Using Laser Interferometry to Detect Nanoscale Motion Across Macroscopic Distances

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Abstract

Laser interferometry was used in an effort to measure nanoscale vibrations in one dimension of both a chosen target as well as in the laser itself, as one component in a system for removing measurement error due to vibrations in beam position monitors along the beam line of a linear accelerator. By splitting the laser beam and varying the path lengths of the legs of its components before recombining them, a phase difference was observed, yielding a measurement of nanoscale lateral movement.

By removing this error from the beam position monitors, a more exact measurement of the position of an electron beam can be made, resulting in a more exact description of the beam's energy, a crucial element in examining data taken from particle accelerators.

Introduction

Laser interferometry uses a beam splitter and mirrors to separate a light source into two separate polarization states and then recombine them. Because each polarization state travels along a different path, at recombination the two states can be out of phase; judicious selection of each path length can result in an interference pattern as a result. More generally, the two legs will be out of phase with each other by a fraction of a wavelength; varying the length of one leg will vary this fraction. Measurement of the phase shift variation then gives information about the change in path length of each leg relative to the other. Thus, by holding one leg at a constant distance from the beam splitter, the relative distance of the other leg can be determined. Because a laser provides a coherent light source, this method of measurement can yield extremely precise measurements of change in position in one dimension.

Beam Energy Measurement

Charged particles moving in an electric field are curved proportionate to the strength of the field as well as their mass, charge, and velocity. At relativistic speeds, such curvature results in synchrotron radiation, with the amount of energy radiated per rotation given by

$$\Delta E = P\left(\frac{2\pi r}{v}\right) = \frac{4\pi K e^2 \gamma^4 \beta^3}{3r}$$

with gamma proportional to mass.

Thus, bending an electron beam in a controlled magnetic field yields two different ways of measuring the beam energy: measuring displacement of the beam itself and measurement of the synchrotron radiation.

The first and more straightforward of these is simple measurement of the beam displacement in a magnetic field. Because the charge and mass of an electron are fixed quantities and the magnetic field of an electromagnet is determined by the experimenter, measurement of the curvature imparted to the beam yields information about velocity and thus total energy of the beam, the only remaining unknown in the equation.

A second magnet of equal strength and opposite charge placed farther down the beam line will return the beam to its original angle, but displaced laterally; in this case, a measurement of the displacement of the now-parallel beam with respect to its original path is equivalent to a measurement of curvature in the single-magnet case.

Alternately, at relativistic energies (v closely approximates c, in this case), one can also measure the emitted synchrotron radiation. Using the formula above as well as the known beam parameters and magnetic field strength, one can determine from the emitted radiation the energy of the bent beam.

Uses

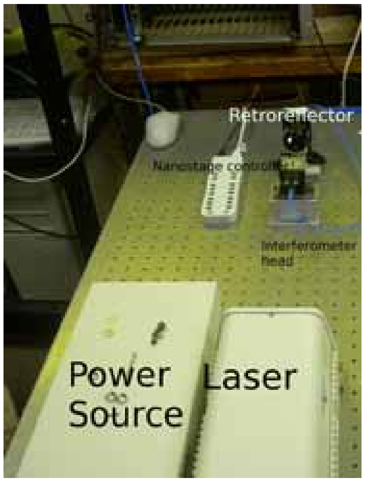
This system was originally designed to be implemented at the Stanford Linear Accelerator Center in Palo Alto, CA, for use with the T474 test beam. However, beam time was scrapped due to safety concerns with at the Accelerator Center, and the end station the project was using was removed to make room for a new project. As such, we were not able to implement our project at Stanford. KEK High Energy Accelerator Research Laboratory in Tsukuba, Japan, however, has expressed interest in using our system for future experiments.

Equipment

The laser used in our setup is a Zygo 1mW heterodyne laser with an external power source that outputs two separate beams of opposite polarization (in the horizontal and vertical planes) and two slightly different wavelengths, both of about 632nm. To split the beam, we use a Zygo interferometer head and optical pickup. Additionally, we use Thorlabs retroreflectors, and for an intermediate setup used ½ wave plates to circularly polarize the laser beam, and a Scout CCD camera for measurement of the lateral displacement of the laser.

Because of hardware difficulties, we were forced to use an outdated data acquisition system and a computer running Windows 98, resulting in limitations on the speed with which we could sample data during test runs.

