NINTH ANNUAL

GASEOUS ELECTRONICS CONFERENCE

PROGRAM

and

ABSTRACTS OF PAPERS

October 31, November 1, 2, and 3, 1956

Pittsburgh, Pennsylvania

jointly sponsored by

Division of Electron Physics, American Physical Society

and

Westinghouse Research Laboratories

NINTH ANNUAL GASEOUS ELECTRONICS CONFERENCE

October 31, November 1, 2, and 3, 1956

PROGRAM

Wednesday, October 31 — 9:00 - 9:30 a.m.
Registration in Reception Room
Westinghouse Research Laboratories

-

A. ARCS

Chairman: L. M. Branscomb, National Bureau of Standards

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	A-2	THEORY OF THE ELECTRIC ARC AT METALS WITH A LOW MELTING POINT, AS COPPER Ragnar Holm Stackpole Carbon Company	3
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	A-5	FAST TIME ANALYSIS OF LOW PRESSURE GLOW TO ARC TRANSITIONS Russell J. Westberg University of California Presented by: Leonard B. Loeb	6

Wednesday, October 31
1:00 p.m.

Luncheon in the Research Laboratories Cafeteria

B. IONS

Chairman: R. E. Geballe, University of Washington

Wednesday, October 31
2:00 p.m.

\- Intermission -

Wednesday, October 31
3:45 p.m.

Tours of the Research Laboratories

C. HIGH TEMPERATURE PLASMAS

Chairman: W. P. Allis, Massachusetts Institute of Technology

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	C-2	(Invited Paper) SOME THEORETICAL PROPERTIES OF THE PINCH EFFECT AND ITS INSTABILITIES J. L. Tuck University of California, Los Alamos Scientific Laboratory	17
		- Intermission - Business Meeting	
	C-3	(Invited Paper) DIFFUSION OF CHARGED PARTICLES ACROSS A MAGNETIC FIELD A. Simon Oak Ridge National Laboratory	18
	C-4	(Invited Paper) SOME HYDROMAGNETIC INSTABILITIES M. Kruskal Project Matterhorn, Princeton University	19
	C-5	(Invited Paper) AN ENERGY PRINCIPLE FOR THE HYDROMAGNETIC STABILITY PROBLEM E. Frieman Project Matterhorn, Princeton University	20
Thursday, November 1 1:00 p.m.		Luncheon in the Research Laboratories Cafeteria	

D. SPUTTERING AND CATHODES

Chairman: E. A. Coomes, Notre Dame University

Thursday, November 1	D-1	SPUTTERING YIELDS FOR LOW ENERGY Hg^+-ION BOMBARDMENT G. K. Wehner General Mills, Incorporated	22

Thursday, November 1
6:30 p.m.

Cocktail Party and Banquet in the Blue Room and Ballroom of the Roosevelt Hotel, Pittsburgh

Professor Sanborn C. Brown, of the Massachusetts Institute of Technology, will present a talk entitled "Count Rumford, the Father of Applied Science."

E. PLASMAS

Chairman: D. Alpert, Westinghouse Research Laboratories

Friday, November 2
9:00 a.m.

Friday, November 2
1:00 p.m.

Luncheon in Research Laboratories Cafeteria

F. BREAKDOWN

Chairman: D. E. Kerr, Johns Hopkins University

Friday, November 2
2:15 p.m.

G. IONIZATION AND AFTERGLOW

Chairman: L. H. Fisher, New York University

Saturday, November 3
12:30 p.m.

Luncheon in the Research Laboratories Cafeteria

Wednesday, October 31

9:30 a.m.

SESSION A

ARCS

Chairman, L. M. Branscomb
National Bureau of Standards

ARC INITIATED DISCHARGE IN MAGNETIC FIELD IN HIGH VACUUM

I. IONIC CENTRIFUGE TYPE OF DISCHARGE

Joseph Slepian
1115 Lancaster Street
Pittsburgh 18, Pennsylvania

A short arc between electrodes in a parallel magnetic field set in the middle of a high vacuum tank gives off a current to the tank wall positive or negative not limited in any way by space charge. With 100 amperes central arc, we have obtained 10 amperes of ions to the walls (and 5 amperes of electrons) with no strain upon the vacuum, and at a voltage too low for emission of electrons by condensing ions.

Study shows that the condition for space charge limitation to a very low value, holding for a source limited to carriers of one sign only, fails completely when the source has carriers of both signs. A discharge occurs with cylinder insulated and at a potential of $-(e/8\ mc^2)\ H^2\ r^2$ e.s.u. receiving both ions and electrons, but with the end walls energized to a still higher voltage and receiving positive ions alone. The ions (and electrons) have a random energy at each point of the discharge equal to the circumferential energy of mean motion of the positive ions, so that this type of discharge is ineffective for isotope separation.

A new type of discharge, the Magneto-Ionic Expander type, is well-suited for that.

THEORY OF THE ELECTRIC ARC AT METALS WITH A LOW MELTING POINT, AS COPPER

A-2

Ragnar Holm
Stackpole Carbon Company
St. Marys, Pennsylvania

The cardinal difficulty for any theory of these arcs has been to explain the abundant emission of electrons from the cathode. The agent must be either field emission or thermionic emission enhanced by the Schottky exponential factor or both phenomena together. In any case, fields of the order of several 10^7 volts/cm are required at the cathode surface. Considering a cathode fall of the order of 10 volts and a field enhancing factor of certainly less than 5, one calculates a thickness of the cathode fall region of one or two times 10^{-6} cm, which is less than a tenth of the mean free path of the ions and atoms at the temperature in question, assuming a pressure of one atmosphere. It is out of the question that the cathode fall region be so much smaller than the mean free path. However, the discrepancy is eliminated if one may assume a metal vapor pressure of at least 10 atmospheres before the cathode. This will be saturation pressure and the temperature in the cathode spot will correspond to it. It will be shown in the lecture that a consistent theory can be formed employing the assumption of a high metal vapor pressure before the cathode. The energy balance is satisfied and the rate of evaporation calculated is in accordance with measurements.

Among detailed results it may be mentioned that the current density at and the temperature of the cathode spot are smaller at high currents (thousands of amperes) than at small currents (tens of amperes) although the emission is essentially thermionic at high currents and essentially a field current at the small currents.

