LINEAR COLLIDER ALIGNMENT AND SURVEY AT THE UNIVERSITY OF OXFORD

Paul Coe, Grzegorz Grzelak, Ankush Mitra, Armin Reichold, Roman Walczak

Abstract

A novel survey approach dedicated to align the components of a Linear Collider (LC) is presented. The 'classical' (open air) geodesy will be not sufficient to perform this task. The proposed solution is an optical measurement system using laser Straightness Monitors (SM) and Frequency Scanning Interferometry (FSI) operating in a vacuum tube. It is expected that such a system will overcome the limitations of the traditional technology and can provide an accuracy of $\mathcal{O}(100\,\mu m)$ over a distance of $\mathcal{O}(0.5\,km)$ which is needed for such a machine.

1 INTRODUCTION

To obtain very high luminosity, the next generation of linear accelerators will collide highly focused beams with vertical dimensions of the order of nanometres. Therefore, the performance of any future linear collider will be crucially dependent on the alignment of its components. This is true for the initial placement during construction as well as the operation and maintenance of the accelerator.

The required precision of controlling the position of accelerator components is of the order of $200\,\mu m$ over a distance of 600 meters [1]. To obtain the above accuracy an alignment system using a stretched wire in conjunction with a hydrostatic levelling system (HLS) is considered. However this is a 'conservative' approach with limitations coming from the principle of the HLS technique which gives an equipotential line (following the curvature of the earth) instead of the true geometric straight line. It cannot be also easily applied to the sloped tunnel sections.

The Oxford LiCAS group (*Linear Collider Alignment and Survey*) is developing an alternative novel survey system. It will use a combination of laser Straightness Monitors (SM) and Frequency Scanning Interferometry (FSI) which is an interferometric length measurement technique. FSI was originally developed at Oxford for the on-line alignment of the ATLAS Inner Detector [2, 3, 4] and straightness monitors developed at Oxford are already used to monitor the deformations of the ZEUS Microvertex Detector [5].

2 OVERVIEW OF THE LICAS PROJECT

Although the above techniques are very promising they have only been adopted for alignment over relatively short distances. The biggest challenge at the R&D stage of this project will be to extend the FSI technology from its current measurement range of $1.5\,m$ to $5\,m$ and the straightness monitors from $2\,m$ up to $25\,m$. Both systems should preserve their resolution of $\mathcal{O}(1\,\mu m)$ after these extensions.

Our interest focuses on the development of a 'general purpose', cheap and scalable survey technology which could be applicable for any future linear collider like TESLA (with FEL) and NLC or even synchrotron radiation sources. This is made possible by recent advances in telecommunication lasers which can be tuned now with high speed over very wide tunning range.

2.1 LiCAS Phase I

To test our apparatus in a real accelerator environment we are collaborating with the DESY metrology group which is developing the concept of an automated survey vehicle.

The proposed instrument is a modular device composed of six 'cars' connected by a vacuum pipe to form a 'train' which is able to travel along the LC tunnel. It measures the 3D position of external reference markers thus providing a well defined reference frame along the tunnel. This is especially important during the installation and later for the service of the accelerator components.

2.2 LiCAS Phase II

The optical instrumentation developed for Phase I of the project could also be applied to an on-line monitoring of the last sections of the collider: Beam Delivery System (BDS) and Final Focus which is most sensitive to misalignment.

A static grid of many FSI and SM lines could be a valuable piece of beam instrumentation which provides an online and absolute position measurement of the BDS components. Such an external system may reduce the time needed and ambiguities present in finding these positions by beam based methods. By combining the FSI measurement with Michelson interferometry (M-FSI) it is feasible to obtain a sensitivity to deflection of $\mathcal{O}(1\,nm)$. This makes M-FSI suitable for the stabilisation of the Final Doublet by using it as a part of an optical anchor system.

As M-FSI is a differential measurement it can be much faster then full FSI cycle (see section 3.6) and may reach measurement frequencies of $\mathcal{O}(10\,Hz)$. The M-FSI data can be treated as 'small corrections' with respect to the FSI measurements. This allows to linearise the system of equations needed to solve the geometry of the whole grid and to cope with a large amount of data in the real time.

In this paper we will focus on the elements of the system essential for Phase I of the project which has a much shorter time scale of approximately 2 – 3 years. The success of Phase I would be considered as a proof of principle for the more complex Phase II.

3 SURVEY VEHICLE FOR LC

The proposed apparatus is developed in collaboration with the DESY metrology team which is working on the macro mechanics of the train and the infrastructure in the dedicated tunnel on the DESY site where the system is supposed to be tested.

3.1 Mechanical design

In figure 1 two of the six cars of the survey train are presented.

