LASER-INDUCED MACH WAVES FOR ULTRA-HIGH-PRESSURE EXPERIMENTS

Damian C. Swift* **and Christian R. Ruiz***

**P-24, MS-E526, Los Alamos National Laboratory, Los Alamos, NM 87545*

Abstract. Laser-driven experiments are a principal technique for inducing pressures in the terapascal regime and higher. However, when high irradiance laser light interacts with matter, it generates fast electrons and x-rays, which may heat material ahead of hydrodynamic loading waves such as shocks. This preheat limits the scope for investigating properties of initially cold material and potentially reduces the accuracy of measurements. A new configuration for laser experiments is proposed, using convergence and irregular reflection of shocks to induce high pressures without such high laser irradiances. Related Mach wave generators have been developed previously for high-explosive drive; the design considerations for laser-driven Mach wave generators are typically dictated by constraints on the laser pulse duration and differ from high-explosive systems. Relations are presented between the pressures achievable with different variants of the laser drive technique and different combinations of materials in the Mach-interaction region. The prospects for isentropic compression using this type of experiment are discussed.

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INTRODUCTION

There are many needs for high pressure experiments, including investigations of the equation of state (EOS) and strength under shock and isentropic loading. Laser-driven experiments are desirable in a number of respects, e.g. the extremely high pressures which can be attained, the flexibility of loading (ease of changing the energy and the temporal shape of the pulse), the concentration of energy, which often reduces 'collateral momentum' (e.g. sabots from a gas gun, high pressure reaction products from high explosives) and so makes experiments easier to conduct and samples easier to recover. However, there are complications with laser experiments, including the onset of preheat at drive pressures over a few hundred gigapascals, and the difficulty of ensuring a drive pressure which is spatially uniform and adequately characterized in time (e.g. constant, for a shock).

Here we discuss designs for experiments which use shock dynamics to ameliorate some of the problems inherent in laser drives for high pressure applications. The basic idea is that a shock wave can be smoothed and increased in pressure, so high pressures can be reached without necessarily requiring laser irradiances high enough to induce preheating, and spatial variations can also be reduced. The relevant concepts have been applied for many years on a larger scale in systems driven by high explosives. Analogous designs are discussed for use with lasers, and some variants are suggested which would be uniquely suited for lasers. Simulation results are presented for initial trial experiments.

SHOCK DYNAMICS AND MACH REFLECTION

Consider a solid cone, initially at some constant pressure (e.g. zero), when an elevated pressure is applied

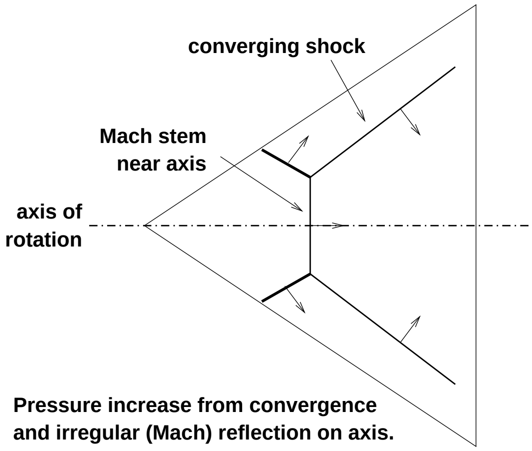

FIGURE 1. Schematic of Mach wave generation in a solid cone.

to the conical surface. The applied pressure induces a conically-converging shock. Convergence increases the pressure as the shock propagates inward. Convergence also acts to smooth spatial variations in the shock: regions which lag have a larger negative curvature, thus locally greater convergence; the pressure increases and the shock accelerates to reduce the lag. Conversely, regions which are ahead of the rest of the shock tend to slow down. These smoothing effects are described by a hyperbolic equation, so deviations from symmetry typically cause underdamped oscillations toward it. It is preferable to start with a reasonably symmetric drive.

The cone axis acts as a rigid boundary: waves in a material with linear response would reflect and double the pressure; real EOS are nonlinear and the pressure is generally higher. At appropriate angles of incidence, nonlinear reflection results in the formation of a Mach stem [1] – a disk-shaped shock of higher pressure – which grows radially outward as it propagates along the axis. (Fig. 1.)