PROBE MEASUREMENTS IN THE HIGH INTENSITY CARBON ARC

M. R. Null and W. W. Lozier
National Carbon Research Laboratories
Parma, Ohio

Probe measurements have been made of the voltage distribution in a high intensity carbon arc over a range of arc currents and arc lengths. The voltage drop at the cathode and the voltage gradient across the arc plasma change but little with different arc currents and arc lengths. However, when the spacing between the electrodes is increased, all of the increase in arc voltage does not appear across the arc plasma. Almost one-half (40 per cent) of the increase in voltage is found at the anode itself.

CURRENT DENSITY AND TEMPERATURE OF HIGH CURRENT ARCS

A-4

W. R. Wilson, T. H. Lee, and J. C. Sofianek
General Electric Company
Philadelphia, Pennsylvania

A method of measuring the current density of arcs of the order of 20,000 amperes is reported. The method consists of placing a small stationary current transformer in the arc plasma. The voltage induced in the current transformer is shown to be proportional to the rate of change of the current linked by the current transformer. The temperature of the arc is calculated from the current density and voltage gradient measurements. A maximum temperature of 19,000° K was obtained. The effects of the current transformer on the arc are discussed. The results are compared with those of Skeats and Schuck.

It has been previously reported by Skeats and Schuck that the luminous cones in an arc are not closely related to the current paths in the arc. It is proposed in this paper that the luminous cones are the relatively cool (3000 to 5000° K) vapor jets flowing in the high temperature (20,000° K) "non-luminous" plasma. The narrowing down of the cones indicates the widening of the boundary layer or mixing zone.

A very important role for the vapor jets in dissipating the energy input to a high current arc is proposed and its relation to the overall energy balance is discussed.

FAST TIME ANALYSIS OF LOW PRESSURE GLOW TO ARC TRANSITIONS

A-5

Russell J. Westberg
University of California
Berkeley 4, California

Presented by: Leonard B. Loeb
University of California

Initial results on time analysis of transitions from an abnormal glow discharge at about 0.1 to 1 mm relatively pure N_2 and 20 ma current to transient power arcs with hundreds of amperes in a 146 cm long tube studied by one photomultiplier tube viewing the cathode triggering the sweep of a fast synchroscope with a second photomultiplier placed at various points down the tube were reported at the last conference.

Techniques have since been perfected to permit measurement of the prebreakdown current, and the potential distribution down the tube as a function of time and position by probes. Complete data over the range of available operating variables have been achieved for relatively pure N_2, $N_2 - O_2$ mixtures, including air, pure A and pure H_2. Potential drops occur up to 500 and less out of 1760 volts applied across the tube and accompany the luminous pulses as they advance down the tube from cathode to anode. Gradients decrease as the pulse advances and are difficult to follow for the reflected pulse of ionization and luminosity moving from anode to cathode. Velocities in the Faraday dark space reach 4×10^9 cm/sec in air. Argon behaves much like N_2. Data accumulated are adequate to permit theoretical analysis of phenomena.

THE DISPERSED TYPE OF COLD CATHODE ARC*

A-6

K. G. Hernqvist
Radio Corporation of America
RCA Laboratories
Princeton, New Jersey

The dispersed (or D-type) arc(1) operates with a cathode consisting of a molybdenum electrode partly immersed in a mercury pool and in the presence of a strong magnetic field parallel to the cathode to anode axis. Ultrahigh speed photographic studies show that the emission current density is extremely low (10 - 100 amps/cm^2). The procedure of establishing the arc will be described. The electron emitting part of the molybdenum surface appears to have properties different from an ordinary wetted molybdenum surface. The importance of these findings for the understanding of the electron emission mechanism of the mercury pool arc will be discussed.

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* Part of this research was supported by the United States Air Force through the Office of Scientific Research of the Air Research and Development Command.

(1) C. G. Smith, Brit. J. Appl. Phys. 4, 252 (1953).

Invited Paper

A-7

THE MECHANISM OF THE DC-ARC-COLUMN AND THE PRODUCTION OF HIGH STATIONARY TEMPERATURES

H. Maecker
Siemens-Schuckert Research Laboratories
Erlangen, Germany

Wednesday, October 31

2:00 p.m.

SESSION B

IONS

Chairman, R. Geballe
University of Washington

SPACE CHARGE FORMATION AND THE NEGATIVE TOWNSEND CHARACTERISTIC

B-1

A. L. Ward
Diamond Ordnance Fuze Laboratories
Washington 25, D. C.

Crowe, Bragg, and Thomas(1) have shown that when the steady state current-voltage characteristic of a uniform field gap is modified by space charge formation, a negative slope region is obtained beyond a certain current. The formulation used by the above authors has been modified only in that α, the first Townsend coefficient, has been changed to depend exponentially upon the inverse square root, rather than the inverse first power of E/P. This dependence allows a satisfactory fit to experimental data over a much wider range of E/P for the rare gases.

Static characteristics have been computed for the rare gases for a wide variety of pressures and gap distances, and with some variation of the first and second Townsend coefficients, initial photocurrents, and positive ion mobilities. Numerical computations were made by the National Bureau of Standards Computation Laboratory on SEAC. Comparisons of the computed characteristics with experimental data taken in this laboratory have been made in a limited number of cases. In some cases the agreement is quite good, whereas in other cases there are marked discrepancies.

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(1) R. W. Crowe, J. K. Bragg, and Virginia G. Thomas, Phys. Rev. <u>96</u>, 10 (1954).

A METHOD OF MEASURING THE MOBILITY SPECTRA OF NEGATIVE IONS IN GAS MIXTURES[*]

E. W. McDaniel
Georgia Institute of Technology
Atlanta, Georgia

and
H. R. Crane
University of Michigan
Ann Arbor, Michigan

A new pulse method of measuring the low-field mobility of negative gaseous ions is described. Negative ions are formed by the capture of the electrons produced in the ionization path of an alpha particle which crosses one end of a long, uniform-field drift tube. The alpha particle enters a proportional counter at the end of its path. The arrival of each individual negative ion at the other end of the drift tube is signalled by a second proportional counter. The first counter triggers the sweep of a synchroscope, and the second counter modulates the beam brightness. A large number of such sweeps is integrated photographically. In each run, with a different gas mixture, a sharp line appears in the photographic spectrum. This gives the drift time for the negative ion in that gas.

