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Electrical resistivity measurements of heavy ion beam generated high energy density aluminium

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Abstract

The high intensity heavy ion beams provided by the accelerator facilities of the Gesellschaft für Schwerionenforschung (GSI) Darmstadt are an excellent tool to produce large volumes of high energy density (HED) matter. Thermophysical and transport properties of HED matter states are of interest for fundamental as well as for applied research. In this paper we present the most recent results on electrical resistivity of HED matter obtained at the High Temperature Laboratory of the Plasma Physics Department of GSI. The targets under investigation consisted of 5 mm long and 0.25 mm diameter aluminium wires. Uranium beam pulses with durations of approximately 200 ns, intensities of about 2×10^9 ions/bunch and an initial ion energy of 350 A MeV have been used as a driver. An energy density deposition of about 1 kJ g^{-1} has been achieved by focussing the ion beam to less than 1 mm FWHM. Under these conditions, resistivities of up to 1.5×10^{-6} Ω m have been observed within 1 μs after irradiation.

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1. Introduction

High intensity heavy ion beams are an excellent tool to produce large volumes of high energy density (HED) matter [1–3]. Presently, the accelerator facilities of the Gesellschaft für Schwerionenforschung (GSI) Darmstadt can provide uranium beams with intensities up to 5×10^9 ions/bunch and durations down to 125 ns FWHM. Focussing such beams to less than 1 mm FWHM provides an energy density deposition of more than 1 kJ g^{-1} in solid samples

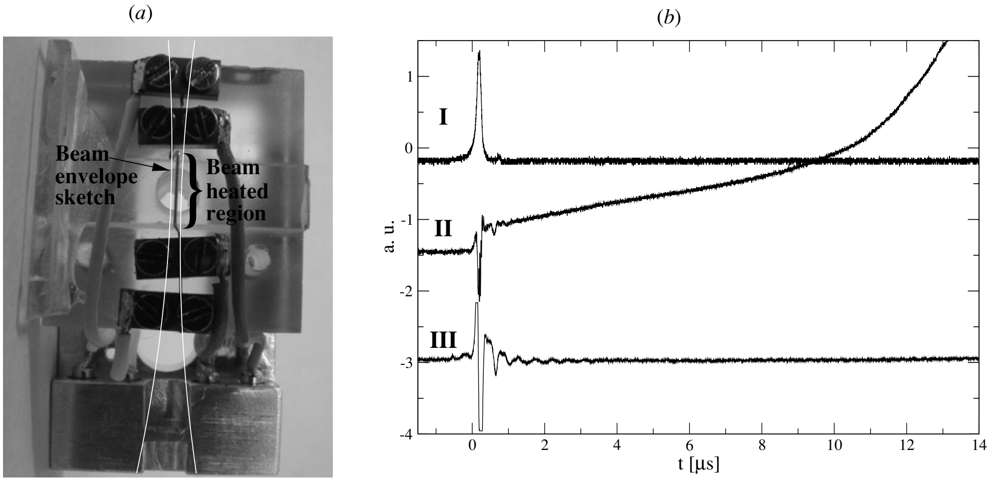

Figure 1. (*a*) The target assembly. (*b*) Typical experimental signals: I—ion beam pulse, II—voltage across the target, III—voltage across the shunt for the measurement of the probe current.

with volumes of the order of 1 mm^3. The investigation of the thermophysical and transport properties of the HED states reached by these samples due to heavy ion beam irradiation is the main goal of the experiments performed at the High Temperature (HHT) Laboratory of the Plasma Physics Department of GSI.

During the last few years a first series of measurements of the electrical resistivity of heavy ion beam generated HED matter has been performed using a two-point difference technique specially developed to comply with the experimental infrastructure at the HHT laboratory [4]. Recently, improvements of the infrastructure at HHT allowed for first measurements using the more precise four-point technique [5]. The results of these experiments are presented in this paper.

2. Experimental setup

The experimental setup has the following main components:

- target assembly;
- pulsed current source to generate the probe current;
- data aquisition system to measure the probe current and voltage at the target;
- streak camera to monitor the expansion of the target due to ion beam heating;
- alignment system to ensure precise positioning of the target within the beam;
- final beam focussing system consisting of three dc quadrupoles.

