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Energy loss dynamics of intense heavy ion beams interacting with solid targets

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Abstract

At the Gesellschaft für Schwerionenforschung (GSI, Darmstadt) intense beams of energetic heavy ions have been used to generate high-energy-density (HED) state in matter by impact on solid targets. Recently, we have developed a new method by which we use the same heavy ion beam that heats the target to provide information about the physical state of the interior of the target (Varentsov *et al.*, 2001). This is accomplished by measuring the *energy loss dynamics* (ELD) of the beam emerging from the back surface of the target. For this purpose, a new time-resolving energy loss spectrometer (scintillating Bragg-peak (SBP) spectrometer) has been developed. In our experiments we have measured energy loss dynamics of intense beams of ^{238}U, ^{86}Kr, ^{40}Ar, and ^{18}O ions during the interaction with solid rare-gas targets, such as solid Ne and solid Xe. We observed continuous reduction in the energy loss during the interaction time due to rapid hydrodynamic response of the ion-beam-heated target matter. These are the first measurements of this kind. Two-dimensional hydrodynamic simulations were carried out using the beam and target parameters of the experiments. The conducted research has established that the ELD measurement technique is an excellent diagnostic method for HED matter. It specifically allows for direct and quantitative comparison with the results of hydrodynamic simulations, providing experimental data for verification of computer codes and underlying theoretical models. The ELD measurements will be used as a standard diagnostics in the future experiments on investigation of the HED matter induced by intense heavy ion beams, such as the HI-HEX (Heavy Ion Heating and EXpansion) EOS studies (Hoffmann *et al.*, 2002).

Keywords: Dense plasma; Energy loss; Heavy ion beam; Plastic scintillator

1. INTRODUCTION

The accelerator facilities at the Gesellschaft für Schwerionenforschung (GSI) Darmstadt offer a unique possibility for experiments with heavy ion beam induced dense plasmas. Using intense beams of highly energetic heavy ions, it is possible to heat rather large volumes of matter at solid-state density to extreme conditions of temperature and pressure (see experimental works, e.g., by Dornik *et al.*, 1996; Funk *et al.*, 1998; Stöwe *et al.*, 1998). The knowledge gained by such experiments is of considerable interest in fundamental research on the equation of state (EOS) of matter, phase transitions, and hydrodynamic behavior of dense plasmas. These phenomena are related to the field of plasma physics, astrophysics, and geophysics, and have an important practical application in inertial fusion energy (Hoffmann *et al.*, 2000).

A large number of experiments on the interaction of moderate and high energy heavy ion beams with laser-produced and discharge plasmas have shown that the measurement of the energy loss of the incident ion beam after the target can be used to diagnose plasma properties (e.g., Hoffmann *et al.*, 1994; Stöckl *et al.*, 1996; Roth *et al.*, 2000, and references therein). The application of intense heavy ion beams as a diagnostic tool is of a special interest for experiments where the ion beam itself is used to generate a dense plasma. The energy loss dynamics (ELD) of an ion beam, that is, the time dependence of the energy loss during the interaction, allows us to obtain quantitative information on the time evolution of the linear density of the target during the heating process due to hydrodynamic response of the heated target matter.

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This information can be used to investigate propagation of intense shock waves, expansion of the material, and other hydrodynamic effects in the heated target. The validity of simulation codes, stopping models, and EOS data can be verified by such measurements.

In this article, we present the continuation of our experimental and theoretical studies on the ELD of intense heavy ion beams interacting with rare-gas solid (RGS) targets (Varentsov *et al.*, 2001). The ELD measurements have been performed with a small and elegant time-resolving energy loss spectrometer, called the "scintillating Bragg-peak" (SBP) spectrometer. The SBP spectrometer has been developed and set up at the High Temperature experimental area (HHT) at GSI. The accuracy of the ELD measurements and the data analysis procedures have been significantly improved. In addition to that, we have carried out advanced two-dimensional hydrodynamic computer simulations of the observed phenomena. To describe the results of the ELD experiments, a new EOS model for solid Ne has been developed (Lomonosov, pers. comm.).

