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Part II

LASER TYPE ULTRA-VIOLET RADIATION FEASIBILITY FOR LIGHTNING AND ATMOSPHERIC PROPAGATION STUDIES

J. R. Stahmann

Lightning & Transients Research Institute
Minneapolis, Minnesota

L&T Report 417
Contract No. AF 19(604)-7984
Project No. 8653

Final Report — Part II

October, 1964

Prepared
for

Air Force Cambridge Research Laboratories
Office of Aerospace Research
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FOREWORD

This report was prepared by the Lightning and Transients Research Institute under Contract AF 19(604)-7984 sponsored by Air Force Cambridge Research Laboratories, Office of Aerospace Research, Bedford, Massachusetts.

The technical program is administered by Air Force Cambridge Research Laboratories and supervised for the Air Force by Dr. E.A. Lewi

Participating scientific and engineering staff taking primary part in the research described in this report included: M.M. Newman, J.R. Stahmann and Ta Chen.

ABSTRACT

The feasibility of a laser type ultra-violet source as a possible substitute for the continuously supported wire antenna, used for artificial atmospheric propagation studies and to trigger lightning for natural lightning channel studies, is considered. The energy required to produce an electron plasma or even a molecular plasma is quite high. A powerful laser beam would provide an intense concentration of energy. However, it is difficult if not impossible to produce lasers with wavelengths below the 1000 A required to ionize air molecules. Laboratory experiments were limited to the use of a 14 kilowatt carbon arc as a source in the far ultra-violet. No long spark diversion similar to that found with a jet plasma (10^7 to 10^8 ions/cc) was observed with the carbon arc source. Methods of selective ionization to distribute the ions over the beam with just the density required for the conductivity of a jet plasma include possible rocket distribution of combustible particles to be ignited by a conventional laser beam for distances of several miles to produce islands of plasma which possibly could allow a discharge to propagate by the step by step process of the branch streamer mechanism.

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I. Introduction

For VLF and other studies in previous programs reported earlier* a high voltage impulse generator was discharged into helicopter, kite, or balloon supported small diameter wire antennas ranging from a few thousand feet to over 3 miles in height. Since the development of a substitute for a continuously supported wire antenna would be of interest in many applications, other methods of producing an antenna by generating an ionized channel are being considered. Methods of producing an ionized channel include rocket launched ionized trails, rocket trails kept ionized by a DC following current, laser ionizing beams, and the use of these methods to trigger a natural lightning channel. This report discusses a preliminary feasibility study of the use of far-ultraviolet radiation for ionization of a column of air for possible extension to the laser technique. Laboratory experiments were limited to the use of a 14 kilowatt carbon arc as a source in the far-ultraviolet. The possible physics and design of an ultraviolet laser/maser is beyond the scope of this report. Indeed such a maser may be quite difficult to achieve since "optical pumping in the ultraviolet and higher frequencies is excluded, because the induced pump rate cannot compete with the fast spontaneous emission rate in the ultraviolet."[9] On the other hand, studies on ultraviolet optical masers are continuing[10, 11] and this report considers their feasibility for producing an ionized column of air for use as a VLF antenna or for triggering a natural lightning stroke.

II. Theoretical Considerations

First consider the energy required to completely ionize a column of air one millimeter in diameter at NTP. The average first ionization potential of air is about 15 electron volts if we consider the more efficient molecular ionization of N_2 and O_2. Since the number of molecules in a column one meter in length is 2.12×10^{19} molecules, the energy required to ionize the air is about

$$2.12 \times 10^{19} \times 15 \times 1.6 \times 10^{-19} = 51.0 \text{ joules/meter}$$

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*AFCRL-TR-60-376, September, 1960 and AFCRL 946

Another way that air can be ionized is by first dissociating the molecules into atoms (7ev) and then ionizing all the atoms ($2 \times 15 = 30$ev) requiring a total energy of $37 \times 51.0/15 = 126$ joules/meter. Of course, it is not necessary to ionize all the molecules to provide sufficient conductivity. As will be shown in the next section the ion density required for sufficient conductivity to cause lightning stroke diversion by a jet plasma is of the order of 10^7 to 10^8 ions/cc as compared with the NTP density of 2.7×10^{19} molecules/cc of air.

However, a photon beam cannot ionize molecules selectively and its energy is likely to be quickly absorbed in the high density air. For example, consider a point source in the center of a sphere one cm in radius. The source radiates over a solid angle of 4π and, since the volume of the sphere is 4.2 cc and the energy required for molecular ionization of air is about 65 joules/cc, the energy required to ionize all the molecules in this sphere is 273 joules. The power required to produce this ionization depends on the recombination time of the ions. The mean lifetime of a one ev electron against electron capture by oxygen molecules has been estimated to be 0.025 μsec.[7] Thus if an electron plasma is required for the antenna and all molecules are kept ionized, a power of $(273/0.025) \times 10^6 \cong 10^{10}$ watts would be required. If the energy could be collimated by the laser technique to the column one millimeter in diameter a power of $(51.0/0.025) \times 10^6 = 2 \times 10^9$ watts/meter would be required. This, of course, would have to be the output power. The input power of a laser would probably be at least 100 times greater.[4] Also the molecules may dissociate and ionize or become ionized to a higher degree by losing several electrons which requires much more energy. For antenna and lightning triggering purposes the beam need not be continuous so that these power levels need be reached for times of the order of a microsecond reducing the average power required to a few thousand watts at a repetition rate of one per second.

