Passage of accelerated particles and quanta through a medium along a reduced-density channel produced by a laser beam

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It is shown experimentally and theoretically that ionization and heating of a medium in a laser beam can produce a reduced-density channel through which accelerated particles (charges, quanta, macrons) and beams can pass without strong scattering and without strong energy dissipation. Estimates are obtained of the running energy release needed for the formation of such a channel, for its formation time, and for its lifetime, which is shown to be able to exceed hundreds of microseconds. Various methods are considered for the production of the energy release; breakdown, plume, optical detonation, etc.—in the beam or across a moving focus in the case of self-focusing in a gas or in a dense medium, or in the case of focusing by a lens with variable focal length.

The passage of charged particles and beams through a medium is accompanied by strong scattering (the multiple scattering angle is $\theta_s \approx (21/\mathcal{E}_{\mathrm{MeV}})\sqrt{L/L_{\mathrm{rad}}}$) and by energy losses to excitation and ionization of the medium $(d\mathcal{E}/dx)_{\mathrm{ion}} \approx (\mathrm{MeV/g})/\beta^2$, which greatly hinders their directional propagation. For example, in the case of nonrelativistic particles, the range is $L_{\max} \approx 10^{-6}\mathcal{E}^2/\rho$, where $\mathcal{E}_{\mathrm{keV}}$ is the electron energy in keV and ρ is the density of the medium. In the case of high-power beams, there is also additional Coulomb spreading. For macroscopic particles, the pressure that resists motion with velocity u is equal to $p \approx \rho u^2$. In the case of quanta, the absorption depends on the density.

We show in this paper that ionization and heating of the medium in a laser beam can produce in a medium a reduced-density channel through which accelerated particles and quanta will travel much farther than in an unperturbed medium.

1. In the case of strong and fast ionization of the medium in a column having an initial radius r_0, the pressure is increased by an amount $p \approx n\epsilon_0 \approx 16$ to 50 atm at $\epsilon_0 \approx 1$ to 3 eV and $n \approx 10^{19}$ cm^{-3}, and when the pressure becomes equalized the density in a column of radius $r_1 \approx r_0(p_e/p_0)^{1/2\gamma}$ the density decreases by a factor $(r_1/r_0)^2 \approx (p_e/p_0)^{1/\gamma} \approx 10$ to 20 times at $\gamma \approx 1.2$ for air. In this case, after the electrons are produced and prior to recombination and trapping, they transfer thermal energy to the ions and atoms of the gas, so that the electrons take part in the increase of the pressure. For a channel to be produced in this manner it is necessary to have a running energy consumption $q_1 \approx \pi r_0^2 n_e I \approx$ J/cm for $r_0 \approx 0.1$ cm at $n_e \approx 10^{19}$ cm^{-3} and at an energy $I \approx 30$ eV for the production of an ion pair.

For example, at a residual temperature in the channel $\epsilon_1 \approx 1$ eV, upon equalization of the pressure the particle density is $n \approx p_0/\epsilon_1 \approx 3\times 10^{-2}\, n_{\mathrm{norm}}$.

The gasdynamic processes during and after the energy release are described in the case of interest to us by the theory of so-called linear explosion. In this case the radius of the shock wave is $r_{\mathrm{sh}}(t) \sim (q_1/\rho_0)^{1/4} t^{1/2}$, and for small distances from the axis the density of the medium is $\rho(r) \approx \rho_{\mathrm{sh}}[r/r_{\mathrm{sh}}(t)]^{2/(\gamma-1)}$. When the shock wave becomes weaker, i.e., at $r_{\mathrm{sh}} \sim r_{\mathrm{cr}} \sim (q_1/\pi p_0)^{1/2}$, such a density distribution is preserved after a time $t \sim r_{\mathrm{cr}}/c_s$, so that the "temperature trail" of the energy release is quite long-lived, until the thermal conductivity and radiation cool the heated column of the medium.

Estimates show that to produce a reduced-density channel it suffices to have a running energy release $q_1 \approx 0.1$ to 1 J/cm at a radius $r_0 \approx 0.1$, and the channel is then formed after a time on the order of $t_f \approx r_0/c_s^R \sim \mu$sec and assumes a steady state after a time $t_{\mathrm{ss}} \approx r_{\mathrm{cr}}/c_{s0} \approx 10$ μsec, and has a lifetime $t_l \gg t_{\mathrm{ss}}$ because of the low rate of energy removal.

The energy release can be produced by breakdown, by optical detonation, by a plume, over some other optical energy-release means, as well as by multiphoton ionization and simple photoionization. Optical sparks up to several dozen meters in length have by now been produced.

The passage of a beam of accelerated particles through a medium with a reduced-density channel produced by laser breakdown was investigated experimentally.

The experimental setup is shown in Fig. 1. The beam from a Q-switched neodymium laser 1 (pulse duration 30 nsec, energy up to 3 J) was focused by lens 2 of focal length 8 cm into the interior of the vacuum chamber 3, in which a high-speed valve 4 admitted within ≈ 100 μsec a cloud of gas in the region of the chamber near the focus of the lens.

