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STREAMER DISCHARGES AS APPLIED TO
LASER TRACK CHAMBERS, HIGH PRESSURE STREAMER CHAMBERS
AND CO₂ TEA LASERS

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STREAMER DISCHARGES AS APPLIED TO LASER TRACK CHAMBERS,
HIGH PRESSURE STREAMER CHAMBERS AND CO₂ TEA LASERS

by

Carl Peter Swail

Thesis submitted in partial fulfilment of the requirements
for the degree of Master of Science.

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Ottawa, Canada

September, 1974.

The undersigned recommend to the Faculty
of Graduate Studies acceptance of the thesis
"Streamer Discharges as Applied to Laser
Track Chambers, High Pressure Streamer
Chambers and CO₂ TEA Lasers" submitted by
Carl P. Swail, in partial fulfillment of the
requirements for the degree of Master of
Science

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ABSTRACT

The construction and operation of two particle detectors (the laser track chamber and the high pressure wide gap spark and streamer chamber) and a CO₂ transverse excited atmospheric pressure (TEA) laser are described.

No directly amplified cosmic ray tracks were observed when a CO₂ TEA laser was fired through a chamber containing argon and krypton at pressures up to 12 atmospheres. The maximum laser intensity was 20 MW/cm². Pre-amplification by a Marx generator produced no effect.

Wide gap sparks were observed at pressures up to 9 atmospheres in a 90% Ne-10% He gas mixture in a chamber with a 3-cm gap, pulsed with a 5-stage Marx generator of 100 kV output voltage. Spark quality improved with pressure allowing greater track resolution as pressure was increased. Streamers were observed at pressures up to 5 atmospheres. No significant change in the streamers was seen as the pressure was increased.

The CO₂ TEA laser consisted of a cathode, 2 cm × 70 cm, 3 cm from the anode. The cathode was a grid of stainless steel wires, 0.25 mm in diameter, pulsed by a 10-stage Marx generator of output voltage 700 kV and pulse duration of 20 nsec.

Maximum input energy density to the laser was 320 J/liter. Peak power output measured with a photon drag detector was 14 MW, with a gas mixture of 30:20:50 ($\text{CO}_2:\text{N}_2:\text{He}$). Maximum output energy was 1.3 J, efficiency was 4%.

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TABLE OF CONTENTS

	Abstract	ii
	Acknowledgments	iv
	Table of Contents	v
	List of Illustrations	vii
	Introduction	1
CHAPTER I	Electron Discharges	3
	1. Introduction	3
	2. Ionization by High-Energy Particles	3
	3. Basic Processes of Gas Discharges	4
	Excitation and Ionization by Electrons and Photons	4
	Motion of Charged Particles	6
	4. Electron Avalanche	8
	5. Streamer Formation	10
CHAPTER II	Wide Gap Spark and Streamer Chambers	13
	1. Introduction	13
	2. Wide Gap Spark Chambers	14
	3. Streamer Chambers	16
	4. High Pressure Wide Gap Spark Chambers	17
	5. High Pressure Streamer Chambers	18
	6. Marx Generators	19
CHAPTER III	CO ₂ Lasers	20
	1. Introduction to CO ₂ Lasers	20
	2. CO ₂ TEA Lasers	23
	3. Double Discharge CO ₂ TEA Lasers	25
	4. Photo-preionized CO ₂ TEA Lasers	26
	5. Electron Beam Preionized CO ₂ TEA Lasers	28
	6. Conclusions	28

CHAPTER IV	Laser Amplification of Particle Tracks	30
CHAPTER V	CO ₂ TEA Grid Laser	34
	1. Introduction	34
	2. Experimental Apparatus	35
	3. Results and Discussion	36
	Peak Power	36
	Pulse Energy	37
	Pulse Timing	37
	Pulse Stability	38
	4. Conclusion	38
CHAPTER VI	Laser Track Chamber	39
	1. Experimental Arrangement	39
	2. Experimental Results	40
	3. Hybrid Chamber	41
	4. Hybrid Chamber Results	42
CHAPTER VII	Wide Gap Sparks and Streamers at High Pressure	43
	1. Experimental Arrangement	43
	2. Wide Gap Sparks at High Pressure	44
	3. Streamers at High Pressures	45
	References	82

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Drift Velocity of Electrons vs E/p	49
2	First Townsend Coefficient vs E/p	50
3	Avalanche Growth as a Function of Time	51
4	Photoionization Cross-section vs $h\nu$	51
5	Schematic Circuit Diagram of Marx A	52
6	Schematic Circuit Diagram of Marx B	53
7	Vibrational Energy Levels of CO_2 and N_2	54
8	Normal Vibrations of the CO_2 Molecule	54
9	Time Sequence of Laser Action in Tealasers	55
10	Double Discharge CO_2 TEALasers	56
	(a) Laflamme	
	(b) Dumanchin	
11	Photoinitiated CO_2 TEALasers	57
	(a) Seguin and Tulip	
	(b) Javan and Levine	
	(c) Judd	
	(d) Alcock and Richardson	58
	(e) Alcock and Richardson	
12	Intensity Threshold vs Pressure	59
13	Observations of Gygi and Schneider	60
14	CO_2 TEA Grid Laser - End View	61
15	Peak Power vs Marx Output Voltage	62
16	Peak Power vs $CO_2:N_2$ Ratio	63

<u>Figure</u>		<u>Page</u>
17	Pulse Energy vs Marx Output Voltage	64
18	Pulse Shapes vs $\text{CO}_2:\text{N}_2:\text{He}$ Mixture	65
19	Pulse Delay vs Marx Output Voltage	66
20	Pulse Width vs Marx Output Voltage	67
21	Distribution of Laser Pulses	68
22	LTC Experimental Layout	69
23	Output from Photon Drag Detector	70
24	Photographs of Dust Spots in LTC	71
25	Marx Pulse Length vs SF_6 Pressure	72
26	$\text{Ne} - \text{He}$ Pressure vs SF_6 Pressure	73
27	Photographs of Different Spark Types	74
28	Variation of Spark Quality with Pressure	75
29	Variation of Spark Quality with Delay	76
30	Detection Efficiency vs Delay	77
31	Photograph of Spark at High Angle	78
32	Photographs of Streamers at High Pressures	79
33	Photograph of Plate-to-Plate Streamers	81

Table

1	Marx Generator Characteristics	48
2	Operating Conditions of LTC	48

INTRODUCTION

In experimental high energy physics the primary tool for the detection of particles and particle trajectories is the track detector. The accuracy with which one can reconstruct a particle event (collision, decay, etc.) is determined in large part by the resolution of the track detector. Considerable effort is therefore being expended in the improvement of particle track detectors. This thesis deals with two possible improvements.

Chapter I contains a general discussion of electron discharges and streamer avalanches (electron avalanches propagated by photoionization) as an introduction to the operating mechanisms of wide gap sparks, streamers and the discharge in the CO₂ TEA grid laser.

An improvement in the resolution of wide gap sparks and streamers could be made if the discharges could be better confined. Streamers are very faint and difficult to photograph. An increase in pressure should be an improvement. Owing to reduced electron mobility the sparks and streamers should be more confined and brighter.

A literature survey of wide gap spark and streamer chambers is given in Chapter II. The experimental work on sparks and streamers at higher-than-atmospheric pressure is contained in Chapter VII.

In conventional streamer chambers, the streamers are kept as short as possible to maintain adequate resolution. This results in faint streamers. If the dc field of the streamer chamber could be replaced by an ac field then the streamer would form in a more confined volume. An intense ac field is available from a high

power pulsed laser. The theory of laser induced tracks is described in Chapter IV. An experiment to search for laser amplified tracks is given in Chapter VI.

While working with streamer chambers, it was observed that the high-voltage Marx pulse could produce a uniform glow discharge in the chamber volume. At this time methods were under development for the production of large aperture CO_2 transverse excited atmospheric (TEA) pressure lasers. It was felt that the Marx generator could be used to produce a uniform discharge for excitation of the gas volume of a CO_2 TEA laser. Chapter III contains a review of the development of the CO_2 TEA laser and in Chapter V is a description of the construction and operation of a grid laser system using a Marx generator for excitation.

CHAPTER I

ELECTRON DISCHARGES

1. Introduction

In this chapter, the motion and interactions of charged particles are considered. These topics are discussed in relation to the formation of electron or Townsend avalanches and streamers, that is, avalanches propagated by photoionization. Electron discharges are of interest as the operating mechanisms in streamer and wide gap spark chambers and CO_2 TEA (transverse excited atmospheric pressure) lasers. For these applications the formation of discharges is considered in gases at atmospheric to several atmospheres pressure, and in electric fields of 15 to 35 kV/cm. The electrode separation in the apparatus used is between 2.5 and 10 cm.

The electron discharges start from a primary source of ionization. In the case of the wide gap spark and streamer chambers, the ionization is created by the passage of a high-energy particle, as discussed in the next section. In the CO_2 TEA laser, the ionization is produced by field emission from the wire grid, caused by the high electric field on the grid.

2. Ionization by High-Energy Particles

The detection and identification of particles is fundamental to high-energy physics. A number of detectors of charged particles have been developed, making use of the ionization trails left by these particles. Charged particles moving through matter exert

strong electrostatic forces on atoms or molecules they come in close proximity with, losing energy by exciting and ionizing these atoms. The ionization trails left by the particles can then be amplified by detectors to give a record of the particles' motion.

The ionization left by the particle consists of the two parts: (1) primary ionization, i.e., direct ionization by the high energy particle and (2) secondary ionization created by the primary ionization. The primary electrons will continue to lose energy by further ionization and excitation until they are below the lowest excitation energy threshold of the gas molecules. Ion pairs created by the primary electrons are called secondary ionization.

Values of primary ionization from a singly charged relativistic particle passing through a gas at atmospheric pressure are 12 ion pairs/cm in neon and 40 ion pairs/cm in argon. The average total ionization present is 37 ion pairs/cm for neon and 100 ion pairs/cm for argon.

3. Basic Processes of Gas Discharges

Excitation and Ionization by Electrons and Photons

In the initial stages of an electron discharge the main method of excitation and ionization is electron collision. For low-energy electrons a collision can result in the following reaction

where the electron has excited the atom or molecule into a higher energy state. The energy of the electron must be greater than the lowest excitation level of the

atom or molecule. If the electron energy is above the ionization threshold, i.e., $U_{\text{electron}} \geq U_{\text{ionization}}$, then there can be ionization by the reaction

Typical ionization potentials for the gases used in streamer chambers and CO₂ TEA lasers are - helium 24.6 eV and neon 21.6 eV.

