International Journal of Thermophysics, Vol. 20, No. 4, 1999

Energy Deposition of Heavy Ions in Matter[1]

M. Geissel,[2-4] M. Roth,[2,3] R. Bock,[3] U. Funk,[2,3] D. H. H. Hoffmann,[2,3] U. Neuner,[3] W. Seelig,[2] S. Stöwe,[3] W. Süß,[2,3] and A. Tauschwitz[3]

The energy loss of heavy ions in matter is completely different from the case of laser beams. Whereas laser radiation produces a plasma on the surface of the target and heats the volume mostly by shock waves, heavy ions penetrate deep into the target with an almost-constant energy loss in the beginning and a very high energy loss at the end of the range, the so called "Bragg peak." This special behavior offers excellent possibilities for the examination of critical points of different materials, the measurement of benchmarks for equations of state, production and detection of X-rays and XUV radiation, investigations in physics of overdense plasma, and many more topics. In particular, heavy ion beams are considered to be a very efficient driver for an inertial confinement fusion power plant. Thus, research on the elementary processes of the energy deposition of heavy ions in matter with respect to inertial fusion energy is of primary interest.

KEY WORDS: heavy ions; high energy density; high-energy laser; intertial confinement fusion energy; plasma physics.

1. INTRODUCTION: INERTIAL CONFINEMENT FUSION

In contrast to the concept of magnetic confinement fusion, which deals with relatively low plasma densities and long confinement times, the concept of inertial confinement fusion deals with nanosecond time scales and up to a thousand times solid-state density. A plastic shielded deuterium–tritium target is illuminated by intense radiation, and the ablation of its surface layer produces a force toward the center of the target, which leads

---

[1] Paper presented at the Fifth International Workshop on Subsecond Thermophysics, June 16–19, 1998, Aix-en-Provence, France.

[2] Darmstadt University of Technology, D-64289 Darmstadt, Germany.

[3] Gesellschaft für Schwerionenforschung (GSI), Plasma Physics, Planckstr. 1, D-64291 Darmstadt, Germany.

[4] To whom correspondence should be addressed.

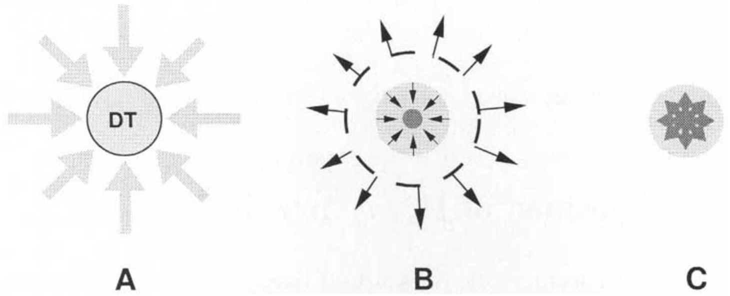

Fig. 1. Schematic of the inertial confinement fusion concept. (A) Irradiation of the target; (B) ablation of the surface layer and compression of the fuel; (C) ignition.

to a compression of the fuel. If the compression is high enough, the temperature and density of the plasma reach fusion conditions—the fuel ignites (see Fig. 1).

It is very crucial to illuminate the target as homogeneous as possible to avoid Rayleigh–Taylor instabilities and a promising method to solve this problem is to put the target into a cavity that is heated to about 300 eV. The Planck radiation of the cavity illuminates the target homogeneously. Heavy ions are a favorite driver for this indirect driven concept because of the high efficiency of the accelerator facilities and their high repetition rate [1]. The energy deposition mechanisms of heavy ions (see Abstract) are also an advantage for the conversion of the beam energy into the desired radiation energy.

Thus, the subject of the work of the GSI plasma physics group is the deposition of energy in dense matter. In two experimental areas the heating of cold matter by heavy ion beams and the energy loss of heavy ions in laser-generated plasma are investigated.

2. ION BEAM-INDUCED PLASMA GENERATION

At the HHT ("high-temperature") experimental area of GSI, the ion beam-induced generation of plasma in cryogenic gas crystals and in lead targets is investigated. Single pulses of less than 500 ns pulse width containing up to 2×10^{10} neon or argon ions with an energy of 300 MeV/U are focused by a plasma lens [2] onto the target, which is located in a vacuum chamber. Whereas earlier experiments dealt with solid rare gas crystals because of their combination of a high density and low cohesive enthalpy, the improvement of the accelerator and the experience in growing cryogenic gas crystals enabled the possibility of using lead targets and hydrogen crystals.

