Effect of size of energy absorption zone on the characteristics of shock waves excited by a strong relativistic electron beam in a metallic target

A. F. Akkerman, A. V. Bushman, B. A. Demidov, S. F. Zavgorodniĭ, M. V. Ivkin, A. L. Ni, V. A. Petrov, L. I. Rudakov, and V. E. Fortov

Division of the Institute of Chemical Physics, USSR Academy of Sciences

(Submitted 3 April 1986)
Zh. Eksp. Teor. Fiz. **91**, 1762–1766 (November 1986)

The influence of the absorption-zone depth of relativistic electron beams (REB) on the characteristics of pressure waves generated in metallic targets is investigated. The experimentally recorded velocity of the free surface of a target from which a shock wave emerges is compared with the results of computer simulation. It is found that for given REB parameters, the pressure-wave parameters calculated for targets of thickness comparable with the classical energy-absorption depth are sensitive to the size of the energy-release zone. The results lead to the conclusion that REB absorption in thick copper and aluminum targets is determined by the classical mechanism.

High-power relativistic electron beams (REB) can deposit into condensed target materials an extremely high (up to 10^{18} W/m^2) specific power, accelerate liners to 10^7 cm/s, and lead to generation of intense shock waves in the megabar range. This is why high-current REB are used in inertial-confinement thermonuclear fusion[1] and also to study the thermophysical properties of matter at extremely high pressures and temperatures by dynamic methods.[2] Even the first experiments on shock-wave generation in condensed media by electron beams have yielded interesting information both on the action of high-current REB on materials and on the thermodynamic and strength properties of materials at high pulsed pressures.[3–5] Of extreme importance for further use of high-current REB in technology, in controlled thermonuclear fusion, and in thermophysical experiments are the physical mechanisms whereby intense beams of relativistic electrons interact with condensed targets, and in particular the dimensions of the energy-release regions.

Experiments[6] on heating of thin (3–10 μm) metallic foils by a focused electron beam have revealed an interesting effect, viz., the energy deposition by a high-current REB exceeds the value predicted by the classical mechanism. The point is that the magnetic field of the high-current beam causes the relativistic electrons to move along cycloidal trajectories, in the exploded foil. The electron trajectories are therefore deflected by the Coulomb collisions through an angle greater than $\pi/2$ over a path exceeding the Larmor radius. The energy-loss density per unit target mass is then increased by a factor I/I_A, where I is the beam current and I_A is the Alfvén current, equal to 17 000$\beta\gamma$ [amperes] (β and γ are the relativistic factors: $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$). This effect, which is important for heating of thin foils of heavy materials, makes the energy-absorption region several times smaller than in the classical energy-release mechanism in cases of practical importance. A number of other physical effects also decrease the region in which energy is absorbed from a strong REB. Examples are interaction of a strong REB with a plasma-anode flare, the presence of strong beam-generated electric fields in the expanding plasma, and others. One can therefore not exclude beforehand the possibility that collective effects also reduce the size of the energy release zone of a strong REB in thick condensed targets. A decrease of the energy-release zone, in turn, alters the strength and other properties of the excited shock waves, since they depend on the size of the energy-release region. It is difficult to determine directly the size of the energy-release zone in experiments with a strong REB, in view of the short duration of the process, the small size of the zone, and the extreme complexity of the time-dependent flow pattern of high-pressure and -temperature plasma. The role played by collective effects in strong REB absorption and in shock-wave generation was therefore estimated here by comparing the experimental data on the dynamics of shock-wave motion with theoretical calculations of this dynamics under various assumptions concerning the size of the energy-release zone. This comparison was made for copper and aluminum, metals that differ substantially in density and hence in the size of the energy-release zone.

The experiments were performed with the "Kal'mar" high-current electron accelerator[7] with the following parameters: beam current 80 kA, electron kinetic energy 0.35 MeV, current pulse width at half-maximum 100 ns, focal spot diameter 2 mm, and total REB energy in the focal spot ~ 1 kJ. We investigated the generation and the dynamics of shock waves in copper targets of varying thickness, using the procedure of Ref. 5, where aluminum was investigated. Flexible quartz light pipes[8] were used to determine optically when the shock wave emerged from the rear surface of anode targets of varying thicknesses, and when the shock wave reached the contact surface of a lucite plate 0.6 mm away from the anode plate. The experimental results are plotted in Fig. 1. It is easy to determine from these plots the damping of the material velocity in a shock wave generated by a high-current REB in a copper target, assuming that the "doubling rule" $w = 2u$ is satisfied for the velocity w of the free surface and the mass velocity u. Note that the results agree well with those of Ref. 9, in which the rear-surface velocity of a copper foil was measured by an electric-contact method. The free-boundary velocities obtained in both procedures agree within to 5%. Thus, knowing the damping of the shock-wave

