Experimental Report: HC-2848

Dynamic compression of matter using high energy lasers in the ns range is becoming a vast field of research. Firstly, since it allows exploring “exotic” states of matter like the Warm Dense Matter (WDM) beyond the static compression range. Secondly, when performed in a lower loading range, it can bring important complementary information to the static studies, shedding light on the kinetics and path of compression-induced structural transitions, nucleation processes and strong textural changes.

Bismuth

Bismuth is an ideal candidate for this kind of study thanks to its rich and complex phase diagram already at quite low pressures (<10 GPa) (Fig 1.). Compressed Bi undergoes the I-II and II-III phase transitions within 3 GPa and the III-V phase transitions around 7 GPa. In a recent study of time-resolved XRD on shock compressed Bi, the sequence of shock induced transformations was followed after compression to 11 GPa. The Bi-I to Bi-V transformation was directly observed without any transient state within 4 ns, whereas intermediate phase transitions (V – III – II – I) were only observed during release. More recently, melting from the high-pressure Bi-V phase was observed at the LCLS XFEL facility in Stanford, with the weak liquid diffraction observed after release of high pressures above 11 GPa, no work has been published in the low-pressure region, where complex crystal structures can be found in static compression experiments.

This proposal was a resubmission of that work with an improved confinement geometry and the opportunity to use a small vacuum chamber that would improve the laser energy deposition on target (remove the laser breakdown in air).

X-ray diffraction measurements were performed at E = 15 keV using the beam from the U17 undulator with the Ru multilayer, characterized by ~ 3 % bandwidth. The X-ray bunch arrival was timed such that t = 0 overlaps with the initiation of the 5 ns Gaussian laser pulse. The delay was then adjusted to probe the sample during peak compression (lasting only 1-2 ns) and later times as the sample releases from the peak compressed state to lower pressures.

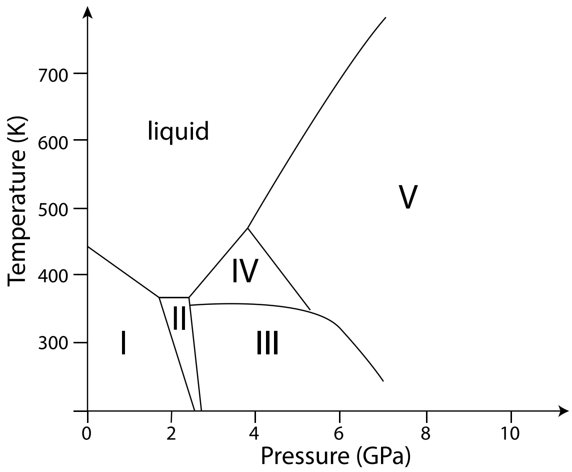

Figure 1: Phase diagram of Bi up to 10 GPa

Diffraction of the 6 µm Bi foil from a single bunch is shown in the left panel of figure 2 (with background subtraction applied). The 3 most intense peaks are observed between 14 and 23 degrees. The right panel of figure 2 shows data collected at 5 ns and 6 ns after laser was initiated (laser energy of 180 mJ, laser spot size ~ 250 µm). In the 5 ns pattern (blue) there is a small amount of uncompressed Bi (ahead of the compression wave) and a new peak forms near 17 degrees that can be indexed to the bcc Bi-V phase. At 1 ns later, there is less uncompressed material as the shock transits the 6 µm foil and most of the sample is compressed to the high-pressure phase. The pressure is estimated to be ~ 8 GPa, using the d-spacing of the Bi-V 110 peak to determine the lattice parameter, and therefore the volume, and comparing with the room temperature equation of state.

