

Production of high-velocity compressional jets by pulsed systems

S. I. Anisimov, A. L. Velikovich, N. G. Koval'skiĭ, M. A. Liberman,
and M. I. Pergament

Institute of Physical Problems, Academy of Sciences of the USSR

(Submitted 17 January 1985)

Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 5, 191–193 (10 March 1985)

Lasers, electron and ion beams, and Z pinches can be used to produce high-velocity compressional jets. An arrangement is proposed for using pulsed systems of this sort to produce compressional jets. Estimates give this new compression method in pulsed systems several advantages over conventional methods for producing high energy densities.

Pulsed systems are used in modern physics research to concentrate energy, to achieve high pressures, and to produce intense sources of neutrons and x rays. One of the most important applications of pulsed systems—high-current electron and ion accelerators, pulsed lasers, Z pinches,

etc.—is to accelerate macroscopic particles to high velocities. These particles can then be used, in particular, to model high-velocity impact, to study the thermodynamic properties of condensed media,^{1,2} etc. The method which has been adopted most widely is the ablation acceleration of thin foils by laser beams or particle beams (Ref. 3, for example). In the present letter we propose a different approach to the problem of acceleration to high velocities, based on the production of compressional jets during the ablation to hollow cones from their outer side. This method has the advantage that it can produce velocities significantly higher than are possible in direct ablation acceleration.

The formation of compressional jets has been studied quite thoroughly.^{4,5} We assume that a pressure pulse P acts on the outer surface of a cone of thickness d_0 . The cone wall begins to move along the normal to the surface. If the wall velocity is high enough, a compressional jet, directed from the vertex of the cone toward its base, forms inside the cone. The velocity of the jet is

$$v_j = v_0 \cot \frac{\alpha}{2}, \quad (1)$$

where α is the vertex half-angle of the cone, and v_0 is the velocity of the material along the normal to the surface of the cone. If the mass of accelerated matter is m , the mass of the jet is

$$m_j = m \sin^2 \frac{\alpha}{2}. \quad (2)$$

The minimum cone vertex half-angle at which a compressional jet forms is determined by the compressibility of the material (by the effective adiabatic index γ) and is given by

$$\alpha_c = \arcsin \gamma^{-1}, \quad (3)$$

so we find the maximum jet velocity v_{jm} to be

$$v_{jm} = (\gamma + \sqrt{\gamma^2 - 1}) v_0 \quad (4)$$

When a laser beam or a charged-particle beam is focused onto the surface of a solid, the pressure of the resulting plasma is significantly higher than the pressures which can be achieved by means of ordinary explosives. It is thus possible to significantly increase v_0 and thus v_j . It follows from numerical calculations and experimental data on the laser acceleration of foils^{3,6} that the ablation pressure during the absorption of light with a wavelength $\lambda \sim 1 \mu\text{m}$ and an intensity I is

$$P \cong 2 (I/10^{13} \text{ W/cm}^2)^{0.6} \text{ Mbar}, \quad (5)$$

while the maximum foil velocity is

$$v_0 \cong 3 \cdot 10^7 \frac{\tau}{\rho_0 d_0} (I/10^{13} \text{ W/cm}^2)^{0.6} \text{ cm/s}, \quad (6)$$

where τ is the pulse length (in nanoseconds), and d_0 is the initial foil thickness (in microns). A laser pulse with an energy of 300 J and a length of 1 ns focused on the outer surface of a polyethylene cone with a wall 5 μm thick and with a generatrix 200 μm long can produce a pressure of about 10 Mbar and a wall velocity $v_0 \cong 2 \times 10^7$ cm/s. Using $\gamma = 5/3$ for an estimate, we find $\alpha_c = 37^\circ$ and $v_{jm} = 3v_0$ from (3) and (4). Under these conditions, we can thus expect the formation of a compressional jet with a velocity of 6×10^7 cm/s and a mass of 5×10^{-8} g.

A cone of a conducting foil with a vertex facing the current channel can be placed in an aperture in the central part of the anode in a Z pinch. In this case the foil is compressed by the pressure created by ablation of the outer surface of the cone by the electron current of the Z pinch. For estimates we consider a noncylindrical Z pinch operated in the regime of "current-shell runaway" with the following typical values: a total energy of 100 kJ, a current ~ 1 MA, a voltage of 100 kV, and a lifetime $\tau \sim 0.1 \mu\text{s}$ for the compressed current channel. The focusing of the current in a noncylindrical Z pinch in the runaway regime involves the formation of a constriction near the surface of the anode as the result of an instability (Ref. 7, for example). In general, the position of the constriction can be arranged slightly away from the axis of the apparatus, but, as can be seen from the experiments of Ref. 8, the fast-electron current can be reliably focused on the axis when the aperture is at the center of the anode.

