THE LINEAR COLLIDER ALIGNMENT AND SURVEY (LiCAS) PROJECT

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Abstract

For the next generation of Linear Colliders (LC) the precision alignment of accelerator components will be critical. The DESY applied geodesy group has developed the concept of an automated "survey train". The train runs along the accelerator wall measuring the 3D position of a set of equispaced reference markers. This reference structure is then used to align the accelerator components.

The LiCAS group is developing a measurement system for the survey train. It will use a combination of Laser Straightness Monitors (SM) and Frequency Scanning Interferometry (FSI). FSI is an interferometric length measurement technique originally developed for the online alignment of the ATLAS Inner Detector. This novel combination of optical techniques is expected to overcome the limitations of traditional open air survey.

The authors describe the LiCAS project, the measurement systems and their integration into the survey train. The technical parameters and constraints will be mentioned. There will also be brief discussion of the second phase of the project to allow on-line monitoring of the LC alignment.

1 INTRODUCTION

Particle physicists are demanding higher performance particle accelerators to deliver high energy, high luminosity beams. This allows one to make precision studies of the mechanisms of electroweak symmetry breaking as well as possible new phenomena beyond the standard model of particle physics.

In order to deliver the high energy, high luminosity beam one requires a long Linear Collider with nanometre sized beams at the interaction point (IP). The planned TESLA collider will deliver a centre-of-mass energy of 0.5 TeV with transverse beam sizes $\mathcal{O}$(nm) at the IP [1]. In order to maintain the luminosity, TESLA requires alignment tolerances of the order of 200 μm over 600 m. This cannot be achieved by conventional techniques of open-air survey as the resolution is limited by air temperature gradients which refract light. The collider will also drift out of alignment due to “ground motion”. Therefore one requires a high precision, automated instrument which can survey the accelerator quickly.

One technique which is currently being pursued is the combination of a stretched wire [2] and hydrostatic levelling system (HLS) [3]. Although this approach can achieve the desired measurement accuracy it has some limitations. The stretched wire cannot be used over curved sections of the accelerator. The HLS can only measure the local geoid instead of geometrically straight sections. TESLA has both curved and straight sections.

1.1 The LiCAS Project Overview

The Linear Collider Alignment and Survey (LiCAS) group aims to provide an optical metrology system for the survey and alignment of a LC. It uses a combination of Frequency Scanning Interferometry (FSI) and Laser Straightness Monitors (SM) inside a vacuum. Both techniques have their origin in particle physics detector alignment and have been developed at the University of Oxford. FSI is an interferometric length measurement system which was originally developed for the online alignment of the ATLAS Inner Detector [4] [5] [6]. The SM is used in the alignment system of the Zeus MicroVertex Detector [7].

The combination of FSI and SM is a novel technique to accelerator alignment which complements the strengths of the two systems. FSI has 1 micron longitudinal sensitivity but weak transverse sensitivity. The SM has 1 micron transverse sensitivity but weak longitudinal sensitivity.

The goals of the project are split into two phases:

Phase I The measurement system is attached to a self-propelled “survey train” which runs along a rail attached to the accelerator wall. The 3D position of an array of reference wall markers will be measured to establish a frame of reference along the tunnel. In the “co-ordinate transfer”, the collider component’s position will be measured with respect to the reference wall markers.

Phase II This is a permanent installation of an optical network to provide real-time alignment information of the collider.

2 PHASE I: THE LiCAS SURVEY TRAIN

The LiCAS survey train is being developed in collaboration with the DESY metrology group. They have developed the concept of a survey train to run along the accelerator tunnel wall and measure the position of a line of reference markers. The DESY metrology group are developing the macro-mechanics, infrastructure and propulsion system for the train [8].

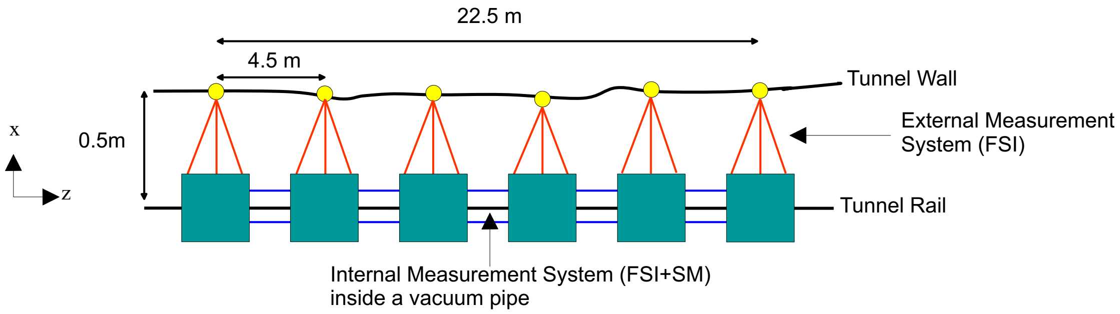

Figure 1: The LiCAS survey train: The survey train is parked in front of the reference markers. The internal system measures the train's internal position while external system measures the 3D position of the reference markers.

