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Investigation of plasma stream collision produced by thin films irradiated by powerful pulsed electron beam

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Abstract

Collision of fast plasma streams in vacuum is investigated. Plasma streams were produced by irradiation of thin foils with a powerful pulsed electron beam. Interaction of the plasma flows was studied by using frame and streak cameras. One-dimensional numerical simulation was carried out. Application of this method for porous ICF targets and high-energy physics is discussed.

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1. Introduction

Porous media are used in inertial confinement fusion (ICF) targets for fuel capsule symmetrization and conversion of radiation [1–3]. The characteristic feature of porous media is the pore collapse under intense pulsed heating. Despite a constant macroscopic density, the hydrodynamic phenomenon in the pores during collapse can exhibit velocities and temperatures considerably higher than the average values. This can lead to higher radiation and alteration of the thermodynamical state of the medium. However, the average time scale of the phenomenon is too small for the most practical media (e.g., aerogel ∼1 ps) which prohibits direct experimental investigation. We introduce physical modelling of the collapse process at a much larger scale (1–10 mm) and time (100–500 ns). The study of pore collapse of arbitrary shape was simplified by introducing one-dimensional collapse of spaced thin foils instead. In this model, porous medium density ρ depends on foil thickness l and spacing R: $\rho = \rho_0 l/(l + R)$, where ρ_0 is the foil density. This approach allows us to easily change the starting conditions (energy density, matter density, etc) to produce a plasma with the desired properties. The measured foil expansion velocities were used for the numerical simulation.

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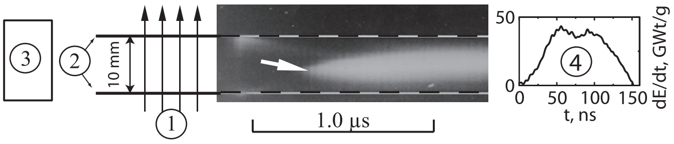


Figure 1. Camera registration of the foil plasma collision. 1—electron beam, 2—10 μm Al foils, 3—camera, 4—specific power history

2. Experimental set-up

An electron beam (1) (electron energy 280–300 keV, current 10–30 kA, pulse duration ≈100 ns FWHM) irradiated thin flat parellel foils (2) in a 4×10^{-4} mm Hg vacuum (see figure 1). Aluminium foils with thickness $l = 10$ μm and mica $l = 14$ μm were used. The gap between the foils R was smaller than the beam diameter (≈12 mm) and beam distribution was uniform to ensure one-dimensional collision. Deposition of energy ($E = 5$–15 kJ g^{-1}) caused evaporation and quick expansion of the irradiated foils. Foil thickness was much smaller than the electron stopping depth so their expansion was almost symmetrical. Hydrodynamical relaxation times were $\tau_H = l/C_S \approx 1$ ns for aluminium and ≈2 ns for mica (C_S is the sound velocity). Thus, the heating was nearly isobaric (For the isochoric case, the media parameters could be: temperature $T = E/C_V \approx 5.5$–16.7×10^3 K and pressure $P = \gamma\rho E \approx 28$–$84$ GPa, $C_V \approx 0.9$ J (gK)$^{-1}$, $\gamma = 2.09$ [9], chaper 11, for aluminium.) The foil's expansion and collision were observed in visible light by using either a streak or a frame camera (3). A frame camera allowed us to obtain two frames with 10 ns exposure at two intended moments.

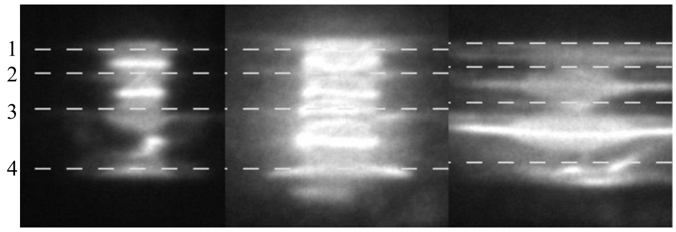
3. Experimental results

A streak camera image is presented in figure 1. The camera slot was located perpendicular to the foils. Foils were fast heated by the electron beam and produced plasma. The obtained plasma expands at high velocities (10–15 km s^{-1}) and produces a bright flash at the time of impact. Then, the plasma expands relatively slowly and exists for more than 2 μs. The average expansion velocity was calculated using the time of beginning of collision (the very left point of the central white wedge) relative to the start of irradiation.

