Acceleration of macroparticles for controlled thermonuclear fusion

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The particle presents a review of published work on methods of acceleration of macroscopic particles. The basic physical possibilities of these methods and their applicability for problems of controlled thermonuclear fusion are analyzed.

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INTRODUCTION

At the present time two approaches to the problem of controlled thermonuclear fusion (CTF) are being successfully developed: on the one hand—creation of a quasistationary thermonuclear reactor with magnetic containment of the plasma, and on the other hand—creation of a reactor with inertial containment of the plasma, in which the thermonuclear energy release from a small highly heated particle of thermonuclear fuel occurs during its hydrodynamical dispersion.

One of the problems in development of a thermonuclear reactor with magnetic containment is the problem of makeup of the reactor fuel burned in the course of the reaction. The most promising method of refueling at the present time is considered to be injection of tablets of thermonuclear fuel into the reactor core with the necessary frequency. According to theoretical calculations,[1] for penetration of a fuel pellet to the necessary depth in the plasma of an operating thermonuclear reactor with a power of about 5 GW, a spherical grain with size of the order of 1 mm must have a velocity of the order 10^6 cm/sec. Attainment of such velocities for fragile pellets of deuterium is a complicated problem.

One of the methods of obtaining a thermonuclear microexplosion for the operation of a thermonuclear reactor with inertial containment is pulsed heating in a high-velocity collision of the macroparticle with a target, when the particle and target are made of the thermonuclear material.[2,3] To obtain a positive energy yield, according to estimates made in Refs. 2 and 3, the size of the accelerated pellet must be of the order of 1 mm for a velocity of the order of 10^8 cm/sec.

It can already be seen from these examples that the acceleration of macroparticles presents great interest for the physics of a high temperature plasma. The problem of acceleration of macroparticles to velocities 10^7–10^8 cm/sec was formulated for the first time in an article by Askar'yan and Moroz.[4]

In the present review we describe the current state of methods of obtaining high velocities of macroparticles and discuss the possibility of use of these methods for the CTF problems mentioned.

1. REQUIRED PARAMETERS OF ACCELERATED MACROPARTICLES

Before going to a description of the models which were used to obtain the parameter values mentioned for the accelerated particles, we shall indicate from what physical considerations these estimates were obtained.

For optimal utilization of fuel injected into a reactor, the time for complete evaporation of the fuel pellet must be of the order of its time of flight through the hot plasma of the reactor. This condition also determines the velocity of the injected pellets. The size of pellet is determined by the requirement of smallness of the number of atoms in it in comparison with the number of atoms in the reactor plasma, and

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the frequency of injection is determined by the rate of burning of the fuel.

The macroparticle velocity necessary for achievement of a thermonuclear microexplosion is determined from the condition of reaching thermonuclear temperatures in collision with the target, and the size of the particle is determined from the condition of a sufficiently large dispersion time of the plasma, which is necessary to achieve a positive energy balance (the energy expended in the acceleration must be less than that released in the thermonuclear reaction).

a) Necessary velocities and size of fuel pellets injected into thermonuclear reactors with magnetic confinement

In an operating thermonuclear reactor with magnetic confinement with a power of 5 GW, according to calculations,[5] fusion of about 0.01 g of DT fuel occurs per second. With a 3% burnup to maintain a stationary reaction it is necessary to inject about 0.4 g/sec of DT mixture or 10^{23} atoms/sec. In direct injection into the reactor of a beam of neutral particles or clusters, large expenditures of energy are required (≈100 keV/molecule), which is not suitable. It is much more suitable to inject pellets of solid fuel (the required energy is estimated[6] to be of the order of 1 eV/molecule). Accordingly, plans for future thermonuclear reactors have included devices for injection of solid fuel pellets. The size of the pellets is limited by the condition of smallness of the number of atoms in the pellet in comparison with the number of atoms contained in the reactor. For $N_p/N_r \approx 0.1$ (for a 5 GW reactor) the necessary pellet size[5] is in the range $1\text{ mm} \leq r_0 \leq 5$ mm for an injection frequency ≈100 pellets per second. The velocity of the particles is determined by the necessary penetration depth $R \approx 1$ m into the reaction zone.

According to the calculations of Gralnik,[1] the dominant process leading to evaporation of a pellet is interaction with thermal electrons (the pellet is transparent for neutrons and bremsstrahling, and the rate of energy transferred by D^+ is 60 times smaller, and by α particles 3–5 times smaller, than by the electron flux). The heat of sublimation of solid DT (or D_2) is small[7] ($\Lambda \approx 0.01$ eV/atom) and with the energy flux transferred by electrons,[5] $q_e \approx 3\cdot 10^{16}$ erg/sec · cm^2, the grain would evaporate very rapidly if there were no screening effects which prevent it.

By way of screening effects we have first of all[1,8] screening of the pellet by a layer of cold plasma which efficiently absorbs the electron energy; this has the result that the energy flow which reaches the phase boundary is much less than the flow far from the pellet. The greater part of this flow is expended in ionization and heating of the vapor ablated from the surface of the pellet.

The second form is electrostatic screening,[9] which is due to the fact that the pellet is charged negatively as the result of the difference in the flow of ions and electrons to its surface:

$$\frac{q_e}{q_1} \sim \left(\frac{T_e}{T_1}\right)^{3/2} \left(\frac{m_1}{m_e}\right)^{1/2} \sim \left(\frac{m_1}{m_e}\right)^{1/2} \quad \text{for } T_e \approx T_1.$$

Magnetic screening of the pellet[10,11] is due to the high conductivity of the plasma cloud formed about the pellet. In one of the models[10] it is assumed that this cloud separates the lines of force, forming a diamagnetic bubble which prevents incidence of the electrons, which are moving along the lines of force to the surface of the pellet. This model is valid for large $\beta = 2n_e kT/(H^2/8\pi)$. In another model,[11] which is more applicable for small β, called a magnetic nozzle, it is assumed that the plasma expands preferentially along the lines of force. The magnetic field in this model is assumed to be captured inside the magnetic nozzle, and the energy transport occurs through the ends of the nozzle.

Allowance for all these effects leads to the following estimate for the evaporation time of the pellet with size 0.1–0.5 cm in an operating reactor of power 5 GW with a magnetic field $B = 30$ kG, a density $n_e = 3\cdot 10^{14}$ cm^{-3}, and a temperature $T_e = 10$ keV: $\tau_{ev} \approx 10^{-4}$–$10^{-3}$ sec.

In order that depth of penetration of the pellet into the plasma be of the order of the plasma size $R \approx 1$ m, the injection velocity V must be $V \approx R/\tau_{ev} \approx 10^6$–$10^5$ cm/sec.

Looking ahead, we note that obtaining velocities ≈10^5 cm/sec for deuterium pellets does not present special difficulties; it is much more complicated to obtain velocities ≈10^6 cm/sec. For this reason experiments in the very near future are needed to determine more accurately the necessary parameters of the accelerated pellets.

b) Condition of occurrence of a small thermonuclear explosion in a high-velocity collision

We shall assume that a spherical macroparticle of radius r_0 traveling with velocity V collides with a target of condensed thermonuclear material (D_2 or DT).[2,3] If the macroparticle velocity V is much greater than the normal velocity of sound v_s of the target material, then in front of the particle there is formed a strong shock wave moving with velocity V. The density ρ_1 beyond the wave front is $\rho_1 = \gamma + 1/\gamma - 1\rho_0$, and the temperature is

$$T_1 = \frac{2\gamma(\gamma-1)}{(\gamma+1)^2}\frac{A}{R}V^2, \tag{1}$$

where A is the atomic weight, R is the universal gas constant, and γ is the adiabatic ratio ($\gamma = 5/3$ for a monatomic ideal gas). The region compressed and heated by the shock is of the order of the pathlength in which it slows down: $l = mV^2/2F$, where $m = (4/3)\pi r_0^3\rho$ is the mass of the pellet, ρ is its density, and $F = (\rho_0 V^2/2)\pi r_0^2$ is the stopping force. Therefore $l = r_0\rho/\rho_0$. If $\rho \approx \rho_0$, then $l \approx r_0$. Substituting numerical values of γ, A, and R into Eq. (1), we obtain $T_1 = 6\cdot 10^{-9}V^2$ (K). The critical temperature for achievement of a fusion reaction in DT is $T_1 \approx 5\cdot 10^7$ K, and therefore the velocity is $V \gtrsim 7\cdot 10^7$ cm/sec.

To obtain a positive energy field it is necessary that the energy released in the reaction zone exceed the energy input. Here it is necessary to satisfy the well known Lawson criterion $n_1\tau \geq 10^{14}$ sec/cm^3, and since

$n_l = \rho_l / Am_H = 10^{23}$ cm^{-3}, we have $\tau \geqslant 10^{-9}$ sec. The time of existence of the plasma is determined by the time of the gas-kinetic dispersion $\tau_k \approx l/v_{sl} \approx r_0/v_{sl}$ (where $v_{sl} \approx 10^8$ cm/sec is the velocity of sound in the heated plasma), since the time of cooling of the plasma as the result of bremsstrahlung $\tau_b \approx 3 \cdot 10^{11} (T/n_l)^{1/2}$ and the time of cooling as the result of electronic conduction $\tau_e \approx r_0^2/\chi \approx 4.2 \cdot 10^{-7} r_0^2$ are much greater for the minimum necessary pellet size $r_0 \approx v_{sl}\tau \approx 0.1$ cm ($\tau_k \approx 10^{-9}$ sec, $\tau_b \approx 5 \cdot 10^{-8}$ sec, $\tau_e \approx 3 \cdot 10^{-8}$ sec). Consequently to obtain a positive yield in a thermonuclear microexplosion in a high-velocity collision of a macroparticle with a target of thermonuclear material, the grain size must of the order of 10^{-1} cm for a velocity ~10^8 cm/sec.

Winterberg[12,13] discusses the possibility of decreasing this velocity by an order of magnitude by increasing the mass of the pellet up to 20 g. Reference 12 proposes for reduction of the velocity an intermediate glancing collision of a plate of mass 20 g traveling with a velocity 10^7 cm/sec with a target of the same material. According to the estimates of the author, the cumulative jet produced in the collision will have the velocity and mass necessary for achievement of the conditions for CTF. Reference 13 proposes for decrease of the pellet velocity to 10^7 cm/sec building into the pellet or target a recess—a hollow cone into which the thermonuclear fuel is packed. In the collision with the target, a compression and heating of the thermonuclear material occurs. This effect, and also the presence of a heavy conical shell (liner) around the thermonuclear plasma, slows down its escape and leads to less severe conditions for achievement of CTF. The author proposes preparation of pellets of superconducting material and accelerating them in a moving magnetic field. Since the length of the accelerator in this method of acceleration does not depend on the size of the pellet ($l_a \sim V^2$; see subsection 2c) a decrease of the pellet velocity by an order of magnitude decreases the length of the accelerator by two orders of magnitude.