The first targets (cryogenic xenon and krypton crystals) offered the possibility to observe the light that had been emitted in the beam–target interaction area, because they were optically clear (see Fig. 2). Thus, spectra have been recorded, and an efficient conversion of beam energy into excimer radiation of 170-nm wavelength has been observed in xenon. Together with the observation of the hydrodynamic motion and, finally, the destruction of the crystals, which was recorded by a high-speed framing camera operating in a backlighted shadowgraph mode, a rise of the temperature from 20 to about 250 K has been measured. Also, the characteristic energy deposition of the ion beams mentioned above (homogeneous volume heating in the beginning, Bragg peak, and definite range) has been confirmed [3]: the interaction area of a 10-mm krypton or xenon cube is heated homogeneously by a 300-MeV/U Ne^{10+} beam, whereas a 200-MeV/U Ne^{10+} beam is stopped at a depth of 27 mm in a krypton crystal. This is the exact value being predicted by numerical codes. At the end of the range, an enhanced energy deposition ("Bragg peak") could also be observed.

An increase in beam intensity and a decrease in the ion beam pulse length lead to an increase in the energy deposition from about 200 $J \cdot g^{-1}$ in xenon and krypton targets to 1 $kJ \cdot g^{-1}$ in lead targets. The temperatures achieved in the lead target experiments (see Fig. 3) exceed 0.2 eV, and pressures of 2 to 3 GPa are observed [4]. By means of several upgrades of the GSI accelerator facilities in the near-future, it will be possible to reach the domain of radiation dominated physics, especially temperatures of 10 eV and beyond.

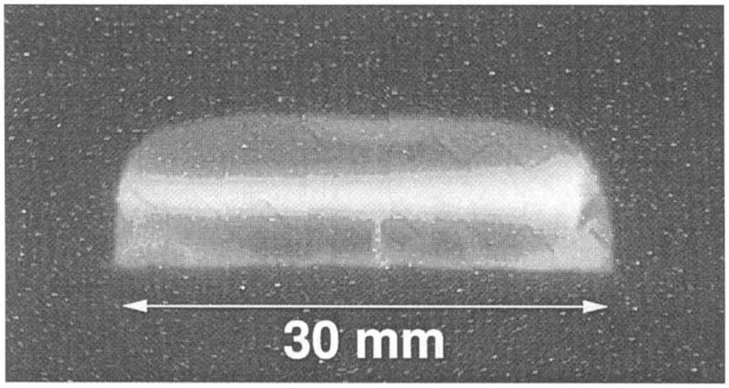

Fig. 2. Picture of the light emission of a 200-MeV/U Ne beam, which is stopped in a 30-mm krypton crystal.

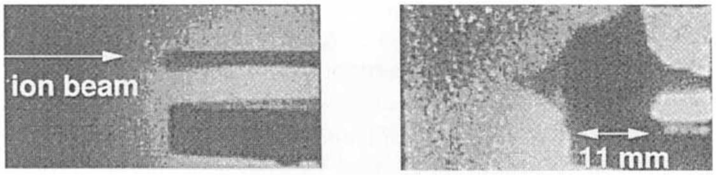

Fig. 3. A 300-MeV/U argon beam is stopped in a 2-mm-thick lead sheet. The target expands both perpendicular to the beam direction and out of the beam entrance point, antiparallel to the beam.

A further topic of the experiments at the HHT experimental area is the energy deposition of heavy ion beams in cryogenic hydrogen targets. The measurement of benchmarks for the design of equation-of-state computer codes, especially the phase transition for metallic hydrogen, is the driving force for these experiments.

3. ENERGY LOSS OF HEAVY IONS IN LASER PLASMAS

Whereas the experiments at the HHT experimental area attempt to generate plasma by heavy ions, the experiments in the Z6 experimental area examine the energy loss of heavy ions in externally generated plasma, because in the present state, the intensity of heavy ion accelerators is not sufficient to produce plasmas that are relevant to inertial fusion. To generate the plasma, a Nd:glass laser with an energy of 100 J in a pulse of 15 ns [5] is focused onto a thin carbon foil. Plasma temperatures reach about 60 eV, and the maximum electron density is the critical density of the laser frequency ($\lambda_0 = 1064$ nm), which is about $10^{21}\ \mathrm{cm}^{-3}$.

The energy loss of heavy ions in plasmas can be described by the Bethe–Bloch formula,

$$-\frac{dE_i}{dz} = \frac{16\pi a_0^2 I_H^2 \bar{Z}_i^2}{m_e v_i^2} \times \left[\underbrace{\sum_{Z=0}^{Z_K} (Z_K - Z)\, n_Z \ln\left(\frac{2m_e v_i^2}{\bar{I}_Z}\right)}_{\text{Contribution of bound } e^-} + \underbrace{n_e \ln\left(\frac{2m_e v_i^2}{\hbar\omega_P}\right)}_{\text{Contribution of free } e^-} \right] \tag{1}$$

where E_i is the energy, $\bar{Z}_i$ is the mean charge state, and v_i is the velocity of the projectile. I_H is the ionization potential of hydrogen, $\bar{I}_Z$ is the effective ionization potential of the charge state Z, and $\hbar\omega_P$ is the plasmon energy. $\bar{Z}_i$ is a sensitive variable, which is dependent on the equilibrium

