# OVERVIEW OF WARM-DENSE-MATTER EXPERIMENTS WITH INTENSE HEAVY ION BEAMS AT GSI-DARMSTADT*

P.A. Ni†, F.M. Bieniosek, M. Leitner, B.G. Logan, R.M. More, P.K. Roy, LBNL, Berkeley, CA, USA
D.H.H. Hoffmann‡, D. Fernengel, A. Hug, J. Menzel, S. Udrea, TU-Darmstadt, Germany
N.A. Tahir, D. Varentsov, H. Wahl, GSI-Darmstadt, Germany
M. Kulish, D.N. Nikolaev, V.Ya. Ternovoi, IPCP-Chernogolovka, Russia
A. Fertman, A.A. Golubev, B.Yu. Sharkov, V. Turtikov, ITEP-Moscow, Russia
J.J. Barnard, LLNL, Livermore, CA, USA

This paper presents an overview of the warm-dense-matter physics experiments with intense heavy ion beams that has been carried out at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany. These experiments are a joint effort of GSI-Darmstadt, TU-Darmstadt, ITEP-Moscow, IPCP-Chernogolvka and LBNL-Berkeley.

GSI-Darmstadt has a long tradition of accelerating intense beams of energetic heavy ions. The existing GSI accelerator facility consists of the universal linear accelerator, UNILAC, the heavy ion synchrotron, SIS-18 and the experimental cooler/storage ring ESR. The SIS-18 can accelerate stable nuclei of all elements in the periodic system (hydrogen to uranium) to more than 90% of the speed of light.

High-energy-density physics (HEDP) experiments with intense heavy ion beams are of considerable interest to both basic research in thermophysics, physics of dense plasmas or astrophysics as well as to applied studies, such as investigating the potential of ion beams as drivers for inertial fusion energy [1].

During the past few years, significant progress has been achieved in experimental investigation of heavy ion beam generated warm dense matter (WDM) [2, 3]. The main goals of the WDM experiments performed at the HHT area of GSI were commissioning of recently developed diagnostic instruments, methods and testing of different beam-target configurations for EOS studies; optimization of transport, focusing and diagnostics of intense heavy ion beams; obtaining new data on thermophysical properties and hydrodynamic response of various materials in HED states near boiling curve, two-phase liquid-gas and the critical point regions.

In the performed experiments, electron-cooled beam of $^{238}U^{73+}$ ions with initial ion energy of 350 AMeV has been used. The intense, up to $2.5 \cdot 10^9$ ions/bunch, ion pulses have been compressed to 110 ns (FWHM) and focused at the target to a spot down to $150\ \mu m$ diameter. The beam intensity and the pulse shape have been measured by current transformers installed in front of the target chamber whereas the upper limit for the focal spot size has been determined by recording beam-induced emission of argon gas at ionic spectral lines [4].

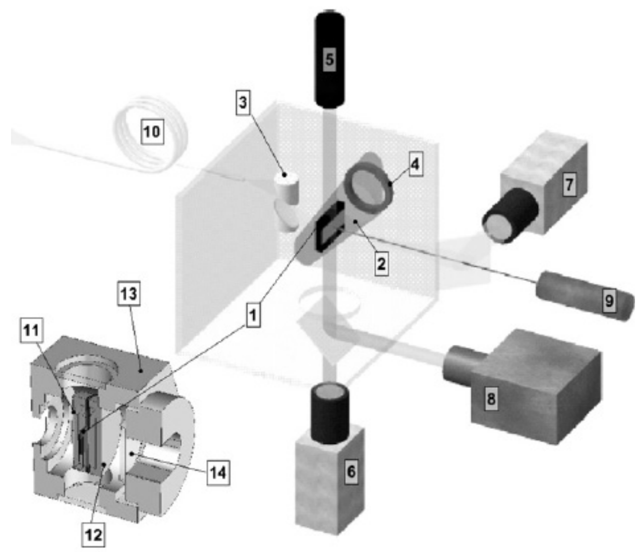


Figure 1: Scheme of the WDM diagnostic instruments and the plain- HIHEX target design at HHT: 1 — sample foil; 2 — ion beam with elliptic focal spot; 3 — pyrometer/spectrometer light collection system; 4 — beam current transformers; 5 — backlighting laser; 6,7 — fast intensified CCD cameras (beam/target optical diagnostics and alignment); 8 — streak camera (target expansion shadowgraphy); 9 — displacement interferometer or VISAR systems (velocity and pressure measurements); 10 — quartz fiber lines to pyrometer and streak-spectrometer (target temperature, spectroscopy); 11 — (gold-coated) sapphire plates; 12 — collimator; 13 — brass container; 14 — outer sapphire windows.