It is clear from the above that the prospects for the possibility of achieving a thermonuclear microexplosion in a collision can be more optimistic if special attention is paid to the design of the pellets and targets.

2. METHODS OF ACCELERATION

Before turning to discussion of methods of acceleration, let us point out one fundamental limitation on the length and time of acceleration due to the limit of the strength $P_{\rm lim}$ of the material from which the pellet is made. Specifically, if we assume that the accelerating pressure is constant with time and equal to the limiting pressure $P_{\rm lim}$, we obtain for the length L_a and the time τ_a of acceleration $L_a \approx 2\rho V^2 r_0/3P_{\rm lim}$ and $\tau_a \approx 4\rho V r_0/3P_{\rm lim}$. In acceleration of a deuterium pellet $P_{\rm lim} \approx 5$ atm, and therefore $L_a \approx 10$ m, $\tau_a \approx 10^{-3}$ sec. In acceleration to obtain a thermonuclear microexplosion of a pellet prepared of the strongest existing materials (for example, the limit of strength of whisker single crystals is $P_{\rm lim} \approx 10^{11}$ dyn/cm^2), the minimum length and time of acceleration are 50 m and 10^{-4} sec, respectively. Here the accelerating pressure on the pellet must be applied quasistatically, and this means that the rise time of the pressure must be no less than r_0/v_s, where v_s is the velocity of sound in the material of the macroparticle. Otherwise the pellet can be destroyed as the result of production of shock waves in it.

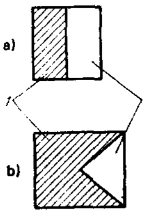

FIG. 1. Composite pellet. 1—Shielding layer, 2—thermonuclear material.

Let us point out also a possibility of extending the applicability of methods of acceleration of a fragile deuterium pellet—use of a composite pellet for acceleration (Fig. 1). One part of it (the shield), which is subjected to the action of the pressure, is made of a strong and denser material, and the other is made of the thermonuclear material. Use of a composite pellet in the form of a hollow steel cone filled with deuterium was proposed in Ref. 15 to decrease the length and time of acceleration in the action of laser radiation. For acceleration of a composite pellet for the purpose of injection into a reactor, however, a further technical difficulty arises as a result of the need of separation and removal of the shielding layer after acceleration.

In Fig. 2 we have shown a plot of the distribution of pressure along a composite pellet (see Fig. 1a) in acceleration of the pellet by application of pressure from the side of the shielding layer. It can be seen from the plot that the pressure on the pellet is $P_p = Pd_0\rho/d_s\rho_s$, where P is the applied pressure, d_0 and ρ are the size of the deuterium pellet along the direction of acceleration and its density, and d_s and ρ_s are the size and density of the shielding layer. For $\rho_s \gg \rho$ and $d_0 \approx d_s$ the pressure on the pellet will be much less than the accelerating pressure, which will preserve it from destruction. However, the minimum length and time of acceleration remain as before, since the pressure P_p applied to the deuterium pellet must not exceed the value for failure. Construction of the shielding layer with a recess which preserves the pellet from breakup, into which the deuterium pellet is deposited

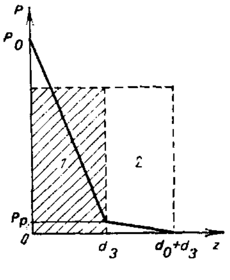

FIG. 2. Distribution of pressure along a composite pellet accelerated along the z axis by a constant pressure P_0 applied at the point $z = 0$.

(see Fig. 1b), will apparently permit decrease of the length and time of acceleration.

a) Centrifuges

Among the mechanical methods of acceleration of macroparticles, the best results are obtained with the rotational method of acceleration (the centrifuge).[16] The greatest linear velocity V achievable in rotation of an object is limited by its strength. Specifically, the stresses arising in the body on rotation are of the order $\rho_c V^2$, where ρ_c is the density of material of which the centrifuge is made. From the condition $\rho_c V^2 \leqslant P_{\mathrm{lim}}$, where P_{lim} is the limiting pressure at which destruction occurs, we obtain for the characteristic values $P_{\mathrm{lim}} \approx 10^{10}$ dyn/cm^2 and $\rho_c \approx 1$ g/cm^3 a value $V \leqslant 10^5$ cm/sec.

Various centrifuge designs and applications, in particular, for injection of pellets into closed magnetic traps, are described in Refs. 16–19.

Reference 19 describes experiments on rotational acceleration of pellets of solid hydrogen,[19] in which a velocity ≈10^4 cm/sec was obtained for pellets of size ≈0.1 cm.

b) Electrostatic acceleration of macroparticles

In this and the next two subsections we shall discuss the acceleration of macroparticles in electromagnetic fields.

The simplest of these methods consists of acceleration of a previously charged macroparticle by an electrostatic field.[20-22] If a macroparticle of mass m carrying a charge q traverses a potential difference U in an electric field, it acquires a velocity

$$V=\sqrt{\frac{2qU}{m}}. \tag{2}$$

The maximum velocity is limited by the maximum charge of the macroparticle and the maximum field strength which can be produced by present methods. Theoretically the maximum charge which can be held on a pellet is limited by the emission of electrons (for negative charge) or by the strength of the pellet (for positive charge). For most materials the positive charge can be an order of magnitude higher than the negative charge.[23,24]

A conducting pellet can be charged by contact with an electrode,[23,24] and a dielectric pellet can be charged, for example, by a beam of charged particles.[25]

The maximum theoretical value of the charge can be estimated from the condition

$$\frac{E_0^2}{8\pi}\leqslant P_{\mathrm{lim}}, \tag{3}$$

where $E_0 = q/r_0^2$ is the electric field at the surface of a pellet with radius r_0. Usually $P_{\mathrm{lim}} \leqslant 10^{10}$ dyn/cm^2 and can reach 10^{11} dyn/cm^2 from whiskers. Setting $P_{\mathrm{lim}} = 10^{11}$ dyn/cm^2, we obtain from Eq. (3) $E_0 \leqslant 10^6$ esu and $q_{\max} = r_0^2 \cdot 10^6$ esu.

The maximum voltage produced by a Van de Graaff electrostatic generator[26] does not exceed 10 MV ≈ $3 \cdot 10^4$ esu, and therefore the maximum pellet velocity is

$$V_{\mathrm{m}}\approx\sqrt{\frac{5\cdot 10^{10} r_0^2}{m}}. \tag{4}$$

Substituting $m = (4/3)\pi r_0^3 \rho$, we obtain

$$V_{\mathrm{m}}\approx\frac{10^5}{\sqrt{\rho r_0}}. \tag{5}$$

For example, for a pellet of radius $r_0 = 10^{-4}$ cm = 1 μm and a density $\rho = 1$ g/cm^3 we obtain $V_{\mathrm{m}} \approx 10^7$ cm/sec. Particles of submicron dimensions have been accelerated by such an accelerator to a velocity $1.12 \cdot 10^7$ cm/sec.[27]

Investigations utilizing an electrostatic accelerator for the purpose of imitating micrometeorites have been described also in Refs. 28–31. Velocities of the order 10^6–10^8 cm/sec can be attained by such accelerators only for particles of very small size.

In order to increase the velocities of macroparticles in electrostatic acceleration, it was proposed in Ref. 33 and carried out in Ref. 34 to use a linear electrostatic accelerator. In this accelerator the charged pellet is accelerated and passes a series of electrodes arranged one after the other, to which voltage is applied synchronously with the motion of the pellet. Here the minimum length of acceleration to a velocity V is

$$l=\frac{mV^2}{2q_{\mathrm{m}}E_{\mathrm{L}}}\approx\frac{2\rho r_0 V^2}{E_0 E_{\mathrm{L}}}. \tag{6}$$

If we take into account that the maximum electric field in a linear accelerator is $E_{\mathrm{L}} \leqslant 50$ kV/cm ≈ 200 esu (Ref. 24) (for example, in Ref. 34 $E_{\mathrm{L}} = 20$ kV/cm was achieved), we obtain

$$l\geqslant 10^{-8} r_0 \rho V^2. \tag{7}$$

Therefore in acceleration of a pellet of radius $r_0 = 10^{-1}$ cm and density $\rho = 1$ g/cm^3 to a velocity $V = 10^8$ cm/sec, the necessary length of accelerator is 10^7 cm = 100 km.

Let us estimate also the length of accelerator necessary for acceleration of a DT pellet of radius $r_0 = 10^{-1}$ cm to a velocity $V = 10^6$ cm/sec. If we take into account that the strength of the pellet is $P_{\mathrm{lim}} \approx 10$ atm,[14] the maximum charge which can be transferred to the pellet is $q_{\mathrm{m}} \approx (8\pi P_{\mathrm{lim}})^{1/2} r_0^2 \approx 10^2$ esu. For an accelerating field strength $E_{\mathrm{L}} = 50$ kV/cm we obtain from Eq. (6) $l \approx 5 \cdot 10^3$ cm = 50 m.

We see that to obtain the necessary velocities it is necessary to have a very great length of electrostatic accelerator. The situation could be improved if the radius R_{cy} of the cyclotron rotation of the charged pellet in a magnetic field turned out to be not too great. Then we would have the possibility of achieving periodic acceleration with cyclic rotation of the pellet as is done in contemporary cyclic particle accelerators. However, the ratio $R_{\mathrm{cy}}/l \approx (1/2)(c/V)E/B \geqslant 1$ for $V \approx 10^6 - 10^8$ cm/sec for constant electric and magnetic fields achievable at the present time ($E \approx 200$ esu, $B \leqslant 10^5$ G).

c) Acceleration in a magnetic field

The following acceleration schemes involving a magnetic field are possible[35-38]: 1) acceleration of a permanent magnet by a magnetic field gradient moving synchronously with it; 2) acceleration of a conducting or superconducting pellet by a magnetic field interacting with the magnetic dipole moment induced in it; 3) acceleration by a magnetic field of a conducting pellet in which an electric current is maintained by an external source (rail gun).

