Excitation of intense shock waves by soft x radiation from a Z-pinch plasma

E. V. Grabovskiĭ and V. P. Smirnov
Troitsk Institute of Innovative and Fusion Research, 142092 Troitsk, Russia

O. Yu. Vorob'ev, K. S. Dyabilin, M. E. Lebedev, A. V. Ostrik, and V. E. Fortov
Scientific-Research Center of the Thermophysics of the Application of Pulses, 127412, Moscow, Russia

(Submitted 25 May 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 1, 3–6 (10 July 1994)

Experiments have been carried out on the excitation of shock waves with pressure amplitudes up to 3 Mbar by soft x radiation in lead. The pulsed x radiation with a power level up to 2 TW/cm^2 used for this purpose was generated by the dynamic compression and irreversible heating of the plasma in two-stage Z-pinch targets at the ANGARA-5-1 device. The experimental results are compared with the results of a numerical simulation, which puts the brightness temperature of the plasma at about 80 eV.

A fundamental problem in the use of concentrated fluxes of charged particles and laser light in controlled fusion[1] and in the dynamic physics of high energy densities[2] is the substantial spatial nonuniformity of the power which is released. This nonuniformity disrupts the symmetry of the spherical compression of the fusion fuel and hinders the excitation of plane shock waves in experiments on the behavior of matter under extreme conditions. One of the most effective ways to solve this problem is to use the x-ray emission from a plasma with an approximately thermal spectrum which arises when directed energy fluxes are applied to a target[3] or during the electrodynamic compression of cylindrical shells in a Z-pinch geometry.[4] The plane shock waves excited by this radiation, which is an extremely simple type of self-similar hydrodynamic flow, might be a more natural and highly rich source of experimental information on both the intensity of the incident x radiation and the physics of the interaction of this radiation with condensed targets.

In this letter we are reporting measurements of the intensity of shock waves in condensed targets of aluminum and lead. The shock waves were formed by applying intense pulses of soft x radiation. The radiation used in the present study was an order of magnitude longer in duration (at a given power level) than that of some earlier studies,[5–7] in which the radiation was generated through a conversion of laser light into x radiation. The radiation in the present study arises as a result of the dynamic compression and heating of a plasma during its centripetal motion in the cylindrical Z -pinch geometry at the ANGARA-5-1 device.[8,9] The emitting plasma is produced through the use of an inner liner: a hollow cylinder consisting of a low-density agar–agar framework in which molybdenum has been implanted (the density of the cylinder is less than 10 mg/cm^3, and its total mass ranges up to 200 μg). The outside diameter of the liner is 4 mm, the thickness of the wall is 0.2 mm, and the height of the liner is 10 mm. The outer liner consists of a

0021-3640/94/010001-04$10.00

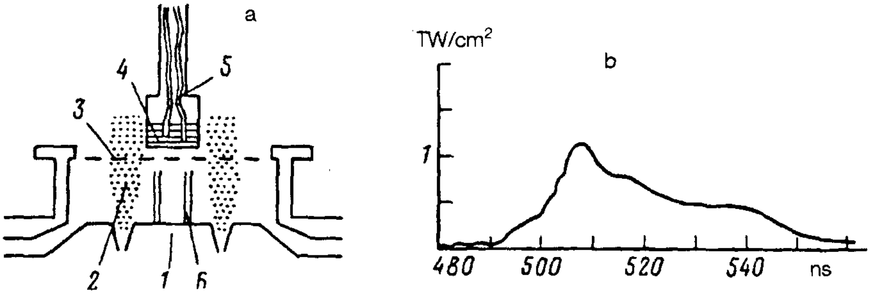

FIG. 1. a: Experimental layout. 1—Cathode; 2—jet of gaseous xenon; 3—anode; 4—target; 5—optical fiber; 6—inner liner. b: Typical oscilloscope trace of the intensity of the x radiation propagating along the liner axis.

supersonic annular jet of xenon with a mass of 150 μg, through which a pulsed current of 3.5 MA is passed (Fig. 1).

The Z-pinch plasma emitted soft x radiation with an approximately Planckian spectrum, with a temperature on the order of 60–120 eV. This radiation was incident on a plane target positioned above the inner liner (at a distance of 1 mm). This target consisted of layers of aluminum 16 μm thick and of lead 80–200 μm thick. The velocity of the shock wave was measured by an optical baseline technique,[10] involving measurement of the difference between the times of arrival of a shock wave at the free surfaces of stepped targets. Radiation was coupled out of the experimental apparatus by means of optical-fiber communications links (quartz–polymer fibers, 80 m long, with an attenuation of 0.4 dB and a bandwidth of 2 GHz). These communications links gave the measurement apparatus a high noise immunity.[11] The end of a fiber (400 μm in diameter) was butted directly against the free surface of the sample. One of the fibers was in contact with aluminum, and another with lead. The on-center distance between the fibers in the target unit was less than 1 mm. Accordingly, at the 4-mm diameter of the bombarded surface of the target, we could ignore spatial variations of the radiation. To eliminate emission from the fibers due to the hard x radiation accompanying the generation of the pulse of soft x radiation, we inserted the fibers in a steel tube in the working chamber. The end of this tube was terminated by the experimental assembly. The optical radiation from the fibers was detected by quartz photodiodes with a time resolution of less than 1 ns. In analyzing the experimental results we made use of the time difference between the leading edges of the signals (the difference between the emission onset times). A time resolution of less than 1.5 ns was achieved. The results of these experiments are shown in Fig. 2, in which we see the measured position of the shock front at various times. The average propagation velocity of the shock wave along a baseline of 80 μm is 7.3±0.6 km/s, and that along a baseline of 200 μm is 4.6±0.3 km/s. According to the shock adiabat of lead, these figures correspond to average shock-compression pressures of 3 and 0.9 Mbar (Ref. 12).

