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Direct laser-driven ramp compression studies of iron: A first step toward the reproduction of planetary core conditions

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ABSTRACT

The study of iron under quasi-isentropic compression using high energy lasers, might allow to understand its thermodynamical properties, in particular its melting line in conditions of pressure and temperature relevant to Earth-like planetary cores (330–1500 GPa, 5000–8000 K). However, the iron alpha-epsilon solid–solid phase transition at 13 GPa favors shock formation during the quasi-isentropic compression process which can depart from the appropriate thermodynamical path. Understanding this shock formation mechanism is a key issue for being able to reproduce Earth-like planetary core conditions in the laboratory by ramp compression. In this article, we will present recent results of direct laser-driven quasi-isentropic compression experiments on iron samples obtained on the LULI 2000 and LIL laser facilities.

1. Introduction

The properties of iron at high pressures are of fundamental interest for geophysics [1–3]. Telluric planets like the Earth have a core, which mainly consists of iron with small quantities of other elements. Pressure and temperature conditions of these planetary cores depend on their size ranging from few Mbar and 6000 K for Earth size planets up to 15 Mbar and 10,000 K for the giant exoplanets ("super-Earth") discovered recently [4,5]. Exploring the material properties of iron in these extreme conditions allows verifying and improving planet formation and structure models, in particular the magnetic field generation and the dynamics of the planetary core. A prominent example is the iron melting curve, which determines the thermodynamic state of the core (solid or liquid) and thus indirectly the presence of a magnetic field.

Beside its direct impact on planetary science, studying materials at high pressures can also give an insight into the structure of matter such as phase transitions at extreme conditions. All data on these unexplored phase boundaries are valuable for verifying models.

While static compression allows very precise measurements, the maximum pressure and temperature conditions that can be presently achieved are presently limited below 4 Mbar and about 4000 K [6], far lower than conditions of super-Earth interiors. Thus, for reaching higher pressures, dynamic compression is necessary. The simplest way of performing dynamic compression is generating a strong shock in the sample. But, due to the highly dissipative nature of this process, this technique cannot achieve the thermodynamic conditions of planetary cores: high compression and low temperature [3,7–10]. The shock temperature is too high compared to those expected for planetary interiors. Isentropic compression

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[11–15] can reach the necessary pressures and densities, but temperatures remain too low. Indeed although the planet formation is almost isentropic, its "origin" begins at the higher mantle temperature value which, for example, 2000 K for Earth. Fig. 1 illustrates the different parameter ranges reachable with the present techniques in the pressure–density plane. To reach planetary core conditions, new compression schemes are necessary like combining isentropic compression with shocks and/or preheating.

In this proceeding, we present two important steps toward laser compression experiments reaching planetary core conditions: first, we studied the $\alpha-\varepsilon$ transition under ramp compression. The $\alpha-\varepsilon$ transition is a solid–solid phase transition in iron at 13 GPa, where the crystalline structure changes from a body cubic centered (bcc) to a hexagonal closed packed (hcp) one. While crossing the phase boundary, the increased compressibility during the coexistence of both phases perturbates the propagation of the compression waves which can result in a shock. However, as the relaxation time of the phase transition is comparable with the compression time, the dynamics of the phase transition plays an important role. Therefore laser-driven ramp compression allows an insight of the relaxation process. Second, we used ramp compression to reach pressures above 300 GPa, which becomes comparable to Earth core pressures, although temperatures are still too low.

2. Experimental setup

The experiments have been performed at the LULI 2000 laser and the LIL (Ligne d'Intégration Laser) laser facility. Both facilities have the ability of arbitrary temporal laser pulse shaping, which is crucial for an optimal compression in the direct laser irradiation scheme [12] used during the experiment. The ramp profile has been optimized using a model based on [16] resulting in an exponential type laser profile, as shown in Fig. 2.

The LULI 2000 laser can deliver up to 400 J at 527 nm wavelength with an arbitrary ramp of up to 5 ns duration. A hybrid phase plate (HPP) was used to obtain a 1 mm diameter flat intensity profile. With these laser parameters, ramp compression up to 2 Mbar is expected, which is well adapted to study the dynamics of the solid–solid $\alpha-\varepsilon$ phase transition under ramp loading. In order to vary the dynamic loading rate, the total energy of the laser was changed, while the temporal profile remained constant.

