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Timing Between Streak Cameras with a Precision of 10 ps

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Abstract

The laser beams irradiating a target at the Nova laser facility comprise a set of ten simultaneous events. Two streak cameras, whose resolutions are 40 ps, record the power history for each beam, five beams to a camera; their time bases are cross-timed with a fiducial pulse. Analysis of data recorded for target experiments conducted over a six month period show the precision for cross-timing signals between two streak cameras to be ±9 ps and for characterizing a single temporal feature of a pulse to be ±5 ps. Beam synchronization at the end of six months was within 20 ps of the synchronization at the beginning of the experiments. A beam timing shift greater than 25 ps can be detected on a single laser shot; shifts of 10 to 20 ps require several shots to detect.

1. INTRODUCTION

The 35-TW, 10-beam Nova laser at the Lawrence Livermore National Laboratory (LLNL) is used for inertial confinement fusion (ICF) and dense plasma research.[1] Small millimeter-size targets are irradiated and compressed with nanosecond-length pulses of 351-nm light. We use the temporal relationship between the target irradiation and target emissions to help verify models that describe the coupling of laser energy to a target and the hydrodynamics of a target implosion. At Nova, two optical streak cameras record the power history for the incident-laser beams, five beams to a camera; information about target emissions such as x rays, neutrons, charged particles, and scattered light are recorded on separate instruments. An optical fiducial system provides signals for temporally relating the time bases of the various instruments.[2]

The timing of the laser beams is adjusted so that all beams arrive at the target simultaneously. Thus, the two images recorded with the incident-beam streak cameras for each target experiment form a unique data set that represents ten simultaneous events. Data from a set of target experiments can be used to evaluate the precision with which events recorded on separate streak cameras can be temporally related under actual Nova operating conditions. The average time of the five beams recorded on one camera forms a good reference time to which each of the ten beams can be compared. A statistical analysis of the data is used to show the relative timing that is achievable between signals recorded on separate cameras, to provide some insight about the long term stability of the beam timing, and to detect changes in beam timing for this large laser system.

In this paper, the following section briefly describes the Nova laser, how its beams are synchronized, and how a fiducial pulse relates the time base of one streak camera to another. Section 3 describes a typical image recorded with a streak camera and how such an image is analyzed. Section 4 discusses how data from Nova target experiments, which we call "shots," are analyzed; and results are presented which show the timing capability of the streak cameras and their ability to monitor the synchronization of the laser beams.

2. NOVA LASER SYSTEM

2.1 Laser beam timing

The Nova laser system is configured in a master-oscillator power-amplifier architecture.[1] One 1.054-μm oscillator pulse is amplified and split into ten spatially separate but temporally identical laser beams at a low power level. Then, each beam is amplified to its final power by a series of rod and disk amplifiers. After the final amplifier, each beam passes through a pair of frequency-conversion crystals which convert the laser wavelength to the third harmonic (0.35 μm) of the oscillator wavelength and a lens which focuses the beam onto a target at the center of the 4-m diameter target chamber.

The ten beams, each of which propagates approximately 75 m between the oscillator and the target chamber, start with a precise temporal synchronization because each beam comes from the same master oscillator pulse. To arrive at the target simultaneously, each beam must have its optical path length carefully adjusted. Once the path lengths are adjusted, synchronization is expected to remain until a laser component is added or removed or the position of a component is changed.

Unfortunately, small path length changes occur frequently in the Nova laser system. Laser maintenance includes an ongoing program for rebuilding and changing laser amplifier modules. Module-to-module variations in laser-glass thickness can cause a 20-ps shift in beam propagation time. The temporary removal of an amplifier requires adjustments to the gain of the remaining amplifiers to maintain beam-to-beam energy balance and the insertion of approximately 230 ps of time delay to maintain beam synchronization at the target. Occasionally the timing of an individual beam is changed by several nanoseconds for use as a diagnostic probe. After such a shot, beam synchronization is re-established by returning timing mirrors to their reference positions. Accurate compensation is routinely made for such path-length adjustments. However, when an error is made, it is not discovered until the next synchronization check. There are many causes for small shifts in beam timing for a large laser system such as Nova.

