Sub-nanosecond single line-of-sight (SLOS) x-ray imagers (invited)


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Sub-nanosecond single line-of-sight (SLOS) x-ray imagers (invited)

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A new generation of fast-gated x-ray framing cameras have been developed that are capable of capturing multiple frames along a single line-of-sight with 30 ps temporal resolution. The instruments are constructed by integrating pulse-dilation electron imaging with burst mode hybrid-complimentary metal-oxide-semiconductor sensors. Two such instruments have been developed, characterized, and fielded at the National Ignition Facility and the OMEGA laser. These instruments are particularly suited for advanced x-ray imaging applications in Inertial Confinement Fusion and High energy density experiments. Here, we discuss the system architecture and the techniques required for tuning the instruments to achieve optimal performance. Characterization results are also presented along with planned future improvements to the design. Published by AIP Publishing. https://doi.org/10.1063/1.5039648

I. INTRODUCTION

High energy density (HED) experiments produce spatially microscopic and temporally transient states of optically opaque matter. Diagnosing such material requires fast-gated x-ray imagers with high spatial resolution. In particular, imploding Inertial Confinement Fusion (ICF) cores at the National Ignition Facility (NIF) produce x-ray emission “hot-spots” with ~50 μm spatial scale and ~100 ps duration.1
In order to accurately characterize implosion performance, <5 μm spatial resolution and ~20 ps temporal resolution are desired. Previously fast-gated x-ray imaging was performed with MCP (microchannel plate) based detectors.2–5
While the temporal resolution of such detectors is sufficient, they have a major limitation: they can only capture a single output image per input image. To generate a record of sequential images, an array of pinhole images can be projected onto the detector, with each pinhole image corresponding to a different time window. However, pinhole imaging places considerable limitations on the image resolution and signal throughput6 while in most cases failing to provide images over a narrow spectral bandwidth. There are multiple advanced imaging applications for ICF science that over come these limitations by providing high spatial resolution with higher throughput over a narrow spectral bandwidth, but these applications are in need of single line-of-sight image recording. Two examples are the NIF KBO7 (Kirkpatrick-Baez Optic) and CBI (Crystal Backlighter Imager) systems. Maximizing the impact of these resource intensive optical systems requires a time-gated detector that can provide multiple sequentially gated-images over the course of the experimental record. This motivated the development of the single line-of-sight (SLOS) diagnostic, which can produce multiple frames with high temporal and spatial resolution along a single line-of-sight.

II. PRINCIPLES OF OPERATION

The single line-of-sighter achieves multi-frame, picosecond imaging by incorporating a burst mode hybrid-CMOS (complimentary metal-oxide-semiconductor) sensor within a pulse-dilation drift tube. The system operation is illustrated in Fig. 1. An x-ray transmission photocathode converts the input x-ray image into an electron image. The electron image is accelerated along the drift tube by a time-dependent electric field that magnifies the image temporally by dilating its longitudinal extent as it propagates. The transverse spatial resolution of the image is maintained by a strong axial magnetic field. Finally, the dilated electron image is captured across multiple frames with nanosecond gates by using a Sandia’s burst mode hCMOS sensor. The effective x-ray gate width of the system is the CMOS gate width divided by the dilation factor.

A. Constant temporal magnification

The temporal magnification, or dilation factor, of the system is determined by the time-dependent velocity of electrons exiting the accelerating region and the length of the drift region. The electron velocities are set by the kinetic energy
As Ref. 4 showed, the instantaneous magnification is through the accelerating region is short, the instantaneous electron pulse over several frames with ns frame widths.

they achieve as they transit the time-varying electric field in the accelerating region. In the limit that electron transit time through the accelerating region is short, the instantaneous photocathode voltage and electrons’ final kinetic energies are equal. As Ref. 4 showed, the instantaneous magnification is given by

\[ M \approx 1 + \frac{L}{V} \left( \frac{|V|}{V_0} \right), \]

where \( L \) is the drift length, \( v_d \) is the drift speed, and \( V \) is the voltage between the photocathode and the anode mesh. Since the SLOS imager aims to achieve multiple frames, and it is desirable for the frames to have the same temporal gate width and separation, a photocathode voltage ramp that achieves constant magnification is desired. The voltage ramp which achieves constant magnification was shown in Ref. 8 to be

