Report on December 2003 Beamtime Experiment at HHT: Near-Critical HED States of Lead Generated by Intense Uranium Beam

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This paper presents a preliminary report on a recent beamtime experiment on investigation of heavy-ion-beam generated high-energy-density (HED) matter. The experiment has been performed at the HHT experimental area of GSI on 11–17.12.2003.

Goals of the experiment. Main goals of this experiment were commissioning of a new multi-channel pyrometer for temporally resolved temperature measurements, improvement of transport, final focusing and diagnostics of full-intensity uranium beams and experimental test of a novel target design as well as of a few ideas on target diagnostics. Eventually, the experiment could also provide new data on thermodynamic properties and hydrodynamic response of lead in HED states. Since lead is one of the few metals which HED states near the critical point have been previously investigated in shock wave experiments [1, 2], it has been taken as a target material in order to validate the usefulness of the HIHEX method [3] for HED research and to benchmark the obtained experimental data.

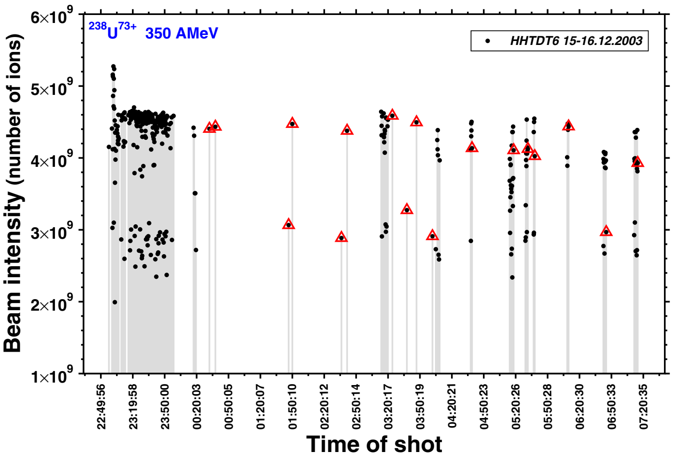

Figure 1: Shot-to-shot record of the beam intensity delivered to the HHT target area. Triangle marks indicate successful shots on the targets.

Ion beam and accelerator performance. In the experiment, intense beams of $^{238}\mathbf{U}^{73+}$ ions with initial energy of 350 AMeV have been used. The GSI accelerator facility has demonstrated excellent performance: the beam intensity was more than $4 \cdot 10^9$ particles/bunch (Fig. 1), whereas the bunch has been compressed in time down to 125 ns (FWHM) (Fig. 2). Such a high intensity of uranium beam and short bunch length have never been previously achieved at GSI. The beam intensity and the temporal shape of the beam pulse have been recorded for every shot by various current transformers installed at the HHT beamline as well as by a fast Rogowski coil in the target chamber.

In order to avoid beam loses, the settings of the beamline magnets have been carefully optimized. The transmission of the beam from SIS-18 extraction to the HHT target area was 100% to the precision of the measurements. Final focusing of the ion beam on the target has been done in absence of the plasma lens, using the beamline quadrupoles. The focal angle has been considerably enlarged by installing special "buterfly"-shaped vacuum chambers in the last two quadrupoles prior to the experiment. The optimization of the beamline transmission and final focusing has been done using the 3^{rd}-order ion-optical code GICO available at GSI. The results of these simulations are in excellent agreement with the measurements performed during the experiment. The distribution of the ion beam intensity at the target position and the focal spot size have been measured by recording beam-induced scintillation of argon gas. The target chamber was filled with argon at pressures 10–900 mbar and the scintillation images have been recorded by high-resolution amplified CCD cameras (DICAM-PRO, PCO) installed in two perpendicular planes. These cameras have also been used for precision beam-target alignment. The measured focal spot FWHM size was 0.85 mm (horizontal) × 1.6 mm (vertical), in accordance to the simulations. Such an elliptical shape and the spot size have been specially chosen in order to match the target geometry.

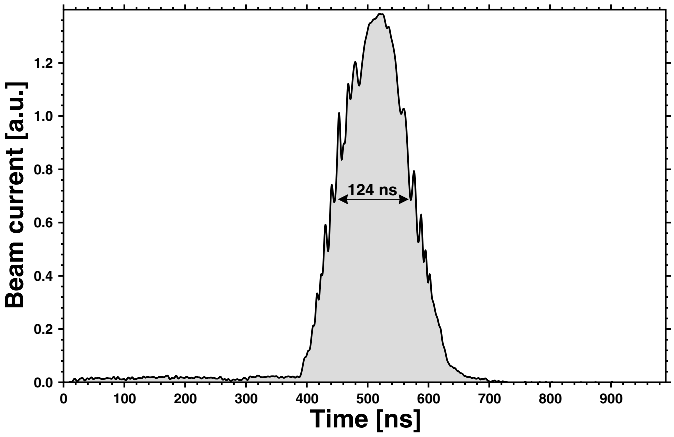

Figure 2: Time profile of the ion bunch after optimized bunch compression.