2.1 The Survey Train

The tunnel wall of the LC is tiled with a line of reference markers placed 4.5 m apart. The survey train is used to measure the 3D position of these reference markers. The accelerator component positions can be then be measured with respect to these reference markers.

Figure 1 illustrates the survey train of six cars parked in front of a group of reference markers. The train has two measurement systems. An internal system of FSI and SM lines which are kept in a vacuum to remove the effects of air refraction. This allows the train to monitor its internal position. The second system is a set of external open air FSI lines which measure the 3D position of the reference markers. As the lengths of the external FSI lines are short, the thermal gradients should be small. Thus the effects of air refraction for these short lengths are minimal. Figure 2 is a conceptual drawing of the survey train. It shows the four internal FSI and SM lines inside a flexible vacuum pipe. The external FSI lines are also drawn with 6 lines per car to each reference marker.

The measurement procedure involves parking the train in front of the reference markers. The train measures its internal position using the internal FSI and SM lines. It then measures the reference markers using the external FSI lines. The train proceeds to move one marker position and the procedure is repeated. Each time one new reference marker is measured; the remainder are re-measured by a different car of the train. Thus every reference marker is measured six times; once per car. This results in a set of measurements which tie each small tunnel section into the global tunnel measurement. This is illustrated in figure 3.

2.2 Laser Straightness Monitors (SM)

The Laser Straightness Monitors (SM) allow the LiCAS survey train to measure inter-car transverse displacements and rotations. The technology has been used in the alignment

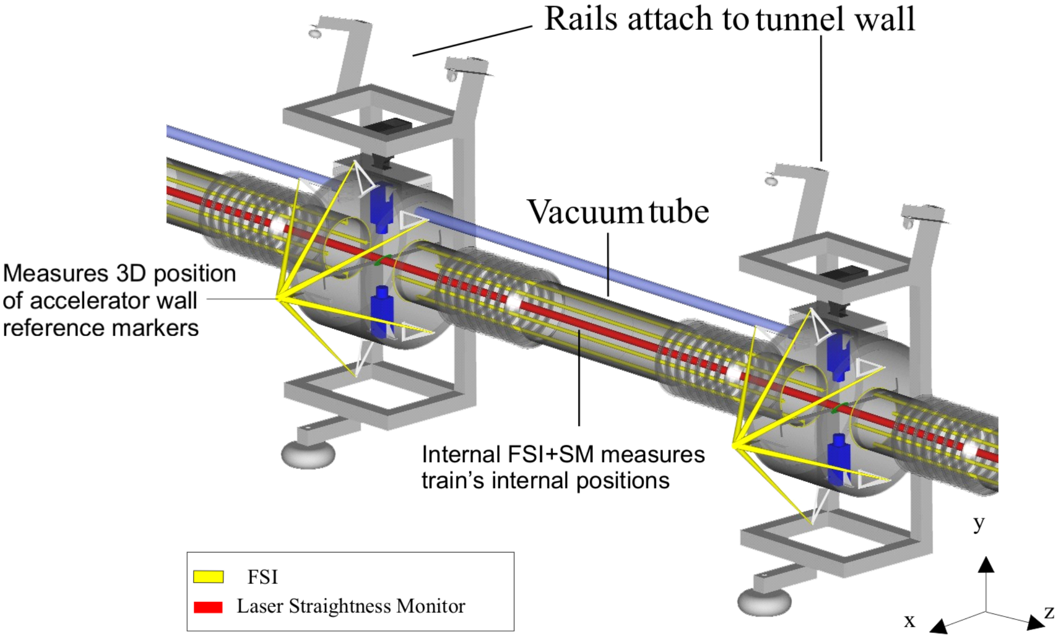

Figure 2: Conceptual drawing of the survey train. It shows the internal SM (red) and FSI (yellow) lines inside a flexible vacuum tube. The external FSI lines are shown with each reference marker measured by six lines; one per degree of freedom. The distance between the cars has been shortened in this picture for clarity