\[ V(t) = \frac{V_o}{[1 + (M - 1)t/T_o]^2}, \]

where \( t \) is the time, \( M \) is the magnification, \( V_o \) is the initial voltage, and \( T_o \) is the initial electron time-of-flight through the drift tube. A major challenge in developing the SLOS instrument was to achieve this precise voltage profile over a \( \sim 1 \) ns record length for various temporal magnifications. This challenge motivated the development of a novel Kentech photocathode pulser (see Sec. III B) utilizing multiple voltage steps with individually programmable delays. When the relative delays between the individual steps are carefully tuned (see Sec. IV), the summation can be accurately fit to the voltage profile given by Eq. (2). This also allows for multiple magnification values to be achieved with a single pulser unit.

B. Spatially uniform image gating

In previous pulse dilation imagers, the photocathode was an impedance matched microstrip transmission line, and a fast, traveling voltage pulse was propagated across the photocathode’s active area. This created a traveling gate across the photocathode, which allowed different positions across the active area to capture different pinhole images at different times. By contrast, single line-of-sight detectors require the image gate to be spatially invariant across the sensor’s active area. To achieve this, counter propagating or “colliding” voltage pulses are introduced from each side of the photocathode transmission line. If the colliding pulses are a linear function of time, then their spatial component will vanish, generating a spatially uniform photocathode voltage. For voltage pulses which are not linear, such as those defined by Eq. (2), exact cancelation will not occur. Instead, the magnitude of the spatial variation across the sensor will be dictated by the ratio of the characteristic time constant of the voltage pulse, \( \tau \approx T_o/M \), to the transit time of the voltage pulse across the sensor’s effective active area on the photocathode. \( t_{\text{transit}} = L_{\text{sensor}}/c \), where \( c \) is the speed of light and \( L_{\text{sensor}} \) is the effective length of the sensor’s active area on the photocathode (i.e., including any transverse magnification provided by the magnetic field). If \( \tau \gg t_{\text{transit}} \), then the pulse will be approximately linear over the length of the sensor and any spatial variation will be small. This implies that the sensor’s length will dictate the maximum achievable magnification (per unit of drift length) for which uniform image gating can be achieved. For the 25 mm CMOS sensors used in the SLOS imager, this results in the condition that the magnification must be less than 400\( \times \)m of the drift length. The highest magnification that has been achieved in the SLOS imager to date is 120\( \times \)m of the drift length. It is shown that this results in a maximum deviation across the active area of \( \Delta M < 2\% \) and maximum temporal shift of \( \Delta \tau \approx 5 \) ps.

C. Spatial resolution

The spatial resolution of the system is provided by a strong axial magnetic field produced by a solenoid coil that encloses the drift tube. Photoelectrons born at the photocathode undergo cyclotron orbits with the characteristic Larmor radius. The input x-ray image is maintained as an electron image as it propagates through the drift tube, with the resolution set by four times the Larmor radius. The Larmor radius is given by

\[ r_L = \frac{m v_{\perp}}{eB}, \]

where

\[ v_{\perp} \approx \sqrt{\frac{T_e}{m}}, \]

\( m \) is the electron mass, \( e \) is the electron charge, \( B \) is the magnetic field strength, \( v_{\perp} \) is the electron velocity perpendicular to the B-field, and \( T_e \) is the average birth kinetic energy of the secondary electrons. Note that \( T_e \) depends on both the photocathode material and x-ray photon energy. Once the electron image is sampled by the CMOS, the combined spatial resolution is given by

\[ \delta = \sqrt{(4r_L)^2 + (\delta_{\text{CMOS}} \times \text{Mag}_B)^2}, \]

where \( r_L \) is the Larmor radius, \( \delta_{\text{CMOS}} \) is the detector’s pixel size, and \( \text{Mag}_B \) is the magnification provided by the magnetic field. In the initial SLOS imagers, the magnetic field is chosen to be axial, so the magnification is nominally 1. In this case, the resolution is ultimately limited by the CMOS pixel size,
nominal 25 μm, and it is desirable to achieve a combined resolution which is below the ~60 μm resolution element (at the detector plane) provided by the imaging optics. The combined resolution was designed to be better than 40 μm, which requires an rL that produces 25 μm resolution in the electron image. For a CsI photocathode under 8 keV x-ray illumination (T.e. = 1.7 eV9), this requires a 6 kG magnetic field. There are additional contributions to the resolution, such as the curvature drift, ExB drift, and ∇B drift, but they have been excluded from Eq. (5) because they are much smaller than rL. 5.