The mobilities of the negative ions in pure oxygen, and in mixtures consisting of varying percentages of oxygen in He, Ne, A, Kr, Xe, CO_2, and H_2 were measured and will be discussed. The mobility of the negative ion in pure SF_6 was found to be .57 cm^2/volt-sec. This agrees well with the range for SF_6^- predicted by the Langevin theory including charge exchange, namely, .46 to .56.

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[*] Supported in part by the USAF, Office of Scientific Research of the Air Research and Development Command.

THE TEMPERATURE DEPENDENCE OF IONIC MOBILITIES: HELIUM, NEON, ARGON B-3

L. M. Chanin and M. A. Biondi
Westinghouse Research Laboratories
Pittsburgh 35, Pennsylvania

Measurements have previously been made of the mobilities of atomic and molecular ions moving in their parent gas for helium(1) and neon(2) at 300°, 195°, and 77°K. The measurements have now been extended to argon. The measured atomic ion mobilities are compared with Holstein's theory(3) in the following table.

T°K	300°K	195°K	77°K
μ_o (expt.) cm^2/volt-sec	1.60	1.95	2.20
μ_o (theory)	1.65	1.85	2.16

As in the case of neon, the agreement is within the combined errors of experiment and theory. This is in contrast to the case of helium where the experimental results fall below the theoretical values at lower temperatures.

The experimental results for the molecular ions are compared with the temperature variations predicted by the Langevin and Hassé-Cook theories. As in the case of neon, the argon values lie intermediate between the limiting cases represented by these theories. For A_2^+ the measured values are 2.7 at 300°K, 2.9 at 195°K, and 2.7 at 77°K.

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(1) L. M. Chanin and M. A. Biondi, Phys. Rev. <u>99</u>, 1658A (1955).

(2) L. M. Chanin and M. A. Biondi, Phys. Rev. <u>100</u>, 981A (1955).

(3) T. Holstein, J. Phys. Chem. <u>56</u>, 832 (1952).

AN ION DIFFUSION CALCULATION

B-4

C. B. Mills
Curtiss-Wright Research Division
Clifton, New Jersey

The effect of an anisotropy in electron motion on ion diffusion in a magnetic field is briefly discussed and compared with experimental values of ion diffusion velocity. A physical description of net plasma motion is described for a stable, high density ionic plasma.

SOME INTEGRABLE CASES INVOLVING BIMOLECULAR PROCESSES IN GASEOUS ELECTRONICS

B-5

Jerome Rothstein
Signal Corps Engineering Laboratories
Fort Monmouth, New Jersey

If the concentration n (respectively p) of negative (respectively positive) ions, $(n = p)$ satisfies $\partial n/\partial t = g\eta^{r} - r\,n^{\nu} + D\nabla^2 n$ (g, r, D respectively, volume generation, recombination, and diffusion coefficients), then if the diffusion term is approximated by $-n/\tau$, n is given explicitly by

$$n(t) = \left(\frac{g}{r} + \frac{1}{4r^2\tau^2}\right)^{1/2} \begin{matrix}\coth \\ \\ \tanh\end{matrix} \left\{ \left(gr + \frac{1}{4\tau^2}\right)^{1/2} t + \begin{matrix}\coth^{-1} \\ \\ \tanh^{-1}\end{matrix} \left[\frac{\left(n_o + \frac{1}{2r\tau}\right)}{\left(\frac{g}{r} + \frac{1}{4r^2\tau^2}\right)^{1/2}} \right] \right\} - \frac{1}{2r\tau}$$

with $n = n_o$ at $t = o$, and coth or tanh applies to $n_o \gtrless (g/r + 1/4r^2\tau^2)^{1/2}$ respectively. For the one dimensional steady state problem, governed by $o = g - r\,n^2 + D\,d^2 n/dx^2$, an explicit solution can be obtained involving Jacobian elliptic functions. D, r, g are taken independent of concentration. Bimolecularity implies common values of g and r for positive and negative ions; ambipolarity indicates the same for D at high concentration with the latter not necessarily implied by the former. The solution for $n(t)$ will be discussed, showing its relation to more approximate or asymptotic ones in the literature, and how their application outside their sphere of validity can lead to erroneous inferences about the existence of separate fast and slow processes.

Thursday, November 1

9:00 a.m.

SESSION C

HIGH TEMPERATURE PLASMAS

Chairman, W. P. Allis
Massachusetts Institute of Technology

HIGH TEMPERATURE PLASMA RESEARCH: SOME PHYSICAL PROBLEMS AND MEASUREMENT TECHNIQUES

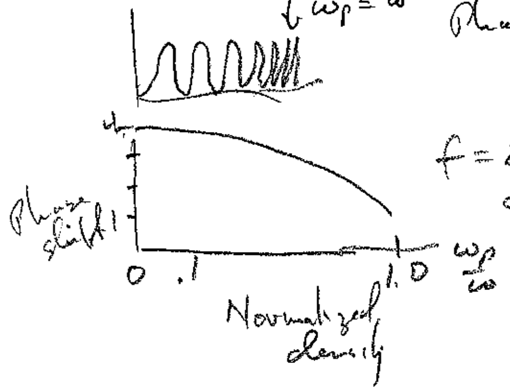
R. F. Post
University of California Radiation Laboratory
Livermore, California

Characterize plasma

1. Long mfpath – collisions unimportant compared with e.m. interactions motional effects.
2. High Elect. Cond. $\sigma \sim 3\times10^{-6}/T^{3/2}$
3. "Diamagnetic", $\nabla(p + B^2/8\pi) = 0$
   Pinch only when energy supplied, ∴ not permanent. Field diffusion
4. Decoupled degrees of freedom
   2 gases – decoupled – electrons + ions
5. "Sticking to magnetic lines"
   Alfvén waves

Scaling law
power $P \propto B^4 R^2 \left[\frac{\langle \sigma v \rangle}{T^2}\right]$

Diagnostics
Interferometer – Chas Wharton



Phase detector

f = 24 mc
d = 15 cm,

Invited Paper C-2

SOME THEORETICAL PROPERTIES OF THE PINCH EFFECT AND ITS INSTABILITIES

J. L. Tuck
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Burkhardt
Phillips
Sawyer
Stovall
} Nuclear Physicists

Allis + others consulting

Tonks ~ 1937
W H Bennett ~1933
self-focusing fields

Relation for pinch (bring plasma off of wall) : $\frac{I^2}{2} = Nk(T_+ + T_-)$
$= N \times 1.6\times10^{-12}[T_+ + T_-]_{ev}$

Example : 10 cm tube
$p = 10\mu \sim (2\times10^{15}/cc)\pi r^2$
$\cancel{\sim 3\times10}^{5}$

$T \sim 5$ ev.

