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Hydrodynamic efficiency of energy transfer in experimental targets illuminated with heavy-ion beams

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The conditions for an experiment are being discussed in which the hydrodynamic efficiency could be measured and an optimum thermonuclear target design worked out that could be performed on a single-channel accelerator facility producing a ^{209}Bi ion beam of ~100 GeV per nucleus. As numerical simulations show, the expected values of the hydrodynamic efficiency are 5-10%, while the optimization of the target-beam system could be performed by compressing D-T gas in a conical cavity and registering some 10^9-10^{11} neutrons per shot.

1. Introduction

The effectiveness of pellet compression in fusion experiments based on the principle of inertial confinement depends strongly on the hydrodynamic efficiency η of the transfer of the absorbed driver energy to the accelerated shell – a liner (Duderstadt & Moses 1982). That is why much effort has been devoted to the experiments of liner acceleration either by means of explosions (Anisimov *et al.* 1980), with high-current electron beams (Bogolubskii *et al.* 1976), or in the course of laser-driven ablation (Vovchenko *et al.* 1977).

When an intense beam of heavy ions (A $\gtrsim$ 200) with the total energy 10-15 kJ and of duration of 5-10 ns becomes available for plasma heating, it will provide an opportunity to perform the measurements of η at an energy deposition level typical for a full-scale project (Bock *et al.* 1984) as well as to investigate the optimum structure of a realistic multilayer target under the conditions of plane-parallel illumination. A highly collimated ($\phi \simeq$ 400-600 μm) beam of ^{209}Bi ions with 10-20 GeV per nucleus can be obtained by transmitting the initial beam of 100 GeV per nucleus through a certain decelerating layer. The initial beam for this purpose could be generated at a facility created on the basis of the existing accelerator (Alexeev *et al.* 1985).

2. Experimental

First, we estimate the angular divergence of the initial beam and the fluxes of secondary particles – δ-electrons, γ-quanta, fission fragments, and neutrons. Straightforward estimates show that the divergence of the ion beam – being mostly due to multiple small-angle Rutherford scattering off the target atomic nuclei – even by the end of the range amounts to no more than $\simeq$20 μm (Kalashnikov *et al.* 1980). And, because the focusing radius is $\gtrsim$200 μm the beam divergence does not degrade the specific energy deposition in the target (~1-5 MJ/g).

Having evaluated the fluxes of secondary electrons and photons generated by ^{209}Bi ions that enter a decelerating gold layer (^{197}Au, ρ = 19.5 g/cm^3) at an energy of 100

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TABLE 1. Parameters of liners

T (mm)	A (mm)	ρ (g/cm^3)	T_e (keV)	U (10^7 cm/s)
100	390	6.9	0.35	3
100	590	2.8	0.06	1.8
20	1190	1.07	0.26	2.9

GeV/nucleus, one finds that practically all of them are being absorbed and thermalized within the range of ^{209}Bi ions and thus have no effect on the energy deposition profile.

The cross-section values for nonelastic nuclear collisions of 100-GeV ^{209}Bi ions that one needs to calculate the fluxes of fission fragments and neutrons are not available from the experiments and, following Beynon & Smith (1985), one might suggest that the characteristic values are within the range 0.001–1 barn. In the most unfavorable case, this effect could cause a ~20% decrease in the concentration of deposited energy, and so the measurements of these cross-sections and of resulting secondary particle emissions become one of the most important experimental tasks on the way to heavy-ion fusion.

3. Results

The above-described collimated ion beam can be used to accelerate multilayer targets, with the hydrodynamic efficiency being measured experimentally, under conditions close to those in the full-scale scheme where the energy input is ~1–5 MJ/g.

Table 1 shows the results of 1-D two-temperature (with one and the same temperature for electrons and ions) hydrodynamic calculations for a plane-parallel target (see figure 1) consisting of a gold tamper (T), a beryllium absorber (A), and a gold liner 10 μm thick. In comparison to a more simple homogeneous target (just a gold foil), the introduction of a low-Z (beryllium) absorber enables one to attain higher values of the hydrodynamic

