NANOMETRE PRECISION INTERFEROMETRIC STABILITY MONITORING SYSTEMS FOR KEY ACCELERATOR COMPONENTS

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Abstract

The MONALISA group develops novel, accurate, nanometre resolution, interferometric systems to monitor relative motions between key accelerator components. We use cost-effective technology developed for the telecommunications market, providing readily scalable, adaptable solutions. Key magnets and diagnostics in the beam-delivery section of the International Linear Collider (ILC) will need to maintain stable relative positions. In particular, the final focus quadrupole magnets require nanometre level stability. Even greater stability requirements will be placed on components for the Compact Linear Accelerator (CLIC). Interferometers provide the only means of monitoring relative positions over long timescales, at the nanometre and sub-nanometre level. The latest results from our novel design, fibre-coupled interferometers will be presented.

PACS: 06.30.Bp, 07.60.Ly, 42.62-b

INTRODUCTION

The high luminosity of future linear colliders will be achieved by tightly controlling beam emittance, extremely small transverse bunch sizes and very well aligned, highly stable accelerators. Key accelerator components will have to be monitored to nanometre levels, especially the final focus quadrupoles.

The initial alignment of accelerators routinely relies upon optical metrology. We are investigating the use of permanently installed optical metrology systems for continuously measuring the relative locations of accelerator components. Measurements will be provided during accelerator operation and down-time, when particle beams will not be available for checking machine alignment.

The “push-pull” scheme for the International Linear Collider (ILC), whereby two detectors are swapped into and out of a single interaction region, presents further alignment challenges: After a detector exchange, the quadrupoles will need to be realigned with respect to one another and with respect to the beam delivery system. Our monitoring system will facilitate repositioning of the final focus quadrupole at the micron level.

We are developing a network of interferometric distance meters to measure the relative position and orientation of a pair of components using multilateration. We aim to record displacements to nanometre precision at a distance of up to 10 metres and a sampling rate of 1 ksample/s. We supplement fixed wavelength interferometry, (which can only measure continuous changes in distance), with an established absolute distance interferometry (ADI) technique [1, 2] to sub-micron precision [3]. Our instruments are designed to be readily scaled up for large metrology systems. That is, once the one-off cost for the laser system is met, the additional cost per distance meter will be small.

An important limitation of optical metrology in air is the variation of refractive index [4]. We use evacuated interferometers to overcome this limitation. A further source of error for our measurements with fixed wavelength interferometry is the uncertainty in laser wavelength. (This error is important with an unbalanced interferometer setup as required by ADI). A feedback system for stabilising the laser wavelength, which locks to a spectral line in rubidium vapour [5], is under development. This feedback system operates at frequencies below 1 Hz. In this paper we investigate the frequency stability above 1 Hz for our lasers and determine the impact on the distance measurement.

DISTANCE METER DESIGN

The distance meter is an unbalanced Michelson interferometer. A schematic of the interferometer is shown in figure 1. Light entering the long arm of the interferometer is reflected back by a hollow corner cube retroreflector. The short arm is terminated by a reflective coating on one face of the beam-splitter cube and hence is wholly contained within glass. The optical path difference between the two arms in vacuo is thus twice the distance from the vertex of the corner cube to the nearest surface of the beam-splitter. A slight angle (exaggerated in figure 1) between the incident beam direction and the normal to the entrance surface of the beam-splitter cube introduces a tilt between the wavefronts from the short and long arms. This creates interference fringes in the detector plane (on the left of the figure), where the fringe pattern intensity is sampled by several equidistant single mode fibres and measured; with one photodiode per fibre. The phase of the interferometer is determined from these samples.

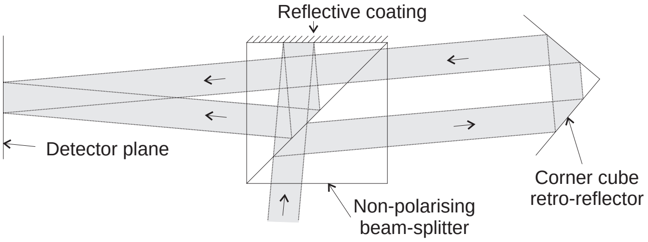

Figure 1: Schematic of the distance meter interferometer design showing light paths from launch collimator to the detector plane.

