

HIGH PRECISION SURVEY AND ALIGNMENT OF LARGE LINEAR COLLIDERS - HORIZONTAL ALIGNMENT -

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1. INTRODUCTION

Future linear colliders of 1 TeV energy – like TESLA at DESY – require new techniques of precise alignment. The demanded accuracy for the horizontal alignment of the accelerator components is 0.5 mm on a 600 m section [4], which can not be achieved with common geodetic measurement methods. Therefore, a new measurement concept, based on straightness measurement with stretched wire and precise distance measurement, had to be developed. A wide variety of sensors such as cameras, incremental length gauges and tiltmeters, are used in the realization. For effectiveness the whole measuring system is built as a train which can act semiautonomous. Concepts of the measuring train and first results of the various sensors of the train will be presented.

2. CONDITIONS

A very high accuracy is demanded for the alignment of all accelerator components to run the linear collider successfully. The standard deviation of every component is postulated to be

0.5 mm transversally and
0.2 mm vertically

off the beam axis over a range of 600 m [4]. This tough requirement has to be looked at in the context of common surveying methods and the conditions given by the tunnel layout.

* The development of this geodetic survey solution for new large linear accelerators takes place as an international collaboration of the Stanford Linear Accelerator Center (SLAC), CA, United States of America, the Bauhaus-Universität Weimar, Germany, the Technische Universität Dresden, Germany, in charge of the Applied Geodesy Group at the German Electron-Synchrotron, Hamburg, Germany.

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2.1 Tunnel and Accelerator

The tunnel is designed with a diameter of 5.3 meters, following a geometrically straight line on the ground plane and the curvature of the earth in most parts. In the start section and close to the collision experiment variations of this design are favored, e.g. a geometric straight line also in the height. Tunnel access approximately every five kilometers means that the surveying service has to please the high demands with only few connections to the earth surface [4].

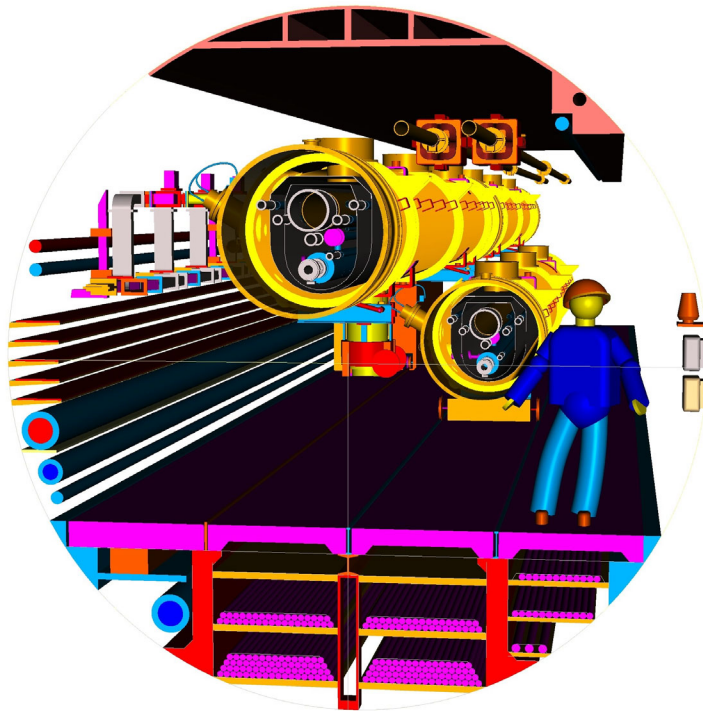


figure 1: tunnel layout

As shown in figure 1, in the current design the components are mounted to the top of the tunnel and several beam lines are installed parallel on different floors. In contrast to today's accelerators with normally two beam lines this means a higher effort for the geodetic survey.

Limited space in the tunnel and also only one tunnel side available for permanent installations like reference targets or hydrostatic leveling system is a problem for tunnel surveys.

2.2 Surveying Services

The main problem when working with optical instruments, e.g. tachometer, is the refraction of air. Already a minimum of temperature variance leads to density variations of the air and causes a high degree of deformation of the optical beam. Measurements through air with a constant temperature gradient of only 0.1 K/m, acting perpendicular to the wave propagation in the line of sight, would cause a displacement of 4.5 mm between the instrument and target in case the line of sight is 600 m long [3].

