GSI-Preprint-95-77
NOVEMBER 1995

CONTRIBUTIONS TO THE
**INTERNATIONAL SYMPOSIUM
ON
HEAVY ION INERTIAL FUSION**

PRINCETON, SEPT. 6 - 9, 1995

(To be published in: Journal of Fusion Engineering Design)

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Heavy Ion Beam Induced Motion in Rare Gas Cryo Targets

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Abstract

At GSI-Darmstadt the first hydrodynamic motion of a heavy ion beam volume heated target could be demonstrated. Therefore Krypton and Xenon cryogenic crystal were irradiated by an intense 300 MeV/u Ne¹⁰⁺-beam. The beam was focused onto the crystals with a minimum beam waist of 1.12 mm × 1.42 mm FWHM. A specific energy of 60 J/g was deposited, leading to hydrodynamic motion and the creation of shockwaves in the target and finally to a total destruction of the target. The escape velocity of the gas streaming out of the heated volume was estimated to 200 m/s. In addition spectra in the vacuum ultraviolet region could be obtained showing the 172 nm Xenon emission band.

1 Introduction

In the inertial confinement fusion scenario with a heavy ion beam driver (HIF), the understanding of the interaction processes of heavy ions with solid material is an important issue. Experimental studies of the target heating processes, the energy deposition profiles, the hydrodynamic response of the target, the cooling mechanisms in the target and the conversion efficiency of the beam energy into thermal radiation are needed to confirm the theoretical estimations used in the design for a HIF test facility (Badger[1, 2]). At the high temperature experimental area, put in operation 1991 at the SIS-accelerator of GSI-Darmstadt (Laux[3]), the production and diagnostic of heavy ion beam driven plasmas in solid material is planned. Relativistic heavy ions, with ranges up to of several centimeters in solids, are an unique tool to heat a macroscopic volume of the target. These plasmas will ultimately have temperatures of a few electron volts and almost solid state density. So it will be possible to determine the equation of state of the target materials in the specified parameter range. In addition hydrodynamical codes could be tested by comparing the calculated results with the experimental observed hydrodynamic motion of the targets.

Up to now the number of experiments concerning heavy ion beam induced plasmas is small. Experiments heating the surface of a solid target have been performed at the GSI MAXILAC-RFQ accelerator (Jacoby[9], and Marth-Olt[8]).

targetmaterial	binding energy [eV/atom]	binding energy [J/g]
Pb	2.03	950
Au	3.81	1870
Kr	0.123	142
Xe	0.172	127

Table 1: Binding energies of some target materials.

One key parameter of these experiments is the specific deposited energy in the center of the heated volume. In general the transversal intensity distribution of the beam is an elliptical gaussian distribution. Thus the maximum specific, deposited energy in the center of the heated volume is given by

$$E_S = \frac{dE}{dx} \cdot \frac{N}{2\pi\sigma_x\sigma_y}, \quad (1)$$

where dE/dx is the energy loss, N the total number of particles, σ_x the standard deviation of the transversal intensity distribution in horizontal direction, and σ_y the standard deviation in vertical direction. As the energy loss of the ions is almost constant at energies of typically 200...300 MeV/u, the energy is deposited uniformly along the heated volume as long as the end of the ion range is not reached. Then the energy loss increases rapidly. The equation shows that a high particle number N together with a narrow transversal intensity distribution is needed. Until now the highest available particle number at the target is $2 \cdot 10^{10}$ Ne^{10+} -ions resulting in a energy deposition of ca. 120 J/g in lead. Table 1 shows the binding energies for some possible target materials. For a complete evaporation of the heated volume the deposited specific energy must surpass the binding energy. With the presently achieved spot radii and beam intensities only rare gas crystals are suitable targets.

2 Experimental setup

2.1 Beamline and beam diagnostics

The beamline of the HHT area at GSI consists of three dipole magnets, two quadrupole-dubletts and a quadrupole-triplett. The second part of the beamline is capable to transport a beam with a maximum rigidity of 6 Tm. The crucial part of the beamline is the fine focusing system. It consists of a quadrupole dublett, a 14.5 degree dipole magnet, and a specially designed quadrupole triplett doing the focusing onto the target. The system has been designed to produce focal spots with radii of $200 \mu\text{m}$ or less for a suggested beam emittance of $1.5 \pi \cdot \text{mm} \cdot \text{mrad}$ expected for the single turn injection mode of the SIS accelerator (Heimrich[4]).

