Two-Dimensional Imaging Velocimetry of High-Strain Rate Deformation in Silicon

S.J. Ali[1,2], R. Smith[2], C. Bolme[2,3], D. Erskine[2], P. Celliers[2], J. Eggert[2], J. Wang[5], S. Brygoo[6], B. Hammel, R. Jeanloz[4], and G.W. Collins[2]

1:Department of Chemistry, University of California, Berkeley, 2:Shock Physics Group, Lawrence Livermore Nat'l Laboratory, 3:Shock and Detonation Physics Group, Los Alamos Nat'l Laboratory, 4:Department of Earth and Planetary Science, University of California, Berkeley, 5: Department of Geosciences, Princeton University, 6: CEA, DAM, DIF

Abstract

The novel 2D-VISAR diagnostic that has been developed over the past few years has provided an unprecedented view into the details of material deformation during shock compression. Utilizing a two interferometer system with quadrature phase recording and an ultrashort illumination pulse, a snapshot of the 2D velocity field of a shocked sample was obtained and the elastic and plastic breakout patterns were extracted. This diagnostic was used to measure the 2D velocity map of shock compressed single crystal silicon in three orientations, [100], [110] and [111]. Varying the probe delay allowed us to track the evolution of complex deformation dynamics at the silicon interface. Characteristic breakout structures were found for each of the three orientations. The elastic breakout shapes demonstrated a dependence on the anisotropic wave speeds in the crystal and the plasticity was found to depend on the crystallographic slip planes.

Introduction

Understanding the nature and dynamics of heterogeneous flow in materials subjected to shock compression is important for many fields of research ranging from high-speed collisions to inertial confinement fusion experiments. Particle waves propagating through a shocked material can be significantly altered by the various deformation mechanisms present in those materials, including anisotropic sound speeds, phase transformations, plastic/inelastic flow and brittle failure. Quantifying the spatial and temporal effects of these deformation mechanisms has been limited by a lack of diagnostics capable of obtaining simultaneous micron resolution spatial measurements and nanosecond resolution time measurements. Combining a line VISAR system and the recently developed 2D VISAR system we have obtained a series of measurements of the two dimensional velocity maps in the context of the 1D VISAR compression history. This effectively allows us to construct a detailed picture of the deformation mechanics in a shocked sample.

