HIGH-PRECISION TIMING OF GATED X-RAY IMAGERS AT THE NATIONAL IGNITION FACILITY*

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Abstract

We describe techniques used to cross-time data acquired by gated x-ray imagers with laser beams at the National Ignition Facility (NIF). The reference time offsets are established using a dedicated full system shot by collecting data from multiple groups of beam with spatial and temporal separation on a spherical target. By optimizing the experimental setup and data analysis, repeatable measurements of 15ps or better have been achieved. This demonstrates that the facility timing system, laser, and target diagnostics, are highly stable over year-long time scales.

BACKGROUND

The NIF is a laser that uses 192 beams to deliver 1.8MJ of laser energy for inertial confinement and high energy density physics experiments [1]. Accurate control and synchronization between the laser beams and target diagnostics is a challenge due to the size and complexity of the facility. Each beam propagates over a path-length that is approximately 1500m long, and the entire facility uses hundreds of accurately coordinated components to synchronously deliver beams to the center of the target chamber within 30 ps rms. In contrast to the kilometer-scale laser beam paths, experimental targets are relatively small – no more than a few centimeters, and physical phenomena of interest often occur in 100ps or less. Synchronizing the diagnostics to record such events relative to the arrivals of the beams is one of the experimental challenges encountered at large laser facilities.

Gated x-ray instruments are used to image time-dependent phenomena in a variety of experiments at the NIF. For example, one important application is characterizing the quality of implosions in Inertial Confinement Fusion (ICF) experiments, where sequences of images are acquired in ~25ps intervals within an overall window of 100-400ps. These images are then analysed to obtain crucial time-resolved information about the implosion, such as shape, size, and brightness [2-4]. High-quality results require accurate measurement of the cross-timing, between the NIF laser beams that drive the implosion and the gated imagers that record the x-rays emitted by the target.

Cross-timing of gated imagers at the NIF is measured using an extension of techniques used previously at other laser facilities such as OMEGA and NOVA [5-7].

THE NIF LASER AND TIMING SYSTEMS

Both the NIF laser and timing systems have been described in detail previously [8-9]. A brief summary is included here to provide context for this discussion.

The NIF Integrated Timing System uses a precision 10MHz master clock to drive a Facility Timing Transmitter that creates an optical serial data stream that is distributed to 14 zones over fiber optics up to 500m distant. Within each zone, the data stream is distributed to programmable 8-channel delay generators. Outputs from these delay generators trigger laser components and target diagnostics.

In addition to timing controls, NIF has a precision Timing Fiducial Reference system. An impulse is created in the Master Oscillator Room that is precisely timed with respect to the laser pulses. This reference pulse is distributed passively throughout the facility and recorded along with signals of interest so that jitter effects can be removed by measuring event timing relative to the reference.

Light from each of the 48 NIF laser quads is sampled at an Input Sensor Package (ISP) following the preamplifier stage just before it is split into four individual beams. Each ISP signal is analyzed for timing, and the arrival of each beam at target chamber center (TCC) is inferred from the difference between the signal time and a reference time after correcting for the arrival of the fiducial pulse on the record.

Reference times for ISP signals are established using the pulse-synch target, a light collection device inserted into the target chamber for pulse synchronization measurements. During these measurements, low power laser pulses are collected separately from each beam and transported out of the target chamber to a digitizer through an optical fiber. These pulses are recorded relative to the fiducial pulse, and individual beams are adjusted to arrive at the same time at TCC relative to this fiducial reference. Concurrently, the laser pulses are recorded relative to the fiducial pulse on the ISP power sensors. These data are used to obtain reference times for the ISP signals relative to the fiducial for beams arriving at TCC at t=0.

GATED X-RAY DETECTORS

The Gated X-Ray Detector (GXD) is an example of a gated x-ray instrument that is used at NIF. It is a general-purpose diagnostic that is commonly used to record sequences of two-dimensional images of x-rays produced in a variety of experiments [10]. Figure 1 shows the

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operating principles and components that are relevant for timing. A pinhole array projects nearly-identical x-ray images onto gold photocathode strips on the surface of a microchannel plate (MCP). A high voltage gate pulse is launched from one end of the stripline, which is effectively a parallel plate transmission line. The gate pulse functions as a “flying shutter” since signal is only produced in the region of peak voltage as the pulse passes. Gate pulses traverse the length of the strip in about 220ps and have an effective integration time of about 100ps. Electrons produced by the MCP are accelerated by a 3kV+ potential across a 500-micron gap and proximity-focused on a phosphor screen. The resulting optical image is relayed through a fiber-optic plate and recorded with a CCD. Some of the gated instruments use photographic film to record the image.

