

MONALISA: A precise system for accelerator component position monitoring

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Abstract

The MONALISA group is developing a nanometre precision, interferometric system to continuously monitor relative position and orientation of crucial accelerator components. The most challenging role at the ILC will be monitoring the final focus quadrupoles. A combination of fixed frequency and frequency scanning interferometry (FSI) maintains nanometre precision, real time readout every few milliseconds. With FSI, measurements can be re-established at the micron level after any interruption in interferometer operation. This is of particular interest when considering the push-pull detector scheme. Interferometric systems, independent of the particle beam, are not disrupted by breaks in accelerator operation. We aim to provide measurements which will allow a return to magnet position at the micron level even after an accelerator interruption of several months. We present a demonstration measurement system and report on measurement precision which is converging on the nanometre resolution required for the ILC.

INTRODUCTION

Future linear colliders in high energy physics, will rely on very tightly focussed beams at the interaction point (IP) to achieve luminosity targets for low cross-section interactions. An important example is the ILC (International Linear Collider) which is the next proposed e^+e^- machine, designed to study with precision the physics highlighted by the LHC (large hadron collider). The final focus at the ILC will require beams a few hundred nanometres wide and a few nanometres high, which must be made to overlap at the IP. Hence the need for nanometre level relative stability (in the vertical direction) for the final focussing magnets.

Fast feedback systems will be used to correct the position and direction of particle bunches within a train, using kicker magnets. The correction signals rely on diagnostic beam position monitors close to the IP. Fast feedback correction is vital for the operation of a challenging accelerator, but does not follow changes in machine alignment when the particle beams are absent; neither in the gaps between particle bunch trains, nor during periods of accelerator inactivity; when machine components can move away from good alignment due to ground motion. An independent system which monitors relative motion, without requiring a particle beam, will greatly reduce the time taken to lock to a good operational alignment for a restarted accelerator and will improve the stability of accelerator opera-

tion from train to train.

The MONALISA group at Oxford are developing stabilisation monitoring equipment which can track motions of neighbouring components, such as the final focus magnets of the ILC, to nanometre precision, using interferometric distance and displacement measurements, independent from particle based measurements. The cost effective, readily scalable solutions developed for the final focus, can also be applied to other parts of the collider, including the many key magnets in the beam delivery section, where sub-micron relative stability will be needed.

At the time of writing, a push-pull system is envisaged for swapping between two detectors at the IP of the ILC. This involves detaching a detector and the final focussing magnets of the accelerator from a fixed location around the IP and rolling across the floor, at right angles to the accelerator axis, to make room for the complementary detector (also equipped with final focus magnets) which rolls into position at the IP from the other side.

Our interferometric techniques for establishing range as well as relative motion will greatly reduce the time taken for a restart after the exchange of two push-pull detectors. We will establish the relative positions and orientations of the final focussing magnets at the micron scale within a few seconds of our system being restarted and thereafter provide continuous, nanometre resolution monitoring of the magnet motions during settling.

The following sections cover: Our interferometer design and principles of operation, the simulation of a monitoring system layout; based on the region around the IP for an ILC detector, the demonstration system at Oxford and a stabilisation monitor under construction at KEK at the ATF2. We present the latest results from our tests in Oxford and our plans for future work.

INTERFEROMETER DESIGNS

Interferometric distance measurements are routinely made with nanometre resolution over sub-wavelength dynamic ranges[1], using either the optical wavelength of a monochromatic source (as reported by Michelson and Morley[2]), or the synthetic wavelength of a multiple source system, where the dynamic range can be extended to a few millimetres; (see for example Dändliker et al.[3].) If a fixed frequency source with extremely narrow linewidth (less than 10 kHz) is used, nanometre precision measurements at ranges of 10 m will be possible in vacuo. We refer to this technique, below as Fixed Frequency Interferometry (FFI).

Absolute distance interferometry using a scanning laser source have been reported for distances up to 40 m (see for example Thiel and Pfeifer[4]) in air, with resolutions better than 1 μm achievable over ranges of up to 6 m. The principle of frequency scanning interferometry (FSI) distance measurement is described below.

Our distance meter interferometer (DMI) prototype design is shown schematically in Fig. 1. This consists of compact, rugged, radiation tolerant components at either end of the measured length. A fibre coupled launch and receive head at one end and a target reflector at the other end. For optimum resolution, the measured path and the end components are placed in a vacuum of 1 mbar or less.

An input fibre-coupled launch collimator provides a low divergence Gaussian beam, for the interferometer. The beam enters a rotated beam-splitter which is slightly rotated relative to the axis of the incoming beam. Transmitted light reflects from a gold surface on one face of the beam-splitter, while reflected light enters the long arm and is reflected from a target reflector (here a mirror; usually a retroreflector) back to the beam-splitter. The returning wavefronts from the different length arms are rotated relative to one another, leading to a fringe pattern, shown on the far left of Fig. 1. This fringe pattern is recorded using a parallel array of readout fibres, allowing the interferometer phase to be reconstructed from raw measurements of intensity.