Experimental Schematic

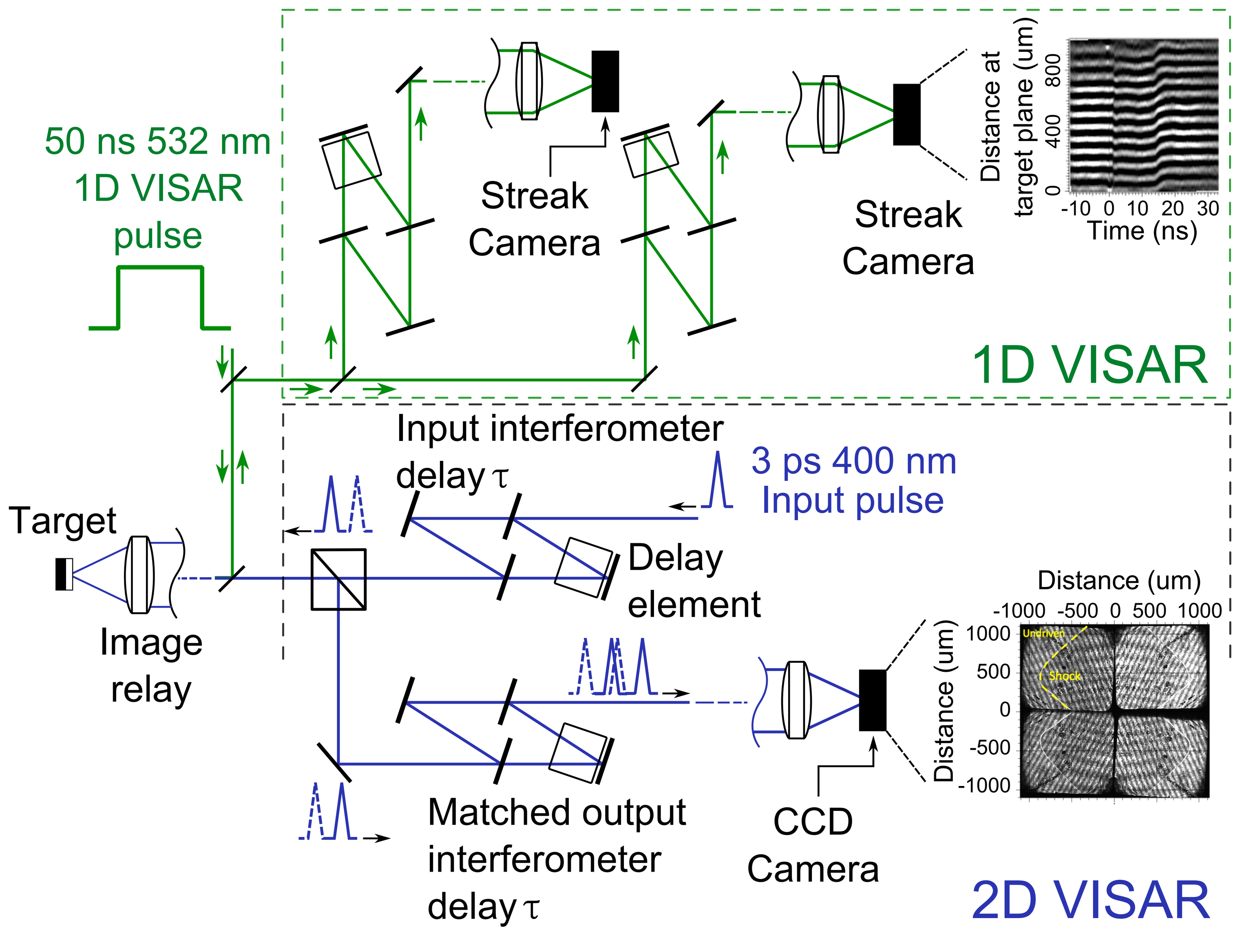


Figure 1. Simplified layout of the diagnostic setup for the combined 1D and 2D VISAR study of the deformation response of shock-compressed silicon.

