Electrical Discharges Guided by Pulsed CO_2-Laser Radiation

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A chain of aerosol-initiated, CO_2-laser-produced, air-breakdown plasmas has been used to guide electrical discharges over distances $\lesssim 2$ m in laboratory air in a direction almost perpendicular to the strongest electric field. The guiding effect existed at average electric fields $\gtrsim 1$ kV/cm and the discharge propagation velocity (10^9 cm/sec at 360 kV) depended on the applied potential. Such laser-initiated current-carrying channels appear to be capable of efficiently transporting relativistic electron beams in pellet-fusion reactors.

One of the outstanding problems in relativistic-electron-beam (REB) driven inertial-confinement fusion[1,2] is that of efficiently propagating the focused high-energy beam from the diode to the target. (A similar problem may also exist in light-ion-beam driven inertial-confinement fusion.[3]) In recent REB experiments[4] the beam was transported along channels formed by "exploding" wires in an atmospheric-pressure background gas, but such techniques are not suitable for repetitively pulsed fusion reactor systems. To transport REB's efficiently, one must establish an azimuthal magnetic field in a highly conducting channel to obtain both beam-current neutralization and pinched-mode propagation. Miller *et al.*[4] have suggested that this may be achieved using "laser-initiated discharge channels."

In this Letter we report new data on the propagation of electrical discharges along laser-initiated channels in the atmosphere. Our channels may differ from those ultimately needed for REB-driven fusion reactors because they are initiated by optical breakdown on natural atmospheric aerosols,[5,6] and they appear to be of larger radius than desirable in a fusion reactor. However, we have demonstrated that (i) electric discharges can propagate along laser-initiated channels even when these channels are perpendicular to the strongest electric field; (ii) guided electric discharges will propagate at average electric field strengths as low as 1 kV/cm; and (iii) the average discharge propagation velocity depends on the applied electric potential and appears to saturate at $\sim 10^9$ cm/sec at an applied potential φ of ~ 400 kV. These observations were made on discharges propagating over distances from 0.5 m to almost 2 m. Other laser systems have reportedly achieved chains of aerosol-induced breakdowns up to 60 m long[7] so that much longer guided discharges may be feasible.

Previously, laser-induced channels in gaseous atmospheres have been noted to guide electric discharges in short gaps under conditions where the laser-produced channel was parallel to the strongest electric field.[8,9] Akmanov, Rivlin, and Schildyaev[10] found that discharges could be inclined at angles up to 30° to a uniform electric field, and Koopman and Saum[11] observed that long guided discharges propagated with unusually high velocities.

In our experiment (Fig. 1) the CO_2 laser beam was directed to define a channel approximately perpendicular to the spontaneous-breakdown path. The 1-kJ CO_2 laser pulse[12] (100-nsec full width at at half-maximum initial spike followed by a 1.5-μsec tail) was focused by a 3-m focal length $f/13$ germanium lens, and produced a chain of apparently discrete air-breakdown plasmas. Aerosol breakdown occurred over lengths of up to 2 m, the diameter of the breakdown region varying from about 10 cm near the positive electrode to 1–2 cm near the point of contact with the ground plane. Streak-camera and schlieren studies have shown[13] that breakdown occurred during the initial spike of the laser pulse in the focal region, and during the tail of the laser pulse for distances > 30 cm away from focus. About 80% (800 J) of the laser energy was absorbed in the breakdown channel, yielding an average absorbed energy density of 0.5 to 1.0 J/cm^3. However, a cylindrical blast-wave analysis[14] of the weak shock observed near the lens focus indicated somewhat higher energy absorption (3 J/cm^3) in that region.