The target consists of a 0.25 mm diameter and about 25 mm long aluminium wire fixed on an insulating support by four copper plates which provide also for electrical contacts (figure 1). The insulating wire support is mounted on a special table which is designed to comply with the target manipulation system. The wire is bent to take a flat top shape. Just the upper horizontal part of the wire, with a length of 5 mm, is exposed to the beam. This part is oriented along the beam axis and is embedded into the beam during irradiation. Due to this, and to the fact that 5 mm is approximately 60% of the range of the beam ions in aluminium, as estimated with the computer code SRIM [6], a homogeneous energy density deposition—no more than 5% variation over the irradiated length of the wire—is achieved.

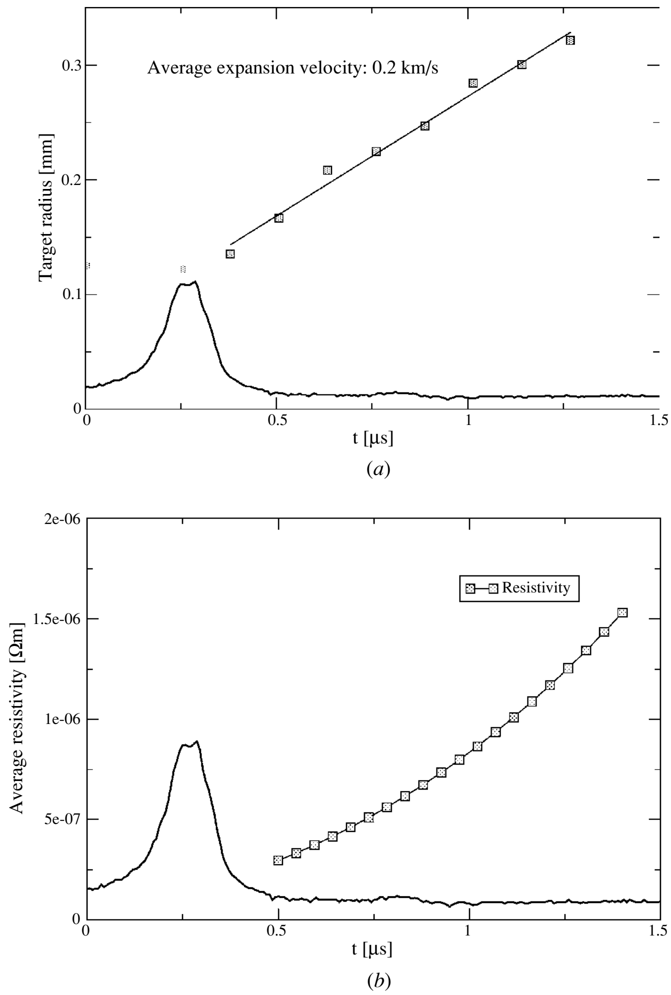

Figure 2. (*a*) Target radius versus time as obtained from streak images. (*b*) Resistivity versus time. In both figures the beam signal is shown for reference.

The pulsed current generator is able to deliver about 10 A to the target. It consists of a 15 μF storage capacitor loaded to approximately 50 V. An IGBT transistor switch allows for the controlled discharge of the capacitor through a current limiting resistor and the target wire. The discharge current has been measured with a 0.1 Ω shunt mounted close to the target assembly on the target manipulator.

Measurements to determine the voltage drop across the target and the shunt were performed using a remotely controlled Tektronix TDS oscilloscope. The connection to the target assembly was provided through 3 m long 50 Ω coaxial cables. The data aquired by the oscilloscope were stored in real time on the controlling computer.

A computer controlled Hamamatsu streak camera with a full picture streak time set to 1.3 μs and a diode laser backlighter have been employed to monitor the target dynamics due to heavy ion beam heating. The 18 ns time resolution of this system was defined by the width of the camera slit and the resolution of the CCD detector.