Absorption of photons by an atom or molecule can also lead to excitation or ionization by the reaction

where $h\nu = U^*$, the energy of the excited state, and

where $h\nu \geq U_{\text{ionization}}$. In the excitation reaction the energy of the photon must equal the excitation energy. In the ionization reaction, any additional energy over $U_{\text{ionization}}$ is carried off by the electron. The absorption of photons by a gas can be expressed as

$$I_x = I_0 e^{-\mu x},$$

where I_x is the photon flux at position x ,

I_0 is the flux at $x = 0$, and

μ is the absorption coefficient which depends on the photon wavelength and the kind and density of the gas.

There is one major difference between ionization by electrons and by photons. The peak probability for ionization by photons occurs at photon energies about 0.1 to 1.0 eV above the ionization threshold, whereas the peak probability for electrons is about 5 to 10 times the ionization energy and is, in fact, zero at the ionization energy. Photoionization cross sections are shown in Fig. 4.

Motion of Charged Particles.

There are two types of charge carrier motion, one due to space charge and the other due to external fields. The motion of charge carriers due to space charge fields is described by the diffusion equation

$$n\vec{v} = -D\nabla n(x),$$

where n is the net concentration of charge carriers, $\vec{v}$ is the velocity of the charge carriers, and D is the diffusion constant. The diffusion constant is a function of the mean free path and the thermal velocity of the gas.

The equation of motion for the drift velocity of an electron or ion due to an external field is

$$m \frac{d^2x}{dt^2} = eE$$

Therefore
$$x = \frac{1}{2} \frac{e}{m} Et^2$$

From this we can derive the ion drift velocity,

$$u_+ = \frac{x}{t} = \frac{1}{2} \frac{e\lambda}{m\bar{v}} E = bE,$$

where

$$b = \frac{e\lambda}{2m\bar{v}} = \frac{e\lambda_0}{2m\bar{v}p}$$

λ is the mean free path of the ion

(λ_0 is the mean free path at $p = 1$ Torr),

t is the time between collisions ($t = \lambda/\bar{v}$),

$\bar{v}$ is the mean thermal velocity.

The important thing to note is that the drift velocity is proportional to E/p .

In the above calculation of drift velocity, elastic collisions were assumed. For small electric fields this is the case, since the ion will not gain enough energy between collisions to ionize or excite the molecule on collision. At higher fields, however, the energy loss during collisions must be considered. The energy loss

per collision is $k \frac{m\bar{v}^2}{2}$ where k is the fractional energy loss per collision. The energy loss per unit time is

$$\frac{k m \bar{v}^2}{2 t} \text{ where } t \text{ is the time between collisions}$$

and

$$t = \frac{\lambda}{\bar{v}}$$

Also, the energy gain per unit time from the electric field is eEu_+ . If we assume that energy loss equals energy gain; then

$$eEu_+ = k \frac{m\bar{v}^2}{2} \frac{\bar{v}}{\lambda} = k \frac{m\bar{v}^3}{3\lambda_0} p$$

Using the expression for the drift velocity derived for the low-field case, $\bar{v}$ can be eliminated from the above by substitution, resulting in

$$eEu_+ = \frac{kmp}{2\lambda_0} \left[\frac{e\lambda_0}{2mp} \frac{E}{u_+} \right]^3$$

Therefore the drift velocity is

$$u_+ = \sqrt[3]{k} \left[\frac{e\lambda_0}{4m} \right]^{\frac{1}{2}} \sqrt{\frac{E}{p}}$$

Therefore, for high fields the ion velocity is proportional to $\sqrt{(E/p)}$ as compared to the low-field case where it is proportional to E/p .

In a similar manner the drift velocity for electrons can be derived. Because electrons have a much smaller mass, energy is lost in all collisions. Therefore the drift velocity is always proportional to $\sqrt{(E/p)}$ and

$$u_- = A\sqrt{E/p}$$

There are differences between the observed drift velocities and the theoretical values. These differences come from a number of sources we have not taken into account. In the case of ions these include

cluster formation around the ion, making the ion heavier and larger and reducing mobility; temporary polarization of the other gas molecules by the ion, the ion induces a temporary electric dipole in molecules which interact to retard the ion as it moves; and transfer of energy to the thermic motion of the gas. For electrons the mean free path λ has a dependence on energy and therefore A is a function of energy. This means that u is not simply proportional to $\sqrt{E/p}$ but has a more complex energy dependence. Typical drift velocities as a function of E/p are shown in Fig. 1.

4. Electron Avalanche

An electron avalanche is formed if the applied field is high enough that the electron gains sufficient energy between collisions to ionize on collision, that is, one requires that $eE\lambda \geq U_{\text{ionization}}$. The number of electrons in the avalanche then grows as $n(x) = n_0 e^{\alpha x}$, where α is the first Townsend coefficient and is the mean number of ionizing collisions per centimeter per electron. The first Townsend coefficient has an E/p dependence in a 90% Ne - 10% He streamer chamber mix as shown in Fig. 2. For operation with a limited range of electric field, 20 - 26 V/cm torr in a streamer chamber, we can make the approximation that α is proportional to the external field, E .

The drift velocities in an electron avalanche are typically 10^7 cm/sec for electrons and 10^5 cm/sec for ions, for a field of 15 to 20 kV/cm atmosphere. Therefore the ions can be considered as being stationary compared to the electrons. The avalanche builds up as a cloud of electrons at the head, leaving behind a region with

positive ions (Refer to Fig. 3). The avalanche grows at the electron drift velocity. The displacement is therefore

$$x = u_e t = b E t,$$

where b is the electron mobility. The avalanche also diffuses outward, perpendicular to the electric field. The radius of the avalanche is given by

$$r^2 = 4Dt$$

where D is the diffusion constant. Experimentally it has been found that $D \propto E^{\frac{1}{2}}$, therefore $r^2 \propto E^{\frac{1}{2}} t$.

The electron avalanche creates a number of photons as well as electrons. The number created depends on the number of electrons in the avalanche. Therefore the number of photons created between t and $t + dt$ is

$$dp(t) = \delta n(t) u_e dt \quad (1)$$

where δ is the number of photons created per electron per centimeter. It has been experimentally determined that δ is approximately independent of the field.

As we have seen

$$n_e(x) = n_0 e^{\alpha x},$$

therefore $n_e(t) = n_0 e^{\alpha u_e t}.$

Taking derivatives gives

$$dn_e(t) = \alpha n_e(t) u_e dt. \quad (2)$$

Combining Equations 1 and 2 gives

$$dp(t) = \frac{\delta}{\alpha} dn_e(t).$$

At one atmosphere in a field of 15 to 20 kV/cm, δ/α is approximately one. Therefore an avalanche of 10^8 electrons produces 10^8 photons. If we attempt to photograph this avalanche, only about 10^3 photons can be collected and

focused by a lens. This will expose, on average, only one 7-micron grain on the film, not enough to detect properly.

5. Streamer Formation

As the primary electron avalanche grows, negative space charge builds up in the head of the avalanche, leaving a positive space charge in the tail. This charge perturbs the electric field, producing higher fields in front of and behind the avalanche as shown in Fig. 3.

Owing to this perturbation of the field the electron avalanche is transformed into a streamer breakdown, that is, avalanche propagation by photoionization. It has been determined experimentally⁽³⁾ that this change takes place when

$$\alpha x_M \approx 20$$

where x_M is the length of the breakdown, called the Meek length. (For our system with a field of ≈ 20 kV/cm the Meek length would be approximately 10^{-2} cm.)

The Townsend coefficient α is roughly proportional to the external field E . Since $x = bEt$, as before we can write

$$x_M \approx Et_M \approx 20/E.$$

Therefore the Meek criterion is that

$$E^2 t = \text{constant}.$$

This criterion can be extrapolated for streamers that can be photographed. The value of $E^2 t/p$ for photographable streamers in 90% neon - 10% helium is typically 2500 to 3500 (kV/cm)²nsec/atm⁽¹⁾ in the range of from 0.1 to 1.0 atmosphere.

The space charge field is given by

$$E' = \frac{eae^{\alpha x}}{3\pi\epsilon_0 r}$$

inside or at the edge of the avalanche. If we assume that this space charge field equals the external applied field, we find that

$$e^{\alpha x_{crit}} = 10^8$$

which is identical with the experimentally determined point, $\alpha x_M \approx 20$.

As has been noted, the electron avalanche stage propagates with a velocity of 10^7 cm/sec toward the anode. In the streamer stage the propagation velocity increases to 10^8 cm/sec with propagation towards both anode and cathode. In the case of the anode-going streamer there are two possible explanations for the increase in velocity, the first that it is due to the increase in field because of the large space charge field. The other is the possibility of gas ionizing radiation. Ultraviolet photons of sufficient energy to ionize are formed in the primary avalanche (Photoionization cross sections in He, Ne, and Ar are shown in Fig. 4.) These photons are emitted in all directions and produce free electrons in the gas. The electrons then produce secondary avalanches, especially the electrons produced in the high field region at the head of the primary avalanche. As these secondary avalanches develop they grow into the primary avalanche, forming the streamer.

The cathode-going streamer moves too fast to be due to an increase in ion velocity. The only explanation is that of gas ionizing radiation produced in the primary avalanche. This radiation initiates secondary avalanches in the higher field region near the tail of the primary

avalanche. These grow into the primary avalanche forming the cathode directed streamer. Since both anode- and cathode-going streamers are observed to propagate at the same velocity, they must propagate by photoionization.

A spark channel forms when the streamer extends from anode to cathode. In a streamer chamber, the streamer development is cut off before this stage by cutting off the applied voltage. In a streamer chamber with an applied field of 16 kV/cm the pulse length is about 20 nsec⁽⁷⁾.

CHAPTER II

WIDE GAP SPARK AND STREAMER CHAMBERS

1. Introduction

Detectors for high energy particles are divided into two main groups, counters and track detectors. Counters detect the passage of charged particles through a sensitive volume. Counters include Geiger-Muller counters and plastic scintillators. These detectors are generally large in area and do not give precise information of track location. Track detectors actually delineate the track and so give more accurate track position. Often the two are used in combination with the counters being used to trigger the track detector when an interesting event occurs.