A pulsed electron beam was passed along the chamber through diaphragms 5. The beam came from an accelerator with a needle-point cathode 6, on which a short voltage pulse (– 50 kV) of duration up to 100 nsec was applied from a 5-stage Marx generator triggered by the

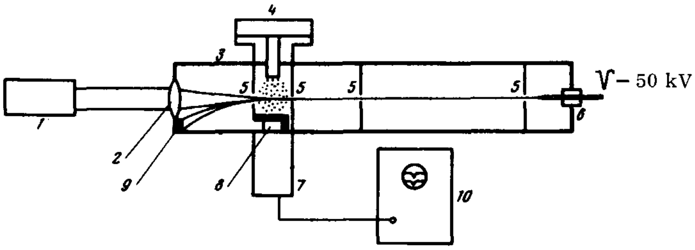

Fig. 1.

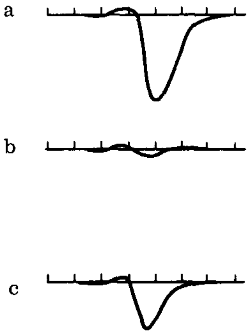

Fig. 2.

laser. The diaphragm closest to the needle, located 10 mm away from the needle, serves as the anode.

The electron and laser beams were made coaxial by using the ordinary visual methods (luminor, adjusting radiation, etc.) with the vacuum already in the chamber. The transmitted electron beam was registered by using the x-rays from lead target 9, on which the electrons were incident after being deflected by a transverse magnetic field. The x-rays were registered with a POPOP scintillator 8 and a type FÉU-30 photomultiplier 7, the output pulse of which was fed to oscilloscope 10 (S8-2 two-beam oscilloscope with memory). The scintillator was covered by an opaque protective shield with a port that admitted quanta only from the target 9. The port was covered by a filter layer that passed quanta of energy $\gtrsim$ 30 kV. The gas pressure in the cloud emitted by the valve was close to atmospheric. The gas pressure over the valve was 8—12 atm.

To estimate the efficiency of the electron gun and the degree of passage of the electron beam through the cloud of gas, the lens was replaced by a Faraday cup that measured the passing charge, or by a luminor. The gas pressure and the dimensions of the cloud were chosen such that the gas caused complete blocking (scattering) of the electron beam. The length of the light spark was close to the thickness of the cloud in the region of its intersection with the beam.

An abrupt increase in the passage of the electron beam through the gas was observed following the production of the laser spark. Figure 2 shows an oscillogram of the signal from the electron beam in vacuum without operation of the valve (a), the vanishing of the signal following the pulsed gas admission (b), and the signal from the electron beam passing through the light-spark channel due to a laser pulse that was flashed 1 μsec prior to the electron gun. The time marker values are 0.1 μsec/division. The beam-scattering angle decreased by not less than one order of magnitude, while the density decreased by hundreds of times. Good passage of the electrons through the channel was observed even 200 μsec after the spark formation, whereas without the spark the electron beam was still strongly blocked by the gas jet. Recognizing that the motion of the gas jet can only decrease the lifetime of the channel, we can state that the channel passes electrons during a time of not less than several hundred microseconds.

We note that in the case of the passage of very strong beams the directivity of the propagation is somewhat improved as a result of the self-induction increase in the electron mass: when account is taken of the induction acceleration, the longitudinal mass of the electron is $m_{\text{eff}} \approx m_0(1 + N_1 r_0 L_1)$, where N_1 is the running number of electrons, L_1 is the running inductance, and r_0 is the classical radius of the electron. However, dissipation of the motion in the medium takes place just the same, and decreases when the channel is produced. We note that the plasma of the channel can weaken the Coulomb spreading of the electron beam and give rise to an inverse self-induction current. Let us point out the difference between our experiments on sounding the channel with accelerated electrons from experiments on the passage of ohmic or breakdown current through a laser-spark plasma, e.g., for the purpose of short circuiting a discharge gap; in these experiments the only important factor is the conductivity of the produced plasma, which perturbs the external electric field of the conducting current.

Great interest attaches to the formation of a channel by a laser beam in a liquid or in a dense body. In this case one can obtain a thousandfold decrease in the density of the medium in the channel, and the dimension of the formed channel can exceed by dozens of times the initial transverse dimensions $r \approx r_0 \sqrt{\rho_{\text{liq}}/\rho_{\text{vap}}}$. The lifetime of such a channel can reach a fraction of a second.

We point out that the energy release can also be decreased by the moving focus of a laser beam. For example, in the case of self-focusing, the motion of the focus is determined by the Kelly relation $L_{\text{Kelly}}(t) \approx a/\sqrt{n_2}(E - E_{\text{thr}})$, and the concentration of the action becomes record-breaking, since the dimensions of the focus can be extremely small (on the order of several wavelengths). This makes the running energy needed to produce the thin channel very small, $q_1 \approx \pi r_f^2 n_e I_{\text{eff}} \approx 10^{-3}$ to 10^{-4} J/cm $(n_e I_{\text{ion}} \approx n_a I_{\text{evap}})$.

A reduced-density channel can increase also the range of neutral particles (neutrons, macrons), and also of ultraviolet and x-ray quanta. For macroscopic particles, the range is $L \approx M/s\rho$, where M/s is the mass per unit particle cross section, i.e., a decrease of ρ increases the range and decreases the loss of particle velocity.

Obviously, a reduced-density channel can be produced in a medium not only by a laser beam, but also by millimeter-wavelength and microwave beams, but their directional concentration is worse than that of light beams.