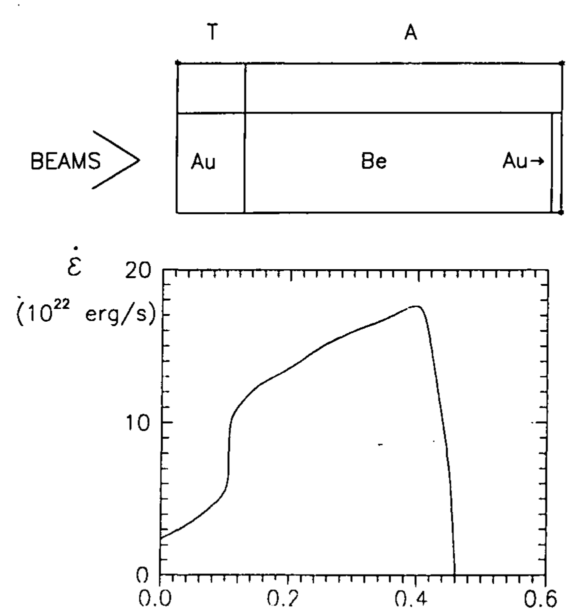

FIGURE 1. Multilayer target design and the energy deposition profile (T, tamper; A, absorber).

efficiency due to the fact that beryllium has higher than gold values of the stopping power per unit mass (Basko 1988).

While in the cold beryllium absorber fast heavy ions lose approximately two times as much energy per unit mass as they do in the gold tamper, this ratio rises to (3–5):1 as the temperature goes up; this is partly due to the Bragg peak, which is more pronounced in beryllium than in gold—and becomes more so as the temperature increases. As a result, less mass of the "working material" (beryllium) is required to absorb a given amount of the beam energy and, consequently, a lesser fraction of that energy is wasted to accelerate the working material (provided that the heavy tamper may be treated as an almost motionless wall).

In addition, the beryllium layer can be used as a kind of power amplifier. If we try beryllium layers of different thicknesses (for a fixed tamper mass and ion range), we will obtain different amplitudes of the shock front arriving at the absorber-liner interface (for this, the ion pulse duration should be comparable to the time interval within which the shock front traverses the beryllium layer). As a result, for practically the same values of the hydrodynamic efficiency we will get accelerated liners with widely differing specific entropies and, in particular, with widely differing spectra and intensities of the X-ray flare generated by the shockwave emerging at the free surface of the liner (see figure 2).

We calculated the hydrodynamic efficiency $\eta = E_k/E_a$ as a function of time for several target configurations; here, $E_k = m(t)u^2(t)/2$ is the kinetic energy of the liner and E_a is the absorbed beam energy. The obtained values of η fall in the range of 5–10%. Figure 3 shows the time dependence of the liner velocity $u(t)$; the final values of u lie in the range $(2\text{–}3) \times 10^7$ cm/s and may differ for different target configurations.

To perform the experimental measurements of η, one has to determine in one and the same experiment the mass of the accelerated liner as well as its final velocity. The needed accuracy of velocity measurements, $\Delta u/u \sim 10\%$, appears high but can be achieved with the photoelectric streak imaging of Schlieren photography of the liner's impact on an obstacle at a certain distance (Bol'shov *et al.* 1987). The major difficulty of determining η is then in measuring the mass of the accelerated material. It can be done, however, with a proper degree of accuracy if one makes use of ion collectors in combination with the plasma calorimetry and ballistic pendulum methods (Basov *et al.* 1982) as well as the registration of the neutral plasma component (Basov *et al.* 1988).

Measuring the total energy of the ion beam poses no major experimental difficulties.

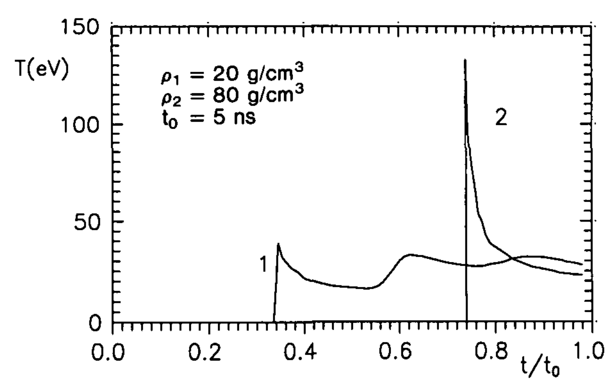

FIGURE 2. Temperature of the free boundary of the 20-μm gold liner vs. time for two target configurations: (1), $A_1 = 225$ μm; (2), $A_2 = 520$ μm; $T_1 = T_2 = 100$ μm.