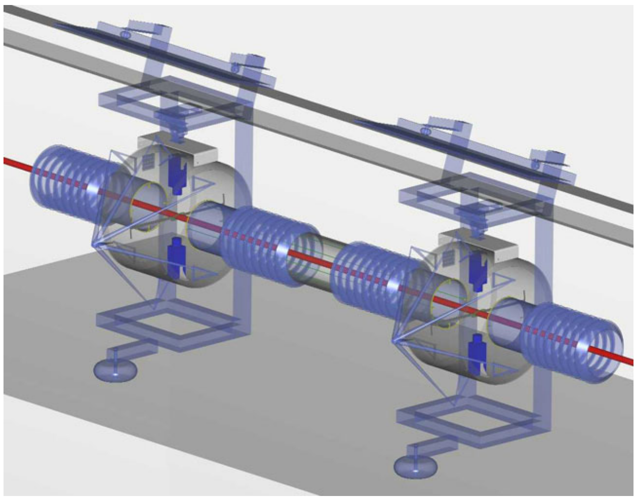

Figure 1: Conceptual drawing of two of the six cars of the survey train. The red line inside the vacuum tube is the straightness monitor. The blue lines indicates the internal and external FSI distance measurements. The relative distance between the two cars is shortened to provide better graphical representation.

The cars are separated by $4.5\,m$ each and supported by the propulsion system designed to move all cars together along the walls of the collider tunnel. All the cars are connected by a vacuum pipe which houses the internal metrology instruments.

The internal metrology system is a network of FSI distance measurements and laser straightness monitors linked in such a way that the full set of 3D co-ordinates (x, y, z position and 3 rotation angles) of each car can be determined with respect to all other cars. This part of the system will be encapsulated in the vacuum tube to avoid limitations due to the air refraction. In addition, each car is equipped with 6 FSI lines which measure the co-ordinates of the external reference markers with respect to the cars. This part of the system operates in open air but the optical path length of the FSI lines are very short (of $\mathcal{O}(0.5\,m)$) and thus the errors due to refraction are negligible.

3.2 Tunnel measurement

The train will initially determine the 3D position of a series of equidistant wall mounted retroreflectors (fig. 2). The

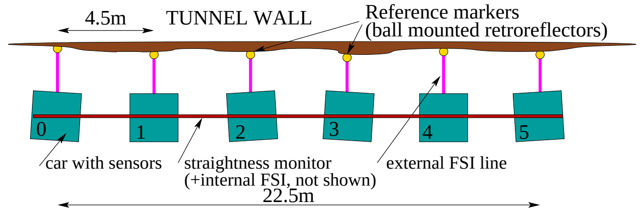

Figure 2: Top view of the survey train illustrating the idea of the LC tunnel measurement. For simplicity, only the straightness monitor and one external distance measurement (FSI line) of each car is presented.

measurement of the position of each marker is performed in 6 fold overlapping steps (as each of 6 cars stops in front of each wall marker). This is a highly overconstrained measurement which can be compared to the procedure in which one uses a short ruler to construct a long straight line.

When the 3D co-ordinates for some set of wall markers are determined the (local) reference frame for this section of the tunnel is defined. Now a second instrument, for example a computer controlled theodolite, can be used to determine the positions of collider components with respect to the reference markers. Such an instrument determines its own position by looking at several wall mounted markers for which the positions are already known. This operation (co-ordinates transfer) cannot be performed by a survey train because of the complicated and irregular structure of collider components.

However, it is very important to have fast and repeated measurements of the regularly located wall markers because the collider tunnel is not stable in the long term on the length scales which are important for proper accelerator alignment. There may also be a great potential for application of the same FSI technology to construct the instrument performing the co-ordinates transfer.

In the next sections the detailed technical solutions used for the FSI distance measurement and the straightness monitor are presented.

3.3 Principle of the FSI measurement

An FSI measurement (fig. 3) is performed using a set-up composed of two interferometers which operate in a configuration very similar to the Michelson interferometer. The main difference is that instead of varying the length of the interferometers arms the frequency of the laser is changing.

Each of the two interferometers are equipped with a beam splitter, two mirrors and photodetector to register the interference fringes. One of them is a reference interferometer and the length difference of both its arms is known. The shorter arm of the second interferometer is also fixed by construction and the length of the longer arm is to be determined.

When such an interferometer is illuminated with variable frequency light from a tunable laser, the output intensity depends sinusoidally on the light frequency (as a function

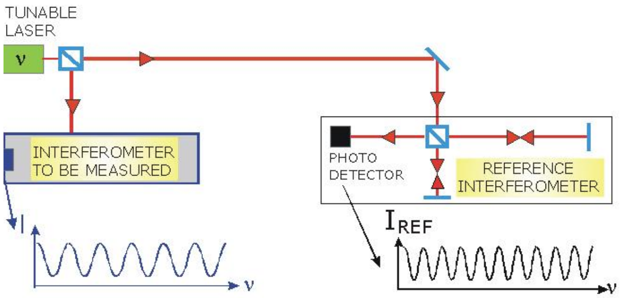

Figure 3: The basic idea of the FSI measurement. For the description see text.

of time $\nu(t)$). The phase of this sinusoid is given by:

$$\Phi(t) = \frac{2\pi}{c} L\nu(t), \quad (1)$$

where L is the unknown path length difference (PLD) between the interferometer arms.