In the first case the force acting on the pellet-magnet is $F_a = (B/\pi) r_0^3 \partial B_a / \partial z$, where B is the constant magnetic field produced by the pellet and B_a is the accelerating magnetic field. In the best case of synchronous motion of the magnetic field gradient with the pellet and $\partial B_a / \partial z = B_a / r_0$ we obtain $F_a = (r_0^2/\pi) B B_a$ and the length for acceleration to a velocity V is

$$l = \frac{4\pi\rho r_0 V^2}{B B_y}. \tag{8}$$

Taking into account that the magnetic field produced by permanent magnets is $B \leqslant 3 \cdot 10^4$ G, we obtain

$$l \geqslant 10^{-8} \rho r_0 V^2. \tag{9}$$

For $\rho \approx 1$ g/cm^3, $r_0 \approx 0.1$ cm and with $V = 10^6$ cm/sec and $V = 10^8$ cm/sec we obtain respectively $l \geqslant 10$ m and $l \geqslant 100$ km.

The force acting on a superconducting pellet in a magnetic field ($\partial B/\partial z = B/r_0$) is

$$F = \frac{1}{c} I r_0^2 \frac{B}{r_0} \approx \frac{r_0 B I}{c},$$

where $(I/c) r_0$ is the magnetic moment of the pellet and I is the current flowing in it: $I \approx r_0^2 j$, where j is the current density.

For the length of acceleration up to velocity V we obtain

$$l = \frac{mV^2}{2F} \approx \frac{c\rho V^2}{2Bj}. \tag{10}$$

When the quantity jB exceeds a certain value characteristic of a given superconductor (type II) it loses its superconducting properties. For the best of the superconductors known at the present time (V_3Ga, Nb_3Ge, Nb_3Sn) Eq. (10) gives $l \geqslant 5 \cdot 10^{-10} V^2$; for $V = 10^6$ cm/sec and $V = 10^8$ cm/sec we obtain respectively $l = 5$ m and $l = 50$ km. To increase the maximum value of jB in the superconducting pellet Winterberg[37] proposed separating it into several insulated layers for the purpose of suppressing Hall currents. According to his estimates, in acceleration to a velocity 10^8 cm/sec the length of acceleration can be reduced in this case to 7 km. A characteristic feature in acceleration of a superconducting pellet in a magnetic field is the fact that the minimum length of acceleration to a given velocity is independent of the size of the pellet.

Thus, the length of acceleration of a pellet-magnet and of a superconducting pellet (5 m) to a velocity 10^6 cm/sec is of the order of the minimum length for nondestructive acceleration of a millimeter deuterium pellet to the same velocity. Therefore it is possible to use a composite pellet: deuterium-magnet or deuterium-superconductor. For removal of the shielding layer after acceleration it is necessary to have a retarding magnetic field, and the total length of the accelerator is increased by a factor of two.

In acceleration by a magnetic field of an ordinary conductor in which induced Foucault currents circulate, the maximum velocity achievable is limited by the smaller of two times: the time τ_σ of penetration of the magnetic field into the pellet $\tau_\sigma = 4\pi\sigma r_0^2/c^2$, where σ is the conductivity) or the time τ_m of melting of the pellet under the action of the joule heat dissipated in it, $Q = (j^2/\sigma) r_0^3 \tau_m$. Equating Q to the heat of melting $Q_m = m(CT_m + \Lambda_m)$ where C is the specific heat in erg/gram · deg and T_m (K) and Λ_m (erg/g) are respectively the melting temperature and heat of fusion, when we take into account that $j = cB/4\pi r_0$ we obtain

$$\tau_m = \frac{16\pi^2 r_0^2 \sigma\rho (CT_m + \Lambda_m)}{c^2 B^2} = \tau_\sigma \frac{4\pi\rho (CT_m + \Lambda_m)}{B^2}.$$

With the field achievable at the present time $B \leqslant 3 \cdot 10^5$ G, for example, for an aluminum pellet we obtain ($\sigma \approx 10^{17}$ sec^{-1}, $r_0 \approx 10^{-1}$ cm, $CT_m + \Lambda_m = 10^{10}$ erg/g): $\tau_\sigma \approx 2 \cdot 10^{-5}$ sec; $\tau_m \approx 4 \cdot 10^{-5}$ sec. These times are comparable with each other and are of the order of 10^{-5} sec. Therefore we obtain for the maximum velocity of the macroparticle

$$V_m = \frac{F_m \tau}{m} = \frac{B^2 \tau}{4\pi\rho_0 r_0} = \text{the minimum}$$

of the two quantities

$$V_m = \min \begin{cases} \dfrac{B^2 \sigma r_0}{c^2 \rho}, \\ \dfrac{4\pi (CT_m + \Lambda_m) \sigma r_0}{c^2 \rho}. \end{cases} \tag{11}$$

With a maximum $B \approx 3 \cdot 10^5$ G, $\rho \approx 1$ g/cm^3, and $r_0 \approx 10$ cm, we have $V_m \approx 10^6$ cm/sec.

In a rail gun[53] a conducting pellet is placed on two linear conductors (rails) and short circuits them electrically. The currents passing along the rails and through the pellet interact with each other and accelerate the pellet. If we write the force acting on the pellet in the form

$$F = \frac{1}{c^2} \frac{\partial}{\partial z} \frac{LI^2}{2},$$

where $L(z) = L(0) + \alpha z$ ($\alpha \approx 1$) is the inductance of the gun and I is the current flowing along the rails and through the pellet, then if we take for the time of acceleration the time of melting of the pellet by the joule heat dissipated in it, we obtain for the maximum velocity of the pellet

$$V_m \approx \frac{4\sigma r_0 (\Lambda_m + CT_m)}{c^2 \rho}, \tag{12}$$

which agrees up to a coefficient with the lower formula of Eq. (11). Consequently the maximum achievable velocities in acceleration in a rail gun would be the same as in acceleration of a conductor by the Foucault currents induced in it.

It should be noted that in acceleration of ordinary conductors by a magnetic field the maximum achievable velocity is limited by their size. For example, to obtain a velocity $V \geqslant 10^8$ cm/sec a conductor of size $r_0 \gtrsim 10$ cm is necessary. For acceleration of such a conductor the energy required is 10^6 times greater than for acceleration to the same velocity of a pellet of millimeter size.

Methods of obtaining a moving magnetic field have been described in several articles.[35,39-41] Up to the present time a very small number of experimental studies have been made of the acceleration of pellets in a magnetic field. Salisbury[39] used a gun with four coils to accelerate a pellet of mass 2.4 g to a velocity $3.5\cdot 10^4$ cm/sec. Harris[40] used a similar gun to obtain velocities up to $2\cdot 10^4$ cm/sec for bodies of mass 4.5 g. In a rail gun[41] an aluminum model of mass 5.2 mg was accelerated to $2.9\cdot 10^5$ cm/sec. In that work an additional external magnetic field was used to reduce the heating of the pellet. At the second conference on megagauss magnetic fields Hoke and Scudder[42] reported the acceleration in a rail gun of a conducting sample of mass 1 g to a velocity $6\cdot 10^5$ cm/sec. Here the magnetic field in the gap between the rails reached 400 kG.

A metal foil exploded by joule heat and accelerated by a magnetic field in a rail gun or coaxial gun represents a concentration of dense high-temperature plasma. Since it has a high conductivity, this cluster is further accelerated and acquires a quite substantial momentum. The momentum of this plasma jet can be used for acceleration of macroparticles. These questions are discussed in subsection 2h.

d) Acceleration by a beam of charged particles

In this section we shall discuss the elastic scattering of a beam of charged microparticles (electrons or ions) by a like-charged macroscopic particle (macron).[43] This method of acceleration differs from acceleration of a macron in ablation by an incident particle beam, which will be discussed later (see subsection 2i). It is evident that for the condition of elasticity of the scattering to be satisfied, the energy of the electrons in the beam $m_e v_e^2/2$ must be less than the potential energy φ_0 at the surface of the charged macron $m_e v_e^2/2 \leqslant e\varphi_0$, where $\varphi_0 = q/r_0$ is the potential at the surface of a pellet with charge q.

We shall assume that along the beam axis there is a strong uniform magnetic field which keeps the beam from spreading. In this case electrons traveling at a distance $r \leqslant 2qe/m_e(v_e - V)^2$ from the center of the pellet will be reflected backwards, transferring to the pellet a momentum $2m_e v_e$, while electrons traveling at a distance $r > 2qe/m_e(v_e - V)^2$ will pass by the pellet, slowing down during the approach to it and speeding up as they leave it, and as a result not transferring momentum to it. Therefore the characteristic scattering cross section is $\sigma = \pi[2qe/m_e(v_e - V)^2]^2$, where V is the velocity of the macroparticle. The average pressure on the macroparticle is $P = 2m_e n_e(v_e - V)^2$ and the force acting on it is

$$F = P\sigma = \frac{8\pi n_e q_m^2 e^2}{m_e v_e^2} \approx \frac{8\pi n_e e^2 E_0^2 r_0^4}{m_e v_e^2},$$

where E is the field at the surface of the pellet (we have assumed that $v_e \gg V$). Substituting into the formula for the force F the electron beam current $J = \pi r_r^2 n_e v_e$, where r_r is the radius of the electron beam, we obtain $F = 8JE_0^2 r_0^4/(m_e v_e^3/e)r_r^2$.

Taking into account that the electron beam is restricted to the limiting vacuum current[44]

$$J_{\lim} = \frac{m_e c^3}{e}\,\frac{(\gamma^{2/3}-1)^{3/2}}{1+2\ln(r_1/r_2)} \approx \frac{m_e v_e^3}{e},$$

where $\gamma = (1 - v_e^2/c^2)^{-1/2} \approx 1 - v_e^2/2c^2$, we find $F \approx (8J/J_{\lim})E_0^2(r_0^4/r_r^2) \leqslant 8E_0^2 r_0^2$ (for a beam radius equal to the pellet radius).

The minimum length of acceleration to velocity V is

$$l \approx \frac{\rho r_0 V^2}{2E_0^2}. \tag{13}$$

When we take into account that the maximum field at the surface of a negatively charged pellet is $E_0 \approx 3\cdot 10^4$ esu, we obtain

$$l \geqslant 10^{-9}\rho r_0 V^2. \tag{14}$$

Equation (13) for the acceleration length has a form similar to Eq. (6) for the acceleration length in a linear electrostatic accelerator. However, the role of the accelerating field in the case of the electron beam is played by the actual field at the pellet surface, which can be made somewhat larger than the linear accelerating field. Therefore the length of acceleration by an electron beam turns out to be smaller. This length can be made still smaller if we use an ion beam for acceleration and charge the pellet positively.

