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ABSTRACT

Benchtop pulsed x-ray systems are commonly used to record dynamic material data on the order of nanoseconds, but pulse timing is often difficult to accurately determine. This study demonstrates that commercially available photodiodes can be used effectively for direct x-ray pulse detection without the need for visible light scintillators. X-ray pulses from four commercially available flash x-ray systems were quantified using one silicon and two indium gallium arsenide (InGaAs) photodiodes. The measured InGaAs pulse durations were strongly dependent on radiation dose in the non-linear operating regime, so the photodiodes were shielded to operate below the 2.5 V non-linear regime threshold. The average pulse duration and pulse arrival time jitter of the photodiodes for each x-ray source were within several nanoseconds with the exception of two sets of measurements that were affected by low instrument sensitivity and electrical noise. These results show that InGaAs photodiodes can be used as effective and repeatable stand-alone timing diagnostics for x-ray pulses as short as 20 ns or less.

I. INTRODUCTION

Time-resolved x-ray diagnostics are commonly used for probing material properties that change during dynamic events. A time resolution on the order of nanoseconds is often required when analyzing temperature, density, phase transitions, and other properties in shocked materials because the shock wave may propagate at several km/s,[1] and chemical reactions in commonly used high explosive materials proceed to completion in just over 10 ns.[2]

State-of-the-art facilities have been developed to produce high flux x-ray pulses on the time-resolved scales needed for these experiments. The x-ray free electron laser (XFEL) at the Linac Coherent Light Source can produce single x-ray pulses with durations on the order of tens of femtoseconds,[3,4] and the Advanced Photon Source is capable of producing 82 ps duration pulses at 153 ns inter-pulse times in its 24-bunch mode configuration.[5,6]

Benchtop flash x-ray systems can also provide short duration and high flux x-ray pulses. Flash x-ray systems are ideal for observing properties of high explosives during detonation,[7,8] ballistic projectiles,[9] or even phase transitions in shocked materials.[10] Current systems only allow for a single pulse during a highly dynamic event since the capacitor banks must be recharged after every pulse, but they provide valuable information about timing and transient material properties if the pulse duration is known.

However, assuming a pulse duration without empirical evidence introduces errors into the results. Mandal *et al.* observed melt pools in shocked aluminum powder by analyzing the x-ray diffraction spectra that changed over 150–450 ns,[11] and significant chemical reactions occur in high explosives over just 10s of nanoseconds behind the leading shock front.[12] A pulse duration uncertainty of 10s of nanoseconds may lead to large errors in the interpretation of kinetic processes in these highly dynamic experiments.

X-ray pulse duration in flash x-ray sources can be measured indirectly by monitoring the pulser discharge[13] or by measuring the visual light emitted from a fast decay time scintillator and a photodiode or photomultiplier tube.[14] Unfortunately, even some of the fastest commercially available scintillators such as lutetium oxyorthosilicate (LSO) and lutetium–yttrium oxyorthosilicate (LYSO) commonly have decay times of around 40 ns,[15,16] which is too long to measure x-ray pulses with expected durations of around 20 ns.[17] Furthermore, the number of visible photons emitted from a scintillator decreases as the decay time decreases.[18] The reduced quantity of photons emitted from rapid decay scintillators becomes exceedingly difficult to detect even with single photon counting diagnostics, especially if the x-ray flux is low and the detector cannot be placed directly in the beam path so as to avoid attenuating the beam ahead of a sample in a dynamic experiment.

Alternatively, Krumrey *et al.* and Corallo *et al.* found that the x-ray flux can be measured directly using silicon photodiodes without the use of visible light scintillators.[19,20] Krumrey found that the responsivity of the photodiodes was dependent on the thickness of the photostimulable layer and that some of the photodiodes displayed a supralinear responsivity relationship with x-ray energy. Kishimoto demonstrated that silicon avalanche photodiodes could be used as timing detectors for synchrotron pulses,[21] and Seely *et al.* calibrated silicon photodiode time responses to synchrotron pulses at different diode bias voltages and wavelengths.[22] However, we are not aware of any work that evaluates photodiodes as direct timing detectors for tabletop pulsed x-ray systems.

In this research, three different types of photodiodes are tested to directly characterize pulses of four commercially available benchtop flash x-ray sources in different configurations without the use of visible light scintillators. These results validate photodiodes as simple diagnostic tools for determining x-ray pulse widths and timing in experiments for which accurate time resolution on the order of nanoseconds is critical.

