The Laser Lightning Rod System: Thunderstorm Domestication

Leonard M. Ball

An unusual application of the laser, namely protection of life and property from lightning, is described. The device relies on multiphoton ionization in mode-locked beams, rather than on collisional (avalanche) electron production. Feasibility is demonstrated numerically, and relevant principles explained. A method of mobile deployment is mentioned, by which economic (as opposed to scientific) feasibility might be achieved.

The Laser Lightning Rod System (LLRS) is a mode-locked laser that produces large scale multiphoton ionization (MPI) in the right places at the right times. Calculations indicate that it will have a useful range of a few kilometers and be capable of predetermining the paths of stepped leader (and hence lightning channel) development throughout a volume determined by this range. To the extent that Vonnegut's electrical theory of tornadoes may be valid, the LLRS may permit the destructive force of tornadoes to be diminished (by providing an alternative path to ground for the lightning currents that would otherwise serve to heat the tornado core). Helicopter-borne, and periodically grounded in a scheme to be described elsewhere, pairs of such systems could give hot pursuit to active thunderstorm cells throughout their lifetimes, diverting all cloud-to-ground strikes harmlessly to ground, even over forested terrain too rugged for surface vehicle penetration or helicopter landing. In contrast to lightning abatement schemes based on chaff dispersal, the LLRS does not litter the landscape, does not require that aircraft go near (or blindly penetrate deep into) the thundercloud, can respond much more quickly to changing conditions, and is better matched to thunderstorm cell drift velocities.

A classical prerequisite for collisional ionization in a laser beam is that the amplitude of free electron motion, as induced by the alternating optical frequency electric field, shall be comparable with the electron mean free path. In the laser-induced long spark demonstrations of Basov and Hagen, the electron mean-free path exceeded the amplitude of motion by factors of about 2000 and 6000, respectively. Yet production of visible laser-induced breakdown in air is known to require about 43 generations of electron multiplication. The classical description is clearly beset by a mean-free-path catastrophe. Explanation of laser-induced breakdown in such cases demands a combination of two nonclassical processes, multiphoton ionization (MPI), followed by drastic single-photon inverse bremsstrahlung (IBI) acceleration of the electrons in the fields of the parent ions. By the IBI process, which is very efficient, the electrons quickly acquire sufficient energy and range to participate in ionizing collisions. Unable to foresee a decade ago in 1964 that the classical mean-free-path catastrophe would be so easily overcome, I prematurely and wrongly predicted that the laser lightning rod would not work.

Experiments by Koopman and Wilkerson have pessimistically indicated that conditions essentially indistinguishable from complete laser-induced breakdown were required for significant leader and channel localization. In these experiments the mistake was made of firing the Marx generator before firing the laser, thereby giving highly ionized corona streamers an unfair advantage (a head start in an exponential race) over the laser-induced ionization in predetermining the leader path. More recently, Koopman and Saum have reported experiments in which the laser was fired first. With this correction they have succeeded in localizing spark channels with 1.06-μm laser beam irradiances well below the breakdown threshold, as I had speculated in 1972.

To see how much ionization is actually required for predetermining the path of the stepped leader in lightning, it is worthwhile to consider another question, namely: why are lightning channels so crooked? The natural path for lightning, and the path established in least time with least energy,
should be a straight line path from cloud to ground. Yet photographs show straight line lightning channels to be extremely rare. Channels frequently exhibit loops\textsuperscript{13–15} that certainly cannot be characteristic of the prestrike electric field. Evidently the direction of leader advance, within each step, is a compromise between electric field direction and some other very wild function of position, with loops clearly demonstrating the dominance of the wild function. By far the strongest candidate for the wild function is instantaneous free-electron concentration.\textsuperscript{16} A small sample of just how wild this function is can be seen in the continuous diffusion cloud chamber. Free electrons are much more important than molecular ions because the former have lesser mass. An electron contributes more than 200 times as much partial current to plasma conduction than does a molecular nitrogen ion of the same energy. Furthermore, because the electron mean free path is almost six times that of ion, the electron in the prestrike dc electric field consistently carries higher energy. Such plasma conduction plays a major role in the rapidly shifting charge distributions that determine instantaneous local electric field direction at the tip of the advancing stepped leader. The free-electron hypothesis and the exponential character of dc electron avalanche growth lead naturally to the prediction that suitable laser beams of modest power may sufficiently perturb the concentration of atmospheric free electrons to predetermine the path of stepped leader development.