The first track detector considered is the cloud chamber. A rapid expansion of the sensitive volume creates a super-saturated vapour in the chamber. Droplets then form on the ion trails left by the particles. The cloud chamber is triggerable but has a very long memory time and long recycling time (~ 20 sec) which means that there is a high background of bad events and low data rate.

The next track detector to be considered is the bubble chamber, in which a method similar to that of the cloud chamber is used. An expansion of the volume superheats a liquid and bubbles form on the ion trails. The bubble chamber has a much shorter memory time and faster recycling time (~ 0.1 sec), however it cannot be triggered. Therefore a data run consists of a series of pictures which must be scanned for interesting events. The

bubble chamber has the advantage of a high interaction rate due to the density of the medium.

In 1959 the spark chamber was developed. A spark chamber consists of a ground plate and high-voltage plate about 1 cm apart forming a gap filled with a gas such as a 90% neon - 10% helium mix. When a high-voltage pulse is applied to the HV plate, after a particle has passed through the gap, a spark will be formed that follows the particle track. An alternating series of high voltage and ground plates will give a track that can be photographed. Spark chambers have a short memory time ($\sim 10 \mu$ sec) and a high recycling time (1 m sec). They can be triggered. However, there are some disadvantages. The resolution is poorer because physical dimensions of a spark are larger than a bubble in the bubble chamber. The spark chamber is not isotropic, track angles of greater than 45° do not record well. A track close to the field direction forms a spark quickly since the avalanches from each electron merge together to form the spark. At large angles the electron avalanches are moving parallel to each other and do not merge. A longer pulse or higher field is needed, than is usually applied to a spark chamber, if tracks are to form. The multiple track efficiency is low since if one spark forms first the energy will feed through that spark and others may not form.

2. Wide Gap Spark Chambers

Wide gap spark chambers were first developed by Alikhanian et al. in 1963, as an improvement on the narrow gap spark chambers for certain applications. In narrow gap spark chambers the sparks were formed

along the field direction, in a wider gap the sparks would follow the track direction. There is much less multiple scattering due to the chamber material for a wide gap chamber than for a multiple plate narrow gap chamber; the multiple scattering in aluminum is approximately ten times that in hydrogen at one atmosphere.

For measurements of the curvature of a particle track in a magnetic field it is desirable to have a track which has constant displacement and intensity over its entire length, where the displacement is the shift in track position due to electric and magnetic fields. This condition is easier to obtain with a single wide gap than with a series of narrow gaps.

The efficiency for tracks of up to 20° is very high, 99.8%, with the efficiency falling to 97.3% at 30° ⁽¹⁰⁾. The cut-off angle for most experiments is 40° to 45° . At about 45° the efficiency falls off very rapidly. Kotenko reported tracks at up to 60° with an efficiency of 75% but he was using ethanol and water vapour as seed gases. These vapours are electronegative and combine with the electrons to form complexes. Since these ions are massive, they do not diffuse very far. Also, ultraviolet photons produced in streamer formation are absorbed heavily by these vapours and so limit the growth of the streamers.

Multitrack efficiency has been quoted by a number of authors to be excellent; Aronson⁽¹⁰⁾ quotes 97% for vertex events; others give as high as 100% for low angles. However, Brenner⁽⁹⁾ et al. in a more recent paper, in which they described the detection of electron-positron pairs, found that if the angular difference between two tracks was greater than 20° then the track closest to the field direction formed first and robbed

most of the energy, leaving the other track too faint to detect.

One disadvantage of the wide gap chamber compared to the narrow gap chamber is that the wide gap chamber has a much longer sensitive time (the clearing field has to work over a larger distance) and so there can be a large background of old tracks. The narrow gap chamber has a sensitive time of about 1 μsec while the wide gap chamber has a sensitive time of up to 10 μsec . However, this time can be reduced by the addition of an electro-negative gas.

Experimenters using wide gap spark chambers give excellent values of momentum resolution; Garron⁽⁸⁾ quotes a value of $\pm 1.4\%$ on a 1 BeV/c cosmic ray track of 40 cm in a 13.3 kG field. This should be compared to the accuracy limit of a 40 cm track in liquid hydrogen of $\pm 2.4\%$, due to multiple scattering. Aronson⁽¹⁰⁾ quotes a value of $\pm 1.1\%$ at 395 MeV/c and notes that this was limited by the measuring apparatus.

3. Streamer Chambers

The wide gap chamber produces visible tracks of particles that pass from one plate to the other. In 1963, G. E. Chikovani and co-workers published a paper on the development of the streamer chamber. In the streamer chamber a very short (20 nsec) high voltage pulse is applied to a wide gap chamber. The field is applied transversely to the particle track. The shortness of the pulse terminates the discharge growth at an early stage. Looking in a direction perpendicular to the field a series of streamers are seen; looking through the electrode, parallel to the field, a series of dots are seen. These dots delineate the track and

can be photographed. Multiple track efficiency is much better than for spark chambers since the pulse is not terminated by spark formation but is terminated externally. Spatial resolution is good, Bulos⁽¹⁾ quotes a value of $\pm 2\%$ for a particle momentum of 10 GeV/c in a 15 kG field using a 2m chamber.

The streamers grow to a length of about 1 cm before enough light is emitted for them to be photographed. Even at this point they are very faint and difficult to photograph; a large lens aperture ($f=1.4$) and very fast film (> 1000 ASA) are needed. It should be noted that the lens aperture is a compromise, being as large as possible to collect light and still maintain adequate depth of field so that the tracks are in focus in the whole volume of the detector.

4. High Pressure Wide Gap Spark Chambers

A number of researchers have built pressurized narrow gap spark chambers. Willis^(16,17) notes that one can obtain greater resolution in a 90% Ne - 10% He gas, by increasing the pressure due to reduced electron diffusion and spark column distortion. He finds that the error in track position decreases with increasing pressure and is approximately proportional to $1/\sqrt{p}$, where p is the pressure. For normal spark chambers the resolution is about 200 μm where the resolution is the error in a straight line fit to the track, with no magnetic field. Willis⁽¹⁶⁾ quotes a resolution of 70 μm at 20 atmospheres.

Akopyan et al.⁽¹⁴⁾ note that at atmospheric pressure, with pure neon in a narrow gap (1 cm) sparks follow particle tracks only up to 10° , but that this is much improved by increasing the pressure. At five atmospheres

sparks follow the particle tracks at 25° to 35° angles 50% of the time. The other 50% the angle is 5° to 10° smaller than the particle tracks.

One other reason for increasing the chamber pressure is to increase the density in the chamber to make it more useful as a target material.

There is some confusion regarding efficiency as a function of pressure. Akopyan⁽¹⁴⁾ says that the efficiency drops slightly as the pressure is increased; he gives an efficiency of 98% at 4.5 atmospheres.

Schnurmacher⁽¹⁵⁾ notes a maximum in the efficiency of between 95% and 100% for a $\frac{1}{2}$ inch gap between 5 and 7.7 atmospheres. Willis⁽¹⁷⁾ gives an efficiency of approximately 99% at 15 atmospheres with an ultraviolet quenching gas added. This is about the same as the efficiencies measured at atmospheric pressure.

5. High Pressure Streamer Chambers

The streamer chamber may be pressurized in an effort to improve the track resolution. Because of more confinement of the electron avalanches, i.e., reduced mobility and increased photoionization cross sections, more compact and brighter streamers can be expected. With atmospheric pressure streamer chambers the number of streamers per centimeter is much less than the particle track ionization per centimeter. 4 streamers/cm compared to 37 ion pairs/cm for neon at atmospheric pressure. Again, due to confinement of the avalanches at higher pressures, fewer of the avalanches starting on each ion pair should grow together. A better measurement of the ionization left by the particle could be made, which would be useful in determining the charge and energy of the particle.

Kulyukin et al.⁽¹⁹⁾ built a streamer chamber that works at pressures up to six atmospheres in He, Ar and Xe. They found that the number of streamers per centimeter dropped slightly from 2.7/cm at atmospheric pressure. The brightness of the streamers did not change noticeably with pressure. Kulyukin's pictures of streamers showed no substantial change in structure with increasing pressure.

6. Marx Generators

The source of high voltage pulses to power the wide gap spark chamber, streamer chamber, and CO₂ TEA laser described in this thesis is a Marx generator. It produces pulses with very fast rise and fall times. The rise time is about 5 nsec, the fall time is 5 to 7 nsec with a shorting gap to cut off the pulse length and 10 nsec with no shorting gap.

A Marx generator is a capacitor bank whose stages are connected by resistors in such a manner that they can be charged in parallel from a dc supply. When the Marx generator is fired the stages are reconnected in series by spark gaps. The output is then the sum of the voltages on each stage, that is, $V_{out} = NV_{stage}$ where V_{stage} is the voltage on each stage and N is the number of stages. Two Marx generators were used in the experiments. The first (Marx A) was a five stage Marx that used a 20 kV charging voltage. It was used to power the wide gap spark and streamer chamber. The other (Marx B) was a 10 stage Marx that used a 70 kV charging voltage. It was used for the CO₂ TEA laser. The Marx characteristics for these two are shown in Table 1 and schematically in Figs. 5 and 6. (Only four of the ten stages of the Marx B generator are shown.) The operation of Marx generators is described by Bulos⁽¹⁾ and Morrison and Smith⁽⁴¹⁾.

CHAPTER III

CO₂ LASERS

1. Introduction to CO₂ Lasers

A laser is a device which produces coherent, monochromatic radiation. The word LASER is an acronym for light amplification by stimulated emission of radiation.

For a gas laser the power source is either a radio frequency or dc discharge, usually directed longitudinally along the laser axis. Gas lasers have very low gas pressure, normally several torr. Laser action is produced by exciting the gas atoms or molecules from the ground state to the excited state (upper laser level) from where they drop spontaneously or by stimulated emission to the lower laser level, emitting a photon as shown in the diagram. To obtain optical gain, there must be more atoms in the upper level than in the lower. This is known as a population inversion.

The laser cavity is made up of two mirrors, one at each end of the gas tube, at least one of which is partially reflecting. The spontaneously emitted radiation is reflected back and forth along the laser cavity producing stimulated emission in phase with it.

