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Multiframe, Single Line-of-Sight X-Ray Imager for Burning Plasmas

K. L. Baker

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Multiframe, Single Line-of-Sight X-Ray Imager for Burning Plasmas

Kevin Baker (15-ERD-064)

Abstract

The purpose of this LDRD project was to demonstrate high spatial and temporal resolution x-ray imaging using optical detectors, and in particular the VISAR and OHRV diagnostics on the OMEGA laser. The x-ray source being imaged was a backlighter capsule being imploded by 39 beams of the OMEGA laser. In particular this approach utilized a semiconductor with the side facing the backlighter capsule coated with a thin aluminum layer to allow x rays to pass through the metal layer and then get absorbed in the semiconductor. The other side of the semiconductor was AR coated to allow the VISAR or OHRV probe beam to sample the phase change of the semiconductor as the x rays were absorbed in the semiconductor. This technique is capable of acquiring sub-picosecond 2-D or 1-D x-ray images, detector spatial resolution of better than 10 um and the ability to operate in a high neutron flux environment expected on ignition shots with burning plasmas.

In addition to demonstrating this technique on the OMEGA laser, several designs were made to improve the phase sensitivity, temporal resolution and number of frames over the existing diagnostics currently implemented on the OMEGA laser. These designs included both 2-d imaging diagnostics as well as improved 1-D imaging diagnostics which were streaked in time.

Background and Research Objectives

The very short burn time and small size of burning plasmas created at advanced laser-fusion facilities means that high-spatial-resolution imaging diagnostics with extremely high time resolution of a few picoseconds will be required for ignited plasma research. These instruments must function in an environment of extremely large neutron

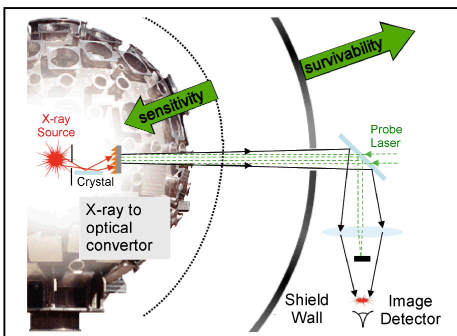

Fig. 1 Fast X-ray to optical conversion process to enable operation in a high neutron flux environment.

fluxes that will cause conventional diagnostics to fail because of radiation damage and induced background levels. A unique new solution to this challenge is to perform an ultrafast conversion of the x-ray signals into the optical regime before the neutrons are able to reach the detector and then to relay image the signal out of the chamber and into a shielded bunker, protected from the effects of these neutrons. This approach is illustrated in Figure 1. Our technique is to perform an ultrafast conversion of the x-ray signals into the optical regime using the small changes in refractive index produced by the absorption of ionizing radiation in semiconductors. The x-ray image is encoded in at most a few ps on an optical probe beam traveling through a 50 to 100 micron thick semiconductor. The optical probe beam can be conveniently relay imaged to a remote shielded location for recording. The all optical conversion process involves no electrical devices, so it highly resistant to EMP effects. Because the signal conversion to optical light is nearly instantaneous, even the effects of neutrons hitting the hohlraum wall and target positioner should not affect the measurement, and the large effects of neutrons interacting with the chamber and target area are completely avoided. The 1 to 2 ps time resolution possible with this technique is comparable to or better than the fastest electronic devices, the DIXI camera and or fast streak cameras, and the 5 to 10 micron detector spatial resolution possible is far superior to the approximately 200 micron resolution of the fast electronic DIXI or streak cameras. Ultrafast picosecond diagnostics based upon these principles can be developed using pulsed or spectrally chirped optical probe beams to encode gated or streaked x-ray images on an optical probe beam. Multiple time snapshots, short x-ray movies with 4 to 20 frames and ps resolution, can be taken from a single line-of-sight by probing the semiconductor with multiple optical beams separated by a combination of probe beam polarization, angle, and wavelength. In addition, it may be possible to make measurements driven by the neutrons from the target at late times close to or even after the neutrons hit the chamber wall with this technique which could not be done in any other way. Multiple gated images and continuous record(streaked) x-ray data with ps time resolution can be recorded without exposing any expensive electronic equipment to the effects of neutron generated EMP and neutron radiation.