For a pellet of density $\rho = 1$ g/cm^3 and radius $r_0 = 0.1$ cm we obtain for the length of acceleration to velocities $V = 10^6$ cm/sec and $V = 10^8$ cm/sec respectively $l = 10^2$ cm and $l = 10^6$ cm $= 10$ km. However, if the pellet is charged positively, then E_0 is limited by the strength of the pellet and the length of acceleration by a beam of protons will be $l \approx \rho r_0 V^2/P_{\lim}$, i.e., of the same order as the minimum length of nondestructive acceleration (50 m). Progress in the production of proton beams (the necessary energy is ≈1 MJ and the pulse duration $\approx 10^{-4}$ sec) may make this method of acceleration realistic.

For a negatively charged deuterium pellet with $r_0 = 0.1$ cm, $\rho = 0.1$ g/cm^3, and $E_0 = 10^4$ esu we obtain for the velocity and acceleration length $V = 10^6$ cm/sec and $l = 10^2$ cm $= 1$ m. Here the energy of the electrons in the beam is $E_e \approx 10^6$ eV and for the limiting vacuum current the pulse duration is $\tau \approx 10^{-4}$ sec, and the diameter of the beam must be of the order of the diameter of the pellet (≈0.1 cm). The technical accomplishment of this method of accelerations would be very advantageous, since the efficiency of the acceleration is high. The problems here are associated with the possibility of charging the pellets to a high potential and also of achieving an energetic electron beam of long duration.

Winterberg[45] has proposed to accelerate instead of a pellet of thin foil which can then be compressed by a pulsed magnetic field into a pellet. In this case the accelerator length $l = \rho\delta V^2/E_0^2$, where δ is the foil thickness, can be made quite small. Difficulties arise here as the result of the rapid emission of electrons from the edges of the foil, which limits the time of acceleration. The minimum estimated length of acceleration of a foil to a velocity 10^8 cm/sec with the electron beams which exist at the present time for a foil thickness $\delta = 1\ \mu$m is 20 m. However, Winterburg overlooks the question of the possibility of charging the foil to the necessary potential. The point is that a thin foil will be transparent to the high-energy electrons of the beam.

e) Gas guns

This is one of the most widely used means of acceleration. Its advantages lie in the reproducibility of the results and also in the possibility of accelerating bodies of a specified shape and of comparatively large mass to comparatively high velocities.

A simplified diagram of acceleration by a gas is given in Fig. 3. The working gas 1 in the expansion chamber 2 at a high pressure P_0 pushes the macroparticle 3 with mass m along a tube (barrel) 4. If S is the diameter of the tube, L is its length, and m_g is the mass of gas in an expansion chamber of volume V_0, then from conservation of energy we have

$$\frac{m_g v_{s0}^2}{\gamma(\gamma-1)}\left[1-\left(1+\frac{SL}{V_0}\right)^{-(\gamma-1)}\right]=\frac{m+\alpha m_g}{2}V^2$$

and for $SL \gg V_0$ we can obtain for the velocity V of the macroparticle on leaving the tube

$$V \leqslant \sqrt{\frac{2}{\gamma(\gamma-1)}}\,v_{s0}\sqrt{\frac{m_g}{\alpha m_g+m}},$$

where v_{s0} is the initial velocity of sound in the working gas ($\alpha \approx (1/3)[V_c/(V_0+V_c)]$ is the fraction of the mass of gas which has come into motion on departure of the projectile from the tube, where V_c is the volume of the tube). The maximum pellet velocity V_m cannot be greater than the maximum velocity of expansion of the gas into a vacuum $V_m \leq 2v_{s0}/(\gamma - 1) \approx \sqrt{T_0/Am_H}$. To obtain the highest velocities it is necessary to choose gases with the smallest atomic weight (helium, hydrogen) and with the highest temperature. The mass of gas must exceed the mass of the accelerated macroparticle. The efficiency of acceleration is $\eta \sim m/(\alpha m_g + m)$. The velocity of the projectile is higher, the greater is the mass of accelerating gas, but the efficiency of acceleration falls off with increase of the ratio m_g/m. The maximum length of the tube is chosen from the condition that the force of the gas pressure on the macroparticle exceed the retarding force due to friction of the projectile on the wall of the tube.

In the simplest gas gun,[46] the so-called pneumatic gun, a working gas at normal temperature is forced under high pressure into the working chamber, at some pressure a diaphragm is ruptured, and the working gas, bursting into the barrel, pushes the projectile. In a gun of this type with helium as the working gas maximum velocities up to $1.7 \cdot 10^5$ cm/sec have been obtained with a projectile weight of 250 g.[46]

Pneumatic gas guns have been used on numerous occasions for acceleration of hydrogen pellets,[19,47-50] and at the present time for pellets of size ≈1 mm a velocity 10^5 cm/sec has been obtained.[19] Here the initial pressure of the working gas significantly exceeded the limit of strength of the pellet, but the authors of this study indicate that destruction of the pellets did not occur.

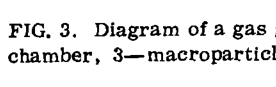

FIG. 3. Diagram of a gas gun. 1—Working gas, 2—working chamber, 3—macroparticle, 4—barrel.

In order to increase the velocity of the projectile, one increases the initial velocity of sound of the working gas by heating: either by transferring to it chemical or electrical energy (in single-stage gas guns) or by rapidly compressing a piston, using an additional stage—a powder gun (in two-stage light-gas guns).

Chemical energy can be communicated to the gas either by burning powder (in powder guns) or by burning an oxygen-hydrogen mixture.[46] In both cases the maximum achievable velocity is $\approx 4 \cdot 10^5$ cm/sec. The higher molecular weight of the powder gases is compensated by the higher temperature of heating in comparison with an oxygen-hydrogen mixture ($T_0 \approx 3000$–4000 K for powder and $T_0 \approx 2500$–3000 K for an $H_2 + O_2$ mixture).

Electrical energy is communicated to the gas by means of an electric arc which is produced between electrodes located in the working chamber.[51] In a typical electrical gun[51] the working gas (hydrogen) located in a chamber of volume 100 cm^3 at a pressure of 140 bars was heated by discharge of a capacitor bank of total capacitance 6000 μF and charged to 16 kV (stored energy ≈800 kJ). Here it was possible to heat the gas to a temperature $T \approx 8000$ K (a pressure of 6000 bars). A projectile of mass 0.1 g and diameter 5 mm was accelerated to a velocity $7 \cdot 10^5$ cm/sec. Here the efficiency of the gun is $\eta = (mV^2/2)/(CU^2/2) \approx 0.3\%$. Increase of the velocity is hindered by contamination of the working gas by impurities released from the electrodes.

This deficiency of electrical gas guns is completely avoided in two-stage gas guns, which were proposed for the first time by Crozier and Hume[52] in 1948. In these guns a light working gas is compressed and heated by a piston which is accelerated by an additional stage—a powder gun.

In order to determine the limiting velocity achievable in two-stage light-gas guns, let us estimate the velocity of sound v_{s1} in the compressed working gas. If we assume that the gas is compressed adiabatically, then it is easy to see that

$$v_{s1} = v_{s0}\left(\frac{P}{P_0}\right)^{(\gamma-1)/2\gamma}, \qquad (15)$$

where v_{s0} is the initial velocity of sound in the working gas and P_0 is its initial pressure.

For $\gamma = 5/2$ we find $v_{s1} = v_{s0}(P/P_0)^{0.2}$. The maximum velocity of sound in the compressed gas is determined in the last analysis by the maximum pressure in the powder chamber, which must not exceed the maximum strength of the gun material. For steel $P_{lim} \approx 2 \cdot 10^{10}$ dyn/cm^2. If $P_0 = 1$ atm $\approx 10^6$ dyn/cm^2, then $v_{s1} \approx 10 v_{s0}$. For hydrogen at normal temperature $v_{s0} \approx 1.6 \times 10^5$ cm/sec, and therefore the projectile velocity is $v \leq v_{s1} \approx 1.5$

$\cdot 10^6$ cm/sec. We note that it is possible to increase v_{s1} by heating the working gas before compression[51] (increase of v_{s0}) or by decreasing the initial pressure P_0, but in order that the mass of gas not be changed in so doing it is necessary to increase the volume V_0 of the working chamber: $V_0 \gtrsim 10mv_{s0}^2/P_0$ for $m_g \approx 10$ m, which greatly increases the size of the apparatus. With nonadiabatic compression of the working gas[51,54] (for this purpose the compressing piston must be made as light as possible) the temperature of the working gas and consequently also v_{s1} becomes somewhat higher than according to Eq. (15), but the difference is insignificant.[55]

To prevent decrease of the pressure in the working gas during acceleration of the projectile, one makes use of a deformable piston and a working-gas chamber of conical shape[53] (with deformation of the piston during its forward motion the end moves faster than the center of mass). For the same purpose one communicates energy to the gas located directly behind the projectile moving in the barrel by successive ignition of arcs by means of electrodes located along the barrel.[51,58]

To increase the velocity of the projectile, use has been made also of a "muzzle" jet,[53] in which an easily deformable ring, encountering a special nozzle at the end of the bore and thereby forming a cumulative jet, pushes the projectile and increases its velocity.

The highest velocity obtained in a two-stage high-quality light-gas gun for a projectile of weight 1 g is $1.2 \cdot 10^6$ cm/sec.[56,57] In this gun use is made of the lightest working gas—hydrogen—and nonadiabatic compression of the working gas by a light deformable piston; the projectile is placed in a ring of material with a low coefficient of friction for the gun barrel and the maximum possible pressure is developed in the powder chamber.

Other methods of increasing the velocity are effective only in guns of low quality and do not provide the maximum possible velocity obtainable in a high-quality light-gas gun.[53]

Note that heating of a light working gas without contaminating it with heavy impurities is possible also by means of laser radiation. Estimates made by the author have shown that by means of such a gas laser gun it is possible to accelerate a deuterium pellet of diameter 1 mm to a velocity of 10^6 cm/sec. Here for a mass of gas in the working chamber equal to five times the mass of the accelerated deuterium pellet, it is necessary to supply it with an energy of the order of 10 kJ.

