SUPERSONIC HEAT WAVE IN LOW DENSITY FOAMS GENERATED BY SOFT X-RADIATION FROM A Z-PINCH PLASMA

M. Lebedev[1], **K. Dyabilin[1]**, K. Eidmann[3], V. Fortov[1], E. Grabovskij[2] and V. Smirnov[2]

[1]*High Energy Density Research Center Russian Academy of Science, Moscow 127412, Russia*
[2]*Troitsk Institute for Innovative and Fusion Research, Troitsk 142092, Russia*
[3]*Max-Planck-Institut fuer Quantenoptik, D-85748 Garching, Germany*

Abstract

A intense soft x-ray pulse of radiation $\approx$ 1 TW/cm^2 generates in low (less than 50 mg/cm^3) density foam a nonlinear radiative heat waves which propagates with a velocity several times higher than the sound velocity. A level of the foam density of 5 mg/cm^3 was achieved in experiments. The experimental measurements are compared with the one dimensional computer simulations results.

1. Introduction

The study of the propagation of the heat waves generated in the low density condensed matters by the intensive soft x-ray flux is of importance for many fields such as inertial confinement fusion, X-ray lasers, and astrophysics. This study was done previously [1,2]. In these experiments x-ray fluxes in the range 10^{13} -10^{14} W/cm^2 at a pulse duration of about 1 ns were generated by focusing a high power laser into hohlraums [1] or on thin converter foils [2]. The foam density was 50 to 80 mg/cm^3 and the thickness less than 1 mm. In this paper we discuss experiments with foam targets in the density range 5 –50 mg/cm^3 and a thickness up to some millimeters. The source of the radiation was a Z-pinch plasma and the total irradiation energy density (in J/cm^2) was nearly the same as with the experiments with the lasers.

2. The experimental conditions and results

The experimental set up is shown on Fig. 1. As the source of the soft x-ray radiation the Z-pinch hot plasma produced by the ANGARA-5-1 installation was used [3]. Eight modules of ANGARA-5-1 pulsed power generators allow to store energy up to about 1.2 MJ and produce 1.2 MV, 150 ns halfsinusoidal pulse at 0.25 Ohm matched load. Electric currents of 3-5 MA were available.

In our experiments for the plasma generation the internal liner as a low density agar-agar annular with the implanted Mo was used. The internal liner diameter was 4 mm, wall thickness 0.2 mm and height 10 mm. As the external liner, a supersonic annular Xe plasma jet was used. The Z-pinch plasma emitted soft X-radiation with typical temperatures 60-80 eV. The spectrum of the radiation was calculated in multigroup approximation as well as studied experimentally [3]. The studies show that the largest deviation from a Planck spectrum occurs at photon energies above 200 eV, where the plasma is almost transparent. Nevertheless , the most substantial part of the pinch plasma spectrum can be well approximated as planckian and this approach will be used here for the simulations of the thermal wave by the MULTI hydrocode [4].

The total x-ray pulse duration was 20÷30 ns FWHM. This radiation was incident on the planar target, which was positioned under the liner. An irradiation intensity of 1 TW/cm^2 was achieved. The targets were made of agar-agar ($\sim C_{12} H_{18} O_9)_n$ or aerogel (SiO_2) with the densities from 5 mg/cm^3 till 50 mg/cm^3.

Electronic optical streak camera was used to detect the radiation in the range 400-800 nm from the heat wave when it reaches the free surface. The sample was imaged with the help of a f/100 (f=1.6 m) objective with 1- fold magnification onto the photocathode of the streak camera, temporal resolution less than 0.3 ns were provided. The diameter of the target was 10mm and the nonuniformity of the irradiation flux intensity within the plasma liner size was 3%. [5].