In the currently employed plane-HIHEX beam-target configuration (see Fig. 1), solid or porous sample foil is placed along an elliptically shaped ion beam, at the origin. On either side of the foil, two sapphire plates are located at variable distances parallel to the foil surface, limiting the

* The work was supported by GSI-INTAS (03-54-4254), ISTC (2107), PRAS (09-2006), BMBF and performed under the auspices of the U.S. Dept. of Energy by LBNL, LLNL, and PPPL under Contracts No. W-7405-Eng-48, DE-AC02-05CH11231, and DE-AC02-76CH3073.
† pani@lbl.gov
‡ hoffmann@physik.tu-darmstadt.de

target expansion and defining the final volume. In order to avoid undesirable direct irradiation of the sapphire plates, a thick tungsten or tantalum collimator is installed in front of the sample. The entire assembly is placed inside a solid brass container with additional sapphire windows at each of the four faces (see Fig. 1). This HIHEX target design allows one to study one-dimensional quasi-isentropic expansion of uniformly heated target material into a buffer gas or vacuum. In particular, HED properties of lead, tin, copper, aluminum, tungsten, tantalum, sapphire, uranium dioxide, porous gold and porous copper have been studied using this design concept (see Fig. 1).

A motorized achromatic 1:1 imaging system built out of two off-axis parabolic mirrors collects the light emitted by beam-heated target and transmits it to a fast radiation pyrometer via 400 mm quartz fiber lines. Using this advanced light collection system and an improved fast 12-channel pyrometer, the color temperatures in the range 1000 K - 16000 K during direct ion-beam heating of tungsten targets have been recorded [5]. The pyrometer allows measurement of brightness temperatures at 12 wavelengths with a nanosecond temporal resolution and the micrometer spatial resolution. The absolute radiation emission recorded by the pyrometer at different wavelengths also allows determination of the physical temperature using different models of spectral emissivity [5]. An example of a pyrometric record is shown at Fig. 2.

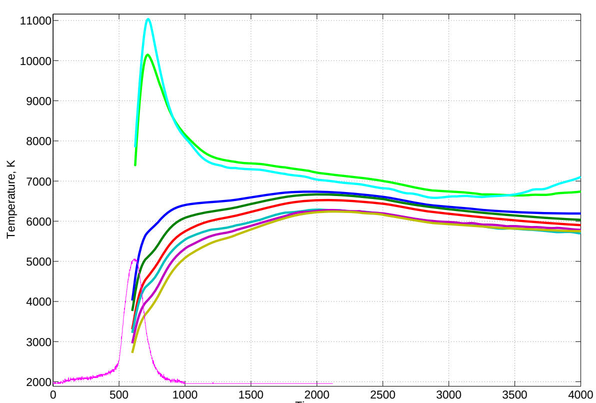


Figure 2: Temperature record of ion beam-heated tungsten foil. Blue, dark green, red, light blue, magenta, brown – brightness temperatures at 550 nm, 750 nm, 900 nm, 1100 nm, 1300 nm and 1500 nm respectively; green and cyan — fitted temperatures with grey and linear law of emissivity respectively [5]; light magenta — temporal profile of heating beam in arb. units.

Porous targets have the advantage that the ion beam range is longer than in a solid-density target, thus slowing down the hydrodynamic expansion time of the heated target. A matter of particular interest is the isotropization of the pore walls as they are heated by the beam, which is expected to scale with the pore size. For example, target dynamics may be affected if the hydrodynamic expansion time to fill in the cells is longer than the beam pulse length.