Designs of light-gas guns, the features of their operation, and their efficiency and possibilities are described also in a detailed monograph.[54]

Thus, in gas guns the maximum possible velocity is limited by the velocity of sound of the working gas $v \leq v_{s1} \approx 10^4\sqrt{T/A}$, which can be increased only by increasing the temperature of the working gas. Heating the gas by dissipation of chemical energy does not give temperatures above 3000–4000 K. Heating of the gas by dissipation of electrical energy can be substantial (up to 8000–10 000 K), but the thermal destruction of the electrodes and walls of the chamber increases the average molecular weight of the gases and thereby decreases v_{s1}. Heating the gas by compression by means of a piston operated by an additional stage—powder gun, which gives the best results, permitting the maximum velocities attainable at the present day, is limited by the maximum pressure in the powder chamber which results in destruction of the gun. Use of contactless heating of the gas, for example, by laser irradiation, which does not lead to an increase of the impurities, greatly reduces the efficiency of acceleration as the result of the small efficiency of high-power lasers. In addition to these factors which limit the maximum achievable velocity in light-gas guns, it should be pointed out that heating of a gas of high density to temperatures above 10^4 K will lead both to significant thermal erosion of the walls of the working chamber and gun barrel, thereby increasing the molecular weight of the working gas and decreasing the time of operation of the gun, and also to a significant increase of the thermal loss as the result of radiation and heat conduction.

f) Explosive accelerators

In these accelerators a macroparticle is accelerated by the expanding gases of a detonated explosive material. The maximum escape velocity of the gases is $v \approx 2v_s/(\gamma - 1)$, where v_s is the velocity of sound in the material heated by the detonation wave $v_s = [\gamma/(\gamma+1)]D$; here D is the velocity of the detonation wave. For the explosive materials known at the present time $D \leq 8 \times 10^5$ cm/sec.[59] This value also limits the maximum velocities in direct acceleration of a macroparticle by the explosion products. However, acceleration of the products of the explosive in a cumulative jet is possible. For this purpose an axially symmetric conical or cylindrical cavity is made in the explosive charge. The cumulative jet is formed in the collision of the explosive products converging symmetrically toward the center. Calculations and experiments show[60-64] that the velocity of the gases in a cumulative jet can be much greater than the velocity of the detonation wave (it increases with decrease of the angle of the conical cavity). However, the mass of the jet decreases. There is therefore an optimal angle at which the cumulative jet gives itself the maximum accelerating impulse. At the optimal angle the velocity of a cumulative jet is of the order of twice the velocity of the detonation wave.

A typical diagram of an explosive accelerator with direct acceleration of the macroparticle projectile by the detonation products is shown in Fig. 4.[59] As a result of the high pressure in the condensed, highly heated explosive material it has a high destructive force ($P_e \approx 2 \cdot 10^6$ bars) and therefore between the projectile (5) and the explosive (3) is placed a cushion (4). At the present time in such systems velocities up to $9.5 \cdot 10^5$ cm/sec have been obtained with macroparticle masses $m \approx 0.1$–1 g.[65,66]

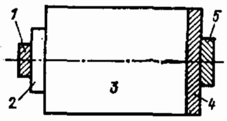

FIG. 4. Diagram of an explosive accelerator. 1—Initiator, 2—intermediate detonator, 3—explosive charge, 4—cushion, 5—macroparticle projectile.

Acceleration by a cumulative jet of explosive has been carried out in Refs. 59–64. Titov *et al.*[60] in acceleration of nichrome spheres of diameter 80–100 μm with a charge of weight 200 g obtained velocities up to $1.4\cdot10^6$ cm/sec. For particles with dimensions of 1 mm the maximum velocities reached are $(1.0-1.2)\cdot10^6$ cm/sec.

If the conical cavity in the explosive charge is provided with a metallic lining, then in the explosion the lining material is ejected, forming either a continuous cumulative jet or breaking up into liners of small size having different velocities. Calculations[67,68] and experiments[69,70] have shown that the velocity of liners produced in this way can reach twice the detonation velocity. It depends on the angle at the vertex of the cone, and for each liner material there is an optimum angle at which the velocity is maximal. By this method velocities above $1.5\cdot10^6$ cm/sec have been obtained.[71] However, in this method there is an uncertainty in the mass of the liner-macroparticle, which must be measured during the travel.

Explosive materials are used also for compression of a light gas in gas guns.[51] In such guns the reservoir with the light gas is surrounded by explosive. In addition to the inconvenience of replacing the gas reservoir after each shot, this method gives no advantage in comparison with the ordinary two-stage gas gun, as a result of the short duration of the accelerations produced. The highest velocity achieved in gas guns of this type is $8\cdot10^5$ cm/sec.[53]

In the gun used by Flagg and Glass[72] (Fig. 5) the hemispherical reservoir of a gas gun was filled with a detonating mixture of O_2+H_2. The hemisphere was surrounded by an explosive charge. The detonating mixture was initiated on the projectile side by explosion of a small wire. The hemispherical detonation wave which propagated from it initiated the explosion of the explosive material simultaneously over the entire hemisphere. This led to a symmetric compression of the gas and a high degree of cumulative effect. A plastic projectile of weight 350 mg and diameter 8 mm was accelerated to a velocity $5.3\cdot10^5$ cm/sec. In one of the accelerators[53] gradual acceleration of the projectile was accomplished by successive pulses from explosion of explosive charges. Here difficulties arise in synchronization of the detonation of the explosives.

We must also mention the possibility of increasing the velocity of liners accelerated by an explosive charge, as proposed in Ref. 73. A plate (the projectile) accelerated by an explosive hits another plate with lower density and rigidity which serves as a buffer, transmitting the acceleration to a thinner rigid plate (the target). Here the target has a velocity greater than the projectile. This process is similar to the amplification of shock waves in a medium consisting of alternating layers with low and high density.[74] By this method it was possible in Ref. 73 to increase the velocity of the target by 1.5 times in comparison with the velocity of the projectile with decrease of the target weight by a factor of two in comparison with the projectile.

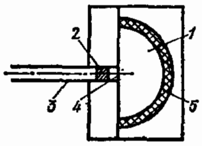

FIG. 5. The gun of Flagg and Glass. 1—Chamber with O_2+H_2 mixture, 2—macroparticle projectile, 3—barrel, 4—diaphragm, 5—explosive charge.

g) Electrothermal accelerators

In the preceding section we have seen that a highly heated condensed material undergoing dispersion can accelerate macroparticles to substantial velocities. The maximum velocity of escape of explosive materials heated on detonation is determined in the last analysis by the chemical energy released as the result of a reaction in the volume of the chemical material:

$$V\leqslant\frac{2v_s}{\gamma-1}\approx\frac{2D\gamma}{\gamma^2-1}\approx\frac{2\gamma}{\gamma^2-1}\sqrt{2Q(\gamma^2-1)}\,, \qquad (16)$$

where $Q\leqslant10^{11}$ erg/g is the heat of reaction.

However, there is an additional method of strong heating of condensed matter, namely heating a conductor by dissipating joule heat in it on passage of an electric current. Accelerators using for acceleration of macroparticles the pressure of a dense plasma arising as the result of electrical explosion of wires are called electrothermal accelerators. The temperature and consequently also the maximum velocity of the expanding plasma are limited by the power supplied to the wire. As a result of the high density of the high-temperature plasma formed in an electrical explosion of a wire, it radiates as a black body,[75] and therefore, assuming that the principal energy loss is due to radiation, we equate the electrical power dissipated in the wire ($W_e=J^2R$, where J is the current flowing through a wire with resistance R) to the radiated power $W_{\mathrm{b.b.}}=\Sigma T^4 S$, where $\Sigma=5.7\cdot10^{-5}$ erg/cm$^2\cdot$deg is the Stefan-Boltzmann constant and S is the area of the radiating surface. We find $T_{\max}\approx(W_e/\Sigma S)^{1/4}$ and the maximum velocity of sound in the plasma is

$$v_s\approx\frac{10^4}{\sqrt{A}}\sqrt{T}\approx\frac{3.4\cdot10^4}{\sqrt{A}}\left(\frac{W_e}{S}\right)^{1/8}. \qquad (17)$$

Energy storage capacitors existing at the present time[76] permit dissipation of an energy $Q\approx10$ MJ in a time $\approx10^{-8}$ sec, and therefore the maximum power is $W_e\approx10^{14}$ W $\approx10^{21}$ erg/sec and the maximum velocity of sound in the plasma for $S=1$ cm^2 is

$$v_s\leqslant\frac{1.4\cdot10^7}{\sqrt{A_0}}. \qquad (18)$$

For the lightest metals (Li) this velocity can reach $(3-5)\cdot 10^6$ cm/sec. Wires or foils are used as the exploding conductors.[76-81]

In Refs. 77 and 78 the pressure of explosion of aluminum foils was used for acceleration of Mylar films of thickness 0.1–0.01 mm. The maximum velocities reached $5\cdot 10^5$ cm/sec for the thinnest Mylar films. The efficiency of conversion of electrical energy to kinetic energy was 10–30% and decreased significantly with decrease of the film thickness (increase of the velocity).

Explosion of a wire has been used[76,79] for acceleration of glass spheres (Fig. 6). A wire 2 was placed in water at the end of a thin glass tube 6 which served as a barrel. After explosion of the wire the hot plasma ruptured the Mylar diaphragm 3 which initially closed the end of the tube and, being forced into the tube, pushed the projectile, which was located immediately beyond the diaphragm. The inertia and low compressibility of the water did not permit the gases to expand in all directions, and therefore almost all the mass of gas was forced into the tube. By this means a high efficiency of the gun was achieved. For glass spheres of mass 1.1 mg maximum velocities of $3.0\cdot 10^6$ cm/sec were achieved. The efficiency of the gun was 5–10%.

Thus, in explosion of conductors the maximum velocities of expansion of the explosion products are significantly higher than those of the products of an explosive material, and therefore in the direct method of acceleration by an electrothermal gun the maximum projectile velocities achieved are three times greater than the velocity of projectiles accelerated by explosive materials and two times greater than the velocity of projectiles accelerated by cumulative jets of explosive materials. Unfortunately, the author is not aware of any work on the cumulative acceleration of a plasma jet produced in an electrical explosion of conductors. However, there are other methods of acceleration of a plasma to high velocities which will be discussed in the next section.

h) Acceleration by a flux of plasma or gas

At the present time a number of methods exist for obtaining ultrasonic flows of a gas or plasma.[82-102] Some of them are used for acceleration of macroparticles.