Fortunately it is likely that a molecular plasma,[8] which has a lower conductivity than the electron plasma by a factor of roughly a thousand, still has enough conductivity for antenna purposes. The molecular plasma is more stable and recombination is slower, slow enough so that it may help explain the phenomenon of ball lightning.[8] Assuming that the recombination time is the same order of magnitude as that of a lightning channel, which maintains a second stroke capability for about 10 milliseconds after the main return stroke without requiring a new leader stroke, the above required powers could be reduced by a factor of $(1/4) \times 10^{-5}$ giving about 5000 watts/meter as a minimum for the one millimeter beam. For a practical laser with a pulse length of less than a millisecond the output power would need to be of the order of 10^5 watts/meter. Since laser pulses have been generated at power levels of over 10^7 watts and much higher power levels are possible[4], a laser could have sufficient power to produce a molecular plasma antenna even if all the molecules in the beam must be ionized, particularly since the laser beam width can be of the order of microns rather than millimeters. If the ion density produced could somehow be reduced to the order of 10^8 ions/cc by some method of selective ionization, a much longer antenna could be produced.

One method of doing this would be to add a small quantity material more easily ionized than air (e.g. toluene at 8.5ev) and then ionize it with a laser having a frequency below that required to ionize air. For such a longer wavelength laser lithium fluoride or other optics might be used. A practical difficulty in using this technique is the absorbtion in air of wavelengths below 1850Å due to ozone formation.[3]

Another method of distributing the ionization would be to ignite small combustible particles distributed in the air with a conventional infra-red laser and already developed optics. Conventional lasers with 1000 joules output and one second of arc are incendiary to paper and wood at distances of about 10 miles.[4]

Following the quantum theory, the energy of a photon required to ionize an oxygen molecule, which has the lowest ionization potential, is 12.5 electron volts. The wavelength of such a photon is computed from

Planck's quantum equation:

$$E = h\nu = \frac{hc}{\lambda}$$

$$12.5 \times 1.6 \times 10^{-19} = 6.63 \times 10^{-34} \times 3 \times 10^{8}/\lambda$$

$$\lambda = \frac{6.63 \times 3 \times 10^{-7}}{12.5 \times 1.6} \cong 1000\text{Å}$$

Thus for ionization of air we are interested in wavelengths less than 1000Å in far-ultraviolet or X-ray regions. Since experimental lasers are outside the scope of this study, methods of collimation of the radiation from a conventional source such as a carbon arc are of immediate interest. We find that lithium fluoride, being a very light transparent substance, can be used for optics in the 1000 to 2000Å range. Coated mirrors are used down to 1216Å. A carbon arc has emission spectra down to 595Å and thus has some energy in the range that will ionize air. The ultraviolet energy from a carbon arc is incoherent but even if it were coherent it would not be possible to collimate it into a narrow beam without optics in this frequency range. For the experimental work described in the next section an open orifice was used.

Since the energy required to ionize all the air molecules in a sphere one centimeter in radius is about 273 joules, we can estimate the power required in the far-ultraviolet to be about 25 kilowatts if we assume a 10 millisecond recombination time. However, as discussed, it is not necessary to ionize all the molecules to obtain good conductivity and experiments described in the next section were set up to check possible air penetration by the far-ultraviolet radiation from an intense carbon arc to an extent sufficient to cause diversion of a long arc.

III. Measurements

The experiment shown in Figure 1 was set up to determine whether or not the plasma of a jet engine has sufficient conductivity to divert a simulated lightning stroke and the effective length of the diverting action.

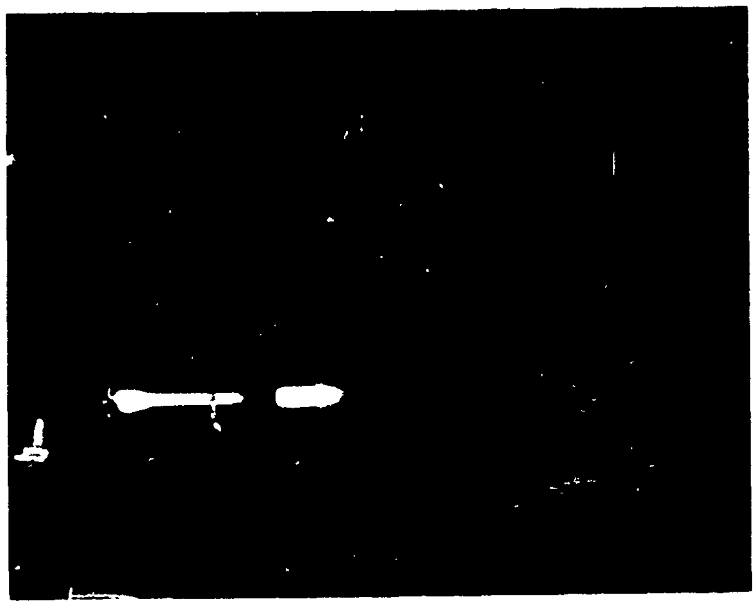


Figure 1(a). Jet flame about 7 inches in length.

