

Title: SUB-NANOSECOND ... MATERIALS

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Sub-nanosecond optical diagnostics of laser-material interaction and dynamic microstructure of materials

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ABSTRACT

Several optical diagnostic techniques are used to evaluate the dynamic response of materials to intense dynamic loading and unloading, high stress and strain, and pressure. Velocity interferometry and electronic streak photography, each with sub-nanosecond time resolution, are used to record dynamic material response. Laser-launched flat plates are accelerated to 10^{12} m/s² with terminal velocities >5 km/s. By impacting these plates into target samples, high strain rates (10^8 sec⁻¹) and pressures >100 GPa have been generated for a duration of 0.8 - 5 nanoseconds. The efficacy and limitations of each technique are detailed and applications to other fields discussed.

1. INTRODUCTION

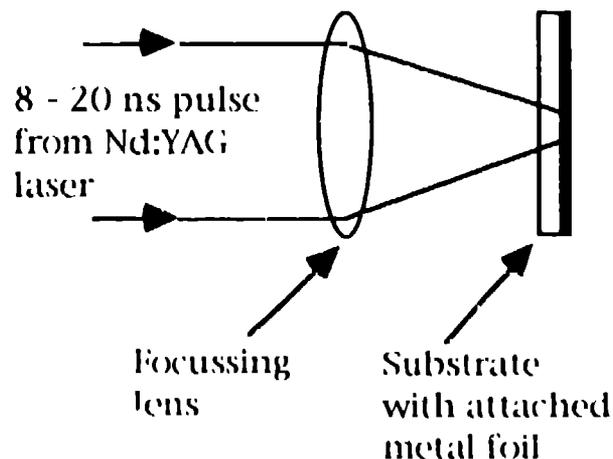
Laser interaction with materials has numerous applications for studying response of dynamic material properties to shock waves. Laser-launched flat plates can easily generate pressures >100 GPa for short-time duration. By keeping the plates small in size (μm , thick \times <1000- μm , diameter) and mass (μg), the kinetic energy of even high velocity plates (1 - 6 km/s) is minimal (<100 mJ, typical). The low kinetic energy provides for easy recovery of samples and permits anyone with modest size laboratory lasers to be able to conduct shock wave experiments that usually require large laboratory gas gun installations. The major differences in small laser-launched plates versus typical experiments of a much larger size are:

- temporal record length and resolution
- impactor acceleration and velocity
- temporal resolution of shock waves
- synchronization
- effects of scaling down the size of the experiments by 1 - 2 orders of magnitude.

The small size of these experiments requires improved temporal resolution, i.e., sub-nanosecond (<0.100-ns possible). Conventional larger scale shock wave and dynamic material property experiments typically resolve 3 - 5 nanoseconds. This presented work details our method of recording sub-nanosecond (100 - 300-ps) temporal resolution by using an electronic streak camera instead of the typical electronic digitizer as the temporal resolver and results in the highest temporal resolution recorded to date by interferometric techniques. Temporal resolution for velocity interferometry by VISAR is limited by the recording technique not the VISAR principle.

2. METHOD FOR LASER-LAUNCHED PLATES

The plate-launch technique has been described in previous publications (Ref. 1 - 3), but will be briefly discussed for clarity. The 8- to 18-ns FWHM pulse from a Nd:YAG laser is directed through an optically transparent substrate with an attached metal foil (Figure 1). At the foil-substrate interface a metal plasma is formed from a few skin depths (50- to 200 nm) of the foil. The plasma forms once a critical power density is reached, usually before the leading FWHM point on the laser pulse. The 0.05-0.2- μm thick, confined plasma from the foil expands and accelerates the remaining thickness of foil away from the substrate. The foil accelerates to a terminal velocity within two laser pulse widths and remains at the terminal velocity for >200 ns.



Laser beam diameter on target: 0.6 - 3.0 mm

Figure 1: Experimental method for plate launch described in Ref. 2.

