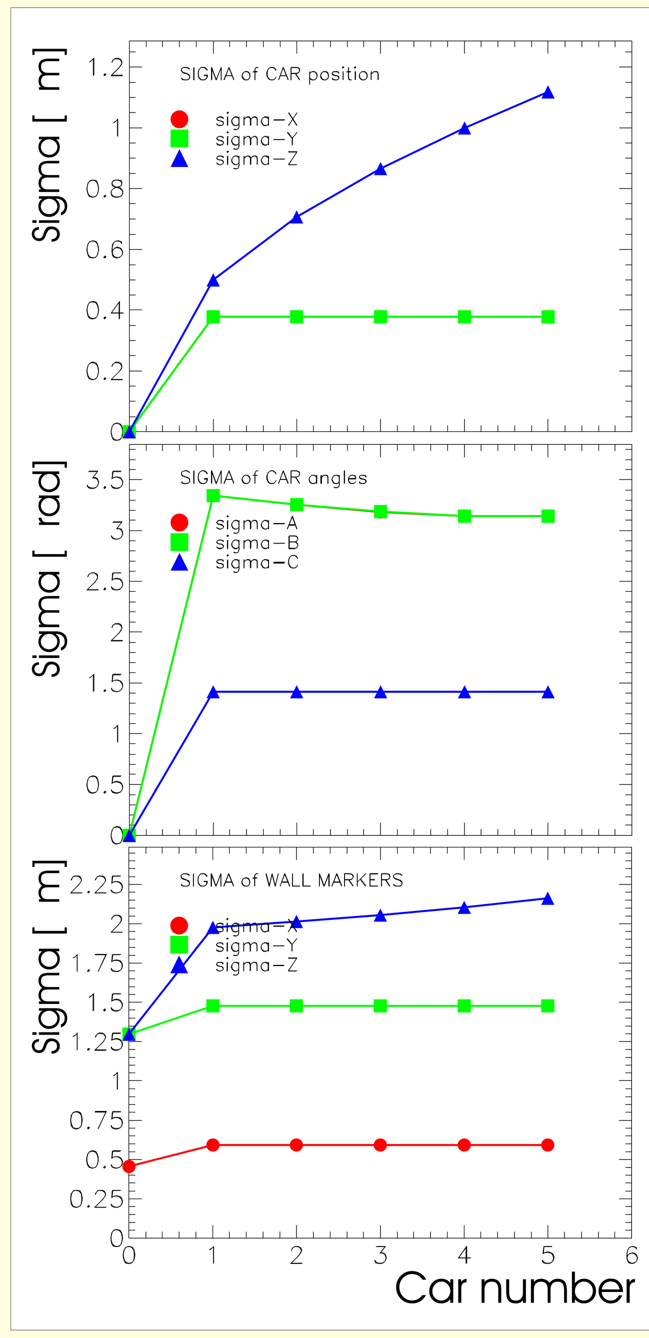
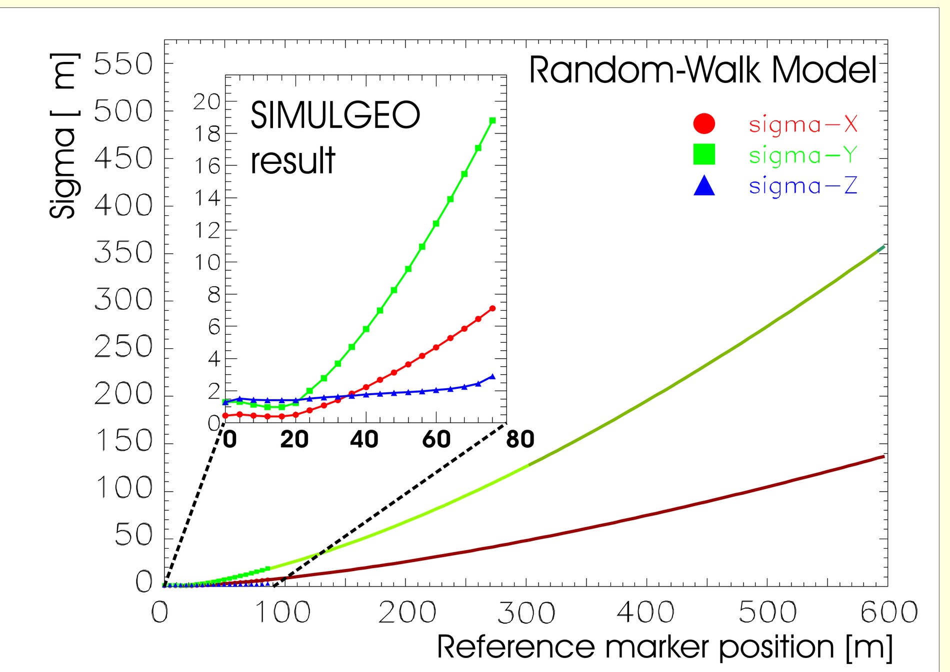


fig 12: SIMULGEO error propagation for 15 stops with a fit of the random walk model and its extrapolation over 600m.