A similar prediction can be reached from a far more conservative and secure viewpoint. Specialists in the study of lightning make a distinction between a stroke and a flash. A flash is what is perceived by eye and brain, and it may be composed of up to 26 separate strokes, or current surges detected by fast instruments, all in the same channel. The criterion for repeated strokes in a channel is\textsuperscript{17} that between strokes the free-electron concentration shall not fall below $10^7 \text{cm}^{-3}$. At higher values, lightning will prefer the old channel to seeking out a new path. If a laser beam can offer a path of equal free-electron concentration at a time shortly prior to or during the descent of a stepped leader, the laser beam should similarly be a preferred path.

The Soviet physicist Akmanov has guided dc sparks in air with a fourth harmonic beam generated by a neodymium glass laser.\textsuperscript{18} The beam irradiance was 300 MW/cm\textsuperscript{2} in a 10-ns pulse, less than 1% of the corresponding threshold for laser-induced breakdown. Most electrons were probably liberated by MPI, instead of by collision. Calculation of MPI rates, though fraught with uncertainty (including a hydrogenic model of diatomic nitrogen), supports this view. Akmanov’s free-electron concentration was $10^{13} \text{cm}^{-3}$, exceeding by six orders of magnitude the criterion for repeated strokes in a channel. A successful LLRS could therefore be built by scaling up Akmanov’s experiment. A diffraction-limited 2650-Å beam can be collimated\textsuperscript{19} over a 3-km vacuum range, with assurance that throughout this range the axial irradiance equals or exceeds Akmanov’s if the total power in the beam is $1.19 \times 10^8 \text{W}$ or more. It will soon be shown that atmospheric absorption is not worth worrying about. Assuming a two-step up-conversion process from the fundamental-frequency beam and a conservative 30% single pass up-conversion efficiency\textsuperscript{20} per step, the power required in the fundamental beam is $1.325 \times 10^{10} \text{W}$. This is less than four times the power of Hagen’s diffraction-limited laser\textsuperscript{21} (which emitted a pulse of about the same length as Akmanov’s), and less than 42% (after adjusting for differences in pulse length) of the power in the output pulse of a Nd glass disk amplifier reported last year.\textsuperscript{22} Thus the feasibility of the LLRS removed from the realm of speculation.

Experience has shown that rapidly moving conductors, especially those that are well grounded, are far more likely to be struck by lightning than stationary conductors at the same altitude because of large scale space charge effects.\textsuperscript{23–27} In this way it is possible to bait lightning strikes from clouds well in advance of the times at which they would otherwise naturally occur, or, as two accidents have already demonstrated, bait strikes from clouds from which strikes might not otherwise emerge at all. With this ability, the rain gush effect\textsuperscript{28} might be exploited to induce cloudbursts at desired times and places, making the LLRS a tool for weather modification. The first accident was a strike to a salt water mine explosion plume\textsuperscript{26} and the second was a pair of strikes to the Apollo 12 spacecraft.\textsuperscript{27} These events were associated with clouds that had exhibited no previous electrical activity. The mine plume was only 74.4-m (244-ft) high when struck, indicating the scale of motion beyond which there is significant probability that such events may occur. If sufficient free-electron concentration can be produced in laser pulse wakes over comparable or larger distances, such wakes should sensibly (with judicious timing) produce similar results. Such a wake might be regarded as an extension of the ground ascending at the speed of light. From the viewpoint of the paper by Brook et al.,\textsuperscript{35} it is difficult to conceive of anything more likely to be struck by lightning. Hagen\textsuperscript{29} has demonstrated laser-induced breakdown in air over a distance of 25 m (one third of the height of the mine plume). There is a possibility that an upward-propagating leader\textsuperscript{30} will originate somewhere along the beam; or, at sufficiently high laser powers, that the entire beam path from laser to cloud will break down simultaneously (no leader whatsoever).