3. EXPERIMENTAL TECHNIQUE

The experimental technique involves placing a target material to be studied 75 - 200- μm from the plane of the foil. A flat plate launched from the foil accelerates to the desired velocity and impacts the target at the prescribed distance (Figure 2). Experimental evaluation of the plate acceleration, impact velocity, and plate flatness is determined by using a transparent target of known shock properties and VISAR corrections for the target material. For qualifying the experimental technique, PMMA was used because equation-of-state and VISAR corrections have been determined (Ref. 4). Since the laser-launched plate accelerates to a terminal velocity in $\sim 20\text{-}40$ ns the flight distance to the PMMA target is usually <100 μm . The short flight distance permits the VISAR target lens to have a depth-of-field over the complete flight path and impact surface of the PMMA target. Dichroic mirrors centered at 514.5 nm are used to direct the argon ion laser illuminating beam for the VISAR and the return VISAR-Doppler-shifted signal. As the plate approaches the PMMA target the

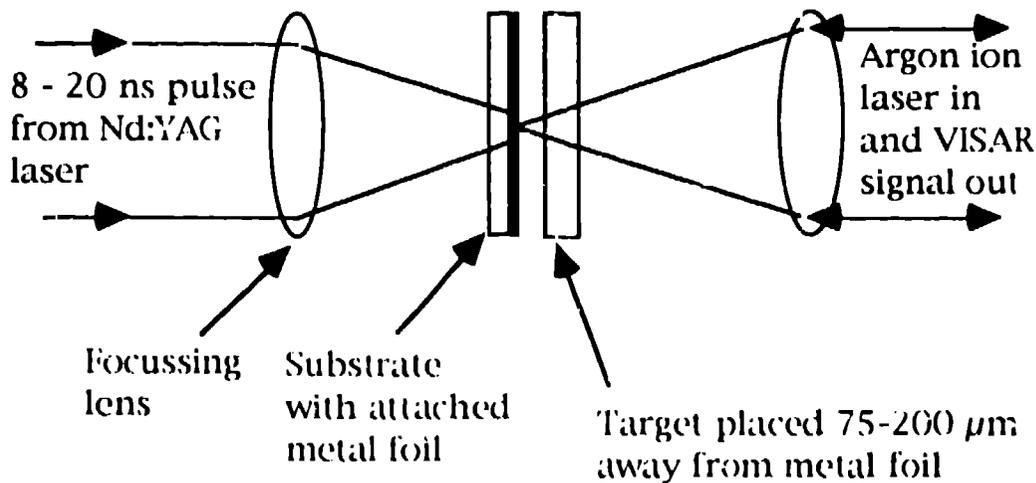


Figure 2: The plate is accelerated toward the target material as a flat plate. The depth of field of the imaging system is greater than the flight distance to the target. The plate acceleration, velocity, and impact on a transparent target can be followed.

ambient air between the plate and target is compressed and heated to ionization, and emits a pseudo-white light that is transmitted through the last dichroic turning mirror. This pseudo-white light is imaged on one-half of the slit of an electronic streak camera. The remaining half of the slit of the camera is used to image the output of six 80- μm diameter optical fibers. Four of the fibers

transmit optical signals from the push-pull VISAR (Ref. 5), one for the Nd:YAG laser pulse, and one fiber for a 100-MHz series of 300-ps laser diode pulses for calibrating the streak rate of the camera (Figures 3 & 4). VISAR optical data are traditionally collected by photomultipliers with amplifiers and recorded on transient digitizers. The temporal resolution of traditional recording methods is limited by the electronics, not the optical VISAR signals. By transferring optical VISAR signals with optical fibers directly on a streak camera, the temporal resolution can easily be improved 1 - 2 orders-of-magnitude. In Fig. 4, left-to-right, are the plate impact, the 300-ps 100-MHz time fiducials, Nd:YAG laser pulse, and the four optical-Argon-ion-laser-VISAR signals (cos, -cos, sin, -sin). Due to the optical path differences, the data recorded for plate impact, laser pulse and VISAR signals are not synchronized. The temporal differences are