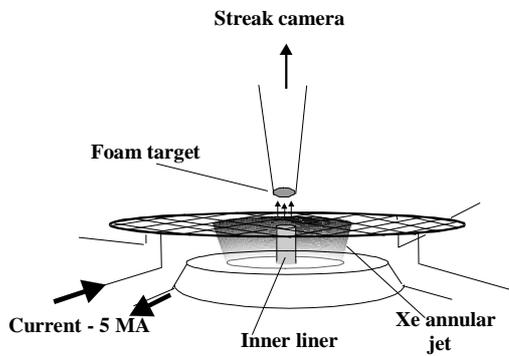A typical streak camera record of the heat wave radiation intensity is shown in Fig. 2.
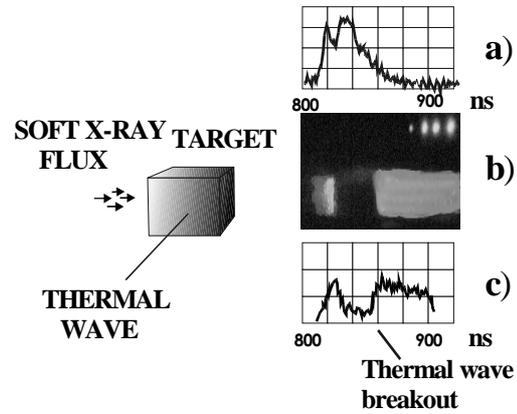

Fig. 1. Experimental set up.

Fig. 2. Irradiated agar–agar target of 2 mm thickness , soft x-ray pulse of 1 TW/cm^2 (a), streak camera record (b) and its densitometer trace (c).

Shot	target	Density mg/cm^3	intensity, 10^{12} W/cm^2	Thickness, mm	Breakout time, ns	Calculated breakout time , ns
2967	agar	10	1.0	1 2	11 31	11 27
2970	agar	20	0.85	1 2	26 43	22 42
2981	agar aerogel	20 50	0.6	1 2	11 61	
2982	agar	5	0.25	1 2	15 27	10 33
2983	aerogel	50	0.55	7.5	163	
2989	aerogel	50	1.0	15	365	
2992	aerogel	50	1.1	2.6	32	
2996	aerogel	50	0.17	3.6	91	
2999	agar	20	0.3	1.7 2.7	39 55	26 43

Table 1. Experimental and calculated results.

Nine successful shots with agar-agar and aerogel foam targets were performed. The x-ray intensity was changed within 0.2-1.0 TW/cm^2. It was measured by the technique described in [6]. The density of the foam targets was changed in the range 5 mg/cm^3 –50 mg/cm^3. These both parameters substantially influenced the velocity of the heat wave propagation. The results of the experiments are presented in Table 1.

3. Comparison with code multi

The experimental results were compared with calculations performed with the MULTI radiative hydrocode [4]. The incident x-rays have been approximated by a planckian drive pulse. The radiative opacities and emissivities were calculated in local thermal equilibrium (LTE) by using the SNOP atomic physics code [7]. As material pure carbon has been used instead of the actual chemical foam composition.

Fig. 3 shows for typical conditions of the experiment (shot #2967) the time evolution of the spatial profiles of the temperature, the density, the pressure and the mean ionization. In the beginning a supersonic heat wave propagates into the foam. Later, hydromotion sets in resulting in expansion of the foam matter and the development of a shock wave.