2.2 Beam synchronization

A series of low-power target shots are taken to adjust the synchronization of the laser beams arriving at the center of the Nova target chamber. Gold disk targets 2 mm in diameter are irradiated with 100-ps full width at half-maximum (FWHM) Gaussian pulses from five of the beams, each focused at a different spot along a line on the surface of the target. Each beam creates a plasma that radiates visible light that is imaged to an optical streak camera. A laser shot is taken, and the relative timing of the beams is determined. Then, the beam delays are adjusted to make the beams simultaneous. Since not all beams can be imaged at the same time, a series of shots must be taken to synchronize all ten beams. Initial shots determine the required time shifts for the individual beams, later shots confirm that the beams are synchronized to about ±50 ps.

A problem similar and related to beam synchronization is the monitoring of the synchronization for the ten beams. Periodically, the beams are checked for synchronization, and timing is adjusted if necessary. However, this task is performed infrequently because the method used takes time away from other target experiments. When a shift in beam timing does occur, it is typically not discovered until the next synchronization check. When a synchronization error is detected and corrected, there is no indication of when synchronization was lost. Beam timing errors greater than 200 ps have existed after the removal of an amplifier module.

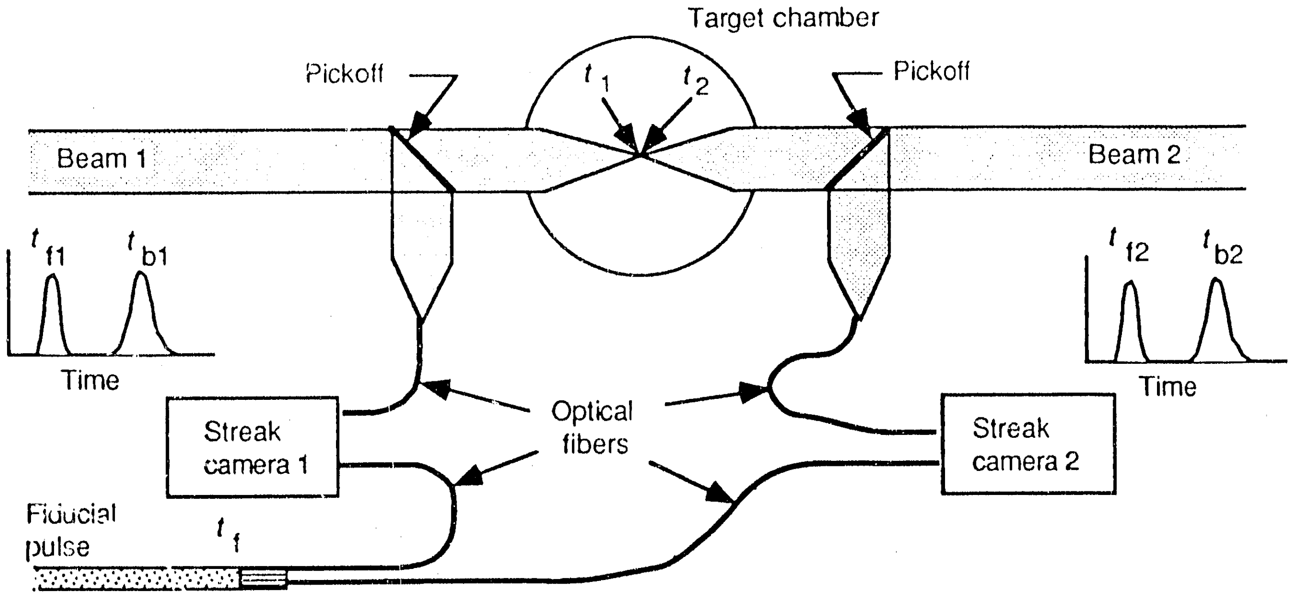


Figure 1. Experimental setup showing the concept of the fiducial system used for cross-timing streak camera time bases.