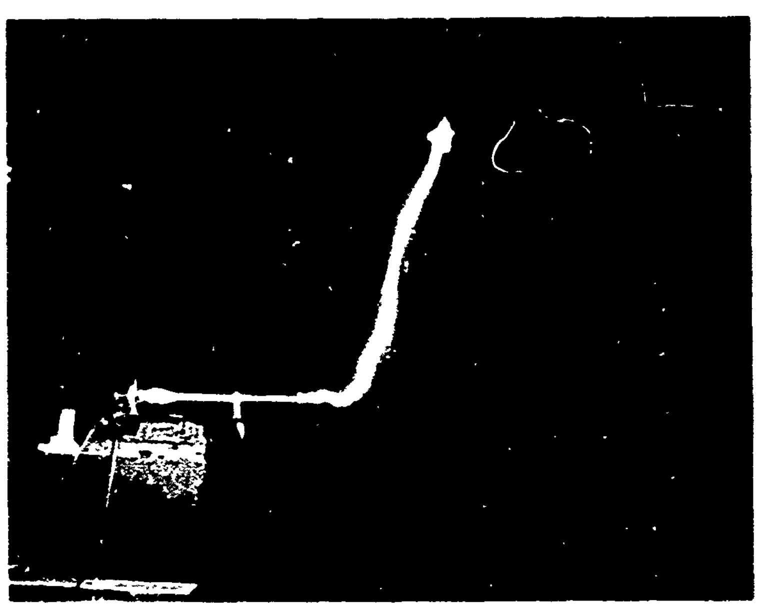


Figure 1(b). Stroke diversion by jet flame.

A small jet engine having a visible flame length of about seven inches was set up as shown in Figure 1(a). A high voltage probe was placed about 36 inches above and 12 inches to the right of the tip of the engine. With the jet engine off, the stroke went directly to the engine. However, when the engine was turned on, the arc was diverted to the end of the visible flame which was slightly closer to the probe, as shown in Figure 1(b). Since the ion density in a jet exhaust plasma is known to be of the order of 10^7 to 10^8 ions/cc[5], this density appears sufficient to trigger a natural lightning stroke or to guide an artificial stroke.

The most intense source available for ultraviolet experimentation was the carbon arc shown in Figure 2. A welding generator supplied 200 to 250 amperes to the arc at a power level of about 14 kilowatts. The light was directed through an aperture placed about four centimeters from the top of the rods. The final shape and size of the aperture was rectangular about 3 x 0.8 centimeters in size giving a beam width of 0.27 radian. In addition to arc diversion tests another method of possibly detecting the presence of ionization was set up as shown in Figure 3. A voltage of 2500 volts was applied between two plates placed so that the light from the arc passed between them. The rectangular shape of the aperture was chosen to permit maximum light between the plates. An electrostatic voltmeter with ammeter shunt was used to measure currents as small as 10^{-12} amperes.

The current between the plates with radiation off was about 5×10^{-12} amperes and increased to about 10^{-9} amperes when the arc was turned on. However, this conduction was traced to the smoke particles produced by the intense heat of the arc. The essential feature of the smoke free setup (Figure 4(a)) was a slight positive air pressure in an enclosure placed around the plates to prevent smoke from entering. Measurements with this setup showed no increase in current when the arc was turned on. In Figure 4(b) baffles prevented light from reaching the plates but permitted the smoke to enter. Currents of the same order as obtained initially (10^{-9} amperes) were measured.

Figure 2(a). Adjustable electrode carbon gap.

Figure 2(b). Enclosed gap with small aperture at top.

