AD-A133 211

ADE 000 545

(2)

NRL Memorandum Report 5187

On Laser Air Breakdown, Threshold Power and Laser Generated Channel Length

A. W. ALI

Plasma Physics Division

September 13, 1983

NAVAL RESEARCH LABORATORY
Washington, D.C.

Approved for public release; distribution unlimited.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: NRL Memorandum Report 5187 — 2. GOVT ACCESSION NO.: AD-A133 211	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): ON LASER AIR BREAKDOWN, THRESHOLD POWER AND LASER GENERATED CHANNEL LENGTH	5. TYPE OF REPORT & PERIOD COVERED: Interim report on a continuing NRL problem.
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): A.W. Ali	8. CONTRACT OR GRANT NUMBER(s): N00024-83-WR-10601
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, DC 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 63514N; S-0384 SL; 24769 47-1910-A-3
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Sea Systems Command, Washington, DC 20362 (A.F. Johnson, Code 05R22)	12. REPORT DATE: September 13, 1983
	13. NUMBER OF PAGES: 21
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Naval Sea Systems Command, Washington, DC 20362 (P.E. Law, SEA 61X32)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lasers, microwave
Air breakdown
Breakdown power threshold
Absorption coefficient
Channel length

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A review is made of the experimental data for the air breakdown threshold power for lasers with wavelength of 0.6954μ to 389μ. A classical theory for the pulsed air breakdown is presented and is utilized to predict threshold power in clean air which is in reasonable agreement with the experimental results. The laser absorption coefficient by the air plasma is discussed in the context of the laser generated channel. It is concluded that one may generate longer channels by controlling the electron density which can be accomplished by controlling the duration of the laser pulse.

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

INTRODUCTION 1

THEORY OF BREAKDOWN 1

BREAKDOWN THRESHOLD POWER 4

EXPERIMENTS AND EXPERIMENTALLY OBTAINED LASER

BREAKDOWN THRESHOLD POWER 8

CLEAN AIR 8

DIRTY AIR 12

THEORETICAL PREDICTIONS 12

MICROWAVE AIR BREAKDOWN 14

RADIATION ABSORPTION LENGTH AND CONCLUSIONS 14

References 18

ON LASER AIR BREAKDOWN, THRESHOLD POWER AND LASER GENERATED CHANNEL LENGTH

1. INTRODUCTION

A plasma coloumn formed in air, by an electric discharge through a laser generated ionization path, has been utilized[1] to receive and transmit RF signals. The laser generated ionization path is understood[2-6] to guide the electric discharge in a straight path and enhance the breakdown streamer speeds.

A plasma antenna formed in this manner and having a length of 50 - 100 meters could play an important role in ship communications under adverse conditions. Therefore, a study of the basic parameters and scaling of an air plasma in terms of its generation and maintenance is essential.

In this report we will review the laser air breakdown theory, calculate the dependence of the breakdown threshold power on the laser frequency and compare with the available data. We will calculate the laser absorption length in order to estimate the power needed to breakdown a given length of air. We will do the same thing for the microwave air breakdown and make comparisons in energetics of the problem.

2. THEORY OF BREAKDOWN

Considerable studies of breakdown in many gaseous mediums and in air have been carried out using microwave radiation[7-9]. With the advent of lasers, laser breakdown studies in air and other gases have been numerous[10].

Breakdown in air occurs when the intensity of the focused radiation (microwave, laser etc.) at the focal spot reaches a critical value. A plasma is generated and is luminous.

The mechanism for air, or gas breakdown can be explained by the classical microwave theory[8,9], where a free electron gains energy from the electric field as it collides with the air species. The electron oscillation energy is

Manuscript approved July 22, 1983.

converted into random motion. This process has been shown to correspond[11] to the quantum mechanical description of the energy gain by the electron from the radiation field through the free-free transitions i.e. the inverse Bremestrahlung. The presence of a free electron is essential for an avalanche breakdown and does not cause any problem in air under laser irradiation, because under ambient conditions there exist, in air at the sea level, 100 - 1000 negative ions and an equal number of positive ions generated by the cosmic rays. These negative ions are loosely bound and are detached under laser irradiation and hence constitute the seed electrons for the air breakdown process.

The equation of motion of a free electron, in air, under the influence of an oscillating electric field, is

$$m \frac{d\vec{v}}{dt} = - \nu_m m\vec{v} - eE \, \mathrm{Exp}(-i\omega t) \tag{1}$$

where ν_m is the collision frequency for momentum transfer, ω is the frequency of the radiation field E, and v is the velocity of the electron. In Equation (1), the term $\nu_m m\vec{v}$ represents a continuous resistive damping force on the electron due to collisions with atoms and molecules. The real part of the velocity in phase with the oscillating field is

$$v = \frac{e\nu_m \, \mathrm{Exp}(-i\omega t)}{m(\nu_m^2 + \omega^2)} \tag{2}$$

The rate of energy gain by the free electron $\left(\int_o^\tau v.E. \, \mathrm{Exp}(-i\omega t)dt \right)$ is

$$\left.\frac{d\varepsilon}{dt}\right)_g = \frac{e^2 E^2}{m\nu_m} \, \frac{\nu_m^2}{\omega^2 + \nu_m^2} = \frac{e^2 E_e^2}{m\nu_m} \tag{3}$$

where $E_e^2 = \frac{E^2 \nu_m^2}{\omega^2 + \nu_m^2}$ is the effective electric field (equivalent to a static field).