2.3 Fiducial concept

A set of diagnostic instruments may have their time bases related to each other by the use of a fiducial pulse. Figure 1 illustrates the concept of the fiducial system used at the Nova laser facility. In this example, power from each of the two incident laser beams is sampled and recorded with a separate streak camera. Samples of the pulses which arrive at chamber center at times t_1 and t_2 arrive at streak cameras 1 and 2 at times t_{b1} and t_{b2}, respectively. (The subscript b indicates a recorded beam time.) A single optical pulse, referred to as the fiducial pulse, relates the time bases of the two streak cameras. The fiducial pulse is split into several less intense pulses and distributed to the various diagnostic instruments through low-dispersion optical fibers. The time at which the fiducial pulse is observed at a streak camera relative to the time t_f when it is injected into the fiducial system remains fixed if the transmission path between the point-of-injection and the detector remains constant. The fiducial signals are recorded by cameras 1 and 2 at times t_{f1} and t_{f2}, respectively.

In general, a fixed time delay temporally relates a signal recorded with a streak camera to the event being observed. Let us define the time intervals Δt_{Ai} and Δt_{Bi} as the propagation delay of laser beam i between the signal pickoff point and the target and between the pickoff point and the streak camera, respectively. Similarly, let us define the time interval Δt_{Cj} as the fiducial pulse propagation time between the fiducial injection point and streak camera j. The following set of equations relate the four recorded signal times to the time of the actual events shown in figure 1:

$$t_{b1} = t_1 - \Delta t_{A1} + \Delta t_{B1} \ ,$$

$$t_{b2} = t_2 - \Delta t_{A2} + \Delta t_{B2} \ ,$$

$$t_{f1} = t_f + \Delta t_{C1} \ , \qquad \text{(Eqs. 1)}$$

$$t_{f2} = t_f + \Delta t_{C2} \ .$$

Equations 1 may be combined to obtain the following equation for the absolute time difference between the two events:

$$t_2 - t_1 = (t_{b2} - t_{f2}) - (t_{b1} - t_{f1}) + C_{21} \ , \qquad \text{(Eq. 2)}$$

where

$$C_{21} = (\Delta t_{A2} - \Delta t_{A1}) - (\Delta t_{B2} - \Delta t_{B1}) + (\Delta t_{C2} - \Delta t_{C1}) \ . \qquad \text{(Eq. 3)}$$

Equations 2 and 3 show that the determination of the time interval between two laser pulses arriving at the center of the target chamber depends on the time intervals between the recorded laser pulses and their respective fiducials and on a constant, which depends on system pulse propagation delays. The value of the constant term is best found by observing synchronized laser pulses for which $t_1 = t_2$. This avoids the propagation of errors associated with summing together measurements of the individual propagation delays. The number of calibration shots and the precision of the synchronization determine the accuracy of C_{21}. Long term stability of the calibration depends on the stability of the individual path lengths that define C_{21}. For this reason, physical control of these paths is critical. A short path a few meters long with few optical components is much easier to control than a long 75 m path with many optical components. It is for this reason that the incident-beam pickoff points are placed as close to the target chamber as possible, after the final amplifiers but before the frequency conversion crystals and focussing lenses.

3. EXPERIMENTAL SETUP AND DATA

Incident-beam data were recorded for ICF implosion experiments conducted over a six month period. Shot data were recorded with a setup similar to that shown in figure 1, only five incident beams rather than one were recorded per camera. Standard

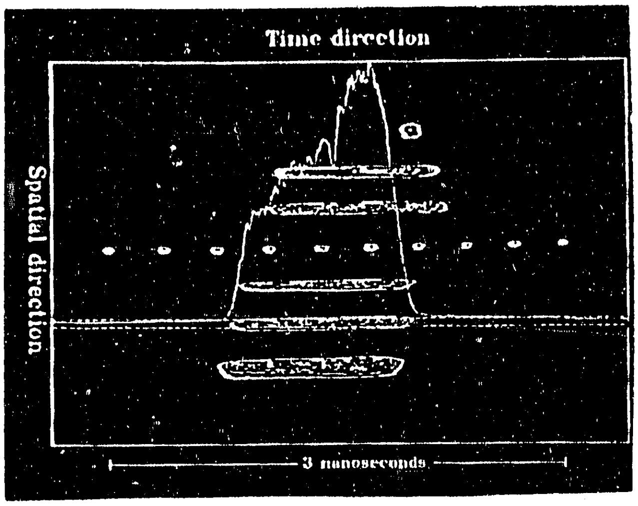


Figure 2. Typical streak camera image. Signals from top-to-bottom are the fiducial, beam 1, beam 3, time-mark generator, beam 5, beam 7 and beam 9. Each signal is analyzed to obtain an amplitude versus time plot like the one for beam 7 shown superimposed on the image.