Relative displacements between ends of the interferometer are recorded via phase shifts. An interferometer with optical path difference D has a measured phase given by:

$$\Theta = \frac{2\pi}{c}\nu D \tag{1}$$

therefore fluctuations in optical path difference are recorded as phase changes. However laser frequency variations can also alter the interferometer phase, hence from equation 1 we obtain:

$$\delta\Theta = \frac{2\pi}{c}\left(D\delta\nu + \nu\delta D\right) \tag{2}$$

Therefore, our displacement sensitivity will depend on controlling the laser frequency.

MEASUREMENT OF LASER FREQUENCY STABILITY

We measured laser frequency stability by comparing against two types of reference: A physical length e.g an interferometer using equation 2 and against the optical frequency of another laser, assuming statistically independent frequency variations. Both methods provide an upper limit: In the former case variations in laser frequency and interferometer length are indistinguishable whereas in the latter case the frequency instabilities of both lasers contribute.

For both comparison methods, laser frequency stability results are given in kHz per Hz$^{1/2}$ across a frequency spectrum. The limit on displacement measurements for an interferometer, can be estimated from the square root of the integrated, squared laser frequency fluctuation spectrum; up to the relevant displacement sampling rate[1]. As a guide, an interferometer path length of 10 m will exhibit phase changes consistent with 1 nm displacements, if the laser frequency fluctuates by 19.2 kHz; at a laser wavelength of 1560 nm.

Physical Length Comparison

We have measured the stability of the Ethernal laser frequency using a distance meter as a length scale. Phase variations of the interferometer are induced by laser frequency changes. The distance meter was set up in air with an optical path difference of 4.64m on a vibration isolated optical table. Changes in laser wavelength will be indistinguishable from changes in interferometer optical path difference caused either by physical length changes, or by changes in refractive index. Interferometer instabilities restrict the results to an upper limit on the stability of our laser wavelength.

The spectrum of measured interferometer phase shift converted to equivalent laser frequency change is shown in fig. 2 for each laser. The spectrum of the Ethernal laser is mostly flat compatible with white noise, expected to be dominated by electronics noise. There is a small cluster of peaks between 100 and 200 Hz. These may correspond to the resonant frequency of some mechanical component of our interferometer, such as the mirror.

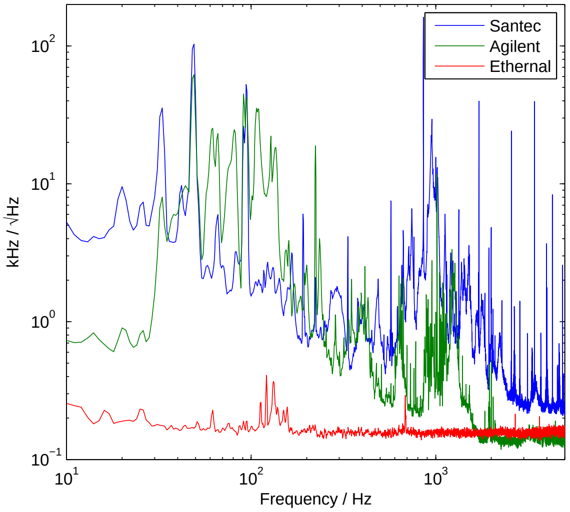

Figure 2: Frequency fluctuation spectra for three lasers measured by comparison with a distance meter.

For a system acquiring displacement measurements at 100 samples per second[2], the laser frequency fluctuations have an upper limit of 2 kHz; integrating between 10 and 100 Hz. This rises to 13 kHz when the integral is extended from 1 to 100 Hz, dominated by interferometer effects. The 2 kHz limit corresponds to a 0.1 nm error contribution to displacement measurements with a 10 m optical path difference.

Comparison of Laser Frequency

The frequency difference between two lasers can be determined by measuring a beat frequency, generated on a photo detector illuminated by both lasers. We use three lasers: One laser for fixed frequency measurements (Orbits Lightwave Model Ethernal ETH-10-1560.49-2-PZ10-T) and two tunable external cavity lasers (Agilent Model 8164A and Santec Model TSL-510); both used for ADI. The three beat frequencies were sampled at 10Msamples/s for 0.2s; limited by the buffer size of our ADC; leaving this technique insensitive below 5 Hz. The change in each beat frequency versus time is tracked with a short time Fourier transform [6]. A time-series of 0.2 s was split into pieces 100 samples (10 μs) long; each multiplied by a Kaiser window with $\beta = 1$ [7]. The Fourier transform of each piece is taken, but is subject to aliasing above the Nyquist frequency of 5 MHz. Separate aliased frequency intervals were distinguished using the amplitude roll-off due to the limited bandwidth of our photo detector (1.9 MHz). Beat

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[1] This involves converting frequency fluctuations to length artefacts, via fluctuations in interferometer phase using equation 2.