On the other hand, the electron loses its energy through elastic and inelastic collisions. Electron energy is also lost by attachment, recombination and diffusion. The total energy lost can be expressed as[12]

$$\left.\frac{d\varepsilon}{dt}\right)_\ell = -\frac{D\bar{\varepsilon}}{\Lambda^2} - \frac{2m}{M}\varepsilon\nu_m - \left(\nu_i\varepsilon_i + \nu_a\bar{\varepsilon} + \Sigma_e\nu_e\varepsilon_e + \nu_r\bar{\varepsilon}\right) \qquad (4)$$

where D is the diffusion coefficient, Λ the diffusion length, $\bar{\varepsilon}$ is the average electron energy, ν_i, ν_a, ν_e and ν_r are the collision frequencies for ionization, attachment, excitations and effective recombinations, respectively, while ε_i and ε_e are the corresponding energies for ionization and excitations, respectively. The second term on the right hand side of Equation (4) represents the energy loss by electrons through elastic collisions. Therefore, the net energy gained by electrons is

$$\frac{d\varepsilon}{dt} = \left.\frac{d\varepsilon}{dt}\right)_g - \left.\frac{d\varepsilon}{dt}\right)_\ell \qquad (5)$$

and this net energy must be > 0 in order for the breakdown to proceed. Furthermore, the time development of the electron density, n_e can be described by

$$\frac{dn_e}{dt} = n_e\nu_i - n_e\nu_a - n_e\frac{D}{\Lambda^2} - n_e\nu_r \qquad (6)$$

where it is obvious that electron attachment, diffusion and recombination will control the cascade ionization, and must be overcome for breakdown to occur.

Equation (6) can be integrated to yield

$$N_e = N_e(0)\, e^{\nu_i' \tau} \qquad (7)$$

Where τ is the duration of the laser pulse, $N_e(0)$ is the number of initial electrons (generally $\simeq 1$) and

$$\nu_i' = \nu_i - \nu_a - \frac{D}{\Lambda^2} - \nu_r \qquad (8)$$

In integrating Equation (7) we have assumed that, for breakdown conditions, the quantities in Equation (8) are constant. The electron build up in air breakdown can also be represented by

$$N_e = N_e(0)\; 2^{K_c} \qquad (9)$$

where K_c is the number of critical generations and for most cases has been taken[10] to be equal to ~ 40. From Equations (7 and 8) one obtains, for the pulsed breakdown, the condition

$$\nu_i = \nu_a + \frac{D}{\Lambda^2} + \nu_r + \frac{0.69\, K_c}{\tau} \qquad (10)$$

2.1 BREAKDOWN THRESHOLD POWER

To calculate the breakdown power in air one can solve[13] the Boltzmann Equation with the appropriate atomic parameters or solve Equations 4 and 6 with the knowledge of the electron velocity distribution and the appropriate atomic processes where rates are electron energy dependent. However, reasonable estimates can be obtained for the breakdown threshold using approximate solutions.

The energy gained by the electrons in the laser field must be expended in various inelastic processes including ionization. Thus during the laser pulse and electron generation (K_c critical generations) we can write

$$\int_0^{\tau} \frac{\partial \varepsilon}{dt}\, dt = K_c \langle I_i \rangle \tag{11}$$

where $\langle I_i \rangle$ is the energy spent per ion pair generation. Using this and Equation (3), the threshold power, P_t, for air breakdown, can be expressed as

$$P_t = \frac{K_c \langle I_i \rangle (\omega^2 + \nu_m^2)}{0.11\, \tau\, \nu_m} \tag{12}$$

where we have utilized $\frac{E^2}{4\pi} = \frac{P}{c}$.

The dependence of the breakdown power on the laser frequency can be deduced from Eq. (12). In air, at atmospheric density and when $\omega \gg \nu_m$, Eq. (12) gives the well known $\frac{1}{\lambda^2}$ dependence of the breakdown threshold power on laser wavelength.

To estimate the threshold power for air breakdown, one must obtain $\langle I_i \rangle$ and ν_m which are electron temperature dependent. For a Maxwellian electron velocity distribution, the rates[14] of electron energy loss in N_2 and O_2 as a function of the electron temperature are shown in Figures 1 and 2, where the losses to various inelastic processes are indicated. It is obvious from these figures that, the energy spent into an ionization event is accompanied by energy loss to various electronic, dissociation, and vibrational excitations of the molecules. The energy lost by an electron to ionization is a small fraction of the total electron energy loss, especially for electron temperatures below 10 eV. For air breakdown, the electron temperature is generally in the range[9,13] of 3 to 4 eV. This implies that the average energy $\langle I_i \rangle$ per ionization event varies from 20 to 10 times the mean ionization