Measuring the integrated phases $\Delta\Phi$ and $\Delta\Phi_{ref}$ where one of them comes from a reference interferometer with known PLD, over a frequency range $\Delta\nu$ one can find L via:

$$L = L_{ref} \frac{\Delta\Phi}{\Delta\Phi_{ref}}. \quad (2)$$

This relates the distance measurement with the measurement of the integral path advance of two interferometers and calibration of L_{ref}. The resolution of such a measurement can be controlled by increasing laser tuning range. But large path lengths differences are challenging for FSI measurements because they give rise to a very rapid phase advance and requires also more optical power.

Furthermore, by simultaneous use of two lasers which are tuned in opposite directions it is possible to cancel very efficiently the errors coming from length drift of the interferometer arms (on the sub-micron scale) during the measurement. Due to the nature of an FSI measurement such fluctuations are magnified by a factor of $\frac{\nu}{\Delta\nu}$ and can be an important source of errors for a single-laser FSI measurement.[1]

3.4 *Straightness Monitor*

The straightness monitor (fig. 4) determines the transverse motion and rotation (along x and y axis) of each car using a beam of light that is partially reflected off beamsplitters and registered by the CCD cameras. By using a second parallel (offset) beam the measurement is also sensitive to the rotation along the z axis.

We intend to use fibre coupled low coherence length laser diodes instead of normal lasers. They have low longitudinal coherence length ($30\,\mu m$) but excellent transverse coherence. Thus, such laser diodes can be efficiently fibre coupled and their use will avoid problems with interference from multiply reflected beams.

[1] For detailed treatment including the drift error corrections see [6].

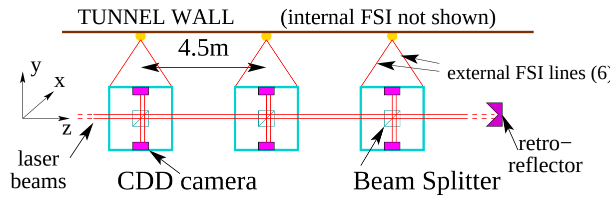

Figure 4: Top view of the survey train presenting the instrumentation of the straightness monitor inside the cars.

Important challenges during the construction of the SM will be to minimise (or calibrate) any beam walk off in the beamsplitter, to reduce distortion in the custom camera optics and to make the splitter–cameras–car unit stable against vibration and drift. We intend to use pellicle beamsplitters to minimise walk off and dispersion. The use of advance carbon fibre re-enforced plastic (CFRP) composites with minimal thermal expansion coefficient in a compact mechanical design of the measurement station will ensure stability of the camera position.

In figure 4 only one of the possible SM configurations is presented. Another option under investigation would be to equip each car with two beamsplitters and use the light beam travelling only in one direction (i.e. without the retroreflector in the last car). The optimal solution will be selected based on the simulation of the performance of the full system using the SIMULGEO [7] software.

The resolution of the SM is expected to be of the order of $\mathcal{O}(1\,\mu m)$ which makes it comparable to the resolution of the FSI system.

3.5 *Internal and External FSI System*

The internal FSI system (fig. 5) is composed of 4 FSI lines of $4.5\,m$ length between each pair of cars. This grid of lines performs a redundant measurement of the z-co-ordinate and is also sensitive to the rotation of the car around x and y axis. Together with the SM system it allows one to overconstrain all 6 degrees of freedom of each car.

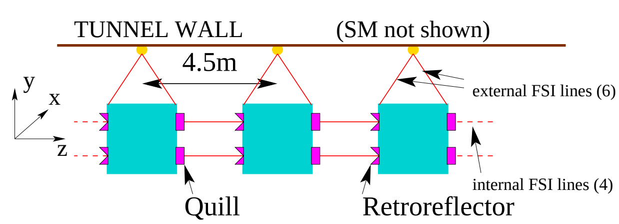

Figure 5: Simplified top view of the survey train presenting the location of internal and external FSI lines.

Outside of each station, 6 FSI distance measurements (each approximately $\mathcal{O}(0.5\,m)$ long) can over-determine the 3D co-ordinates of the external markers (wall mounted retroreflectors). There is an option under consideration to locate two such markers in front of each car at different heights with respect to the tunnel floor. Such a solution will help to resolve the uncertainties related to the rotation of the whole train around the axis formed by the tunnel reference markers.