In the frame camera experiments, we used several foils placed with different distances between them. This technique allowed us to observe different stages of the same process in one frame. Images (*a*) and (*b*) in figure 2 represent two stages of expansion of four 10 μm Al foils at 80 and 150 ns from the beginning of irradiation, respectively. Initial foil positions are shown as dashed lines. The empty spans between the foils are (from top down) 2, 3 and 5 mm. Image (*a*) shows the developed collision zones in the first two spans and the very beginning of collision at the bottom span. Image (*b*) shows the further evolution of the process. In image (*c*) (figure 2), the analogous experiment with thin dielectric foils (mica) is shown. For all foils (metal and dielectric), the observed bright flashes were more intense compared to the foils irradiated by the electron beam.

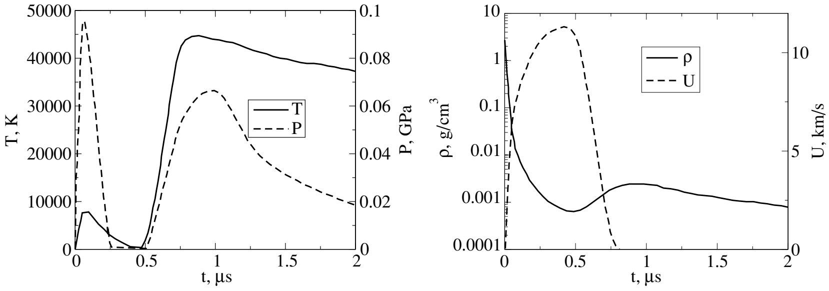
4. Numerical simulation

Electron beams have long been used for shockwave generation and thermodynamical experiments (see, e.g., [4]). For interpretation of experimental results for the case of two 10 μm Al foils we have used a 1D hydrodynamical simulation. The simulation of electron



(*a*) (*b*) (*c*)

Figure 2. Frame camera images for the experimental set-up with four foils (initial positions marked with dashed lines) placed with 2, 3 and 5 mm gaps. (*a*) and (*b*) Aluminium, (*c*) dielectric (mica).



(*a*) (*b*)

Figure 3. Numerical simulation results for temperature T, pressure P, density ρ and bulk velocity U for the media element 0.1 μm deep in foil.

stopping was carried out with the Monte Carlo technique using ENDF/B-IV libraries. Target expansion was described by the system of one-dimensional radiation hydrodynamics equations in Lagrange coordinates [5] in the two-temperature [6] single-velocity [7, 8] approximation. Numerical estimates for solid and liquid phases were based on the Mie–Gruneisen equation. The plasma phase was simulated within the approximation of the local applicability of the Saha equation. Considering that the viscous heating occurs for the ion component only [9], chapter 6, and the energy transfer between the components is a much slower process, the electron gas is compressed adiabatically with the electric forces. The plasma was taken as quasineutral. Electron density was proportional to ion density: $n_e = Zn_i$, where Z is the average degree of ionization. To describe the thermal radiation transfer and its influence on the energy deposition in the target, the conjugation of volumetric radiation for the optically thin target layers and radiation heat conductivity for the inner optically thick layers was used. To reduce simulation time, the external border of the expansion area was taken as a solid wall in the middle between foils. The effects of volume charge and electromagnetic fields were neglected. No significant difference between T_i and T_e was found.

Numerical simulation as shown in figure 1 was carried out (see figure 3). The maximum calculated temperature in the irradiated foils reaches 7000 K. Outer foil layers are accelerated in a pressure rarefaction wave to velocities up to 9–10 km s^{-1}. Collided plasma has the calculated temperature 40 000 K and density $\approx 10^{-3}$ g cm^3 (collision with fixed wall). These parameters can be easily controlled using the beam and geometry factors.

5. Conclusions

We consider it essential to develop the understanding of porous media behaviour at high rates of energy deposition in view of pore collapse hydrodynamics. In particular, the numerical simulation for the measured velocities predicted a plasma temperature five times higher than the foil material temperature. The foil matter under these conditions is completely single ionized [10]. Thus, the irradiated pore walls collapse, then the produced plasma expands and collapses again. The hydrodynamic equilibrium of density and pressure can be achieved during the time of 2–3 such cycles. The process of uniformity establishment for temperature and charge state requires additional study.

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