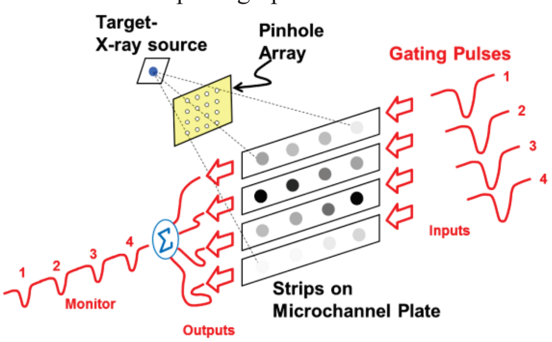

Figure 1: Gated X-ray Detector principle of operation. See text for details.

Several varieties of gated x-ray instruments are used at the NIF, but all share the above basic operating principles. For this discussion, we concentrate on GXDs that are fielded on a Diagnostic Instrument Manipulator (DIM). GXDs are inserted into the 10m-diameter target chamber in a DIM for each shot and are sometimes swapped with other diagnostics over the course of a few days.

Typically, GXDs have a RMS trigger jitter of 25ps. Since this is larger than the precision required for interpreting the physics measurements, the gate pulses are time-multiplexed upon exiting the strips and digitized for post-shot timing analysis. A second digitizer channel records the fiducial reference pulse as shown in Figure 2.

The time associated with the first gate is found from cubic interpolation of five sample points near the inverted peak, resulting in a measurement with an uncertainty of about 12ps. The time of the fiducial reference pulse is obtained using a midpoint interpolation technique described in reference [11] that has a typical uncertainty of 10ps or less.

By convention, an event that emits x-rays at laser time t=0 at the center of the target chamber will be imaged with the gate centered on the first GXD strip at t_{gate}=0. The gate time for a particular shot is determined from the monitor and fiducial pulse analyses described previously and a monitor reference time. Given a monitor reference time m_0 and fiducial reference time f_0, the time t_{gate} the gate pulse propagates past the center of the first strip is given by

$$t_{gate} = (m - m_0) - (f - f_0) - r/c \qquad (1)$$

where m and f are the monitor and fiducial times on the shot, r is the detector distance from the x-ray source, and c is the speed of light. The monitor reference time is determined from data gathered during dedicated cross-timing shots as described in the next section.

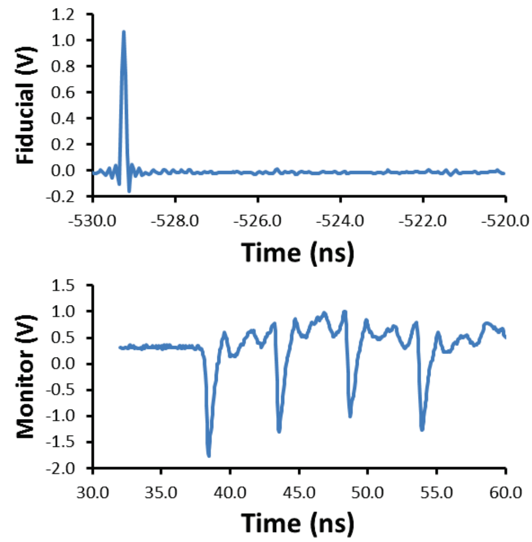

Figure 2: A two-channel digitizer record showing the fiducial reference pulse (top) and the GXD monitor signal (bottom). The negative pulses correspond to the time-multiplexed gate pulses that propagated through strips 1 through 4, respectively.

CROSS-TIMING EXPERIMENT DESIGN

Synchronization between the GXD and the NIF laser is subject to the trigger jitter in the timing system and the jitter in the operation of the GXD. Precise determination of the actual shot timing requires dedicated experiments where the data is directly related to the beam arrival time on target. Several considerations influence the setup of a timing experiment. Where possible, facility impacts are minimized by avoiding non-standard laser configurations and through the use of simple targets that are easy to position. The experiments are designed to incorporate multiple timing references for increased precision, reliability, and consistency verification.