Targets

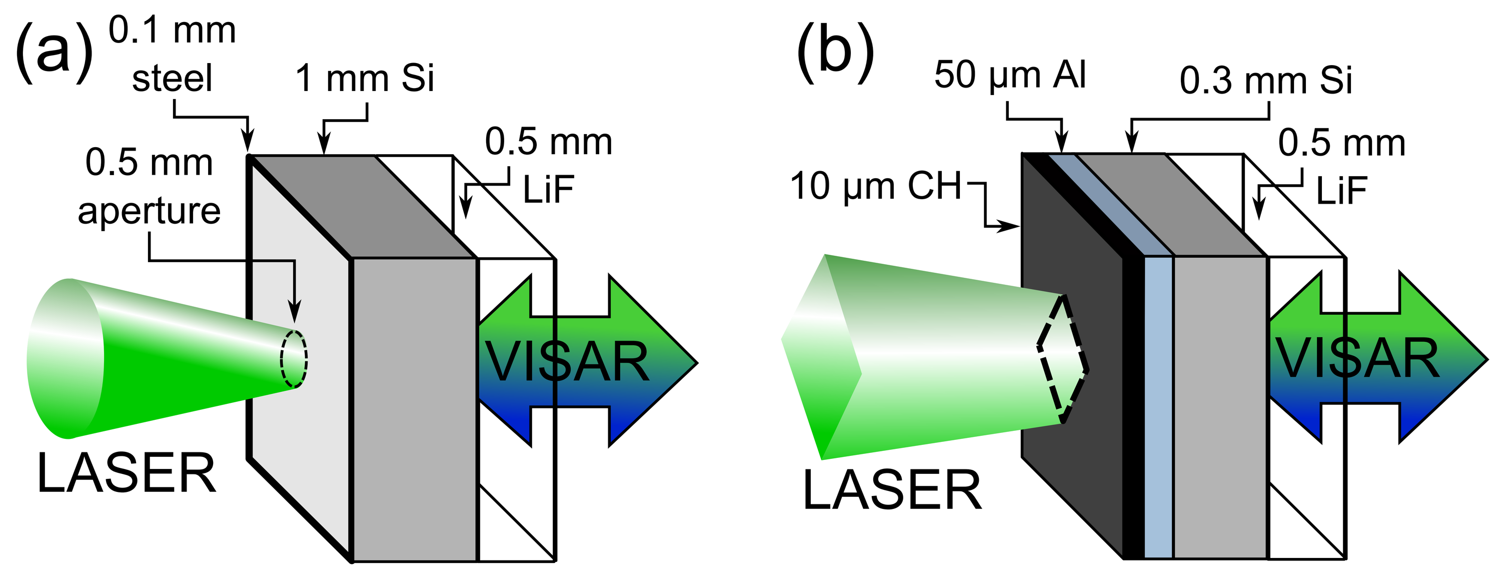


Figure 2. **(a)** Target design for spherical shock compression of single crystal Si. The drive laser was focused down to over fill a 0.5 mm aperture within a 100 micron thick stainless steel plate. This ensured a circular pressure drive input to the Si. After shock transit the time dependence and the spatial structure of the Si/LiF velocity was recorded with the 1D