D. Electron detection by CMOS

After propagating through the drift tube, the electron image has dilated longitudinally by the magnification factor so that a ~100 ps input x-ray pulse can be sampled across several CMOS frames of nanosecond gate widths. This is achieved with the use of a burst mode hybrid-CMOS sensor, which was recently developed by Sandia National Laboratories as part of the Ultrafast X-ray Imager (UXI) program.11 These sensors achieve multi-frame, time-gated imaging by coupling a Read-out Integrated Circuit (ROIC) directly to a photodiode pixel array. Electron-hole pairs created in each photodiode pixel can be collected and stored by a series of capacitors within each ROIC pixel. This allows for multiple frames to be stored in pixel on a time scale of nanosecond and readout up to several seconds later. To date, two and four frame operation with gate widths down to 2 ns has been demonstrated.12,13

While the CMOS’s silicon photodiode is sensitive to electrons, the quantum efficiency is a strong function of the incident electron energy. In the range of useable electron drift energies of the SLOS instrument (0.5-2 keV), the detection efficiency is less than ~10%. To overcome this low efficiency regime, electrons are given additional kinetic energy immediately before striking the sensor by an electric field in the boost region shown in Figs. 1 and 2. This is achieved with a ~3.5 kV “drift bias” placed across two meshes at the rear of the drift tube and requires the entire drift region and photocathode to be floated at ~3.5 kV DC from ground. The drift bias increases the electron energies incident at the CMOS to 4-5.5 keV and the corresponding detection efficiency to ~30%-55%. However, the voltage profile given by Eq. (2) results in electron energies which decrease as a function of time such that the detection efficiency and energy deposited by the electrons will decrease as a function of time. The implication of this is that later frames will record fewer counts at the CMOS detector.

III. INSTRUMENT ARCHITECTURE

The instrument consists of three main modules: the Kentech electronics with the solenoid capacitors, the solenoid vessel with the drift tube assembly, and the CMOS sensor with its associated electronics. The layout of these components is shown in Fig. 3(a).

A. Kentech electronics

The Kentech electronics set produces the electrical sources necessary to operate the instrument: the solenoid pulser, photocathode pulser, DC drift bias, as well as power and optional trigger signals for the CMOS. The pulser also outputs a series of monitors to observe the solenoid and photocathode pulses and diagnose performance. The pulser electronics can be remotely controlled with an external command computer.

The solenoid pulser is responsible for charging the storage capacitors and discharging their stored electrical energy into the solenoid coils. Solenoid switching is performed by a SCR (silicon controlled rectifier) and drives a current pulse through the solenoid coils to generate the axial magnetic field. The pulse has a peak current of ~1 kA and a duration of ~1-10 ms, resulting in the necessary 6 kG peak B-field within the solenoid vessel. The total capacitance of the solenoid storage capacitors is chosen to ensure sufficient energy is stored to produce the required magnetic field strength.
The photocathode pulser consists of two individual modules: a slow pre-bias pulser and a fast avalanche pulser. The pre-bias pulser is a ~10 ns MOSFET based pulser, which sets the initial voltage of the photocathode of ~2.5 kV below the ~3.5 kV DC bias of the anode mesh (~6 kV relative to ground). The second photocathode pulser is a series of 8 avalanche transistor stacks which form a programmable pulser. Each individual avalanche pulser contributes a +400 V step with a 100 ps rise time to the waveform at the photocathode. The photocathode voltage is the linear sum of eight such steps. These pulsers have individual programmable delays which can be set with ~10 ps precision over a ~1 ns range. When combined, these 8 avalanche stacks drive the photocathode from ~2.5 kV to +500 V, generating the desired ramp shape given by Eq. (2). In addition to having programmable delays, the individual channels also vary in shape characteristics, with 4 being as fast as possible and 4 being somewhat slower and more varied in the temporal profile. This variation in shape aids in ramp tuning. The fast channels are most useful early in time when the desired ramp is steepest, and the slower channels provide better fits to the desired ramps late in time. Note that with ~400 V and 8 channels, the avalanche pulses actually bring the photocathode to a positive voltage. This serves the function of turning the photocathode emission off at late times. Finally, the Kentech electronics includes a ~3.5 kV DC supply to float the drift tube and provide the drift bias, which is needed for efficient electron detection.