In 1964 Patel et al.⁽²⁰⁾ produced the first CO_2 molecular laser, a continuous discharge laser. The laser transitions are shown in Fig. 7. Patel⁽²¹⁾ described the lasing action of the $\text{CO}_2 - \text{N}_2 - \text{He}$ four level system. The lasing radiation is produced between vibrational states of the CO_2 molecule. The CO_2 molecule has three vibrational modes, as shown in Fig. 8, one of which is degenerate. The first state v_1 is the symmetric stretch mode and is denoted $(v_1, 0^0, 0)$. The second is the bending mode and is denoted $(0, v_2^s, 0)$ where the superscript s is the degeneracy. The third is the asymmetric stretch mode and is denoted $(0, 0^0, v_3)$. Nitrogen, being a diatomic molecule, has only one vibrational state, a symmetric stretching state.

The upper laser level is the (00^01) state and the lower level is the (10^00) state. The population inversion is produced by selective excitation by molecular collisions between CO_2 and N_2 . In the case of Patel's

laser the N_2 was excited by an electron discharge as described in Chapter I. Nitrogen cannot decay from the first vibrational state to the ground state by dipole radiation since it is forbidden by quantum mechanical rules. Therefore the first vibrational state has a long lifetime, 8.8 sec at a pressure of a few torr. The nitrogen is then mixed with the carbon dioxide in the laser cavity. The nitrogen excites the CO_2 to the $(00^0 1)$ state by resonant transfer of energy in molecular collisions. The $(00^0 1)$ state is excited preferentially since there is only an 18 cm^{-1} (0.02 eV) energy difference between it and the first vibrational state of nitrogen. This compares with a thermal energy, kT , at room temperature of 210 cm^{-1} . The other CO_2 states are much further away in energy and so the probability of excitation is very much less.

The $(00^0 1)$ level has a much longer lifetime than the $(10^0 0)$ level. Therefore, there are conditions (lifetimes along with selective excitation) which allow a population inversion. Note that for quantum mechanical reasons, the $(10^0 0)$ to $(00^0 0)$ and $(00^0 1)$ to $(01^1 0)$ transitions are forbidden. Laser radiation at 9.6μ can also be produced with the transition $(00^0 1)$ to $(02^0 0)$. Unless the optical system has been designed to favour an output at 9.6μ , rather than at 10.6μ , only one tenth of the total radiation will be of 9.6μ wavelength. This is due to competition between the transitions: energy is robbed from the 9.6μ transition to feed that at 10.6μ .

In the case of a CO_2 laser in which the CO_2 , as well as the N_2 , is excited by an electron discharge, it should be noted that the $(00^0 v_3)$ levels are preferentially excited by this discharge. These excited states can then cascade to the $(00^0 1)$ state through successive collisions with CO_2 molecules in the ground state, exciting them to the $(00^0 1)$ state.

Conventional CO_2 lasers work at low pressures, about 50 torr or less. Using Q-switching methods,

pulsed CO_2 lasers have been produced with maximum peak powers of about 50 kW. A Q-switched laser usually uses a rotating mirror as one end of the laser cavity so the cavity mirrors are aligned for only a short period of time. In this way the laser medium can be pumped to the upper laser level for a long time and the energy will come out in a short intense laser pulse. It was noticed that increasing the pressure in the laser increased the power out. Owing to an increase in the density of molecules there are more molecules available for laser action and there is a faster transfer of energy. An obvious step then would be to get the laser to work at atmospheric pressure. However, an increase in pressure means that the discharge voltage must also be increased. Soon the voltage required for a longitudinal discharge becomes too high to handle easily. The answer to this is to produce a discharge transverse to the laser axis.

Beaulieu⁽²²⁾ was the first to report a transverse excited atmospheric (TEA) laser with outputs in the megawatt range.

2. CO_2 TEA Lasers

The transverse excited atmospheric laser uses a fast high voltage pulse to excite the gas. For efficient excitation the high voltage pulse should be short compared to the lifetime of the excited CO_2 molecules. At atmospheric pressure this lifetime is of the order of 10 μsec for CO_2 . It is therefore desirable to have excitation times of the order of one microsecond.

The TEA laser uses a gain switching mechanism in a manner somewhat similar to the rotating mirror of the Q-switched system. The sequence of events is shown in Fig. 9. The voltage increases on the laser electrodes

until the gap breaks down and the voltage falls to zero. The current pulse starts as the gap breaks down and builds to a maximum. The gain starts to increase from the time the gap breaks down and rises as the current flows through the gas and the energy becomes uniformly distributed. The gain reaches a maximum near the end of the discharge. The laser pulse occurs at a fixed time later due to the time required for the laser field to reach a maximum. As an example of this consider a laser with a 1.2 m cavity and a 30% reflecting mirror at one end. When the gas is excited spontaneous radiation is emitted in all directions. To obtain the laser field only that part within 1 mrad of the optical axis is important, that is, an initial signal power of 10^{-12} to 10^{-15} W. Therefore to build a peak power of 10^6 W requires 36 to 42 round trips or approximately 300 nsec. This accumulation will in fact take longer since the calculation assumes constant gain at its maximum value but the gain is growing during this period.

The gain reaches a high value before the laser field can depopulate the upper laser level, which leads to a giant pulse output similar to that of the Q-switched type. The main pulse is usually followed by a less intense and longer pulse or tail. This tail occurs since the first pulse equalizes the populations of upper and lower laser levels. Then, since the lifetime of the lower level is shorter than that of the upper level, a population inversion again builds up and a second output pulse occurs. If nitrogen is present in the gas, the excited nitrogen can feed energy into the upper laser level, as already explained, and this adds to the magnitude and duration of the tail.

The first CO_2 TEA lasers were of the helical pin-to-pin type⁽²⁴⁾. One row of pins was connected to ground,

the other set was pulsed through resistors on each pin. The resistors limited the current through each pin to prevent arcs. This system produced a stable discharge. However, the efficiency was reduced owing to the I^2R power losses in the resistors.

Resistorless electrodes have been used by several groups^(24,25,45). However, they are confined to a limited range of operating conditions. These systems rely on a fast rise-time, short pulse to form numerous discharges and before an arc can form, the discharge is cut off.

In the search for greater output powers of CO_2 TEA lasers certain constraints become important. Beaulieu⁽²³⁾ gives as a maximum energy output 2.5 to 20 J/lit depending on the gas mixture. He also gives the maximum output energy density for present optical materials as ~ 5 J/cm². Therefore to get very high powers, lasers must be developed with large cross-sectional areas. Scaling up of the systems in use did not work since to maintain the same energy densities the discharge capacitors had to be made bigger and this increased the discharge time constant, making the probability of arcing much higher. To get around this problem several methods were used to pre-ionize the gas and insure a uniform large-volume discharge.

3. Double Discharge CO_2 TEA Lasers

The first technique is to use a double discharge. There is a first discharge at the anode to create a high density of free electrons which can then be accelerated by the main discharge. This produces a uniform discharge over the whole volume. Laflamme et al.⁽²⁶⁾ apply a high voltage pulse to a mesh anode which first breaks down to a dielectric covered electrode,

the dielectric producing an even distribution of discharges. Then the main gap breaks down. The setup is shown in Fig. 10a. Using a laser with a discharge cross section of 9 cm^2 and an input energy of 53 J/lit , they produced an output energy of 5.5 J/lit and a peak power of 4 MW .

Lamberton and Pearson⁽²⁷⁾ used a system similar to that of Laflamme. With a discharge area of 8 cm^2 and an input of 125 J/lit they produced an output of 5.25 J/lit .

Dumanchin et al.⁽²⁸⁾ use a different method. They have a series of trigger wires in glass tubes along the cathode as shown in Fig. 10b. A high-voltage pulse is applied to the cathode. The cathode breaks down first to the wires because of their close proximity, creating a high electron density near the cathode. The capacitor coupling the trigger wires to ground then charges up bringing the potential on the wires to that of the cathode. As the voltage pulse builds up the main gap breaks down. The discharge area was 20 cm^2 and active volume 1.75 lit . The input energy was 120 J/lit and the output was 18 J/lit with a peak power of 35 MW . Pan et al.⁽²⁹⁾ built a CO_2 TEA laser using the Dumanchin design. The discharge area was 60 cm^2 and the volume was 5.5 lit . The input energy was about 70 J/lit and the output energy was 17 J/lit .

4. Photo-preionized CO_2 TEA Lasers

Another method is that of ultraviolet preionization, in which the gas volume is irradiated by ultraviolet light before the main discharge. This radiation preionizes the gas mainly through absorption by the $584 \text{ \AA}$ He line.

Seguin and Tulip^(30,31) used a series of tungsten pins behind a mesh anode to irradiate the discharge

volume through the mesh, Fig. 11a. They measured electron densities of $10^{11}/\text{cm}^3$. On a discharge cross section of 3 cm^2 they reported an output energy of 50 J/lit.

Javan and Levine^(32,33) used xenon flash lamps on either side of the discharge, Fig. 11b, to provide the ultraviolet radiation. The laser was $1 \text{ cm} \times 1 \text{ cm}$ and 20 cm in length. The maximum output energy, 15 J/lit, was produced with a 1:1:1 ($\text{He}:\text{N}_2:\text{CO}_2$) gas mixture heavily doped with tri-n-propylamine. The tri-n-propylamine was used as a seed gas because it has a low ionization potential, 7.23 eV. Electron densities of $10^{13}/\text{cm}^3$ were measured. The authors determined that a two-photon process was responsible for the photoionization. This is a two-step process; the first photon is absorbed by the molecule, exciting it half way to the ionization limit; the second photon then ionizes the molecule.

Judd⁽³⁴⁾ also used a spark discharge as the ultraviolet source, Fig. 11c. He measured electron densities exceeding $10^9/\text{cm}^3$ at a distance of 10 cm from the source and attained an output energy of 40 J/lit.

Richardson and Alcock^(35,36) utilized two different schemes to produce the ultraviolet sparks. In the first, Fig. 11d, they used a series of pins behind a mesh anode. When the Marx generator is fired, high voltage builds up between the anode and pins producing a large number of arcs which are the ultraviolet source to preionize the main discharge volume. After a preset delay the main discharge occurs. On systems with discharge cross sections of 26 and 58 cm^2 and an input energy of 250 J/lit they achieved greater than 30 J/lit output energy. The second method, Fig. 11e, used an independent ultraviolet source consisting of a series of copper pads on a dielectric surface. High voltage arcs are

produced between these pads from a power supply independent of the main discharge. This flashboard is placed behind one of the grid electrodes. The delay between the triggering of the flashboard and the main discharge was about 2 μ sec. With this system and a discharge cross section of 600 cm^2 they were able to discharge energies of 200 J/lit into the volume. The output energy is not given.