$I \cong 13{,}000$ amps

Observations of pinch effect
Ware (?) ~1950

Los Alamos 1952
50,000 v for millisecond
Betatron. magnet

Easy to produce pinches in high Z gases.

$$\bar{r} = \left(\frac{c^2 E^2}{4\pi p}\right)^{1/4}$$

E = elect field at surface of pinch

$$I^2 = \int_0^t E\,dt \Big/ \ln(\bar{R}/R)$$

$\bar{R}$ = original radius

Invited Paper

C-3

DIFFUSION OF CHARGED PARTICLES ACROSS A MAGNETIC FIELD

A. Simon
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Bohm
Bishop
Massey

Experiment + theory apply only
to weakly ionized plasma
Linear in densities
Plasma T = 1-5 ev.

Computed D ~ 20 cm²/sec. for $B = 3700$ gauss, $p = 1.4\mu$, $kT \sim 2$ ev } argon $\sigma \sim 4 \times 10^{-15}$ cm², $\lambda \sim 5$ cm

Expt $D \sim 3 \times 10^3$

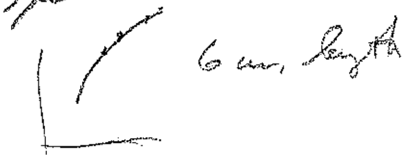
$D^B_{amb} \sim \frac{2 v_\perp^3}{3\omega^2 \lambda}$ Bohm gave $D \propto 1/B$ based on oscillations
classical $D \propto 1/B^2$

Oak Ridge
Knight Expt to find D(B) - favors $1/B^2$ clearly
But magnitude is large ~10^3

Simon: take asymmetry into account more fully

$\xi \sim \frac{pl}{H}$ - length of arc
B-field length
linear p-dependence shown in 26 cm arc length from 1-3μ

when length < mfp $\xi \sim \frac{\sqrt{lp}}{B}$ -



∴ Diff. rate across field is ion cut-off in B
along " is ambipolar, no B.

Work at Tufts decay of H ions in afterglow in low B
Los Alamos - Dreicer

Slepian
- Simon's calc. in error
" answer in classical

Invited Paper

C-4

SOME HYDROMAGNETIC INSTABILITIES

M. Kruskal
Project Matterhorn
Princeton University
Princeton, New Jersey

Most material given in '52 at Princeton
Content now

Proc Roy Soc 1954
Kruskal + Schwarzschild

stationary discharge - is it stable?

$$\rho \frac{d\mathbf{v}}{dt} = j \times B - \nabla p$$ (force balance

$$\nabla \cdot (\rho v) = -\partial\rho/\partial t$$

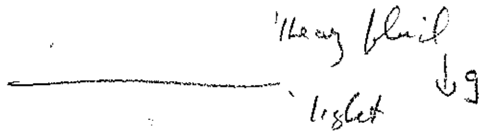
$$E + v \times B = \frac{1}{\sigma} j \sim 0$$ Ohm's law (not clearly justified in plasmas)

$$\frac{1}{p}\frac{dp}{dt} = \frac{\gamma}{\rho}\frac{d\rho}{dt}$$

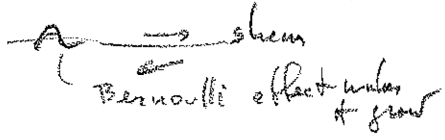
$$\nabla \times B = \mu j$$
$$\nabla \cdot B = 0$$
$$\nabla \cdot E = \frac{1}{\varepsilon}\rho$$

Pinch $\longrightarrow j$ p

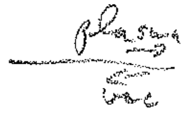
Modes - axial symmetry $m=0$
- displ. of center $m=1$
elliptical $m=2$



Northrup - Phys Rev '56
Helmholtz instability



Bernoulli effect makes it grow



AN ENERGY PRINCIPLE FOR THE HYDROMAGNETIC STABILITY PROBLEM

E. Frieman
Project Matterhorn
Princeton University
Princeton, New Jersey

Lundquist PR 1951 originator of approach

Too difficult to solve hydromagn. eqs.

Pot. Energy of plasma $W = \int dv \left\{ \frac{B^2}{8\pi} + \frac{p}{\gamma - 1} \right\}$ $\gamma = c_p/c_v$ p = density.

Example $\nabla \times E = -\frac{\partial B}{\partial t}$

$E + v \times B = 0$

Then $\nabla \times (v \times B) = \frac{\partial B}{\partial t}$

Put $v = d\xi/dt$

Then $\delta B = \nabla \times (\xi \times B)$

δW = change for a displacement ξ

$= W_f - W_i$

$= \int \left\{ Q^2 - j \cdot (Q \times \xi) + \gamma p (\nabla \cdot \xi)^2 + (\nabla \cdot \xi) \xi \cdot \nabla p \right\} d\tau$

$Q = \nabla \times (\xi \times B)$

$\nabla p = j \times B$

$\nabla \times B = j$, $\nabla \cdot B = 0$

By inspection sometimes can see whether trial fns (instability) give $\delta W < 0$

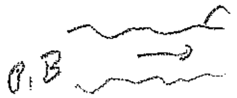
or can minimize δW, particularly in simple geometry
variational principle

This approach has 2 bad features - lack of detailed knowledge of plasma processes
- lack of knowledge re rates
(But use Rayleigh's principle)
$\omega^2 = -\delta W / \frac{1}{2} \int \rho \left(\frac{d\xi}{dt}\right)^2 d\tau$

But does answer questions re instability

Teller
Longmire
Brand : fluting type of instability
Need surface terms in δW $\int dS (\xi \cdot n)^2 n \cdot \left[\nabla \left(p + \frac{B^2}{2}\right)\right]$
$+ \int Q^2 dS$

2nd prob. : cylindrical sym.



waves on surface
only axial B

when $p / (B^2/8\pi) \ll 1$
have general sol. $\delta W \propto M''V''$
V = vol. ψ = M. flux
M = mass
$V'' = \partial^2 V / \partial \psi^2$
$M'' = \partial^2 M / \partial \psi^2$

Thursday, November 1

9:00 a.m.