Shown in the same figure are results of a numerical simulation of the process. In these calculations, the equations of motion, which expressed the conservation laws in Euler form, were integrated numerically by the Godunov method on a movable Lagrange

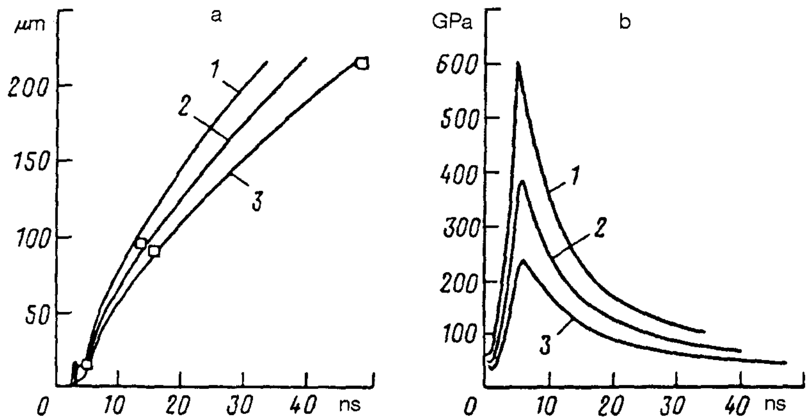

FIG. 2. a: Time evolution of the position of the shock front. Points—Experimental; solid curves—theoretical for several blackbody radiation temperatures. 1) 100 eV; 2) 90 eV; 3) 80 eV. b: Theoretical evolution of the pressure at the shock front at the same temperatures.

grid.[13] An algorithm which broke up the cells in the energy-deposition zone was used to attain the necessary spatial precision. The calculations of the pressure and sound velocity as functions of the specific internal energy and density used wide-range equations of state, which describe the results of dynamic experiments and which reproduce the melting, evaporation, and ionization of the material.[12] Energy transport inside the target was calculated in the approximation of multigroup radiation diffusion.[14] The frequency range of the incident radiation, $(0-10)kT/h$, was broken up into ten groups. A system of diffusion equations for each frequency group was solved by an implicit scheme on each time step after the calculation of the hydrodynamics. As a result, radiation energy fluxes integrated over the spectrum were found through a summation of the group fluxes. In these calculations we used spectral absorption coefficients found by a method incorporating bremsstrahlung processes, photoionization, and transitions in lines, calculated from a modified Hartree–Fock–Slater model.[15]

We see that the results of the numerical simulation agree with the experimental results, within the measurement errors, if we assume the brightness temperature of the plasma to be 80 eV. We wish to stress that the shock wave detected by us was excited by the radiation, rather than by a coherent plasma jet or by an electron beam. Since the radiation pulse is longer than that in experiments in which shock waves are excited through the conversion of laser light into x radiation, it becomes possible to increase the target thickness and thus substantially reduce the effect of sample preheating, which distorts the hydrodynamic picture of the process.

We wish to thank the ANGARA-5-1 staff. This work was supported by the Russian Fund for Fundamental Research (Project 94–02–03430–a).

[1] J. J. Duderstadt, *Inertial Confinement Fusion* (New York, 1982).
[2] S. I. Anisimov *et al.*, Usp. Fiz. Nauk **142**, 395 (1984) [Sov. Phys. Usp. **27**, 181 (1984)].
[3] D. L. Matthews *et al.*, J. Appl. Phys. **54**, 4260 (1983).

[4] P. J. Turchi and W. L. Baker, J. Appl. Phys. **44**, 4936 (1973).
[5] T. Endo *et al.*, Phys. Rev. Lett. **60**, 1022 (1988).
[6] Th. Lower and R. Sigel, *Proc. of 7 Int. Workshop on the Physics of Nonideal Plasmas* (Markgrafenheide, 1993).
[7] E. M. Campbele *et al.*, Laser and Part. Beams **9**, 209 (1991).
[8] A. V. Branishkiĭ, *Proceedings, Eighth International Conference BEAMS-90* [in Russian] (Novosibirsk, 1990), p. 437.
[9] V. A. Gasilov *et al.*, JETP Lett. **53**, 85 (1991).
[10] L. V. Al'tshuler *et al.*, Zh. Eksp. Teor. Fiz. **73**, 1866 (1977) [Sov. Phys. JETP **46**, 980 (1977)].
[11] V. G. Ageev *et al.*, JETP Lett. **48**, 659 (1988).
[12] A. V. Bushman *et al.*, *Equation of State of Metals at High Energy Densities* [in Russian] (IKhF RAN, Chernogo lovka, 1992).
[13] A. V. Bushman *et al.*, *Thermophysics and Dynamics of Intense Applied Pulses* [in Russian] (IKhF AN SSSR, Chernogolovka, 1988).
[14] A. V. Bushman and V. E. Fortov, Sov. Tech. Rev. B Term. Phys. **1**, 219 (1987).
[15] V. E. Fortov and I. T. Yakubov, *Physics of Nonideal Plasmas* [in Russian] (IKhF AN SSSR, Chernogolovka, 1984).

Translated by D. Parsons