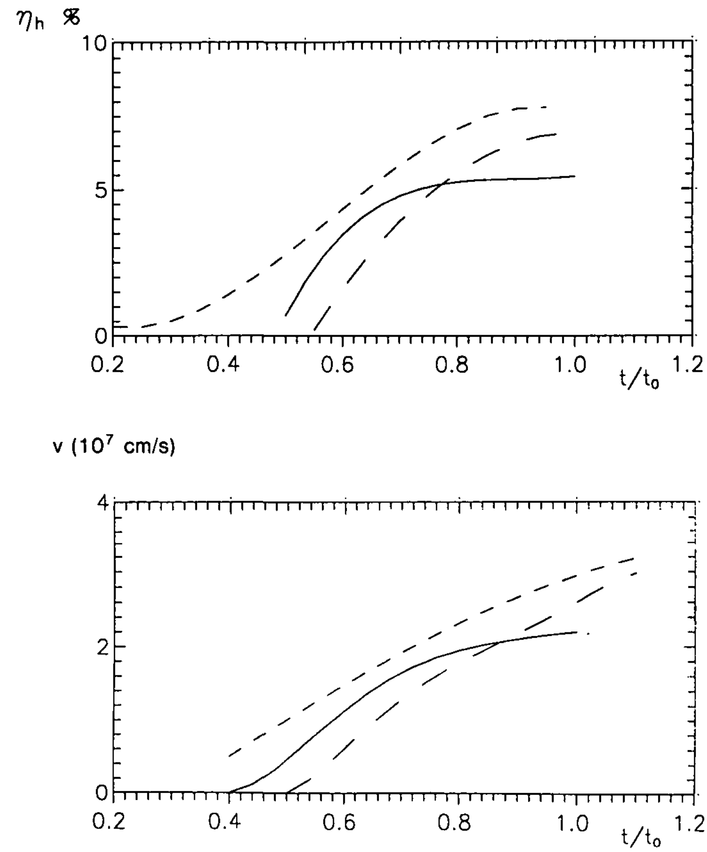

FIGURE 3. Hydrodynamic efficiency and liner velocity vs. time.

4. Discussion

It would be natural to use the accelerated planar liner for energy accumulation in D–T gas inside a conical cavity with dimensions of the order of the ion beam diameter. To evaluate the plasma parameters inside such a cone, we performed quasi-two-dimensional calculations within the framework of the two-temperature (that of radiation and matter) hydrodynamics in a hydraulic approximation. Table 2 presents thus obtained values of the mean temperature and neutron yield in a cone with a height and radius equal to 0.3 mm, the initial D–T density 6×10^{-3} g/cm^3, and the initial liner velocity 3×10^7 cm/s. Illustrated is the influence of various "loss channels" as one successively accounts for the electron heat conduction χ_e, radiative diffusion χ_F and the wall motion m_Λ.

TABLE 2. Neutron yield from a conical target

	No. of Losses	$+\mathcal{X}_e$	$+\mathcal{X}_F$	$+m_\Lambda$
$\langle N \rangle_{DT}$	$2.5\ 10^{11}$	$1.1\ 10^{10}$	1.10^{10}	1.0^9
T_e (keV)	>1.8	≲1.2	≲1	≲1
ρ (g/cm^3)	10–20	10–20	10–20	10

Special significance of this latter type of experiment is due to the sensitivity of the thermonuclear neutron yield to the compression regime. Hence, the detection of thermonuclear neutrons would be a good diagnostic criterion for the optimized target configuration and for the adequacy of physical models used in numerical simulations. We emphasize that for the fluxes being considered the thermonuclear neutrons can be reliably distinguished from the ^{209}Bi fission neutrons with the aid of the threshold activation detectors (Kramer-Ageev *et al.* 1976).

The results of this article can be summarized as follows:

1. A single-channel facility for accelerating heavy ions, providing a specific energy input $\gtrsim 1$ MJ/g, enables one to investigate the hydrodynamic efficiency of energy transfer for realistic target designs under the conditions of plane-parallel illumination.
2. As numerical simulations show, the expected values of the hydrodynamic efficiency are 5–10%, and by simply varying the thickness of the low-Z absorber one can prepare different final states of liners concerning matter density and temperature.
3. The experimental optimization of the target design and of the ion beam parameters can be achieved by means of neutron diagnostics for a D–T gas compressed inside a conical cavity, when some 10^9–10^{11} neutrons per shot could be expected.

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