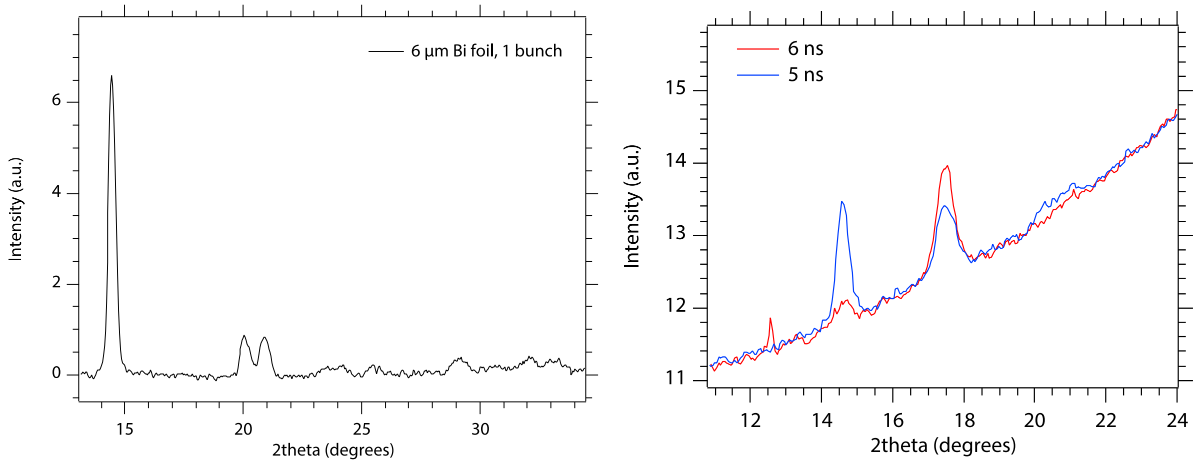

Figure 2: Left) Integrated diffraction profile from a single X-ray bunch (from hybrid mode, < 8 mA). X-ray energy ~ 15 keV, diffraction from a 6 µm thick Bi foil (with PMMA and plastic confinement layers). **Right)** Formation of the Bi-V at ~ 8 GPa

Delays between the X-ray and laser were adjusted between 0 and 25 ns with varying steps from 0.2 ns up to 5 ns. Multiple shots were collected as damage is induced from the laser ablation on an area slightly larger than the laser focal spot. For each target (~ 12 x 12 mm), between 6 and 10 laser 'shots' could be obtained. The laser energy was adjusted between 60 and 250 mJ to reach maximum pressures between 1 and 8 GPa. In Bi we observe the same sequence of transitions from the high-pressure Bi-V phase at pressures > 5 GPa. At pressures < 5 GPa, we see compression to one of the lower pressure phases (Bi II or Bi III), but the increase in peaks for the low symmetry structures have made initial analysis difficult to identify the particular phase based on the resolution and flux of the data.

Tin

A second experiment was also carried out to take advantage of the total number of shifts available to us. "quasi"-single crystal Sn foil (25 µm thick) was compressed at various laser energies and delays. A maximum pressure of ~ 9 GPa was achieved in Sn (based on the room temperature equation of state and the compressed phase lattice parameters). The ß-Sn to bct transition was observed as well as significant texturing of the initial bright single crystal spots (figure 3).

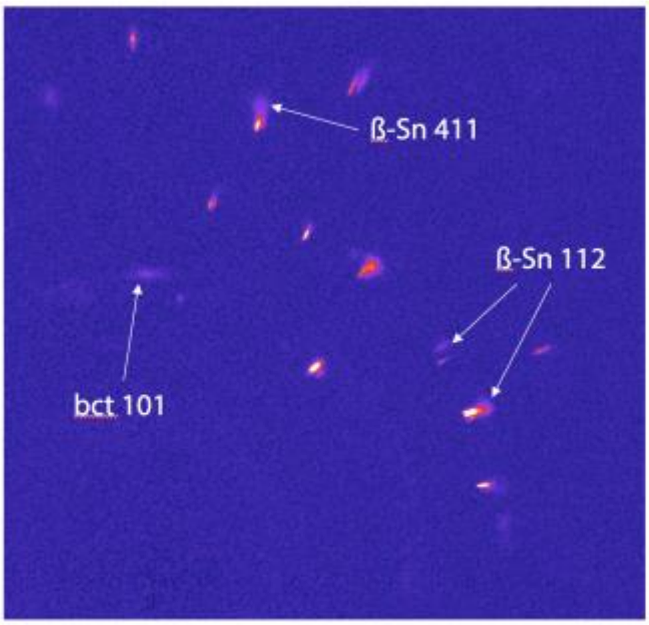

Figure 3: A portion of the 2D detector showing the new phase (bct 101) and the compressed ß-Sn single crystal peaks coexisting as the shock reaches the phase boundary.