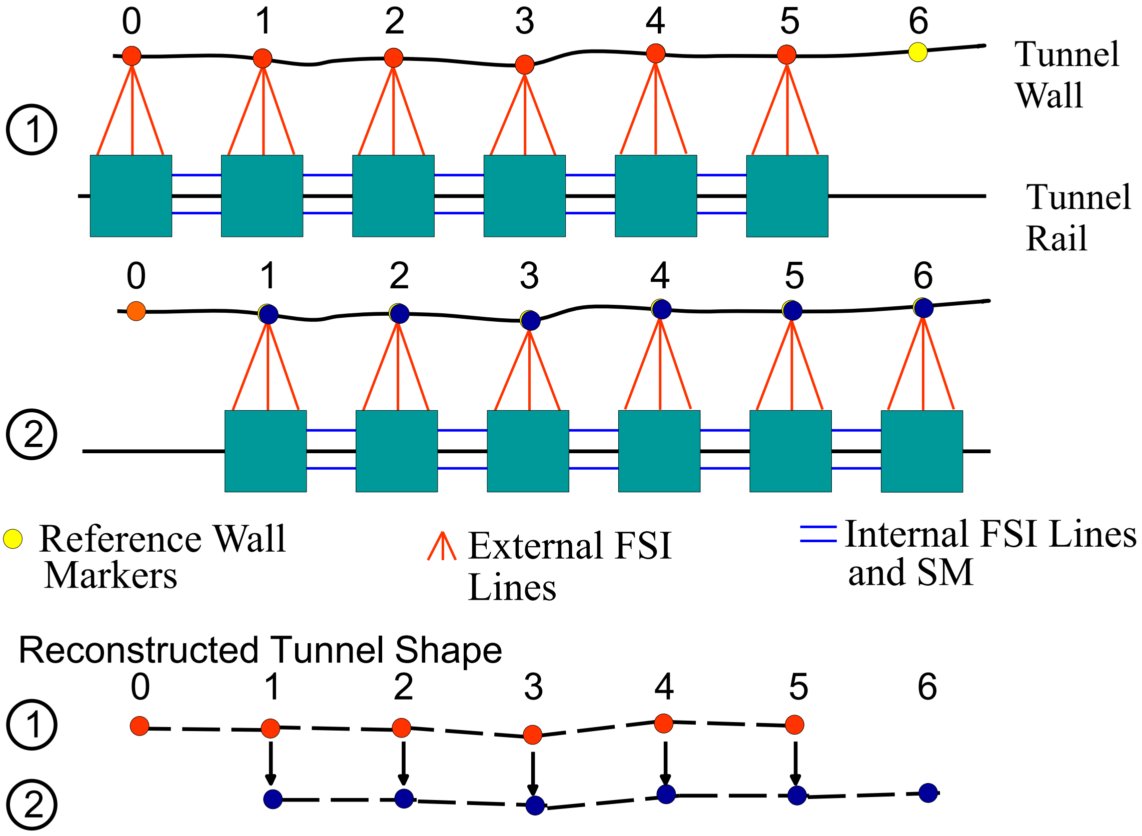

Figure 3: Measuring the reference markers: The train is shown in two positions. In the first position, it is parked by reference markers 0 to 5. It measures their position and this is reflected in the reconstructed tunnel shape for that portion. In the second step, the train measures reference markers 1 to 6. Their positions are reflected in the reconstructed tunnel shape for that portion. The two tunnel shapes are joined together by matching the measured reference markers. In this way many small measured tunnel sections are brought together to give the complete tunnel shape.

