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A 100 ps gated x-ray spectrometer

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ABSTRACT

Material opacities are of interest in many fields. We have developed a Bragg reflection spectrometer that is gated for imaging samples in a laser heated environment for opacity measurement. A micro-channel plate is coated with a photocathode material and a fast pulse is launched across it. Electrons are converted to photons in a phosphor and recorded on film. Optical gate pulse widths of 100 ps are achieved. Some optical pulse width and sensitivity enhancements are noted at launch and termination. Events of interest are 200 ps long. The framing window is approximately 250 ps in length. Timing jitter is a problem. The instrument timing networks have been examined, and the source of jitter is still unknown. Timing to 50 ps resolution is desired. Close in proximity to the laser-driven event leads to complications in shielding from hard x-rays, hot electrons and shock-driven damage. High Z materials provide shielding from hard x-rays. Magnets screen out hot electrons produced by laser-matter interactions. Filters provide energy fiducials. PCD's provide high resolution timing measurements. Data is recorded on film in a specially designed film pack. The instrument is designed to be used in the NOVA Laser Facility at Lawrence Livermore National Laboratory.

KEY WORDS: MCP, Timing, jitter, Bragg, optical gate, PCD

1. INTRODUCTION

Opacity of materials at elevated temperatures has been and will continue to be of interest to physicists and astrophysicists. Temperatures in the 50-180 eV range are reproducible via various driving technologies available today. Lasers, pulse power, and explosively driven magnetic compression all yield temperatures and densities of interest. Los Alamos National Laboratory's P-Division investigates phenomena in all these regimes. The instrument reported on here was produced to measure the opacity of material in a laser driven environment.

Lasers are capable of delivering kilojoules of energy in very short time frames. Wavelengths of the particular laser dictate the conversion efficiency of the energy delivered. This instrument was designed for use at the Lawrence Livermore National Laboratory's NOVA Laser Facility, capable of delivering a 30 kJ, 0.35 micron wavelength, few nanosecond pulse. Further, it was designed to make use of the NOVA SIM tube re-entrant port technology. This consists of a six inch o.d. tube extending approximately 2 meters into a 2.3 meter radius target chamber. Diagnostics are loaded via a load-lock, evacuated, and driven to a predetermined location via lead screw. Engagement of a connector block allows power and signal interface to the exterior of the chamber. Start signals (triggers) and diagnostic timing signals can thus enter and exit the target chamber at the appropriate time.

Close in diagnostics for laser-matter interactions are thus readily available, provided they meet the criteria for the SIM tube geometry. Space is at a premium. Complications are the harsh environment, as close as 10 mm, to 30 kJ of energy, and the need to use the instrument on a regular basis. Shielding from blast and radiation backgrounds must not compromise the instruments designated measurement. Considerable time and effort goes into producing robust designs for use in the SIM tubes.

The first generation of this spectrometer was used in a time-integrated mode. Signal to noise ratios of greater than 1 were readily achievable at low temperatures. Point projection spectroscopy allowed for discrimination between sample heating effects and opacity measurements. However, the desire to measure samples at more elevated temperatures resulted in greater contributions from the background. To overcome this the instrument was reconfigured in a time gated, intensified mode. Building on work already done at LLNL, a gated MCP was coupled to the Bragg spectrometer and this was integrated into a SIM compatible housing. This instrument has the capability to image in both the spectral and spatial domain. Figures of merit for MCP gating technology have been discussed in the literature¹. This paper will address the use and integration of one gated MCP instrument.