2. EXPERIMENTAL SETUP

The experiments were performed at the HHT experimental area of the GSI plasma physics group. Intense heavy ion beams are delivered by the heavy ion synchrotron SIS-18 and guided to the HHT experimental area. A plasma lens (Stetter *et al.*, 1996) was used as a final focusing system. An elaborate cryogenic system is available at the HHT experimental area (Funk, 1999), allowing remotely controlled preparation of RGS targets of different materials and geometries in an evacuated target chamber. The cryo-crystals were produced in a growing chamber and the shape of the crystals was exactly defined by the shape of the chamber. In our experiments, the crystals were cubes with a base area of 8 × 8 mm. The faces of the crystals were oriented perpendicular to the beam axis. Since the crystal is destroyed by the ion beam, a new crystal had to be grown for every following experimental shot. The growing time was in the order of 5–15 min depending on the type of gas used.

Various beam and plasma diagnostic tools are installed around the target (see Fig. 1). Due to the large focusing angle of the plasma lens, the ion beam can be focused into a spot of less than a millimeter in diameter. The focusing properties can be controlled by moving a quartz scintillator array to the target position or by recording the fluorescence of the residual gas in the target chamber. The beam intensity and time profile were recorded by fast current transformers. A small part of the incident ion beam (less than 0.2%) that escapes the target in the vicinity of the beam axis enters the SBP energy loss spectrometer. Most of the beam is stopped in a carbon-beam dump behind the target.

The SBP energy loss spectrometer (Varentsov, 2002) is installed behind the carbon-beam dump, which has a 10-mm aperture along the axis. The spectrometer consists of a collimator, a fast plastic (Bicron, BC-408) scintillator block or an organic liquid (BC-517H) scintillator module with a recirculation system, and a streak unit (Fig. 1). A modular collimator with about a 1-mm aperture selects ions escaping the target with very small angles around the beam axis. These ions are stopped in the bulk of the fast scintillator.

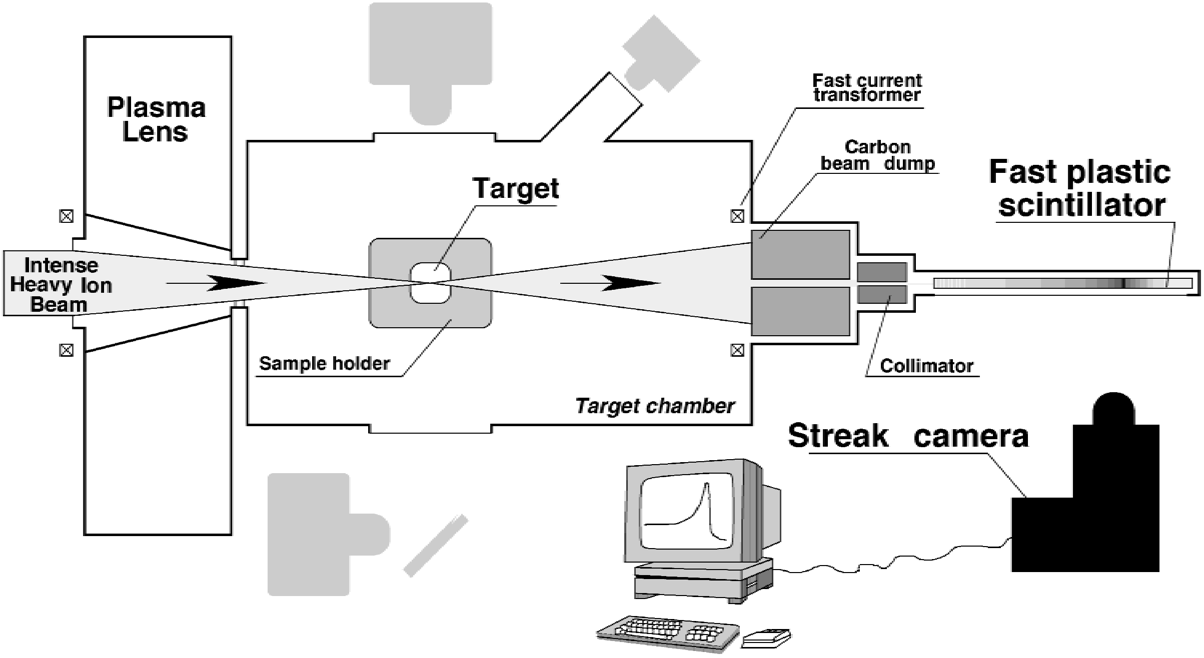

Fig. 1. Scheme of the experimental setup for the energy loss dynamics measurements and the SBP spectrometer (not to scale).