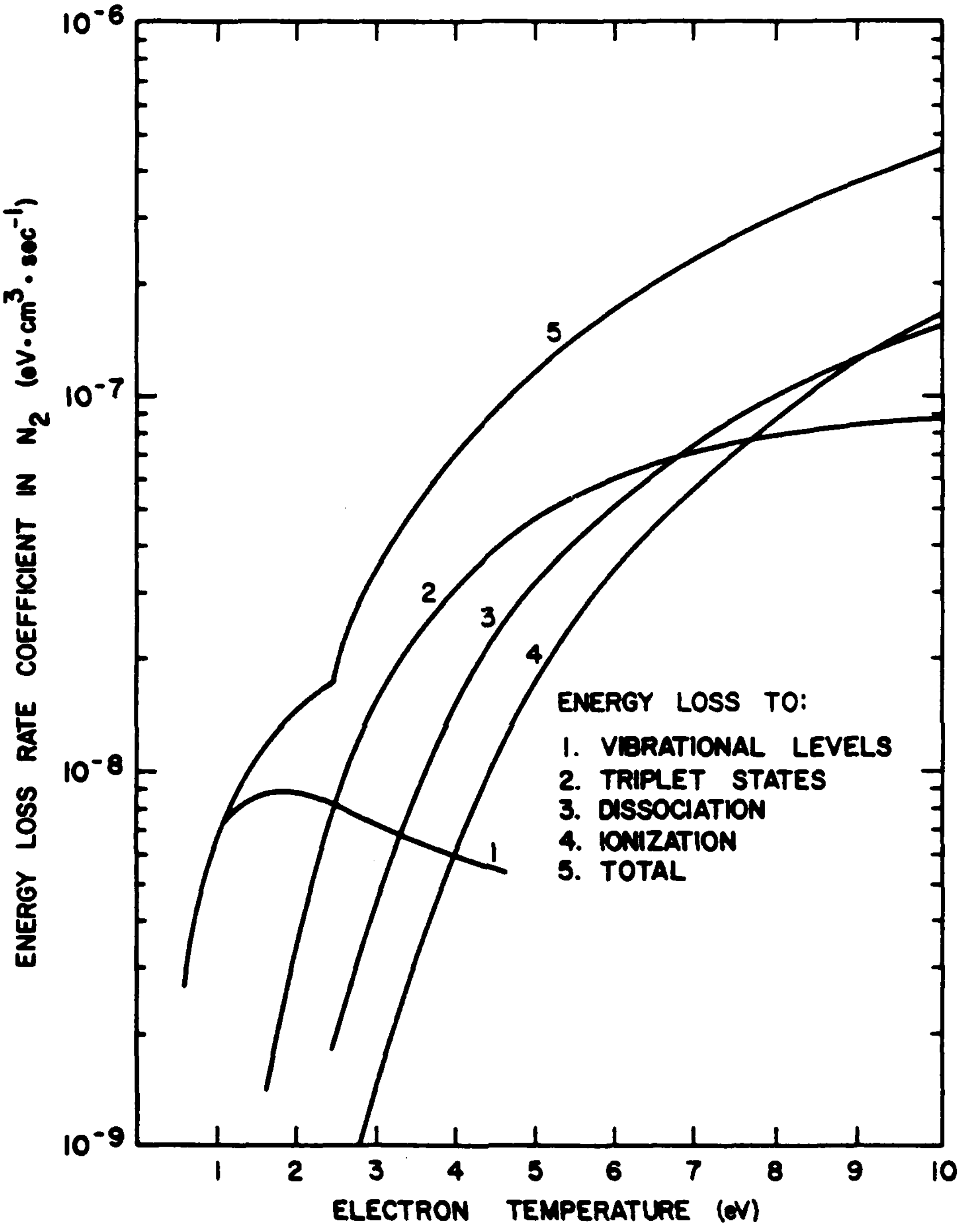

Fig. 1 — Electron energy loss rate in nitrogen

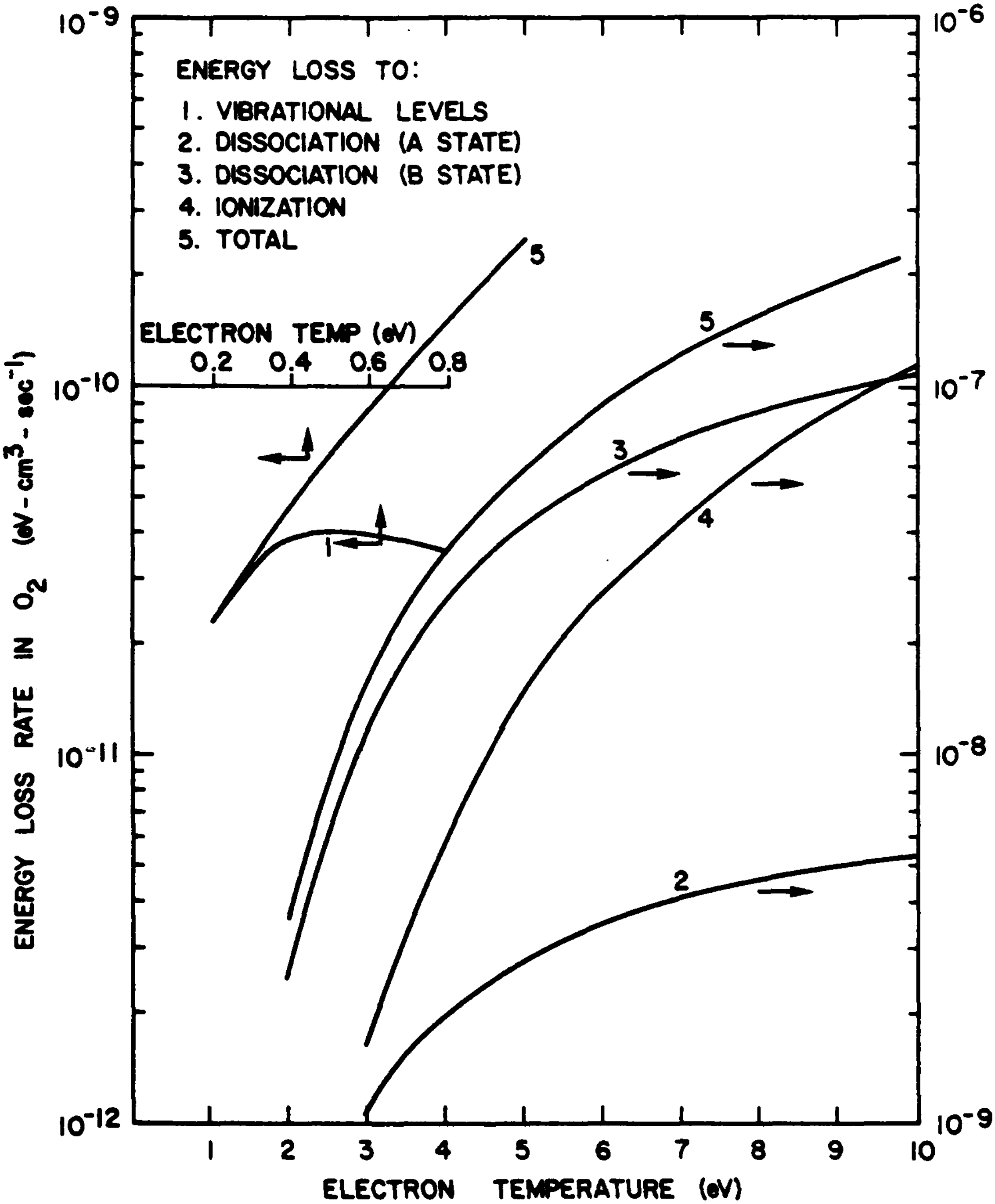

Fig. 2 — Electron energy loss rate in oxygen

energy of the air molecule (14.8 eV). The momentum transfer collision frequency[15] for the same temperature range in air (1 atm) is $\sim 3.7 \times 10^{12}$ sec^{-1} for electrons with a Maxwellian velocity distribution.

3. EXPERIMENTS AND EXPERIMENTALLY OBTAINED LASER BREAKDOWN THRESHOLD POWER

Air breakdown experiments have been performed[16-23] over a wide range of air pressure and laser wavelengths. Since our interest is in the breakdown at the sea level (1 atm) we will concentrate on breakdown at this pressure and give a brief review of these experiments in terms of the other relevent characteristics. These characteristics are laser wavelength, laser pulse duration and the measured breakdown threshold power.

3.1 CLEAN AIR

It should be noted, at the outset, that breakdown threshold power is higher in pure air compared to dirty air[17-19] (air with dust particles). For clean air the threshold power is higher when the focused laser spot size is smaller. This is clearly due to the effect of diffusion on the breakdown process. Furthermore, the breakdown threshold power is higher for shorter laser pulse durations (< 1 nsec).