II. EXPERIMENTAL METHODS

A Thorlabs DET10A silicon (Si) detector and two Thorlabs indium gallium arsenide (InGaAs) detectors, PDA05CF2 (IGA-A) and DET10N2 (IGA-B), were assessed as x-ray pulse diagnostic instruments. Manufacturer specifications for the three different photodiodes and the abbreviations used in this work are summarized in Table I. The photodiodes were covered in a thin layer of black tape to ensure any measured signals were not produced by visible light. The IGA-A photodiode includes an internal fixed gain amplifier, but the IGA-B and Si photodiodes do not include any internal amplification. All three photodiodes were operated in the reverse-bias mode.

Two Golden Engineering battery-powered flash x-ray sources (XRS3 and XRS4) and two Scandiflash flash x-ray sources (SCF150 and SCF450) were used in this research. The Scandiflash SCF150 system was pulsed using a 1 mm tip tungsten anode (W kα, 59.3 keV), and the SCF450 system was pulsed with a 0.8 mm tip molybdenum anode (Mo kα, 17.4 keV). The x-ray sources and relevant specifications are compiled in Table II.

TABLE II. Specifications for the flash X-ray sources used in this research.

Source	Output voltage (kVp)	Anode material
XRS3	270	Tungsten
XRS4	370	Tungsten
SCF150	150	Tungsten
SCF450	450	Molybdenum

The non-linear regimes of the three photodiodes were first characterized to determine a signal threshold for the subsequent full width at half maximum (FWHM) pulse duration measurements. Above the photodiode saturation threshold, charge carriers in the photostimulable material layer of the sensor induce an electric field, which decreases the carrier mobility.[23,24] This reduction in mobility causes the signal to become non-linear, which produces lengthened and incorrect pulse duration measurements. One millimeter thick lead sheets were arranged around the photodiodes to attenuate the x-ray radiation during the pulse characterization measurements to ensure that each photodiode was operating in the linear regime. The Si photodiode was fixed directly to the output faces of the x-ray sources tested, and the IGA photodiodes were placed ~1 m from the x-ray sources.

A Tektronix MSO58B oscilloscope was used to the record photodiode signals at 0.8 or 1.6 ns measurement intervals and 13 bit or 14 bit resolution, respectively. Double-shielded BNC cables were used to mitigate the effects of RF noise in all the measured photodiode signals. Ferrite coils, aluminum foil shielding, and a passive RF filter were added to reduce the noise in the IGA-A signals during the SCF150 and SCF450 pulse characterization tests.

III. RESULTS

The linear and non-linear photodiode responses were determined by exposing the photodiodes to incrementally higher radiation doses via reduced lead shielding and decreasing the standoff distance between the x-ray sources to the detectors. The SCF150 system was used to characterize the Si and IGA-B photodiodes, and the battery-powered XRS3 was used to characterize the IGA-A photodiode. The Si photodiode was found to be considerably less sensitive than the two InGaAs photodiodes and had to be fixed directly to the output face of the SCF150 x-ray tube to obtain a readable signal above the noise background.

TABLE I. Manufacturer specifications for the silicon and InGaAs photodiodes evaluated in this research.

Photodiode	Abbreviation	Material	Active area (mm^2)	Rise time (ns)	Power supply
DET10A	SI	Si	0.8	1	AC
PDA05CF2	IGA-A	InGaAs	0.2	2.3	AC
DET10N2	IGA-B	InGaAs	0.8	5	Internal battery

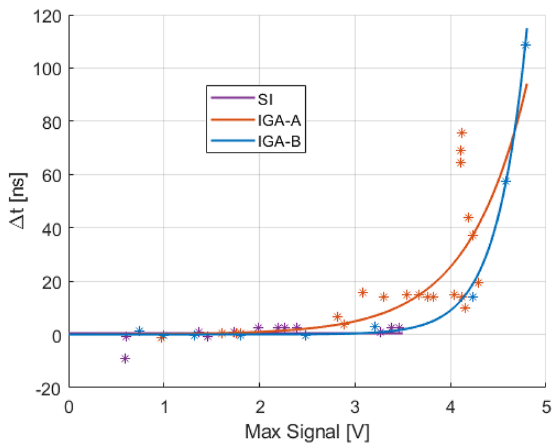

FIG. 1. Pulse duration time residual data points are scatter plotted for the three photodiodes used in this work. The pulse duration mean for each photodiode was the mean of the datasets in the linear response signal region below 2.5 V.

