Development of a Straightness Monitor Using Laser Interferometry: The CCD Camera Approach

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Abstract:

This paper is concerned with the measurement of nanoscale vibrations in one dimension using laser interferometry. Using an interferometer to split a laser beam and recombining the beam after bouncing one off of a set target and the other of the object being monitored for vibration allows the measurement of phase difference to find a difference in position in the laser of the object. A set of CCD Cameras can be used to monitor the motion of the laser.

This method can be used to measure the displacement of an electron or positron beam in a linear accelerator after it is bent by a series of magnets. This increased accuracy in measurement of position allows for a better measurement of the energy of the electron beam, an important piece of information for particle physicists.

As research in physics moves forward, the need for ever better technology and experimental methods becomes more and more apparent. This is particularly true in the case of particle physics, where the probing of physical phenomena on such a small scale can only be done with huge accelerators and powerful detectors. Currently the most powerful accelerator is the Tevatron, located at Fermi National Laboratory. Despite the great amount of energy provided by this proton-antiproton collider, physicists still look to move forward to the next generation of more powerful colliders to explore the realm of particle physics even deeper. Already, the physics community is preparing for the first runs on the Large Hadron Collider (LHC) located by Geneva on the Swiss-French border. This new collider will be able to accelerate particles seven times the energy of the Tevatron. This new energy increase will provide physicists great opportunities to test theories that were previously untestable because of the limits of previous accelerators.

The LHC is just the next link the chain of technological and experimental advances in particle physics. Already particle physicists are coming up with designs to build even better accelerators. One of the main problems with the Tevatron and the LHC is that they both collide protons or antiprotons, which are not fundamental particles, but are composed of several smaller pieces. Because of this, the collision of protons and antiprotons is quite messy, because the extra quarks and gluons inside the protons and antiprotons get in the way of the primary collision. A more ideal collision would be one between fundamental particles, like electrons or positrons. Such a collision would be much cleaner and easier to understand. A circular collider like the Tevatron and the LHC could not be used to accelerate electrons and positrons, though. The problem lies in the fact that when particles with charge accelerate, they give off energy in the form of radiation. In circular colliders, the particles are constantly undergoing centripetal acceleration, and thus, they are constantly giving off energy. This is not as much of a problem for large particles like protons and antiprotons, but for small particles like electrons and positrons, this radiation significantly affects the energy that they can reach. Current particle accelerators cannot accelerate electrons to energies much higher than 100GeV.

To solve this problem, physicists have designed linear colliders in which the particles do not curve around in a circle, but go in a straight path towards their target. This design also has its challenges. Instead of receiving a small kick each time the particle goes around the circle, the particle must receive all it energy in one pass. So a linear accelerator is going to need to be long and accelerate the particle very quickly. Indeed, plans for a new International Linear Collider call for a 40km beamline with an electrical potential of $25\frac{MV}{m}$ along it.

Another challenge that a linear collider presents for particle physicists is measuring the energy of the beam. While the energy of a beam in a circular accelerator can be determined by the strength of the magnetic field used to bend the beam, no such method is readily available in a linear accelerator. One method of measuring the beam energy in a linear accelerator is being worked on a group from University College London. They are testing a design for a chicane of four bending magnets. By placing these magnets in the beamline, the beam will be directed from its path by some displacement (dependent on the energy of the beam and the strength of the magnetic field) and then redirected back into its original path. So by measuring the displacement of the beam and the magnetic field strength, the energy of the beam can be calculated.

The largest challenge to this idea lies in measuring the displacement of the beam. The displacement of the beam is quite small, on the order of only 5mm. For accurate analysis of the data, the error on the energy can only be one in ten thousand, so the position must be measured on the scale of 100's of nanometers. Inside the beamline, the position of the beam can be measured using microwave cavities called beam position monitors (BPMs). The BPMs are able to measure the position with respect to the beamline with the appropriate precision, but the beamline itself can vibrate during the operation of the accelerator. Thus, a system is needed to track the motion of the beamline with respect to a stationary reference point. One proposed system to do this is an application of laser interferometry.

Our lab group began work on such a system over this summer. One of the first projects was the creation of a computer simulation of a laser in the interferometer system. Code was written using the language C++ that allowed a range of optical setups with reflective and refractive surfaces as well as free propagation through the air. After telling the computer where to put the optical devices, the initial beam position and direction of the laser were entered, and the computer would output the final position, direction and total optical pathlength of the laser. This program has been debugged and used to model our different optical setups in our work with laser interferometry.