One of the earlier air breakdown experiments in air was carried out by Tomlinson, et al[16] using ruby (6943Å) and neodymium glass (1.06 μ)lasers. A Q-switched laser with a peak power of 5M Watt with a 40 nsec pulse width at half maximum was focussed into small spot sizes (10^{-5} - 3×10^{-5} cm^2) to break down air, N_2 and O_2. For ruby laser (λ = 6943Å) the breakdown threshold power in air, at one atmosphere, was measured to be $\sim 1.8 \times 10^{11}$ W/cm^2. On the other hand, the breakdown threshold power in air using the neodymium laser (1.06 μ) was measured to be 6.8×10^{10} W/cm^2. The breakdown threshold power in N_2 for both wavelengths was always slightly higher than that for air. Stricker and Parker[24] have measured the breakdown threshold power in N_2 using 1.06 μ laser and found it to be ~ 8.5 x 10^{10} W/cm^2 which is very close to the value measured by Tomlinson, et al[16]. The air breakdown measurements at 2.7 μ and 3.8 μ lasers (HF and DF, respectively) have been conducted by Deka, et al[21] and Soileau[23]. Deka, et al[21] using a multiline pulsed HF/DF laser with pulse length of ~ 120 nsec report a breakdown threshold power of 6 x 10^{10} W/cm^2 for air at one atmosphere using HF laser. The threshold power at DF laser is found to be lower by a factor of 2 which is in good accord with the theory (λ^2 dependence). However, Soileau[23] reports that the breakdown threshold powers of Air by HF and DF lasers are 1.0 x 10^{11} W/cm^2 and 8.2 x 10^{10} W/cm^2, respectively. These values[23] were obtained relative to air breakdown at 10.6 μ (CO_2 laser) where the value was 1.27 x 10^{10} W/cm^2.