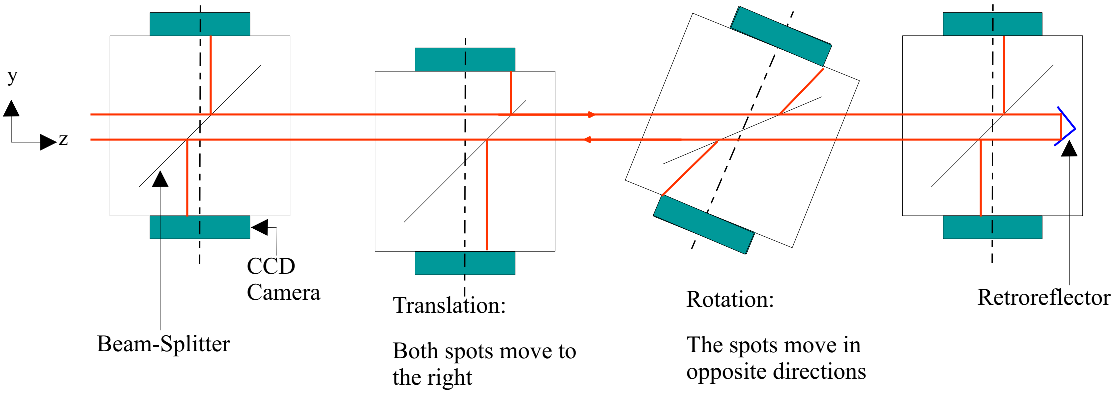

Figure 4: Optical arrangement of SM in the LiCAS Survey Train: It shows one car which has been translated and one which has been rotated. It shows that for a translation, both beams on the CCD cameras move in concert. However for a rotation, the beams on the CCD move in contrary.

system of the Zeus MicroVertex detector (MVD) which was developed at the University of Oxford [7].

In the survey train a collimated fibre coupled laser is used which has low longitudinal coherence length ($50 \mu m$) but high transverse coherence. This allows efficient coupling into a single-mode optical fibre but reduces interference from spurious reflections. The beam is intercepted by a beam-splitter and the reflected beam goes to a CCD camera. The beam passes through six beam splitters in total; one beam-splitter per car. At the last car, the beam is reflected back via a retroreflector. The beam subsequently passes thorugh the same beam splitters; thus each beam-splitter is intercepted twice. A second camera on the car observes the relfection off the second interception. This arrangement is illustrated in figure 4. By correlating the images from the two cameras one can differentiate translations from rotations.

2.2.1 SM extensions for LiCAS

In the Zeus MVD, the length of the SM is 2 m. For LiCAS the range of the SM must be twice the length of the train which is ≈ 50 m. To have a beam with minimal divergence requires a wide beam beam diameter to be greater than the CCD viewing area. This is compensated for by adding demagnification optics in front of the CCD cameras.

The LiCAS SM uses two parallel beams to allow measurements of rotation about the z-axis [1]. This is illustrated in figure 5. As the car rotates about the z axis, one observes the

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[1] The tunnel axis is defined with z along the tunnel axis and y is vertically up. The x axis is towards the reference markers on the tunnel wall

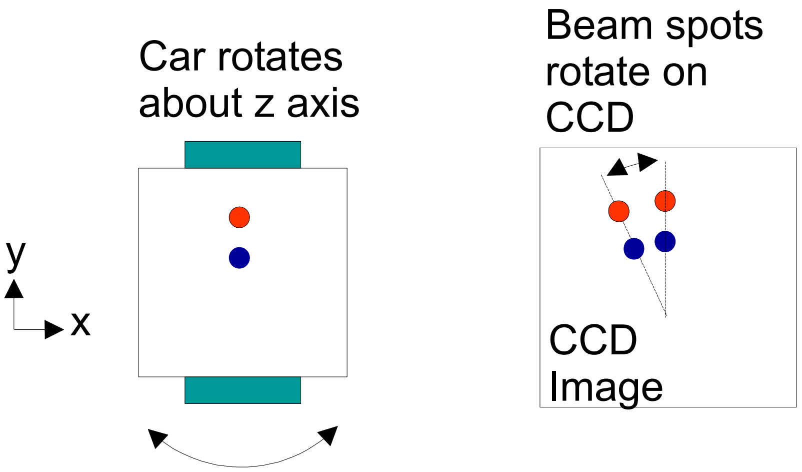

Figure 5: Two SM beams allow rotation about the z axis to be measured: As the car rotates, the angle of the beams with respect to the CCD changes

angle of the beams with respect to the CCD changes.

The use of the single beam-splitter and retroreflector is one possible configuration for a SM. Another possible arrangement is to use two beam splitters at right-angles to each other. This avoids the need for a retroreflector. Both arrangements are currently under evaluation.

2.3 Frequency Scanning Interferometry (FSI)

Frequency Scanning Interferometry (FSI) is an interferometric length measurement technique developed at Oxford for the online alignment system of the ATLAS Inner Detector [4] [5] [6]. The measurement resolution to date is $1\,\mu m$ over 1.5 m. This will have to be extended to $1\,\mu m$ over 5 m for LiCAS.

Figure 6 illustrates how FSI measures length. The example shows two interferometers: a reference interferometer of known length $\mathcal{L}$ and a measurement interferometer of length $\mathcal{D}$. The tunable laser sweeps through a frequency range $\Delta\nu$ and one observes a sinusoidal modulation at the photodetector.