The actual setup used to monitor the motion of the BPMs is fairly simple. We used a Zygo 1mW heterodyne laser with an external power source that outputs two separate beams of opposite polarization and two slightly different wavelengths, both of about 632 nm, a Zygo interferometer head, optical pickup and Thorlabs retroreflectors. The system works by using the interferometer to reflect one polarization state of the laser beam off of a retroreflector mounted on the object to be monitored (in our case the BPM) and recombined with the other polarization state that was reflected off of a retroreflector mounted to the interferometer. If the object moves, the retroreflector attached to it will move, changing the optical pathlength of the associated polarization state. The recombined beam is then captured by the optical pickup and the computer measures the difference in wavelength between the two polarization states to find any relative changes in position of the object. This setup will be tested using a nanoscale moveable stage with a nominal minimum step size of 50nm. A retroreflector will be mounted on the moveable stage so that a motion of the object can be simulated with well controlled steps by the stage. (See Figure 1)

One problem with this setup is making sure that the laser and interferometer don't move. Any motion of the laser or interferometer would result in a bad distance measurement of the object to be measured. Originally we tried to use another setup with the same laser to track any motion of the beam. We split the beam with another interferometer and put a glass wedge in the beam path before the retroreflector to change the optical pathlength as the laser moved back and forth across the wedge. However, the change in optical pathlength through the wedge are cancelled by the change in actual distance to the retroreflector when the laser moves back and forth, so this setup did not work as intended. After a number of similar optical setups, the idea was abandoned, and a new method of tracking the motion of the laser was created.

The next (more successful, but still in development) method of tracking the motion of a laser beam is to point the laser at a CCD camera. After decreasing the intensity of the beam to a level that the camera can handle, programs can be written to find the centroid of the laser by examining the light intensity at each pixel and track its motion in the vertical and horizontal planes. All of the tests performed so far in this project have the setup of a laser pointed at a Basler Scout CCD camera of 1024x756 pixels with a size of 4.65x4.65 micrometers at varying distances. The CCD camera has been isolated from background light by a being placed in a box with a small hole for the laser to pass through. The image taken by the camera is seen in Figure 2.

A LabView interface is used to run the CCD camera, analyze the data and write it to a file. We are using four different algorithms that independently find the centroid of the laser. In the future, these methods will be tested to find which is more accurate in finding the centroid by placing the CCD camera on a moveable stage and seeing which algorithm tracks the motion best. The first is similar to the method used in quadrant detectors. In this method, the image taken from the camera is separated into four quadrants and the intensity of the laser is summed in each of the quadrants. Then taking the intensity to be focused in the center of each quadrant, the centroid of the laser can be found by comparing the relative intensities of adjacent quadrants. For example, the method for finding the horizontal component of the centroid position, that is, the number of pixels from the left side of the image to the centroid, when comparing the top two quadrants is given by the following formula:

$$D(\text{centroid}) = D1 + [I2 / (I1 + I2)] * D12$$

where D1 is the (horizontal) number of pixels from the origin to the center of the left quadrant, I1 is the intensity in the left quadrant, I2 is the intensity in the right quadrant, and D12 is the number of pixels between the centers of the two quadrants. This same formula can be used to compare the bottom two quadrants to also find the horizontal component of centroid position. Similarly, the vertical component of centroid position can be given by comparing the left or right two quadrants. The same idea can be used so that:

$$D(\text{centroid}) = D1 + [I2 / (I1 + I2)] * D12$$

where D1 is the (vertical) number of pixels from the origin to the center of the top quadrant, I1 is the intensity in the top quadrant, I2 is the intensity in the bottom quadrant, and D12 is the number of pixels between the centers of the two quadrants.

The second method uses the same idea as a center of mass calculation. Taking the origin to be in the top left corner of the image, the intensity of each pixel is divided by the total intensity of the entire image and then multiplied by the number of pixels from the origin in the horizontal plane to find the horizontal coordinate of the centroid and in the vertical plane to find the vertical coordinate. So the horizontal coordinate is given by the formula:

$$D(\text{centroid}) = (\Sigma I_i * r_{xi}) / (\Sigma I_i)$$

where I_i is the intensity of each pixel and r_{xi} is the horizontal distance from the origin to each pixel. Similarly, the vertical coordinate of the centroid position is given by the formula:

$$D(\text{centroid}) = (\Sigma I_i * r_{yi}) / (\Sigma I_i)$$

where I_i is the intensity of each pixel and $r_{yi}$is the vertical distance from the origin to each pixel.

