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Laser-Generated Metallic Hydrogen

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Hydrogen reaches the minimum conductivity of a metal at 140 GPa (1.4 Mbar) and 3000 K. These conditions were achieved using a two-stage light-gas gun. We have investigated computationally the use of a laser-heated hohlraum to shock compress hydrogen to these conditions in samples sufficiently thin that the metallic fluid might be quenched metastably on release of dynamic pressure. A configuration was found such that the duration of maximum pressure is sufficiently long that the hydrogen film cools by thermal conduction before pressure is released.

Introduction

Hydrogen reaches the minimum electrical conductivity of a metal at 140 GPa (1.4 Mbar), 0.6 g/cm^3 (ninefold compression of initial liquid-H_2 density), and 3000 K in the fluid phase [1,2]. It is not known how, nor even whether, this metallic fluid could be quenched on release of dynamic pressure to a metastable solid glass. However, if metastable hydrogen glass could be synthesized, then the potential benefits are substantial: a quantum, mostly-diatomic metal with novel physical properties, including room-temperature superconductivity [3], and other novel electrical, magnetic, optical, thermal, and mechanical properties; a dense fuel for higher energy yields in inertial confinement fusion; a very light-weight structural material; a fuel, propellant, or explosive, depending on the rate of release of stored energy; and an aid in the synthesis of novel hard materials [4]. Quenching the metallic phase is a formidable problem which will probably require additives, such as B and P, which are needed to make Pd metallic glass, and will also require the ability to perform a large number of experiments to try various possibilities.

High-intensity lasers are an attractive way to produce and try to quench metallic hydrogen. The laser pulse duration is typically a few ns, and its time history can be varied. To remove heat by thermal conduction into the surrounding walls, the hydrogen sample must be a layer ~1 micron thin. As a result, the diameter of the hydrogen sample need be only ~0.1 mm to achieve a one-dimensional shock compression. Samples this small require a laser of only modest intensity to achieve a metallic fluid. Alternatively, a high-power laser could have a relatively large focal spot and, thus, could be used to process a large number of samples simultaneously. In addition, samples this thin are not required to be cryogenic liquids. The thin (~micron) samples could be made using a gas fill system. At 300 K, an H_2 gas pressure of < 0.3 GPa produces a density of 70 mg/cm^3, comparable to the density of liquid-H_2 at 20 K. This pressure over a small area is readily contained by strong quenching media, such as relatively thin diamond sheets. Gas samples also have the advantage that the initial H_2 density and, thus, the final density and temperature are readily tuned by choice of initial gas pressure up to ~0.5 GPa. The metallic nature of small samples 0.1 mm in diameter could be characterized by optical reflectivity; superconductivity could be characterized with a SQUID magnetometer.

To investigate the feasibility of quenching laser-produced metallic hydrogen, calculations were performed with laser-heated hohlraums to find a configuration in which hydrogen temperatures of ~3000 K quench by thermal conduction, while the pressure remains above 140 GPa.

Simulations

Using one-dimensional computer

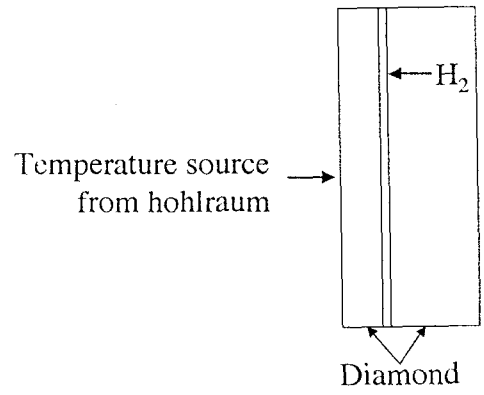

Fig. 1. Schematic of configuration.

simulations, we found appropriate configurations. The base case is illustrated in Fig. 1. The hydrogen layer is initially 1.67 μm thick with a density of 30 mg/cm^3. It is positioned between two diamond layers. Diamond was chosen because it is a good thermal conductor. Also, because diamond is not very compressible, shock-induced temperatures are relatively low. The diamond front-surface, facing toward the laser, is 50 μm thick; the rear diamond layer is 1 mm thick, chosen so thick to eliminate edge effects from the rear free surface. The temperature history in the laser-heated hohlraum is represented by a square pulse with an amplitude of 52 eV and a duration of 8 ns, longer than the time scale shown in Fig. 2. The resulting time histories of pressure and temperature, respectively, in the middle of the hydrogen layer are illustrated in Fig. 2 below.

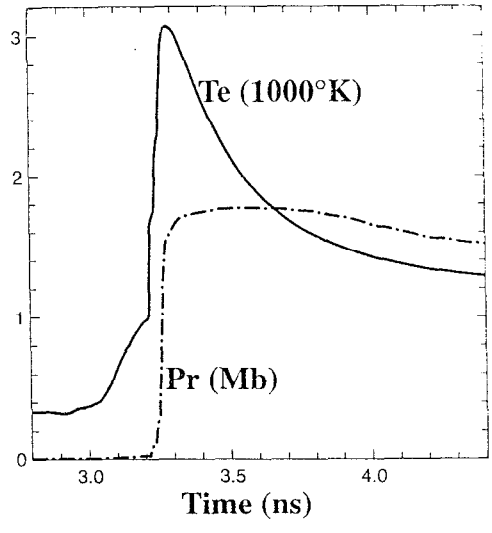

Fig. 2. Pressure and temperature in the hydrogen as a function of time.

When the incident shock from the diamond reaches the hydrogen, a series of reverberating shocks in the hydrogen brings the pressure up to 180 GPa and the temperature to 3100 K. Thermal conduction from hydrogen into the diamond quickly reduces the hydrogen temperature to ~1200 K, while the pressure is maintained above 140 GPa. Since the melting temperature of hydrogen at 140 GPa is ~1400 K [5], the hydrogen layer is likely to be solid at this point. Because of the fast time scale, the solid is highly disordered. After 8 ns, the pressure releases, while the temperature hovers around 1000 K.

The peak temperature in the hydrogen is tuned by choice of initial density. If the initial density is relatively low (high), then the hydrogen temperature is relatively high (low) as the hydrogen pressure reverberates up to the pressure in the diamond. For example, if the initial density is decreased from 30 to 20 mg/cm^3, the peak temperature rises from 3100 to 4700 K.

The time to quench hydrogen temperature by thermal conduction is adjusted by varying the initial thickness of the hydrogen so that thermal conduction time is fast compared to the 8 ns that pressure is applied, but slow compared to the time of shock reverberation up to peak pressure.

Variation of the thickness of the front layer of diamond allows variation of the initial hydrogen density. For example, if the diamond thickness is reduced from 50 to 20 μm, then a 1.1 μm thick layer of hydrogen with a density of 45 mg/cm^3 produces temperature and pressure pulses similar to those of the base case. If the diamond thickness is increased to 100 μm, then a 2.5 μm layer of hydrogen with an initial density of 20 mg/cm^3 produces a similar result.

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