EXPLOSIVE GENERATORS

Several groups have presented designs for Mach wave generators driven by the detonation of chemical explosives. There are design variants in the initiation of the explosive, which changes the phase speed of the detonation over the surface of the cone. The simplest design uses a solid cone, embedded in a cylinder of explosive [2]. Energy transfer from the detonating explosive can be optimized by imploding a hollow cone onto a coaxial solid cone; the implosion process accumulates mechanical work as the reaction products expand, which can easily induce a shock depositing more internal energy than from the shock transmitted directly from the detonation wave. One design has induced shocks of 250 GPa in the PMMA inner cone, which is transmitted as $\sim$500 GPa in a Cu sample [3]. The pressure can be further increased if used to accelerate a flyer which then impacts a stationary target, A smaller system (0.5 kg of the HMX-based explosive EDC29), with a simpler initiation system to induce a ring initiation at the apex end, has been developed and tested, with sample pressures $\sim$100 GPa [4].

CONCEPTS FOR LASER-DRIVEN MACH WAVE GENERATORS

Laser-driven Mach wave generators can be envisioned with several different configurations. Most designs possible with detonating explosives have a laser-driven analog. Starting with the same basic platform of a cone, the pressure may be induced by laser ablation over the outer surface (Fig. 2). The pressure drive may also be induced in other ways, such as with a laser-heated hohlraum: laser energy is used to induce a thermal radiation field – typically soft x-ray – in a hohlraum, and the thermal radiation induces the shock over the cone; this scheme has the advantage that the radiation field is spatially smoother than the original laser beams.

The laser energy may also be used to generate pressure through confined plasma ablation [5]. The cone would be enclosed in a medium transparent to the laser light, e.g. sapphire. Confining the ablation plasma greatly increases the efficiency of energy transfer to the cone, similarly to the way in which laser-driven flyers operate.

Regardless of the way in which the pressure is applied to the outside of the cone, designs with a solid cone could be replaced by a hollow cone imploded onto a solid inner cone. This variant is appropriate if the pressure can be sustained for a time comparable with the time to accelerate the hollow cone to maximum speed.

An intriguing possibility for laser drives is that the

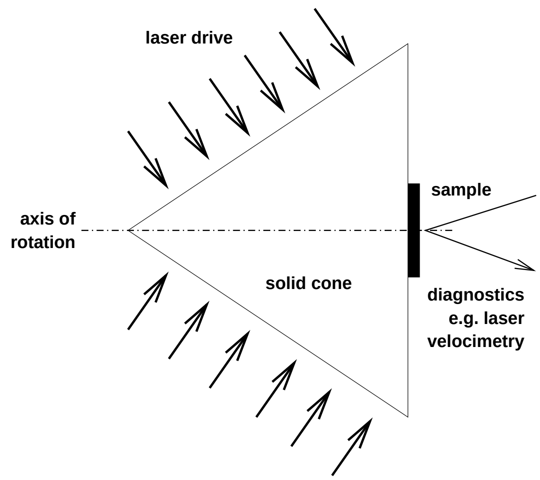

FIGURE 2. Schematic of Mach wave generation in a solid cone driven by laser ablation.

Mach wave could be induced in a planar target, by spatial variation of the laser irradiance or temporal variation in the arrival of different portions of the drive pulse over the surface. Specifically, if the drive beam has a ring of high irradiance around a central region of low irradiance, or if the central portion of the beam arrives later, a Mach wave may be induced.

Other degrees of freedom include the precise profile of the cone (a curved cross-section could be used) and the laser irradiance history.

APPLICATIONS OF MACH WAVE GENERATORS

The obvious application of Mach wave generators is to shock loading experiments – or shock and release – to study the properties of the sample material. Ideally, the cone material would be chosen to have a well-characterized EOS, and the Mach wave generator would be reproducible and characterized carefully in advance. The sample would be attached to the flat base of the convertor cone in which the Mach wave is induced. Standard diagnostics include time-of-arrival (e.g. by change in reflectivity) and velocimetry of the free surface or surface in contact with a release window. Release windows are less likely to be useful at terapascal-scale pressures. The Mach wave configurations would be compatible with some of the more exotic diagnostics demonstrated on laser-driven experiments, including x-ray diffraction, x-ray radiography, emission spectroscopy, Raman spectroscopy, and polarization-dependent reflectivity.