5. Electron Beam Preionized CO_2 TEA Lasers

One final preionization method is the use of an electron beam, where the beam is fired through the laser discharge volume to preionize the gas. Electron densities of $10^{13}/\text{cm}^3$ have been measured. Lasers have been reported with cross-sectional areas of 200 cm^2 producing output energies of 2000 J/pulse (50 J/lit) and peak powers of 100 MW. Electron beam systems, however, are very large and complex.

6. Conclusions

In conclusion, the double discharge systems are an improvement over the earlier simpler systems but are themselves limited. Few have been built with electrode gaps of more than 5 cm, and most have input energies of less than 200 J/lit. The maximum output energies are less than 20 J/lit. The double discharge systems have some ultraviolet preionization since sparks are produced which illuminate the laser volume. They are not, however, as efficient ultraviolet sources as the ultraviolet preionizing systems. With ultraviolet preionization interelectrode gaps have been built of up to 30 cm (600 cm^2 cross section). They are capable

of greater than 400 J/lit input and outputs of 50 J/lit.

Using electron beams, large cross sections and energy outputs of 50 J/lit are also possible. One major advantage of both the ultraviolet and electron beam preionizing systems is that electron densities can be produced that are high enough to allow a discharge to form when the applied voltage is not sufficient to produce breakdown across the main gap. This makes it much simpler to form a uniform large volume discharge without arcs, and the discharge voltage can then be tuned to excite preferentially the upper laser level.

CHAPTER IV

LASER AMPLIFICATION OF PARTICLE TRACKS

The laser track chamber was designed with the intention of solving some of the difficulties with the streamer chamber.

Streamers can be produced that are as short as 2mm but to record them a complex image intensifier system is needed since the light output is very low. Streamers that can be directly photographed must be at least one centimeter long, which results in a loss of resolution of the particle track. Even one-centimeter streamers are very faint and therefore there is a serious depth of field problem in photographing them. Streamers are not isotropic, that is, particle tracks along the field direction are much brighter than those perpendicular to the field and so produce bright flares on the film. This is because the streamers of a track in the field direction grow together to form a spark channel between the electrodes. The laser track chamber (LTC) was designed to overcome these problems.

One solution would be to replace the dc field of the streamer chamber with an oscillating field. In this way the streamer would grow in a relatively small volume. The ac field would have to be of very high frequency (>10 GHz) so that the period of

oscillation would be much shorter than the dc field pulse applied to the streamer chamber (~20 nsec in duration). Since it is very difficult to get uniform electric fields in a large volume with the magnitude and frequency required, the best source is a laser beam.

There are two processes that produce laser breakdown in a gas. One is multiphoton ionization, that is, the simultaneous absorption of a number of photons to ionize the atom. Because of the large number of photons required for multiphoton ionization to occur, especially at long wavelengths, the probability of ionization by this means is very low and little is produced. Multiphoton ionization will also occur on impurities in the gas. The second and dominant mechanism is that of cascade ionization, that is, collisional ionization of the atoms by electrons. The electrons are accelerated by the laser field until they have sufficient energy to produce ionizing collisions.

(37,43)

Grey Morgan derives an equation for the threshold intensity for amplification by a laser of free electrons to the visible state.

Consider first the continuity equation for electrons in a discharge,

$$\frac{\partial n}{\partial t} = n\nu + D\nabla^2 n - \text{div}(nu) - Rn^2 - \beta nN$$

where n is the electron concentration

ν the ionization frequency

D the diffusion coefficient

u the electron drift velocity

R the recombination coefficient

β the electron attachment coefficient

and N the neutral atom concentration, $N = N_0 p = 3.56 \times 10^{16} p$.

To simplify the continuity equation, a number of assumptions are made:

1. Since the electromagnetic field of a laser is oscillatory, there is no net motion of the electrons due to the electric field. Therefore $u = 0$.
2. Only non-attaching gases will be considered. Thus $\beta = 0$.
3. The laser pulses considered are very fast and so there will be little recombination. Therefore set $R = 0$.
4. For a laser track chamber we consider the uniform irradiation of a large volume ($> \text{several cm}^3$). The diffusion losses out of this volume from a discharge in the volume can be neglected.

Therefore the continuity equation is now much simplified:

$$\frac{\partial n}{\partial t} = n\nu$$

We now wish to relate the ionization collision frequency to the laser power intensity. The ionization collision frequency is the sum of the ionization frequency due to electron collision, ν_1 , and the photoionization

frequency, ν_{ex} . We can relate ν_i and ν_{ex} to the Townsend coefficient α and the excitation coefficient θ .

$$\text{Therefore } \nu = \nu_i + \nu_{ex} = u_-(\alpha + \theta).$$

Over the ranges we are considering α/N , θ/N , and u_- are proportional to E/N .

$$\text{Therefore } \nu/N = k(E/N)^2$$

where k is a constant for a particular gas.

Using Poynting's theorem, one can express E in terms of the laser power intensity, $P(t)$.

$$\text{Therefore } \frac{\nu}{N} = \frac{377}{N^2} \left(\frac{\nu_e}{\omega} \right)^2 k P(t),$$

where ν_e is the momentum transfer collision frequency and ω is the laser frequency. Substituting this expression into the continuity equation and integrating

$$n(t) = n_0 \exp \left[\frac{377}{N} \left(\frac{\nu_e}{\omega} \right)^2 k \int_0^t P(t) dt \right].$$

Now take the laser pulse to be triangular of width 2τ and height $P_{\max}$. Integrating over time we get

$$\frac{n(2\tau)}{n_0} = \exp \left[\frac{377}{N} \left(\frac{\nu_e}{\omega} \right)^2 k P_{\max} \tau \right].$$

In the gases of interest, ν_e is approximately independent of electron energy and is proportional to the gas pressure,

$$\nu_e = ap.$$

$$\text{Therefore } \frac{n(2\tau)}{n_0} = \exp \left[\frac{377 p a^2 k P_{\max} \tau}{3.56 \times 10^{16} \omega^2} \right]$$

For an amplification of

$$\frac{n(2\tau)}{n_0} = e^Y$$

$$Y = \frac{p a^2 k P_{\max} \tau}{10^{14} \omega^2}$$

$$\text{therefore } P_{\max} \propto \frac{\omega^2}{\tau p}$$

A plot of the theoretical threshold intensity, $P_{\max}$, as a function of pressure for various gases is shown in Fig. 12. Argon and krypton have been determined to be the best gases available, since their laser breakdown threshold, that is, the lowest power density required to produce a visible plasma in the gas, is lower than that for the other noble gases, neon and helium.

The equation for the threshold intensity is not valid for high pressures and for short pulses. The average rate of energy gain by an electron for cascade ionization is given by

$$\frac{d\bar{\epsilon}}{dt} = \frac{e^2 E^2}{m \omega^2} v_{\text{eff}} \frac{\omega^2}{\omega^2 + v_{\text{eff}}^2}$$

where $\bar{\epsilon}$ is the average electron energy and v_{eff} is the effective collision frequency.

The minimum in the threshold intensity occurs when $\omega = \nu_{\text{eff}}$. In argon this minimum occurs at about 150 atm⁽⁴⁴⁾. For very short laser pulses, that is, subnanosecond pulses, the threshold curve flattens. This is because for very short pulses insufficient collisions occur for avalanche breakdown and multiphoton ionization is the predominant mechanism.

In 1963 Schneider proposed the idea of a laser track chamber. At the time there were no lasers available that would provide the several tens of joules per cm² required. Now, however, intensities

of the needed magnitude are relatively easily produced.

In 1969 Gygi and Schneider (38,39) reported an attempt to find laser tracks. Their pressure chamber was 10 x 10 x 10 cm and used β -particles to produce tracks. They used a 4 GW, 7 n sec pulsed laser at a wavelength of 1.06μ and beam diameter of 1.5 cm. The laser was triggered on a signal from a photomultiplier which detected the passage of a particle through the chamber. In argon at 14 and 20 atmospheres several pictures were taken which showed a number of small dots about 0.1 mm in diameter even though in their experiment they were a factor of 100 below the predicted threshold. At the time, Gygi and Schneider felt that these were produced by free electrons from the ionization by previous beta particles and that the large bright flares were due to recent beta particles (a beta particle produces 3000 ion pairs/cm which will produce an overexposure or flare on the film). Photos of their results are shown in Fig. 13. They have since said that they feel that the dots are due to breakdown on dust particles in the gas. More will be said about this later.

Since Gygi and Schneider's experiment considerable work has been done in the development of the CO₂ TEA

laser. At the CO_2 wavelength of 10.6μ and a pulse length of 200 n sec the threshold intensity is reduced by over three orders of magnitude. It has also been observed, by Smith (40), that the CO_2 laser will cause breakdown only if there is an external source of ionization or there are impurities in the gas. This means that there will be no self-breakdowns due to the intense laser field.

CHAPTER V

CO₂ TEA GRID LASER

1. Introduction

During experiments with streamer chambers it was observed that if the high voltage plane, consisting of a series of fine wires, was in the gas volume, a discharge formed from the wires. A uniform glow was seen throughout the rest of the chamber volume. At this time new methods of uniformly exciting large volumes were being developed to build larger CO₂TEA lasers (the reasons for large-volume lasers are discussed in Chapter III). It was felt that the method which gave such a uniform discharge in the streamer chamber could be used to excite the volume of a CO₂ TEA laser.

The discharge is produced as follows. Field emission in the strong electric field near the wires (>100 kV/cm) produces free electrons, which grow into an electron avalanche, as described in Chapter II. The avalanches change to photo-propagated streamers and spread out into the interelectrode volume, creating a uniformly ionized region. This allows the Marx generator to discharge its energy through the conductive volume without arcs forming.

Early experiments were done with a very large gas volume (15 cm × 75 cm separated by an 8.75 cm gap), but it was found that the Marx generator did not have sufficient energy to excite the volume. The volume was reduced until lasing was observed. The design and operation of this laser will be described in this chapter.