Scientific Approach and Accomplishments

Experiments on the OMEGA Laser

Given that this LDRD was only for a single year, the emphasis was on making changes to existing diagnostics on the OMEGA laser facility at the Laboratory for Laser Energetics to enable the demonstration of the concepts described above. That is to show that x ray images could be made by imaging an x-ray source onto a semiconductor to create a spatially dependent index of refraction change in the semiconductor. This spatially dependent index of refraction change could then be detected via an optical instrument such as the VISAR and the OHRV diagnostics at the OMEGA laser facility.

The OMEGA laser facility was utilized for this experiment. A total of 39 beams with SG4 phase plates were used to implode a backlighter capsule to create the spatially dependent x-ray source. The 39 beams had a combined energy of 19.5 kJ and utilized a laser pulse shape which was a 1 ns square pulse in time, SG10vA01. The backlighter capsule itself was a 9 um thick, 860 um diamter CH capsule with no fill gas. In addition to the VISAR and OHRV diagnostics, an x-ray framing camera, XRFC, was used to capture two-dimensional images of the imploding backlighter capsule. The XRFC was located on TIM3 and had a 16 pinhole array with a magnification of 12. The pinholes were 6 um in diameter with 4 mil Be filtering. Figure 3 shows the 2-D x-ray images captured by the XRFC. At ~600 ps the capsule size is 500 um in diameter and the capsule size at 1.2 to 1.4 ns ~250 um. Peak emission is seen between 1.2 to 1.4 ns.

The x-ray emission from the backlighter capsule was also imaged onto a semiconductor, diamond or quartz, using a miniature x-ray snout as shown in Fig. 3a. As displayed in Fig. 3b, the VISAR then probed the semiconductor from the back and measured the induced phase change inside the semiconductor due to the impinging x rays. The DANTE diagnostic was also used to measure the spatially integrated x-ray emission from the capsule as a function of time. A comparison between the VISAR and DANTE diagnostics is shown in Fig, 3c. Specifically a lineout of the semiconductor phase change measured by the VISAR is compared to the DANTE diagnostic, channel 11.

Figure 2: XRFC images of the imploding backlighter capsule.

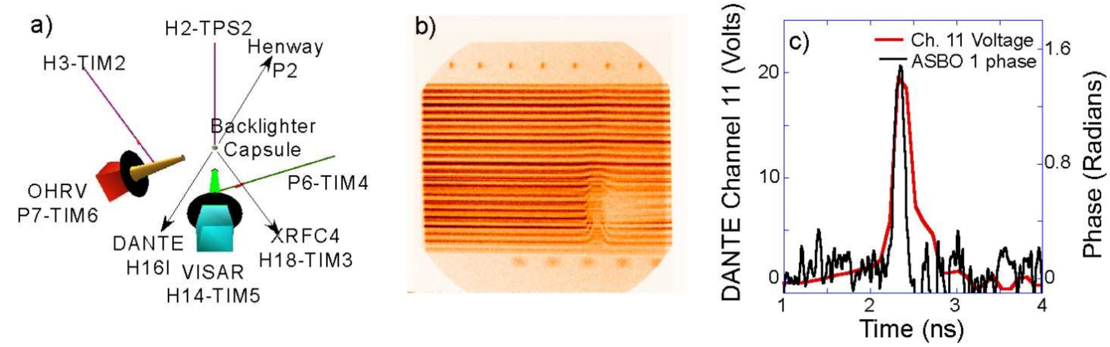

Figure 3: (a) VisRad image of the experimental setup to image the backlighter capsule onto a semiconductor. (b) VISAR measurement of the x-ray induced phase change in the semiconductor and (c). Lineout comparison of the DANTE channel 11 trace(red) with the VISAR trace(black).

