Expansion of evaporating lead after ion-beam and shock-wave loading[*][†]

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In this paper we discuss and compare some recent results on expansion dynamics of evaporating lead obtained in heavy-ion beam driven HIHEX (Heavy Ion Heating and Expansion) experiments at GSI-Darmstadt and in high-explosive driven shock-wave loading and release experiments at IPCP-Chernogolovka.

During the past decade, extensive studies on the problem of metal evaporation after intense shock loading in high-explosive driven experiments have been carried out at IPCP-Chernogolovka [1–4]. In such experiments, different release isentropes are traced with the same shock wave generator by varying the initial pressure, P_s of the buffer gas (helium) that defines the final expansion pressure for the sample material. Brightness temperatures of a sample at different wavelengths are measured using the fast pyrometry technique during the whole course of an experiment. These experiments have addressed the fundamental problem of locating the critical point and liquid-vapor coexistence curve (binodal) in the $P-T$ phase diagram for Pb, Sn, Ni, W and for other metals.

In the critical point and binodal regions, basic thermodynamic properties of matter change rapidly from those of condensed states to the gaseous ones. This causes certain anomalies in hydrodynamic behavior of the target material while crossing the binodal or approaching the critical point. In shock-wave experiments, no hydrodynamic peculiarities (as compared to equilibrium EOS description) has been observed if the release isentrope crosses the binodal curve from the side of gaseous or plasma states [2]. However, as it was first shown by Novikov [5] in experiments for porous samples and low P_s values, target expansion velocity (U_s) in the two-phase region is exceeding that predicted by the models bases on wide-range equilibrium EOS. Detecting a decrease in $P_s(U_s)$ slope at the point $P = P_{entr}$, where the release isentrope is crossing the binodal is therefore a common method for determining the binodal location.

In our previous studies on lead samples, an abrupt increase of the U_s was measured on the release isentropes entering the two-phase region from the liquid side of the $P-V$ diagram [1, 2]. This sudden jump was explained by disintegration of the evaporating surface and development of the so-called boiling wave, in contrast to homogeneous volume boiling. The measured value of the increased expansion velocity after this jump can be described under assumption that all the available energy of superheated liquid is spent on formation and acceleration of the vapor with final thermodynamic parameters on the binodal defined by P_s, whereas the liquid phase retains the initial velocity.

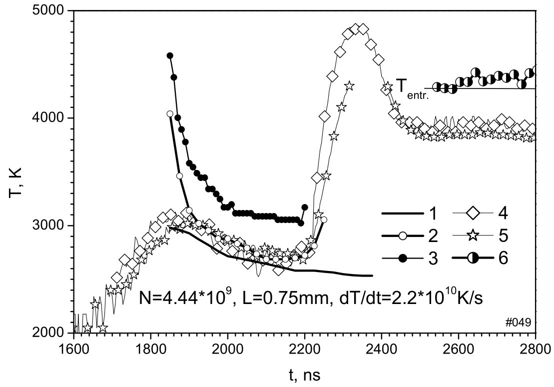

Figure 1: Evaporating lead temperature along release isentropes (shock-wave loading experiments) and in ion-beam heating and expansion experiment. Shown are brightness temperatures on shock-loading release isentropes: **1** — $151\,\mathrm{GPa}$, **2** — $180\,\mathrm{GPa}$, **3** — $223\,\mathrm{GPa}$ at $700\,\mathrm{nm}$ and in heavy-ion-beam driven experiment (beam intensity $N = 4.44 \cdot 10^9$ ions/pulse, expansion length $L = 0.75\,\mathrm{mm}$) : **4** — at $650\,\mathrm{nm}$, **5** — at $750\,\mathrm{nm}$, **6** — grey-body approximation of physical temperature.

Recently, a series of experiments on heavy-ion-beam generated high-energy-density (HED) states in matter has been carried out at the HHT area of GSI [6, 7]. The main aims of these experiments were commissioning of diagnostic instruments and methods for the future HEDgeHOB collaboration experiments at FAIR [8] as well as tests of different beam-target configurations such as the plane-HIHEX experiment concept [9] using helium as a buffer gas. In these experiments, new data on thermophysical properties and hydrodynamic response of various materials (including Pb, Sn, Cu, Al, W, Ta, $\mathrm{Al_2O_3}$ and $\mathrm{UO_2}$) in HED states in the two-phase liquid-vapor region near binodal and the critical point has been obtained. A fast multi-channel radiation pyrometer has been used as a key diagnostics in these experiments [10]. This allows for a quantitative comparison between the target expansion dynamics after ion-beam heating and the shock-wave loaded release isentrope data.