If a macroparticle is placed in a gas or plasma jet, a force $F \approx S\alpha\rho_p(v_p - V)^2/2$ will act on it, where v_p is the velocity of the plasma flux, ρ_p is its density, S is the maximum cross-sectional area of the pellet at right angles to the flow, and $\alpha \approx 1$ is an entrainment coefficient which depends on the shape of the macroparticle. From this formula it is evident that the maximum velocity of a pellet in acceleration by a plasma flux is equal to the velocity of the plasma flux itself.

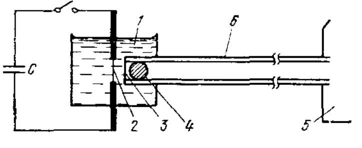

FIG. 6. Electrothermal accelerator. 1—vessel with water, 2—wire, 3—diaphragm, 4—macroparticle, 5—vacuum chamber, 6—glass tube (barrel).

Assuming that a spherical pellet of radius r_0 is accelerated in a pulsed gas flow for a period of time τ, we find its velocity after acceleration to be

$$V = \frac{F\tau}{m} \approx \tau \frac{\rho_p v_p^2}{2} (4\rho r_0)^{-1}. \tag{19}$$

In this formula we have assumed that $v_p \gg V$. Thus, the pellet velocity will be higher, the higher is the density of the momentum of the plasma flux $\rho_p v_p^2 \tau/2$. This quantity is extremely important in determining the efficiency of a pulsed plasma flux in acceleration of macroparticles. In spite of the fact that the velocities of plasma fluxes which are obtained at the present time reach 10^8 cm/sec, the velocities of pellets accelerated by this method, as far as we know, do not exceed $4\cdot 10^6$ cm/sec.[80] This is due to the low momentum density of existing pulsed plasma flows. In any case the maximum achievable velocity in acceleration by a plasma is equal to the smaller of the two quantities:

$$v_{\max} = \min \begin{cases} \tau \dfrac{\rho_p v_p^2}{2} (4\rho r_0)^{-1}, \\ v_p. \end{cases} \tag{20}$$

In Table I we have listed the characteristics of high-velocity plasma flows obtained by present methods.

It should be noted that in inelastic collisions of the particles of a plasma with an accelerated object the rate of transfer of kinetic energy to the object is comparable with the rate of transfer of thermal energy,[43] which can lead both to an additional reactive acceleration with ablation of the object and to an undesirable phenomenon—change of mass of the object on acceleration, and sometimes to its complete evaporation. The question of in what cases the reactive acceleration becomes comparable with the gas kinetic acceleration or exceeds it will be discussed in the next section.

Experiments on acceleration of glass spheres of diameter 35 μm have been described in Ref. 90. In this work a hydrogen plasma heated by an electrical discharge expanded through a Laval nozzle. The maximum velocity of the spheres reached $3\cdot 10^6$ cm/sec. The low density of the plasma did not permit acceleration of larger macroparticles.

In Ref. 91 a plasma obtained in explosion of a thin foil was accelerated in a rail-gun accelerator. The maximum velocities of the Pyrex spheres of diameter 0.15 mm accelerated by this plasma reached $1.6\cdot 10^6$ cm/sec.

In Ref. 92 an electrodynamic compressor was used to increase the density of a plasma obtained in explosion of a foil. In acceleration of glass spheres of diameter 125 μm by this gun, velocities up to $1.5\cdot 10^6$ cm/sec were obtained.

Reference 93 describes a two-stage accelerator whose first stage was a light-gas gun and the second—a coaxial accelerator with an electrodynamic compres-

TABLE I. Characteristics of plasma guns.

Type of accelerator	v_p, cm/sec	ρ_p, g/cm³	τ, μsec	P_d, dyn/cm²	P_r, dyn/cm²	V_{max}, theory	V_{max}, experiment	η, % efficiency
Coaxial accelerator filled with gas or plasma produced by a ruptured foil[83,100]	10^7–10^8	10^{-12}–10^{-10}	≈ 10	10^2–10^6	10^3–10^8	10^5 cm/sec for $r_0=0.1$ cm, $\rho_0=0.1$ g/cm³	—	≈ 0.5
Coaxial accelerator with magnetic compression[92,93]	10^6–10^7	10^{-8}–10^{-7}	≈ 100	$5\cdot10^3$–$5\cdot10^6$	$1.3\cdot10^{-4}$ $-3.6\cdot10^7$	$3\cdot10^5$ cm/sec for $r_0=0.1$ cm, $\rho_0=0.1$ g/cm³	$1.5\cdot10^6$ cm/sec for $d=125$ μm	≈ 0.1
Rail gun[82,91]	$3\cdot10^7$	≈ 10^{-9}	≈ 100	≈ 10^5	$3\cdot10^5$	$3\cdot10^3$ cm/sec for $r_0=\rho_0=0.1$	$1.6\cdot10^6$ cm/sec for $d=150$ μm, glass	—
Cumulative gas jet[83,86]	≈ 10^7	≈ 10^{-12}	≈ 1	≈ 10^2	$3\cdot10^2$	—	—	—
Titanium accelerator[94]	≈ 10^8	≈ 10^{-10}	≈ 10	≈ 10^6	10^8	10^5 cm/sec for $r_0=0.1$ cm, $\rho_0=0.1$ g/cm³	—	—
Voitenko accelerator[87-89]	≈ 10^7	≈ 10^{-6}	≈ 1	$5\cdot10^7$	$1.5\cdot10^8$	$1.5\cdot10^4$ for $\rho_0=0.1$ g/cm², $r_0=0.1$ cm	—	—
DeLaval nozzle[90]	≈ $3\cdot10^6$	—	—	—	—	—	$3\cdot10^6$ cm/sec for $\rho_0=6$ g/cm³, $r_0=35$ μm	—
Deflagration (burnup) accelerator[95]	≈ 10^8	≈ 10^{-10}	≈ 50	≈ 10^6	70 atm (theory), 60–80 atm (experiment)	$4\cdot10^5$ cm/sec for $r_0=0.1$ cm	—	≈ 0.5

sor. In this work glass spheres of diameter 0.6 mm were accelerated up to $2\cdot10^6$ cm/sec.

In recent years several experimental studies have also been made to check the possibility of use of the technique of accelerating fragile dueterium pellets by a gas or plasma flux.

In combination with the method of obtaining pellets from a liquid hydrogen jet, this method was used in Ref. 101 to obtain velocities of the order of 10^4 cm/sec of pellets of diameter 210 μm with an electron frequency $2.6\cdot10^4$ sec^{-1}. To obtain a pellet velocity of $\approx10^6$ cm/sec with a gas dynamic pressure $\rho_p v_p^2/2 \leqslant P_{\lim}$ and a gas flux velocity $v_p\approx10^6$ cm/sec (too high flux velocities will lead to ablation of the pellets) a gas jet with a density $\rho_p\approx10^{-5}$ g/cm³ is necessary. Here the time duration and length of the acceleration will be of the order of the minimum values for nondestructive acceleration (10^{-3} sec and 5 m, respectively). The possibility of obtaining gas jets with these properties requires special discussion. We note also that in addition to the problem of obtaining the gas jet there is also a problem of cutting it off in order not to introduce impurities into the reactor.

An experimental study of the possibility of acceleration of deuterium pellets by means of a coaxial plasma gun filled with hydrogen was carried out in Ref. 102. Glass spheres of diameter 1 mm were accelerated to a velocity $3\cdot10^3$ cm/sec. In the same study it was proposed, in order to obtain higher velocities, to use higher-velocity plasma guns so that the reactive jet would make possible further acceleration on ablation of the pellet.

i) Ablation accelerators

With intense heating of a part of an object, that part will fly off with a high velocity in one direction and push the unevaporated part of the object in the opposite direction as the result of the reactive recoil momentum. Macroparticle accelerators operating on this principle are called ablation accelerators.[4] Various methods of heating can be used: ablation by electromagnetic radiation,[4] by an electron beam,[4,103] by a proton beam,[104] by an ultrasonic gas or plasma flux,[105] or by induction currents.[38]

The velocity of a macroparticle can be determined by means of the well known Tsiolkovsky formulas:

$$V=v_r\ln\frac{M_1}{M_2}, \tag{21}$$

where M_1 is the initial mass of the macroparticle, M_2 is its final mass, and v_r is the velocity of the reactive jet. In contrast to ordinary reactive acceleration, in ablation acceleration the source of heating is outside the accelerated object.

From the law of energy conservation, written in the form[106]

$$W=\frac{dM}{dt}\left(\Lambda+\frac{\gamma^2}{\gamma^2-1}v_r^2\right)$$

(here W is the absorbed part of the power of the incident energy flux, dM/dt is the rate of evaporation of the pellet, and Λ is the heat of sublimation), it is evident that the incident energy flux is expended in sublimation of the pellet material and in acceleration and heating of the vapor. Studies carried out in Refs. 15 and 106 of the efficiency η of ablation acceleration,

$$\eta=\frac{M_2\,(V^2/2)}{(M_1-M_2)\,\{[\gamma^2/(\gamma^2-1)\,v_r^2]+\Lambda\}}\approx\left(1-\frac{1}{\gamma^2}\right)\frac{M_2\ln^2(M_1/M_2)}{M_1-M_2},$$

have shown that in acceleration of a pellet to a velocity $V\geqslant(2\Lambda)^{1/2}$ the efficiency is maximal for $V\approx v_r$: $\eta\approx(1-\gamma^{-2})\cdot0.64$; here $M_1/M_2\approx2.5$.

The maximum efficiency in this case differs by a factor $(1-\gamma^{-2})$ from the maximum efficiency in reactive acceleration. It must be noted that this formula was obtained without taking into account the radiation of the vapor of the reactive jet. However, recent studies[104,107] have shown that up to 50% of the energy input can go into radiation, so that the efficiency is about a factor of two lower than given by this formula. On the other hand, if the pellet is accelerated to a velocity $V \leqslant (2\Lambda)^{1/2}$, then the efficiency η is maximal for $v_r \approx (2\Lambda)^{1/2}(\gamma^2-1)/\gamma^2$, and in this case $\eta \approx \Delta M/M_1 \approx V/(2\Lambda)^{1/2} \to 0$ as $V \to 0$. In the latter case it is not advantageous to evaporate a large mass of the pellet for $v_r \approx V < (2\Lambda)^{1/2}$, since the principal energy in this case will be expended in sublimation of the material.