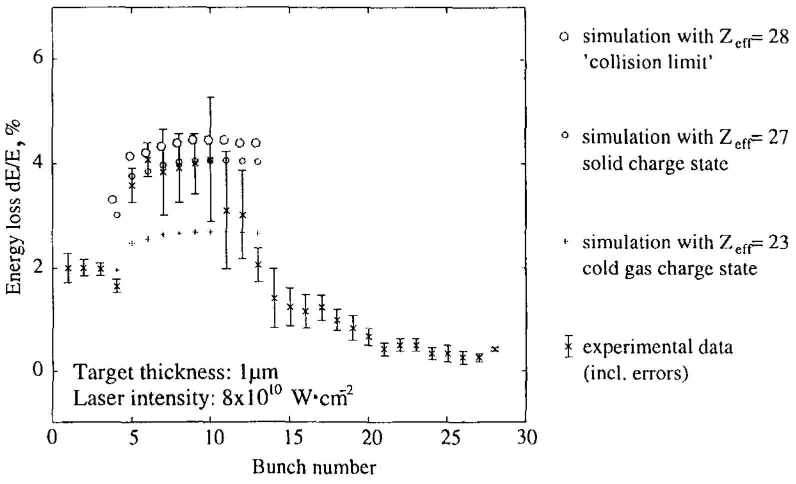

Fig. 4. Comparison of measured energy loss with calculated data.

processes in the target. It can be estimated by the semiempirical Betz formula for gases,

$$\bar{Z}_i \approx Z_{K,i}\left[1-\exp\left(-0.555\left(\frac{m_e v_i^2}{2I_H}\right)^{0.5875} Z_{K,i}^{-0.607}\right)\right] \tag{2}$$

$$\Delta\bar{Z}_i \approx 0.27\sqrt{Z_{K,i}} \tag{3}$$

where $Z_{K,i}$ is the nuclear charge of the projectile. An energy loss of ^{68}Zn ions with 5 MeV/U initial energy and initial charge state of 12^+ of about 4% is observed, which cannot be explained by the common theoretical models (see Fig. 4), although the modeling took into account the density profile of the target plasma. Whereas these models predict a charge state of $Z_{i,\,\mathrm{eff}} = 23$, a self-consistent solution of the energy loss formula that matches the measured data leads to a charge state of 27 [6]. To achieve more detailed data for this topic, time resolved charge spectroscopy is in progress.

4. FUTURE OF GSI PLASMA PHYSICS

The work of the Heavy Ion Plasma Physics group at GSI will benefit very much from the "*high current upgrade*" of the GSI accelerator facilities, which is currently under construction. Beam intensities will increase beyond 10^{11} particles per bunch for the high-energy experiments. New buncher cavities of the GSI heavy ion synchrotron that will be installed during the next 2 years will further decrease the pulse width. Thus, the energy deposition will dramatically increase and provide conditions to get closer to the plasma parameters relevant for fusion research.

To create an efficient X-ray backlighting system, on the one hand, and to produce target plasmas with higher densities and temperatures, on the other, a new Nd:glass laser system will be installed. This system will reach the kJ/PW regime. The combination of a high-power laser beam and a high-power heavy ion beam will then offer unique possibilities to examine the generation of high-energy density in matter.

ACKNOWLEDGMENT

This work was supported by the BMBF of the Federal Republic of Germany.

REFERENCES

1. R. O. Bangerter and R. M. Bock, *Energy from Inertial Fusion* (International Atomic Energy Agency, Vienna, 1995), p. 111.
2. M. Stetter, M. Dornik, D. H. H. Hoffmann, R. Kowalewicz, P. Spiller, S. Stöwe, and A. Tauschwitz, *Fus. Eng. Des.* **32–33**:503 (1996).
3. M. Dornik, V. P. Dubenkov, A. Filimonov, D. H. H. Hoffmann, M. Kulish, W. Laux, W. Seelig, B. Sharkov, P. Spiller, M. Stetter, C. Stöckl, S. Stöwe, W. Süß, and H. Wetzler, *Fus. Eng. Des.* **32–33**:511 (1996).
4. S. Stöwe, R. Bock, B. Bryunetkin, M. Dornik, V. E. Fortov, U. N. Funk, M. Geißel, S. Golubev, D. H. H. Hoffmann, M. Kulish, V. Mintsev, B. Sharkov, A. Shutov, P. Spiller, M. Stetter, N. A. Tahir, and V. Yakushev, *Nucl. Instr. Meth. A* **425**:61 (1998).
5. C. Stöckl, M. Dornik, D. H. H. Hoffmann, J. Jacoby, W. Laux, M. Roth, W. Seelig, P. Spiller, M. Stetter, S. Stöwe, W. Süß, and H. Wetzler, *Laser Particle Beams* **4**:561 (1996).
6. M. Roth, *Experimentelle Bestimmung des Energieverlustes schwerer Ionen in lasererzeugten Plasmen*, Ph.D. thesis (Darmstadt University of Technology, Darmstadt, 1998).