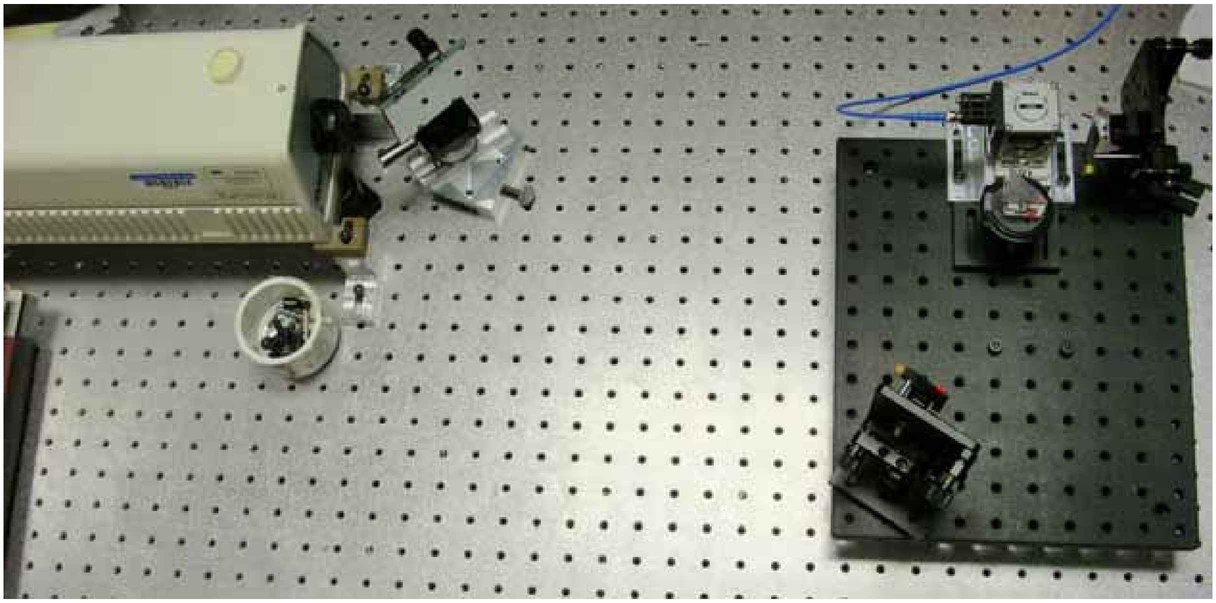
Mechanical Setup



The beam position measurement system works by reflecting one polarization state of the laser beam off of a reflector mounted onto the target to be tracked; as the target vibrates, the physical (and therefore the optical) pathlength is changed, and the change is recorded at the optical pickup. The other leg is reflected off a retroreflector mounted to the interferometer head itself, resulting in a stable pathlength.

For this setup, the retroreflector is set on a nanoscale movable stage with a nominal minimum step size of 50nm. Previous iterations used a scale with a minimum scale size of

25.4 microns; thus the computer-controlled nanoscale allows for much finer controlled movements for the test setup.



The setup pictured in the photograph above is a secondary measurement system intended to detect lateral position shift in the laser itself. Note that the retroreflectors are replaced with right angle prisms so as to keep each leg of the beam in the same vertical plane, so that the outgoing and returning beam would travel through identical amounts of glass in the central prism.

By moving the black stage in the photo laterally, we were able to move the laser through more or less glass (n=~1.5), changing the physical path length somewhat and the optical path length greatly. Unfortunately, all changes in optical path length are entirely negated by the angle made as the beam exits the glass; full working of the optics of the problem revealed that the two corrections canceled each other exactly, for all angles of incidence and for any optical material.