Presently the SIS has to be operated in multi turn injection mode in order to get sufficiently high beam intensity. This operation causes an increase in emittance up to $40 \pi \cdot \text{mm} \cdot \text{mrad}$, resulting in an increased radius of the focal spot of $750 \mu\text{m}$.

For measuring the beam intensities and beam transmission current transformers are available. A fast current transformer is used to measure the time structure of the beam with a time resolution better than 1 ns. Two integrating current transformers (ICTs) are used for measuring the beam intensity and the transmission through the fine focusing system. With the ICTs the beam intensity can be determined with an accuracy of better than 2% (Laux[5]).

Figure 1: Typical beam current signal recorded by the fast current transformer.

Figure 1 shows the typical time structure of the beam extracted from SIS. The signal is recorded by the fast current transformer. The beam pulse consists of four bunches. The bunches have a width of 80 ns FWHM and are 270 ns apart from each other. The whole beam pulse has a duration of $1.1 \mu\text{s}$. The transverse intensity distribution of the beam is measured by an assembly consisting of a cer-doped quartz glass scintillator and a gated CCD-camera. The CCD-camera is viewing the scintillator with an angle of 45 degrees to the beam axis. The camera records the beam induced light emission of the $200 \mu\text{m}$ thin scintillator plate. With the measured intensity of the beam and the measured transverse intensity distribution it is possible to calculate the specific energy deposited in the target. This is an important input parameter for hydrodynamical calculations. The scintillator is placed at the distance of the focal plane of the fine focusing system to check the actual focal size.

2.2 Target preparation

The method for growing rare gas crystals is adopted from Nahme and Schwentner [7]. A plexiglass(PMMA) box (growing chamber) is pressed against a sample holder made of aluminum. The sample holder is cooled down to a temperature of 20 K by the use of a closed cycle, two stage refrigerator. Rare gas injected through a hole in the ceiling of the box condenses at a pressure of 300–400 mbar on the surface of the sample holder. After 15–20 minutes the crystal has reached a height of 5–7 mm depending on the used rare gas. The box is lifted up leaving a free standing, optically clear rare gas crystal. By varying the shape of the growing chamber crystals of different geometry could be obtained. For the described experiments two boxes are used: one with a square base of 10×10 mm, and another with rectangular base of 30×8 mm in order to stop the ion beam.

2.3 Target diagnostic setup

In figure 2 the diagnostic setup around the target crystal is shown. The sample holder and the crystals were placed inside an evacuated target chamber ($p \leq 10^{-3}$ mbar). A gated CCD-camera was used to observe the phenomena related to the self emission phase of the crystal. A high speed multi framing camera VFU-1 was used to examine the hydrodynamical processes in detail during and after the self emission phase of the target crystal. The camera operates mechanically with a rotating mirror [6]. The rotation speed of the mirror can be changed in discrete steps, so the interframe time could be varied. At the maximum rotation speed of 70000 rotations per minute the interframe time is $1.7 \mu\text{s}$. In one shot 60 pictures could be taken. A xenon flash lamp is used for backlighting to observe also the phases after the crystal self emission. A beam splitter was used to enable observation of the crystal with both cameras.

To examine the spectral distribution of the self emitted light in the vacuum ultra-violet (VUV) range, a monochromator was installed. The VUV-monochromator has 1 m focal length and f/10.4 entrance aperture. Time integrated spectra have been recorded in the range from 100 nm to 200 nm.

3 Experimental Results

The first hydrodynamic motion induced by an intense relativistic heavy ion beam could be demonstrated in an experiment in October 1994. Beams of 300 MeV/u Ne^{10+} -ions were focused onto a $850 \mu\text{m} \times 750 \mu\text{m}$ ($\pm 11\%$) focal spot size inside Krypton crystals. The maximum deposited specific energy during this experiment amounted to 60 ± 13 J/g (Dornik[10]). This still is about a factor of two below the binding energy of Krypton (see table 1). In the experiment scheduled in June 1995 the target diagnostics were widely expanded, so that more detailed information about the occurring processes inside the targets could be obtained.

Figure 2: Schematic setup of the experiment.