The length is determined by comparing the change in phase of the measured interferometer, Φ_{GLI}, to that in the reference interferometer, Φ_{Ref}. The ratio of the two is equal to the ratio of lengths (see equation 1).

$$\mathcal{D} = \mathcal{L}\frac{\Delta\Phi_{GLI}}{\Delta\Phi_{Ref}} \tag{1}$$

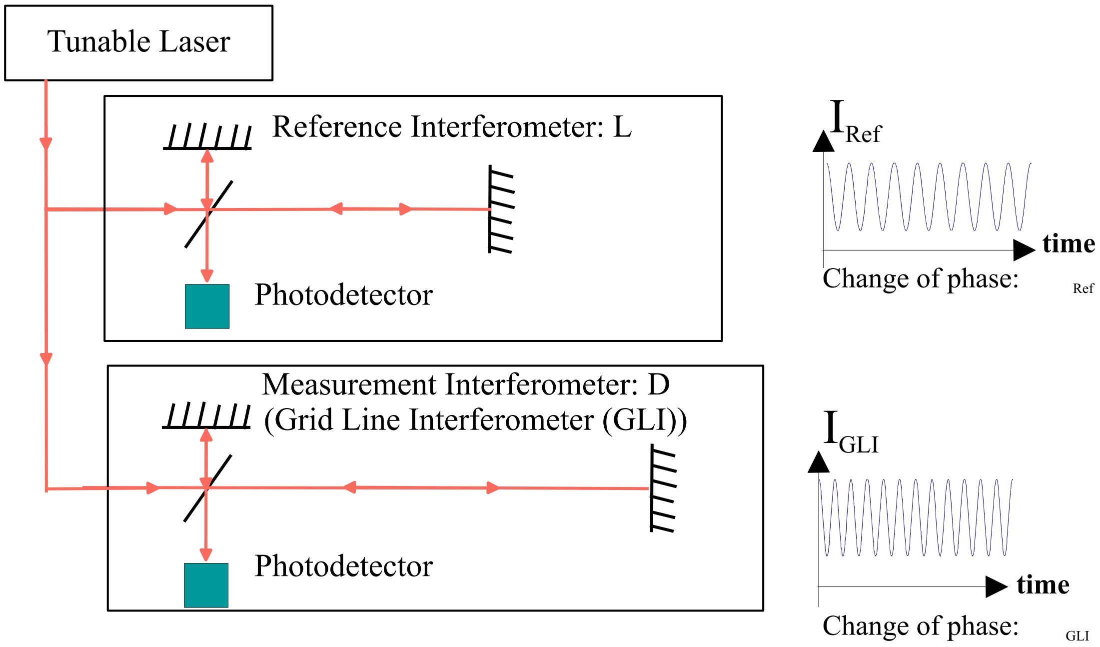

Figure 6: FSI: Light from a tunable laser goes to two interferometers. A reference of known length $\mathcal{L}$ and a measurement interferometer of length $\mathcal{D}$. As the laser sweeps through a frequency range $\Delta\nu$, the intensity at the photodetector is sinusoidally modulated. The ratio of the phase change of the two interferometer signals is equal to length ratios.

Further details on the measurement process can be found in [4] [9].

2.3.1 FSI extensions for LiCAS

For the LiCAS system, the FSI operating wavelength has been moved from 800 nm (ATLAS) to the Telecoms wavelength of 1510 nm - 1640 nm. This allows one to exploit the telecommunications market of Dense Wavelength Division Multiplexing (DWDM). This gives a source of “off-the-shelf” high quality tunable lasers and integrated optics. Another advantage is one can use Erbium Doped Fibre Amplifiers (EDFA) which provides a scalable source of tunable laser power.

Current Telecoms tunable lasers offer a much greater performance compared to the Ti:Sapphire tunable lasers used in ATLAS. The main features are listed below:

1. Greater continuous, mode-hop free tuning range of 130 nm (ATLAS: 0.2 nm)

2. Faster continuous tuning rate of 5 THz/second (ATLAS: 1.5 GHz/second)
3. Laser can be amplitude modulated via an external electrical signal

The first two points reduce the susceptibility to "thermal drift" [4] [9]. Small length fluctuations in the measured interferometer lead to errors magnified by a factor of $\frac{\nu}{\Delta\nu}$. These errors are eliminated using two lasers which scan in opposite directions in frequency. In the LiCAS system $\frac{\nu}{\Delta\nu}$ is reduced and the smaller total tuning time dramatically reduces the thermal drift during a scan.