Detector designs for improved sensitivity and data frames

Given that this LDRD was only for a single year, the emphasis was on making changes to existing diagnostics on the OMEGA laser, including VISAR and OHRV. In addition several designs which follow indicate how those or similar diagnostics could be changed to increase their sensitivity, dynamic range or frame number to make them more amenable to the function of detecting x rays and in replacing current technology.

The current VISAR system on OMEGA uses carrier frequency interferometry to determine the phase. An increase of an order-of-magnitude in phase resolution could be achieved by converting the operation to a phase shifting interferometry mode. The VISAR phase sensitivity for the Omega laser is quoted as being ~λ/20. The ± 0.05 fringe uncertainty applied to the most sensitive VPF (30 mm etalon with VPF_0=1.7 km s^{-1} $fringe^{-1}$) indicates that the system detection limit is ~ 0.09 km/s.[1] Using a phase shifting VISAR approach a phase sensitivity of better than an order of magnitude could be obtained. This would enable better equation of state data to be obtained within the pressure range of interest in ICF. This has a large effect on the peak growth rate of hydrodynamic instabilities in ICF implosions for instance.[2]

One such phase shifting design is shown in Fig. 4 in which a micropolarizer array is used. The phase shifts come from the pixel at the measurement location and one or two pixels on either side of the measurement location depending on the number of desired phase shifts(3, 4 or 5). The micropolarizer array can be made using lithographic techniques to ensure precise angular rotations and pitch of the polarizing elements. This would most easily be accomplished with a Michelson interferometer employing retroreflectors but could also be done with the existing Mach-Zehnder interferometers. The phase shifting VISAR correctly accounts for background signals and for the amplitudes of the two beams. The phase shifts can also be designed to minimize the sensitivity of the interferometer to detector nonlinearities for instance which will be present in the streak camera and CCD detector such that it can detect much smaller phase shifts than a carrier frequency interferometer.[3] In particular four phase shifts with a relative $\pi/2$ phase shift would be insensitive to quadratic detector nonlinearities and six phase shifts with a relative $\pi/3$ phase shift would be insensitive to detector nonlinearities up to and including the fourth power. Phase shifting interferometers can easily detect phase shifts of $\lambda/100$ with the best systems capable of measurements of better than $\lambda/1000$. This could then provide an increase in accuracy over the current carrier frequency VISAR diagnostics of more than an order of magnitude.

The design presented in Figure 4 could be implemented on the existing Omega and NIF VISAR diagnostics with the addition/substitution of a relatively small number of components. The phase shifting in the interferometer designs is accomplished by sending orthogonally circularly polarized beams through a polarizer.[4-6] When left-hand and right-hand circularly polarized beams pass through a polarizer at an angle θ, the phase is advanced and retarded by the amount θ, respectively. The overall phase difference between the two electric fields after passing through the polarizer is then 2θ. By rotating the polarizer by $\theta = 45$ degrees between adjacent pixels, the phase difference between the interfering electric fields is increased by 90 degrees.