Cross-timing shots for GXDs at the NIF use 4.7mm diameter hollow plastic sphere targets with a 1.5µm gold coating. These targets are large enough to accommodate a large number of spatially-separated 1.2mm diameter beam spots without overlap, and the spherical shape makes it possible to view many such spots from any target chamber port. Laser beams deposit energy in the gold coating, creating plasma that emits x-rays that are recorded with the GXD. Cross-timing is achieved by imaging a train of 100-ps Gaussian pulses that are spatially and temporally offset. All four beams in each quad are pointed to the same location on the target to ensure sufficient signal is produced. Each quad is pointed

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to a different location on the sphere. Additionally, a long (~3ns) pulse is used for one quad, providing a spatial reference that facilitates image analysis. Figure 3 shows a typical beam pointing configuration, and Figure 4 shows the associated quad timing for the experiment.

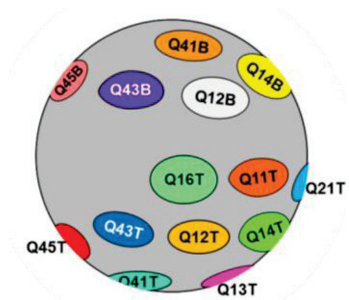

Figure 3: Typical beam pointing for cross-timing shot as viewed from the equator of the target chamber at 78° azimuth. All 4 beams in each quad are pointed to the same spot.

Staggering the four GXD gate pulses by 200ps creates a continuous record spanning about 800ps. As shown in Figure 4, the main trigger is usually set to center this record within a sequence of pulses that occur at 100-150ps intervals. Complete brightness histories of 3-5 pulses are obtained with this configuration.

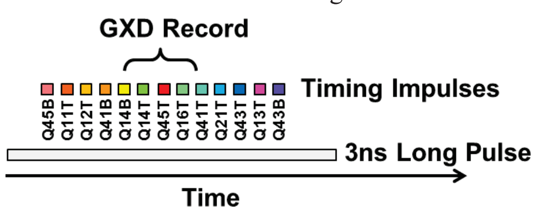

Figure 4: Beam timing for cross-timing shot with pointing as shown in Figure 3. The GXD trigger is set to image signals from the quads indicated by the braces.

X-rays from the beam spots incident on the target are imaged onto the detector using an array of pinholes at 1X magnification, where the pinhole spacing has been designed to maximize the number of images without overlaps. A 25μm polyimide filter blocks photons with energies below 1 keV.

CROSS-TIMING DATA ANALYSIS

After a GXD image has been acquired from a timing shot, the first analysis step is to associate the visible features with the individual laser quads. As shown in Figure 5, the long pulse from quad Q12B is visible near the top of every pinhole image since it persists for longer than the 800ps overall recording window. The actual separation of the images relative to the pinhole spacing provides a estimate of the source-detector distance with a precision of about 1mm. Features due to short-pulse quads are easily identified by their positions relative to the Q12B feature. The x-ray signals from Q14B, Q14T, Q16T, and Q41T are indicated in Figure 5.

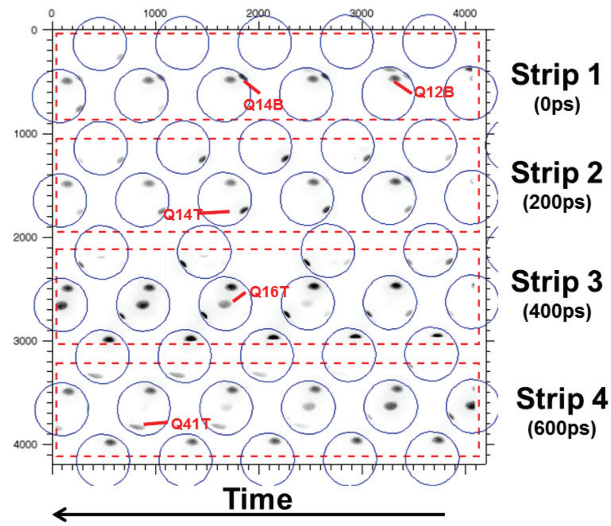

Figure 5: GXD image from timing shot N130117. Strip boundaries are indicated by red dashed lines, and the gate travel is from right to left. The strips were delayed in 200ps intervals as indicated. The outline of the spherical target within each pinhole image is indicated in blue.