In the last experiment Krypton and Xenon was used for target preparation. The spot radii obtained had a minimum size of $1.12\text{ mm} \times 1.42\text{ mm}$ FWHM and the beam intensities were of the same order as in the previous experiment. Thus the specific deposited energies were approximately $20 \pm 5\text{ J/g}$ with a Ne^{10+} -beam. The beam energy was chosen to be 300 MeV/u for the first part of the experiment where the 10 mm crystals were examined. In a second step the energy was changed to 200 MeV/u . So it was possible to stop the beam inside the 30 mm rare gas crystals. This results in an inhomogeneous energy deposition profile at the end of the ion beam range. The situation is comparable to the scenario of a converter inside a fusion pellet where the beam is completely stopped.

The picture series obtained by means of the VFU-1 framing camera contain a large amount of information about the hydrodynamical motion of the target. Figure 3 shows 4 pictures extracted from a series of pictures showing a shot on a Krypton crystal. The first image exhibits the self emission phase of the crystal. The self emission begins with the beam penetrating the crystal and take a few microseconds. Then the Xenon flash lamp is used to visualize the following processes. So the next three pictures present a dark crystal in front of a bright

Figure 3: Pictures of a Krypton crystal after heavy ion beam penetration at different times.

background. On the second picture - $35.2\ \mu\text{s}$ later than the first picture - two gas jets could be seen on each side of the crystal. These jets are located on the points where the beam entered and escaped from the crystal. The velocity of the expanding gas was estimated under the suggestion that the expansion starts immediately after the beam penetration. The velocity determined by this way was estimated to $200 \pm 20\ \text{m/s}$, which is almost the sound velocity of Krypton at 250 K. The third picture shows the disintegration of the gas jet in the vacuum. Simultaneously the destruction of the whole crystal begins. Macroscopic crystal fragments are visible on the last pictures. The final result is the total destruction of the Krypton crystal. The destruction process is probably caused by shockwaves inside the crystal.

Figure 4: A 200 MeV/u beam was stopped in a Xenon crystal. The picture shows the beam induced emission along the beam path.

As mentioned above also experiments to stop the beam inside 30 mm Krypton and Xenon crystals are made. The beam energy was reduced to 200 MeV/u and the range of the Ne^{10+} -beam was calculated theoretically to 24.4 mm in Xenon and 27.2 mm in Krypton respectively, with the TRIM code developed by Ziegler and Biersack [11]. In figure 4 the light emission of the beam heated volume inside a Xenon crystal is shown. The beam entered the crystal from the left side and was completely stopped. The exposure was made with a integration time of $20\ \mu\text{s}$. The range determined from this picture is $25 \pm 1\ \text{mm}$. An increase of the beam waist and intensity of the emitted light could be seen at the end of the range related to the bragg peak. Here theorie predicts that the angular straggling and the energy loss of the beam is strongly enhanced.

A typical VUV-spectrum in the range from 160 nm to 185 nm emitted from a 30 mm Xenon crystal is shown in figure 5. The broad line has been identified

Figure 5: VUV-spectrum emitted from a 30 mm Xenon crystal.

as the vacuum ultraviolet emission band of Xenon centered at 172 nm at 15 K crystal temperature emitted by self trapped excitons (STE) (Schwentner[12]). The maximum of the observed emission band is located at 169 nm which could probably be explained with a higher lattice temperature of the target crystal of 27 ± 1 K. The origin of the small peak between 175 nm and 180 nm is unknown up to now.

4 Conclusions and Outlook

The presented experiments show for the first time the production of hydrodynamic motion in a heavy ion beam volume heated target. The existence of a plasma in the heated region could not be proved, because the maximum specific deposited energies were found to be a factor of two below the binding energies of Krypton and Xenon. Nevertheless parts of the heated material were evaporated and gas jets streaming into the vacuum could be seen. Finally the total destruction of the rare gas crystal by shockwaves was observed.

An increase of the specific energy deposition will lead to plasma conditions inside the heated volume. In the next experiments a plasma lens system will be available to improve focusing despite high beam emittance (Stetter [13]). A reduction of the focal spot size at least by a factor of two is expected leading to an increase of the specific energy deposition by a factor four. Exciting new results from these experiments are expected. A further improvement will be possible in the next few years by the installation of a high current injector at the

SIS-accelerator. Then SIS can operate in single turn mode with an small beam emittance. This will further improve the focusing to radii of $200\text{ }\mu\text{m}$ or below and the specified deposited energies by two orders of magnitude.

Acknowledgement

This work was supported in part by NATO Research Grant No.931324, by NATO Linkage Grant No.920584, and by the German Federal Ministry for Education and Research (BMBF) under Contract No. 06ER358.

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