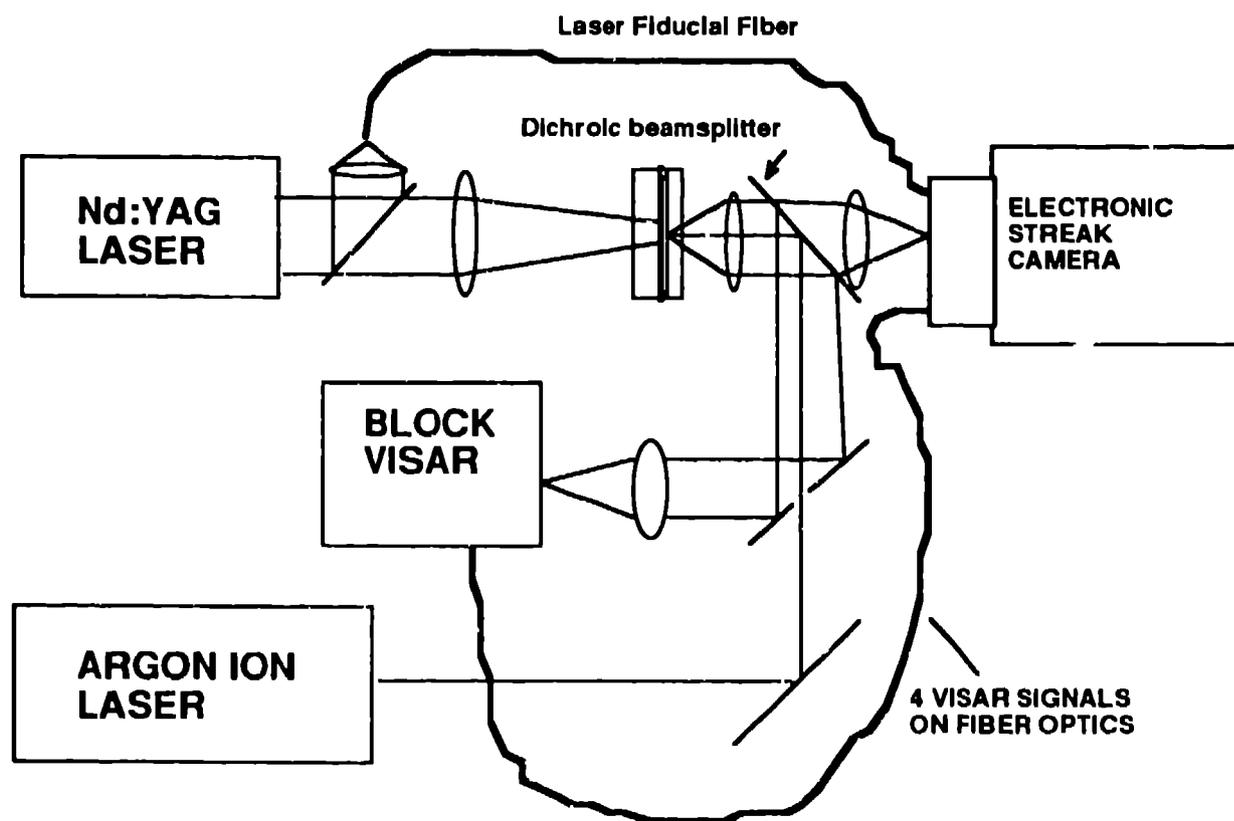


Figure 3: Experimental Method for Streak Camera VISAR with image of plate impact. A dichroic beamsplitter is between the optical elements of the streak camera imaging system. The pseudo-white light of the plate impact is imaged on the slit of the streak camera and the doppler shifted interferometry signals are reflected into the VISAR optical system.