B. Solenoid vessel and drift tube design

The solenoid is wound onto the primary vacuum vessel. It is a hollow Ultem cylinder wound along its entire length with two layers of insulated square copper wire. Additional wire layers are added near the end of the vessel to reduce the curvature of the B-field at the tube ends. After winding, the copper wire is potted with epoxy and terminal blocks gather the solenoid leads that attach to the solenoid pulser. Depending on the length of the instrument, it may be desirable to wind multiple individual coils which can be driven in parallel to reduce the solenoid pulse duration.

The drift tube makes up the main mechanical structure of the instrument. It houses the photocathode, meshes, and CMOS sensor. It also uses the pulsed and DC biases from the Kentech pulser to establish the potential regions shown in Figs. 1 and 2. The drift tube is shown in Fig. 3(b). It can be broken down into several fundamental portions: the photocathode assembly [Fig. 3(c)], the drift tube, and the CMOS housing and feedthrough flange [Fig. 3(d)]. The photocathode and anode mesh assembly consists of an 18.9 mm wide metal layer (200 nm of Al or 50 nm of Au) on a quartz substrate suspended 1.6 mm above a nickel anode mesh. An Au photocathode is used for UV testing. For x-ray use, the Al conductor suspended 1.6 mm above a nickel anode mesh forms a 25.4 × 12.7 mm active area. Icarus 1 is a two frame sensor that was fielded. Icarus 2 is a four frame sensor that began commissioning in the spring of 2018. The Icarus sensors have variable timing modes, whereby the gate width and frame to frame separation can be independently adjusted in nanosecond increments. The fastest mode demonstrated to date (“2-2” mode) yields gate widths down to 2 ns and frame separations of 4 ns (peak to peak). In addition, the Icarus can be run in the split hemisphere timing mode, whereby independent 1024 × 128 hemispheres can be offset temporally in 2 ns steps. This allows for as many as 8 frames to be captured at different times with Icarus 2 (4 in the case of Icarus 1). The detailed design and operation of these sensors is beyond the scope of this paper and has been described elsewhere. However, several novel considerations were required for the successful operation of the Icarus sensor within the SLOS instrument.

First, the Icarus sensor has 160 electrical connections that must penetrate the vacuum barrier. This was achieved by the development of a multilayer PCB feedthrough flange, shown at the end of the drift tube in Fig. 3(d). Second, the drift tube presents large sources of electrical noise, with multiple kilovolt voltage sources of varying durations in close proximity to the Icarus sensor and readout electronics. In comparison, a single count from the sensor corresponds to just 78 µV at the ROIC. This represents a voltage rejection of 7 orders of magnitude. To ensure low noise operation of the sensor, the Icarus is housed in a grounded Faraday cage, which is composed of a Cu-coated Ultem 1000 housing and a Ni wire shield mesh (shown in Figs. 2 and 3).

IV. INSTRUMENT TUNING

Before the Icarus sensor was installed, the correct photocathode voltage ramps for constant magnification needed to be established. This presents two fundamental challenges. First, the photocathode voltage and the corresponding electron drift energies resulting from each avalanche channel needed to be accurately measured. Second, the individual delays of the avalanche pulser channels must be tuned, so the summation results in the voltage profile given by Eq. (2).

Initial measurements of the transmitted avalanche channels were made downstream of the photocathode with an 8 GHz oscilloscope. However, it was found that this measurement lacked sufficient bandwidth. It also did not account for the finite length of the acceleration gap or other effects which
may alter the shape of the waveform at the photocathode. To overcome this, the electron energies were inferred by making accurate time-of-flight measurements of electrons exiting the drift region. A photodiode sensitive to both electrons and UV light (Opto Diode AXUVHS11) was installed in the rear of the instrument, and a 50 nm Au photocathode was illuminated in a transmission geometry with 21 ps (FWHM), 266 nm UV laser pulses. By measuring the delay between the UV pulses and electron pulses recorded by the photodiode (as shown in Fig. 4), the photocathode voltage as a function of laser arrival time relative to the photocathode voltage ramp was inferred. This allowed for the voltage generated at the photocathode by each avalanche pulse to be measured with high precision.