The electrical discharge was initiated by applying a fast-rising positive potential of up to 360 kV to the high-voltage electrode. Current-voltage characteristics, similar to those shown in Fig. 1, indicated that the time t_s required to form a high-current discharge increased as the applied voltage decreased. A similar increase in t_s occurred as the delay time τ between the firing of the laser

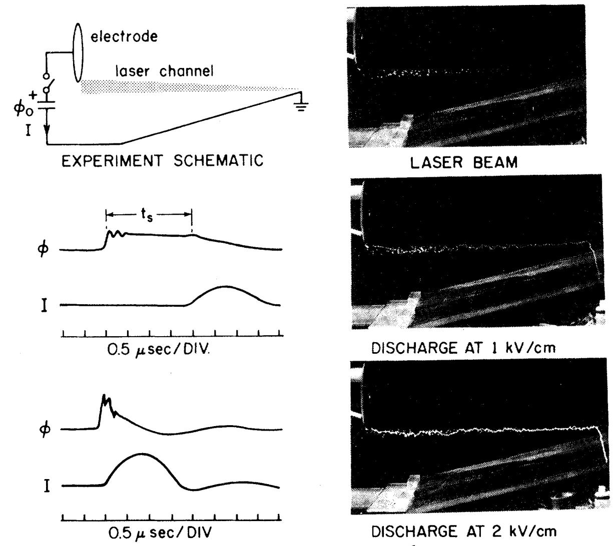

FIG. 1. *Top left:* The experimental system used to create laser-guided electrical discharges (laser incident from left). The horizontal distance L from the electrode along the laser beam to the ground plane could be varied from 0.5 to 2.0 m. The vertical distance from the bottom of the electrode to the ground plane was 0.4 m. *Top right:* Open-shutter photograph of laser-produced air breakdown sparks with no applied voltage. *Center:* Voltage and current traces, and open-shutter photograph, for a guided discharge at φ = 180 kV, L = 180 cm, and τ = 20 μsec; t_s is the discharge formation time. The peak current was 1.5 kA. *Bottom:* Voltage and current traces, and open-shutter photograph, for a guided discharge at φ = 360 kV, L = 180 cm, and τ = 20 μsec. The peak current was 3.0 kA. (In both cases shown, the discharge "jumps" directly to ground after guiding for ~ 130 cm.)

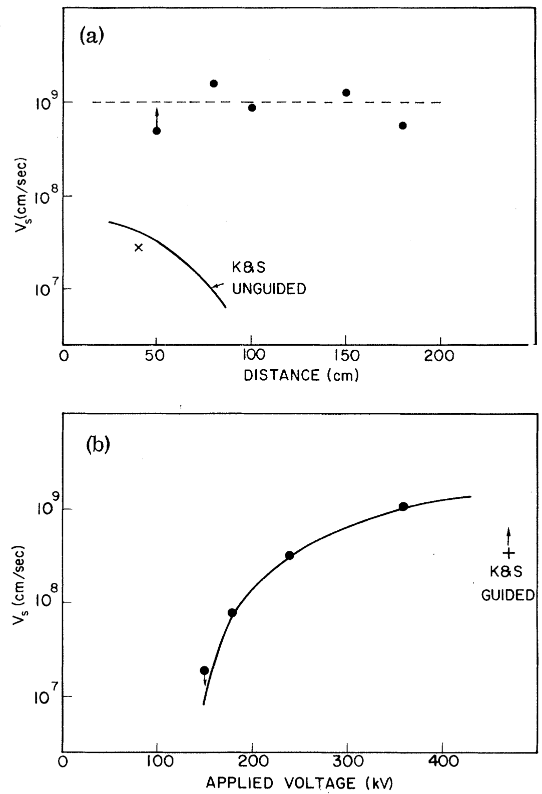

FIG. 2. (a) Variation of the velocity (V_s) with the distance (L) in guided discharges at a constant applied voltage (φ = 360 kV). (b) Variation of the velocity (V_s) with the applied voltage for guided discharges. Delay times (τ) vary from 10 to 100 μsec. ↑ shows that a minimum value was obtained. ↓ shows that a maximum value was obtained. Cross, unguided discharges in this experiment. Results obtained by Koopman and Saum (K + S) in Ref. 11 are shown for comparison.