The FSI system requires two lasers to remove thermal drift. In the ATLAS system, a pair of mechanical choppers are used to separate the signals from the two lasers. During data acquisition, the chopper timing must be carefully controlled.

Amplitude modulation of the lasers allows the signals to be separated without the need for choppers. One can amplitude modulate (AM) each laser at a different frequency, f_i. The output signal at the photodiode is a superposition of the AM and FSI modulation of each laser. The individual FSI laser signals are separated using a lock-in amplifier set to the laser's modulation frequency, f_i [2]. This is illustrated in figure 7. The laser amplitude demodulation can be extended to N lasers modulated at their own unique frequency. Hence a single photodiode can read out several lasers simultaneously. A prototype system to demonstrate this has been built and tested.

The design of the FSI interferometer heads has been changed for the LiCAS system. It will add focusing optics to collimate the output beam (see figure 8). This will increase the power reflected off the retroreflector which will allow the long 5 m lengths to be measured. The design will also use a single fibre for delivery and return. The two signals are separated using a fibre splitter. This single fibre design will simplify the optics and mechanics of the system. The collimation compensates for the power lost though the fibre-splitters.

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[2] This is the same principle as used in AM radio.

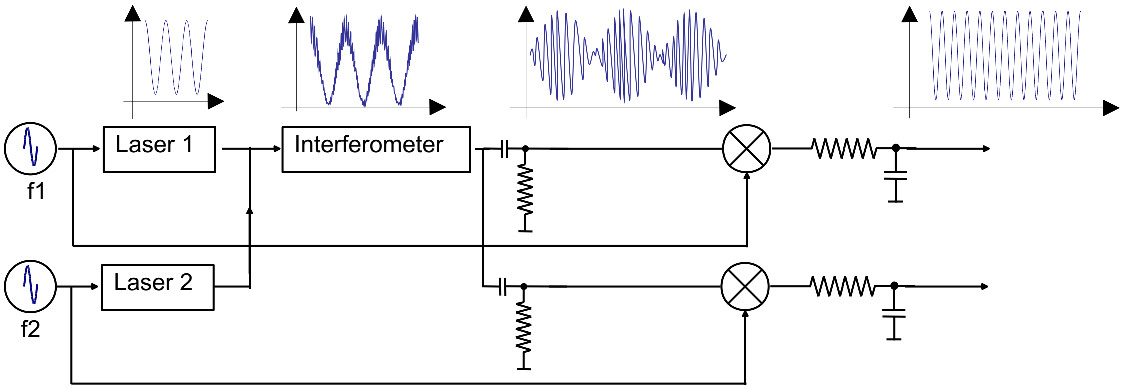

Figure 7: FSI AM System: A sine-wave oscillator at frequency f_i modulates the laser's amplitude. It passes into the interferometer and the output is a superposition of the FSI and laser modulation. The FSI signal is recovered by passing the photodiode output through a high pass filter and then multiplying it by the original modulation source. The multiplied signal goes through a low pass filter to recover the original FSI signal. This lock-in technique is similar to AM radio demodulation. Additional lasers can be added to the system and recovered using the same method.

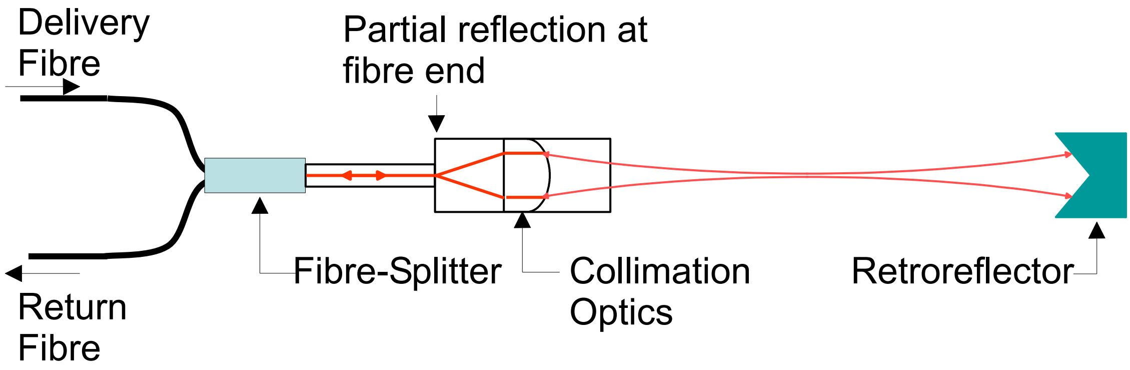

Figure 8: The LiCAS FSI measurement interferometer: Light from the tunable laser is delivered to the interferometer via the Delivery Fibre. It then passes through fibre splitter. Some of the light at the end of the fibre is partially reflected. The remainder of the beam passes through focusing optics to collimate the output beam. This is reflected back to the interferometer head via the retroreflector. The two reflected beams pass through the fibre splitter again and a portion of the beam enters the Return Fibre. This fibre is coupled to a InGaAs photodiode which reads out the FSI signal.