2. EXPERIMENT

The experiment consists of a sample placed in a laser-heated environment. Approximately 25 kJ of 354 nm light are delivered in eight beams arrayed symmetrically about the sample. The laser energy is converted to blackbody radiation and the sample is heated to approximately 180 eV. After one nanosecond of drive, a 200 ps interval of no drive is followed by a 450 ps backlighter driven by several kJ of 532 nm light. The backlighter is small (25 μm x 100 μm), such that it can be considered to be a point source. Backlighter drive times are short to avoid source size expansion problems. Apertures directly opposite each other on the target allow x-rays from the externally mounted backlighter to enter and exit the holhraum. These apertures also form the defining aperture for the imaging system. Collimators within the spectrometer are needed to reduce background light coming from other areas of the holhraum. These x-rays are measured both spectrally and spatially at the detector. It is important to the experiment to know the drive time and temperature of the sample as well as the interval between the drive and the backlighter. Also of interest is the evolution of the sample environment. As it heats the sample self-emits, contributing to the recorded data. This must be subtracted from the data. Implementing a fast, high fidelity recording system has allowed a detailed examination of the drive evolution and sample heating (see Figure 1.) Two Tektronix SCD5000's record time frames of 20 ns full sweep. One 20 ns recording captures the main trigger and gate pulse, giving high fidelity in looking at trigger to gate pulse jitter (20 ns in 1000 pts for a time resolution of 20 ps/pt) The second 20 ns recording captures the gate pulse and the two PCD's, thus confirming the overall drive to backlighter timing. Overall bandwidth capabilities also yield good quality pulse shapes, insuring verification of gate pulse performance (a measure of the gain), drive symmetry, and backlighter performance in one recording. Some, but not all, of these parameters are recorded via other standard NOVA diagnostics. High bandwidth recording has contributed significantly to understanding the experiment.

3. INSTRUMENTATION

3.1 Spectrometer

The spectrometer is of the Bragg reflection type (see Figure 2). It uses a convex curved crystal with a 3.81 cm radius of curvature. The crystal currently in use is KAP, procured from CRISMATEC. The mandrel for curving the crystal was produced from acrylic material to reduce fluorescence contribution to the background from high Z material in the spectrometer housing. The crystal is formed over the mandrel via a full perimeter clamp that is hidden from the direct radiation of the line of sight. Wavelength range is approximately 670 eV to 4 keV. Detector recording length restricts single event coverage to 80 % of this range, centered about 2 keV. The imaging aperture is fabricated on the target, and the spectrometer provides a highly collimated line of sight (LOS.) Laser matter interactions lead to high energy background in the form of hard X-rays and hot electrons and these must be shielded against. To this end the spectrometer is surrounded in high Z material in one inch thickness. Magnets are embedded in the collimator to direct electrons into low Z material. Beam scrapers are also provided to define the rays projected on the crystal. Light traps at the initial collimator also help in suppression of scattered background. The interior of the spectrometer is of low Z material to reduce fluorescence contribution to the signal. Absorption filters are placed in the spectrometer housing to provide cold material absorption edges of known energy on the spectrum. A combination of K and L edge materials are used.

Two diamond photo-conducting diodes (PCD's) are embedded at separate locations to allow monitoring of various aspects of the experiment. Since gating is employed, the gate pulse should arrive at the correct time, ± 50 ps. One PCD is in the interior of the spectrometer housing to monitor laser drive time and target evolution. The second PCD is in the forward collimator housing to monitor laser drive of the point projection backlighter. From this signal one can monitor the separation time of the laser drive on target vs. laser drive of the backlighter. This allows some measure of certainty in the time of the recorded gate pulse.

The detector geometry must be robust to alignment errors as well as close in hazards relating to laser driven experiments. Alignment is accomplished by pivoting in 2 dimensions about a point some 3 meters from target chamber center, aligning to a ball at target chamber center (TCC) with a viewing scope directly opposite the diagnostic.

Debris from target material and the inline absorption filters leads to shock wave driven damage to the Bragg crystal every shot. Initial PCD's were not adequately protected either, leading to early failure and replacement. While the PCD's are not monitored or calibrated for spectral content, they are made of natural type II diamond and vary in sensitivity by factors of two or three. One would like to keep sensitive PCD's working to increase signal recording

possibilities. Good diamond PCD's exhibit rise times of less than 100 ps in the 1 mm by 3 mm by 1 mm thick size used here. Time responses of the PCD's were measured at the EG&G LINAC facility at Santa Barbara, which produced a 15 ps electron pulse at 16 MeV, giving bremsstrahlung up to this energy. PCD time response was measured at < 40 ps rise and < 100ps FWHM. This source has since been decommissioned.