and 2D VISAR. **(b)** Target design for planar shock experiments. In these experiments a 1 mm square planar drive was launched into the target assembly. A dual band 532/400 nm anti-reflection coating applied to the LiF free surface ensures no back-reflections of the VISAR probe beam from this interface.

Raw Data and Analysis

Line VISAR

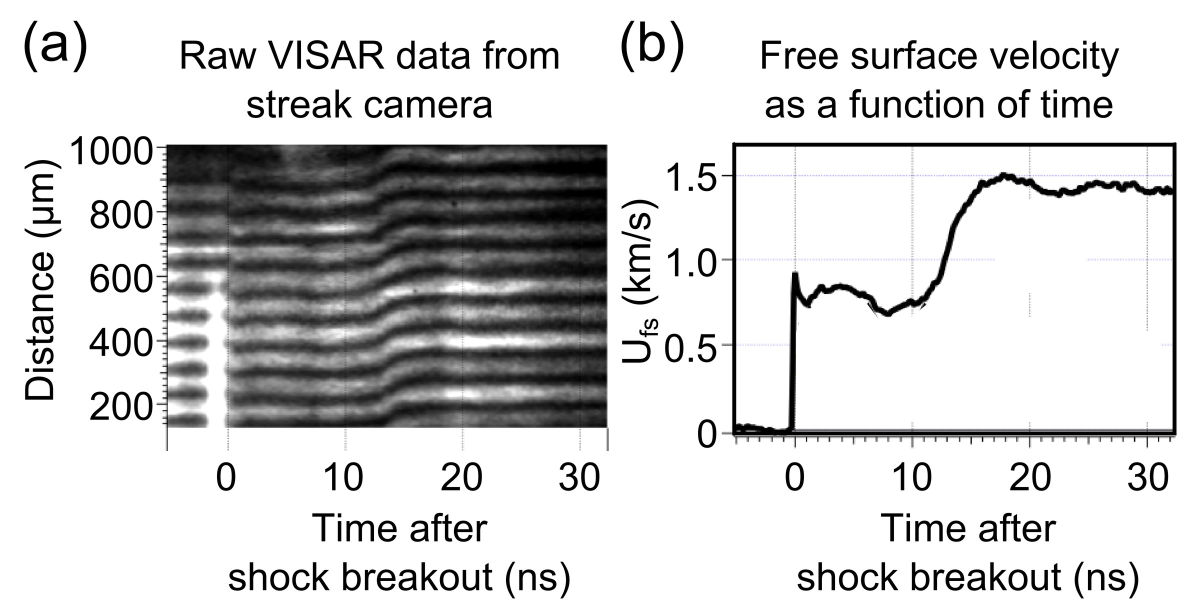
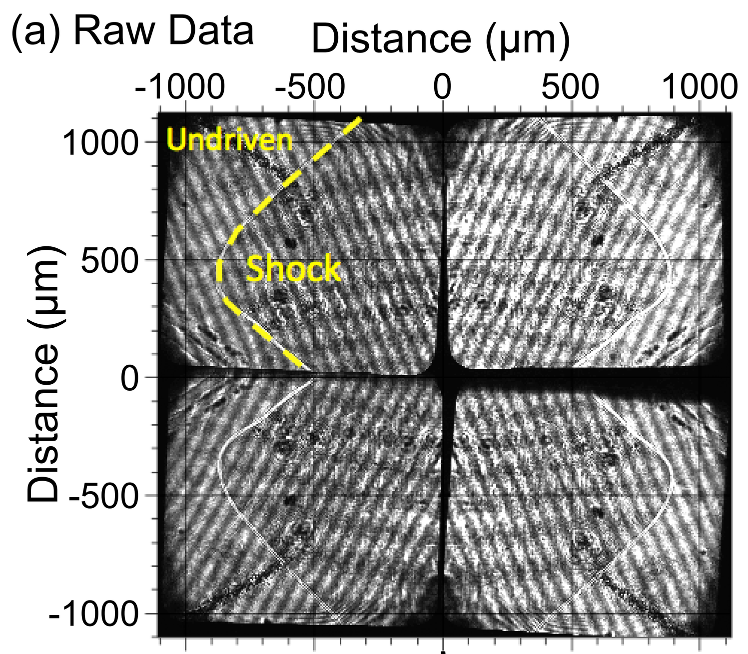