SESSION C

HIGH TEMPERATURE PLASMAS

Chairman, W. P. Allis
Massachusetts Institute of Technology

SPUTTERING YIELDS FOR LOW ENERGY Hg^+-ION BOMBARDMENT[*]

D-1

G. K. Wehner
General Mills, Incorporated
Minneapolis 13, Minnesota

Sputtering yields for normal incident Hg-ions were measured in the energy range 30 ev to 400 ev for Au, Ag, Cu, Pt, Ni, Al, Ti, W, Mo, Ta, Fe.

The targets are immersed like large negative Langmuir probes in a low pressure Hg-plasma of high density (Hg vacuum arc discharge at 1μ gas pressure, ion current densities 10 ma/cm^2). Absolute yield values are obtained by measuring the weight loss from the target, relative values by measuring the speed with which sputtered material is deposited on a glass collector. By using a glass ribbon, which can be shifted magnetically, a number of measurements can be performed without opening the tube.

With yields essentially independent of gas pressure, tube geometry, and ion current density, the scattering of measuring points remains within ± 10 per cent. Yields above the sputtering threshold are roughly proportional to the ion energy. The slope is essentially determined by the atomic weight, the heat of sublimation, and the crystal structure of the target material.

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[*] This work is sponsored by the Office of Naval Research under Contract NONR 1589(08).

ANALYSIS OF LOW ENERGY SPUTTERING

E. Langberg
Radio Corporation of America
RCA Laboratories
Princeton, New Jersey

Starting with the assumption that the atomic interaction in metals can be reasonably approximated by the Morse potential(1) the validity of the binary collision mechanism for energy transfer in the lattice is examined.

A two-collision sputtering mechanism is postulated for sputtering near the threshold. Under optimum energy transfer conditions, the analysis of this process gives the ion energy for a sputtering threshold of a surface particle tied by N bonds.

Under a prolonged ion bombardment a surface contains particles with N ranging from a maximum determined by a complete surface to a minimum determined by inaccessible bonds.

Sputtering yield vs. energy function is derived and shown to consist of a parabolic and a linear part. Predicted and experimental(2) Pt – Hg^+ curves are compared.

Two thresholds are defined: the actual intercept of the yield curve and the intercept of the extrapolation of its linear part. The two thresholds are computed for twenty metals bombarded by Hg^+ and compared with experiment.(3)

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(1) J. C. Slater, <u>Intr. to Chem. Physics</u> (McGraw-Hill Book Company, Inc., New York 1939), chapter 27.

(2) G. K. Wehner, Advances in Electronics <u>7</u>, 239 (1955).

(3) G. K. Wehner, Phys. Rev. <u>93</u>, 633 (1954).

STATISTICAL MECHANICS OF CATHODE SPUTTERING III

Don E. Harrison, Jr.
University of Louisville
Louisville, Kentucky

This paper is a continuation of the author's statistical treatment of the cathode sputtering problem.(1) New theoretical curves have been calculated from the Transport Theory, using sputtering thresholds as predicted by Wehner,(2) and fitted to Keywell's experimental data.(3)

Satisfactory fitting can be obtained for six systems with mass ratios between 0.04 and 0.80 by varying a single parameter. The theory is also satisfactory for Kr bombarding Cu, which is the only available set of data for mass ratio greater than unity. The fitting is adequate, but not as good, for the system He-Pb.

The theoretical implications of certain new experimental data will be discussed.

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(1) D. E. Harrison, Jr., Phys. Rev. <u>102</u>, 1473 (1956).

(2) G. K. Wehner, Phys. Rev. <u>102</u>, 690 (1956).

(3) F. Keywell, Phys. Rev. <u>97</u>, 1611 (1955).

A NOVEL FORM OF HOLLOW CATHODES AND ITS DISCHARGE CHARACTERISTICS

A. D. White
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

Rare gas discharges to certain types of hollow cathodes have switching and transmission properties which are presently of considerable interest to the field of electronic switching. In addition to the usual high negative resistance (10^5 - 10^7 ohms) characteristic of discharges at low currents (10^{-6} - 10^{-4} amperes), these discharges exhibit a second region of negative resistance (10^2 - 10^3 ohms at speech frequencies) at currents of a few milliamperes. At typical operating pressures of 1/10 atmosphere of neon, the current density at the cathode surface is approximately 0.1 amp/cm^2. Under these conditions, tube life is limited by the rate at which material is sputtered from the cathode surface. Experimentation with a variety of cathodes has indicated that, for all practical purposes, the effects of sputtering (i.e., cathodic erosion and gas cleanup) are eliminated even at current densities in excess of 0.6 amp/cm^2 by a choice of cathode geometry approximating a spherical cavity having a small aperture. That this is a uniquely stable configuration is suggested by the observation that hollow cathodes of other shapes tend to become spherical during operation of the discharge. The nature of the high-current, negative volt-ampere discharge will be discussed in terms of plausible physical processes.

PHOTONS IN THE NEGATIVE GLOW

D-5

D. J. Rose and J. Eisinger
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

A tube has been built which permits measurement of electron emission from the cathode by photons produced in a glow discharge. The tube is of parallel plate construction with one movable and one fixed electrode. The latter contains a central region with many small holes drilled at 45°. Behind this perforated region is a small movable parallel plate collector. A co-planar annular guard disk surrounds the fixed electrode, which isolates a discharge in the main gap from the collector region. All parts of the tube seen by the discharge, including the collector, are molybdenum. A glow discharge is run in the main gap with either the fixed or movable electrode as cathode. By measuring the collector current as a function of its potential and gap spacing, one can isolate the effect of photons which penetrate the holes. The photocurrent at the cathode for a given E/p can then be calculated and compared to the main discharge current. For hydrogen, it is large, and a considerable fraction appears to arise from resonance radiation: cathode photo-emission ~~is comparable to or larger than~~ about $\frac{1}{2}$ the ionic secondary emission. Results obtained with neon will also be discussed.