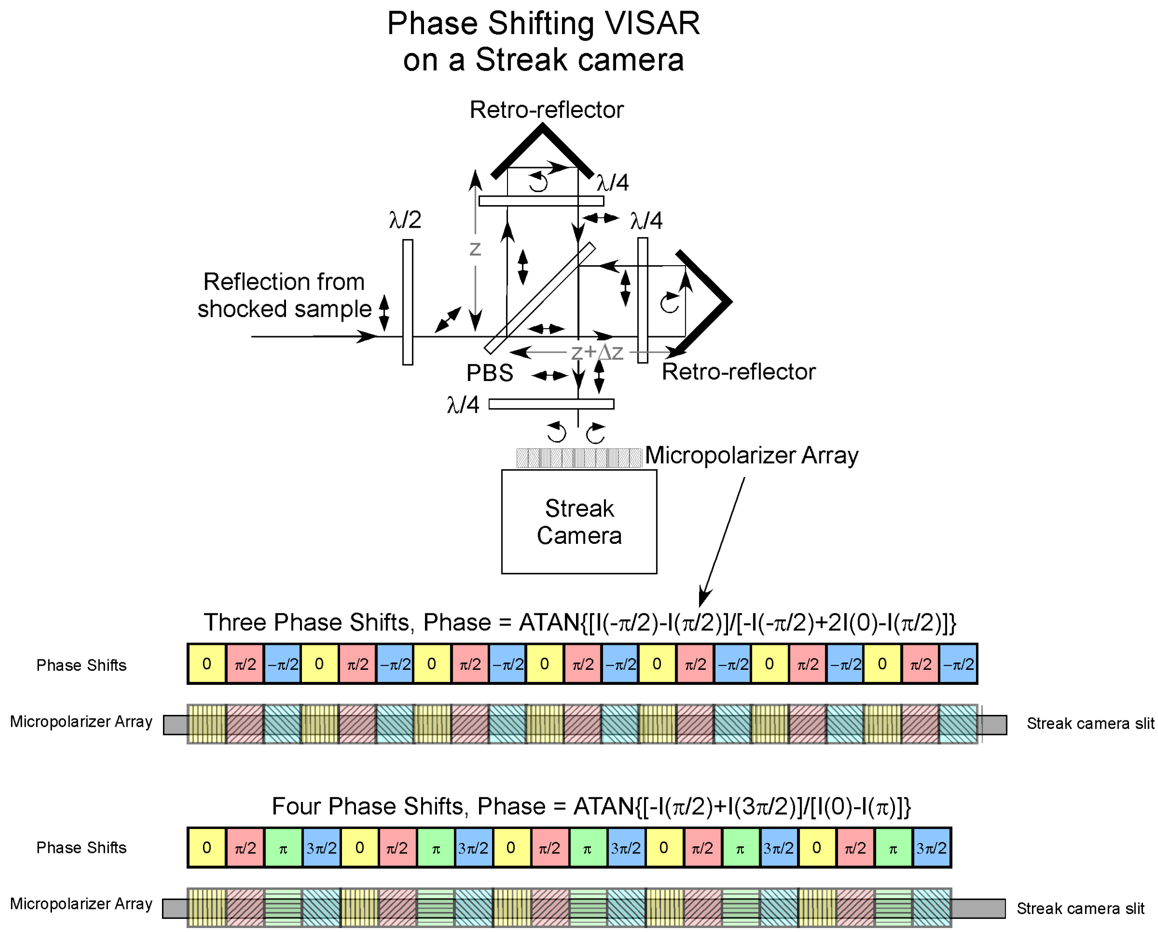

Fig. 4 Phase shifting VISAR, using a pixelated micropolarizer array, with a Michelson interferometer coupled to a streak camera.

A four frame 2-D x-ray imager design is shown in Fig. 5. This can have more than an order-of-magnitude shorter integration time than gated x-ray imagers, ~1 ps, and up to an order-of-magnitude higher sensitivity than DIXI or the current implementation of OHRV on the OMEGA laser. This utilizes a new time differential interferometer which measures the relative x-ray induced optical phase shifts at two precisely defined time intervals. It operates in a similar manner as an optical VISAR detector, however, our design results in a truly common path interferometer.[7,8] In the design presented in Fig. 5 the probe laser enters from the left side and the x-ray source would be imaged onto the GaAs semiconductor from the right hand side. The probe enters from the left and passes through an apodizer and then through a diffractive optical element to split it into four or more separate probe beams. These separate probe beams then pass through a delay glass array which puts a different time delay on each of the probe beams. They then pass through an A-cut crystal to provide a set time delay between the two polarizations of each of the four probe beams. They are then imaged onto the semiconductor where the two orthogonal polarizations of each of the probe beams sample the phase of the GaAs semiconductor at two times separated by the delay introduced by the A-cut crystal. The four probe beams are then imaged onto a charge coupled device(CCD) after passing through a quarter wave plate, to make them circularly polarized, and then a pixelated polarizer array, to enable four phase shifts to be measured by the CCD camera. The result is four frames of data taken at different times along a single line-of-sight with the gate time set by the time delay in the A-cut crystal.