3.2 Electronics

The instrument electronics consist of a trigger network, pulse forming network, coaxial to stripline transmission line, Au photocathode stripline gain element, monitor signal pickoff (resistive), and a termination of matched impedance. (See Fig. 3) The trigger network consists of a simple two active device circuit that accepts the single master trigger provided by NOVA and splits it to the 4 individual pulsers. The pulser network is of the avalanche transistor type. It consists of four stages of avalanche transistors, across which 2.2 kV is held off until avalanche. Some small gain in peak voltage is noticed during avalanche, resulting in a peak delivered voltage of ~2.7 kV. per card into 50 ohms. The pulse has a risetime of 95 ps and a full width at half maximum (FWHM) of 350 ps (see Figure 4.) This pulse is not Gaussian in shape. It exhibits a steep rise and some ringing on the decay. Investigation lead to the finding that the optical gate response is dominated by the electrical gate pulse peak shape and leading edge rise time. Initial optical gate widths were measured at the LLNL Short Pulse facility (202 nm, 3 ps), and later at the LANL Trident Laser facility using the front end only (1 micron, 300 fs, 1 joule pulse converted to x-rays by an aluminum target.) Optical gates measured at these two wavelengths were similar within 5 ps.

3.3 Detector

The detector used in this diagnostic is a gated MCP (see Figure 4). In this type of detector a stripline structure is laid down on a MCP. The stripline must embody certain characteristics, namely it must satisfy some impedance network and provide a length and width to be of interest to the experiment. For the instrument, we chose a stripline of 25 mm. width and forty millimeter length. The width was chosen to provide the required spatial resolution. The length was readily procurable and standard in the housing used. An MCP L/D ratio of 40 was specified to provide the gain projected to be needed.

The MCP's are procured from Galileo Electro-Optics, uncoated and hydrogen fired only. LANL then applies the stripline and photo cathode coatings (5000 Å Copper and 1000 Å Gold) and the ground coating. The MCP is then mounted in a intensifier module. The intensifier module consists of a MCP, P-11 phosphor coated fiber optic face plate, a UV light block, and striplines for delivery of the gating pulse.

Standard intensifier modules of this design have a blocking capacitor to allow for application of DC bias to control sensitivity, but the stripline configuration of interest for this diagnostic lead to a low impedance stripline. Initial optical gate studies performed at EG&G's LINAC Facility indicated severe optical gate width enhancement, resulting in optical gate times of nanoseconds. Time domain reflectometry studies of the original intensifier module performed by the authors and R.C. Smith, P-Division/LANL with a Hewlett-Packard 54124, indicated there were significant impedance mismatches at the launch and termination of the photocathode stripline. Also noted in TDR's of the structure were peculiarities of pulse shape due to launch position, i.e. the four 50 ohm cables were summed on a single wide strip at the intensifier module interface. Pulses launched from the interior two cables possessed subtle differences from exterior launched pulses. One can imagine that the voltage wave propagating down the stripline is not a simple plane wave. The gating pulse applied to the MCP has times of the order of some of the feature sizes in the intensifier module. This suggests a multi-modal propagation of the gating pulse. The transmission line impedance ($\approx 4 \Omega$) puts great emphasis on the quality of the terminations of the lines. Small inductances in series with the transmission line are large fractions of the line impedance at these frequencies. The coupling of the multi-mode transmission of the gating pulse with these mismatches in termination leads to a complicated pattern of reflections on the transmission lines. Considerable effort was taken to remove these artifacts, resulting in a new taper at launch and the matched parallel resistive termination. Figures 6 shows the optical gate width and length after corrections in the module. Optical gate width is still slightly enhanced at the launch and termination of the MCP (see Fig. 7.) Tests for confirmation of the corrected optical gate were performed at the Trident Laser short pulse front end facility. Further investigation of this phenomena is ongoing. Since this implementation, P.M. Bell and collaborators (private communication) at LLNL have demonstrated improved tapered stripline structures. These structures have been well integrated with vacuum and mechanical considerations.