Chan et al[20] using a CO_2 laser with a pulse length of 160 nsec obtained breakdown threshold powers in air at 1000 Torr which vary from 5.5 x 10^9 W/cm^2 to 1.3 x 10^9 Watt/cm^2. This varriation is due to variation in the laser spot size and correspondingly on the electron diffusion length. The diffusion length for these measured powers were 1.6 x 10^{-3} cm to 4.8 x 10^{-3}, respectively.

Measurements of air breakdown threshold power at longer laser wavelength have been conducted by Woskoboinikow, et al[22]. They utilized submillimeter lasers from D_2O with a pulse duration of 75 nsec, and obtained threshold powers of 5 x 10^6 W/cm^2 and 5 x 10^5 W/cm^2 for λ = 359 μ and λ = 385 μ , respectively. These experimental data are summarized in Table 1 and are shown in Figure 3.

TABLE I - Clean Air Breakdown Threshold Power
For Various Laser Wavelengths

Wavelength in μ

Ref.	0.6943	1.06	2.7	3.8	10.6	359	385
16	1.8(11)	6.8(10)* 8.5(10)N_2					
21			6.0(10)	3.2(10)			
23			1.0(11)	8.2(10)	1.27(10)		
20					(1.3-5.5)(9)		
22						5(6)	5(5)
24		8.5(10)N_2					

* 6.8(10) means 6.8 x 10^{10} W/cm^2

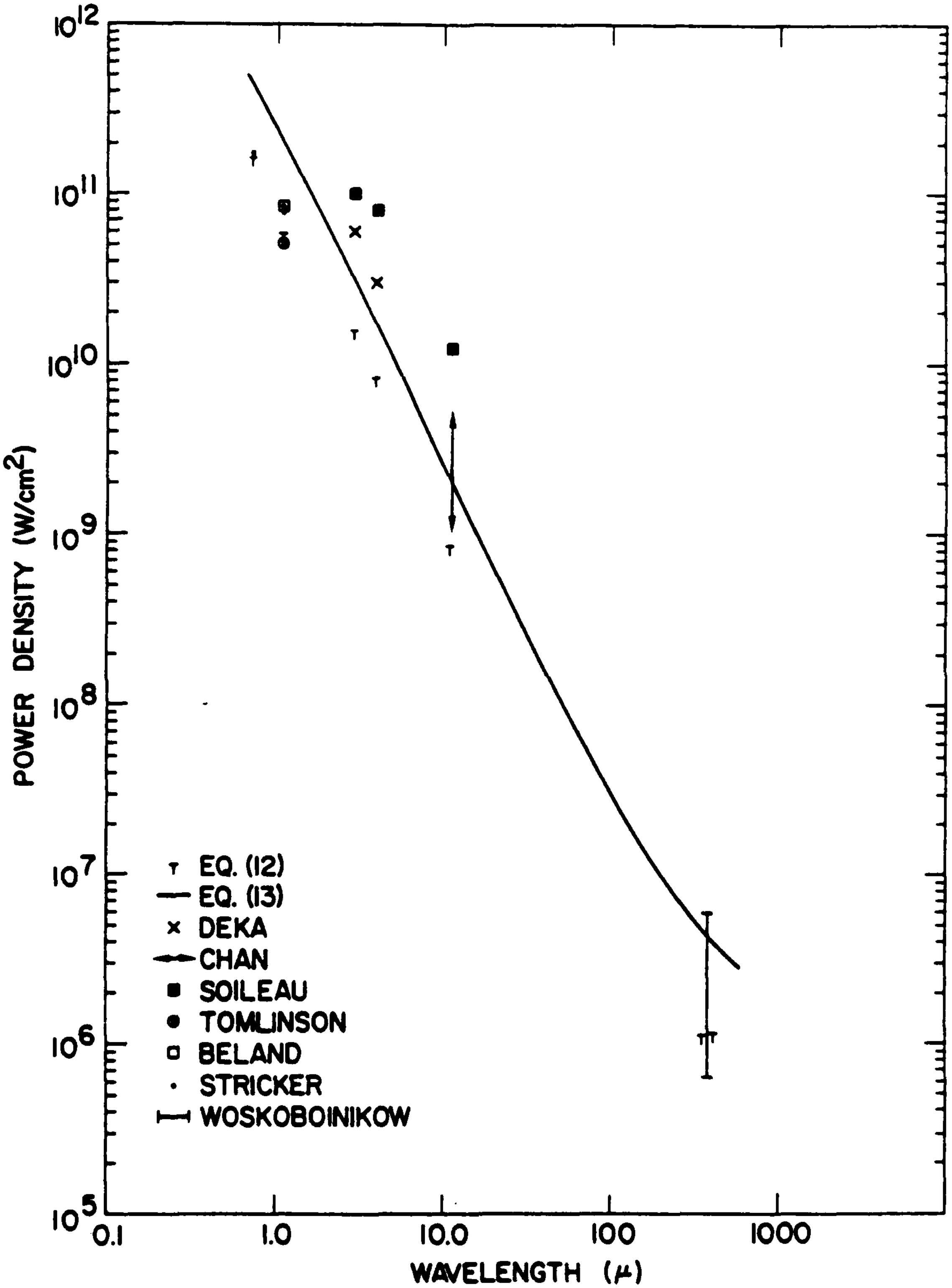

Fig. 3 — Experimental and theoretical air breakdown threshold power as a function of laser wavelength