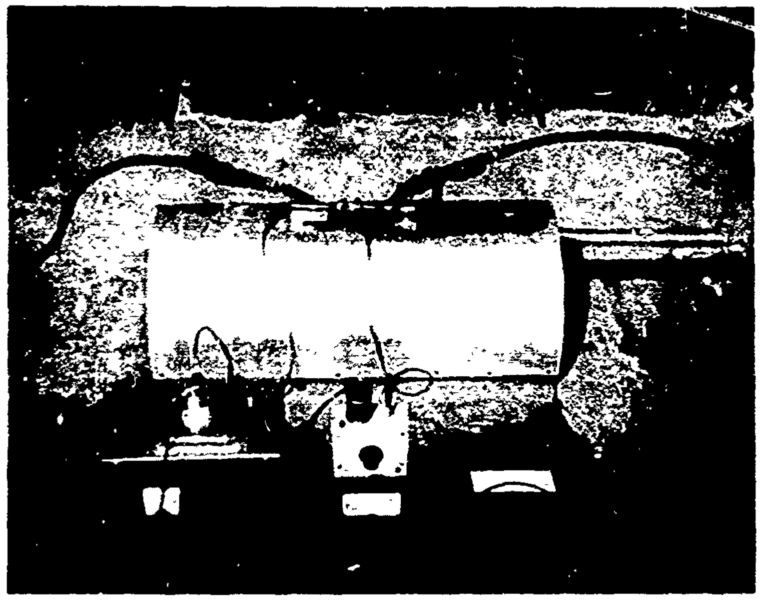


Figure 3(a). Initial setup for measurement of possible ion current.

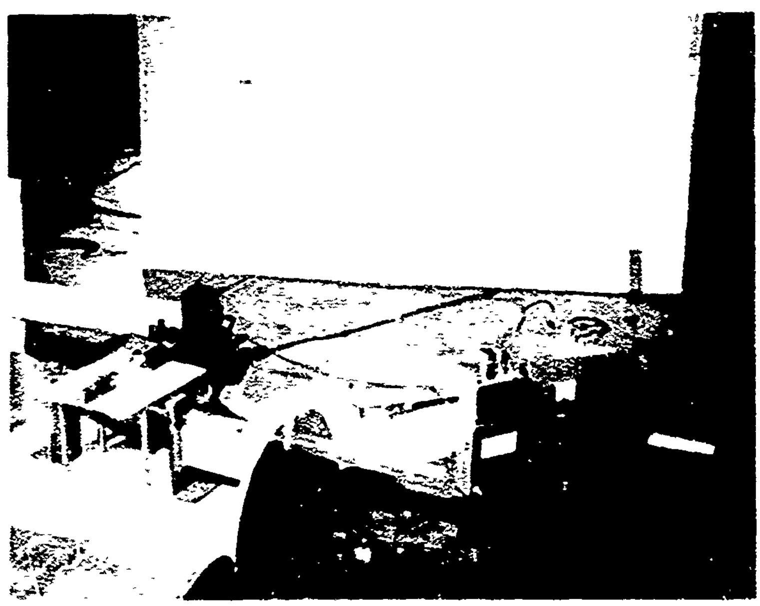


Figure 3(b). Setup with open arc and blower to reduce effects of smoke.

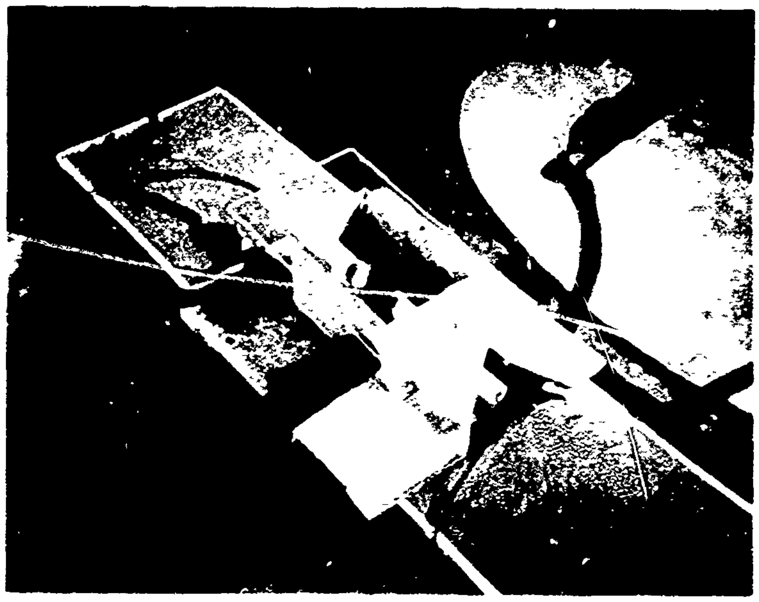


Figure 4(a). Setup for smoke free electrode gap.