Since it is necessary to know the gate pulse time of arrival at the MCP in relation to the backlighter drive, a resistive divider pickoff (6:1 voltage ratio) is provided at the matched termination of the photocathode stripline.

Placement there avoids the risk of power loss before gate pulse launch onto the active element stripline. Photocathode striplines are resistive in nature and suffer from voltage loss during gate pulse transit of the stripline. Measured peak pulse height is an indicator of the gate pulse peak voltage as delivered to the photocathode.

The fiber optic face plate (FOFP) is coated on one side with Indium Tin Oxide (In:SnO) to provide bias for electron transport from the MCP to the phosphor converter ($\approx 400 \Omega\text{-cm}$). The bias field is +3 kV, across a 0.5 mm gap, yielding resolutions in the 50 micron range. Better resolution has been obtained, however at the cost of intensity (Landen and Bell² and Grantham, et al.³). Data is then recorded via film in proximity focus to the back of the FOFP. A custom film pack was made to house sheet film. T-MAX 400, pushed two stops during development, was chosen for this application.

4. TIMING

As stated previously, the time frame of interest is approximately 200 ps. Since the instrument provides only a single frame of information, timing the gate pulse to arrive at the MCP in conjunction with the x-rays of interest to better than 50 ps was desired. This has proved very difficult to achieve. Sub-nanosecond timing is always difficult in transient events. All trigger systems have jitter, caused by instabilities generated by trigger initiation techniques, thermal instabilities in materials, trigger transport and regeneration, fan-out techniques, and harsh electrical environments. The master trigger at NOVA is provided from a network of three lasers. These lasers are timed to within 100 ps, manually, before each shot. This then becomes the ultimate trigger jitter achievable unless the instrument has large jitter contributions.

In this instrument, stripline impedance (4 ohms) requires the energy from four pulse cards, and the time of arrival has to be synchronous to within 10 ps or significant pulse shape distortion occurs leading to peak pulse height decay that causes uncontrollable gain variations. This results in decreased gain and longer gain periods. The instrument jitter is composed of the two active element fan-out to the pulser cards and the jitter in the avalanche on the pulser cards themselves. Careful selection and matching of avalanche transistors and diodes minimizes the pulser jitter. However, in use at NOVA the instrument has experienced overall system jitter in the 200-300 ps range. Investigations into the contributing components took several paths. Onboard fan-out jitter was found to be some 10 ps. Pulser jitter (avalanche jitter) also proved of order 10 ps. Initial full system testing indicated a strong thermal component to trigger stability and the gate pulse shape reproducibility. Thermal tests showed a large jitter component due to inadequate control of the average temperature of the pulser cards at trigger time indicating individual component sensitivity to temperature. The instrument was placed in a vacuum chamber of some volume to simulate NOVA conditions. Various power on times were investigated. They ranged from very shortly after instrument turn on to 15 minutes of power on. Studies indicated that the individual pulser cards fired at slightly different times (50-100 ps observable) with shorter than three minute warm-up time. Some drift to the trigger was also observed due to thermalization. Tests were performed using a DG535 trigger generator as used at NOVA; and all signals were recorded on a calibrated Tektronix SCD5000 oscilloscope (see Figure 8). DG535 trigger pulses were displayed on the same trace as the instrument gate pulse to eliminate scope jitter. Sweep times were 10 ns full screen with 10 ps/pt resolution. Normally, a three minute power on cycle precedes the shot at NOVA but we have found that this is not sufficient thermal warm-up for the instrument to achieve sub-100 ps jitter. Note that initial timing the pulsers was performed at air and over a significant time span that inadvertently lead to thermal stability. Actual use is always in vacuum, with an irregular series of times between test pulses (during a procedure called rod shots) and hence the need for some thermalizing time before the real event. The thermal tests performed by B. Davis and Walsh⁴ indicated that warm-up times of ten minutes or more were needed to ensure pulser synchronicity and overall trigger stability. Some reproducible drift of the summed pulser trigger time was noted during the thermal tests; and the ten minute plus time allowed for eliminating this component of the jitter also. When properly thermalized, the total instrument trigger jitter contribution is ± 40 ps. The on board jitter does not add to the overall system jitter. The authors have not been successful in isolating the remaining 200+ ps of jitter recorded at NOVA. NOVA operations provide a 7912 transient digitizer record of the gate pulse, the two PCD's, and a fiducial pulse. Although this system is sub-gigahertz in recording bandwidth, it does provide adequate peak to peak information for the timing of the individual signals.