LLNL optical streak cameras equipped with S1 photocathodes and CCD readouts were operated with temporal resolutions of about 40 ps. Each camera recorded seven time dependent signals: sampled portions of five incident 1.05-μm laser beams, a fiducial pulse, and a series of time-mark-generator pulses. The Nova laser beams are number 1 through 10. One camera recorded signals from the odd-numbered beams while the other camera recorded signals from the even-numbered beams. A typical streak camera image is shown in figure 2.

Each image was analyzed to obtain a set of temporal profiles that are similar to a set of oscilloscope traces that show signal amplitude versus time. Image analysis includes corrections for spatial variations in streak camera sensitivity, nonlinearities in the streak camera time base, and misalignment between the streak tube extraction grid and deflection plates.

Figure 3 shows samples of the two laser-pulse shapes and the fiducial pulse that were used for the implosion experiments. Each 1.05-μm laser pulse was converted to 0.35-μm pulse between the pickoff point and the target by frequency conversion crystals. Even though the conversion process is a nonlinear function of beam intensity, the 1.05- and .35-um pulse shapes are similar because each pulse shape consists of 100-ps transitions between nanosecond intervals of nearly constant intensity. While the relative amplitude of the low-level pedestal to the main pulse may change, the time of the sharp transition does not. The fiducial signal comes from a single, 1.05-um, 100-ps Gaussian fiducial pulse that is split into several less intense pulses and transmitted to the streak cameras through low-dispersion optical fibers. An optical time-mark generator provides a series of .8-μm, 100-ps wide optical pulses spaced 333-ps apart for checking the sweep rate of the streak camera time base.

Only laser pulses with a distinct temporal feature can be included in a statistical analysis to demonstrate cross-timing between steak cameras and the ability to detect timing shifts. The laser pulse shapes for implosion shots all featured a 100-ps rise time between background and a relatively constant power level, which lasted at least 1 ns. The single-point timing feature used to characterize these pulses is the instant when the laser pulse reaches an amplitude of one half its initial step height. The 100-ps FWHM Gaussian fiducial pulse is characterized by the time midway between the half-maximum amplitude points on the leading and trailing edge of the pulse.

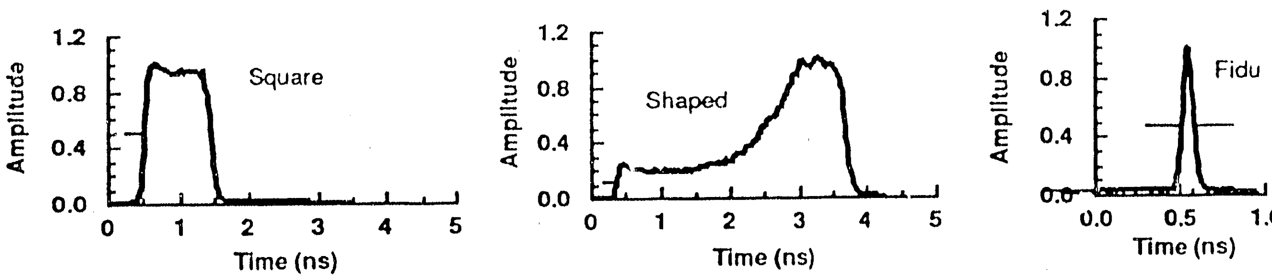


Figure 3. Typical laser and fiducial pulse shapes.

4. Statistical Analysis and Results

The precision with which streak camera time bases can be cross-timed and the stability of laser-beam timing can be determined from a statistical analysis of the incident-laser data taken for many laser shots. Once the laser beams are synchronized, they are expected to be remain synchronized until an adjustment is made to an optical path. If no change occurs in the optical path between the beam pickoff point and the target or the path between the pickoff point and the streak camera, then any change in beam timing observed on the streak camera represents a change made in the optical path of that beam. Best beam synchronization exists for target shots taken immediately following a set of beam synchronization shots. Over a period of time, with the replacement of amplifiers and optical components, the relative timing of individual beams will shift.