2. Experimental Apparatus

The laser cathode, a stainless steel grid of wires 2 cm × 70 cm, was separated by a 3-cm gap from a flat copper anode, 6 cm × 73 cm. The wires making up the cathode grid were 0.25 mm in diameter and were separated by 6 mm. The electrodes were contained in a Plexiglas tube, 12 cm in diameter with a 0.5-cm wall thickness. NaCl windows set at the Brewster angle for a wavelength of 10.6 μ ($56^{\circ}12'$) were in both ends of the tube.

The laser was driven by a 10-stage Marx generator (Marx B). Its characteristics are given in Table 1. The output pulse was several hundred kilovolts in amplitude and was about 20 nsec in duration. The pulse risetime was 5 nsec and the fall time was 10 nsec. The energy stored in the Marx at the highest voltage (35 kV) was 132 J, corresponding to an input energy density to the laser discharge of 320 J/lit.

The optical cavity was made up of a 10-m radius, 100% reflecting brass mirror and a 77% reflecting germanium flat separated by 2 m.

The output of the laser was measured by a photon drag detector, to determine peak power and pulse shape, and a Gen Tec pyroelectric energy detector. To measure peak power and energy simultaneously, an NaCl flat was placed in the beam to reflect 8% of the beam into the Gen Tec detector. The photon drag detector measured the remaining beam.

3. Results and Discussion

The electron discharge was not uniform along the wire. Discharges started at random points approximately 3 mm apart. Within 1 cm of the wire cathode they merged together to form a uniformly excited volume.

Peak Power

The maximum beam area was about 1.3 cm $\times$ 1.6 cm. The area varied with Marx voltage. There are several reasons why the beam occupied less than 20% of the discharge cross section. The input energy density may not have been high enough, especially at the edges of the discharge. As has been mentioned, the discharge was not uniform close to the cathode, reducing the optical gain in this region. The geometry of the Brewster angle windows restricts the output size, in particular, the regions near the anode and cathode are cut out.

The peak power as a function of the Marx output voltage for various gas mixtures is shown in Fig. 15. The results shown are more recent data than those given in Reference 25. The area of the photon drag detector was 0.5 cm $\times$ 0.5 cm, much smaller than the beam area. In determining the peak power, the area difference was corrected for by assuming an even power intensity over the measured beam area. At the maximum Marx voltage of 700 kV the peak power was still rising for the richer CO₂ content mixes. The maximum peak power obtained was about 14 MW with 30:20:50 (CO₂:N₂:He) mixture. The 30:20:50 mixture was determined to be the best mixture, as was the case for the pin-plate system⁽²⁴⁾. Higher CO₂ content caused severe arcs which interrupted the optical path, eliminating or degrading the output.

It was observed, however, that some arcs, formed on the edge of the discharge volume, produced very little effect on the output. This was because the undisturbed volume was still large enough to allow lasing to occur.

The variation of peak power with $\text{CO}_2:\text{N}_2$ ratio (Fig. 16) for constant helium content shows a maximum at about 1.5:1.

Pulse Energy

Figure 17 shows the variation of pulse energy as a function of Marx voltage. The maximum energy out was about 1.3 J for the 30:20:50 mixture at a Marx voltage of 600 kV. The maximum laser efficiency can be calculated using this energy measurement. Efficiency here is defined to be the ratio of output energy to input energy of the volume swept out by the beam, that is, a volume $1.87 \text{ cm}^2 \times 70 \text{ cm}$ (0.131 liter). The energy stored in this volume was 42 J and therefore the efficiency is about 4%.

As was mentioned in Chapter III the addition of nitrogen to the gas results in the pulse having a larger tail. This result is shown in Fig. 18. As the nitrogen content is increased, the tail becomes more pronounced. With no nitrogen (e.g., 40:0:60) there is almost no tail, while for large amounts of nitrogen (e.g., 7:13:80) a second pulse forms.

Pulse Timing

The delay time of the laser pulse is defined as the time between the breakdown of the last gap of the Marx generator and the appearance of the laser pulse. The variation of time delay for the grid laser as a function of Marx voltage is shown in Fig. 19. The time delay

decreases with increasing Marx voltage and with increasing CO_2 content. This is similar to the result found by Tan⁽²⁴⁾ for a pin-plate system. The minimum delay time measured was ~ 300 nsec.

The pulse width, that is the full width at half maximum, is shown in Fig. 20 as a function of Marx voltage. As the Marx voltage and CO_2 content are increased the pulse width becomes smaller. The minimum pulse width was about 200 nsec for a 30:20:50 gas mix.

Pulse Stability

The peak power stability of the grid laser was measured by plotting the number of pulses at a given peak power as a function of the peak power for a constant Marx voltage (600 kV) and $\text{CO}_2:\text{N}_2:\text{He}$ ratio (30:20:50). The results are shown in Fig. 21. The plot shows a variation of about 30% on either side of the mean.

4. Conclusion

The fast high voltage pulses from a Marx generator provide a means of exciting large volumes of gas without arcs forming. However, the fast high voltage pulses from our Marx generators do not appear to be efficient in exciting the CO_2 laser levels for laser action. This is shown by the low efficiency measured.

CHAPTER VI

LASER TRACK CHAMBER

1. Experimental Arrangement

The experimental arrangement for the laser track chamber is shown in Fig. 22. The beam from the CO₂ TEA laser, a Lumonics Research type 103, was reflected from a concave mirror of 5-m radius. The focused beam passed through the laser track chamber.

The chamber was a lexan tube 35 cm long and 7.5 cm in diameter, with walls 0.3 cm thick. On the ends were NaCl windows 1.25 cm thick and 2.5 cm in diameter. Plastic scintillators 2.5 cm × 30 cm were placed above and below the chamber to detect the passage of cosmic rays through the chamber. A germanium photon drag detector was used to monitor the beam behind the chamber.

The laser output energy was 10 to 12 J per pulse. The pulse had a narrow initial spike duration of 200 nsec and a low-power tail of 600 nsec as shown in Fig. 23. The delay between the scintillator coincidence and the arrival of the laser pulse was less than 4 μsec. The laser beam was 1.5 cm in diameter at the chamber and had a fairly uniform intensity over most of its area, as determined by its burn pattern on thermofax paper. The maximum ^{energy} density of the beam at the chamber was 4 J/cm² and, assuming all the energy was in the initial spike, the intensity was 20 MW/cm². For the run with argon, the chamber was closer to the mirror and therefore the beam diameter was larger and the intensity was reduced.

2. Experimental Results

The chamber was filled with argon and krypton at various pressures. The gas mixtures, pressures, and laser intensities used are given in Table 2. Observations were done by dark-adapted eye as it has been found that the eye is a more sensitive detector than any film. At each experimental condition approximately 100 firings were observed. No cosmic ray tracks were seen.

The only visible effect was that occasionally the beam volume was delineated by a number of bright spots of about 0.1 mm apparent diameter. These were similar to those observed by Gygi and Schneider and are shown in Fig. 24. It was found that these spots were due to small particles of dust blasted off the teflon retaining rings on the end caps. The dust could be removed by flowing the gas.

In this experiment the laser intensity was at least a factor of two below the predicted intensity threshold as shown in Fig. 12. However, the beam was intense enough to cause considerable damage to the chamber windows. This problem became so troublesome that towards the end of the experiment the laser energy, for some pulses, was totally absorbed by the upstream window, producing a bright flash on the outside surface. Until window materials are found that can withstand the high pressures and laser beam intensities needed, direct amplification of laser tracks will not be feasible.

3. Hybrid Chamber

In an attempt to reduce the laser intensity needed for track formation, a hybrid system was used. The system consisted of a Marx generator which was used to amplify the particle track to the pre-visible stage, at which the avalanches are still less than 1 mm long, and a laser was used to amplify the avalanches to the visible stage. With this system streamers should have been formed that were more localized and brighter than in normal streamer chambers and the laser intensity needed could be reduced to a more manageable level.

The laser track chamber was used with electrodes inserted in the volume. The electrodes were 2.5 cm x 30 cm and were separated by 3 cm. They were made of brass and were rounded to prevent corona from the edges. The electrodes were pulsed by the small Marx generator (Marx A), Fig. 5, which produced a nominal 100 kV pulse. An SF₆ shorting spark gap was in parallel with the electrodes. By varying the pressure in this spark gap the high-voltage pulse length was controlled. The laser, again a Lumonics Research type 103, was fired through the chamber after a time delay, which was controlled by an EG & G gate generator.

The laser output was lower than in the first experiment, being 6 J per pulse. The energy density in the chamber was 2.4 J/cm². The delay between the coincidence, indicating the passage of the particle, and the firing of the Marx generator was about 150 nsec. The delay between the Marx generator pulse and the laser pulse was approximately 3 μ sec.

Hybrid Chamber Results

A study of the wide gap sparks and streamers as a function of pressure was first done with no laser beam, to determine the viability threshold. This work, is discussed in the next chapter. The Marx pulse length was then adjusted to just below that needed for viable sparks. The laser was fired through the chamber and observations were made for laser induced tracks. Again the detector was the dark-adapted eye. Argon and a 90% Ne - 10% He streamer chamber mixture were used for gas pressures up to 11 atmospheres. No laser tracks were observed using the hybrid system.

At one point the Marx pulse length was adjusted to produce bright wide gap sparks. No amplification of the part of the track in the laser beam was observed. A "shadow" of the spark was observed at the output of the chamber when the beam was monitored on a thermofax paper. This part of the beam was either absorbed or reflected by the spark. No effort was being made here to create laser tracks; the effect of the beam on the spark was being observed to determine the power intensity needed to amplify the discharge. Although some of the beam energy was absorbed no change in the spark was seen. Breakdown studies have shown that more energy is absorbed by a viable plasma than is reflected.

In conclusion, the laser beam energy density obtained was not sufficient to produce laser amplified tracks even when the tracks were pre-amplified using a Marx generator.

CHAPTER VII

WIDE GAP SPARKS AND STREAMERS AT HIGH PRESSURE

1. Experimental Arrangement

In the search for laser tracks using the hybrid Marx generator and CO₂ TEA laser system, which has been described in a preceding chapter, work was done on the properties of streamers and wide gap sparks at higher-than-atmospheric pressure. Wide gap sparks and streamers are also of interest in themselves as has been discussed in Chapter II.