3.2 DIRTY AIR

The data presented in the preceeding section was for the breakdown in clean air. However, several air breakdown experiments[17-19] have been performed by introducing a variety of particulates with particle diameters larger than 0.1 μm (clean air is generally assumed to have particulates no larger than 0.1 μm in diameter). The threshold power for breakdown was measured as a function of the focal spot for various particulates and particle diameters. These measurements show that particulates (dust particles, etc.) lower the threshold power and this lowering is larger for particles with larger diameters. For example, for carbon particles with diameters of $\sim 50\ \mu$ added to air, the dirty air breakdown threshold power is lowered[19] to 5×10^9 W/cm^2 compared to the clean air case of 2×10^{11} W/cm^2 for $\lambda = 1.06\ \mu$. For $\lambda = 10.6\ \mu$ and particle diameters[18] of 2.2 μ the dirty air breakdown is reduced to 2×10^8 W/cm^2 compared to the case of clean air of 2×10^{10} W/cm^2.

4. THEORETICAL PREDICTIONS

Using the classical microwave breakdown theory we arrived at Eq. (12) for the breakdown threshold power. This equation is derived for a breakdown spot size large enough where the diffusion losses are ignored. For the momentum collision frequency of electrons in one atmosphere of air we use a value of 4.0×10^{12} and for $\langle I_i \rangle$ we use a value of 290 which is 20 times the average ionization energy of the air molecule (14.5 eV). The results of our calculations, shown in Figure 3, are given by the symbol T at each wavelength, compared with the experimental data which are represented by different symbols for different experiments. These data are presumably for breakdown of clean air.

Our theoretical predictions using Eq. 12 shown in Figure 3, differ from the experimental data by a factor which varies from 1 to 3.8.

An emperical formula for the breakdown threshold power based on the microwave air breakdown experiments, given by Kroll[13] reads

$$P_{th} = 1.4 \times 10^{6} \, [p^{2} + 2.4 \times 10^{-6} f^{2}] \qquad (13)$$

where P is the pressure in units of atmosphere and f is the radiation frequency in GH_z. This expression has no dependance on pulse length, however, for breakdown with pulses longer than 50 nsec, the power becomes almost independent of the pulse length. Expression (13) is also shown in Figure 3 for comparison with the experimental data.

A theoretical explanation for the lowering of the breakdown threshold power is that the dust particles absorb laser energy and hence are heated and evaporated and the laser breakdown occurs in the vaporized region which has a larger neutral particle density compared to the air density. For the threshold power to be minimum, the quantity $\omega^2 + \nu_m^2/\nu_m$ must be equal to 2ω (see Eq. 12). This implies that $\omega = \nu_m$. For example, when $\lambda = 10.6\ \mu$ the collision frequency of electrons with neutrals is $\sim 1.8 \times 10^{14}\ sec^{-1}$, which implies a neutral density of approximately 78 atmospheres. This explanation is plausable especially if one recalls the behaviour of the breakdown threshold power in nitrogen as a function of pressure. The minimum of the breakdown threshold power is[25] near 100 atmospheres, i.e. the breakdown power is lowered with increasing density until it reaches a minimum near 100 atmospheres then will start rising beyond the minimum due to increased energy losses by electrons.

5. MICROWAVE AIR BREAKDOWN

In order to generate an ionized channel one may also use microwave radiaion which requires less threshold power for air breakdown compared to lasers. However, this power may not go below 1.4×10^6 W/cm^2 which is the threshold for breakdown, in one atmosphere, under CW and pulsed conditions where the pulse durations are in the μ second range.

To calculate the breakdown threshold power we may use equation (10). In this case we can not ignore the attachment, since the microwave frequencies are much lower than lasers which in general can autodetach the negative ions (O_2^-) . Hence

$$\nu_i = \nu_a + \frac{0.69\ kc}{\tau} \tag{14}$$

The attachment frequency in one atmosphere of air is 7.8×10^7 sec^{-1}. This is obtained by using attachment rate coefficients[26] of 2.4×10^{-30} cm^6/sec and 8.6×10^{-32} cm^6/sec for O_2 and N_2 as the third body, respectively. Thus assuming a pulse length of 1 μ sec, a microwave radiation with wavelength of 1 cm and $k_c \simeq 36$, the ionization frequency required by Equation (14) is 1×10^8 sec^{-1}. This corresponds to a reduced electric field of 40 V cm^{-1} Torr^{-1} (See Fig. 4 which is based on Eq. 12 of Ref. 14). Such an electric field implies a threshold power of 1.2×10^6 W/cm^2 in very close agreement with the accepted value of 1.44×10^6 W/cm^2.