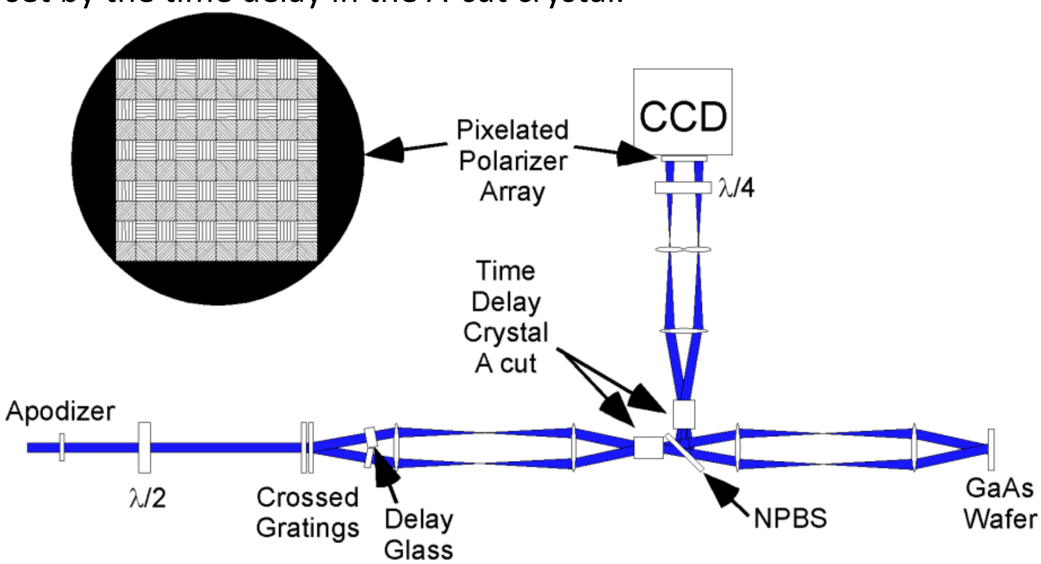

Fig. 5 Phase shifting VISAR, using a pixelated micropolarizer array, with a Michelson interferometer coupled to a streak camera.

Impact on Mission

Our research into performing ultrafast conversion of diagnostic x rays into the optical regime and relaying the signal out of a test chamber for evaluation of plasmas is important to LLNLs strategic focus to understand the physics of high-energy-density plasmas for inertial-confinement fusion, stockpile stewardship, and basic astrophysical science. This will be particularly important for studying burning plasmas on the National Ignition Facility.

Conclusion

For this LDRD it was demonstrated that the VISAR and OHRV diagnostics on the OMEGA laser could be made to function as x-ray detectors. This approach demonstrated that by using the time-differential nature of these diagnostics that the limitation associated with the time response, in particular the fall time, of semiconductors could be overcome to enable then to function as fast x-ray detectors. This technique is capable of acquiring sub-picosecond 2-D or 1-D x-ray images, detector spatial resolution of better than 10 um and the ability to operate in a high neutron flux environment expected on ignition shots with burning plasmas. In addition to demonstrating this technique, several designs were made to improve the phase sensitivity, temporal resolution and number of frames over the existing diagnostics currently implemented on the OMEGA laser. These designs included both 2-D imaging diagnostics as well as improved 1-D imaging diagnostics which were streaked in time.

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