This remotely monitored instrument allows FFI displacement measurements and FSI distance measurements to be made along the same line of sight simultaneously; thereby achieving high precision and large dynamic range. The target is nanometre resolution, with a dynamic measurement range of 10 metres and a displacement readout rate between 100 Hz and 1 kHz.

A tunable laser (HP8641A) was used in scanning mode, to generate FSI fringes for a test distance measurement of a 200 mm long (400 mm round trip distance) DMI by comparison with a reference interferometer. Individual length measurements are shown in Fig. 4.

SIMULATIONS OF AN IP REGION MONITOR

Monitoring the relative vertical displacement of the final focus quadrupoles (QD0) will be the most demanding geometrical measurement at the ILC. The ILC reference design report (RDR) [5] proposes a train repetition rate of 5 Hz. In every ms long train there will be 3000 bunches (a bunch rate of 3 MHz). In between bunches, the 200ms gap allows time for a significant shift of the final focus magnets, given that the final focus beam spots are 6 nm across in the vertical direction. A MONALISA system tracking these magnet motions to a precision order 10nm, provides the fast feedback system with the ability to converge after as few wasted bunches as possible, at the start of each train. Thus MONALISA can provide a great improvement to the delivered ILC luminosity.

A simulation of such a MONALISA system at the interaction region was performed using the opto-geometric package SIMULGEO [6]. This simulation placed two 0.5m long stable platforms under each QD0 magnet buried inside the concrete floor. The platforms are coupled to each other using a straightness monitor allowing the pair to be treated as a single rigid 0.5m by 2m platform. The geometry is shown in Fig. 2. The position of each QD0 magnet is referenced to the buried platforms, using DMIs; where each QD0 requires a minimum of six DMIs to the nearest platform. The DMI lines fall within the instrumented return yoke of the detectors, to avoid disrupting particle detection.

The compact straightness monitor (CSM) geometry is shown in the inset of Fig.2. DMIs are arranged in a bow tie configuration, with 4 interferometers in the vertical plane and another four in one horizontal plane. An asymmetry of at least 1 mm is important for resolving ambiguities; assuming a DMI distance resolution of 0.5 nm. We further assume that the optical elements placed on the end-platforms are stable to 0.5 nm with respect to each other. This instrument monitors all six degrees of freedom from platform to platform. The precision depends on distance metre performance, mounting stability and size of the end platforms.

The QD0 simulation had 500 mm tall by 250 mm wide end platforms for the CSMs. A distance metre precision of 0.5nm a mounting stability of 0.5nm are assumed throughout. The mounting stability is very challenging, probably needing the platforms to be monitored with more interferometers, made from thermally stable materials and monitored for temperature changes. This aspect requires further investigation. The lack of space at the quadrupoles adds to the challenge.

Assuming the above tolerances, the simulation prediction is for 8nm precision in the vertical and 380nm horizontally; a best case scenario. Such a system can deliver the required performance.

Other ILC monitoring roles

An external monitoring network could be used to measure from upstream of each QD0, to project the position information of the QD0s into the accelerator tunnel. Many of the key magnets within the beam delivery section, (the final 2 km of accelerator before each final focus magnet), also require sub-micron relative stability. Although the resolution over such large distances will be weaker, a MONALISA system would be good enough to allow components to be kept in ideal positions on a continuous basis.

The MONALISA system can monitor at all frequencies between 1 kHz and weeks. Hence it can make several measurements during a single train, which can be used to cross-check if the fast feed-back drift and the magnet position correlates during a train. It can also observe shifts caused by tides or the moon cycle and allow for correction of the BDS magnets. It can be used to distinguish between magnet motion and drifts caused by unwanted changes of magnetic fields.

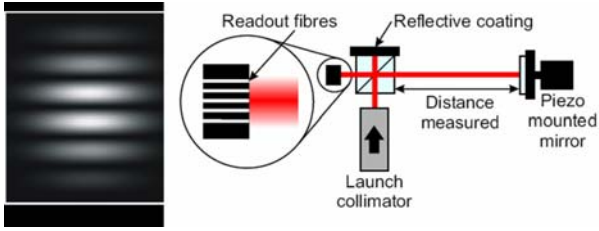


Figure 1: Schematic view of MONALISA distance metre interferometer (DMI) setup.