Figure 3. **(a)** Raw data from the VISAR diagnostic **(b)** Free surface velocity extracted from the raw image in **(a)**

2D VISAR



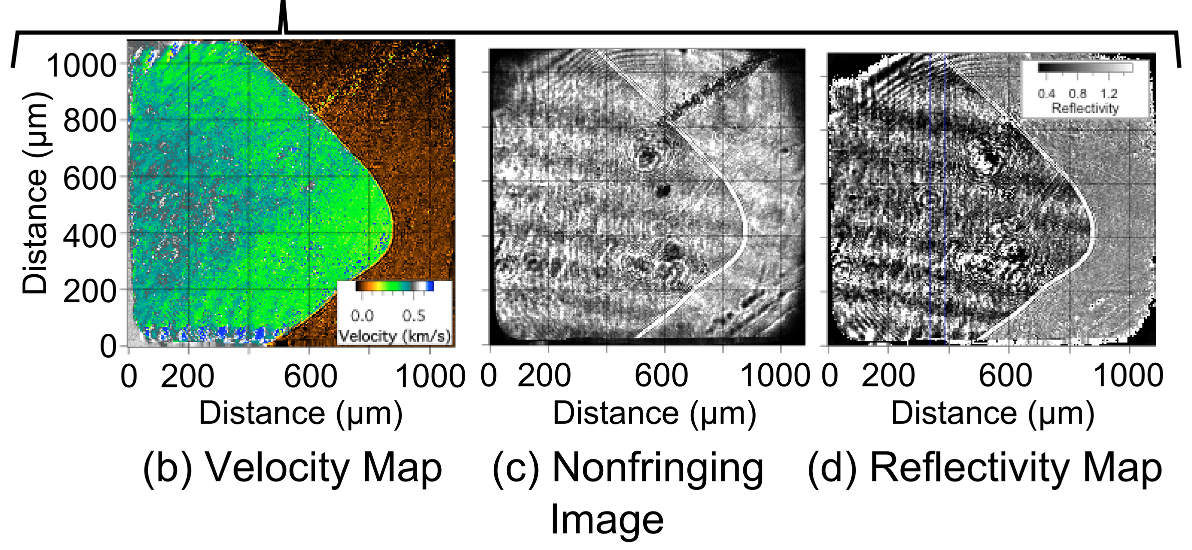


Figure 4. **(a)** Four images of the shocked sample are recorded on a CCD. Each image shows the corner of the shock wave emerging at the Si/LiF interface from the target described in Fig. 1(b). The four images differ in phase. **(b)** The quadrature fringe pattern allows for the velocity map to be determined. **(c)** Through summation of the four channels a non-fringing image, which is averaged over the reflectivities at the times of the two 3 ps pulses, can be generated. **(d)** Using a pre-shot reference a relative map of reflectivity at 400 nm can be obtained.