[2] We assume downsampling from a bandwidth limited (higher) acquisition rate.

frequency ambiguities were resolved up to 15 MHz. The maximum of each Fourier spectrum is plotted against time (in 10 μs steps) shown in figure 3; after ambiguities have been removed.

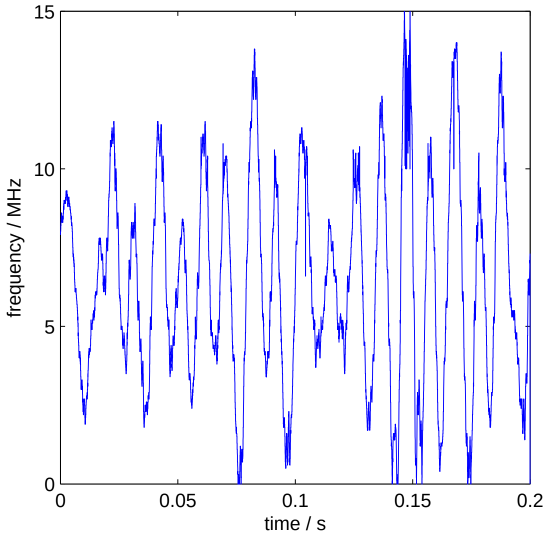

Figure 3: Unwrapped (anti-aliased) beat frequency signal for the Agilent Ethernal laser pair.

The beat frequency results are consistent with a much poorer frequency stability for the Santec laser compared to the others. This is not a surprise as this laser tunes over the largest range at the fastest tuning speed.

The beat frequency of the most stable pair, (the Ethernal and the Agilent lasers) was dominated by the fluctuations in the Agilent laser frequency. The laser beat frequency spectrum is shown in figure 4, in good agreement with the Agilent length comparison spectrum. With the same assumptions as used for the physical length comparison, the upper limit (from the Agilent laser) is 160 kHz over an interval from 10 Hz to 100 Hz.

CONCLUSIONS

Displacement measurement techniques are being developed using novel design distance meter interferometers with narrow linewidth lasers. We have studied the frequency stability of three lasers, at measurement frequencies above 1 Hz. Two independent techniques were employed and found to be in reasonable agreement.

The hierarchy of laser stability was found to be as expected, with larger tuning range lasers having less stable frequencies. The fixed frequency laser, which will provide our highest precision displacements measurements, has been shown to have a frequency stability ten times better than we require.

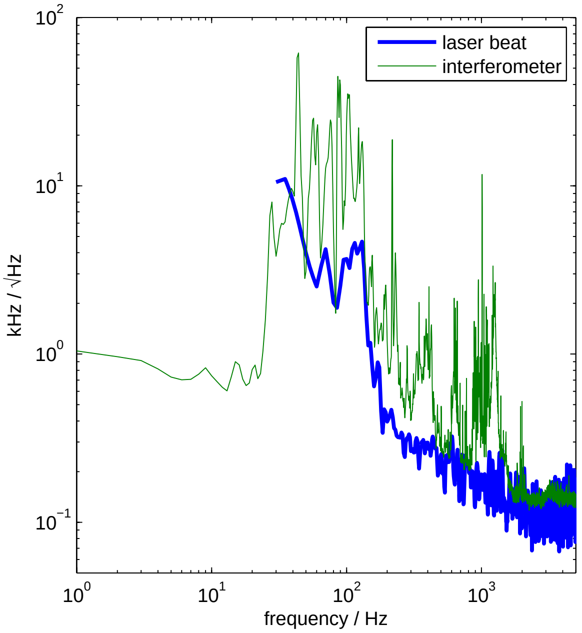

Figure 4: Spectrum of measured laser frequency difference between the Ethernal fixed frequency laser and the Agilent tunable laser (no tuning signal applied). Overlaid are the beat frequency results with the Agilent spectrum from figure 2.

ACKNOWLEDGEMENTS

This work is supported by the Commission of the European Communities under the 6^{th} Framework Programme "Structuring the European Research Area", contract number RIDS-011899 and by STFC.

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