 0038-5646/86/111043-03$04.00

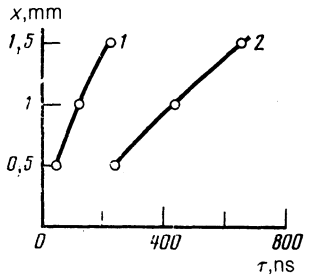

FIG. 1. Time of emergence of shock wave from the free surface of a copper target (curve 1) and time to reach the contact surface of a lucite plate (curve 2) vs the target thickness x.

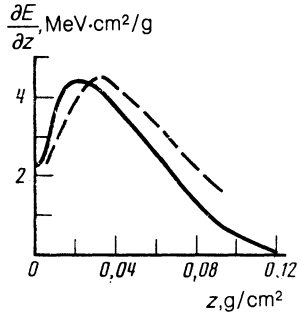

FIG. 2. Plots of absorption of 0.35-MeV electrons in copper (solid curve) and aluminum (dashed).

material velocity in copper and aluminum[5] targets we can compare the experimental curves with the theoretical ones calculated with and without allowance for collective processes.

Shock-wave generation in copper targets was numerically simulated with a computer model described in Ref. 5. A semi-empirical wide-range copper equation of state[10] was used in the calculations. In the parameter region of interest to us this equation of state is based on a considerable number of dynamic experiments[2] and is therefore very reliable (see Ref. 11 for details). The energy released by the REB in the target material was described, for the specified hydrodynamic density profiles, by the Monte Carlo method[5] including only the classical energy-loss mechanisms, viz., elastic electron–nucleus, electron–electron, and inelastic bremsstrahlung interactions. In this numerical method, the individual electrons moved on randomly selected piecewise linear trajectories. The electrons were elastically scattered at the corners, between which they moved linearly and lost kinetic energy through ionization and bremsstrahlung.

Figure 2 shows the energy-release plots of 0.35-MeV electrons in copper and aluminum (solid and broken traces, respectively), calculated by the Monte Carlo method. The abscissas are the mass distances $z = \rho_0 x$, where ρ_0 is the normal density of the material and x is the distance p traversed by the electron in the target in the direction of its initial velocity. It follows from the curves of Fig. 2 that the calculated size of the absorption zone is practically four times longer in aluminum than in copper.

A plot of the damping of the material velocity behind the shock wave as the latter penetrates into the copper target is shown in Fig. 3a. The solid curve is experimental, while curves 1 and 2 are respectively the results of one-dimensional and two-dimensional calculations. The calculations were made for three target thicknesses, 0.5, 1.0, and 1.5 mm. It can be seen from Fig. 3a that, just as in Ref. 5, the two-dimensional calculations agree well (to within 10%) with experiment. This attests to the validity of the physical model assumed in the calculations. Curve 3 of Fig. 3a is the result of a two-dimensional calculation under the assumption that the depth of the absorption zone is one-third that of the classical depth for the same energy input. In the hydrodynamic calculations we assumed an energy-absorption function in the form $dE/dz = 3\Phi(3z)$, where $\Phi(z)$ was calculated by the Monte Carlo method. The calculation shows that the decrease of the energy-release volume by collective effects substantially reduces the amplitude of the shock waves in the target, and the result is a noticeable decrease of the velocity of material behind the wave front.

The maximum amplitudes and the character of the damping of the shock waves in the target are qualitatively determined by two factors—the specific energy input to the energy-release zone and the geometry of this zone. A decrease of the zone size as a result of collective effects causes an increase of the specific and local energy inputs, which increases the pressure and raises the temperature of the energy-release region, thereby strengthening the shock wave in the target in the immediate vicinity of the focal spot. Reducing the size of the energy-release zone, however, causes the rarefaction waves that propagate from the free surface of the target to overtake the shock wave sooner, thereby weakening the latter. It can be seen from Fig. 3a that with the experimental parameters so chosen the influence of the second factor predominates and the pressure waves are clearly weaker.