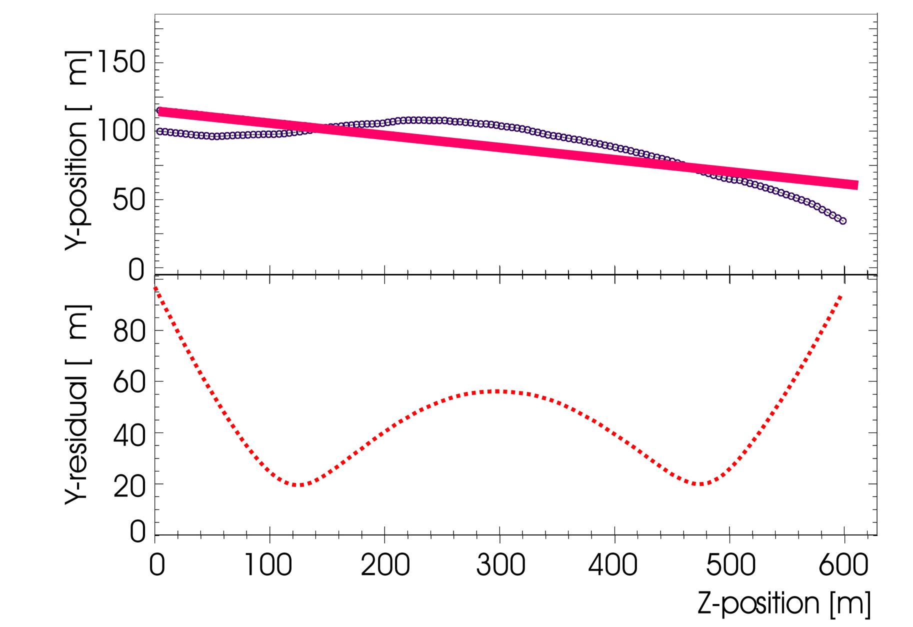


fig 13: Upper: A single random walk trajectory. Lower: Mean residua between random walk model and straight line.

(0) RTRS = Rapid Tunnel Reference Surveyor
(1) LSM = Laser Straightness Monitor
(2) FSI = Frequency Scanning Interferometry (details see next poster)
(3) SIMULGEO: *Simulation and reconstruction software for optogeometrical Systems*, L.Brunel, CERN,CMS note 1998/079.
(4) two transverse offset-errors and two angle-errors.

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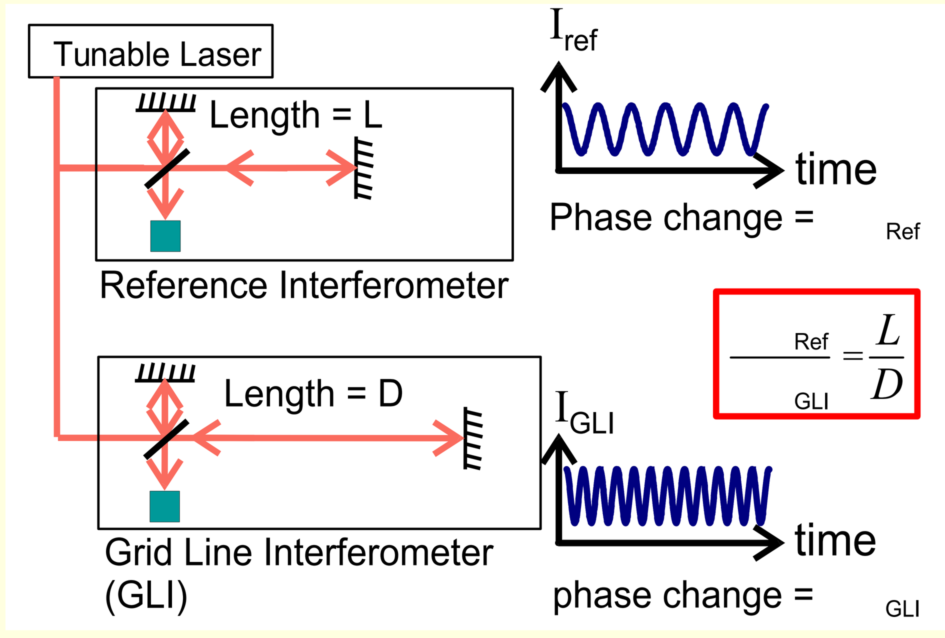
LiCAS-RTRS Survey System for Ultra High Accuracy Tunnel Networks