Relative beam timing is determined with a two pass analysis technique. The first pass identifies when individual beams experienced timing shifts and which individual data points are potentially bad. In the second pass, calibration constants are calculated and beam times and timing shifts are estimated.

For the first pass, relative beam timing is assumed to remain unchanged over the entire shot series. For each shot, all beams are assumed to strike the target simultaneously. One beam is selected as the reference, and average calibration constants for the other nine beams are calculated from the entire set of data. Then, the beam times relative to the average time of the odd-numbered beams are determined for each shot. Shifts in beam timing and suspicious data points are fairly easy to locate with plots of beam time versus shot number; finding the cause for a shift is often much more difficult. As an example, figure 4 shows the relative times for beams 7 and 8 versus shot number. Both beams show timing shifts for shots 18 through 20 that are caused by failure to correct data recorded at a slower sweep rate for misalignment of the streak tube extraction grid and deflection-plates. The shift in timing for both beams at shot 48 was caused by a 500-ps delay in the reference beam (beam 3), which was used as a diagnostic probe for this shot. The shift in beam 8 timing at shot 58 was caused by a 100 ps adjustment during a synchronization check. For shots 64 through 67, all even beams showed nearly an identical shift which was traced to improper analysis of a weak fiducial pulse. Besides, these shifts, two unexplained shifts also occurred during this shot sequence: beam 7 shifted at shot 32, and beam 8 shifted at shot 30.

For the second pass, we assume that occasional discrete changes in path lengths occur. The proper data from which to calculate a beam calibration constant comes from the shots between a synchronization series and the first identifiable time shift in that beam. New calibrations are calculated for each beam, and the beam times relative to the odd-beam cluster average are recalculated for each shot. Then for each beam, average time shifts are calculated for each shot group identified in the first pass. Figure 5 shows the beam times and average times versus shot number for beams 7 and 8. The 75-ps shift in beam 8 timing at shot 30 and the 100-ps correction made at shot 58 are easy to detect as is the 40 ps timing shift for beam 7 at shot 32.

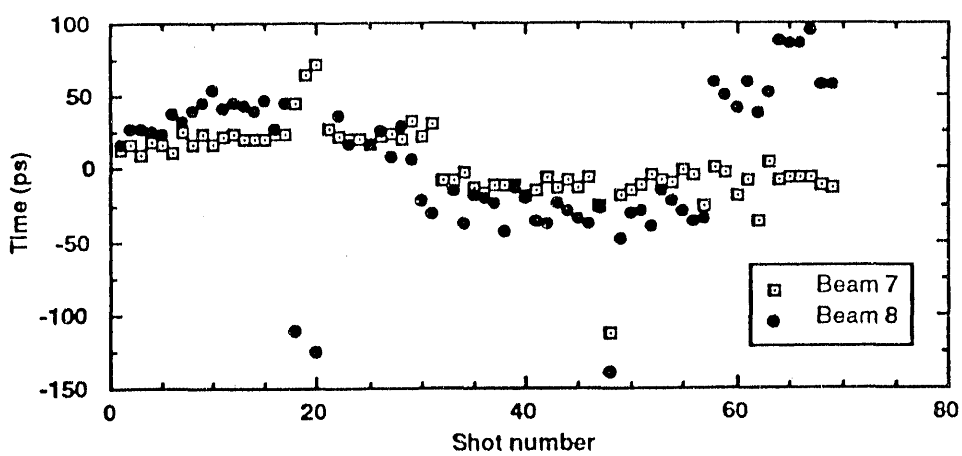


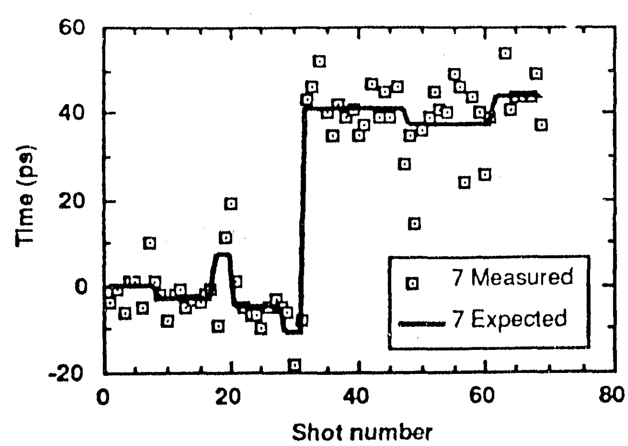
Figure 4. First-pass beam times relative to the average time of the odd beams versus shot number for beams 7 and 8. Times calculated during the first pass of the data analysis identify when timing shifts occurred.