and the application of the high voltage approached the millisecond range. An average velocity of discharge propagation V_s was defined as the ratio of the discharge length L to the time t_s. In normal (unguided) long-spark experiments this velocity would have been equivalent to the average leader velocity since the streamers and the return stroke travel much faster.[15] V_s was found to be independent of L for constant applied voltage within the range 10 μsec $\leq \tau \leq$ 100 μsec [Fig. 2(a)]. For delay times below 10 μsec, V_s decreased (e.g., τ = 2 μsec; $V_s \sim 3\times 10^8$ cm/sec) because in the region away from focus the laser-produced air-breakdown path was not yet optimally formed. At delay times greater than 100 μsec, V_s again decreased (e.g., τ = 2000 μsec; $V_s \sim 10^8$ cm/sec) as the laser-produced channel lost its guiding ability. The average discharge propagation velocity for guided discharges at φ = 360 kV and $L \leq 200$ cm was $V_s \sim 10^9$ cm/sec. This is significantly larger than the analogous velocity in unguided discharges both in our own experiments, e.g., $V_s \sim 3\times 10^7$ cm/sec at φ = 360 kV, and as measured by Koopman and Saum[11] at φ = 470 kV [Fig. 2(a)]. Although local streamer velocities as high as 5×10^9 cm/sec have been reported in (unguided) long-spark experiments,[15] leader velocities usually range between 10^6 and 10^7 cm/sec rising to ~ 10^8 cm/sec at very high field strengths.[16] The velocity measured in our guided discharges is close to the return-stroke velocity calculated by Loeb[17] (~ 1.2×10^9 cm/sec) and that measured by Dale and Aked[16] [$(1-1.5)\times 10^9$ cm/sec].

In Fig. 2(b), the average discharge velocity for guided discharges is shown to be a strong function of the applied voltage, φ, for the delay range 10 μsec $\leqslant \tau \leqslant$ 100 μsec, saturating near $V_s \sim 10^9$ cm/sec at an applied potential of ~400 kV. The measurement by Koopman and Saum[11] established a lower limit for this velocity which is consistent with the present data.

For discharge lengths $\leqslant$ 2 m and for positive potentials, the breakdown threshold for unguided discharges in the atmosphere corresponds to an average electric field ($\overline{E} = \varphi/L$) of ~5 kV/cm. By contrast these laser-guided discharges required much lower field strengths, $\overline{E}$ = 2 kV/cm and 1 kV/cm, and propagated more rapidly, $V_s = 10^9$ cm/sec and 10^8 cm/sec at φ = 360 kV and 180 kV, respectively,

The observation that V_s was not dependent on L or $\overline{E}$ but depended on the applied voltage φ suggests that in the prebreakdown stage, when a potential wave[17] must have propagated along the laser-produced channel, the channel conductivity was sufficient that a large fraction of the value of φ appeared in this wave even as it approached the ground plane. This is consistent with the ability of the discharge to "jump" approximately 10 cm to the ground plane, as shown in Fig. 1, after already traveling approximately 130 cm along the laser channel.

During the CO_2-laser pulse, the guiding properties of the laser-produced channel and the enhanced discharge propagation velocity could be explained by the presence of a quasicontinuous path of plasma with electron density $\geqslant 10^{12}$ cm^{-3}, which is sufficient to cause the transition from a "streamer" to a "return stroke" stage of discharge propagation.[17] At later times, simple recombination-rate calculations[11] suggest that high concentrations of free electrons are unlikely to exist in ambient air, but that substantial populations of low-ionization-potential negative ions (O_2^-) are created when laser-produced air-breakdown plasmas recombine. At temperatures around 1000°K, which schlieren photographs indicate for our laser-produced channels, thermal collisional detachment counteracts the formation of these ions and allows a significant population of free electrons.[18,19] Measurements by Reilly, Singh, and Weyl[20] indicated electron densities $\geqslant 10^{12}$ cm^{-3} in similar laser-produced air sparks up to 1 msec after the laser pulse. If these laser-produced channels were quiescent they would exist until thermal conduction effects cooled them on time scales of ~0.2 sec.[9] However, both our own optical diagnostics[13] and those of Ref. 20 indicate that the laser-produced channels are turbulent and mix with the surrounding air in a time of 1–2 msec. This cooling allows electron attachment to dominate, the free-electron population falls below that of a well-formed leader[17] (~10^{11} cm^{-3}), and the laser-produced channel no longer can guide an electric discharge.