The track chamber has been described in the section on laser tracks. A 5-stage Marx generator applied a field of between 16 and 20 kV/cm to the chamber electrodes. The development of sparks and streamers could be cut off at different stages by varying the high-voltage pulse length applied to the electrodes. The pulse duration was controlled by the sulphur hexafluoride (SF₆) pressure in a spark gap which was in parallel with the chamber. A plot of the variation of pulse length with SF₆ pressure is shown in Fig. 25. The terminations consisted of series of resistors attached between the high voltage and ground electrodes. Infinite termination was used for most experiments.

On a coincidence trigger from two scintillators placed above and below the chamber, the Marx generator was fired. The minimum delay time between the coincidence signal and the appearance of the high-voltage pulse on the electrodes was from 100 to 200 nsec, although this delay could be increased to determine the memory time of the gas.

The experiment consisted of observing two phenomena: wide-gap sparks, and streamers at as high a pressure as possible.

2. Wide Gap Sparks at High Pressure

Wide-gap sparks were first investigated as a function of gas pressure in a streamer chamber gas mixture, consisting of 90% Ne - 10% He. Sparks were observed at pressures up to 9 atmospheres.

Figure 26 shows the variation of pulse length (SF_6 pressure) needed to produce sparks of different intensities. Examples of these are shown in Fig. 27. Jitter in the spark gap produced variations in the high voltage pulse length and therefore the spark intensity. The jitter was averaged to determine the spark type at a particular SF_6 pressure.

The maximum voltage of the Marx generator was not sufficient to produce sparks at pressures above 9 atmospheres. No reasons were discovered that would prevent creation of sparks at higher pressures if higher voltages or longer pulses were used.

The quality of the sparks was observed as the pressure was increased. In Fig. 28 are examples of wide gap sparks at 1 and 6.4 atmospheres. At atmospheric pressure the sparks were not straight and near the high voltage electrode tended to align themselves along the electric field. At 6.4 atmospheres the sparks were straighter with less tendency to align themselves along the electric field. This shows an improvement in accuracy of track measurement with increased pressure and is in agreement with the trend found by other workers as mentioned before.

Also studied was the variation of spark quality with delay. Sparks became very distorted for delays of 10 to 20 μsec . The spark in Fig. 29a (10 μsec delay)

was at a pressure of 6.4 atmospheres, and the spark in Fig. 29b (20 μ sec delay) was at a pressure of 1.7 atmospheres. The sparks were much thicker and feathered out as delay was increased. This is due to the diffusion of the electrons. The gas memory extended to between 20 and 30 μ sec in a clean gas. This would produce a background of old tracks in an experiment and would not be desirable. The memory time can be reduced by poisoning the gas with a vapour of high electron attachment coefficient.

Fig. 30 shows a plot of efficiency of observation as a function of delay at atmospheric pressure, the efficiency decreases with increasing delay. This decrease was more pronounced at higher pressure and was probably due to faster recombination at the higher gas densities.

As has been seen by other investigators building wide-gap spark chambers at atmospheric pressure, it was found that as the angle of inclination was increased the spark intensity became fainter. Fig. 31 shows a high angle track at 1.7 atm. This should be compared to those in Fig. 27b.

3. Streamers at High Pressure

At an angle of about 45° to the electric field the sparks broke up into individual streamers along the field. Streamers were studied to a pressure of 5 atmospheres by looking at cosmic ray tracks. The chamber was set on end with the electrodes vertical. The scintillators were placed as shown in the accompanying sketch.

Streamer quality did not seem to improve with increasing pressure as had been hoped. Streamers were still about $\frac{1}{2}$ to 1 cm long before they could be photographed. They were not more confined and brighter.

It was felt that due to confinement of streamers at high pressures the angle at which sparks change to streamers should have become larger as the pressure was increased. No significant change was seen.

In Fig. 32 are examples of streamers at various pressures. The photographs were taken from the side view, parallel to the field, and so show up as streamers, not the more usual end on dots. This is the reason they are so faint. They were photographed this way because of the solid electrodes and to allow a better view of the growth process. If the high voltage pulse goes on too long streamers are formed which go from plate to plate. This is shown in Fig. 33. The flares

off the high voltage plate are due to field emission, which becomes more of a problem for long high voltage pulse lengths and higher pressures.

Because of the small acceptance angle and therefore small number of streamer tracks observed, it was difficult to obtain data for a systematic study of the properties of streamers. To overcome this problem a run was done at the National Research Council electron Linac. The chamber was set in the electron beam and had 2.5×2.5 cm scintillators before and after the chamber. The chamber could be rotated to produce tracks at any desired angle. The beam intensity was reduced until there was, on average, one coincidence per beam pulse, that is, one 35 MeV electron per beam pulse. The chamber was checked with cosmic rays prior to each run and produced tracks similar to those already seen. However, when the beam was turned on the chamber was filled with corona from the high voltage electrode. No tracks were seen. The field emission was probably due to ionization by a "halo" surrounding the beam. The major problem when working at the electron Linac was that the chamber could not be viewed directly due to radiation danger and so corrections could not be made while the chamber was operating.

Although high pressure streamers do not appear to be an improvement over those at atmospheric pressure, they can be formed and would be useful if one wanted to increase the pressure in the chamber for higher target density.

TABLE 1Marx Generator Characteristics

	<u>MARX A</u>	<u>MARX B</u>
Capacitor Stages	5	10
Capacitance per Stage	1500 pf	21.6 nf
Maximum Charging Voltage	20 kV	± 35 kV
Nominal Output Voltage	100 kV	700 kV
Maximum Stored Energy	1.5 J	132 J

TABLE 2Operating Conditions of LTC

<u>GAS</u>	<u>PRESSURE</u>	<u>LASER INTENSITY</u>
Pure Ar	10 atm	10 MW/cm ²
Pure Ar	12 atm	10 MW/cm ²
70% Kr, 30% Ar	11 atm	20 MW/cm ²
93% Kr, 7% Ar	11 atm	20 MW/cm ²

Drift velocity of electrons
in argon⁽³⁾

Drift velocity of electrons
in neon⁽⁴⁾

Drift velocity of electrons
in helium⁽³⁾

FIG. 1 DRIFT VELOCITY OF ELECTRONS VS E/p .

FIG. 2 FIRST TOWNSEND COEFFICIENT VS E/p . (1)

FIG. 3 AVALANCHE GROWTH AS A FUNCTION OF TIME (2)

FIG. 4 PHOTOIONIZATION CROSS-SECTION VS $h\nu$ (2)

FIG. 5 MARX A (41)

FIG. 7 VIBRATIONAL ENERGY LEVELS OF CO₂ AND N₂⁽²⁴⁾

FIG. 8 NORMAL VIBRATIONS OF THE CO_2 MOLECULES ⁽²⁴⁾

- a Voltage pulse
- b Current pulse
- c Gain curve
- d Laser output

FIG. 9 TIME SEQUENCE OF LASER ACTION IN TEA LASERS (23)

Double discharge laser. The gas container and the electrodes are shown in transverse section. E—Transparent plastic gas enclosure, S—shaped electrode, G—grid electrode, T—dielectric covered electrode, CT—trigger capacitor, CS—energy storage capacitor, RL—current limiting resistor, RC—charging resistor, PS—high voltage dc power supply, SW—triggered spark gap, TR—trigger unit controlling the firing of SW. Not shown are the mirror, the semitransparent window, and the gas supply and metering system.

(a) Laflamme (26)

(b) Dumanchin (28)

S - cathode
A - anode
W - trigger wires

FIG. 10. DOUBLE DISCHARGE CO₂ TEA LASERS

Discharge configuration: C, main discharge capacitor; electrode area, $0.004 \mu\text{F}/\text{cm}^2$; R, charging resistor, $250 \text{ k}\Omega$.

(a) Seguin and Tulip⁽³⁰⁾

(b) Javan and Levine⁽³³⁾

(c) Judd⁽³⁴⁾

FIG. 11 PHOTOINITIATED CO_2 TEA LASERS

Schematic of Marx bank excitation circuit. C_1 —storage capacitors, $0.1 \mu\text{F}$; C_2 —trigger capacitors: $C_1 \sim 180 \text{ pF}$ (5-cm system), $C_2 \sim 100 \text{ pF}$ (7.5-cm system); C_3 —cathode capacitor, 100 pF ; $\text{SG}_1, \text{SG}_2, \text{SG}_3$, pressurized nitrogen spark gaps.

(d) Alcock and Richardson⁽³⁵⁾

Schematic diagram of the electrode configuration. (a) The preionizer electrode. (b) The preionizer electrode situated behind one of the main discharge electrodes.

Excitation circuits of the main discharge and of the preionizer. Legend: $\text{SG}_1, \text{SG}_2, \text{SG}_3$ —high-pressure spark gaps for Marx bank; $C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10}, C_{11}, C_{12}, C_{13}, C_{14}, C_{15}, C_{16}, C_{17}, C_{18}, C_{19}, C_{20}, C_{21}, C_{22}, C_{23}, C_{24}, C_{25}, C_{26}, C_{27}, C_{28}, C_{29}, C_{30}, C_{31}, C_{32}, C_{33}, C_{34}, C_{35}, C_{36}, C_{37}, C_{38}, C_{39}, C_{40}, C_{41}, C_{42}, C_{43}, C_{44}, C_{45}, C_{46}, C_{47}, C_{48}, C_{49}, C_{50}, C_{51}, C_{52}, C_{53}, C_{54}, C_{55}, C_{56}, C_{57}, C_{58}, C_{59}, C_{60}, C_{61}, C_{62}, C_{63}, C_{64}, C_{65}, C_{66}, C_{67}, C_{68}, C_{69}, C_{70}, C_{71}, C_{72}, C_{73}, C_{74}, C_{75}, C_{76}, C_{77}, C_{78}, C_{79}, C_{80}, C_{81}, C_{82}, C_{83}, C_{84}, C_{85}, C_{86}, C_{87}, C_{88}, C_{89}, C_{90}, C_{91}, C_{92}, C_{93}, C_{94}, C_{95}, C_{96}, C_{97}, C_{98}, C_{99}, C_{100}$ —low-inductance (20 nH) capacitors; SG_4 —high-pressure delay spark gap; SG_5 —spark gap.