The emitted light from the scintillator can be observed by a streak camera (Hamamatsu C2830, sweep unit M2548) through a slit window in the scintillator holder. The streak camera is installed perpendicular to the scintillator axis. A very narrow (a few tens of microns) slit at the entrance of the streak camera cuts a longitudinal profile of the incident light along the scintillator axis. Two-dimensional (range vs. time) scintillation images on the exit screen of the streak camera are recorded by a cooled high-resolution (1024 × 1024 pixels) CCD camera (Hamamatsu ORCA). The ion beam energy loss spectra can then be obtained at every time moment from the specific luminescence profiles (Bragg curves), detected by the SBP spectrometer by using a special data analysis procedure (Varentsov, 2002).

3. EXPERIMENTS AND RESULTS

During the commissioning of the SBP spectrometer, several series of ELD measurements with different ion species and rare gas cryo-crystals (RGS targets) have been carried out. We report here the results of two recently performed ELD experiments with RGS Ne and Xe target materials.

In the first experiment, we studied the interaction of a ^{238}U ion beam with solid Ne targets ($\rho = 1.49$ g/cm^3). The initial beam energy was (190 ± 5) MeV/u. One rectangular ion pulse of 1.1 μs duration contained about 1.2×10^9 particles. The beam was focused by the plasma lens to a (590 ± 60) μm (FWHM) spot in the center of the target. According to the performed simulations, the maximal specific energy deposition in the target was about 1.6 kJ/g for this case.

Another experiment was performed with ^{40}Ar projectiles and solid Xe cryogenic targets ($\rho = 3.4$ g/cm^3). The initial beam energy was (291 ± 2) MeV/u and the beam contained about 5.5×10^{10} particles in a 1.12-μs bunch. A focal spot of about 740 μm (FWHM) was produced by the plasma lens. The maximal specific energy deposition in this experiment was 0.57 kJ/g.

We have also made several experimental series with intense (more than 10^{10} ions/pulse) beams of ^{86}Kr and ^{18}O projectiles interacting with solid Xe, Ne, and D_2 targets. To verify the EOS values for Ne, precision ELD measurements with ^{238}U beams of a lower intensity (about 10^8) and different initial energies in solid Ne targets have been performed as well. These experimental results and corresponding computer simulations will be reported in our future papers.

The ELD data, measured during the first of the experiments described above, is presented in Figure 2. Initially, the range of a 190 MeV/u ^{238}U beam in solid Ne is smaller