IONIC OSCILLATIONS IN HOT CATHODE DISCHARGES

D-6

Walter J. Graham
U. S. Naval Research Laboratory
Washington 25, D. C.

A study has been made to determine the mechanism of the low frequency oscillations frequently observed in hot cathode gas diodes. While at higher currents one encounters conventional relaxation oscillations, the phenomenon of interest here is the existence of rather undistorted sinusoidal oscillations, the frequency of which is independent of circuit reactances. Such oscillations occur predominantly in the "anode-glow" mode, but also in the "ball-of-fire" mode. Measurements (using direct scope observation and also superheterodyne technique) have been made in rare gases, as a function of pressure, current, and cathode temperature. Observed frequencies are in the kilocycles to megacycles range. The results, particularly the drop in frequency with increasing pressure, tend to discount the possibility of ion oscillations of the usual Langmuir-Tonks type, but rather support strongly the suggested hypothesis of ions oscillating in the minimum of the cathode-anode potential profile. Some evidence has been obtained for $1/\sqrt{M}$ dependence by using gas mixtures. Brief mention will be made of the possibility of adapting such a device to diagnostic studies of ion composition of an active discharge (for example to determine the presence of molecular ions).

THE VANISHING COEFFICIENTS IN SERIES EXPANSIONS OF PERIODIC DISTRIBUTION FUNCTIONS

T. E. VanZandt
Sandia Corporation
Albuquerque, New Mexico

When the velocity distribution function is expanded in a series of orthogonal functions, the vanishing coefficients can be determined prior to solving Boltzmann's equation either (a) by reasoning whether each term can or cannot be generated by the applied force, or (b) by requiring that each non-vanishing term be functionally invariant under the same transformations which leave invariant the boundaries and Boltzmann's equation with the given force. The latter condition is briefly derived, and results as obtained with it are presented for several configurations of force and boundaries. For example, if the applied force is the traveling electric wave $\underset{\sim}{E} = E_o \underset{\sim}{i} \cos(\omega t - \beta z)$ and the boundaries are infinitely distant, the distribution function would be expanded as

$$f(\underset{\sim}{v},\omega t-\beta z) = \sum_{\ell,m,n} \left[f_{\ell mn}(v) \cos \ell(\omega t-\beta z) + g_{\ell mn}(v) \sin \ell(\omega t-\beta z)\right] Y_n^m(\theta,\varphi),$$

where $\cos \theta = v_x/v$ and $\tan \varphi = v_y/v_z$; and those coefficients must vanish for which the sum $\ell + m + n$ is odd.

Friday, November 2

9:00 a.m.

SESSION E

PLASMAS

Chairman, D. Alpert
Westinghouse Research Laboratories

PROBE MEASUREMENTS OF IONIZATION IN FLAMES

W. E. Rice, I. R. King, and H. F. Calcote
Experiment Incorporated
Richmond 2, Virginia

Cylindrical probes have been employed in attempts to determine the positive ion concentrations in flames, mostly at atmospheric pressure. Simple Langmuir probe theory predicts many of the observations correctly. The concentrations of ions calculated from the measurements by means of the simple theory must be corrected by the factor a/ℓ, where a is the probe radius and ℓ the mean free path of the ions. Measurements on flames containing known concentrations of alkali metals give values for ion and electron concentrations which agree with those calculated from Saha's equation. These results confirm the use of the correction factor, which is essentially empirical. In addition it is found that experimental and theoretical wall potentials agree, and the electron temperatures are somewhat higher than the adiabatic flame temperature (2800°K and 2270°K). The sheath thicknesses calculated by several procedures are in agreement. However, it is found that the distance of interference of the two probes except in the reaction zone is considerably larger than the calculated sheath thickness and in salted flames is independent of the probe diameter. The resolution of the probe in the reaction zone suggests that the interference distance there is smaller than this. When a second probe is placed 1 cm downstream from the first probe, very little current is detected by the downstream probe, indicating that the rate of ion formation is slow. The work is being continued toward the development of a theoretical understanding of the observations.

STUDIES OF COMBUSTION ZONE IONIZATION UTILIZING FOCUSED ELECTROMAGNETIC BEAMS

W. W. Balwanz
U. S. Naval Research Laboratory
Washington 25, D. C.

Focused low energy electromagnetic beams used as probes provide a means of studying the conductivity of ionized gaseous media. Such a system is particularly desirable in studying combustion zone phenomena, since the probing beam does not cool or otherwise materially disturb the normal flow of the combustion gases. A 1.25 centimeter wavelength system has been utilized at the Naval Research Laboratory to conduct exploratory measurements on the ionization in low pressure combustion zones of acetylene, alcohol, gasoline, ammonia, hydrogen sulfide, carbon disulfide, and hydrogen flames. The fuels were premixed with oxygen and burned in a vacuum chamber at a pressure of between 3 and 4 millimeters of mercury. A Meeker type burner 4 inches in diameter and 19 inches long, partially filled with glass beads to facilitate mixing, was used. Measurements were made of the absorption of electromagnetic energy propagated through the flame. The experimental results were used to determine the electron densities, which, in some cases, were 6 orders of magnitude greater than the values calculated assuming thermodynamic equilibrium.

E-3

MICROWAVE MEASUREMENTS OF HIGH ELECTRON DENSITIES[*]

S. J. Buchsbaum
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

The conventional microwave method for measuring plasma electron densities is limited in its validity to relatively low concentrations ($\approx 10^9$ cm^{-3}). Following a theoretical development by Persson, a method is presented whereby much higher densities can be measured. The method is based on eliminating the effect of ac space charge on the probing microwave field. This is accomplished by ensuring that the electric field be everywhere perpendicular to electron density gradients. In addition, an experimental discussion is presented on the effect of neighboring modes on the measuring mode in a microwave cavity.

Measured up to $\sim 10^{11}$

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[*] This work was supported in part by the Army (Signal Corps), the Air Force (Office of Scientific Research, Air Research and Development Command), and the Navy (Office of Naval Research).