The thickness of foil from which the cone is made must be significantly greater than the scale length for the thermal conductivity of the foil material and also significantly greater than the stopping length for the bulk of the fast electrons:

$$d_0 \gg \sqrt{\chi \tau}, \quad d_0 \gg L_e. \quad (7)$$

Under the conditions listed above we would have $L_e \cong 20 \mu\text{m}$ and $\sqrt{\chi \tau} \cong 10 \mu\text{m}$, so that we could choose the wall thickness to be $d_0 \cong 100 \mu\text{m}$. Taking the diameter of the current channel at the plasma focus to be on the order of 1 mm, we can assume the length of the generatrix of the cone to be $l \cong 1$ mm. The plasma pressure on the ablation surface is estimated from (3), in which we need to set $I = jU$ (j is the current density, and eU is the energy of the fast electrons). When a current of 1 MA is focused in a millimeter-size channel with $U \cong 100$ kV, we obtain a pressure of several megabars. The Joule heating in the cone during the last stage of the collapse of the current shell is about 0.1 mJ/g and causes evaporation from both sides of the foil. This heating, however, is substantially less than the heating which results from the stopping of the fast electron beam (the corresponding vapor pressure is lower by about an order of magnitude). We also note that the aperture in the anode can be initially covered with a thin (3–5- μm) foil to protect against evaporation and damage to the cone by the current during the initial stage of the pinching. The evaporation of this foil during the approach of the current shell will improve the focusing of the discharge current on the

cone. In this case we would have to take into account in Eq. (5) the circumstance that the collapse time is about an order of magnitude shorter than the length of the current pulse for the particular cone dimensions selected. An estimate analogous to that above puts the velocity of the compressional jet at $\sim 3 \times 10^7$ cm/s at a jet mass $\sim 2 \times 10^{-5}$ g for a noncylindrical Z pinch with the parameters listed above.

Estimates indicate that this new method also holds promise when pulsed charged-particle beams are used. In this case, of course, several specific requirements will have to be satisfied. In some cases it may prove advantageous to use a plane geometry, i.e., to bombard a hollow plane wedge instead of a cone. The uniform application of a beam to the outer surface of such a wedge will produce a plane compressional jet inside it. The concentration of energy by virtue of the convergence of the plane jets at the axis can be intensified by connecting wedges with parallel generatrices to an extended corrugated surface.

¹B. M. Manzon, Usp. Fiz. Nauk **134**, 611 (1981) [Sov. Phys. Usp. **24**, 662 (1981)].

²S. I. Anisimov, A. M. Prokhorov, and V. E. Fortov, Usp. Fiz. Nauk **142**, 395 (1984) [Sov. Phys. Usp. **27**, 181 (1984)].

³G. H. McCall, Plasma Phys. **25**, 285 (1983); J. Gran *et al.*, Phys. Fluids, **26**, 588 (1983).

⁴G. Birkhoff, D. McDougall, E. Pugh, and G. Taylor, J. Appl. Phys. **19**, 563 (1948).

⁵J. M. Walsh, R. G. Shreffler, and F. J. Willig, J. Appl. Phys. **24**, 349 (1953).

⁶K. Eidmann, G. P. Banfi, *et al.*, in: Laser Plasma Interaction Experiments at $\lambda = 1.3 \mu\text{m}$ and $0.44 \mu\text{m}$. Preprint D-8046, Max-Planck-Institut für Quantenoptik, Garching, 1983; A. Gm. M. Maaswinkel, K. Eidmann, *et al.*, in: Comparative Study of Laser Acceleration of Thin Foils at Wavelengths $0.44 \mu\text{m}$ and $1.33 \mu\text{m}$. Preprint D-8046, Max-Planck-Institut für Quantenoptik, Garching, 1983.

⁷A. L. Velikovich and M. A. Liberman, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 449 (1978) [JETP Lett. **27**, 420 (1978)].

⁸S. Denus, L. Pokora, *et al.*, Fiz. Plazmy **9**, 755 (1983) [Sov. J. Plasma Phys. **9**, 437 (1983)].

Translated by Dave Parsons