After the individual x-ray spots are identified and associated with the different quads, their intensities are plotted as a function of time based on horizontal position in the image, the gate velocity, and the strip delays. The resulting intensity histories are fit with Gaussian profiles as shown in Figure 6. These fits are used to accurately determine relative peak times, within the GXD record, for each visible quad.

The relative peak time of each quad signal p is used to calculate a monitor reference time m_0 using the relation

$$m_0 = m + p - t_q + \Delta - r/c \tag{2}$$

where m is the monitor time, t_q is the quad arrival time at target chamber center (TCC) as measured at the input sensor, r is the inferred distance of the detector from TCC, and c is the speed of light. The quantity Δ is a path length correction, on the order of 10ps, that arises because the beams encounter the target surface about 2.35mm from TCC. Results from several quads are combined to give a result with reduced uncertainty. For a typical cross-timing experiment, error analysis calculations indicate an expected statistical uncertainty of about 18ps for the monitor reference relative to the fiducial based on four quads captured in the recording window. Inspection of equation (1) shows that this uncertainty contributes directly to cross-timing uncertainty in subsequent experiments that use this reference.

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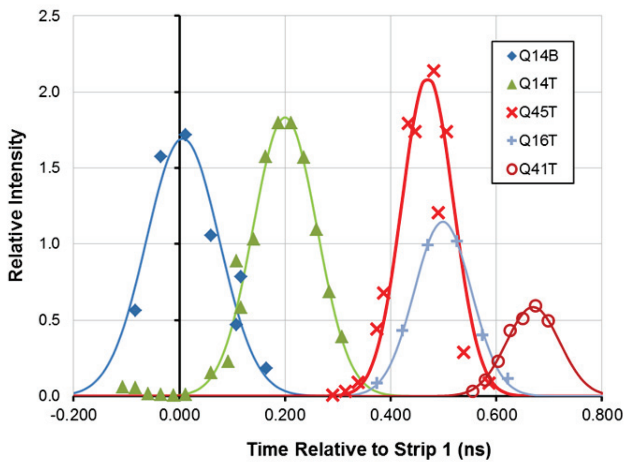

Figure 6: Intensity histories for the x-ray spots indicated in Figure 5. Signal levels from the individual images are plotted as points, and Gaussian fit profiles are indicated with solid lines.

MONITOR REFERENCE STABILITY

Limited statistics are available regarding the reproducibility of monitor reference measurements, but we present results from five timing shots conducted over a period lasting just over one year in Table 1. Two GXDs mounted on two different DIMs participated on these shots, often when the primary purpose of the shot was to obtain timing data for other instruments. The variation among the measurements is less than 10ps for the two GXDs and is consistent with the statistical uncertainty described in the previous section. In particular, the observed 7ps difference for the polar GXD over an interval of nearly a year reflects the highly stable fiducial reference, fiber optic distribution network, laser beampath, optics, and DIM cables. It is also notable that the two GXDs were removed and re-installed in their respective DIMs several times during this period. These results indicate that the electrical monitor connections can be consistently re-established without introducing detectable errors in interpreting the timing on a shot.

Table 1: Monitor Reference Measurements for 2 GXDs

Shot Number	Date	Polar GXD m_0-f_0 (ns)	Equatorial GXD m_0-f_0 (ns)
N120105	1/5/2012	632.243	
N120302	3/2/2012		560.168
N130103	1/3/2013	632.250	
N130114	1/14/2013		560.170
N130117	1/17/2013		560.176

For the period under consideration, one GXD was mounted in the polar DIM at the top of the target chamber, and another was mounted in an equatorial DIM and viewed the side of the target.

CONCLUSION

We have summarized the control and reference aspects of the NIF Integrated Timing System, along with the pulse-synch system used to measure and establish beam arrival times at the target. GXDs are diagnostics used to image time-dependent phenomena resulting from laser interactions with the target, and cross-timing GXDs with the laser is crucial for extracting results from the data that is collected. We have described the techniques used to acquire and analyze GXD cross-timing data using dedicated NIF shots. Timing references obtained from a small number of shots are reproducible to within 10ps and are consistent with the expected statistical uncertainty of 18ps. This repeatability indicates a high level of stability for a system with many distributed components.

ACKNOWLEDGMENT

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