The third and forth methods are extensions of the second method. In the third method, a lower threshold is put on the intensity, so that all intensities below a specified level are ignored. Then the algorithm used in the second method is applied to find the coordinates of the centroid. Similarly, the fourth method ignores the intensities of all pixels that are a certain distance away from the centroid as determined by the second method. Thus, a circle is drawn around the pixel calculated by the second method, and all pixels outside of the circle are ignored. The algorithm used in the second method is again applied to find the coordinates of the centroid. These four methods are being compared to find the best algorithm to track the centroid of the laser beam from the image taken by the CCD camera.

Experiments are currently being done to find the error on these measurements of the centroid position. In order to do this, we have been studying the root mean square (RMS) of the recorded centroid position over time. The error on position is directly related to the RMS, so lowering the RMS means that the error on the position measurement will also be lower. In trials when the distance between the laser and the camera is .5 meters, the RMS of the centroid position is averaging at just over .2 pixels. (Figure 3) However, the RMS increases as the distance from the laser to the camera increases. After a certain distance the RMS begins to level out and become fairly constant as seen in Figure 4. More experiments are planned to confirm this trend and establish if the RMS actually approaches a point asymptotically. One method that could curb this increase of RMS with distance is to build a vacuum chamber to put the laser beam through. We plan to test this idea in the future.

CCD cameras can be used to monitor the angular and translational motion of the laser by using a beam splitter to redirect part of the beam into a camera upline, while having the rest of the laser terminate at a camera downline. (Figure 5) The cameras can then track the changes in position from each of these two locations. By comparing these two measurements, and calculating the error on the measurements, a computer can tell if the laser has stayed in the same position, moved laterally or rotated.

In this way the motion of the laser can be monitored, providing more accurate measurements of the motion of the BPM. These measurements can in turn be used to calculate the energy of a beam in a linear accelerator to a greater degree of accuracy. This will help particle physicists better understand what is happening inside the collisions that take place inside of linear accelerators, and help keep experiments moving forward to probe new aspects of the universe.