The reactive pressure P_r acting on the pellet is

$$P_r = \rho_p u v_r = v_r I\left[\Lambda + \left(\frac{\gamma^2}{\gamma^2-1}\right)\frac{v_r^2}{2}\right]^{-1}, \tag{22}$$

where u is the velocity of the evaporation wave and $I = W/S$ is the intensity of the incident power flow ($I = \rho_p v_p^3$ for the case of bombardment by particles having a finite mass and $I = E^2 c/4\pi$ for the case of electromagnetic irradiation, where v_p is the velocity and ρ_p is the density of the incident flux).

If the ratio of the reactive pressure to the dynamic pressure ($P_d \approx I/v_p$) is

$$\frac{P_r}{P_d} = \frac{v_r v_p}{\Lambda + [\gamma^2/(\gamma^2-1)](v_r^2/2)} \gg 1,$$

then in acceleration of a macroparticle the main role will be played by the reactive pressure. In order to learn in what cases this inequality will exist, it is necessary to relate the velocity of the reactive jet to the parameters of the incident flux.

The case of action of electromagnetic radiation has been repeatedly discussed theoretically.[4,108,109] In particular, it has been shown that the ratio $P_r/R_d \approx v_p/v_r = c/v_r \gg 1$, and therefore the ablation pressure will always be much greater than the light pressure and the velocity of the reaction jet will be $v_r \approx (I/\rho_c)^{1/3}$, $\rho_r \approx \rho_c$, where $\rho_c \approx 2 \cdot 10^{-11} A/z\lambda^2$ is the critical density of the plasma for the wavelength λ of the laser radiation. For example, for the case of bombardment of a hydrogen pellet by CO_2 laser radiation with $\lambda \approx 10.6$ μm with an intensity $I \approx 10^{12}$ W/cm², which is easily achievable by present methods, we obtain $v_r \approx 10^8$ cm/sec.

Processes of interaction with solid targets of ultrasonic plasma flows or a compensated beam of ions have been less studied. We note that apparently these processes will be analogous, since the energy transferred by the ions in ultrasonic plasma flows is much greater than the energy transferred by electrons, and the action of the latter on the target need not be taken into account. A one-dimensional model of the heating of an aluminum target by protons has been discussed in Ref. 104. In Ref. 101 estimates were made of the ablation pressure of a plasma flux on the surface of a deuterium pellet and it was proposed to use it for acceleration of deuterium pellets to a velocity 10^6 cm/sec for the purpose of injection into reactors.

For calculation of the ablation pressure of a plasma flow the author made use of the model proposed in Ref. 108 for the case of bombardment by laser radiation. It was assumed that the incident plasma flux is composed of hydrogen (or a beam of protons) and also that the accelerated macroparticle is a hydrogen pellet.

For the depth of penetration of the protons into a weakly ionized hydrogen plasma the following approximate formula has been used[111]:

$$l_r(\text{cm}) \approx \frac{4.5 \cdot 10^{-1} E^{2/3}}{\rho},$$

where E (in ergs) is the energy of the protons.

The region of the parameters of the plasma flow for which the reactive jet pressure exceeds the gas dynamical pressure is cross-hatched in the (n_p, v_p) plot (Fig. 7).

The velocity of the reactive jet can be evaluated approximately from the formula $v_r \approx 3 \cdot 10^{-3} v_p^{5/9} n_p^{1/3} r_0^{1/3}$ (cm/sec) and its density from $\rho_r \approx 5 \cdot 10^{-17} v_p^{4/3}/r_0$ (g/cm³).

For example, for the case of a deflagration (burnup) hydrogen gun[95] $n_p = 10^{14}$ cm^{-3}, $v_p = 10^8$ cm/sec, $\rho_p = 2 \times 10^{-7}$ g/cm³, $v_r = 2 \cdot 10^6$ cm/sec, $P_d \approx 10^6$ dyn/cm² ≈ 1 atm, and $P_r \approx 70$ atm. The experimental value of the pressure of a flow onto a solid target measured in Ref. 95 is 60 atm. The temperature of the plasma of a reactive jet is $T_r \approx 10^{-8} v_s^2/\gamma \approx 10^4$ K, that is, the plasma is weakly ionized and use of the formula of Ref. 111 for the absorption depth is justified. The ablation pressures produced in action of various plasma guns on solid targets are given in Table I.

We shall point out the limitation of the applicability of the above model due to the great depth of penetration of energetic protons into the accelerated pellet. From the condition $l_r \ll r_0$ we obtain $v_p \ll 3 \cdot 10^{10}$ cm/sec $\approx c$.

Similar calculations have been made for the case of bombardment of a hydrogen pellet by an electron beam. Here the electron penetration depth into the plasma was assumed to be classical: l_e (cm) $\approx 2.4 \cdot 10^{12} E^2/\rho$, where E (erg) is the electron energy, and in addition collective effects[112] were not taken into account nor was the possible charging of the pellet.[43]

From the condition that the electron penetration depth

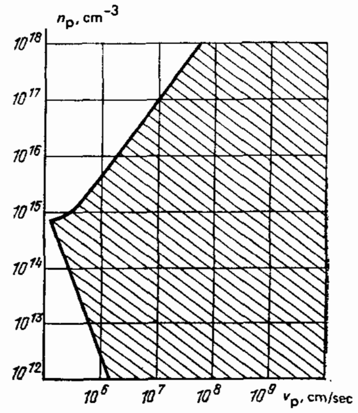

FIG. 7. Region of parameters of plasma jet n_p and v_p (cross-hatched) in which it is necessary to take into account ablative pressure.

into the condensed matter of the pellet be much less than the size of the pellet $l_e(\rho=\rho_0) \ll r_0$ we obtain for the electron velocity $v_e \ll 4.2 \cdot 10^9$ cm/sec (for an electron energy $E \ll 10$ keV).

The ratio of the reactive pressure to the dynamical pressure $P_r/P_d \approx 10^{-6} n_e^{1/2} v_e^{4/3}/r_0^{1/3} \gg 1$ for all cases which are of interest for the discussion. The velocity of the reactive jet can be estimated approximately from the formula $v_r \approx 2 \cdot 10^4 n_e^{1/3} v_e^{-1/3} r_0^{1/3}$, and its density from $\rho_r \approx 10^{-40} v_e^4/r_0$.

We note that for an electron beam in vacuum there is a limitation on the maximum achievable ablation pressure, due to the limiting vacuum current[44]: $J = \pi r_r^2 n_e e v_e \leqslant J_{\lim}$, from which we obtain for a nonrelativistic beam $n_e \leqslant m_e v_e^2/\pi r_r^2 e^2$, and $n_{e,\max} \approx 2 \cdot 10^{-7} v_e^2 \approx 2 \cdot 10^{11}$ cm^{-3} for $r_r = r_0$. The maximum pressure on the pellet is $P_{\max} = P_r(n_{e,\max}, v_{e,\max}) = 2.3$ atm and here $\rho = 6 \cdot 10^{-6}$ g/cm^3 and $v_r \approx 4 \cdot 10^5$ cm/sec.

Let us estimate the maximum possibilities of a laser and a plasma flux in ablation acceleration.

If we assume that the acceleration occurs in the optimal regime, so that $V \approx v_r$ and $M_1/M_2 \approx 2.5$, then it is easy to find that

$$V_{\max} \leqslant \frac{Q^{1/2}}{r_0^{3/2} \rho_0^{1/2}} \left(1 - \frac{1}{\gamma^2}\right)^{1/2}, \tag{22'}$$

where Q is the absorbed part of the energy incident on the pellet.

For present-day high-power lasers $Q \leqslant 10^5$ J $= 10^{12}$ erg. Therefore for $r_0 = 0.1$ cm and $\rho_0 \approx 1$ g/cm^3 we obtain $V_{\max} \leqslant 30\sqrt{Q} \approx 3 \cdot 10^7$ cm/sec. To preserve the integrity of the pellet it is necessary to accelerate it at pressures which do not exceed the destruction pressure. This can be achieved without reducing the efficiency of acceleration, by increasing the wavelength of the laser, and in this case for the same reactive jet velocity its density is decreased ($\rho_r \sim 1/\lambda^2$) and consequently also the pressure on the target $P_r \sim \rho_r v_r^2 \sim 1/\lambda^2$. However, in this case it is necessary to increase the acceleration time ($\tau \sim \lambda^2$).

In ablation acceleration by a plasma gun, in principle the maximum achievable velocity is equal to the velocity of the plasma flux, but in order that the pellet mass change insignificantly during acceleration it is necessary that $V \leqslant v_r$, where v_r is the velocity of the reactive jet. For example, for the most powerful of the present-day guns[95] ($v_p \approx 10^8$ cm/sec, $n_p \approx 10^{14}$) for $r_0 = 0.1$ cm we obtain $v_r \approx 2 \cdot 10^6$ cm/sec. For a velocity $V = 10^7$ cm/sec the pellet mass decreases by 150 times. Actually, however, even velocities $V \approx v_r$ are not achievable, as a result of the small duration of the pulses of plasma guns. For example, for the case of acceleration of a deuterium pellet by the gun mentioned with $\rho_0 = 10^{-1}$, $r_0 = 10^{-1}$, and $\tau = 4 \cdot 10^{-5}$ sec, we obtain $V \approx 4 \cdot 10^5$ cm/sec.

At the present time the greatest number of experimental studies have been carried out on light-reaction acceleration. In Refs. 4 and 41 it was shown that the pressure of a reactive jet is c/v_r times higher than the light pressure and it was proposed to use this to obtain hypervelocities. The first experimental results on acceleration of macrons by laser radiation were published in 1967.[113,114] These papers reported particle velocities reaching 10^6–$3 \cdot 10^6$ cm/sec.

A recent article[115] reported acceleration of a polyethylene foil of thickness 15 μm by light reaction to a velocity $5.1 \cdot 10^6$ cm/sec, which was obtained with a neodymium laser light-flux density $I \approx 10^{13}$ W/cm^2 with an efficiency of conversion of light energy into kinetic energy of the order of 6.6%. References 15 and 116 were directed at learning the optimal conditions for light-reactive acceleration.