Streak Camera Image at Slit

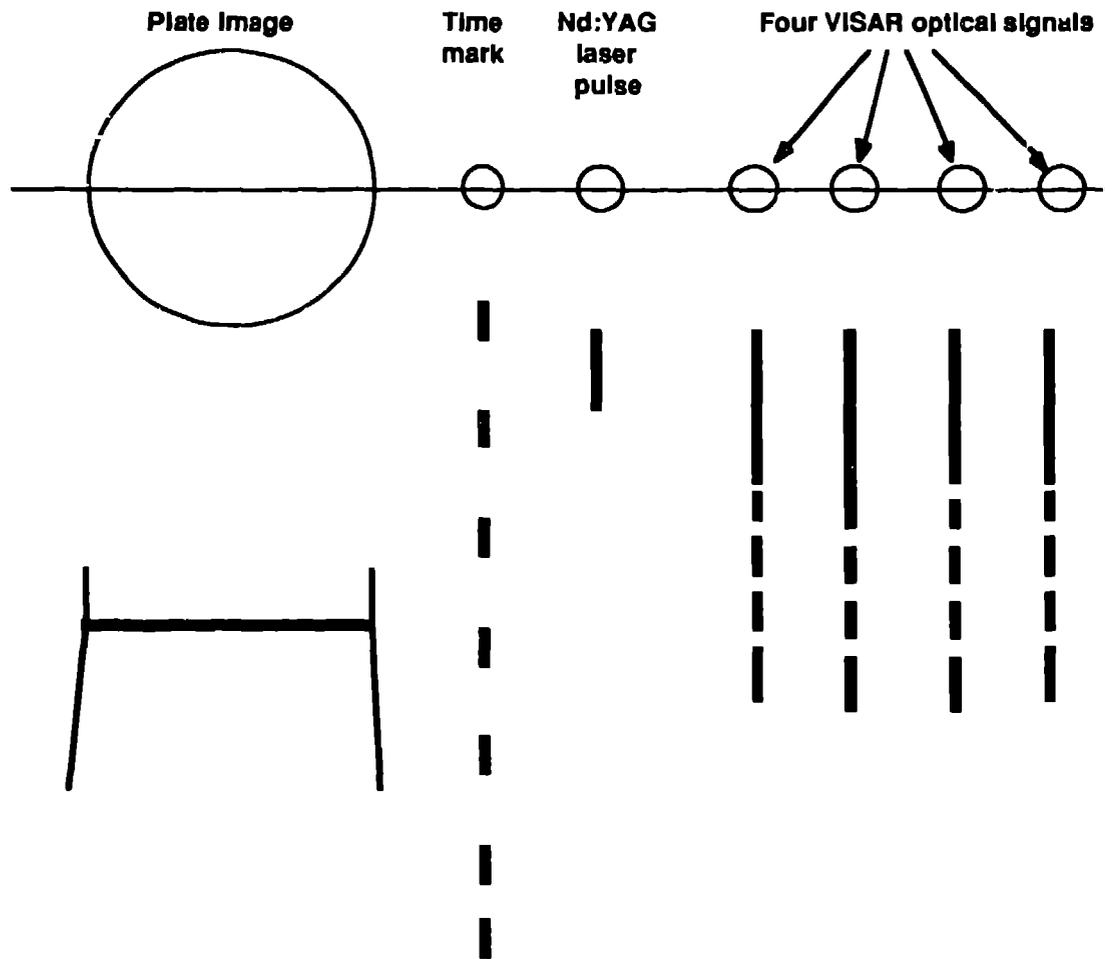


Figure 4: Static and dynamic streak camera representation for VISAR, fiducial, laser pulse, and plate impact data.

calibrated to ± 0.1 -ns. All VISAR signals are synchronized to < 100 -ps total difference. Typical raw recorded data are shown in Figure 5. The temporal intensities of the VISAR quadrature signals are converted and reduced (Ref. 6) and shown in Fig. 6. From the data in Fig. 6, the first plate motion, acceleration, terminal velocity, impact time, and interface velocity can be quantified (Fig. 7). The plate flatness is determined by the streak rate and magnification of the plate impact on the PMMA target. Total time difference over the central 80% of the impact can be < 200 -ps. Plasma velocity around the plate periphery can be evaluated for lateral velocity.