Material placed on the base of the cone can be chosen to vaporize on shock and release by the Mach wave. If allowed to expand, the vapor would drive a compression wave into a sample spaced some distance from the Mach cone; this is analogous to the method of generating quasi-isentropic compression by vaporizing a layer of material directly with the laser [6], but should allow higher pressures to be reached without laser-induced preheat. Building on the isentropic compression concept, the expanding vapor can be used to accelerate a flyer shocklessly. This flyer can then be impacted with a sample to induce a shock wave. This scheme is closely analogous to the explosive-driven scheme in which pressures around 5 TPa were induced in the sample [3].

SCOPING CALCULATIONS

Prototype design calculations were made, to allow design variants to be tested on lasers such as TRIDENT and OMEGA.

The baseline design was a cone 10 mm high with a base 10 mm in diameter, made of solid Cu. A representative time scale for low pressure experiments is the time for a weak shock to propagate along the axis: a couple of microseconds. Applying the drive pressure for a time of this order requires a ‘long’ laser pulse, hence only a relatively low irradiance is possible. Confined ablation is assumed to increase the energy efficiency. At some irradiance, damage to the transparent substrate would limit the energy transmission. A confined ablation pressure $\sim$10 GPa has been demonstrated in TRIDENT experiments with a sapphire substrate.

Hydrodynamic simulations were performed using a 2D Eulerian hydrocode, representing the drive pressure as a constant pressure void. Meshes were 0.1 mm square. With the baseline design, a narrow Mach wave was generated, the pressure increasing to of order 100 GPa near the base of the cone. (A ‘transmissive’ boundary was used over the base of the cone; this was not perfectly transmissive, and also reflected a shock wave. Thus the pressures calculated

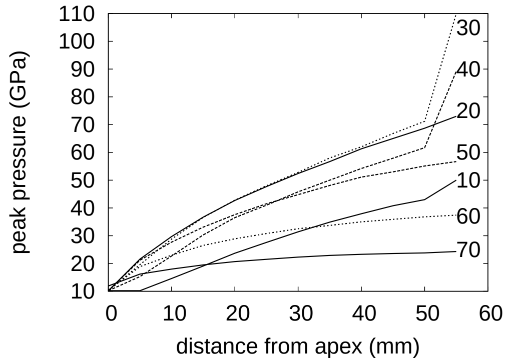

FIGURE 3. Pressure as a function of distance from the cone apex, for different cone half-angles (in degrees). The cone was Cu, with a sustained 10 GPa drive.

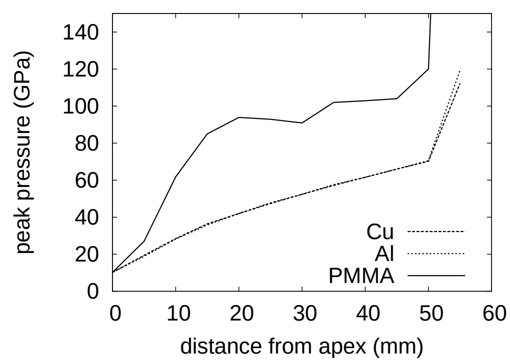

FIGURE 4. Pressure as a function of distance from the apex, for different cone materials. The cone had a half-angle of 28.8° – the optimum value for Cu – and had a sustained 10 GPa drive.

at the base were higher than 100 GPa.) Simulations were performed varying the height of the cone. The maximum pressure in Cu was achieved for a cone angle of 28.8° (Fig. 3).

The sensitivity to cone material was explored. Cu and Al gave similar Mach wave pressures; poly(methylmethacrylate) (PMMA) was predicted to give a significantly greater pressure (Fig. 4). The equation of state of PMMA may not be accurate at these pressures, so the predictions should be viewed with caution, but it seems likely that PMMA is a more appropriate material to use. Because of the impedance mismatch, low-impedance cone materials would induce an even greater pressure in the sample than would high-impedance materials.

Based on the confined ablation experiments performed at the TRIDENT laser, it should be possible to sustain the pressure over a cone of this area for ∼50 to 100 ns, which should be ample for the Mach wave to form. The Mach pressure increases faster than linearly with the applied pressure, so it would be advantageous to use a higher drive pressure if possible. It is likely that confining windows can be pushed to somewhat higher pressures, but free ablation would be necessary for drives over a few tens of gigapascals.

CONCLUSIONS

Several designs are possible for laser-driven Mach wave generators. These offer potentially great flexibility in pressure and applications. It should be possible to perform meaningful initial scoping experiments with a laser of the energy and capability of TRIDENT, and thereafter to stage up to much higher pressures using OMEGA and NIF.

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