Lindholm – impact theory

E-4

THE BALMER LINES AS INDICATORS OF THE PHYSICAL STATE OF A PLASMA

H. Margenau
Yale University
New Haven, Connecticut

This paper reports new results of a theoretical study concerning the structure of the Balmer lines emitted in a plasma of high ion density. Reliance on the Holtsmark theory leads to two errors: (1) the theory itself requires modifications, and (2) the effect of the electrons becomes important and must be included. We intend to show particularly how point (2) can be treated and how the electrons modify the Holtsmark shape. The departures from that shape depend on the temperature as well as the density of electrons and should provide, in principle, an independent measure of the electron temperature. Point (1) will be left for casual discussion if time permits.

FURTHER RESULTS ON COULOMB INTERACTIONS IN A PLASMA*

E-5

Harry Dreicer
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

The Boltzmann-Fokker-Planck transport equation described elsewhere(1) has been solved numerically(2) with non-linear and integral terms of the equation retained in their exact form. The electronic excitation of molecules is included, but inverse collisions of the second kind have been neglected. The ionization degree, β, is limited to less than 10 per cent so that the effect of electron-ion encounters on resistive heating can be ignored.

The effect of electron-electron encounters on the distribution function, average electron energy, and the inelastic collision rate is the problem investigated. Results are given as a function of $\frac{E}{p}$ and β, and the transition of the distribution function from $\beta = 0$ to the Maxwellian distribution is shown to occur at a β predicted by energy relaxation rates.

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* Work done under the auspicies of the U. S. Atomic Energy Commission.

(1) H. Dreicer and W. P. Allis, Eighth Gaseous Electronics Conference, Schenectady, New York 1955.

(2) I am indebted to Mr. T. Doyle who coded this problem for the IBM 701.

COLLISIONS OF SLOW ELECTRONS WITH ATOMS AND IONS[*]

A. A. Dougal and L. Goldstein
University of Illinois
Urbana, Illinois

The characteristic time required for equipartition of energy through electron collisions with the ion and atom constituents of the plasma has been investigated experimentally. A guided microwave interaction technique was employed for heating the electron temperature to increments above that of the ion and gas temperature, and for probing the plasma during the subsequent transient when the electron temperature relaxes to that of the ions and atoms. The theoretical predictions of Landau(1) and Spitzer,(2) which are based on appropriate averages over binary electron-ion collisions, for the characteristic time of return to temperature balance due to the long range Coulomb interaction between electrons and ions are verified well within an order of magnitude. In neon at 300°K, 0.9 mm Hg, 5.5×10^{11} ions per cm^3, the characteristic time of equipartition is 16 microseconds, being predominantly determined by energy exchange through electron-ion collisions. Also, the effective momentum transfer collision cross sections for electrons (temperatures from 77 to 300°K) with helium and neon atoms were established during this study.

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[*] Supported by the Air Force Cambridge Research Center.

Preceding page in paper incorrectly no.

(1) L. Landau, Physik. Z. Sowjetunion 10, 154 (1936).

(2) L. Spitzer, Jr., Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York 80 1956).

NON-MAXWELLIAN ELECTRON ENERGY DISTRIBUTIONS IN PLASMAS, DETERMINED BY A NEW GRAPHICAL METHOD

G. Medicus
Advanced Development Branch
Wright-Patterson Air Force Base, Ohio

As described in the Journal of Applied Physics, October 1956, the electron energy distribution in plasmas for approximately isotropic electron velocities is quickly obtained graphically from probe curves. Precise evaluations of probe curves from hollow hot cathode diodes with 1 mm Ne showed a fast electron group entering the plasma through a cathode fall of 16 - 17 v, gaining small additional energy in the plasma fields and ionizing cumulatively through the 16.6 volt metastable Ne level. The secondaries constitute a slow group which is Maxwellian at least up to about 4 times the mean thermal energy, E_T, with temperatures from about 2000°K at the lowest ($\approx$10 ma), up to $30{,}000^\circ$K and more at high ($\approx$ 0.5 a) diode currents. Once the originally fast electrons are slowed down to 4 - 5 E_T, they are integrated into the Maxwellian part of the distribution. The higher the diode currents, the more the total distribution approaches a Maxwellian, ionization by the fast Maxwellians predominating over that by the cathode fall electrons. The study of the energy exchange between the two groups, facilitated by the new graphical method, will furnish fundamental information on the generation of the common Maxwellian distribution of plasma electrons.

PLASMA OSCILLATIONS IN A MAGNETIC FIELD

Ira B. Bernstein
Project Matterhorn
Princeton University
Princeton, New Jersey

The small oscillations of a completely ionized plasma in a constant external magnetic field is treated by the Laplace transform method. The full set of Maxwell equations is employed. The ion dynamics are included and are shown to have a very small effect on the frequencies as long as the ion and electron temperatures are equal. The limit of pure electron oscillations is considered. It is concluded, in contradiction with the results of Gross,(1) that there is no damping of waves propagating perpendicular to the external magnetic field, and, in contradiction with the conclusion of Gordeyev,(2) that there can be no self excitation of oscillations about thermal equilibrium.

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(1) E. P. Gross, Phys. Rev. 82, 232 (1951).

(2) G. V. Gordeyev, JETP 6, 660 (1952).

PLASMA OSCILLATIONS*

E. I. Gordon
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

Some experimental results are given which indicate that plasma oscillations of the type described by Looney and Brown(1) are caused by the interaction of two oppositely moving beams, and the plasma. A theory will be presented which predicts under what conditions of gas pressure, beam current density and velocity, and density distribution of the sheath, single beam,(2) or double beam oscillations can start. The usual upper pressure limitation for the existence of oscillations is explained by the maximum available emission from a cathode.

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* This work was supported in part by the Army (Signal Corps), the Air Force (Office of Scientific Research, Air Research and Development Command), and the Navy (Office of Naval Research).

(1) D. H. Looney, S. C. Brown, Phys. Rev. 93, 965 (1954).

(2) Allen et al, Brit. J. Appl. Phys. 6, 320 (1955).

Friday, November 2

2:15 p.m.