We define the expected beam time is the beam time at the synchronization check plus any identified timing shifts and the beam timing error Δt as the difference between the experimentally determined beam time and the expected beam time. The standard deviation $\sigma_{\Delta t}$ of the timing shift represents the precision with which a beam can be timed relative to the average time of the odd beam cluster. For an even-numbered beam, $\sigma_{\Delta t}$ represents the precision with which a signal recorded on one camera can be timed to the time base of another camera; for an odd-numbered beam, $\sigma_{\Delta t}$ represents the precision with which an individual beam can be characterized by a single-point timing feature.

The values for $\sigma_{\Delta t}$ clearly show an odd-even effect: $\sigma_{\Delta t}$ is 5 ps for the odd beams and 9 ps for the even beams. Two factors influence these values: the precision with which the time of a single pulse can be characterized and the number of time measurements required to make the beam time determination. For the odd-numbered beams, only one time, the beam time, must be measured. But, for the even-numbered beams, three measurements must be made: the beam time and two fiducial times. Because the rise time of the laser pulse and the fiducial pulse are similar, the measurement error for each pulse is expected to be comparable and $\sigma_{\Delta t}$ for the even beams is expected to be $\sqrt{3}$ times greater than for the odd beams. The 9 ps standard deviation measured for the even beam represents the single shot precision with which two events recorded with separate streak cameras can be cross-timed.

Another way to show the cross-timing error introduced by the the fiducial pulses is to compare the average time of the even beams to the average time of the odd beams for each shot. (See figure 6.) The standard deviation for the average time of the even beams represents the standard deviation caused by two fiducial pulse time measurements. Since $\sigma_{\Delta t}$ for the average cluster time is 7.25 ps, each fiducial measurement is made with a precision of 5 ps.

The shift in beam timing over the six month span of these shots is an indication of the long term stability of the beam timing. From data like that shown in figure 5, beam timing shifts that occur after the initial synchronization shots are easy to identify. Beam 8 had the largest shift; between shots 30 and 58 it was out of synchronization by 70 ps. The timing shift was discovered and corrected during a periodic synchronization check which occurred after shot 57. Beam 7, which shows a 38-ps shift in one discrete jump at shot 32, did not show up as being out of sync with the other beams when synchronization was checked at shot 57. There are two possible explanations: either the synchronization method is not sensitive enough to spot a 40-ps shift in beam timing, or the length of an optical path bringing either the sampled laser beam or the fiducial pulse to the streak camera changed by about 1 cm while beam timing remained unchanged. For each beam, except 7 and 8, beam timing after six months had changed less than 25 ps.



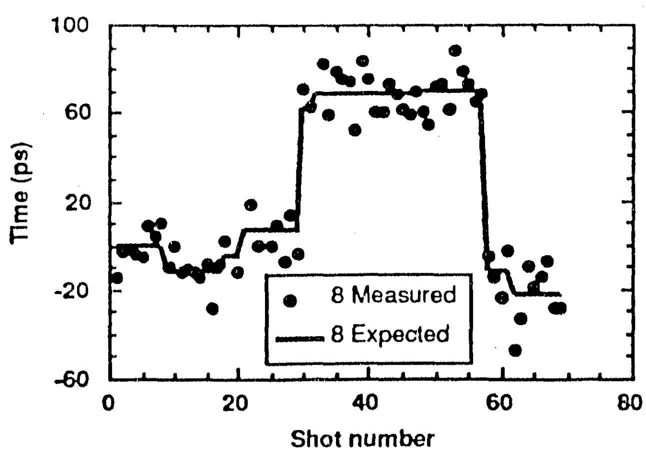


Figure 5. Beam times relative to the average time of the odd beams versus shot number for beams 7 and 8. Average beam time for groups of shots show magnitude of shifts in beam timing.