2.4 Simulations

The LiCAS group have been investigating the overall performance of the system using SIMULGEO an opto-geometrical reconstruction software [10]. The simulation includes all the internal and external FSI and SM lines. The results of the simulations are shown in figure 9. The key feature has been the train's sensitivity to rotation about the z axis which in turn affects the error of the extracted reference marker's y (height) position. This has led to a change in the train design to include tilt sensors and two rows of reference markers.

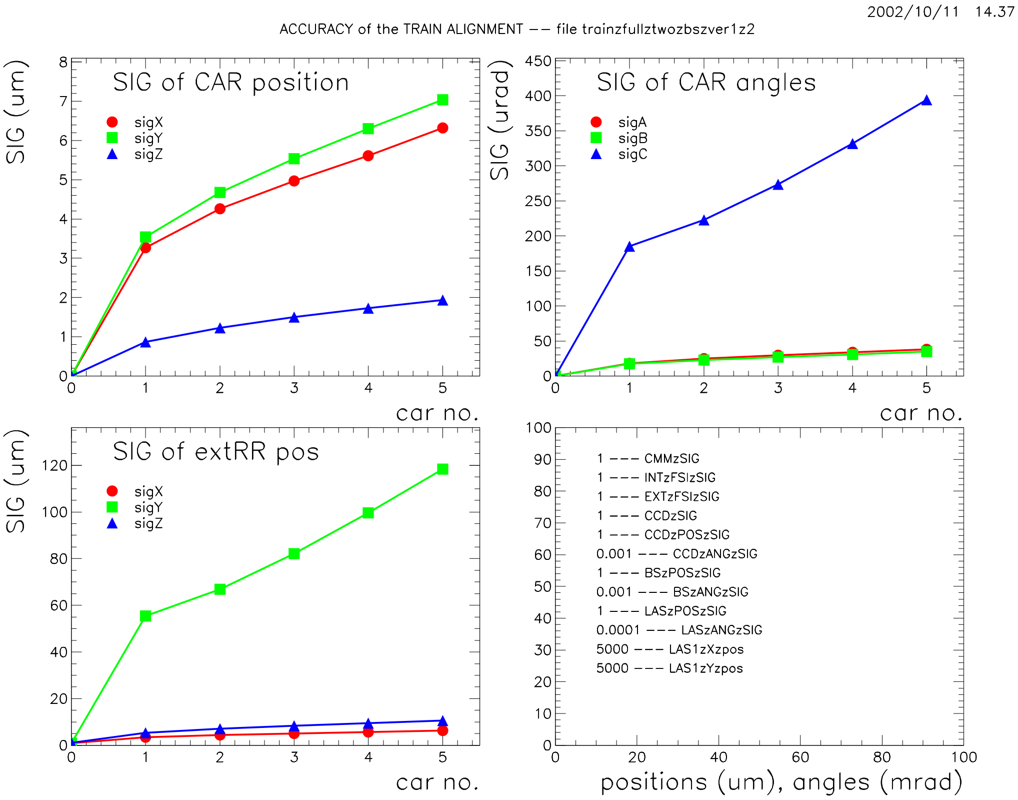

Figure 9: Simulated performance of the Survey Train: The x-axis for each graph is the train car numbered from 0 to 5. The zeroth car is taken to be the datum point. The top-left gives the simulated errors of the measured car's position in x,y,z. The top-right gives the simulated errors of the measured car's rotation about the x,y,z axis; in the graph this is labelled as A,B,C respectively. The top two graphs combine to give the extracted error of the reference marker's position. The large error in the y position is correlated to the large error in the rotation of the car about the z axis.

3 PHASE II

The system can be applied to provide an on-line alignment system for a linear collider. This would be a permanent installation which is an extension of the survey train in Phase I. The arrangement is shown in figure 10. The concept is to place a measurement station of FSI lines and SM to an accelerator component. This would continuously monitor the position with respect to neighbouring stations (accelerator components).