A similar analysis was carried out also for aluminum.[5]

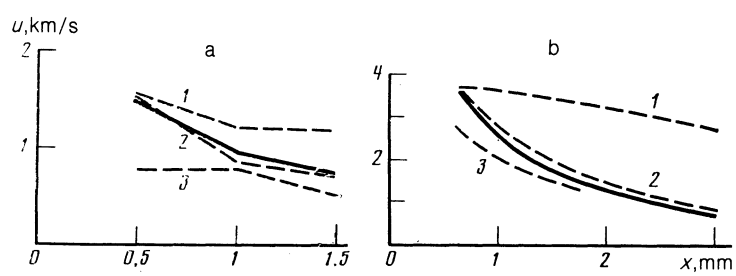

FIG. 3. Damping of material velocity u behind the front of a shock wave as the latter propagates into the interior of a copper (a) and aluminum (b) target. Solid curves—experiment, curves 1, 2, 3—computer simulation; 1—one-dimensional calculation, 2—two-dimensional calculation with decreased energy-release zone.

Figure 3b shows the dependence of the material velocity u on the distance x. The solid curve shows the experimental data, while curves 1 and 2 show the one- and two-dimensional calculations. Curve 3 of Fig. 3b is the result of a two-dimensional calculation under the assumption that the depth of the absorption zone, at the same energy input, is one-third the classical value. It can be seen from the curves of Fig. 3b that the pressure-wave attenuation is larger in this case. This is due to the larger electron-absorption depth in aluminum than in copper.

Naturally, the difference between curves 2 and 3 in Figs. 3a and 3b decreases at large distances, in agreement with the theory of the point blast,[12] when the flow parameters cease to depend on the details of the energy-release zone but are determined only by the amount of energy released.

It can thus be concluded from the experiments and calculations that, under the conditions considered, collective plasma effects have little influence on the absorption of a high-current REB and that its absorption can be described by the classical mechanism.

The authors thank A. M. Prokhorov, P. P. Pashinin, and I. K. Krasyuk for help with the experiments and for stimulating discussions.

[1]M. Babykin, Electron Thermonuclear Fusion, in: Itogi nauki i tekhniki (Science and Engineering Summaries), V. D. Shafranov, ed., Vol. 1, part 2, Nauka, 1981, p. 51.
[2]V. E. Fortov, Usp. Fiz. Nauk **138**, 361 (1982) [Sov. Phys. Usp. **25**, 781 (1982)].
[3]F. C. Perry and M. M. Winder, J. Appl. Phys. **47**, 127 (1976).
[4]B. A. Demidov, M. V. Ivkin, V. A. Petrov, *et al.*, Zh. Tekh. Fiz. **50**, 2205 (1980) [Sov. Phys. Tech. Phys. **25**, 1285 (1980)].
[5]A. F. Akkerman, A. V. Bushman, B. A. Demidov, *et al.*, Zh. Eksp. Teor. Fiz. **89**, 852 (1985) [Sov. Phys. JETP **62**, 489 (1985)].
[6]S. L. Bogolyubskiĭ, B. P. Gerasimov, V. I. Liksonov, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 202 (1976) [JETP Lett. **24**, 172 (1976)].
[7]B. A. Demidov, M. V. Ivkin, V. A. Petrov, *et al.*, Atomn. Energ. **46**, 100 (1979).
[8]V. E. Bespalov, M. M. Bubnov, V. I. Vovchenko, *et al.*, Pis'ma Zh. Tekh. Fiz. **10**, 55 (1984) [Sov. Tech. Phys. Lett. **10**, 24 (1984)].
[9]B. A. Demidov, M. V. Ivkin, V. G. Kirilenko, *et al.*, Zh. Tekh. Fiz. **54**, 155 (1984) [Sov. Phys. Tech. Phys. **29**, 86 (1984)].
[10]L. V. Al'tshuler, A. V. Bushman, M. V. Zhernokletov, *et al.*, Zh. Eksp. Teor. Fiz. **78**, 741 (1980) [Sov. Phys. JETP **51**, 373 (1980)].
[11]A. V. Bushman and V. E. Fortov, Usp. Fiz. Nauk **140**, 177 (1983) [Sov. Phys. Usp. **26**, 465 (1983)].
[12]L. I. Sedov, *Similarity and Dimensionality Methods in Mechanics*, Academic, New York (1959).

Translated by J. G. Adashko