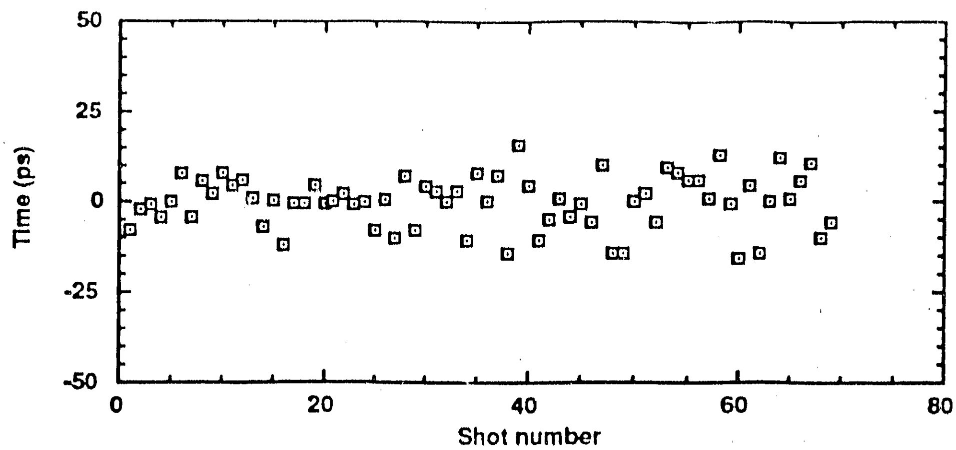


Figure 6. Average time of even beams relative to the average time of the odd beams versus shot number.

5. Summary

The incident laser beams arriving at a target at the center of the Nova target chamber comprise a set of ten simultaneous events. Signals from each beam are recorded on two streak cameras, five beams to a camera. The average time for five beams recorded on one camera forms a good reference to which all the beams can be timed. For 100-ps rise-time pulses, the time of the 50% point on the leading edge of the pulse is a good quantity with which to characterize the beam timing. A set of 69, ten-beam shots taken over a six-month period were analyzed to determine the quality of the beam timing available at Nova. A two pass analysis technique is used: in the first pass, the occurrence of beam timing shifts and suspicious data points are identified; and in the second pass, beam times relative to the average time of the odd-numbered beams recorded on one camera are determined. Then, the discrete shifts in beam timing are determined. From the beam times and the beam timing shifts, cross-timing precision between streak cameras and long term laser-timing stability are examined.

Beam timing errors are used to determine the precision with which a temporal measurements can be made. Since the beam times are referenced to the average time of the odd-beam cluster, odd beam measurements represent the precision with which an individual beam can be characterized with a single number representing the leading edge of 100-ps rise time pulses. The even-beam measurements, which each include errors introduced determining times for a beam and two fiducials, show the precision with which the time bases of two cameras can be cross-timed. Cross-timing precision between two cameras was found to be ±9 ps, and the precision for characterizing a single pulse from a streak camera to be ±5 ps. The average time of the even beam cluster relative to the average time of the odd beam cluster shows the precision for cross-timing between the two time bases to be 7.25 ps and shows the precision for characterizing each of the two fiducial pulses to be ±5 ps.

The experimental data demonstrate the long term stability of the beam timing and our ability to detect shifts in timing. Seven of the ten beams showed a shift of 10-ps or less at the end of six months. The maximum timing shift for eight of the beams during the six month period was less than 25 ps. Beam 8 had the maximum error of 70 ps. This timing shift was detected and corrected during a synchronization check. The data analysis shows when the initial timing error occurred and when the correction was made. A 38 ps timing shift for beam 7 was identified at shot 32. However, no timing error was detected at shot 58 when the beam synchronization was rechecked. Either, the synchronization check is not sensitive enough to spot 40-ps shift in timing or a path length in the beam 7 splitter to streak camera distance occurred. A beam timing shift of 27 ps (3σ) can be easily detected on the first shot after it occurs. A precise estimate for the time shift is best found with a large number of data points. Several shots are required to detect shifts of 10 to 20 ps.

6. Acknowledgments

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7. References

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