(e) Alcock and Richardson⁽³⁶⁾

FIG. 12 Intensity Threshold Vs. Pressure

FIG. 13 OBSERVATIONS OF GYGI AND SCHNEIDER (38)

FIG. 14 CO₂ TEA GRID LASER — END VIEW

$\text{CO}_2:\text{N}_2:\text{He}$

FIG. 15 PEAK POWER VS MARX OUTPUT VOLTAGE

FIG. 16 PEAK POWER VS $\text{CO}_2:\text{N}_2$ RATIO

FIG. 17 PULSE ENERGY VS MARX OUTPUT VOLTAGE

PULSE SHAPE
CO₂ : N₂ : He RATIO

65

40 : 0 : 60

30 : 10 : 60

0.5 μ sec

20 : 20 : 60

10 : 30 : 60

20 : 0 : 80

13 : 7 : 80

10 : 10 : 80

7 : 13 : 80

FIG. 18 PULSE SHAPES VS CO₂ : N₂ : He MIXTURE

FIG. 19 PULSE DELAY VS MARX OUTPUT VOLTAGE

 $\text{CO}_2:\text{N}_2:\text{He}$

FIG. 20 PULSE WIDTH VS MARX OUTPUT VOLTAGE

DISTRIBUTION OF GRID LASER PULSES

FIG. 21 DISTRIBUTION OF LASER PULSES

FIG. 22. Experimental Layout

Horizontal Scale - 200 nsec/division

Vertical Scale - arbitrary power units

FIG. 23 OUTPUT FROM PHOTON DRAG DETECTOR

FIG. 24 PHOTOGRAPHS OF DUST SPOTS IN LTC

Pulse Length vs SF_6 Pressure
Ne-He at 50 psig

FIG. 25 MARX PULSE LENGTH VS SF_6 PRESSURE⁽⁴²⁾

FIG. 26 Ne-He PRESSURE VS SF₆ PRESSURE (42)

(a) Faint

(b) Medium

(c) Bright

FIG. 27 PHOTOGRAPHS OF DIFFERENT SPARK TYPES

(a) 1 atmosphere

(b) 6.4 atmospheres

FIG. 28 VARIATION OF SPARK QUALITY WITH PRESSURE

(a) 10 μ sec delay

(b) 20 μ sec delay

FIG. 29 VARIATION OF SPARK QUALITY WITH DELAY

FIG. 30 DETECTION EFFICIENCY VS DELAY

FIG. 31 PHOTOGRAPH OF SPARK AT A HIGH ANGLE

(a) 1.7 atmospheres

FIG. 32. PHOTOGRAPHS OF STREAMERS AT HIGH PRESSURES

(b) 3.7 atmospheres

FIG. 32 (cont.) PHOTOGRAPHS OF STREAMERS AT HIGH PRESSURES

FIG. 33 PHOTOGRAPH OF PLATE-TO-PLATE STREAMERS

REFERENCES

1. F. Bulos, A. Odian, F. Villa and D. Yount, "Streamer Chamber Development", SLAC Report no. 74.
2. O. C. Allkofer, Spark Chambers, Verlag Karl Thiernig Kg., Munich (1969).
3. H. Raether, Electron Avalanches and Breakdown in Gases, Butterworths, London. (1964).
4. S. C. Brown, Basic Data of Plasma Physics, 1966, M.I.T. Press, Cambridge (1967).
5. B. Rossi, High Energy Particles, Prentice-Hall Inc., Englewood Cliffs, N.J. (1952).
6. E. Segre, Nuclei and Particles, Benjamin, New York, (1965).
7. R. F. Snell, "The Development of a Medium Sized Streamer Chamber System", MSc. Thesis, Carleton University (1970).
8. J. P. Garron, D. Grossman and K. Strauch, "Properties of Wide-Gap Spark Chambers", Rev. Sci. Instr., 36, 264 (1965).
9. E. Brenner, D. Grossman, D. Petersen, F. D. Rudnick, J. H. Scharenguivel, K. Strauch, J. K. Walker, D. Wern, M. Wong and S. L. Wu, "Observations on the Performance of Wide-Gap Spark Chambers", Nucl. Instr. and Methods, 103, 469 (1972).
10. S. H. Aronson, R. C. Catura, H. H. Chen and K. W. Chen, "A Study of Wide-Gap Spark Chambers", Nucl. Instr. and Methods, 46, 93 (1967).
11. L. P. Kotenko, G. I. Merzon, A. D. Uinogradov and N. G. Vlasov, "Wide-Gap Spark Chamber Filled with Neon and Ethanol or Water Vapours", Nucl. Instr. and Methods, 54, 119 (1967).
12. W. R. Dawes and R. M. Kalback, "Observation of Particle Trajectories in a Wide-Gap Spark Chamber", Nucl. Instr. and Methods, 31, 41 (1964).

13. L. P. Keller, R. A. Schluter and T. O. White, "Operational Characteristics of a Wide-Gap Spark Chamber", Nucl. Instr. and Methods, 41, 309 (1966).
14. G. S. Akopyan, N. Kh. Bostandzhyan, G. A. Marikyan and K. A. Matevosyan, "Characteristics of High-Pressure Spark Chambers", Translated from Priroda i Tekhnika Eksperimenta, 3, 45 (1967).
15. G. L. Schnurmacher, "Spark Chambers Using Helium or Hydrogen at High Density", Nucl. Instr. and Methods, 36, 269 (1965).
16. W. J. Willis and W. Bergmann, "High Resolution Optical Spark Chamber", Nucl. Instr. and Methods, 91, 29 (1971).
17. W. J. Willis, V. Hungerbuehler, W. Tanenbaum and I. J. Winters, "High Resolution Wire Spark Chamber", Nucl. Instr. and Methods, 91, 33 (1971).
18. M. Atac, "High Resolution Low Temperature Wire Spark Chambers", Nucl. Instr. and Methods, 93, 521 (1971).
19. M. M. Kulyukin, D. B. Pontekorvo, I. A. Falomkin and Yu. A. Shcherbakov, "Recording Particle Tracks in a Helium-Filled High-Pressure Streamer Chamber", Instr. and Exp. Tech. (USA), 6, 1372 (1965).
20. C. K. N. Patel, W. L. Faust and R. A. McFarlane, Bull. Am. Phys. Soc., 9, 500 (1964).
21. C. K. N. Patel, "Selective Excitation Through Vibrational Energy Transfer and Optical Maser Action in N_2-CO_2 ", Phys. Rev. Lett., 13, 617 (1964).
22. J. A. Beaulieu, "Transversely Excited Atmospheric Pressure CO_2 Lasers", Apply. Phys. Lett., 16, 504 (1970).
23. J. A. Beaulieu, "High Peak Power Gas Lasers", Proc. of the IEEE, Vol. 59, no. 4, 667 (1971).
24. K. O. Tan, "Studies of TEA CO_2 Lasers Driven by Marx Generators", M. Eng. Thesis, Carleton University (1972).

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2

25. R. W. Morrison and C. Swail, "A New Method of Exciting Uniform Discharges for High Pressure Lasers", Phys. Lett., 40A, 375 (1972).
26. A. K. Laflamme, "Double Discharge Excitation for Atmospheric Pressure CO₂ Lasers", Rev. of Sci. Instr., 41, 1578 (1970).
27. P. R. Pearson and H.M. Lamberton, "Atmospheric Pressure CO₂ Lasers Giving High Output Energy per Unit Volume", IEEE J. of Quantum Electronics, QE-8, 145 (1972).
28. R. Dumanchin, M. Michon, J. C. Farcy, G. Boudinet and J. Rocca-Serra, "Extension of TEA CO₂ Laser Capabilities", IEEE J. of Quantum Electronics, QE-8, 163 (1972).
29. Y.-L. Pan, J. R. Simpson, A. F. Bernhardt and S. E. Kiergan, "Generation of a Multigigawatt Nanosecond CO₂ Pulse", IEEE J. of Quantum Electronics, QE-10, 44 (1974).
30. H. Seguin and J. Tulip, "Photoinitiated and Photosustained Laser", Apply. Phys. Lett., 21, 414 (1972).
31. H. Seguin, J. Tulip and J. McKee, "Enhancement of Photoelectron Density in TEA Lasers Using Additives", Apply. Phys. Lett., 23, 527 (1973).
32. A. Javan and J. S. Levine, "The Feasibility of Producing Laser Plasmas Via Photoionization", IEEE J. of Quantum Electronics, QE-8, 827 (1972).
33. J. S. Levine and A. Javan, "Observation of Laser Oscillation in a 1-atm CO₂-N₂-He Laser Pumped by an Electrically Heated Plasma Generated by Photoionization", Apply. Phys. Lett., 22, 55 (1973).
34. O. P. Judd, "An Efficient Electrical CO₂ Laser Using Preionization by Ultraviolet Radiation", Apply. Phys. Lett., 22, 95 (1973).
35. M. C. Richardson, A. J. Alcock, K. Leopold and P. Burtyn, "A 300-J Multigigawatt CO₂ Laser", IEEE J. of Quantum Electronics, QE-9, 236 (1973).

36. M. C. Richardson, K. Leopold and A. J. Alcock, "Large Aperture CO₂ Laser Discharges", IEEE J. of Quantum Electronics, QE-9, 934 (1973).
37. C. Grey Morgan, "New Developments in Electronic Position Detectors", CERN 69-29, 143 (1969).
38. E. Gygi and F. Schneider, "Note About an Experiment for a Track Chamber Based on Laser Excitation", CERN ISR-GS/69-46 (1969).
39. "Laser Chambers in the Future ?", Note in CERN Courier of February 1970.
40. D. C. Smith, "Gas Breakdown Dependence on Beam Size and Pulse Duration with 10.6μ Wavelength Radiation", Apply. Phys. Lett., 19, 405 (1971).
41. R. W. Morrison and A. M. Smith, "Overvoltage and Breakdown Patterns of Fast Marx Generators", Report, Dept. of Physics, Carleton University (1971).
42. Krauss, L. M., "Wide Gap Sparks at High Pressures", Report, Dept. of Physics, Carleton University (1973).
43. F. Morgan, L. R. Evans and C. Grey Morgan, "Laser Beam Induced Breakdown in Helium and Argon", J. Phys. D: Apply. Phys., 4, 225 (1971).
44. A. J. Alcock, "Recent Developments in Laser Induced Gas Breakdown", Presented at Laval Conference May 1971, Unpublished.
45. K. A. Laurie and M. M. Hale, "A Pin-Electrode Atmospheric-Pressure CO₂ Laser", IEEE J. of Quantum Electronics (Corresp.), QE-7, 530 (1971).

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