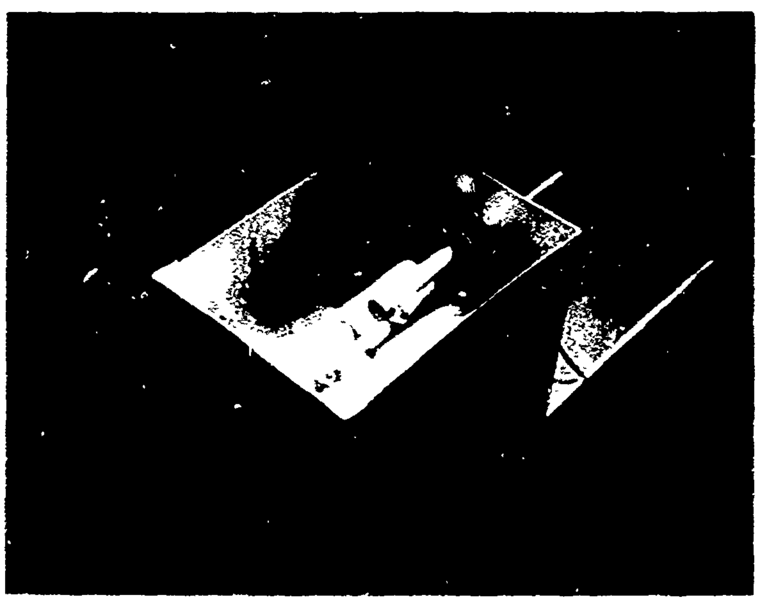


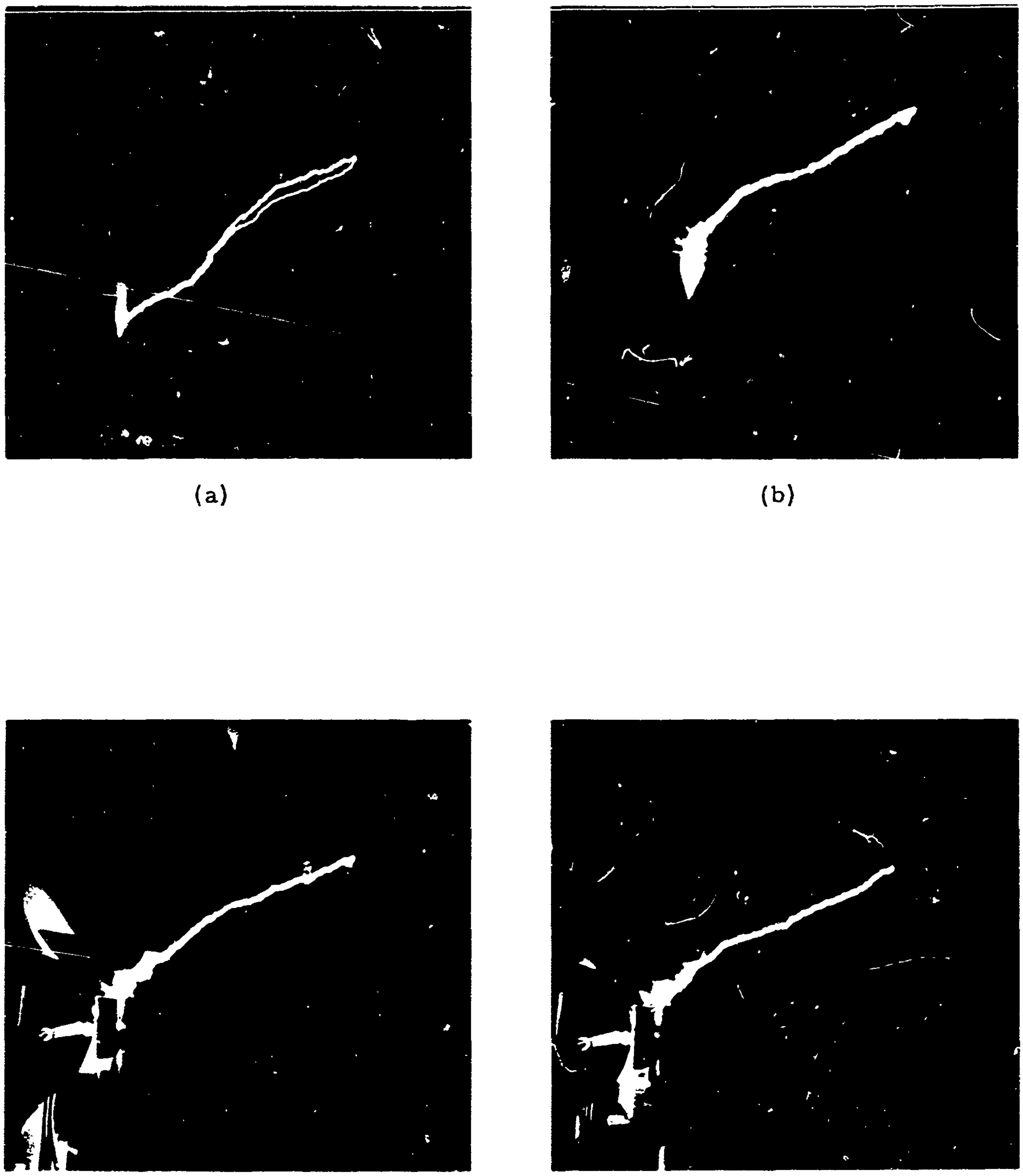
Figure 4(b). Setup for light free electrode gap.