TABLE III. XRS3 and XRS4 pulse measurements with SI, IGA-A, and IGA-B photodiodes.

X-ray source	Photodiode	Pulses	μ_{duration} (ns)	1σ (ns)	Pulse jitter (ns)
XRS3	SI	20	21.6	1.1	152.8
XRS3	IGA-A	20	22.3	1.3	152.7
XRS3	IGA-B	20	25.4	0.7	152.5
XRS4	SI	20	14.7	1.2	71.3
XRS4	IGA-A	20	21.3	0.8	71.5
XRS4	IGA-B	20	22.6	0.6	71.1

Non-linearity is herein quantified as the time residual of the measured x-ray pulse duration, $\Delta t = t_{\text{pulse}} - \mu_{t,\text{linear}}$, where t_{pulse} is the measured pulse duration and $\mu_{t,\text{linear}}$ is the average pulse duration in the linear response region below 2.5 V. The non-linear response of the Si detector could not be characterized because the maximum signal from the photodiode was 3.45 V without any radiation attenuation, and the Si response appeared to be fairly constant through this maximum signal threshold. The IGA-B response also appeared to be fairly constant for signals up to 3.5 V; however, the IGA-A pulse duration appeared to increase when the maximum signal

TABLE IV. Scandiflash SCF150 and SCF450 pulse measurements with IGA-B and IGA-A photodiodes.

X-ray source	Photodiode	Pulses	μ_{duration} (ns)	1σ (ns)	Pulse jitter (ns)
SCF150	IGA-A	20	40.3	5.6	78.1
SCF150	IGA-B	20	53.5	1.0	77.7
SCF450	IGA-A	17	18.8	1.7	31.1
SCF450	IGA-B	25	19.1	2.9	29.9

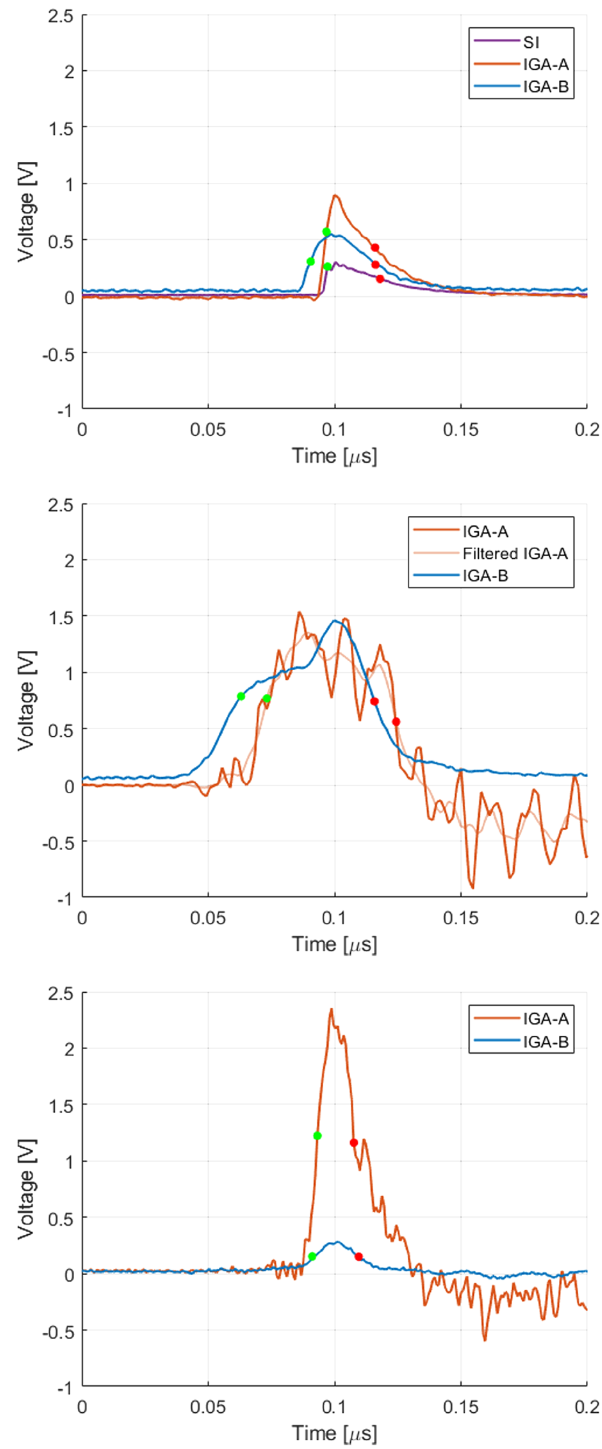

FIG. 2. Photodiode signals from the XRS3 (top), SCF150 (middle), and SCF450 (bottom) systems are shown. The green and red dots mark the FWHM start and end time, respectively. Lead shielding and standoff distances between each photodiode and the x-ray sources were individually adjusted such that the maximum signals were limited to 2.5 V. A moving average filter was applied to the SCF150 IGA-A signals to obtain more accurate measurements from the datasets.

approached 3 V. The exponential functions were fit to both InGaAs photodiode curves to model their non-linear behavior as shown in Fig. 1.