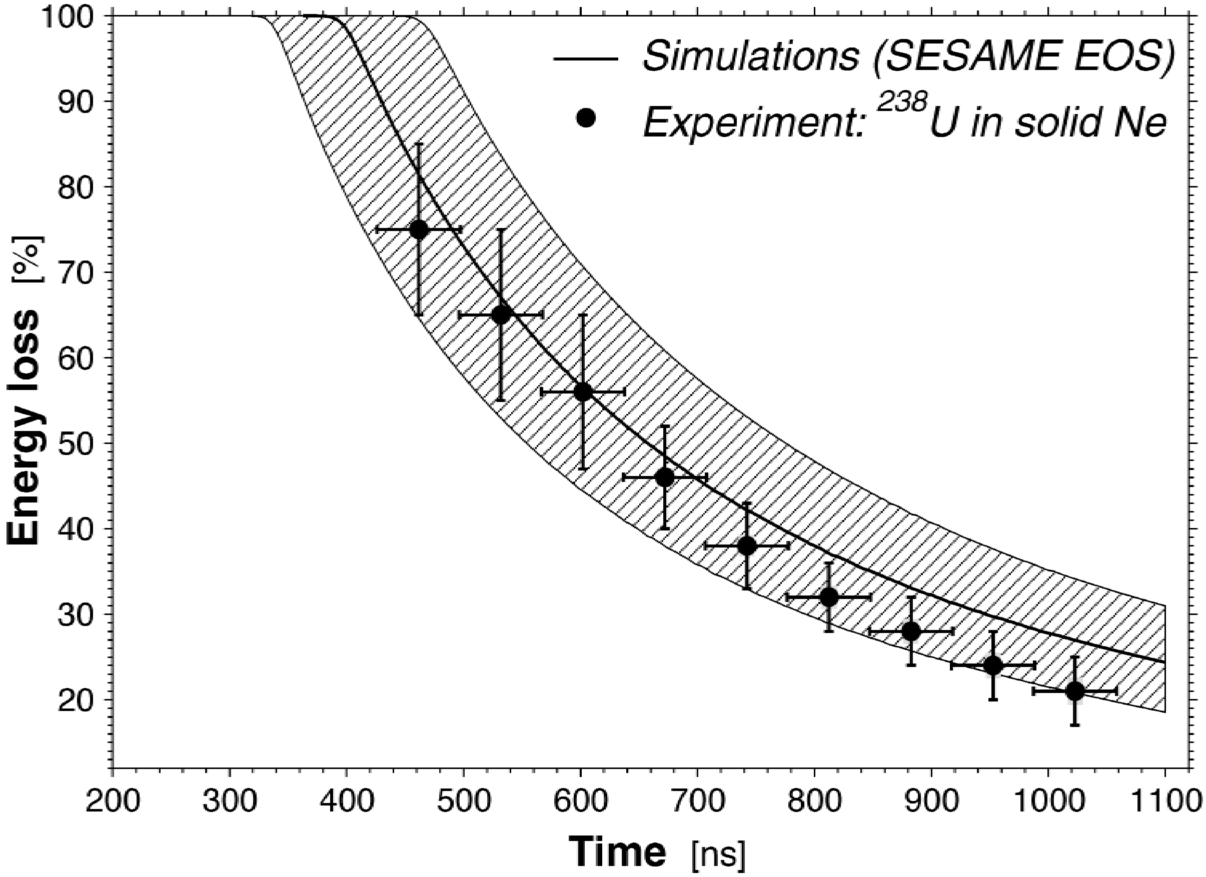

Fig. 2. Measured and simulated ELD dependence of intense ^{238}U, 190 MeV/u ion beam interacting with solid Ne target.

than the length of the crystal. The beam is thus completely stopped in the target, and therefore, for a certain period of time, no data could be recorded by the SBP spectrometer. However, due to the continuous heating of the target by the beam and the following hydrodynamic radial motion of the target matter, the linear density on the axis is continuously decreasing. As a consequence, the beam penetrates further and further into the target. At about 350 ns the projectiles escape the target and are detected. Since the linear density of the target decreases, the energy loss of the incident ion beam decreases as well, and the energy of the escaping projectiles increases. The error bars of the experimental data points shown in Figure 2 have been calculated after statistical processing of the ELD data, recorded in a number of interactions with identical targets. The size of the error bars was mainly determined by the shot-to-shot fluctuation of the ion beam intensity from the accelerator. The corresponding simulation results, which are also plotted in Figure 2 will be explained in the next section.

In the latter experiment, the range of 291-MeV/u ^{40}Ar ions in solid Xe is larger than the target length, and the data could be recorded by the spectrometer already from the beginning (Fig. 3). Initially, the ^{40}Ar ions lose only about 16.5% of their energy in the target. The energy deposition profile is almost uniform along the axis. Nontheless, due to the high intensity of the beam, the target material is heated up to 4800 K in this experiment. Rapid hydrodynamic radial expansion of the heated matter efficiently reduces the density in the interaction volume. Therefore, the energy loss of the ions escaping the target is continuously decreasing during the interaction, down to about 6% by the end of the beam pulse. The precision of the ELD data measured in this experiment is determined by the systematic error. This error arises in the data processing procedure, that is, from the range–energy calibration for the SBP spectrometer's scintillator (Varentsov, 2002), where the stopping data calculated with the SRIM code (Ziegler *et al.*, 1996) is used. The level of this systematic error is estimated to be about ±2%. The size of the statistical error bars indicated in Figure 3 is already smaller than this value.