6. RADIATION ABSORPTION LENGTH AND CONCLUSIONS

Once a plasma is generated and the electron density is enhanced, the plasma electrons become good absorbers of the incident radiation. For this reason it is necessary to generate only enough ionization, to guide a discharge,

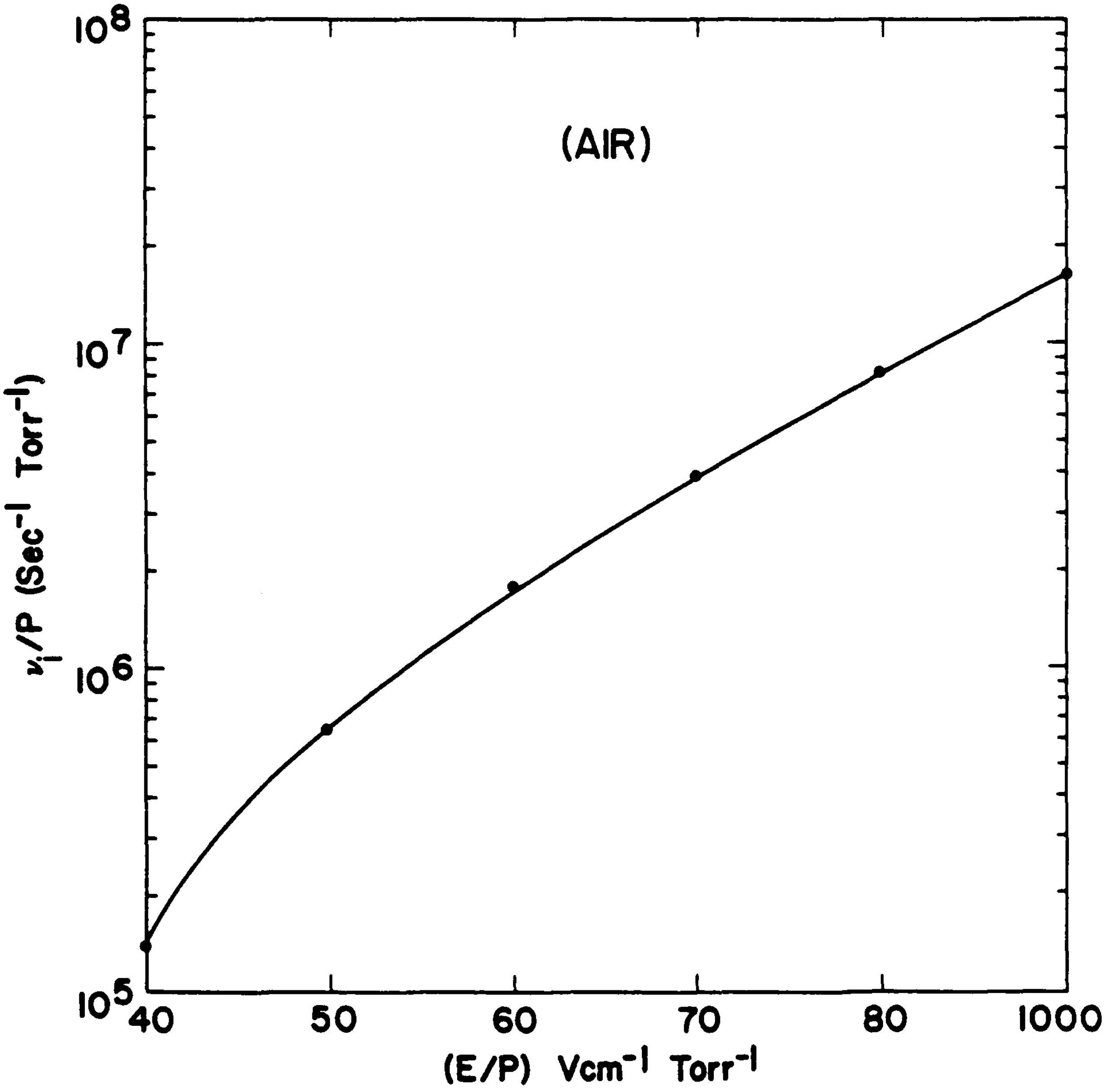

Fig. 4 — Reduced ionization frequency in air as a function of E/P

by limiting the pulse length to avoid a complete air breakdown which results in the absorption of radiation and thus limit the length of the laser produced channel.

The absorption length, when the electron ion Bremsstrahung predominates is[27]

$$\alpha_p = 6.5 \times 10^{-24} \frac{N_e N^+ \lambda^2}{T^{3/2}} g \qquad (15)$$

where g is the gaunt factor($g = 0.5 \ \ln \frac{2.4 \times 10^3 T}{(N_e)^{1/3}}$)

On the other hand when the degree of ionization is small, applicable to microwave air breakdown, the electron neutral Bremstrahlung predominates and the absorption coefficient can be approximated by

$$\alpha_n = \frac{0.1 N_e \nu_m}{\omega^2 + \nu_m^2} \qquad (16)$$

From these relations one can obtain the relevent absorption coefficients and hence the corresponding absorption lengths.