The exponential function fit the IGA-B dataset well, but the IGA-A dataset was poorly approximated by the exponential fit. The cause for the poor IGA-A function fit was unclear, but it confirms that reliable measurements cannot be obtained with the photodiodes in the non-linear region where the response is inconsistent. The data shown in Fig. 1 support that the photodiode pulse time duration residuals are independent of signal voltage and, therefore, radiation dose, below 2.5 V because the residuals are limited to 2.3 ns with the exception of the lowest signal Si pulse.

Both the XRS3 and XRS4 sources were pulsed 20 times to obtain the average pulse duration $\mu_{duration}$ and 1σ pulse arrival time jitter data compiled in Table III. The jitter is herein defined as 1σ in pulse arrival time.

The XRS4 Si maximum signals were only about 50 mV above the noise floor because the photodiode could not be placed directly at the x-ray tube output face. The low 14.7 ns average pulse duration may not be reliable because the photodiode signal quickly falls below the noise floor as it decays. The Si photodiode was not included in subsequent testing with the Scandiflash systems because the InGaAs photodiodes demonstrated a similar or better performance and higher sensitivity.

The pulse measurements for both Scandiflash systems and InGaAs photodiodes are compiled in Table IV.

A moving average filter was applied to the SCF150 IGA-A datasets because accurate FWHM measurements could not be obtained from the raw datasets. A comparison of pulses from the XRS3 and Scandiflash systems is shown in Fig. 2.

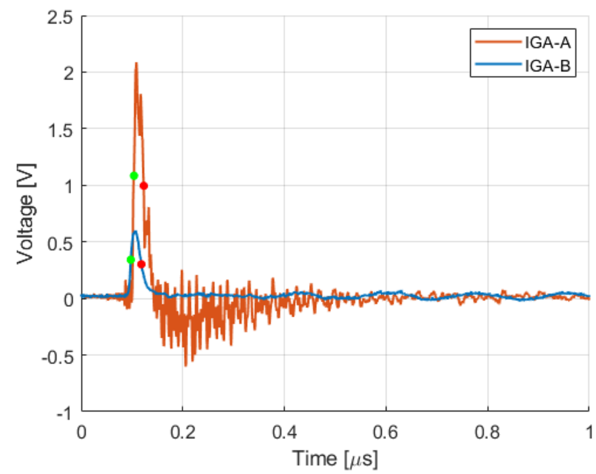

FIG. 3. Comparison of the electrical noise in IGA-A and IGA-B photodiode signals during SCF450 system pulsing. The IGA-A showed a large amount of high frequency noise even after double-shielded BNC cables, ferrite coils, isolation transformers, and a passive RF filter were used. There was significantly less high frequency noise in the battery-powered IGA-B signals, but longer period low voltage oscillations appeared. The peak amplitude of the signals is not directly indicative of sensitivity because different shielding and standoff configurations were used for each photodiode.

IV. DISCUSSION

The Scandiflash 150 and 450 systems produced x-ray pulses on the order of 10s of nanoseconds, but the rapid discharge of the pulsers during operation briefly moved the building electrical ground. The IGA-B InGaAs photodiode was specifically chosen for testing because it is battery-powered and not connected to the building ground via AC power supply. The difference in signal noise between the battery-powered and AC-powered InGaAs photodiodes is highlighted in Fig. 3.

However, oscillations of about ±100 mV with periods of around 150 ns were still present in some IGA-B traces. The oscillations may be attributed to electrical waves reflected between the anode–cathode junction and the pulser.