Results

Spherical Shocks

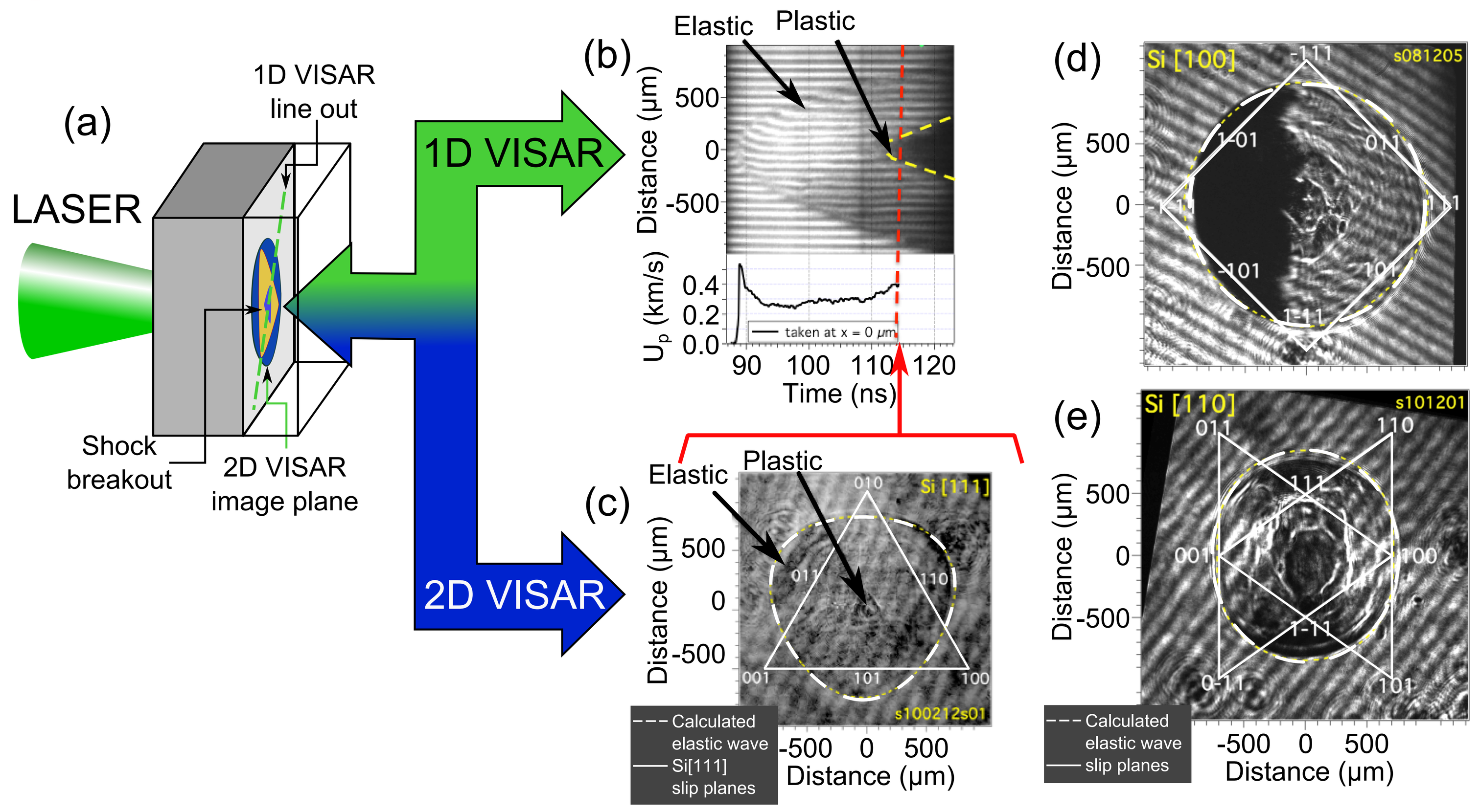


Figure 5. **(a)** Target assembly **(b)** VISAR trace and particle velocity history at the Si/LiF interface **(c)** 2D VISAR image of shocked Si[111] taken at 114 ns reveals a three fold symmetry in the elastic and plastic waves. The shape of the elastic wave can be well reproduced by using the elastic constants for Si and calculating the transit time as a function of angle (dashed line). **(d)** 2D VISAR image of shocked Si[100] showing elastic wave shapes and slip planes **(e)** 2D VISAR image of shocked Si[110] showing elastic wave shapes and slip planes