Stroke diversion measurements are shown in Figures 5, 6, 7 and 8. Control strokes with carbon arc off are shown in the top photos while strokes with the carbon arc on are shown at the bottom. With the probe positioned as shown in Figure 5, the stroke tended to hit the top of the asbestos plate rather than the aperture when the carbon arc is on and also once when the arc was off, although this was evidently a surface discharge. The top of the plate was slightly closer to the probe than the aperture and smoke from the top could have influenced the stroke when the carbon arc was on. With the probe in a lower position (Figure 6) no diversion due to horizontal radiation is evident. The horizontal beam was selected to reduce smoke in the beam; however, even with a vertical beam (Figures 7 and 8), no diversion was evident though in Figure 8(d) the stroke passed very close to the beam.

IV. Conclusions

An intense carbon arc does not produce sufficient ionization of air due to radiation in the far-ultraviolet at distances of four or five centimeters from the carbon arc to divert a long spark. In a rough check of conduction between charged plates, no ionization could be detected except due to smoke from the arc. These measurements confirm the theoretical result that the far-ultraviolet produced is quickly absorbed by ionizing the air in the immediate vicinity of the arc. Even a powerful 250 megawatt TRIGA triggered reactor would distribute its energy over 4π steradians so the energy in a given direction is much reduced. For example, the energy in a one minute arc from a TRIGA reactor would be only about 0.5 watt.

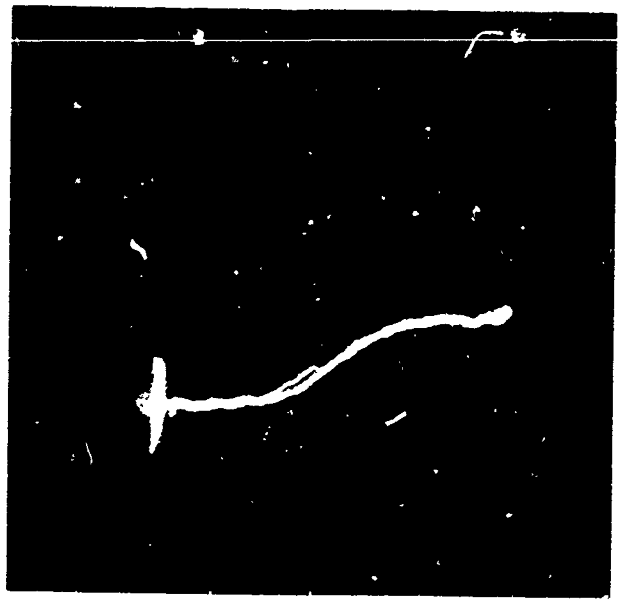
A laser with coherent light output can concentrate all its energy in a beamwidth as narrow as one-second and solid state lasers can produce over 1,000 joules of energy with peak powers above 10 megawatts.[4] Recently a trillion-watt laser was forecast by C. H. Townes[12] for a 10 $\mu\mu$sec. pulse. However, it is difficult, if not impossible, to produce lasers and optical collimating systems for wavelengths below the 1000 A required to ionize air molecules. In addition, the ion density near the power source is likely to be much higher than necessary for initiating channel conduction resulting in early high energy absorbtion and poor power efficiency over the beam length.



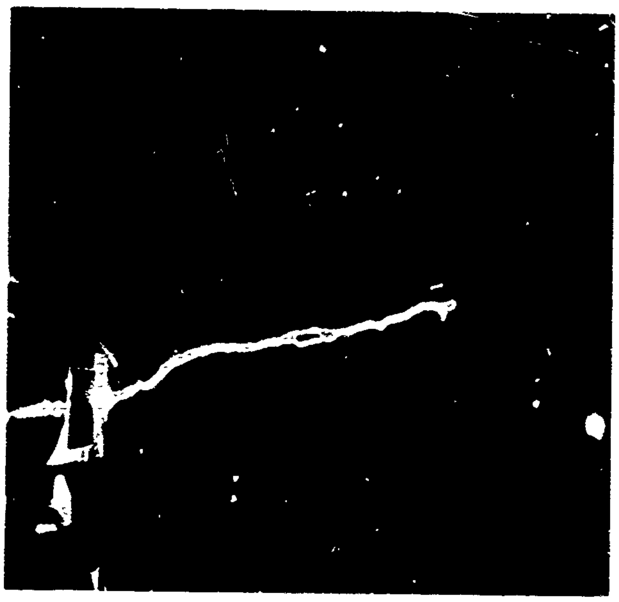
(a) (b) (c) (d)

Figure 5. Horizontal diversion measurement, electrode two feet above beam centerline with gap of 42".