Target design and experimental scheme. A thin ($250\,\mu m$) foil of the target material is placed vertically along the ion beam, at the origin. The thickness of the foil is much smaller than the horizontal beam spot size, while the vertical beam extension is large. This target geometry therefore provides homogeneous volume heating of the sample and plane quasi-1D character of the hydrodynamic expansion of the heated target matter. Two sapphire plates are located parallel to the foil from both sides at certain distances, limiting the expansion and defining the final volume. In order to avoid undesirable direct heating of the regions close to the foil and the sapphire plates by the beam, a thick slit diaphragm made of tungsten is installed in front of the foil. The whole target assembly is placed in a solid copper casing with additional sapphire windows at the faces. Besides protecting the target chamber and equipment from deposition of activated vapor of the target material after irradiation, this solid copper casing can serve as a sealed-off high pressure vessel. Therefore this target construction allows one to study quasi-isentropic expansion of target material into a buffer gas (e.g. — helium at different pressures) or vacuum.

Light emitted by the target in a certain area located far enough from the Bragg peak has been registered. This ensures the uniformity of the parameters and 1D character of the hydrodynamic response over the registration region. On one side of the target foil, the emitted light is observed by two electronic streak cameras. One streak camera has the entrance slit aligned along the beam axis and another one perpendicular to the beam axis. This allows the check of the uniformity of the target physical state in two planes. On the other side of the target, the light emitted in VIS/NIR wavelength region has been guided into 400 μm quartz fibers using a 1:1 imaging system. The position of the observation region on the target can be adjusted by moving the fiber with three step motors. On the other end, these fibers were connected to a fast 6-channel pyrometer for time-resolved temperature measurement and optionally, to a small fiber optic spectrometer (USB2000, Ocean Optics Inc.) for recording time-integrated spectra.

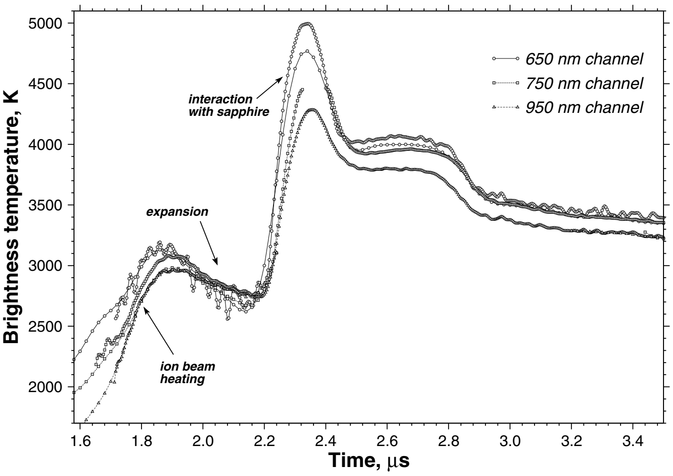

Figure 3: Part of a typical pyrometer record: a lead target heated by ^{238}**U** beam, $4.44 \cdot 10^9$ ions/bunch.

Fast radiation pyrometer. In the performed experiment the key diagnostic instrument was a fast multichannel radiation pyrometer. This novel device recently developed by IPCP-Chernogolovka and GSI-Darmstadt allows one to record the evolution of target temperature with ns time resolution. The pyrometer analyzes the target radiation in the 500–1500 nm wavelength region, given by available interference filters and sensitivity of the photodetectors. There are no beam splitters used in the construction of the device but a filter itself acts as a mirror reflecting the radiation outside its transmission window toward the following channels for further wavelength filtering. This solution, together with a high amplification of the photodetectors, dramatically increases the sensitivity of the instrument. In fact, it was possible to trace the evolution of target temperature down to the level of about 800 K. The maximum brightness temperature measured in this experiment was about 5000 K. Other characteristics of the pyrometer are a high dynamic rage ($> 10^3$) provided by low-noise wide-band amplifiers and a modular design. At the moment the pyrometer has six channels and each channel provides two signals at different amplification levels simultaneously. The modular design of the device allows easy exchange of the filters and upgrade for additional channels. The absolute calibration of each channel has been done with a laboratory tungsten ribbon lamp (OSRAM Wi17/G) before the experiment. A typical pyrometer record for one of the experimental shots is shown in Fig. 3.

Summary and outlook. As a result of the beamtime experiment, it has been demonstrated that the fast multichannel radiation pyrometer is an indispensable diagnostic tool for HED studies with intense heavy ion beams. The data on temperature evolution of near-critical HED states of lead during ion-beam heating and quasi-isentropic expansion will be presented as soon as all the results are fully analyzed. It is also planned to compare this experimental data with 3D hydrodynamic simulations taking into account radiation transport phenomena. The usefulness of the quadrupole system for the final focusing of large-emittance uranium beam has been proved experimentally. Using the quadrupoles provides the focal spot size sufficient for such experiments while giving a full control over the beam shape and position, which is necessary in order to match a target design. The problem of vacuum windows damaging by intense beams, typical for a plasma lens focusing, can also be avoided.

The test of novel ideas employed in the "plane-HIHEX" target design has shown its great potential for future HED experiments. The precision of target positioning and alignment will be enhanced after constructing and installing a new six-axis target manipulator. The signal-to-noise ratio and quality of the pyrometric signals will be improved by using a better input optical system which will allow collecting the target radiation over a larger solid angle. However, in order to obtain the complete information on the thermodynamic state of the target, evolving of additional advanced diagnostic methods is still necessary. Therefore the development of an interferometric (VISAR) technique for pressure measurement as well as involvement of backlighting and shadowgraphy for recording the target density evolution is planned for future experiments. After validating the experimental design and diagnostic methods with test target materials such as lead, the ion-beam generated HED states in other materials of interest including copper, gold and uranium dioxide will be studied.

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