Measurement Principle of the LiCAS-RTRS

FSI Technique

FSI is an absolute distance measurement technique. Two interferometers are exposed to laser light of variable wavelength. The pathlength difference of the unknown interferometer is determined by comparing the phase advance seen at its output to that seen in an interferometer of known path lengths. To compensate interferometer length-drift errors, two lasers are used simultaneously, tuning in opposite directions. Both are amplitude modulated at different frequencies and demodulated into separate readout channels.



Principle of an FSI distance measurement

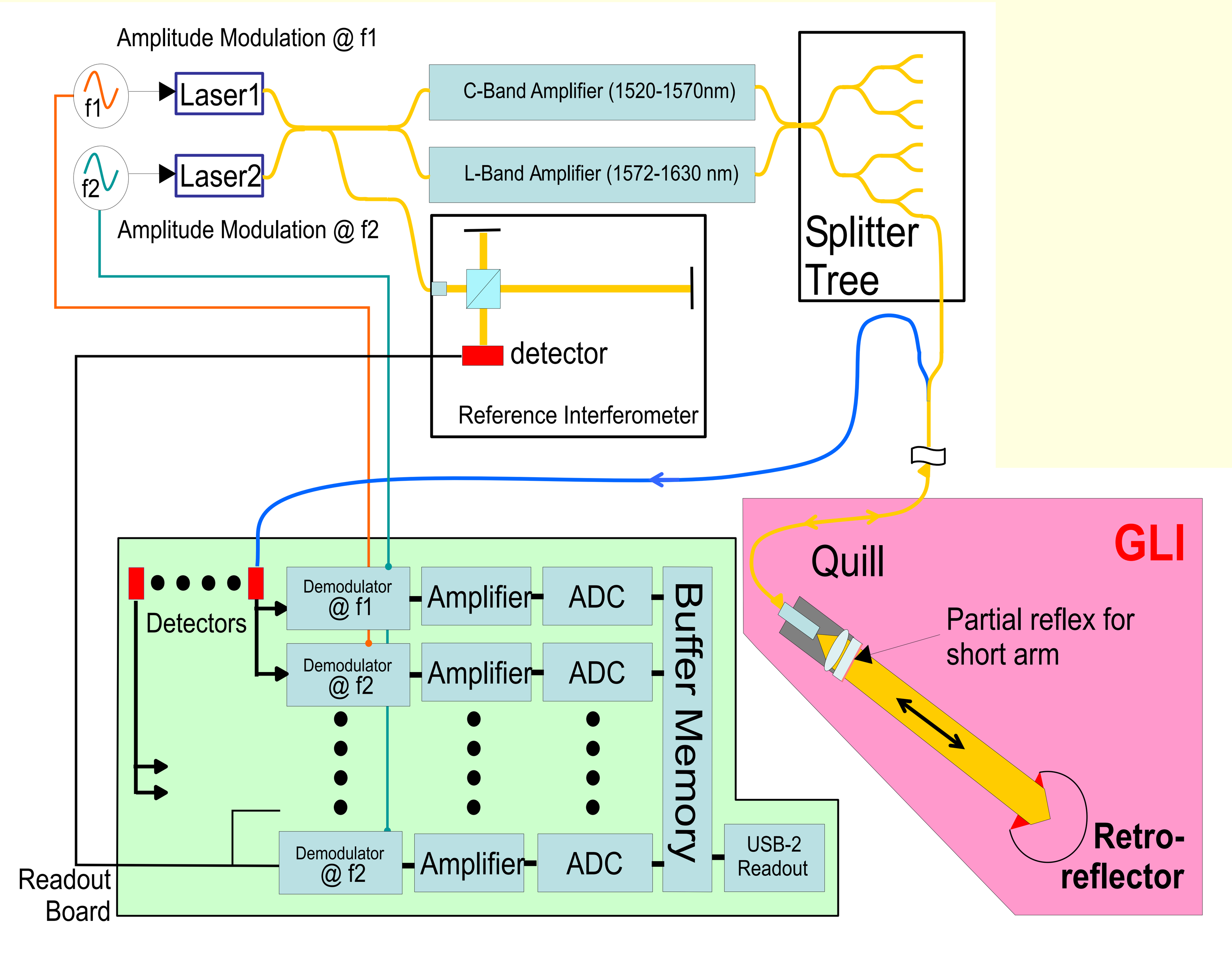


fig. 1: FSI system with two amplitude modulated lasers for drift error compensation. The Erbium doped fibre amplifiers and splitters needed for multiple interferometers are also shown

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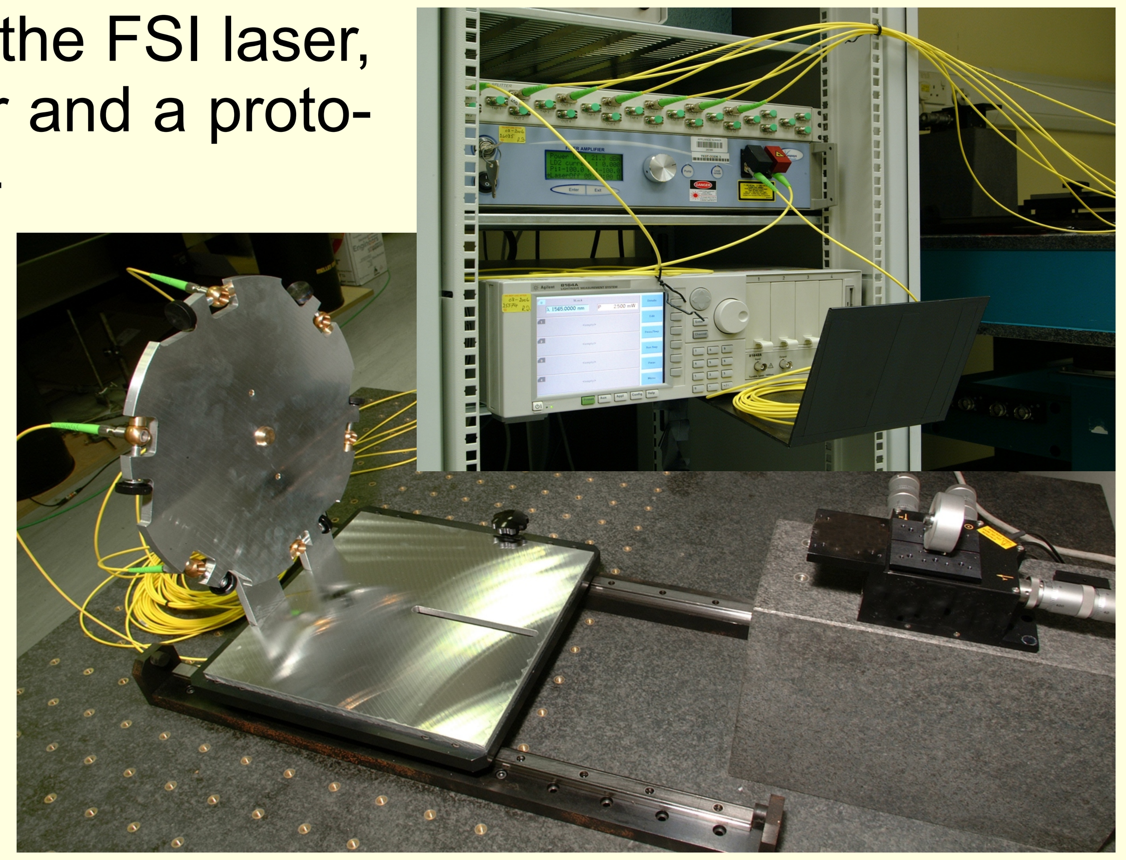
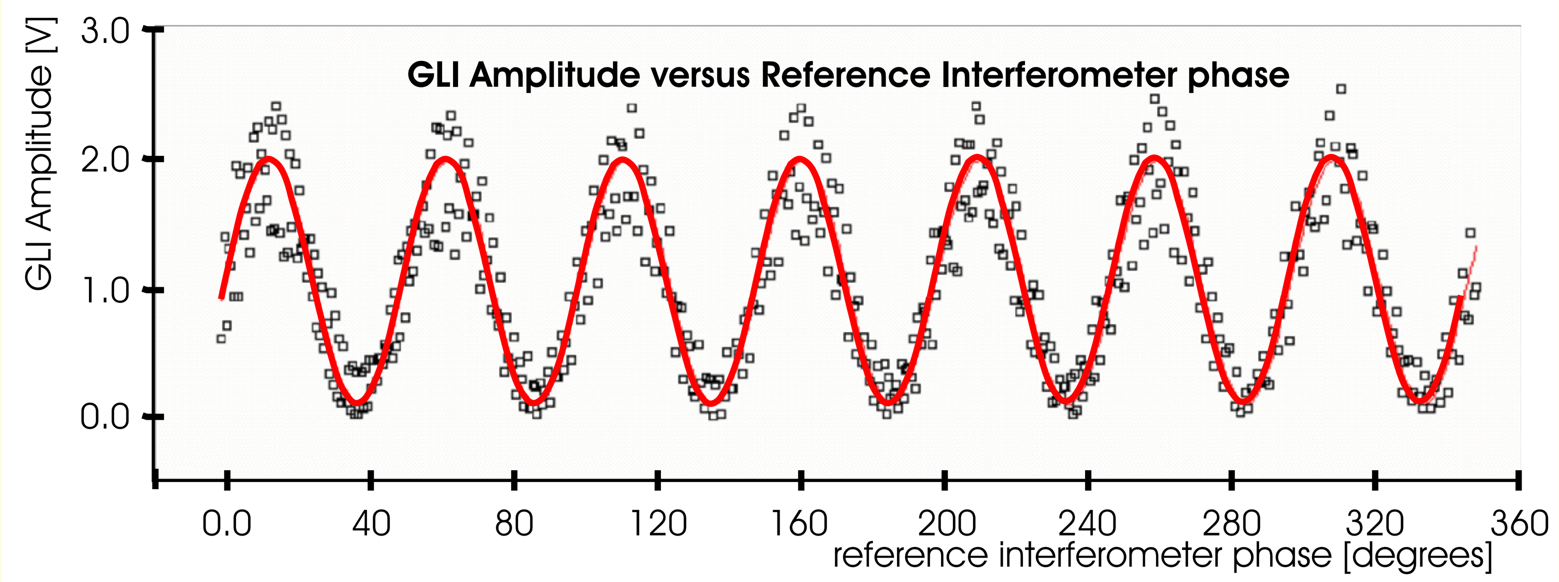
FSI Implementation