2.3 Consequences

To avoid a falsification of the measurements on account of refraction and to deal with the conditions in the tunnel as described above, a new measuring technique for the new generation of linear accelerators has to be developed. The following concept shows a possible solution in theoretical contemplation, tests results of sensors and the overall project.

3. GEODETIC SOLUTIONS

On the base of a permanent installed reference network in the tunnel, every component of the new accelerator can be determined with its coordinates by free stationing. In this paragraph the concept and the realization of the determination of a reference network shall be presented as well as the alignment of the accelerator.

3.1 Reference network

The refraction of air as main interference makes it necessary to determine the reference network by high-precision, non-optical distance measurements, such as a multi-point-alignment. To give an impression about the general function of this type of survey, a 3-point-alignment as minimum configuration shall serve as an example.

3.1.1. Concept: 3-point-alignment

Assuming a bar of steel as a fix and moveable structure, it can serve as basic structure reference for an alignment. Perpendicular distance measurements can be made from the bar to get distances to targets nearby. These targets are mounted in equidistances to the tunnel wall, but will not be adjusted prior to the measurement. By measuring the distances s_{i-1} , s_i , s_{i+1} from the bases on the bar to the opposite targets and the distances $s_{i-1,i}$, $s_{i,i+1}$ between the base points, the angle β_i can be calculated as well as the distances $d_{i-1,i}$, $d_{i,i+1}$ between the targets. These are the common elements of a traverse: distances and directions.

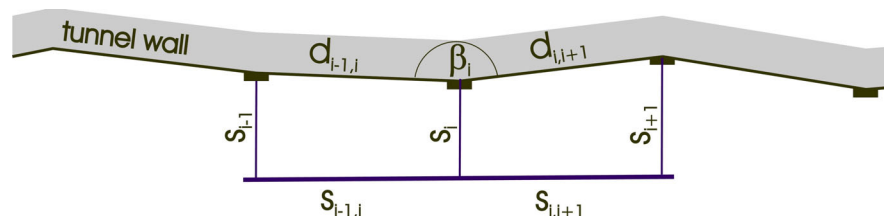


figure 2: single measuring position

By taking measurements in the intervals of the targets to the adjoining three targets on the wall for every target the angle and distances can be calculated. This means a virtual station on the target with two measured distances and one angle.

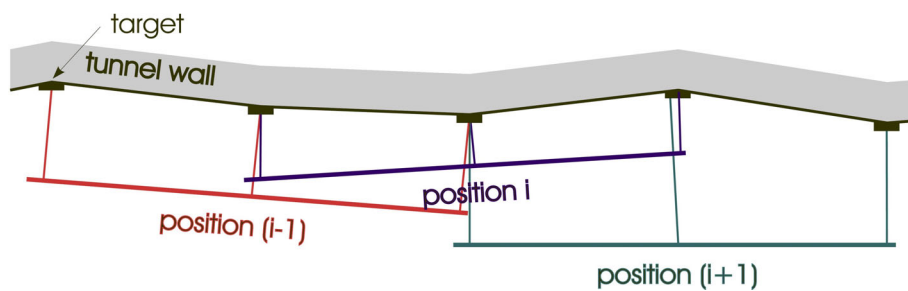


figure 3: measurement positions

This concept is sufficient for a test base and short distances between the targets. Tests show a general agreement compared with theoretical contemplations and with a laser interferometer on a test base of 25 m in length [2].

3.1.2 Realization: Multi-point-alignment

In comparison of mechanical design, economical aspects and the required accuracy, a interval of points of approximately 4.5 m is going to be established. Because of this distance it is no longer possible to use a bar as a reference. Therefore the straightness reference is replaced by a stretched wire, which means that not only the target on the tunnel wall has to be measured contact free but also the wire.

To gain redundancy, to lower the accuracy demand of a single measurement and to have several options in choosing the distances between two reference points not only three targets per measurement will serve information. A higher number of six targets will satisfy these demands. Especially skipping targets, e.g. measuring every second reference point, is possible for faster, but less accurate surveys.