Experiments[116] on acceleration of deuterium cylinders of diameter 300 μm by the radiation of a CO_2 laser with energy 0.5 kJ and pulse duration 50 nsec showed that the deuterium pellet is broken into fragments emitted in a cone with angle ≈60°, although the velocities of the fragments reached $8 \cdot 10^5$ cm/sec.

In order that there be no destruction, it is necessary to reduce the intensity of the bombardment, but in this case the length and time of acceleration increase and problems arise of obtaining extended high-power action and of incidence of the entire laser radiation on the pellet in the acceleration path. For solution of these problems it was proposed in Ref. 117 to use the observed phenomenon of the transverse generation wave of a solid-state laser to obtain a high-power extended giant pulse and motion of the ray focus. Reference 118 discussed the possibilities of this method and observed motion of the focus with use of a lens with spherical aberration. In Ref. 119 the motion of the focus was used to increase the efficiency of acceleration, and velocities up to $3.5 \cdot 10^5$ cm/sec were obtained for particles of mass $3 \cdot 10^{-4}$ g with an energy input ≈130 J.

The action of an electron beam with intensity $5 \cdot 10^8$–10^9 W/cm^2 focused onto solid targets of various materials was investigated in Ref. 103. The energy of the electrons in the beam was 50–100 keV, the beam current $I \approx 40$ kA, the pulse duration 0.2–1.5 μsec, and the energy density at the focus 110–260 J/cm^2. Here the specific recoil impulse reached 10 dyn·sec/J, which is of the same order as the recoil impulse obtained with the same flux densities in action of neodymium laser radiation. The fraction of the energy estimated by the authors as going into kinetic energy of the vapor was 20%. Here the ejected mass was (20–200) $\cdot 10^{-2}$ g/J and the pressure at the target $P \approx 10^3$–$5 \cdot 10^3$ atm. These numbers show that the action of electron beams is similar to that of laser beams of the same intensity and that it is possible to use them for reactive acceleration of macroparticles. When we take into account that the efficiency of electron beams is higher than that of laser beams, in some cases the use of electron beams is to be preferred.

A recent publication[120] reported acceleration by an electron beam of a polyethylene film of thickness 10 μm to velocities $(5$–$7) \cdot 10^6$ cm/sec. However, this was done not with the direct action of the beam on the polyethylene target, but with the radiation and expansion of a 5-μm gold foil strongly heated by the beam.

The ablative properties of high-velocity plasma jets have been studied in Refs. 105 and 121. In Ref. 105 in comparison of the action of the free operation of a neodymium laser and of a plasma flux of the same intensity it was shown that for $I \approx 10^5$–10^7 W/cm^2 the action of plasma fluxes is similar to the action of light radiation. The ablation of pellets accelerated by plasma fluxes has been pointed out by many experimental workers,[91,92] but as far as we know there has been no study of the ablative pressure in acceleration.

Application of Foucault currents induced in a conducting macroparticle for explosion of part of it for the purpose of reactive acceleration of the remaining part has been discussed by Winterberg.[38] He showed that with use of a magnetic field $B \approx 10^7$ G it is possible to accelerate a conducting pellet with a finite size $r_0 \approx 10^{-1}$ cm to a velocity $V \approx 10^8$ cm/sec in a length of 10 cm. Winterberg does not take into account the possibility of mechanical destruction of the pellet during acceleration. No experimental studies are known on reactive acceleration with use of the energy of Foucault currents for ablation.

3. APPLICATION OF ACCELERATION METHODS FOR PURPOSES OF CONTROLLED THERMONUCLEAR FUSION

a) Acceleration for refueling of thermonuclear reactors

It is clear from the above that obtaining velocities of 10^5 cm/sec for deuterium pellets appears to present no great technical difficulties. Foster and Milora[19] already have reported achievement of this velocity in a pneumatic gun. Perfection of methods of rotational acceleration and gas dynamical entrainment will apparently permit velocities of 10^5 cm/sec to be obtained in the near future with a high injection frequency. It is much more difficult to obtain a velocity of 10^6 cm/sec for deuterium pellets. At the present time this velocity has been obtained only for fragments of a hydrogen pellet accelerated by laser radiation.[116] For this reason experiments are needed in the very near future to determine with greater precision the parameters of accelerated macroparticles (velocity, size, injection frequency).

In Table II we have listed the most promising methods of acceleration of deuterium fragments to a velocity of 10^6 cm/sec. Explosive and electrothermal methods are not included in the table, since they produce high short-time forces on the accelerated object and therefore are not applicable for acceleration of fragile deuterium pellets. In the table we have taken into account also that acceleration by magnetic methods is possible with use of a composite pellet. Evidently in ablative acceleration by laser radiation it is also necessary to use a composite pellet with a shield layer which is subjected to the bombardment. The fact is that a deuterium pellet is transparent for the radiation generated by contemporary high-power lasers at intensities not producing breakdown at its surface, and the intensity of radiation sufficient for breakdown produces a pressure of the reactive jet on its surface which is significantly higher than the destructive pressure.

TABLE II. Possible methods of acceleration for the purpose of refueling a thermonuclear reactor (foı deuterium pellets with diameter 1 mm with velocity $\approx 10^6$ cm/sec).

Method	Efficiency	Limitations on possibility of accomplishment	Experiment
1. Two-stage light-gas gun	$\eta \approx \frac{5\cdot 10^{9}}{V^{2}} \approx 5\cdot 10^{-3}$[54]	1. High pressures of working gas 2. Difficult to achieve high injection frequency	—
2. Gas laser gun	$\eta \approx 5\cdot 10^{-3}\eta_L$, where η_L is the laser efficiency	1. High pressures of working gas 2. Achievement of a nondestructible working chamber transparent to radiation	—
3. Elastic scattering of electron beam	$\eta \approx 1$	1. Necessary to achieve long pulse duration with high electron energy	—
4. Gas dynamical entrainment	$\eta \approx 0.01-0.1$, continuous power 1 MW/cm^2	1. Necessity of creating stationary gas flow with $v_p \approx 10^{16}$ cm/sec, $n_p \approx 10^{19}$ cm^{-3}	$V \approx 10^4$ cm/sec for $d \approx 210$ μm (Ref. 101)
5. Ablation by plasma flux	$\eta \approx 10^{3}-10^{-1}$	1. Necessity of creating gun with parameters $n_p \approx 10^{14}$ cm^{-3}, $v_p \sim 10^8$ cm/sec, $\tau \approx 1$ μsec	—
6. Acceleration of deuterium-magnet or deuterium-superconductor composite pellet	$\eta \approx 10^{-1}-10^{-2}$	1. Removal of auxiliary pellet 2. Synchronization of pellet and magnetic field motions	—
7. Acceleration of composite pellet by ablation by laser radiation	$\eta < 0.01\eta_L$, where η_L is the laser efficiency	1. Difficult to achieve high injection frequency 2. Necessity of removing plasma with high atomic weight A	$V = 3.5\cdot 10^5$ cm/sec for g of Ni (Ref. 119)

We can draw the following conclusions. The most highly promising method from the point of view of efficiency is acceleration of a charged pellet by an electron beam elastically scattered by it, but accomplishment of this method obviously faces great technical difficulties which cannot be foreseen beforehand, since there have been no experiments. The most suitable method would be gas dynamical entrainment, since combination with it of the method of breakup of a liquid jet to obtain deuterium pellets[101] would enable one to avoid the problems of a high injection frequency.

The light-gas gun and the laser ablation method have been best studied experimentally, but in addition to the low efficiency of these methods, many complicated technical problems stand in the way of their use. To accomplish ablation by a plasma flux, a gun with a long pulse duration is necessary.

TABLE III. Methods of acceleration to obtain thermonuclear microexplosion.

Method	Expected energy expenditure (efficiency)	Experiment	deficiencies
1. Acceleration of superconducting pellets by a moving magnetic field	Efficiency can be high	—	Large length of accelerator, development of new superconductors is necessary
2. Elastic scattering of beam of charged microparticles by a charged macron of the same sign	Efficiency can be high	—	*Development is necessary* of sources of charged microparticles with large pulse duration $\approx 10^{-4}$ sec *and high energy* ≈ 5 *MJ*
3. Ablation method	Efficiency $\eta < 0.2\eta_s$, where η_s is the efficiency of the radiation source	10–15 μm, laser, electron beam 10^7 cm/sec	Low efficiency, and lack of sufficiently energetic sources

b) Acceleration to obtain a thermonuclear microexplosion

The methods possible in principle of obtaining velocities of 10^8 cm/sec are given in Table III. In acceleration of a superconducting pellet by a linear electrostatic accelerator and by a traveling magnetic field an extremely great acceleration length is necessary (≈ 100 km). The situation is not greatly improved by use of special projectiles and targets[12,13] which permit the restriction to velocities $\approx 10^7$ cm/sec with macroparticle dimensions one or two orders of magnitude greater (acceleration length ≈ 1–10 km with a significant increase of the energy input). Greater hopes are placed on creation of new types of superconductors[122] which will maintain higher currents and magnetic fields than those which exist at the present time, and also on progress in the field of megagauss technology. Of the ablative methods of acceleration, apparently the best results can be obtained by the laser ablation method, since the velocities of the reactive jets in bombardment by an electron beam and plasma flux are small (see subsection 2i). However, the energy necessary for acceleration $Q \approx mV^2/2\eta \approx 0.5$ MJ$/\eta \approx 1$ MJ even with the maximum acceleration efficiency ($\eta \approx 0.5$) is not available with contemporary pulsed lasers.

To achieve the method of elastic scattering of a beam of charged microparticles by a similarly charged macron it is necessary to develop electron and ion beams with a long pulse duration ($\approx 10^{-4}$ sec) and high energy (≈ 5 MJ).

There is one additional possibility of achieving the necessary parameters of macroparticles—acceleration of a large number of very small particles with subsequent formation of a condensate.[38] The possibility of electrostatic acceleration of a dust cloud with subsequent condensation has been discussed in Refs. 3 and 38. In order that the potential produced by the particles of the cloud be significantly less than the accelerating voltage, as is shown in Ref. 38, the size of the cloud of dust must be greater than 300 m.

Although the accelerated macroparticle parameters achieved at the present time evoke no special optimism, nevertheless our analysis of the known methods of acceleration shows that they are far from exhausted.

Intensive development of the technology of high-power electron and ion beams, plasma accelerators, laser and megagauss technology, and also progress in creation of new types of superconductors can make this direction in controlled thermonuclear fusion promising.

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