Brightness temperature profiles on release isentropes measured for lead samples initially shocked up to 151, 180

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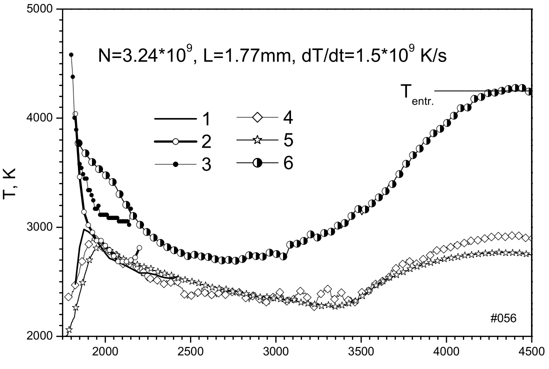

Figure 2: Evaporating lead temperature along release isentropes (shock-loading) and in ion-beam driven experiment with long expansion length. See caption to Fig. 1 and explanations in the text.

and $223\,\mathrm{GPa}$ pressures are shown in Fig. 1 and Fig. 2 along with the corresponding results of ion-beam driven experiments, all for expansion to a final pressure of about $0.1\,\mathrm{MPa}$. For the ion-beam experiments, the physical temperature approximated by fitting all the data from the six-channel pyrometer to the grey-body model are shown as well. The heavy-ion-beam experiments performed using intense beams of $^{238}\mathrm{U}$ ions with initial energy of $350\,\mathrm{AMeV}$ are described elsewhere [6, 7]. The data obtained in a shot with high beam intensity $N = 4.44 \cdot 10^9$ and short expansion length (the gap between $250\,\mu\mathrm{m}$-thick lead target foil and a sapphire window) $L = 0.75\,\mathrm{mm}$ and for lower intensity $N = 3.24 \cdot 10^9$ and long expansion length $L = 1.77\,\mathrm{mm}$ are shown in Fig. 1 and in Fig. 2, respectively.

It is seen from Fig. 1 that the temperature profile during the expansion phase observed in the ion-beam driven experiment is close to the $180\,\mathrm{GPa}$ release isentrope of shock-loaded lead (line ”2” in Fig. 1). According to the EOS model for lead [11], this isentrope crosses the binodal curve on the phase diagram at the point $P_{entr} = 50\,\mathrm{MPa}$, $T_{entr} = 4243\,\mathrm{K}$ and $E_{entr} = 0.727\,\mathrm{kJ/g}$. As it has been shown in shock-wave experiments, expansion of lead along this isentrope to the final pressures below $10\,\mathrm{MPa}$ is accompanied by the surface evaporation and generation of the boiling wave phenomena [2].

In the corresponding beam-driven experiment, total duration of the heating pulse was about one microsecond with FWHM of $125\,\mathrm{ns}$.. During the heating phase, the sample foil is melted and starts to evaporate at the free surface. While expanding, the lead vapor is rapidly cooling down and at the moment when its temperature becomes sufficient for homogeneous nucleation (near the vapor spinodal line), liquid droplets appear inside the vapor and the boiling wave is formed. After this moment, the expansion dynamics is governed by the surface evaporation processes. These issues have to be taken into account in the hydrodynamic simulations for correct modeling of the HEDP experiments.

When the expanding lead which consists of a mixture of vapor and liquid metal droplets impacts on the sapphire window, it is being compressed and further heated (see Fig. 1, $t \approx 2300\,\mathrm{ns}$). According to the EOS model [11], such weak (quasi-isentropic) shock compression will transform the material into pure vapor state and the droplets shall disappear. On the other hand, a certain time is needed for such transformation. Therefore, if the heating rate is high enough, the liquid droplets can be overheated up to spinodal temperatures. To realize such overheated states for pressure below the critical, one needs a heating rate dt/dT which is at least higher than $10^9\,\mathrm{K/s}$ [12]. In other experiments on electrically exploded tungsten wires, the authors have not observed the overheating even at the heating rates of $10^{12} - 10^{13}\,\mathrm{K/s}$ [13].

In our experiment with short expansion length (Fig. 1), at the moment of the impact on sapphire the heating rate was about $dt/dT = 2.2 \cdot 10^{10}\,\mathrm{K/s}$ and the overheating is clearly observed. The maximum temperature of about $4860\,\mathrm{K}$ measured in this experiment is close to that of the liquid spinodal at $50\,\mathrm{MPa}$ pressure. On the other hand, in the second experiment with a longer expansion and lower beam intensity (see Fig. 2), the heating rate at the moment of impact was considerably smaller ($dt/dT = 1.5 \cdot 10^9\,\mathrm{K/s}$) and therefore the overheating process does not take place.

It is to be noted that the physical temperature of lead (grey-body approximation, line ”6” in Fig. 1) after the impact on the sapphire window — about $4300\,\mathrm{K}$ — is fully consistent with the discussed above value $T_{entr} = 4243\,\mathrm{K}$ at the point where the corresponding expansion isentrope ($180\,\mathrm{GPa}$ in the shock-wave release experiment) is crossing the binodal. This fact can be taken as an additional confirmation for above interpretation of the ion-beam driven experiment on the expansion dynamics of evaporating lead.

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