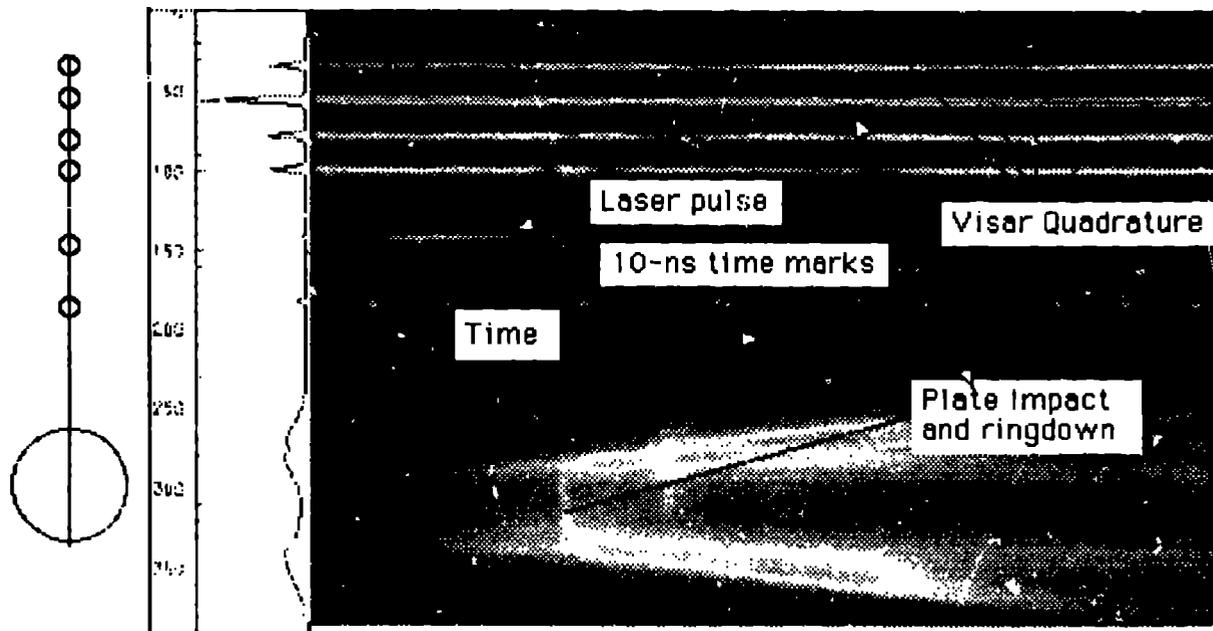


Figure 5; All data signals are recorded on one streak record. The time synchronization of the VISAR data is ± 100 ps. The image is time shifted by 44 ns from the VISAR signals due to differences in optical path length.

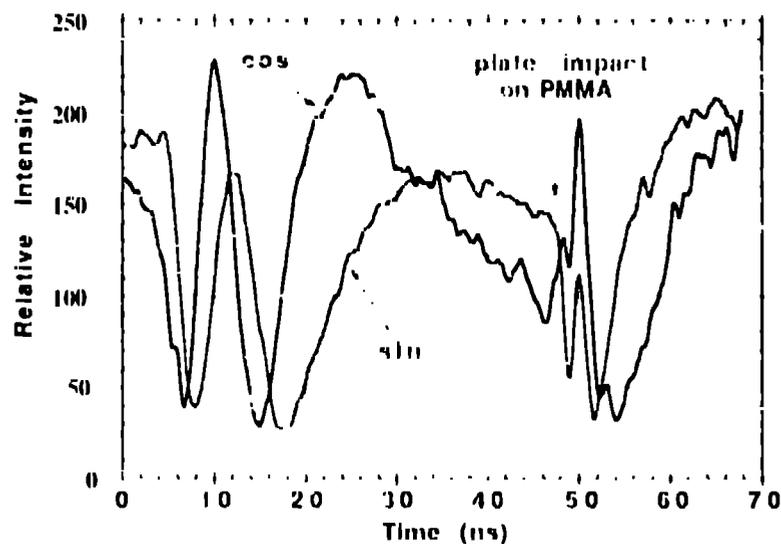


Figure 6: Interferometer (sin & cos) signals related to change in velocity. The velocity per fringe is 1 km/s. The plate accelerates from zero time to 17 ns, and then decelerates on impact.

4. EXPERIMENTAL PLATE IMPACT RESULTS COMPARED WITH MODELS

The plate impact in Figure 7 is expanded to resolve the fine structures of the shock ringdown (Fig. 8). The experimental results are compared with two different code calculations (Ref. 7 & 8). The experimental data agree quite well with both codes. Differences can be attributed to ambient air "cushioning" the impact, structure within the 3.5- μm aluminum plate, and/or temporal resolution (300-ps) of the recorded data.