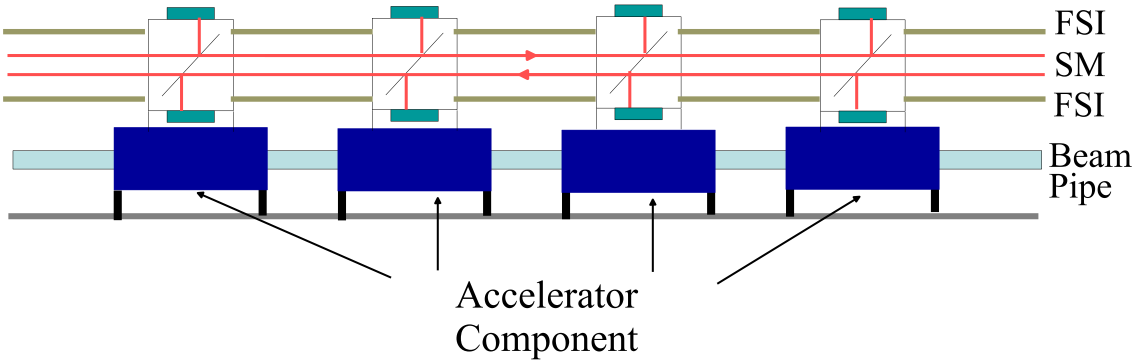

Figure 10: LiCAS Phase II: An illustration of how the survey train from Phase I can be adapted to the on-line alignment of a LC. Each accelerator component has a measurement station with SM and FSI lines between each one. The FSI system has an additional fixed frequency laser added which allows Michelson interferometry as well as FSI. This enhances the system to give micron precision absolute measurements (FSI) and nanometre differential precision (Michelson).

The FSI system would be extended to include a fixed frequency laser. This would combine Michelson and FSI interferometry. FSI provides a micron precision absolute length while the Michelson gives nanometre precision differential measurements. This M-FSI system extends the precision of the system to nanometre resolutions. This is of enormous benefit to a linear collider as it would give real time information of the collider components alignment.

4 CONCLUSION

The LiCAS group aim to develop an optical metrology system to aid the survey and alignment of a future linear collider. The system is based on optical techniques which have been developed at the University of Oxford. LiCAS will exploit these techniques and increase the range and precision to meet the demanding alignment tolerances of a linear collider.

This system is currently under development at the University of Oxford in collaboration with the DESY metrology group. By the end of 2004, a complete prototype is expected to be ready for evaluation at a DESY test tunnel.

References

[1] (ed.) Brinkmann, R. et al. TESLA: The superconducting electron positron linear collider with an integrated x-ray laser laboratory. technical design report. pt. 2: The accelerator. DESY-01-011.

[2] Andreas Herty amd Johannes J Prenting. High precision survey and alignment of large linear colliders - 2D horizontal alignment. Seventh International Workshop on Accelerator Alignment, November 2002.

[3] Markus Schloesser and Johannes J Prenting. High precision survey and alignment of large linear colliders - vertical alignment. Seventh International Workshop on Accelerator Alignment, November 2002.

[4] Paul Andrew Coe. *An Investigation of Frequency Scanning Interferometry for the alignment of the ATLAS semiconductor tracker.* Doctoral thesis, University of Oxford, 2001.

[5] Ankush Mitra. *Development of an APD amplifier for the runtime alignment of the ATLAS Inner Detector and SUSY studies.* Doctoral thesis, University of Oxford, 2002.

[6] David Howell, Armin Reichold, Todd Huffman, Paul Coe, Stephen Gibson, and Ankush Mitra. ATLAS-SCT-alignment: Overview. Final Design Review ATL-IS-ES-0026, University of Oxford, May 2001.

[7] T. Matsushita, S. Boogert, R. Devenish, and R. Walczak. Optical alignment system for the ZEUS micro vertex detector. *Nucl. Instrum. Meth.*, A466:383–389, 2001.

[8] Johannes J Prenting. TESLA - the range of survey and alignment work. Seventh International Workshop on Accelerator Alignment, November 2002.

[9] Paul Coe. Frequency Scanning Interferometry - A versatile high precision, multiple distance measurement technique. Seventh International Workshop on Accelerator Alignment, November 2002.

[10] Laurent Brunel. SIMULGEO: Simulation and reconstruction software for optogeometrical systems, 10 November 1998. CMS NOTE 1998/079.