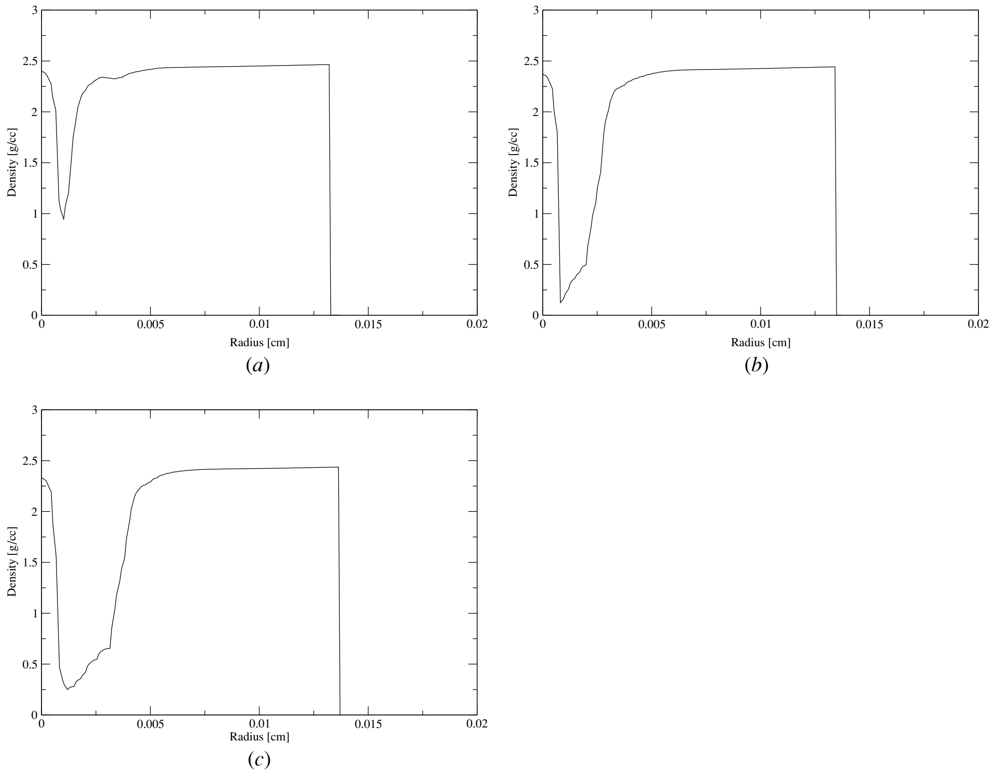

Figure 3. Simulated radial distribution of the target density just after beam heating (*a*) 100 ns, (*b*) 200 ns and (*c*) later. The development of a low density region close to the axis of the target can be observed.

The uranium ion beams delivered by the GSI accelerator facilities for these experiments had an intensity of 2×10^9 ions/pulse, a pulse duration of approximately 200 ns FWHM and an initial ion energy of 350 A MeV. This beams have been focussed down to a focal spot of less than 1 mm FWHM leading to deposited energy densities of about 1 kJ g^{-1}. Because the target wire and the beam have to be aligned precisely along the same axis, their position has been monitored by two CCD cameras looking perpendicular to this axis from two orthogonal directions. Gas scintillation has been used to visualize the beam.

3. Results and discussion

The experimental voltage signals show a common time evolution pattern: a fast increase during the heavy ion pulse is followed by a slow increase—subsequently called plateau—and finally again a strong increase accompanying the breakdown of the wire. This pattern is consistent with results previously obtained by the two-point difference method at similar levels of energy deposition. Typical experimental signals are shown in figure 1. The distortions induced by the ion beam, clearly visible in these signals, prohibited the estimation of the resistance of the target during irradiation. It is one of the main goals of future developments to reduce this influence on the experimental signals.

The expansion of the wires reaches a practically constant velocity of about 0.2 km s^{-1} shortly before the end of the irradiation. This, coupled with the observed linear increase of the voltage signal measured across the target at a constant current value, leads to a t^3 increase of the average resistivity over the first 900 ns of the plateau (figure 2). The values of the resistivity vary during this time interval from $3 \times 10^{-7}\ \Omega$ m to $1.5 \times 10^{-6}\ \Omega$ m. The uncertainty of these values is about 30% and is mostly given by uncertainties in the measurement of the target diameter.

Simple estimations based on the deposited energy density suggest that the target is driven into liquid metal states. Nevertheless, the observed resistivity values are larger than those of liquid aluminium [7]. Thus a better insight into the target evolution is needed. This can be presently obtained just through computer simulations, which have been performed with the BIG2 2D-hydrodynamic code [8]. The results of these simulations suggest that the bulk of the target has an expansion velocity which is much smaller than the measured one and that due to expansion cooling the target interior becomes inhomogeneous, with a very low density region building up close to the target axis (figure 2). Such a situation may indeed lead to an increased apparent resistivity of the irradiated sample. Nevertheless, further investigations are necessary to fully understand the experimental observations.

4. Conclusions

The work presented in this paper provided the first results on the electrical resistivity of HED aluminium generated by intense heavy ion beams. The performed experiments also indicated which future improvements are needed for more precise measurements of this fundamental property of matter. Correlated with detailed diagnostics of the physical state and structure of the investigated samples, such measurements will provide for a better understanding of the HED states which will be achievable for the first time under laboratory conditions at the future facility for antiproton and ion research (FAIR) of GSI [1, 2].

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