Mode-locking a laser should greatly increase its effectiveness in the LLRS. A fundamental result of the quantum theory of multiphoton ionization is that the instantaneous rate of ionization produced by an $N$-photon process is proportional to the $N$th power of the instantaneous beam irradiance.\textsuperscript{31} It is a simple exercise in elementary calculus to show that mode-locking increases the time-average rate of $N$-photon ionization by a factor $m^{N-1}$, where $m$ is the number of modes locked together. This ignores de-
plication of the target molecule population due to ionization during the averaging period (twice the cavity transit time) and assumes that energy absorbed by the target population does not exceed the energy available in the beam. No such problems arise until free-electron concentration far exceeds LLRS requirements. To appreciate fully the magnitude of this rate multiplier, we note that m can be as large as 60,000 for the neodymium glass laser,33 that N is at least 4 for ionization of molecular nitrogen in a fourth harmonic beam,34 and that N is at least 14 for ionization of molecular nitrogen in a beam at the fundamental frequency. In these two cases the factor $m^{N-1}$ assumes the values of $2.16 \times 10^{14}$ and $1.31 \times 10^{32}$, respectively, so avalanche multiplication of the initial electron population is clearly unnecessary. Worry about such details as a sea-level atmospheric extinction coefficient of approximately 1.5 km$^{-1}$ at 2650 Å (Ref. 35) is also unnecessary.

Of these rate multipliers the smaller is possibly the more important, as the normal rate of the 14-photon process may be so low as to defeat the larger multiplier. MPI theory is treacherous here, and further investigation is needed. Theory indicates with certainty only that for 1.06-μm or shorter laser beams is the N-photon ionization rate (ignoring possible accidental resonances) an extremely sensitive monotone decreasing function of N (at constant wavelength and irradiance),36–40 which explains why it is advantageous (at least in the absence of mode-locking, and probably generally) to work with the fourth harmonic beam, as Akmanov18 did, instead of with the fundamental. A further benefit of mode-locking is that the efficiency of up-conversion to the fourth harmonic is greatly increased.41–43 A two-step process, with almost 100% efficiency in the first step,44 and at least 30% in the second, should be possible. Ionization produced by successive mode-locked pulses will be cumulative for times up to the free-electron lifetime in air, estimated by Koopman and Saum45 to be about $10^{-8}$ sec. For wavelengths as long as the 10.6-μm band of the carbon dioxide laser the situation seems to be reversed (according to formulas presented by Keldysh37), with ionization rate by then an increasing function of N. This is an extremely interesting situation, since N is more than 100 at this wavelength and since Beaulieu46 has noted that picosecond mode-locked pulses can be expected from CO$_2$ lasers operated at cavity pressures of 10 atm and above. An m-value of 12,000 is reasonable.47 Beaulieu’s suggestion might also apply to pulsed nitrogen laser systems in the uv, if gain can be reduced to the extent that one end of the cavity can see the other. Such reduction occurs automatically, on the downslope of every self-terminating pulse. An m-value of about 2150 is reasonable.48 Despite the obvious and enormous benefits of mode-locking, it was not attempted in the experiments of Akmanov, Hagen, Koopman and Wilkerson, or Koopman and Saum.

Other candidates for the LLRS laser include broadband tunable dye systems that can simultaneously exploit the advantages of mode-locking, harmonic up-conversion, and tuning of the harmonic to MPI resonances. With many laser types there may be an appreciable risk of laser-lightning accident, especially if Q-switching is done by the saturable absorber method (with the possibility of inadvertent mode-locking). Operation below the breakdown threshold carries with it a false sense of security. Laser systems intended for the remote sensing of gaseous air pollutants via Raman backscattering,49,50 for example, are almost optimized for such an accident (Block Engineering should be grateful for the limited bandwidth of their second harmonic ruby pollution sensing system).

The real attractiveness of the LLRS concept, and the key to its success, lies in extreme mobility51 and carefully chosen firing times.52 Optimum vehicle positions and laser firing times can, in principle, be computed with input from a variety of suitable transducers. Ideally, a central processor should have strike predictive capacity, which might include the ability to do accurate digital real-time simulation53 of several thunderstorm cells simultaneously, including dynamics, thermodynamics, and charge separation processes.54–56 Less ideally, it might employ simple majority-vote logic, in which case the laser should be capable of pumping and firing within about 150 μsec (Ref. 57) of confirmation of stepped leader emergence from the cloud base. Such rapid response is feasible by double-pulsing the pumping flashlamps.58 Transducers might include field mills, wide-field, narrow-band spectral radiometers (WFNBSR’s), microwave radiometers, and Doppler radars. Microwave radiometers59 give the earliest warning of stepped leader presence. WFNBSR’s at 1800–2200 Å, 5680 Å, or 6563 Å (Refs. 60 and 61) confirm leader emergence from the cloud base and consist of collimating stops located at the front focal points of wide angle lens systems that are, in turn, followed by interference filters.62 Doppler radars63 monitor thunderstorm cell velocity fields and precipitation. Field mills64,65 are used for advance estimation of times of either probable successful baiting or natural stepped leader formation.