4. COMPARISON WITH SIMULATIONS

To advance our knowledge about the interaction phenomena between the heavy ion beams and the solid targets observed in the experiments, numerical simulations have been per-

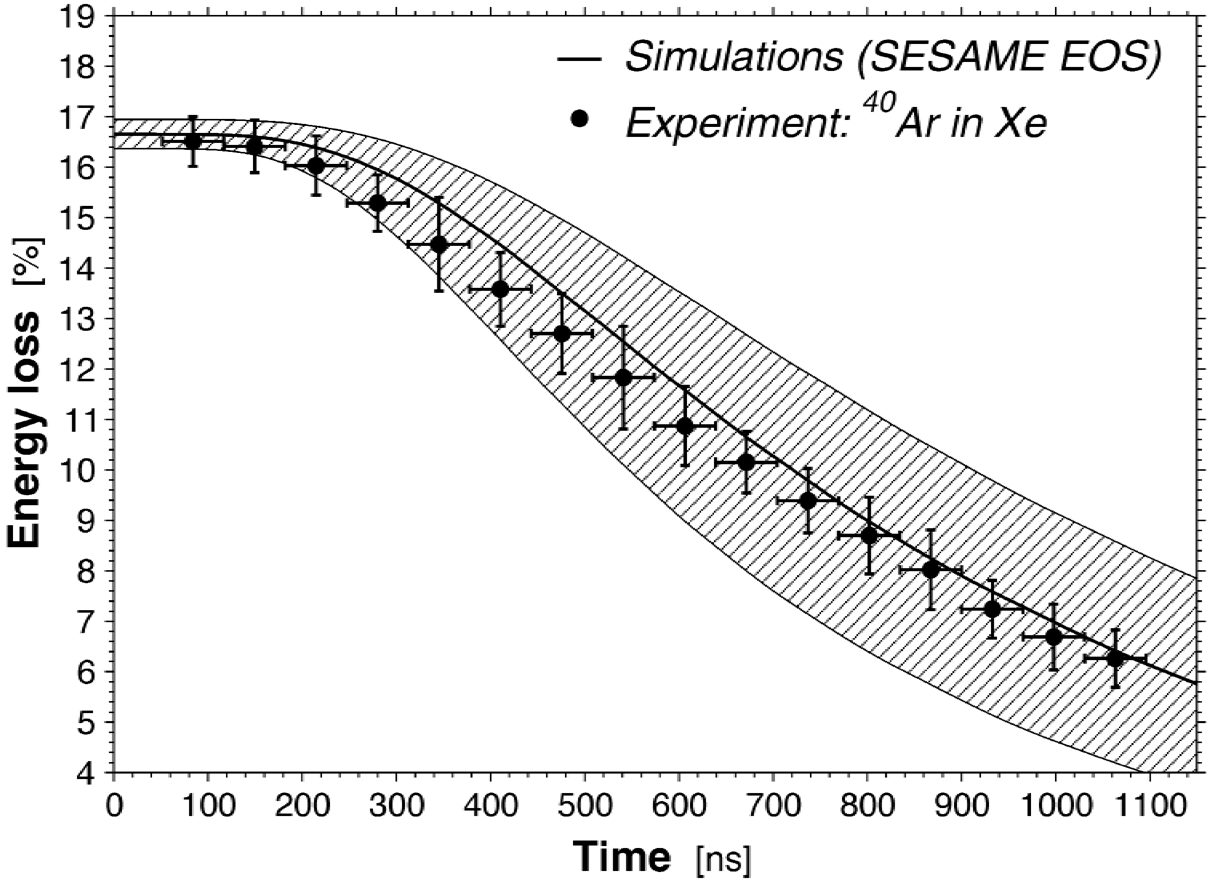

Fig. 3. Measured and simulated ELD dependence of intense ^{40}Ar, 291 MeV/u ion beam interacting with solid Xe target.

formed. For this purpose we employed a sophisticated two-dimensional hydrodynamic code called BIG2 (Fortov *et al.*, 1996). In most of the simulations, the SESAME EOS data from the Los Alamos Laboratory has been used. In addition to that, we have also used an advanced EOS model for Ne ("ChTEOS"), recently developed at the Institute of Problems of Chemical Physics, Chernogolovka, especially for the present ELD studies (Lomonosov, pers. comm.). The ion beam stopping calculations were based on SRIM (Ziegler *et al.*, 1996) data. The cold stopping model is valid for these simulations since in the target temperature is below 0.5 eV. The beam parameters such as beam envelope, time profile of the ion bunch, and the intensity which we used in the simulations were the same as in our experiments.

As an example of the performed simulations, in Figure 4 we show two-dimensional (axis–radius) plots of the density, temperature, and physical phase state of the target material at different time moments during the irradiation. This simulation has been done for the above experiment with a ^{238}U, 190 MeV/u beam and a solid Ne target.