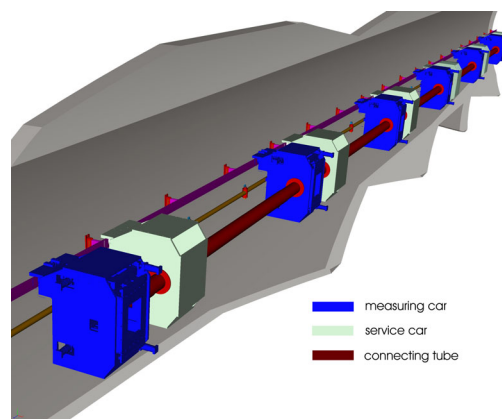


figure 4: position of the train at targets

The preparation of a measurement and the collecting of data is split up into the following steps: First the train runs to the next target position at the tunnel wall, stops in front of it and fixes itself to the track and tunnel to take a stable position during measurements. Afterwards rotations for every car will take place that will level every single car. Approaching the target with an outer block of sensors and carrying out the same action with an inner block of sensors in regard to the wire, a standby position of the train will be reached. Starting all sensor measurements at one moment create the survey data. After a check and storage in a data base the train can move to the next target position.

Measuring the wire and six targets at the same time results in a construction complying to the number of targets with six measuring cars of about 25 m in length. It seems clear that a construction with these dimensions should be moved automatically and in regard to the huge

number of points in the tunnel it should be possible to work semi-autonomous. The solution is a train consisting of different components, running on a track at the tunnel wall.

For taking the measurements to the target on the tunnel wall and to the wire, a measuring car equipped with all sensor technology is designed. There are cameras for the recognition of the target and the wire as well as incremental length gauges and tiltmeters.

The data and all passive measuring equipment is placed on a separate service car adjacent to each measuring car. These cars have moreover a computer and the drive for the train. The computers are linked by local computer network.

At the ends of the train wire stretching modules will be installed to get the stress for the wire. All components will be linked by connecting tubes that finally form the train.

During the measuring operations in the tunnel data acquisition, storage and plausibility checks are done. Post-processing, e.g. geodetic network adjustment, will be done in the office.

3.1.2.1 Measuring car

The first measuring car – regarded in driving direction – comes to a stop in front of the target on the tunnel wall. Due to equidistances between the targets all cars will stop in the nearly right position. To cause the exact placement in front of the target a car consists of several cages. They also act to level the car.

As the track is mounted on the tunnel wall it can not be absolutely straight because tunnel movements after the installation cause a deformation of the track. For that reason the cars are displaced and a correction is necessary to level them. Linear guides on each side of the cage can either make a shift in the same direction, which means an adjustment in the position. Or they can run against one another which means a rotation of the car.

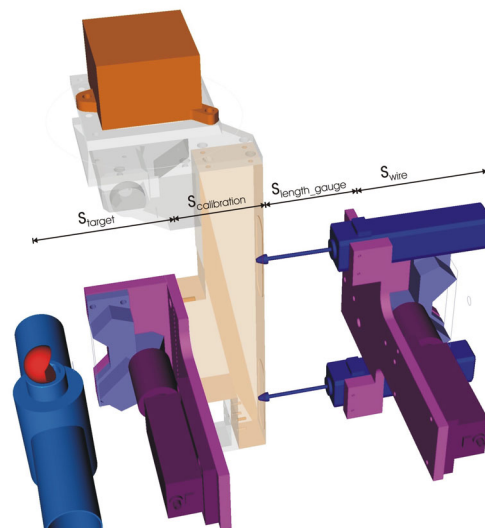


figure 5: measuring of horizontal distance

These rotations are possible along the axes of the tilt sensor which means the two perpendicular axes in horizontal. A rotation around the vertical axis is not important, because the disorientation of a car will be determined by a camera and the numerical correction will be calculated.

After this first step the drives shift two blocks with sensors. The outer block with a camera and a specially designed prism system as well as a high precision tilt sensors working in two axes moves to the target. The inner block moves to the wire also equipped with the same camera-prism-system and has additionally two incremental length gauges.

As figure 2 shows the distance s_i between the target mounted on the tunnel wall and the wire as straightness reference is composed of four distances: s_{wire} , $s_{\text{length_gauge}}$, $s_{\text{calibration}}$ and s_{target} (figure 5). The possible rotation of the inner block can be detected by the incremental length gauges.