Photographs of the FSI laser, amplifier, splitter and a prototype of the external 6-line FSI network in a calibration set-up. The target of the six lines is mounted on precise motorised motion stages.



FSI Analysis

To extract length from a time series of GLI and reference intensities, a Carré algorithm is used to determine the reference phase as a function of time. The GLI and reference amplitudes are plotted against this phase and sinusoids are fitted to them. The ratio of the periods of these sinusoids measures the ratio of the interferometer lengths.



Laser Straightness Monitor (LSM)

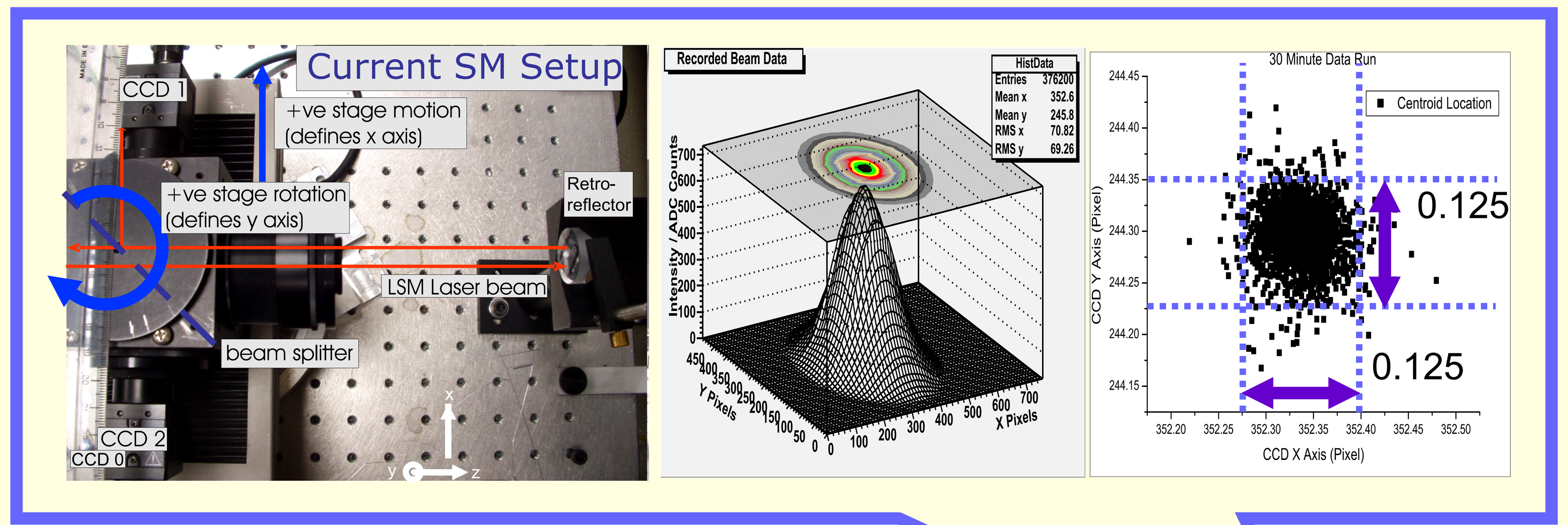
Purpose

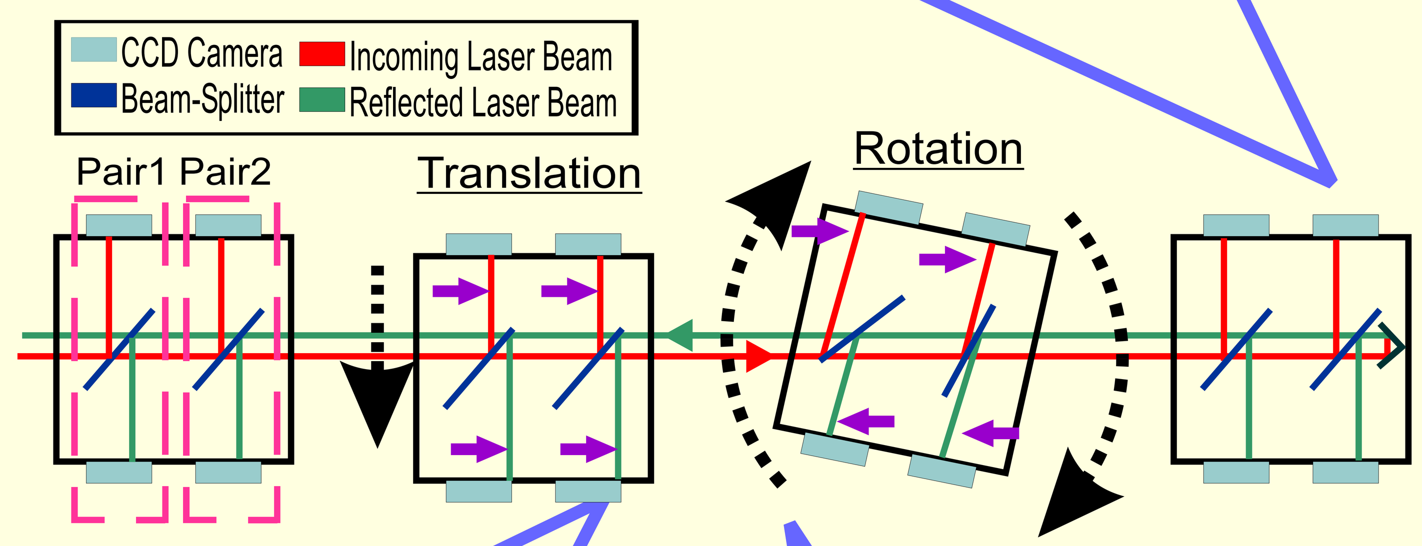
- Measure car transverse translation and rotation
- Must have 1 m precision over length of train

Operating Principle

The Laser Straightness Monitor (LSM) measures the displacment and orientation of each car from an ideal straight line. A laser beam provides the reference straight line which passes through each car and is reflected back by a corner cube retro reflector in the last car, returning antiparallel to the incoming beam but with an unknown transverse offset.

Each car has a pair of parallel beam splitters which intercept the beam. The reflected beams are recorded by 4 CCD cameras which gives 8 measurements. These are used to determine each car's vertical and horizontal displacements and rotations about the x and y axis. Together, the LSMs of all cars also measure the unknown retro reflector walk.





Low Coherence length diode lasers are used to avoid unwanted interference