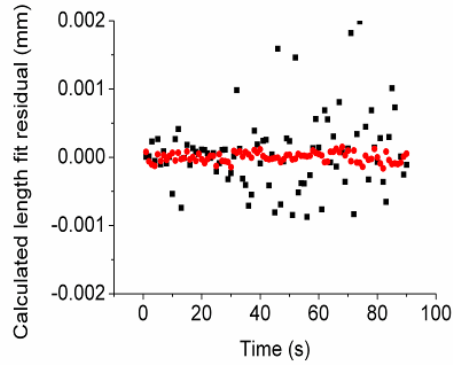


Figure 4: A time series of repeated measurements using FSI over an optical path difference of 400mm. The standard deviation of the measurements is 750nm when the beam path is uncovered (black points), and 70nm with a covered beam path (red points).

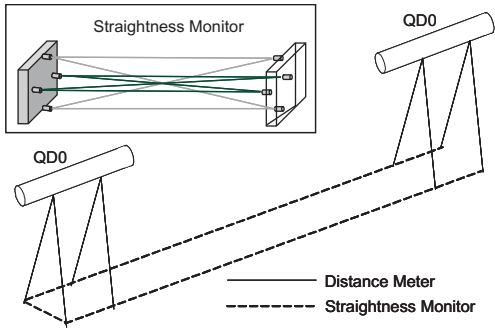


Figure 2: Setup of MONALISA system at ILC final focus. The thin lines are distance metres. The dashed lines represent compact straightness monitors (CSM). The inset shows the geometric setup of a single CSM.

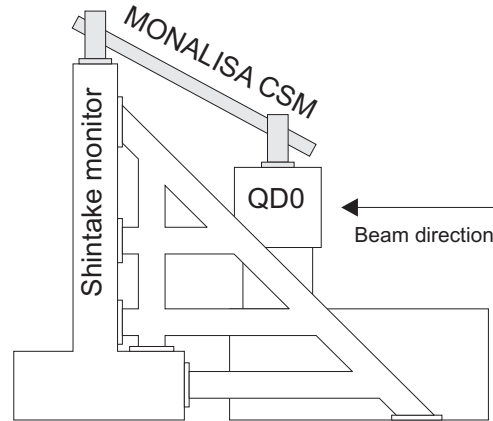


Figure 5: Setup of MONALISA system at ATF2. The CSM is shown shaded. Not shown are vacuum bellows on the CSM and a support structure to ensure forces are not applied to the Shintake monitor and final quadrupole.

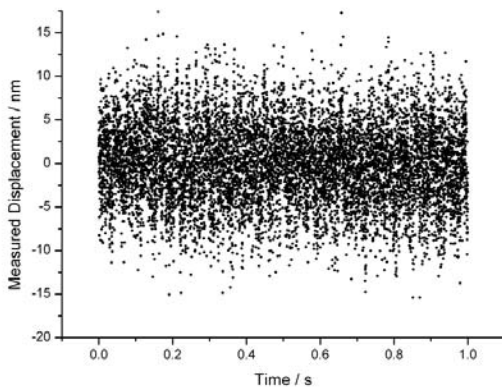


Figure 3: A time series of repeated measurements using FFI over an optical path difference of 400mm. The standard deviation of the displacement measurements is 5nm. The beam path was covered whilst taking these measurements.

INTERFEROMETER PRINCIPLES

Interferometers discussed here use amplitude division[7] of light into two arms, to produce a signal on a photodetector, given by

$$I = B + A \cos \theta \quad (1)$$

The phase term can be expanded as

$$\theta = \left(2\pi \frac{\nu D}{c} + \theta_0 \right) \quad (2)$$

where B and A are the background and sinusoidal amplitudes respectively, D is the OPD between the arms of the interferometer, ν is the optical frequency of the light and θ_0 a general offset phase.

Distance measurements using Frequency Scanning Interferometry (FSI) [8] (typically with sub-micron preci-

sion) will be combined with Fixed Frequency Interferometry (FFI) to make displacement measurements of nanometre precision.

Frequency Scanning Interferometry : FSI

Given equation 2 for the phase of an interferometer signal, if the OPD or the optical frequency are increased, the phase of the signal increases. The respective increase required in each parameter, to shift the phase by $+2\pi$ is given by these relations

$$\begin{aligned}\Delta\nu_{2\pi} &= \frac{c}{\nu} (= \lambda) \\ \Delta\mathcal{D}_{2\pi} &= \frac{c}{\mathcal{D}}\end{aligned}\quad (3)$$

In any interferometer measurement, both ν and \mathcal{D} change, to affect the phase θ . In FSI the aim is to change ν rapidly and smoothly while sampling interferometer intensity data and processing numerically to obtain the corresponding interferometer phase shift $\Delta\theta$. The change of frequency can be determined precisely by reference to frequency standards[9] or more typically by measuring the corresponding phase change in a reference interferometer, illuminated by the same tunable laser and read out simultaneously. The ratio of measured OPD to reference OPD is approximately the ratio of induced phase shifts in each interferometer.