A series of experiments with porous samples has been carried out in close GSI-LBNL collaboration (Fig. 3). The experiment studied the effect of pore size on target behavior using existing diagnostics, for example by measuring the target temperature as a function of pore size and compare with model predictions of the physics of porous targets. The analysis of experimental results and hydrodynamic simulations are underway.

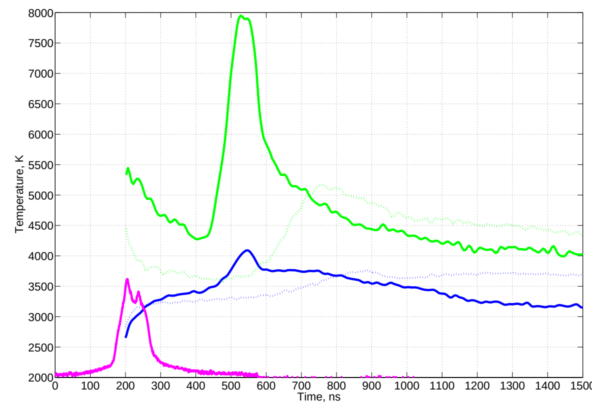


Figure 3: Pyrometer record comparison of solid (solid lines) and porous (dashed) gold foils. In this experiment porous sample has 35% of solid density. Blue — brightness temperatures at 900 nm, green — fitted "grey" temperatures [5], magenta — temporal profile of heating beam in arb. units. In the graph, first peaks are due to heating with beam followed by the decrease in temperature due cooling expansion and second peak is caused by impact of the expanded matter against sapphire windows (see Fig. 1).

The target expansion velocity is measured using a backlighting system consisting of a powerful laser or xenon flash lamp, interference filters and an electronic streak camera. The expansion velocities over 2 km/s have been detected for the lead foil targets (Fig. 4).

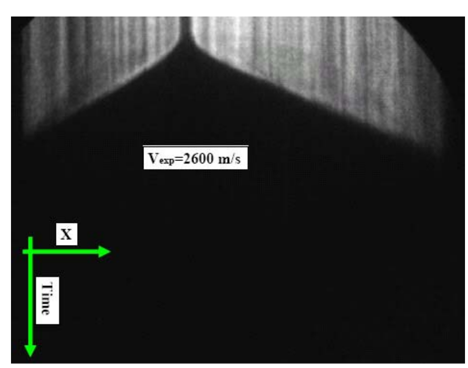


Figure 4: Expansion of a lead foil recorded by streak camera. Foil expansion rate estimated from the slope in this record is 2600 m/s.



 

Target pressure is determined at the moment of impact by measuring the displacement history of the gold-coated outer surface of the sapphire plate (see Fig. 5). For this purpose, two displacement interferometers of different types have been designed and successfully used in the experiments [6]. In addition to the interferometer, a Doppler-shift laser interferometer is being incorporated to the experiments right away [7].

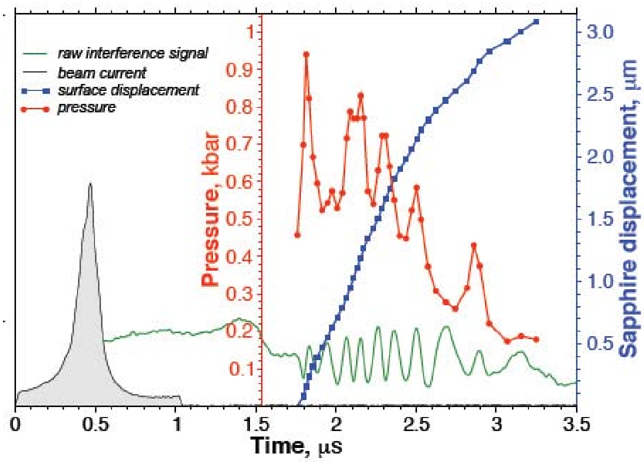


Figure 5: Typical recorded of displacement interferometer in experiment with lead target. Dotted curve is the beam intensity signal from fast current transformer and the dashed line is raw interferometer signal. The interference fringes first appear at the moment when the beam-heated, expanding target material impacts on the sapphire plate and its back surface gets in motion. Blue curve show history of sapphire surface displacement obtained by counting of interference fringe positions. At time when elastic disturbance reaches back surface of sapphire, velocity of sapphire surface is proportional to the pressure profile at the leadsapphire interface. The characteristic periodic structure later visible on the pressure signal is due to the reverberation of the induced sound waves between two surfaces of the sapphire plate.