5. SUMMARY

Gated MCP technology has been successfully applied to a Bragg spectrometer. Short gate times have lead to significant signal to noise gains in the data. This has allowed the authors to push to new regimes in sample temperatures. However, these gains were not easily won. Difficulties in gate pulse delivery to the detector, non-

uniform gain arising from impedance mismatches in the physical geometries, timing considerations, and an as yet undiagnosed jitter component provide challenges not fully anticipated at the onset of the experimental series. We have learned that generating, delivering, and recording picosecond time frame electrical pulses requires attention to engineering detail, ingenuity, persistence, and patience. Low impedance striplines possess many inherent problems. In essence, the problem becomes delivering a multi-kilovolt pulse to a structure wherein parasitics of various forms may dominate. Add to this the need for picosecond jitter in the timing considerations and a requirement to record all this with high fidelity to understand experiment evolution, and one is presented with a challenge.

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Figure 1: Experiment timing diagram showing the sequence of laser drives to target and backlighter. Also shown are gate pulse time for photocathode stripline and the two PCD's used to accurately measure the time intervals. Lower left corner is actual trace recorded during the experiment. First pulse is the gate pulse, second pulse is an artifact reflection, third pulse is the PCD-Crystal showing sample drive followed by backlighter drive only. Resolution of trace is 20 ps/pt on the SCD5000.

Figure 2: Schematic view of the spectrometer in the experimental configuration. From left to right are the high Z collimators, high Z shielding, diffraction element, gated intensifier module and film pack. Two PCD's are shown, one located on the forward collimator and one on the spectrometer housing.

Figure 3: Gate pulse electrical flow diagram. Four pulses launched into 50Ω coaxial cable and summed at module stripline interface. Launch and termination of photocathode stripline shows reflected pulse generation location

Figure 4: Pulser output at launch into 50 Ω cable. Narrow sampling scope trace indicates triggering and avalanche reproducibility

- Gate pulse: -1000V maximum, 100 ps risetime, 350 ps FWHM
- Phosphor Bias: +3 kV
- Phosphor type: P-11
- MCP-Phosphor Gap: 0.5 mm
- Spatial Resolution: ≈ 25 micron
- Film: T-MAX 400 sheet film

Figure 5: Schematic view of intensifier module.

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Figure 6 a): Digitized CCTV image of optical gate showing optical gate width and record length

Figure 6 b): CCTV image of optical gate width, relative intensity only (asynchronous triggering)

Figure 7: Digitized gate pulse at launch, midstrip and termination showing enhanced gate width at launch and termination after module impedance matching. Peak heights are normalized.

Figure 8: Resistive monitor pickoff indicating trigger jitter and gate pulse peak variation after sufficient warm-up time. In this recording the gate pulse is inverted and leads the DG535 trigger pulse. The 32% level of leading edge rise time of both pulses was used to normalize measurement of trigger jitter.