5. TECHNIQUE APPLICATION

We believe that use of shock waves generated by laser-launched plates is feasible for determining dynamic spall strength, elastic-plastic wave separation, dynamic bond strength of dissimilar materials, surface or grain-boundary effects, and Hugoniot elastic limits. The small size permits studying material attributes difficult to quantify by other large scale experimental methods and may permit evaluation of:

- dynamic spall strength at $\geq 10^7$
- local grain size effects
- grain boundaries
- shock and release within one grain
- small samples of valuable or toxic materials
- bond strengths between similar or different materials
- Hugoniot elastic limits
- separation of elastic-plastic shock velocities

6. CONCLUSION

Streak recording of velocity interferometry (VISAR) data is limited only by the temporal resolution of the streak camera and provides the highest temporal resolution possible of particle velocity measurements. By using one streak camera to record both VISAR data and the plate impact image, a complete understanding of the plate performance can be obtained. This experimental method of recording data has wide applications in studying the dynamic properties of materials.

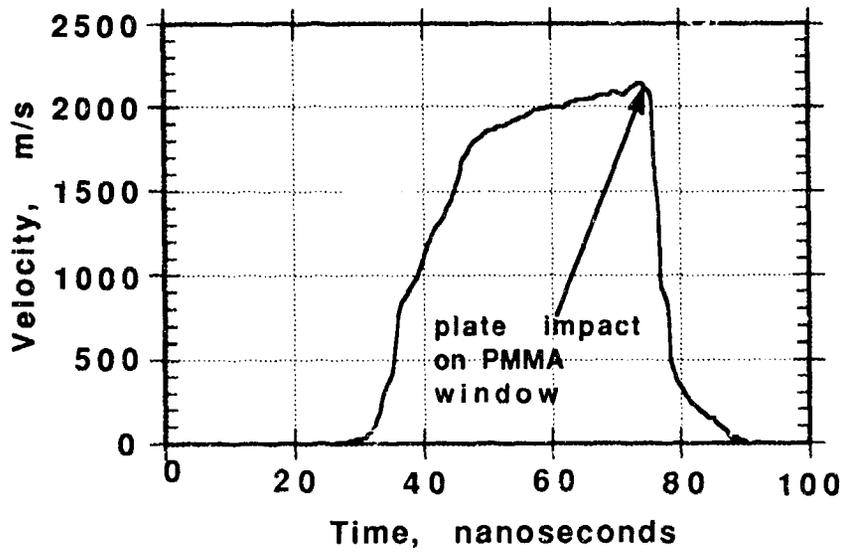


Figure 7: Reduced VISAR data and plate impact from Fig. 5 & 6. The plate accelerates to a near-terminal velocity and impacts the PMMA target.

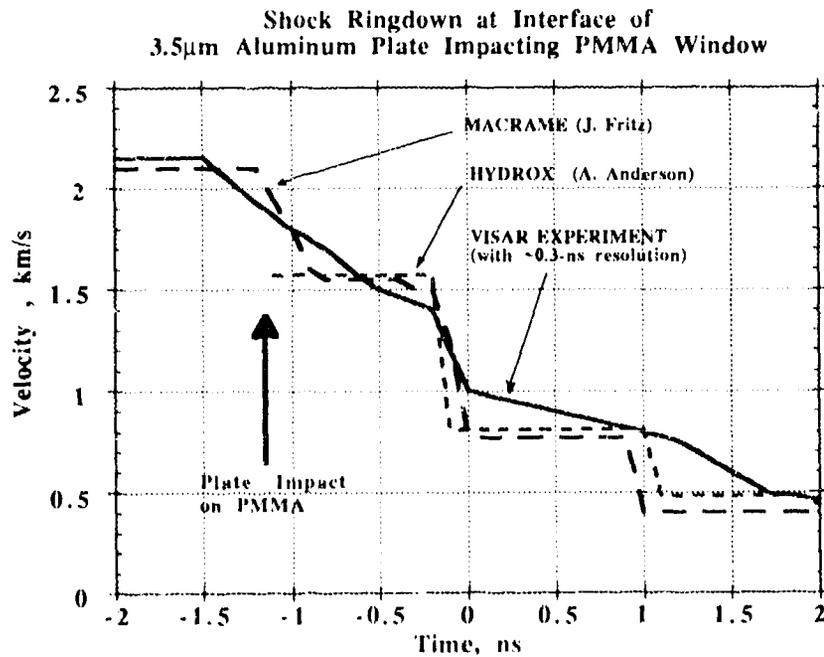


Figure 8: Experimental shock wave ringdown from impact compared with two different models.

7. ACKNOWLEDGMENTS

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