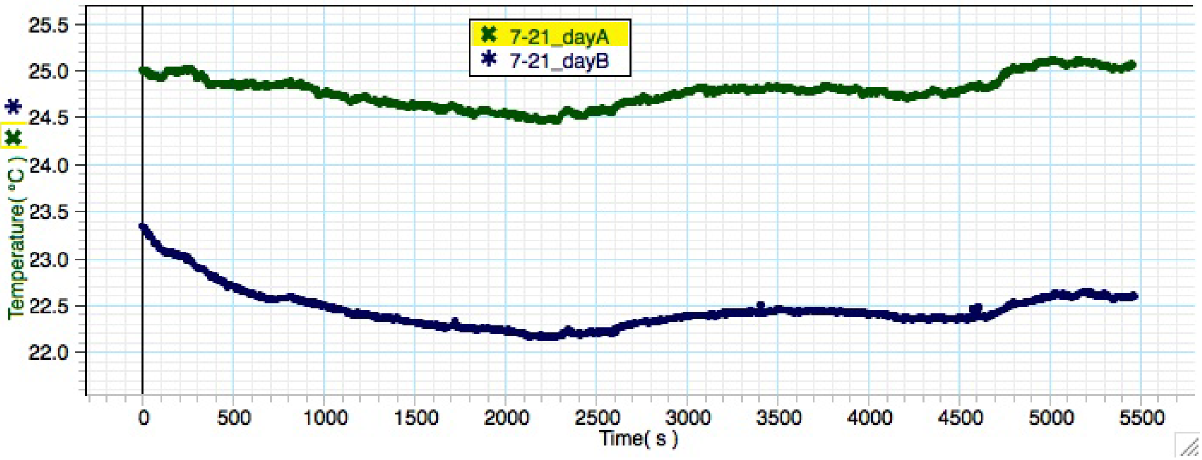
Before this calculation was carried out, alignment was a constant issue in this setup; in order to correct this problem, we added another right angle prism as shown below, with ½ wave plates added such that the beam would first be circularly polarized and then upon passing through the wave plate would emerge in a polarization state at a right angle to its original, allowing it to pass through the polarizing beam splitter unimpeded. A further two passes through the wave plate restored the original state, allowing the two beams to be recombined as before; the extra path length and distance in the same vertical plane allowed for easier alignment but did not correct the ultimate problem inherent in the setup, meaning that it had to be abandoned.

While this setup did not work, a second one using a CCD camera to record the laser’s lateral position based on its mean intensity was implemented. When a second, non-polarizing beam splitter is used in the current measurement system, a percentage of the laser is permitted to pass on in its original direction. A CCD camera is then mounted at the end of the beamline, and by recording changes in the average intensity density records the lateral motion of the laser, allowing for correction to the data based on vibrations in the laser itself.

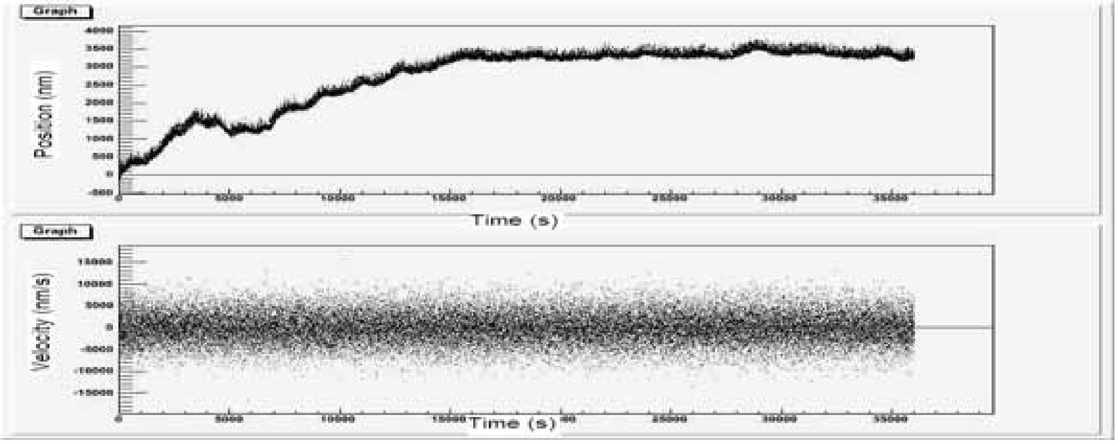
In theory, both the CCD camera setup as well as the current straightness monitor can be used across macroscopic distances of several meters or more, and this will be tested in future setups; however, as distances grow between the beamsplitter and its target, the coefficient of refraction of the air must be taken into account as an increasing correction depending on both the temperature and pressure of the air. If this is determined to be a sufficient problem, a vacuum setup may be required for more precision.