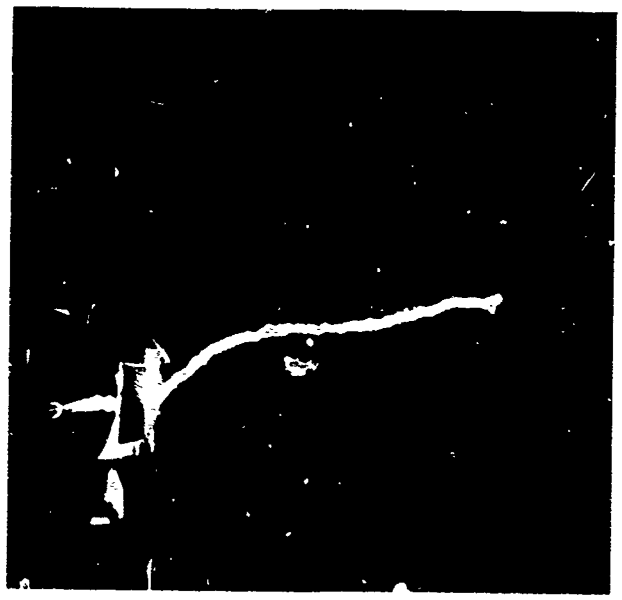
(a)



(b)

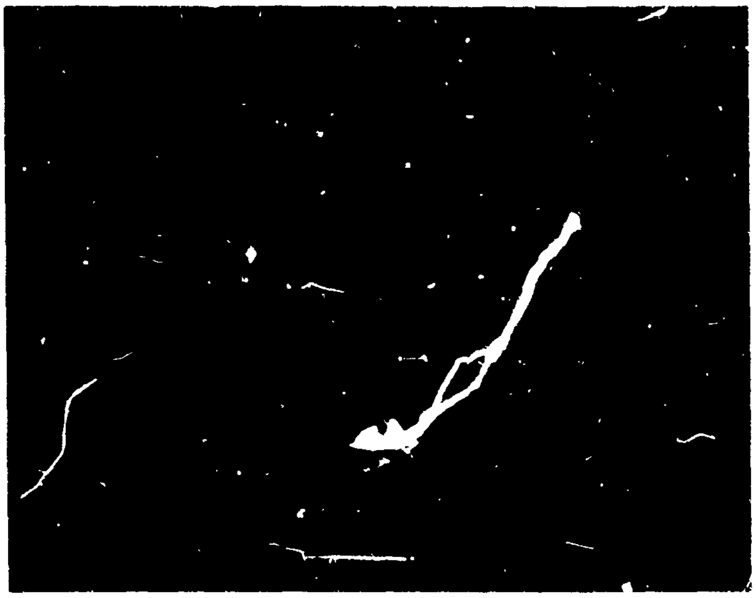


(c)

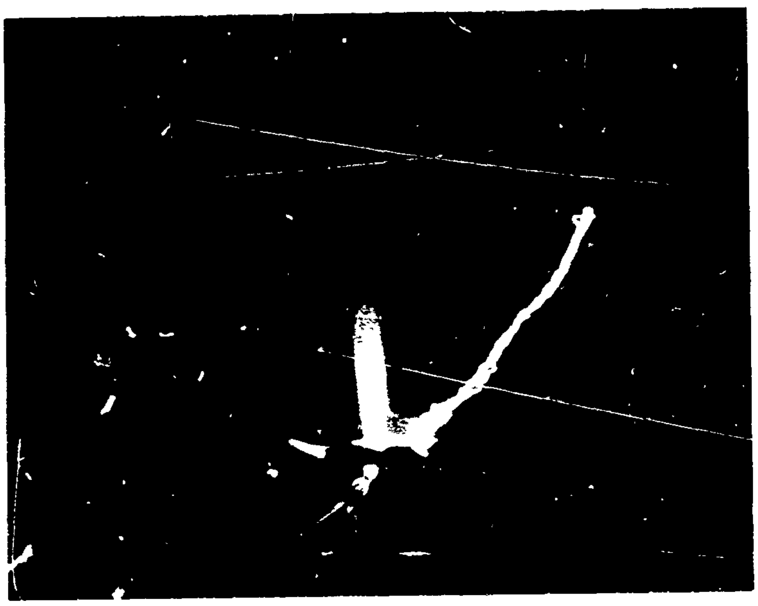


(d)

Figure 6. Horizontal diversion measurement, electrode one foot above beam centerline with gap of 41".

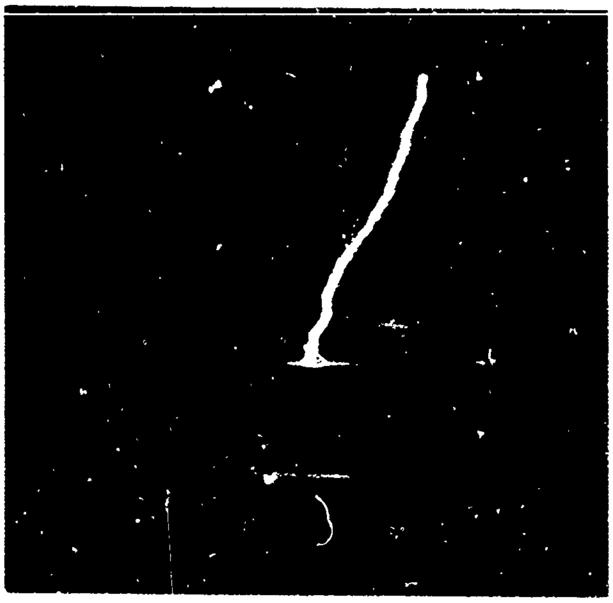


(a)