Full scale experimentation of the kind here proposed is potentially, unless executed with great caution, extremely dangerous and costly. Precautions66 might begin with a long grounded metallic tube or barrel through which the laser beam must pass before beginning its skyward journey. Lightning currents, by virtue of the radial component of the electric field, their high frequency content, and the skin effect, should transfer from the laser beam path to this barrel. If necessary, transfer can be encouraged by a strong transverse magnetic field. The laser beam is injected through a small port at a point roughly midway along the barrel. At injection, the beam is subjected to an acute angle deflection, giving the beam path much higher inductance than the barrel.67 The barrel is grounded from the bottom end. A hypersonic gas blast, as in ordinary circuit breaker technology,68 can be actuated at will between the laser and injection port. A subsonic upward gas stream
prevents hailstones and raindrops from entering the top end of the barrel. Barrel walls must withstand significant curshing pinch forces (currents of 500,000 A), sudden ohmic and plasma heating, thermal erosion, and pressures from explosive expansion of trapped plasma. Interlocks inhibit laser firing while dangerous currents are present (firing is always in advance of such currents).

Further refinement of the LLRS would probably follow most rapidly from further research in the following problem areas:

1. experimental confirmation of theoretical prediction of accelerated MPI due to mode-locking,
2. theoretical and experimental molecular MPI rates,
3. MPI rates at 10.6 μm,
4. development of high pressure mode-locked CO₂ lasers,
5. MPI resonances,\
6. direct conversion to the fourth harmonic in self-healing nonlinear media,
7. damage in nonlinear crystals,
8. current frequency spectra,
9. barrel pinch, heating, and blast,
10. assurance of prompt coupling of lightning currents to barrel walls,
11. fine structure effects in atmospheric uv transmission (measurements with lasers or tunable parametric oscillator systems, instead of values from handbooks, to facilitate tradeoffs against weak focusing),
12. development of high pressure pulsed nitrogen mode-locked uv lasers, and
13. self-induced transparency in air for vacuum uv radiations.\

In connection with all small-scale MPI measurements employing focused laser beams, it should be remembered that the problem of relating collimated beam irradiance to focused beam irradiance is far from trivial, especially for single elements, with account made for both aberration and diffraction.\

Most LLRS principles and features are described in greater depth in a 104-page, extremely limited edition manuscript copyrighted by the author in 1972. An updated revision is planned, and with sufficient interest it might be published in monograph form.

This investigation has received no support whatsoever from any source, public or private.

References
9. L. M. Ball, letter to C. B. Moore dated 21 August 1964. Moore is now Professor of Physics at the New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801.
13. L. M. Ball, Ref. 7, Fig. 4, p. 43.5.
16. L. M. Ball, Ref. 7, p. 43–47.
32. L. M. Ball, Ref. 7, pp. 37–37.5.
34. This assumes a photoelectric threshold for diatomic nitrogen at 796 Å, taken from Technical Report 62-15-N, Geophysics Corporation of America, pp. 16 and 77. Another threshold for ionization of molecular nitrogen appears at 661 Å. This report was prepared prior to 1964, probably in 1962. There is no indication of authorship.
36. This trend can be seen by inspection of the graphs of H. B. Bebb and A. Gold, Refs. 2 and 31, which are independent of the Soviet "adiabaticity parameter."
38. A. M. Perelomov, V. S. Popov, and M. V. Terentev, Sov. Phys. JETP 23, 924 (1966). In a footnote on p. 931, these authors allude to an error in Keldysh's Eq. 21.
40. Peressini suggests an adjustment of the domain of validity of Keldysh's Eq. 21.
51. L. M. Ball, Ref. 7, pp. 68–70.
52. L. M. Ball, Ref. 7, pp. 66–68.
57. L. M. Ball, Ref. 7, pp. 67–68.
66. L. M. Ball, Ref. 7, p. 70.
67. W. J. Humphreys, Physics of the Air (McGraw-Hill, New York, 1940); see comment about bends on p. 393.
76. L. M. Ball, Ref. 7, pp. 2–7.
79. L. M. Ball, Ref. 7.