Initially, the beam is completely stopped in the target and deposits there its entire energy. The temperature of the target material is increasing and therefore, a pressure gradient in the radial direction is induced. In addition, a shock wave moving forward in the axial direction is generated behind the Bragg peak of the stopped ions (see Fig. 4). At 100 ns after the beginning of the beam pulse, the temperature of Ne is above the melting point, and a lower density channel consisting of the liquid material is formed. At the same time, due to the continuous beam heating, an intense density wave of the compressed material penetrates outward in the radial direction, driven by the pressure gradient. The melting (two-phase, liquid–solid) front is following the radial density wave. As a result, the linear target density in the vicinity of the axis is decreasing and the ions can penetrate deeper and deeper into the target.

Already at about 350 ns from the beginning of the irradiation, the first ions are able to escape from the back surface of the target due to the reduction in target density. However, the temperature in the interaction region is still growing and the radial density wave, while moving outward from the axis, leaves behind it a wider and wider channel of liquid material. After about 500 ns, one can see (Fig. 4) that the temperature and density of the target material are sufficient for the second phase transition to take place inside the target: Liquid Ne is evaporating and a "gas bubble" is formed inside the liquid material. Due to the further heating and decrease in density, the region of evaporated target matter is expanding in the axial and radial directions. At about 700–800 ns, this region, developing from inside of the target, joins the gas jets of expanding target matter emerging from the front and back surfaces of the target. Finally, at about 900 ns from the beginning of the beam pulse a low-density channel of the gaseous Ne is formed around the beam axis. This channel is surrounded by a layer of liquid material, which, in turn, is confined by a radially expanding wave of the compressed target matter at super-solid density.

The ELD dependence obtained from this simulation is shown in Figure 2 along with the corresponding experimental data. The dashed "confidential corridor" of the calculated ELD is a compilation of many individual simulations, performed with different initial parameters. These parameters, such as initial beam energy on the target and focal spot size, have been varied within the measurement accuracy limits. In spite of a relatively large uncertainty of the simulations due to low precision in measuring the initial interaction parameters and a systematic discrepancy between the calculated ELD curve and the measured data, one can see that in this case the results of the sophisticated two-dimensional simulations are in a good quantitative agreement (below 10%) with the experimental ELD data.

The results of similar simulations and the ELD data, measured in the corresponding experiment with an intense ^{40}Ar beam and solid Xe target, are shown in Figure 3. In this case, the enlargement of the "error bar" of the simulations toward the end of the irradiation time is caused by inaccuracy in the beam focal spot size measurements. Although there is a visible deviation in the measured ELD dependency compared to the calculated curve, one has to admit that the experimental ELD data is well represented by the corresponding hydrodynamic simulations.

The observed systematic discrepancy in the shape of the ELD curve can be caused by a limited accuracy of the EOS values for the RGS materials in both cases. Further theoretical and numerical investigations on this problem will be carried out and a more detailed paper on this subject will be published later.

5. CONCLUSIONS

Intense heavy ion beams can be used to generate high-energy-density states in matter by impact on solid targets. Measurement of the energy loss dynamics of the beam emerging from the back surface of the target during the interaction process provides information about the physical state of the interior of the target. We believe that the ELD measurement technique is an excellent diagnostic method for HED matter. It specifically allows for direct and quantitative comparison with the results of hydrodynamic simulations, providing experimental data for verification of computer codes and underlying theoretical models.

For the first time, the energy loss dynamics of highly energetic intense heavy ion beams penetrating through rare-gas solid targets was observed experimentally. The energy of the projectiles escaping the target was measured during the ion-beam-induced heating of the target matter with time resolution. For this purpose, a new time resolving energy loss spectrometer has been set up.