Analysis of and corrections to the data

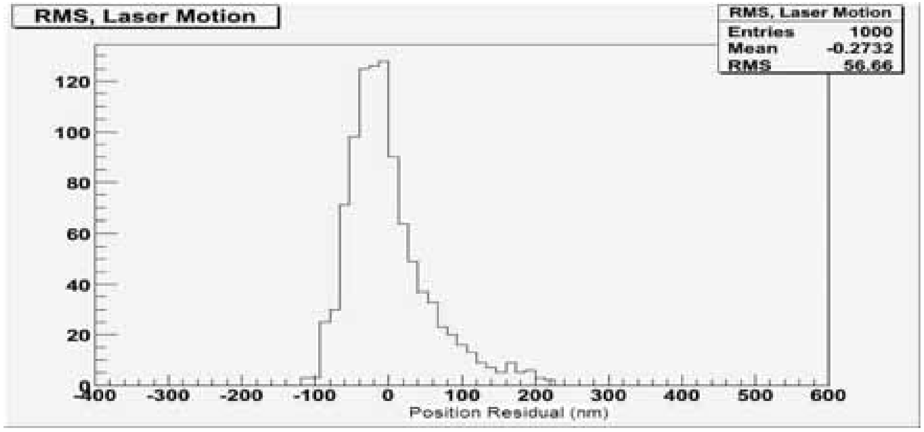
The largest of the corrections to be made to the data taken from any optical setup attuned to nanoscale precision is drift due to thermal expansion and contraction.



As shown in the graph above, the temperature in the testing room varied over ~1 degree, causing significant expansion and contraction on the nanometer scale. (Al has a coefficient of thermal expansion of 23.1 μm·m^{-1}·K^{-1} at 25° C, so even across test distances of ~.5m, thermal expansion and contraction covered distances in the tens of micrometers, a significant correction to our measurements.) Unfortunately, our temperature probes did not agree with each other exactly; however, only relative change is of real interest in calculating the thermal drift of the system, so this did not introduce a severe problem.



Analysis of the data gathered on test runs was carried out in root via programs made in C++. We recorded the position and velocity of the test position over the course of several hours, often ten or more, and also recorded the RMS of the position data. The first hour or so of data taking generally showed a large shift in position due to the cooling effect caused by as many as five people leaving the room as well as turning the lights off, which caused the temperature to drop by as much as a degree, resulting in the aforementioned thermal contraction of the system.



Data was gathered at the rate of one event per second, meaning that one standard 10-hour run gave 36,000 data points, a fairly large sample. Larger sample sizes were taken, but did not show any significant differences. Given better computing hardware, we would have been able to take data more rapidly to allow more points per unit time, but for current purposes this was unnecessary.

Future Work

In the coming months, we plan to extend our system by using a beam splitter to divert a percentage of the incoming laser beam so that it is not reflected back into the pickup and is instead free to continue on downstream. Using this diverted beam, we plan to add copies of the existing system, allowing us to measure the position of multiple beam position monitors simultaneously. Such simultaneous measurement would allow not only for more data to be produced, but also to calculate a relative position shift between beam position monitors, allowing for more accurate measurement of the movement of the actual electron beam.

KEK Linear Accelerator Laboratory in Tsukuba, Japan (高エネルギー加速器研究機構*Kou enerugii kasokuki kenkyuu kikou*) has expressed an interest in our measurement system for vibration detection in the vertical direction of their beam position monitors. As such, we hope to have a full system running and able to take data by the the end of the Fall semester of 2008, in time for the KEK board of directors' review.

Conclusion

As the first step in a larger system, the laser interferometry system described can be used to accurately measure vibrations to an accuracy on the order of tens of nanometers (10^{-8}m), and the CCD camera system is capable of tracking the motion of the laser itself, helping to eliminate error in two separate degrees of freedom. By implementing such a system in a linear accelerator system, measurement error could be reduced greatly, ultimately resulting in more accurate measurement of the energy of an electron or positron beam, thereby resulting in more effective experiments and better analysis of their outcomes.

Further Reading

For further information concerning the CCD camera setup, data and results, see Thomas Rehagen, *Development of a Straightness Monitor Using Laser Interferometry: The CCD Camera Approach.*

For information regarding software, simulation, and an overview of linear accelerators, see Matthew Lucia, *Development of a Straightness Monitor Using Laser Interferometry.*