With the individual avalanche pulses measured, generating the desired photocathode voltage requires accurately setting the relative delays for the 8 avalanche channels. This was done by performing offline, non-linear least-squares fits where the measurements of the 8 channels were used to fit Eq. (2) for various magnifications. This fitting process is particularly susceptible to finding local minima, so it was combined with a brute force approach which systematically varied the initial positions of the individual pulser channels. This ensured that the best possible solution was found. From this method, several solutions from the offline fitting process were measured with photodiode scans, and the best fit for each magnification was chosen for a final online optimization. In this step, the programmable delays were adjusted at the 10 ps level by an online non-linear least-squares algorithm that compared the measured photocathode voltage to the desired waveform.

There are several non-linear effects that can occur when combining the individual avalanche pulses that make this method a somewhat intuitive and ad-hoc solution, but excellent fits to the desired ramp shapes can be achieved. Results from this process are shown in the photodiode traces in Fig. 4. Two 21 ps UV laser pulses simultaneously record the electron time of flight (pulse position) and instantaneous magnification (pulse to pulse separation) as a function of laser arrival time. The fit to the desired photocathode ramps derived from the photodiode measurement and the associated magnification profile are shown in Fig. 5. In this example, a magnification

![Figure 4](image1.png)  
**FIG. 4.** A series of photodiode measurements made in a 40 cm drift tube with two 21 ps laser pulses separated by 50 ps striking an Au photocathode. For each trace, the laser arrival time at the photocathode is delayed relative to the photocathode voltage ramp. The first peak, at ~2 ns, corresponds to direct UV illumination (1.3 ns time-of-flight) of the photodiode, and the second peak(s) corresponds to electrons which have drifted through the instrument. At early times, while the magnification of the system is low, the two pulses are unresolved, and later, when the magnification increases, the pulses segregate. By fitting Gaussians, the electron time of flight and instantaneous magnification can be measured as a function of laser arrival time. Note that the decreasing intensity as a function of time is a result of the decreasing electron kinetic energy combined with the diode’s detection efficiency and the increased electron pulse width.

![Figure 5](image2.png)  
**FIG. 5.** (Top) The desired photocathode voltage as a function of time (blue line) vs. the measured kinetic energy of electrons inferred from electron time-of-flight (red circles). (Bottom) The desired magnification as a function of time (blue line) vs. the measured magnification inferred from the Gaussian fits (red circles).
of $85 \times m$ was achieved for a duration of $\sim 350$ ps, and the magnification over that duration is constant to within $\pm 3\%$. This process has been used to generate magnification profiles in the range of $40–120 \times m$ of the drift length. The accuracy and duration over which a flat magnification can be achieved was found to be limited by the number of avalanche channels, their range of shapes, and the maximum programmable delay of each channel.

V. INTEGRATED SYSTEM PERFORMANCE

With the photocathode ramps established and the Icarus sensor installed, the integrated system results in multi-frame, single line-of-sight imaging capable of sub-100 ps resolution. This result is shown in Fig. 6. Two laser pulses separated by 100 ps cannot be resolved by the 2 ns gate width of the Icarus 1 sensor, but with a temporal magnification of $40\times$ provided by pulse dilation, the two pulses can be resolved and recorded independently. Further characterization of the integrated system performance was studied with x-ray measurements of the spatial resolution and UV measurements of the temporal resolution.

A. Spatial resolution

The transverse spatial resolution depends on both the photocathode material and photon energy (as discussed in Sec. II C), so the image characterization must be performed with an x-ray source of the appropriate photon energy and a CsI photocathode. The spatial resolution of the system was tested at the COMET laser on the Jupiter Laser Facility at Lawrence Livermore National Laboratory with a $\sim 8$ keV laser produced copper K$_{\alpha}$ source. Those measurements are reported in Ref. 14 and the spatial resolution was found to be 37 $\mu$m. In addition, Ref. 14 reported spatial mapping tests to characterize any image distortions arising from non-uniformities in the magnetic field.