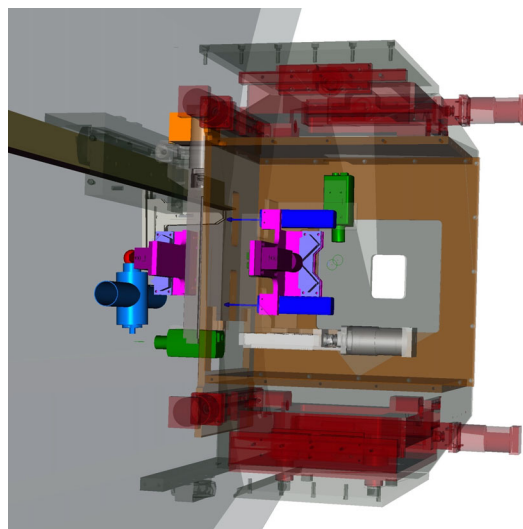


figure 6: measuring car

A 3-dimensional model of the car in figure 6 shows the cages to compensate the degrees of freedom. Shifts in tunnel axis and to the tunnel wall as well as rotations in these axes are possible. The outer block with sensors can move to the target in horizontal and vertical position. The same movements can be carried out by the inner block with sensors.

3.1.2.2 Sensors

For the necessary measurements four sensor types are in use: CCD cameras without an additional prism block, CCD camera with an additional prism block, incremental length gauges and inclination sensors.

3-DIMENSIONAL POSITIONING SENSOR

Using a high-resolution CCD camera with a two prism block and macro lens (see figure 7) produces a photogrammetric stereo model with two virtual camera positions on the CCD chip. The virtual optical axes are arranged in an angle of 90 degrees.

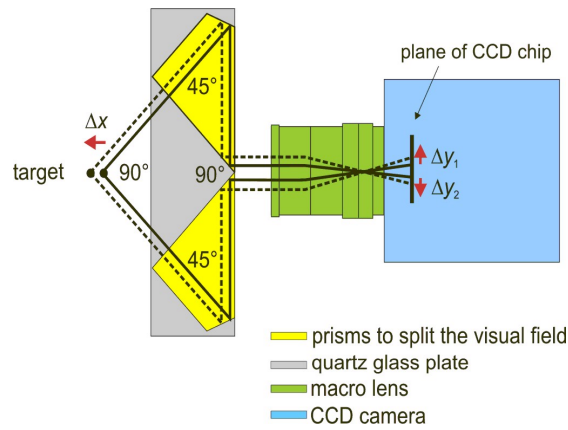


figure 7: 3-dimensional positioning sensor

Changes in the distance Δx to the target are detected by the change of the pixel coordinates y_i on the CCD chip. The difference $\Delta y = \Delta y_2 - \Delta y_1$ as well as the magnification β of the lens lead to the following equation:

$$\Delta x = \frac{1}{\beta \cdot \sqrt{2}} \cdot \Delta y \quad (3.1)$$



figure 8: camera with prism block

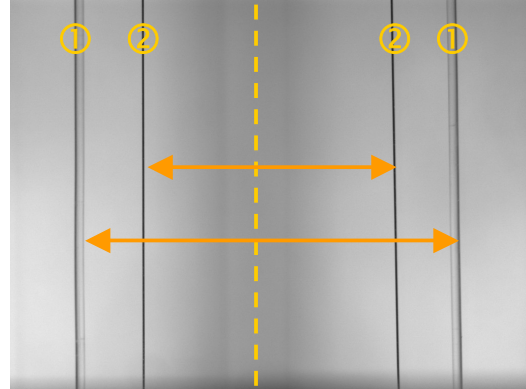


figure 9: stereo model of two wires

The combination of prisms and camera leads to a split image on the CCD chip of the camera, where the object of interest is shown in both split images. Changes in the distance to the object always cause a shift on both split images.

The survey photograph in figure 9 shows two wires. They can be seen on the left split image as well as on the right split image. The arrow lines show which wires belong together. On the basis of the measuring concept the result of the figure is that the two wires are not in the same distance to the camera [1].

INCLINATION SENSOR

The inclination sensor in every car is used to minimize the tilt of the two sensor blocks in interaction with the drives. Little deviation of the horizontal plane will be measured and corrections will be calculated.

The Schaevitz LSO-1° inclination sensor will be used in the prototype of the car. Tests of long term stability, drifts and shock resistance show that due to the mode of operation this inclinometer is a faster and more reliable way to get results compared to the Leica Geosystems' Nivel20.

As vibrations occur as the train runs along the track. The sensors in the car are exposed to these disturbances. After a vibration influence of e.g. one minute the Schaevitz and Leica inclinometer have a very unequal performance until a stable measurement can be taken again.

In contrast to a short time of about 20 seconds to stabilize the LSO-1° inclinometer, the Nivel20 takes about 100 minutes to settle down completely. The long settling time is caused by the viscous fluid used in the inclinometer.