It is clear that the absorption coefficient, for lasers, is proportional to the product of $N_e^2 \lambda^2$. Hence, to minimize laser absorption in the air plasma one must reduce this product, by appropriate selection of λ and laser pulse width. In the first place a longer λ is desireable in that lower breakdown threshold powers are required to break down the air. However, the absorption coefficient is proportional to λ^2 which enhances absorption and thus reduce the absorption length (laser channel). On the other hand, high power lasers in the short wavelength are not as abundant as high power lasers in the long wavelength range (i.e. 1-10 μ). Therefore, one could rely on these lasers for air breakdown and further reduce the desired power by introducing particulates into the air (dust particles, organic molecules, etc.). However, an important parameter that could be utilized to control the electron density is the laser pulse width. By reducing the electron density one reduces the absorption length and thus increases the length of the laser generated channel. An illustration in this regard is warranted. Consider, a neodymium laser at $\lambda = 1.06\ \mu$, an electron temperature of 10^4°K and an electron density of 10^{17} cm^{-3}. The absorption coefficient is $\sim 6.5 \times 10^{-3}$ cm^{-1} which corresponds to an absorption length of ~ 150 cm. However, if one reduces the electron density to 10^{16} cm^{-3} the corresponding absorption length becomes 150 meters. Therefore, it is of great interest to know the *minimum* electron density needed to guide an electric discharge. So that one can tailor the radiation (laser and microwave) in such a manner to produce a channel with the desired residual conductivity. This can be accomplished by using comprehensive air chemistry codes, developed by the author at NRL, to provide the time histories of the free electrons in the laser produced channel. This attempt should be coupled to the development of an electrically driven discharge channel code to provide the energetics for the maintenance of such a channel.

REFERENCES

1. J. R. Greig, R. E. Pechacek, M. Raleigh, T. Dwyer, D. P. Murphy and J. M. Perin "Characteristics Of An Atmospheric Discharge Plasma As An RF Antenna", NRL Memorandum Report 4815 (1982).

2. J. R. Vaill, D. D. Tidman, T. D. Wilkerson and D. W. Koopman, Appl. Phys. Lett. 17, 20 (1970).

3. D. W. Koopman and K. A. Saum, J. Appl. Phys. 44, 5328 (73).

4. J. R. Greig, D. W. Koopman, R. F. Fernsler, R. E. Pechacek, I. M. Vitkovitsky and A. W. Ali Phys. Rev. Lett. 41, 174 (1978).

5. D. W. Koopman, J. R. Greig, R. E. Pechacek, A. W. Ali, I. M. Vitkovitsky J. de Phys. Coll. 7 Suppl. #7 Tome 40, C7, 419 (1979).

6. R. F. Fernsler, J. R. Greig, J. C. Halle, R. E. Pechacek, M. Raleigh and I. M. Vitkovitsky, NRL Memo Report 4380 (1981).

7. M. A. Herlin and S. C. Brown, Phys. Rev. 74, 291 (1948).

8. S. C. Brown in Encyclopedia of Physics, Vol. 22, S. Flugge, Ed., Springer-Verlag Berlin (1956).

9. A. D. MacDonald "Microwave Breakdown In Gases", Wiley, New York (1966).

10. See e.g. (a) J. F. Ready "Effects of High Power Laser Radiation", Academic Press, New York (1971) and References Therein. (b) C. DeMichelis, IEEE J. Quant. Electron QE-5, 188 (1969) and References Therein.

11. P. F. Browne, Proc. Phys. Soc. 86, 1323 (1965).

12. A. W. Ali and T. Coffey "On the Microwave Interaction With Matter and Microwave Breakdown of Air", NRL Memo Report 4320 (1980).

13. N. Kroll and K. Watson, Phys. Rev. A5. 1883 (1972).

14. A. W. Ali, "The Electron Avalanche Ionization of Air and a Simple Air Chemistry Model", NRL Memorandum Report 4794 (1982).

15. S. Slinker and A. W. Ali, "Electron Excitation and Ionization Rate Coefficients for N_2, O_2, NO, N and O", NRL Memo Report 4756 (1982).

16. R. C. Tomlinson, E. K. Damon and H. T. Buscher in "Physics of Quantum Electronics" Edited by Kelley, Lax and Tannenwald, McGraw-Hill, New York (1966).

17. D. C. Smith, Appl. Phys. lett. 19, 405 (1971).

18. D. E. Lencioni, Appl. Phys. lett 23, 12 (1973).

19. D. E. Lencioni, Appl. Phys. lett. 25, 15 (1974).

20. C. H. Chan, C. D. Moody and W. B. McKnight, J. Appl. Phys. 44, 1179 (1973).

21. B. K. Deka, P. E. Dyer, D. J. James and S. A. Ramsden, Opt. Comm. 19, 292 (1976).

22. P. Woskoboinikow, W. J. Mulligan, H. C. Praddaude and D. R. Cohn, Appl. Phys. lett 32, 527 (1978).

23. M. J. Soileau, Appl. Phys. lett, 35, 309 (1979).

24. J. Stricker and J. G. Parker, J. Appl. Phys. 53, 851 (1982).

25. D. H. Gill and A. A. Dougal, Phys. Rev. lett., 15, 845 (1965).

26. H. Shimamori and Y. Hatano, Chem. Phys. 21 187 (1977).

27. Y. P. Raizer "Laser Induced Discharge Phenomena" Consultants Bureau, New York (1977).