B. Temporal resolution

The combined temporal resolution of the system is the product of the CMOS gate width and the temporal magnification provided by pulse dilation. Characterization was performed with “gate scans,” where the arrival time of the UV laser at the photocathode is scanned and a series of images record the charge collected by the sensor. The best resolution was achieved with $95\times$ magnification and the CMOS running in a 2-2 timing mode (nominal 2 ns gate width with 4 ns frame to frame separation). This is shown in Fig. 7. The Icarus sensor produced two frames with 2.6 ns gate widths (FWHM) and 4.6 ns frame separation. When combined with the

![Image of two 21 ps laser pulses, with the “+” arriving 100 ps before the “x,” recorded with the photocathode biased to $\sim 2.5$ kV DC (top) and with the photocathode ramp and drift tube length set to $40\times$ magnification.](image1)

![Graph showing gate scans of the two frame Icarus 1 acquired by scanning the laser arrival time at the photocathode. Average CMOS counts (circles) with a $-2.5$ kV DC bias on the photocathode (top) vs. the full photocathode waveform achieving a temporal magnification of 95 (bottom). Gaussian fits (solid lines) to the measured CMOS response with the FWHM reported in the legend.](image2)
95x magnification, the system produces two frames with 28 and 31 ps gate widths (FWHM after deconvolution of the 21 ps laser) and 50 ps frame separation. The total record length in this mode is ∼100 ps. The decrease in intensity between the first and second frames observed in both Figs. 6 and 7 is a result of the decreased kinetic energy of the electrons in the second frame combined with the reduced quantum efficiency of the CMOS detector to lower energy electrons. Additional timing modes have been developed and characterized by utilizing different Icarus timing modes (gate width, separation, and hemisphere delay) and temporal magnifications. The longest total record length achieved is 350 ps.

C. Space charge and dynamic range considerations

During the characterization of temporal performance, space charge broadening of the electron pulse was observed at high CMOS count levels. If the x-ray flux and the associated current density in the region of the photocathode become high enough, Coulomb repulsion will induce velocity dispersion of the electron pulse. This sets up a competition between the velocity dispersion introduced by the photocathode voltage ramp and the velocity dispersion due to space-charge effects. To study this effect, we have performed calculations with the two-dimensional axisymmetric particle in cell code XOPIC. Results are shown in Fig. 8. The magnitude of the broadening depends on the x-ray illumination function, as well as the drift tube operating parameters such as the effective frame width, temporal magnification, and drift voltage. Figure 8 allows us to make several important observations. First, the space-charge broadening increases rapidly with current density, and second, the onset of the broadening is a strong function of the photocathode extraction voltage when the voltage profiles for constant magnification are used. Indeed, if we choose an upper limit for the broadening fraction (e.g., 20%), we see that the current carrying capacity or the effective dynamic range [i.e., electrons/(pixel/gate) width] of the drift tube will scale as

\[
I_{\text{max}} \propto V^{3/2},
\]

where \(I_{\text{max}}\) is the maximum electron current and \(V\) is the photocathode voltage. This result was also derived by Prosser in Ref. 8. The implication is that later frames, which drift at lower voltages, will experience the most broadening or accommodate the fewest electrons. In addition to the longitudinal dispersion, the space-charge effects also create an electric field perpendicular to the drift axis. However, this manifests as an \(ExB\) drift and is a much smaller perturbation to system performance.

There are a few ways to mitigate the space-charge broadening and increase the instrument’s dynamic range: larger spatial resolution element, increased temporal magnification, or increased photocathode voltage. Of course, larger spatial or temporal resolution elements are undesirable, so the best way to increase the dynamic range is to operate at the highest possible photocathode voltage and temporal magnification. Alternatively, it may be beneficial to choose photocathode voltage ramps which maximize the dynamic range instead of providing constant temporal magnification. Finally, it is the dynamic range in x-rays that is most important for this system and CsI produces many electrons per x-ray photon (on average 34 electrons/8 keV photon\(^{16}\)), which decreases the effective x-ray dynamic range of the system. By far, the best way to reduce the impact of space-charge broadening is to use photocathodes that produce only a few electrons per absorbed x-ray photon.

VI. APPLICATIONS

The SLOS imager can be applied to a variety of imaging applications to provide multiple sequentially gated frames. To date, two instruments have been constructed and deployed, and a third instrument is in the final design phase. SLOS-TRXI (Time Resolved X-ray Imager) was developed for use at the OMEGA laser facility, and SLOS1 or SLOS-CBI was developed for the NIF. These instruments are shown in Fig. 9. Finally, hardened Single Line-of-Sight (hSLOS) is the next generation of SLOS instruments developed for the NIF and is currently in the final design phase.