The photodiode pulse duration measurements were similar for each x-ray source tested with the exception of the XRS4 Si and SCF IGA-A measurements. We recommend the IGA-B battery-powered photodiode for the direct detection of pulsed x rays with durations on the order of nanoseconds because the IGA-B had similar sensitivity as the IGA-A, but it did not experience the same ground bounce issues because it was not connected to the building electrical ground. The longer rise time of the IGA-B photodiode did not appear to significantly impact its performance since the average measured pulses in the XRS3, XRS4, and SCF450 experiments were within 3.1 ns of the faster rise time IGA-A and the standard deviation in pulses as measured by the IGA-B was similarly low.

The pulse arrival time jitter was very consistent between photodiodes for each x-ray source. The detector material and rise time did not appear to influence the pulse jitter because the photodiode jitter times were within 300 ps of each other during XRS3 testing and within 400 ps of each other during XRS4 testing. The difference in the x-ray system jitter for the SCF450 as measured by the IGA-B and IGA-A was higher at 1.2 ns, but it may be attributed to the lower number of pulses measured by the IGA-A as compared to the IGA-B. Regardless, all three photodiodes are excellent pulse time-of-arrival diagnostics for benchtop flash x-ray systems if an uncertainty in pulse time-of-arrival of 1.2 ns or less is acceptable.

Note that the signal intensities are not directly indicative of x-ray dose since the sensitivity of each photodiode to each x-ray pulse differs. Not only do the active surfaces of the diodes absorb different fractions of x rays at different energies, but the number of electron hole pairs generated per incident x-ray photon increases at higher x-ray energies and depends on the bandgap energy in the semiconductor.[25,26] Even relative dose measurements of the pulsed x-ray sources used in this research are difficult. In separate experiments, we used a Radcal 10X6-6M ion chamber dosimeter to record the average dose/pulse of the 150 kVp flash x-ray system. In the same test configuration, the ion chamber recorded an average dose of 42.2 mrem/pulse when a tungsten anode was used in the x-ray tube and 329.3 mrem/pulse when a molybdenum anode was used. The lower energy characteristic emission of the molybdenum anode configuration likely caused the substantial increase in measured dose relative to the tungsten configuration because the ion chamber was more sensitive to lower energies in the 10–40 keV range. The actual dose of the tungsten configuration is likely higher because of the higher energy characteristic emission, but neither the dosimeter nor the photodiodes used in this work can accurately measure the absolute or relative x-ray doses of the sources because they do not absorb uniformly over the entire x-ray energy spectrum, and both the end point energy and the characteristic emission energies of the sources vary.

Although silicon and InGaAs photodiodes are typically used for visible and infrared light measurements, respectively, the results indicate that repeatable x-ray pulse measurements can also be obtained without the use of scintillators. However, the InGaAs photodiodes were significantly more sensitive to the x-ray radiation of the sources than the silicon photodiode. This suggests that the photodiode responses are primarily determined by harder energy bremsstrahlung x rays because the 3.2 mm thick silicon sensor and 2.2 mm thick InGaAs sensors similarly absorb nearly all softer energy x rays up to 17.4 keV.[27]

V. CONCLUSION

These results indicate that silicon and InGaAs photodiodes can be used as pulse timing diagnostics for x-ray systems that do not produce enough flux to be detected using scintillators with rapid rise and decay times. However, users should first quantify the linear and non-linear regimes of each photodiode used to ensure that the photodiodes are not operating in the non-linear regime where the measured pulse duration is a function of x-ray dose. The battery-powered IGA-B is a suitable timing diagnostic for benchtop pulsed x-ray systems on account of its high sensitivity and lower susceptibility to electrical noise, but the AC-powered IGA-A would also perform well when used with battery-powered pulsed x-ray systems or if it were used strictly as a time-of-arrival diagnostic for pulsed x-ray systems connected to the building electrical ground. The InGaAs photodiodes evaluated were more sensitive to x-ray wavelengths and were better suited for direct x-ray pulse detection than the silicon photodiode, but faster photodiodes with smaller active areas than the ones evaluated in this work are needed to quantify pulses on the picosecond and femtosecond timescales at synchrotrons and XFELs. Future research is also needed to determine the optimal diode bias at different x-ray wavelengths. Both the high sensitivity of the InGaAs photodiodes and the low sensitivity of the silicon photodiode may be moderated via optimized biases for the detector materials and active areas.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Cameron B. Brown: Data curation (equal); Formal analysis (lead); Investigation (lead); Methodology (equal); Writing – original draft (lead); Writing – review & editing (equal). **Dennis K. Remelius**: Conceptualization (equal); Investigation (equal); Resources (equal). **Laura B. Smilowitz**: Conceptualization (lead); Formal analysis (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Project administration (lead); Resources (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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