The atmosphere in a REB-driven inertial-confinement fusion reactor may not be air at atmospheric pressure and thus the details observed above that depend on air chemistry may not be applicable. Also, the creation of conducting channels using aerosol-induced optical breakdown in a reactor environment with CO_2 or Nd:glass lasers may not be the optimum means of creating such channels. In a wet-blanket type of fusion reactor, where there is expected to be lithium vapor at ~10 Torr, it may be possible to create an ionized channel using nonresonant multiphoton ionization. In a high-density–gas-blanket type of fusion reactor, small quantities (~10^{12} cm^{-3}) of a readily ionizable species such as lithium vapor could be added to allow creation of an ionized channel by resonant excitation.[21] Regardless of how the conducting channel is created, the properties of electrical discharges propagating along it should be similar to those reported here.

In conclusion, we have shown that laser-initiated current-carrying plasma channels, similar to those required for REB-driven inertial-confinement fusion, can be created using aerosol-initiated, CO_2-laser–produced air breakdown. Creation of such channels requires only a small average electric field of 1 to 2 kV/cm along the laser-produced ionization channel, and the discharge propagation velocity is enhanced to 10^8 and 10^9 cm/sec for applied potentials of 180 and 360 kV, respectively.

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Specific Heat of Dilute Solutions of ^{3}He in ^{4}He and the ^{3}He-Quasiparticle Excitation Spectrum

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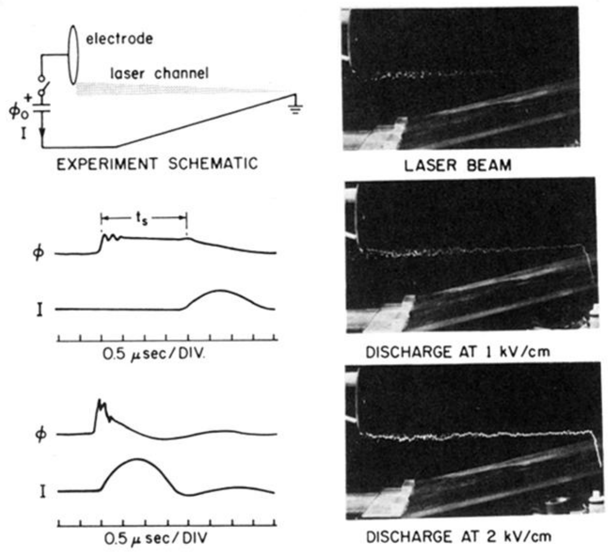
High-precision measurements of the constant-volume specific heat of ^{3}He-^{4}He solutions with up to 1% ^{3}He are presented for the temperature range 70 mK $< T <$ 1 K. The data are inconsistent with three previously proposed ^{3}He-quasiparticle excitation spectra: (1) a spectrum which is purely quadratic in wave number k, (2) a spectrum which is quadratic for small k and possesses a "roton" minimum at larger k, and (3) a spectrum which as a k^4 term in addition to the k^2 term at all values of k.

Thirty years ago Landau and Pomeranchuk[1] (LP) proposed that ^{3}He atoms in dilute solutions of ^{3}He in ^{4}He should behave as an ideal Fermi gas with a quasiparticle excitation spectrum $\hbar^2k^2/2m_3^*$. Various recent experiments[2-8] on ^{3}He-^{4}He mixtures have, however, demonstrated that this energy spectrum is not completely adequate. In order to explain the experimental results, it has been suggested that the spectrum should also contain[2] a term proportional to k^4 or that the spectrum possesses[9-11] a rotonlike minimum. In the latter case, the spectrum in the region of the minimum is approximated by $\Delta_3+\hbar^2(k-k_3)^2/2\mu_3$. Neutron-scattering measurements,[8] although consistent with the LP spectrum at small wave numbers k, do show deviations from the quadratic form which increase with increasing momentum. Unfortunately, because of resolution problems at the larger values of k, these measurements are inconclusive regarding the existence of a possi-



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