A. SLOS-TRXI

SLOS-TRXI was installed at the target chamber wall of the OMEGA laser at the Laboratory for Laser Energetics (LLE). SLOS-TRXI has a 75 cm drift tube and achieves magnifications as high as 95x. It is currently being used as a time-resolved pinhole imager, and it is run with a two frame Icarus sensor in the hemisphere delay mode. Pinholes 166.5 mm from target chamber center (TCC) are projected onto the CsI photocathode 2238 mm from TCC providing a spatial magnification of 12.4 to capture self-emission x-ray images with 10 µm spatial resolution (at the target) across four 30 ps frames, covering a ∼120 ps total record length. This allows for the evolution of the x-ray hotspot morphology and size to be
characterized. While advanced optics such as KB and Wolter are being evaluated to improve the spatial resolution, the benefit of using the SLOS diagnostic for pinhole imaging is that multiple images can be averaged for each frame to improve signal-to-noise ratio. SLOS-TRXI has successfully recorded images on multiple cryogenic implosions at the OMEGA laser with total neutron yields above $1 \times 10^{14}$. Those results and additional details on SLOS-TRXI can be found in Ref. 17.

**B. SLOS-CBI**

The CBI system uses a portion of the NIF drive laser to generate a high energy x-ray backlighter. X-rays transmitted through the target are diffracted by a bent crystal optic to image ICF implosions over a narrow spectral bandwidth. Unlike self-emission imaging, which captures the hot material within the x-ray hot-spot, CBI diagnoses the surrounding cold ablator material. When fielded with SLOS1, the combined system, SLOS-CBI, can record multiple frames over the duration of the implosion. The result will provide late-time radiographs of the cold ablator, allowing for improved characterization of the implosion symmetry and capsule perturbations. SLOS-CBI was fielded on NIF in the Fall of 2017 and has since recorded a capsule implosion. SLOS-CBI has operated a two frame Icarus 1 in a 50 cm drift tube. This system achieved image gate of $\sim 35-150$ ps with total record lengths up to 350 ps. A series of major upgrades have since been made to the SLOS-CBI instrument. Most notably, a four frame Icarus 2 sensor has been installed. In addition, improvements were made to increase the sensitivity of the Icarus, reduce the sensor gate width below 2 ns, and mitigate image artifacts from the meshes. Final characterization of the upgraded system is underway, and SLOS-CBI is scheduled to record additional capsule radiographs of NIF implosions.

**C. hSLOS**

The SLOS-TRXI and SLOS-CBI instruments were not designed to be radiation hardened instruments, and while they have been successfully operated at total neutron yields above $10^{14}$, operating at higher yields will require a true radiation hardened device. To accomplish this, the next SLOS imager, hardened Single Line-of-Sight (hSLOS), is being designed to operate in the NIF for neutron yields up to $5 \times 10^{16}$. hSLOS will require a total redesign of the camera and pulser electronics. Additional upgrades to the system are also planned. First, hSLOS will accommodate two photocathodes and two four-frame Icarus II sensors. This will enable a total of 8 or 16 frames, depending on the application. The photocathodes will be driven from $-5$ kV by 12 avalanche channels to reduce space charge broadening and increase the dynamic range. hSLOS will also utilize a segmented drift tube to accommodate the addition of a catchup ramp in place of the DC drift bias. This catchup ramp will compensate the electron energy dispersion in the boost region such that all the electrons impinge on the sensor with an equal 5 keV of kinetic energy. Surface passivation of the Icarus 2 diodes will also increase the detection efficiency for all frames. Finally, additional materials are being evaluated to identify high-efficiency photocathodes that produce fewer electrons per absorbed photon to further increase the system’s dynamic range. hSLOS will be suitable for a variety of applications on the NIF, including the CBI and KBO systems.

**VII. SUMMARY**

In conclusion, we have demonstrated an imager capable of capturing multiple sequential frames from a single input image. To date, we have achieved 2 and 4 frame operation with sub-30 ps temporal resolution and 40 $\mu$m spatial over a $12 \times 25$ mm active area. We have also demonstrated a method for achieving constant temporal magnifications over several hundred picoseconds. Additional improvements are underway to create a radiation hardened instrument with more frames, increased temporal resolution, and increased dynamic range.
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