Planar Shocks

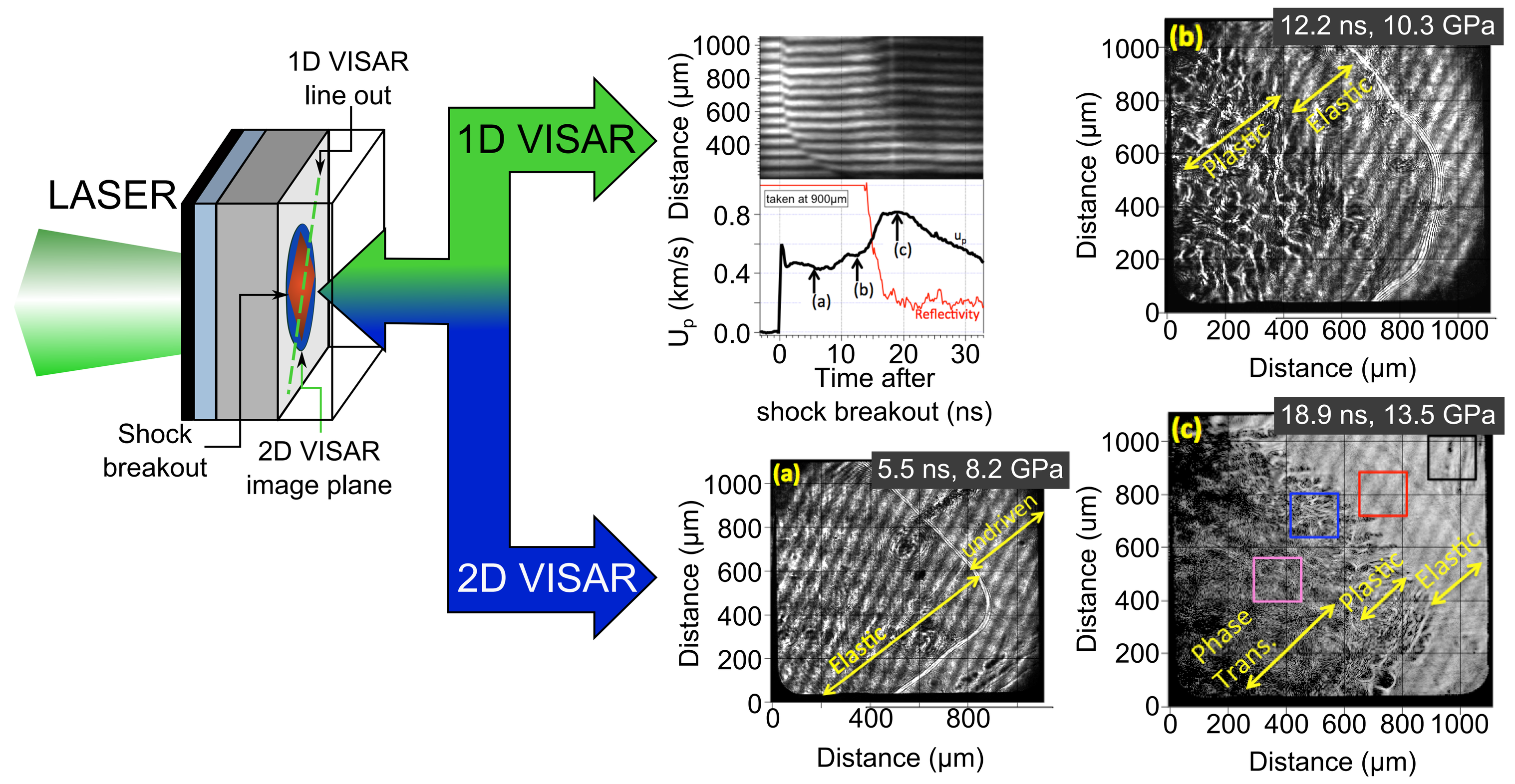
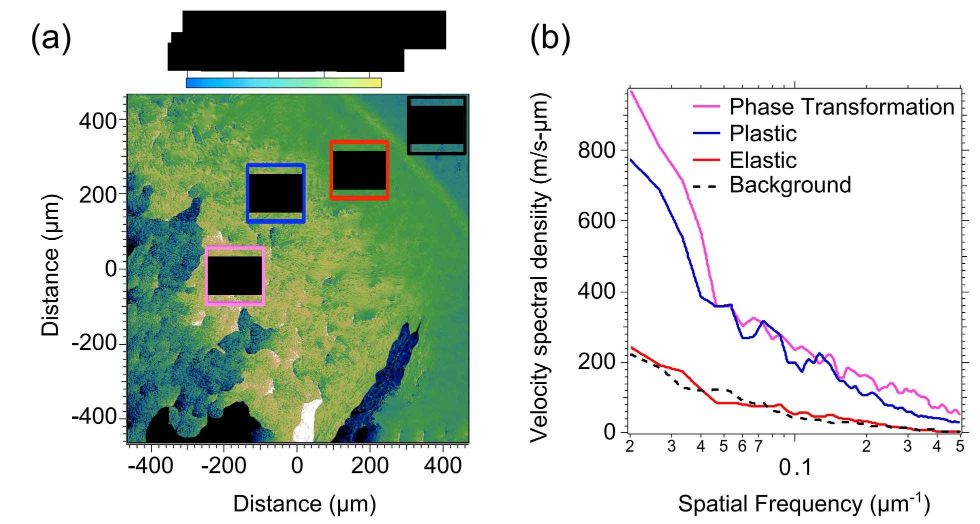


Figure 6. **(a)**Target assembly **(b)** VISAR trace and particle velocity history at the Si/LiF interface **(c)** 2D VISAR image of elastic compression at the Si/LiF interface. The corner of the spatially square shock from the square drive laser focal spot is visible. **(d)** A later probe time during which a smooth low-pressure elastic region is observed around the central high pressure plastically deforming portion of the drive. **(e)** A structural phase transition from the diamond structure can now be observed at the peak pressure in the center of the drive.

Figure 7. **(a)** Velocity map of image in Fig. 6(e) with four squares representing regions associated with undriven (black), elasticity (red), plasticity (blue) and the phase transformation (pink). **(b)** The velocity spectral density for each region in **(a)** is shown.



Acknowledgements

The authors wish to acknowledge Stephanie Uhlich and Walter Unites for help in the target preparation, Jim Cox for the engineering support in construction of the 2D VISAR and the JLF staff for invaluable support in running this experiment. This work was performed under the auspices of the U.S. Dept. of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Suzanne Ali works under the support of the Lawrence Scholar Program at Lawrence Livermore Nat'l Lab. Jue Wang's participation was supported by National Laser User's Facility award DE-NA0000856.