INCREMENTAL LENGTH GAUGES

The horizontal installation position of the length gauges – as shown in figure 5 – leads to the application of motorized length gauges. These come into action after both sensor blocks are fixed in their measuring position.

CAR ROTATION DETECTION

For the detection of a possible non-parallel position to the wire, a camera measures the rotation of the wire in relation to the sensor blocks.

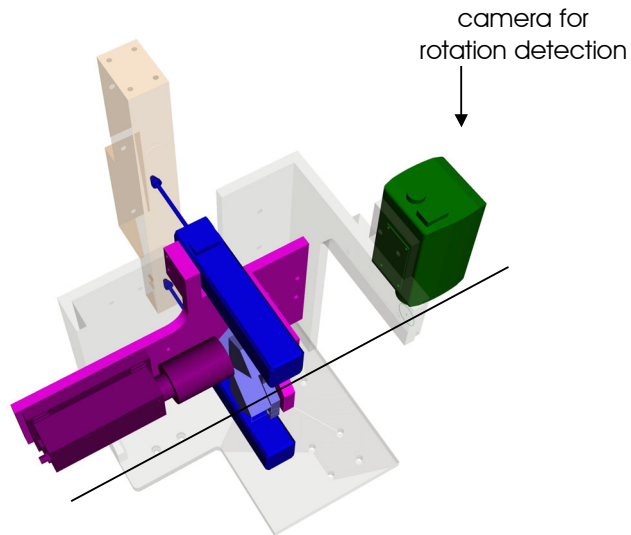


figure 12: car rotation detection

The green camera in figure 12 has a wide perspective to measure a picture of the wire. By calculating the parameters a and b of the linear equation (3.2) the rotation of the car in respect to the wire can be determined.

$$y = a \cdot x + b \quad (3.2)$$

3.2 Accelerator alignment

For the setting out of the accelerator and its components a separate, constructive different car will be used. It runs on the same track as the train and can be fixed along the track without any restrictions to the position.

By using a sufficient number of neighbouring reference points on the tunnel wall a free station can be calculated for the surveying instrument on the car. An industrial total station as well as a laser tracker are suitable for the transfer of 3-dimensional coordinates to the components. The coordinates are the result of the 2-dimensional adjustment of the multi-point-alignment and the hydrostatic leveling systems 1-dimensional height. A high degree of automation can be achieved by using these instruments with an automatic target recognition.

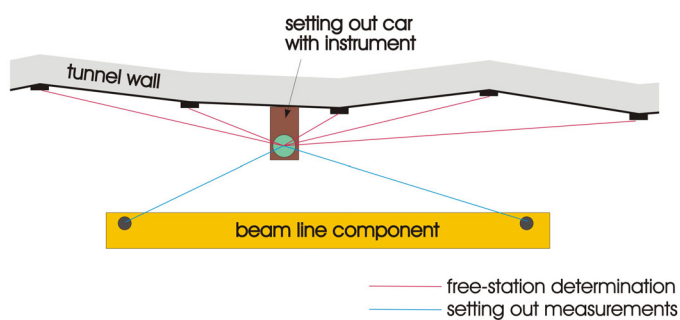


figure 13: setting out concept for beamlines

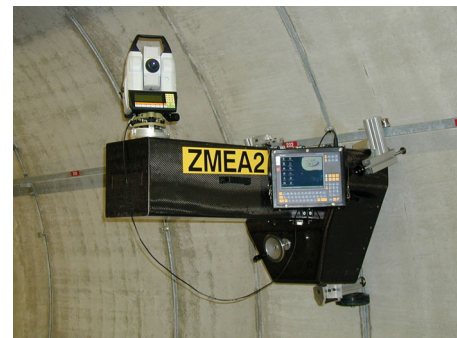


figure 14: prototype of setting out car

4. CONCLUSION

As far as theoretical contemplations and sensor tests show, the concept of a multi-point survey train is a possible solution for the alignment of a future linear collider with accelerator lines of several kilometers in length.

Sensor tests have lead to a selection that will be used in a first prototype. Due to this knowledge the mechanical construction of a set of three cars is in progress and will be finished in 2003. Tests of sensor interaction and a specific software engineering can take place when the prototype is running on its test base at the DESY facility. The configuration will show the practicability in a test environment of about 80 m in length, where influences that might occur in the tunnel can be imitated.

With the integration of the new developed free surface hydrostatic leveling system [5], 3-dimensional coordinates can be created as a reference network and a test adjustment of components can take place.

5. REFERENCES

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