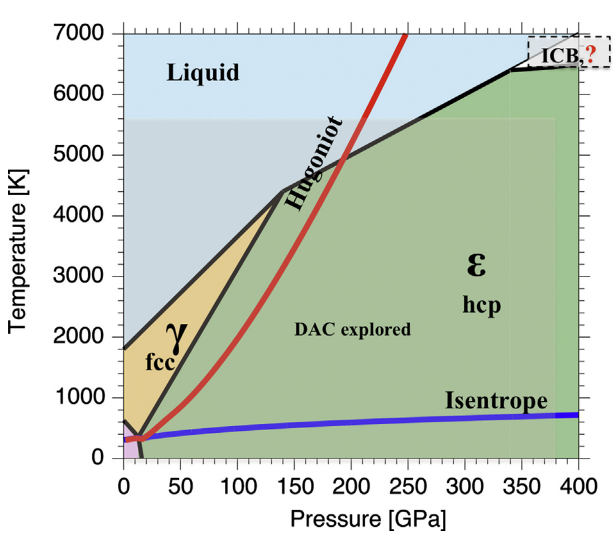

Fig. 1. Phase diagram of iron showing known phase boundaries and the limitations of present compression schemes. The Hugoniot and the isentrope are taken from the SESAME tables. Earth inner core boundary (ICB) conditions are reachable neither with shocks nor with static compression.

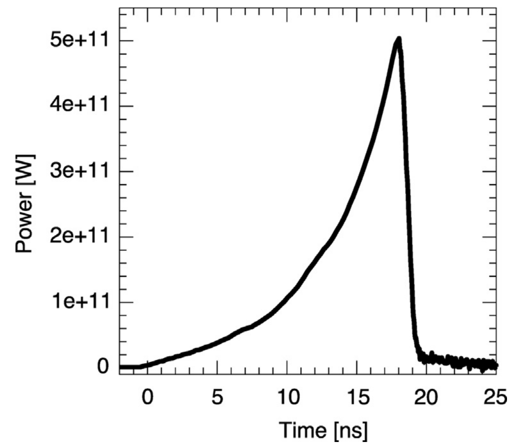

Fig. 2. Typical temporal laser pulse profile for ramp compression. As a result of optimization, the shape is rather exponential and not linear. The particular ramp profile was produced during the LIL campaign.

The LIL laser delivered up to 5 kJ at 351 nm with an arbitrary ramp up to 20 ns duration. The focal spot was also smoothed with a phase plate, giving a flat intensity profile of 800 μm diameter. Here, due to the higher energy and longer pulse duration, pressures up to 10 Mbar are expected, which corresponds to super-Earth planetary cores conditions.

The target samples were iron foils of high purity either free standing or coated onto a sapphire, which served as an impedance matched release window. However, all results presented in this article have been obtained with free standing samples. The iron thicknesses were 13 μm and 70 μm for LULI and LIL experiments respectively. The lateral size of the sample was typically 3 mm × 3 mm, thus much larger than the focal spot.

In order to characterize the sample thermodynamic conditions generated in the sample, we measured the free surface velocity of the rear side of the targets with a line VISAR [17] system operating at 532 nm. This system allows measuring the velocity interferometrical with high 1D spatial resolution ($\approx$10 μm) and high temporal resolution (<100 ps). In order to leave the ambiguity of a phase jump, two VISARs with different sensitivities have been used. A typical VISAR output in our isentropic compression experiment is shown in Fig. 3; the absence of discontinuities in the fringe pattern indicates a smooth increase of the free surface velocity, which is a signature of a shockless compression.

We employed also a SOP (Streaked Optical Pyrometer) to determine the surface temperature. As iron temperatures on quasi-isentropic compression are expected to be quite low, i.e., below the detection threshold of this diagnostic ($\approx$5000 K), the SOP served as a sanity check for the absence of strong shock, which would heat the sample above the detection limit. In the presented experiments, no emission was observed, as expected for a low entropy compression. Therefore we do not discuss this diagnostic any further.

3. Dynamics of the $\alpha-\varepsilon$ transition

The dynamics of the $\alpha-\varepsilon$ transition are of great importance for isentropic compression experiments to reach Earth core conditions, as the compression path crosses this transition and favors shock formation. Beside its importance for the design of isentropic compression experiments, the characterization of this transition dynamics allows also testing models of this transition.

In order to study the dynamics of the $\alpha-\varepsilon$ transition, we varied the loading rate of the ramp. This was achieved by changing the laser