The sophisticated numerical simulations of the observed phenomena have been performed. The results of the simu-

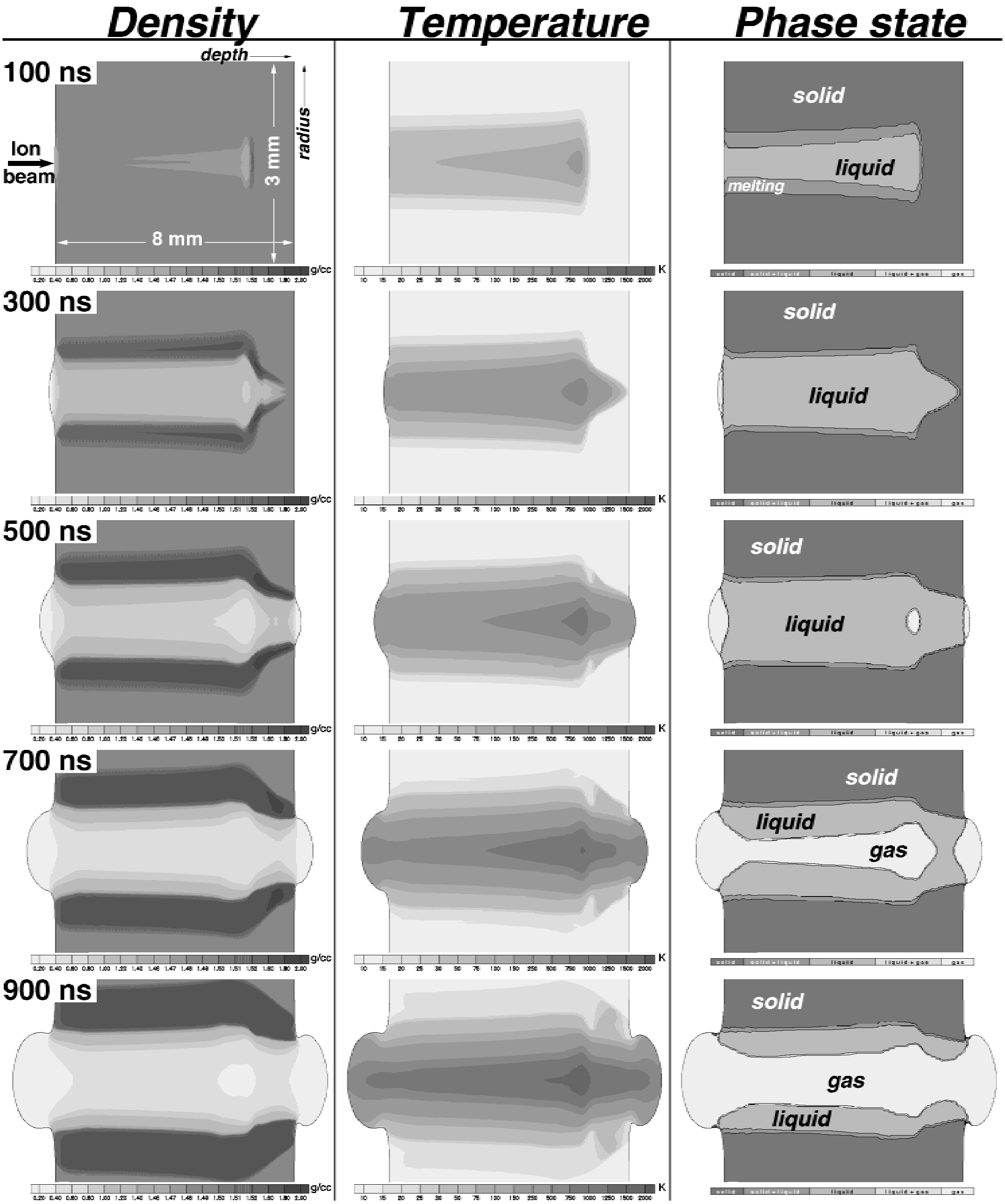

Fig. 4. Hydrodynamic simulations for a performed experiment: ^{238}U beam interacting with solid Ne target. Two-dimensional (radius–depth) fields of target density, temperature, and physical phase state are shown at different time moments during the irradiation. The simulations were performed using the BIG2 code and ChTEOS equation of state model. The false-color grayscale pallete shows the target density $\rho \in [0.2–2.0]$ g/cm^3 and temperature $T \in [10–2000]$ K.

lations are in good agreement with measurements. A more detailed study on the interaction processes between intense heavy ion beams and cryo-targets will be carried out, including the influence of the EOS model for the target material on the ELD values.

The ELD measurements will be used at the GSI–Darmstadt as a standard diagnostics in the future experiments on investigation of the HED matter induced by intense heavy ion beams, such as the HI-HEX (Heavy Ion Heating and EXpansion) EOS studies (Hoffmann *et al.*, 2002).

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