One of the main research areas for the internal FSI system is the collimation optics needed to increase the intensity of the returning light. An issue which is common to the internal and external FSI systems is the absolute calibration. We intend to mount the components of both ends of the interferometers, i.e. the interferometer heads (quills) and retroreflectors, into spheres in such a way that places their centres into the centre of each sphere. This will make the distance measurement largely independent of the orientation of the sphere. The external FSI system will be integrated into the skeleton of the car forming a mechanically rigid body together with the internal measurement system.

We expect to reach the resolution of the FSI system to be $\mathcal{O}(1\,\mu m)$ for the internal lines and $\mathcal{O}(0.2\,\mu m)$ for the external lines.

3.6 FSI lasers

The heart of an FSI system is a pair of tunable lasers that provide the light for the individual lines through single mode optical fibres via a tree of fibre amplifiers and splitters. We intend to use telecommunications lasers and erbium doped fibre amplifiers (EDFA) at infrared ($1510 - 1640\,nm$) wavelengths as a cost efficient source of a $100\,mW$ tunable laser light. One of the main points of investigations is related to the use of amplifiers with a wider continuous wavelength and narrower line compared to the commercial TELECOMS applications.

Modern telecommunication lasers can be tuned continuously over a range of $130\,nm$. This is almost a factor of ten more compared to the ATLAS FSI system and is expected to increase the resolution compared to what has already been achieved for ATLAS ($0.12\,\mu m$ over $40\,cm$). In the ATLAS system a maximum tuning range of $16\,nm$ was covered by making several coarse tuning jumps between relatively short continuous tuning sections of $0.2\,nm$ range.

A further advance above the ATLAS technology would be to allow the light from both lasers to be simultaneously present in the interferometers (the ATLAS system chops between the two lasers beams). This is possible by modulating the amplitude of both lasers at different frequencies and separately demodulating them with a lock-in amplifier system at the detector (akin to the AM radio modulation–demodulation method). Also the tuning speed of TELECOMS lasers is much faster ($5\,THz/sec$ compared to $1.5\,GHz/sec$ for ATLAS lasers). These two facts would reduce the time needed for a single scan and thus reduce the error from the length drift of the interferometer. Altogether we hope to reduce the quantity $\frac{\nu}{\Delta\nu}$ which is critical for the drift sensitivity by a factor of $\mathcal{O}(300)$ over the ATLAS technology and to decrease the total tuning time of a single FSI scan from $1\,min$ to about $3\,sec$.

Furthermore we hope to be able to use the same fibre for delivery and readout of the signal from the FSI interferometers, simplifying the mechanics and optics significantly. This is made possible by using fibre splitters which are now readily available, low cost devices at the telecommunication wavelength. Since this method would loose half of the return light it is essential to have good light collimation and high output power from the amplifiers.

Finally there is also a frequency measurement system and DAQ system for light detection. All this additional equipment will be located in one or two auxiliary cars behind the actual instrument.

4 SUMMARY

We have presented the basic ideas of a modern survey apparatus which is currently under construction at the University of Oxford in collaboration with the DESY metrology group. It will be a fully automated optical system making use of the Frequency Scanning Interferometry and Straightness Monitors. These are the latest technological achievements developed for the alignment of the ATLAS Inner tracker and ZEUS Microvertex detector at Oxford. Having the knowledge and experience already accumulated during the R&D and productions of the above systems we hope to extend these technologies to face the very demanding requirements for the alignment of a Linear Collider.

5 REFERENCES

[1] "TESLA, The Superconducting Electron-Positron Linear Collider with an Integrated X-Ray Laser Laboratory", Technical Design Report, DESY 2001-011.

[2] A.F. Fox-Murphy et al., "Frequency scanned interferometry (FSI): the basis of the survey system for ATLAS using fast automated remote interferometry", Nuclear Instruments and Methods in Physics Research A 383 (1996) 229-237.

[3] P.A. Coe et al., "A novel Dual-Laser Frequency Scanning Interferometry Distance Measurement System", to be published in Measurement Science and Technology.

[4] A. Mitra, "Development of an APD amplifier for the Runtime Alignment of the ATLAS Inner Detector and SUSY studies", D.Phil. Thesis, Oxford 2002.

[5] T. Matsushita et al., "Optical Alignment System for the ZEUS Microvertex Detector", Nuclear Instruments and Methods in Physics Research A 466 (2001) 383-389.

[6] P.A. Coe, "An investigation of Frequency Scanning Interferometry for the alignment of the ATLAS semiconductor tracker", D.Phil. Thesis, Oxford 2001.

[7] L. Brunel, "SIMULGEO: Simulation and reconstruction software for optogeometrical systems", CERN CMS Note 1998/079.