We have compared the measured and calculated breakthrough times of the shots made with agar-agar foam targets, because the chemical composition of this foam type is close to pure carbon which was taken for the calculation. Fig. 4 presents the time dependence of the measured and calculated position of the heat wave front for the shot #2967.
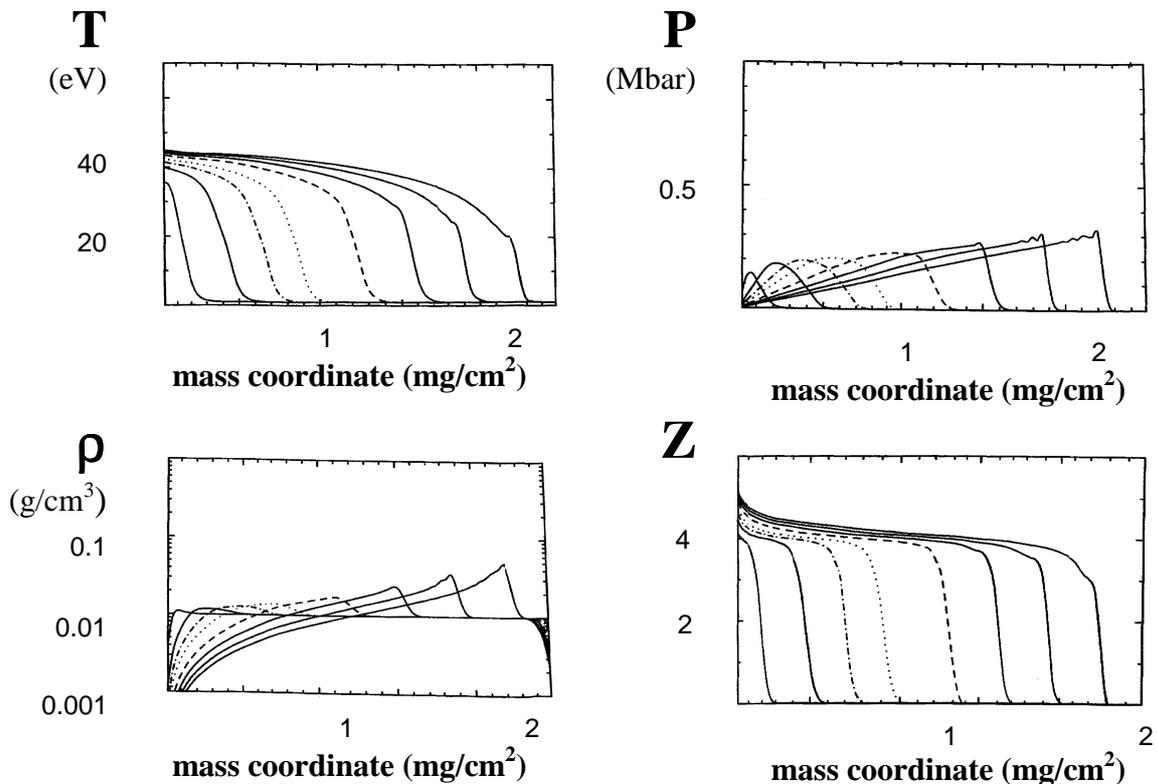

Fig. 3. Plots of temperature (**T**), pressure (**P**), density , (**ρ**),ionization charge (**Z**). Calculation by code MULTI: agar-agar, density 10 mg/cm^3, intensity of irradiation 0.7 TW/cm^2. Time=2.5/5/7.5/10/15/20/25/30 ns.
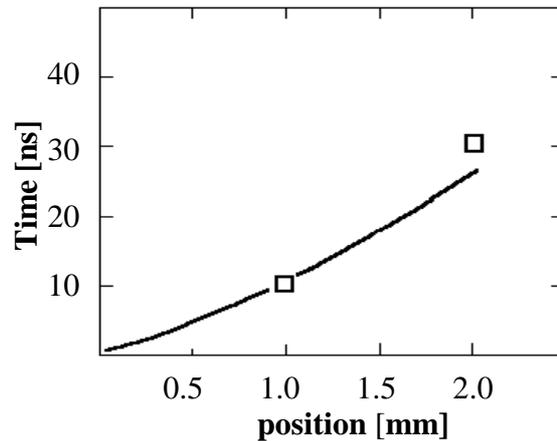
Fig. 4. Thermal wave front position for experiment #2967. Squares - experimental points. Solid curve - code MULTI.

The comparison of measured and calculated breakthrough times of other shots is shown in Table 1. The agreement is within a factor of 1.5. The deviations are attributed to uncertainties in the measured x-ray intensity, which is about 30%. Also note, that several approximations have been made in the calculations concerning the spectral and temporal dependence of the drive pulse and the chemical composition of the foam. Nevertheless, the results demonstrate that the experimental technique presented here is well suited to study radiation hydrodynamics and opacities of hot dense plasma.

Acknowledgments

References

[1] J. Massen, G.D. Tsakiris, K. Eidmann et al.: Physical Review E **50**(6), 5130-5133 (1994)

[2] T. Afshar-rad et al.: Phys. Rev. Lett. **73**, 74 (1994)

[3] E. Grabovskij. V. Smirnov, S. Zakharov et al.: JETP **82** (3), 445-45 (1996)

[4] Ramis et al.: Comput. Phys. Commun. **49**, 475 (1988)

[5] V. Fortov, K. Dyabilin, M. Lebedev et al.: Laser and Particle Beams **14**(4), pp. 789-792 (1996)

[6] A. Branizkij, G. Oleinik: *Proceed. 11-th Intern. Conf. On High Power Particle Beams*, Prague, Czech Rep., 1996, P-2-10

[7] K. Eidmann: Laser and particle beams **12**(2), 223-244 (1994)