However any OPD change during the frequency scan, $\delta\mathcal{D}$ has a significant impact on precise measurements of the phase shift. The phase shift is in error by $\delta\mathcal{D}(\nu/\Delta\nu)$, where the factor $\nu/\Delta\nu$ is typically greater than 100. For given operational conditions, the faster the laser is tuned, the smaller this error will be. This error could be eliminated by independent monitoring of the OPD changes, using a second laser, not available in the tests discussed below. The system used fibres to connect a tunable laser to the distance meter under test and a reference Michelson interferometer. Throughout the system, all fibres were single-moded, terminated in angle polished ends to suppress reflections. Without such precautions, unintended optical paths would have been present.

REPEATABILITY MEASUREMENTS

To achieve high precision measurements we need to both understand and minimise the uncertainties in the system. For fixed frequency interferometry the major uncertainties that must be controlled when making measurements over a long distance (10m) are the refractive index along the beam path, and the frequency of the laser source. For frequency scanning interferometry it is the phase measurement uncertainty that must be minimised. In addition we must develop a good understanding of systematic error sources in this measurement.

Repeated measurements were taken at a nominally fixed distance in FFI mode. These measurements were taken in

air, and without frequency stabilisation. Indeed, we used an external cavity laser which, although good for FSI, will have an inherently less stable fixed frequency than other lasers. For these reasons we expect the repeatability to be significantly lower than for the final system. Nevertheless we achieved a standard deviation in our measured displacements of 5nm when measuring over 1 second at an optical path difference of 400mm, see Fig. 3. These measurements put an upper limit on our phase measurement precision, as the deviations will be due to variations in laser frequency and refractive index in addition to errors in phase measurement.

The time over which data was taken to evaluate the repeatability was chosen as a trade-off between two competing considerations. It must be significantly above the timescale corresponding to the bandwidth of our electronics (50kHz at present, giving a time period of 20 microseconds) in order to take enough independent measurements to obtain reasonable statistics. We also want the time to be as small as possible, so as to minimise variations from sources other than errors in phase measurement (laser frequency and refractive index variations), as we are interested only in determining the phase measurement uncertainty here. The period chosen was 1 second.

For FSI, repeated measurements were again taken at a nominally fixed distance, but unlike with FFI, each measurement takes 1 second to obtain. Over the several seconds required to take repeated measurements, a measurable variation was always observed. So, over the longer time period that a number of repeated measurements takes, it was not possible to simply assume a constant distance. A linear trend was fitted to a section of data and removed from it. The variation of the residuals from this trend was then calculated as an upper limit on the repeatability of the FSI measurements. The standard deviation of the residuals was 750nm for an uncovered beam path, and 70nm for a covered beam path, see Fig. 4. Both of these are at an optical path difference of 400mm. This large decrease in the spread of results achieved simply by covering the beam path hints at yet another decrease in the spread of results in future when we take measurements in vacuum with this system.

In future, we will measure over larger distances than we have here, up to 10m. With an improved system (in vacuum, with a stabilised laser) and we aim to achieve repeatabilities of the order of 1nm with fixed frequency interferometry at this range. We aim to keep the frequency scanning interferometry measurements' repeatability well below a micron over this distance, and also to improve understanding of systematic effects to ensure that the accuracy, as well as the resolution are below the micron level.

ATF-2 AT KEK

The ATF-2 project aims to produce electron beams with a low emittance and a final focus spot size of nm. The final magnet before the IP is a vertical focusing quadrupole QD0

shown in relation to the IP in Fig 5. A shintake monitor [10] provides beam diagnostics to measure the beam size at the IP. Due to the long integration times required for a beam profile measurement, the shintake monitor must maintain good vertical stability with respect to QD0. We will install a compact straightness monitor (CSM) to monitor relative vertical motion between these two critical components, to a target resolution on the order of nanometres.

SUMMARY

The MONALISA project has demonstrated good resolution for both frequency scanning and fixed frequency measurements in air. In a 400 mm optical path length interferometer, a distance measurement rms of 70 nm was achieved when the turbulence was reduced with a simple cardboard enclosure placed over the interferometer. The corresponding result without the enclosure was 750 nm. Using the same interferometer in fixed frequency mode, with an un-stabilised laser, a short term resolution limit of 5 nm in air was measured. A 5 Hz sawtooth test displacement with an amplitude of 2 microns was easily detected. Our future plans are to evacuate the interferometers to improve resolutions for both modes, to stabilise a fixed frequency laser using a Rb87 saturated absorption reference and to combine both FSI and FFI modes in the same measurement. Once these improvements have been demonstrated in Oxford, they will be deployed at the ATF-2 facility at KEK Japan. At the ATF-2 we will install a compact straightness monitor, to measure relative vertical displacement on the nanometre scale, between a final focus quadrupole magnet and a shintake monitor. This will demonstrate the suitability of our system for similar roles at the ILC and other challenging accelerators.

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