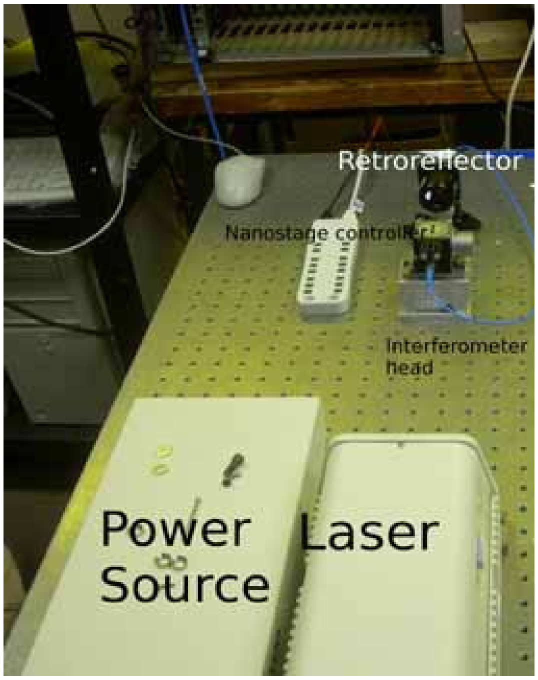

Figure 1. Interferometer/Nanostage Setup

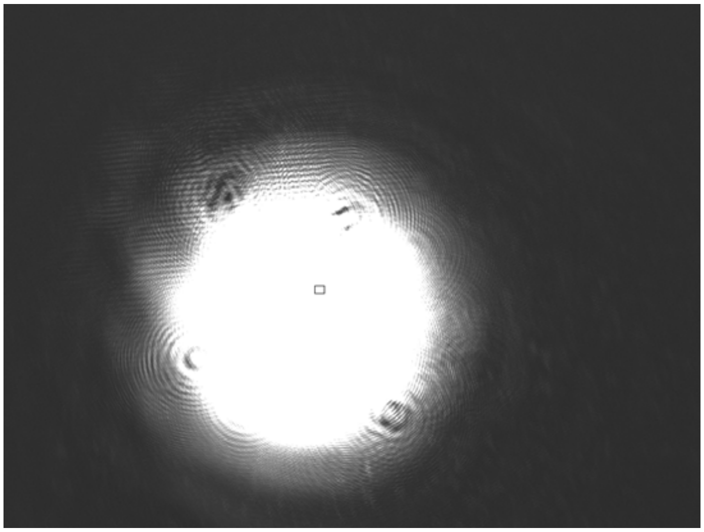

Figure 2. Image of Laser in Camera

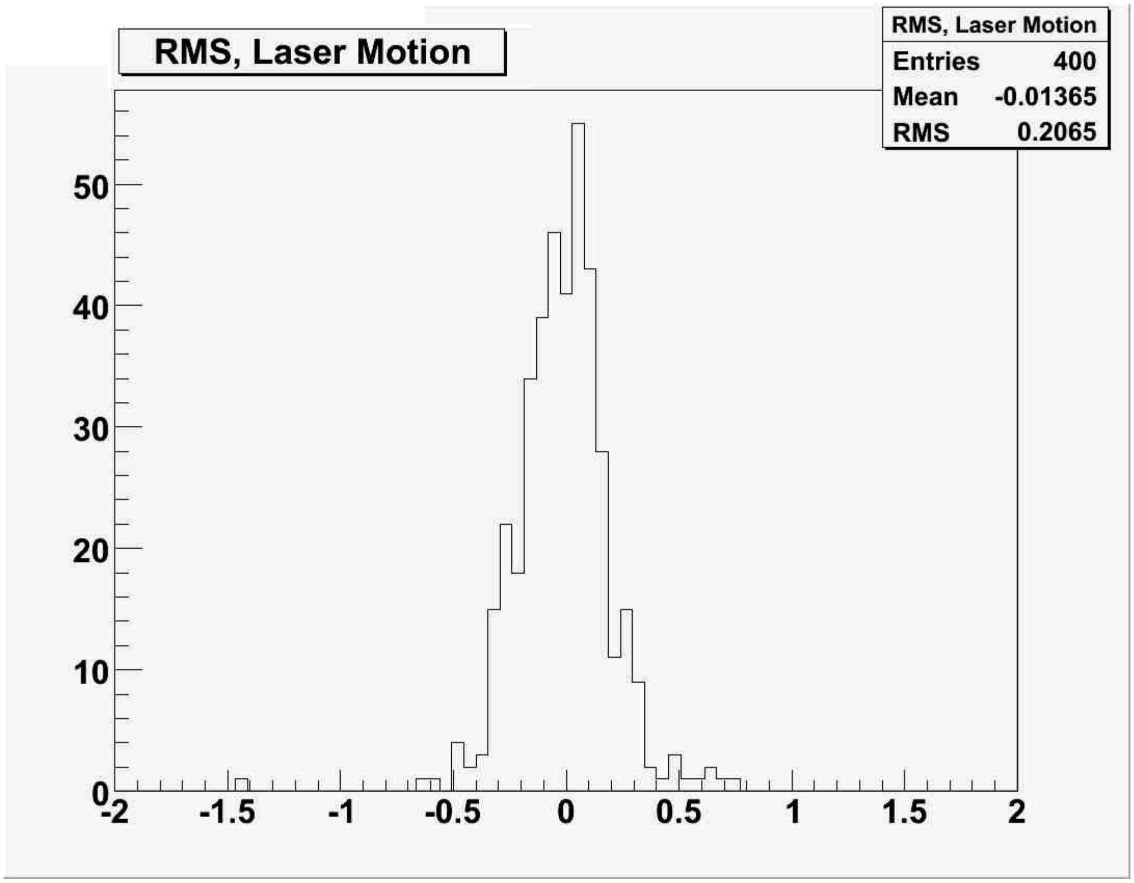