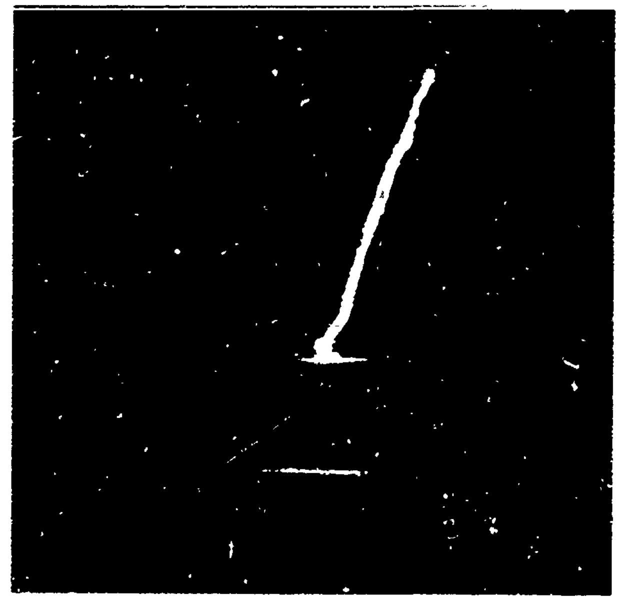


(b)

Figure 7. Vertical diversion measurement, electrode two feet from beam centerline with gap of 22".



(a)



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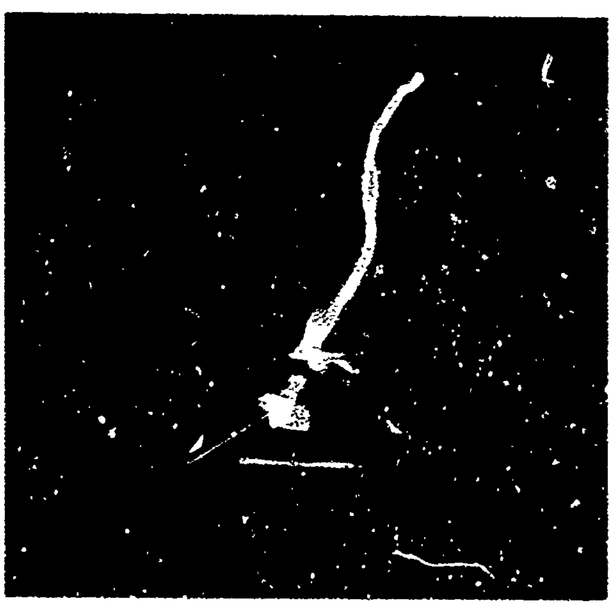

(c)

(d)

Figure 8. Vertical diversion measurement, electrode one foot from beam centerline with gap of 30".

A possible method of selective ionization would be to introduce a trail of particles having a lower ionization potential than air into the air by means of a rocket just prior to the artificial discharge or expected natural discharge. Radiation above 1000Å could then be used to ionize the substance but the air would probably still absorb much of the energy for wavelengths below 1850Å by ozone production unless a "window" wavelength were found below 1850Å or a substance with a low enough ionization potential to use wavelengths above 1850Å could be utilized.

Since a laser can be incendiary at distances of miles, a laser technique might also be used to produce islands of plasma by igniting particles of a substance distributed by a rocket at the time of the discharge. Since only heat is required, the energy can be distributed by a conventional laser and optical system. The discharge could possibly propagate between the islands similar to the step by step propagation of the natural lightning branch streamer mechanism.

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Report on Feasibility of Producing Long Ionized Conducting Channel	Air Force Cambridge Research Labs. Office of Aerospace Research Bedford, Mass.

13. ABSTRACT The feasibility of a laser type ultra-violet source as a possible substitute for the continuously supported wire antenna, used for artificial atmospheric porpagation studies and to trigger lightning for natural lightning channel studies, is considered. The energy required to produce an electron plasma or even a molecular plasma is quite high. A powerful laser beam would provide an intense concentration of energy. However, it is difficult if not impossible to produce lasers with wavelengths below the 1000 Å required to ionize air molecules. Laboratory experiments were limited to the use of a 14 kilowatt carbon arc as a source in the far ultra-violet. No long spark diversion similar to that found with a jet plasma (10^7 to 10^8 ions/cc) was observed with the carbon arc source. Methods of selective ionization to distribute the ions over the beam with just the density required for the conductivity of a jet plasma include possible rocket distribution of combustible particles to be ignited by a conventional laser beam for distances of several miles to produce islands of plasma which possibly could allow a discharge to propagate by the step by step process of the branch streamer mechanism.

(Author)

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Unclassified
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Channel Ionization	8, 7	3				
Lightning Diversion	8, 4	2				
Antenna	4	2				
VLF Propagation	4	1				
Ultra-violet	10	2				
Laser	10	1				
Jet-exhaust	10	1				

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