Transient darkening has been observed in initially transparent materials such as quartz when rapidly heated to high temperature (WDM) by a laser [8] and in a cold quartz fiber irradiated by an intense electron beam pulse [9]. A simple model describes the transient response of the material that should be applicable to both WDM and irradiation by a charged particle beam [10].

A series of experiments dedicated to transient darkening of sapphire has been carried out at GSI [5]. In these experiments the ion beam impacts a sapphire plate ar room temperature, and transient effects on optical transmission, optical emission and electrical conductivity are observed.

Results indicate a distinct effect of the ion beam on the optical transmission in a sapphire sample. In case shown at (Fig. 6), the ion beam has caused temporal reduction in transparency but the sample itself remained undamaged. It is seen that during the interaction, the sapphire looses its transmission qualities at 550 nm, 750 nm and 900 nm while no changes at longer wavelengths (not shown in figure) were observed. After approximately 6 $\mu s$ the transmission gradually returns to its initial state.

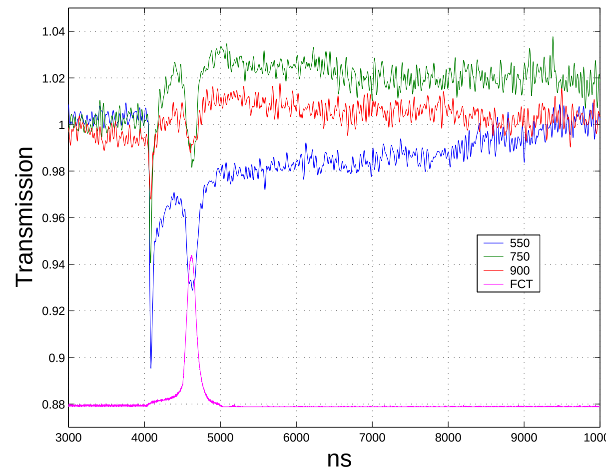


Figure 6: Transmission of the sapphire sample at various wavelengths during ion beam irradiation. Blue — transmission at 550 nm, red — 750 nm, green — 900 nm, magenta — temporal profile of heating beam in arb. units.

To summarize, it was shown that using intense heavy ion beam that is presently available at GSI and employing the HIHEX beam-target design concept, it is possible to investigate basic thermodynamic and transport properties of HED metal states in the two-phase liquidgas region and near the critical point.

## REFERENCES

[1] W.F. Henning, Nucl. Instr. and Meth. B 214 (2004) 211.

[2] D.H.H. Hoffmann, A. Blazevic, P. Ni, O. Rosmej, M. Roth, N.A. Tahir, A. Tauschwitz, S. Udrea, D. Varentsov, K. Weyrich, Y. Maron, Laser Part. Beams 23 (2005) 47.

[3] N.A. Tahir, et.al., Nucl. Instr. Meth. A544, (2005)16-26.

[4] F. Becker, A. Hug, P. Forck, M. Kulish, P. Ni, S. Udrea and D. Varentsov, Laser and Particle Beams, Volume 24, Issue 04, pp 541-551.

[5] P. Ni, PhD thesis, TU-Darsmatdt (2006), http://elib.tu-darmstadt.de/diss/000720/

[6] M. Kulish, et al., Displacement interferometer technique for plasma pressure diagnostic, in: GSI Report High Energy Density in Matter Produced by Heavy Ion Beams, no. GSI-2006-02, GSI-Darmstadt, 2006, p. 12.

[7] J. Menzel, Master thesis, TU-Darsmatdt (2006).

[8] D.F. Price, et.al., Phys. Rev. Lett. 75 (1995) 252.

[9] P. Lyons, Fiber optics in transient radiation fields, SPIE, vol. 541; Radiation Effects in Optical Measurements, 1985, pp. 89-95.

[10] F.M. Bieniosek, et. al. Nucl. Instrum. Methods Phys. Res. A544 (2005) 268-276.