Figure 3. RMS of Test Run when Distance from Camera to Laser = .5 meters

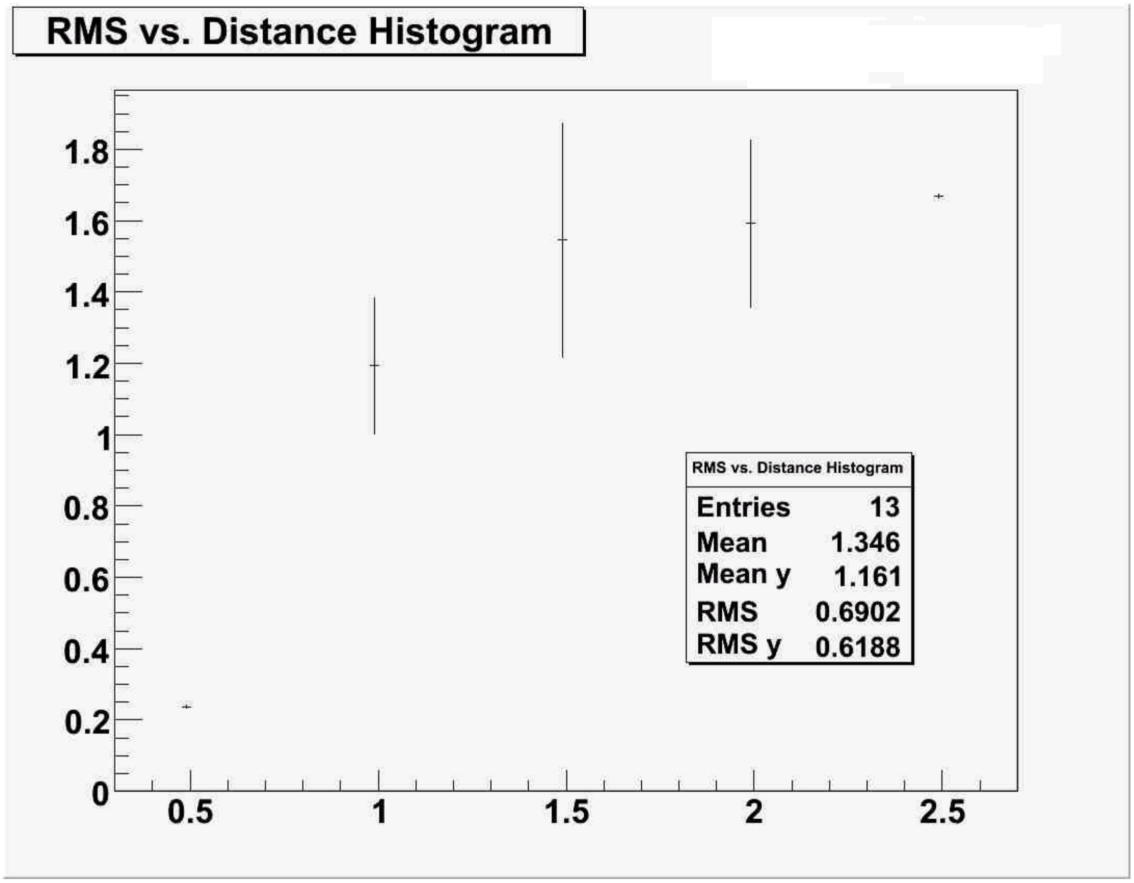

Figure 4. RMS vs Distance

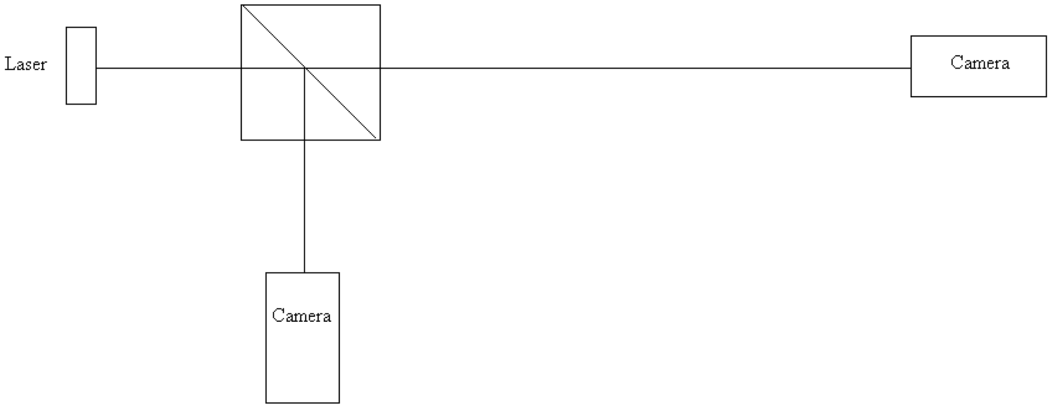

Figure 5. Two Camera Setup

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