SESSION F

BREAKDOWN

Chairman, D. E. Kerr
Johns Hopkins University

F-1

ELECTRON ENERGY DISTRIBUTION IN THE HIGH FREQUENCY MULTIPACTING MECHANISM[*]

Albert J. Hatch[**] and H. Bartel Williams
Physical Science Laboratory and Physics Department
New Mexico College of Agriculture and Mechanic Arts
State College, New Mexico

A previously developed statistical theory(1) of electron multiplication in the high frequency low pressure multipacting breakdown mechanism (secondary electron resonance) has been extended to the calculation of the energy distribution of electrons arriving at an electrode surface. Electron arrival energy distributions have been calculated for aluminum electrodes at a 3 cm separation and applied 70 mc/sec voltages of 150 and 600 peak volts. The 150 rf volt distribution has a minor peak at 35 ev due to 3/2 cycle transit time electrons and a major peak at 100 ev due to 1/2 cycle electrons. The 600 rf volt distribution has only a major peak at 470 ev due to 1/2 cycle electrons.

Experimentally determined electron arrival energy distributions have been obtained at 10^{-4} mm Hg pressure by an electrostatic filter analysis of electrons emerging from a small sampling aperture in a multipacting electrode.
The observed energy distributions for parameters as above compare favorably with the theoretical distribution.

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[*] Work supported by the Bureau of Ordnance, U. S. Navy.

[**] Now at Argonne National Laboratory, Lemont, Illinois.

(1) A. J. Hatch and H. B. Williams, Phys. Rev. <u>89</u>, 339A (1953).

LOW PRESSURE HIGH FREQUENCY DISCHARGE*

H. Bartel Williams and Albert J. Hatch*
Physical Science Laboratory and Physics Department
New Mexico College of Agriculture and Mechanic Arts
State College, New Mexico

The low pressure discharge (0.5 to 10 microns Hg) which is triggered by the multipacting mechanism will be described. Electrons and positive ions issue from a small aperture cut in one of the electrodes. Preliminary studies have been made of the behavior of the electron and ion peaks as various parameters are changed. Three different modes of operation have been observed. The physical appearance of these modes as well as the conditions under which they occur will be discussed.

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* Work supported by the Bureau of Ordnance, U. S. Navy.

* Now at Argonne National Laboratory, Lemont, Illinois.

(1) A. J. Hatch and H. B. Williams, Phys. Rev. 89, 339A (1953).

EFFECT OF MAGNETIC FIELD ON HIGH-FREQUENCY ELECTRODELESS DISCHARGE AT LOW PRESSURE

Elsa L. Huber, Howard T. Ozaki, and Alfred Kleider
Hughes Research Laboratories
Culver City, California

The influence of magnetic fields ranging from zero to 100 oersteds on starting potentials of the high-frequency low-pressure electrodeless discharge has been examined. Data will be presented for two flat-ended cylindrical Pyrex discharge tubes of lengths 1.6 and 2.8 cm containing air at 10^{-5} mm Hg. The tubes were placed in crossed dc magnetic and rf electric fields at frequencies of 10 to 100 mc/sec.

For small magnetic fields, curves of starting voltage <u>vs</u> frequency have the same general shape as for zero field, but they are shifted toward higher voltages and the cut-off frequency is lowered. Once the discharge is started, it can be extinguished again either by increasing the voltage or decreasing the magnetic field. Combined curves of starting and extinction voltages define the boundaries of a breakdown region in either the voltage-frequency or the voltage-magnetic field plane. At higher magnetic fields, starting voltages become sensibly independent of frequency.

A qualitative interpretation will be given in terms of the secondary electron resonance phenomenon.

F-4

BREAKDOWN OF AIR AT MICROWAVE FREQUENCIES[*]

Lawrence Gould and Louis W. Roberts[**]
Microwave Associates, Incorporated
Boston, Massachusetts

A theory for uniform field breakdown in air at microwave frequencies is developed and applied with success to predicting values of breakdown over a wide range of experimental conditions. Three distinct types of breakdown are treated: C.W. (continuous wave) breakdown, single pulse breakdown, and multi-pulse breakdown. The conditions for breakdown are determined from a solution of the electron continuity equation for an average electron in which electron ionization, attachment, and diffusion are the dominant mechanisms. Modulation of the electron average energy at twice the frequency of the applied field becomes important at either high pressure or low frequency and modifies the values of the breakdown field. The breakdown field strengths are shown to be determined from a single curve for each type of breakdown power, either C.W. or pulsed. These theoretical curves are in accordance with the experimental results, thus verifying the assumptions and the values of the coefficients used in the theory.

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[*] This work was supported by the Bureau of Ships under Contract NObsr-63295.

[**] Now at Bomac Laboratories, Incorporated, Beverly, Massachusetts.

ANODE STREAMERS OBSERVED IN STEADY POTENTIAL BREAKDOWN AT LOW OVERVOLTAGES FOR GAPS RANGING FROM POINT-TO-PLANE TO UNIFORM FIELDS IN AIR

F-5

G. G. Hudson and L. B. Loeb
University of California
Berkeley 4, California

The sequence of luminous events in the breakdown of various gap forms in room air at atmospheric pressure with steady potential as revealed by a photomultiplier placed at various points along the gap, the fast oscilloscope sweep being triggered by another photomultiplier viewing the anode, was reported in preliminary fashion at the last Conference. Techniques have been improved and extended to include sparks between 25 cm diameter spheres and planes with gaps ranging from 0.5 to 9 cm long, using a small air blast driven Van de Graaff generator to reduce electrical noise. For overvoltages, less than 2 per cent of all sparks were initiated by streamer sequences starting from the anode. Time, intensity, and position data permit pulse form and velocity for primary and secondary streamers to be measured by cross plots. Following arrival of the secondary in vicinity of the cathode, there results the brilliant main stroke whose direction of motion can, in some instances, be determined and appears to vary with gap geometry. That is, the main stroke appears not always to start from the cathode on arrival of the secondary streamer, but may start from the anode or simultaneously from anode and cathode. More accurate information is beyond resolving power of the equipment.

EXPERIMENTAL EVIDENCE FOR THE EXISTENCE OF SECONDARY IONIZATION IN OXYGEN AT HIGH PRESSURE*

D. J. DeBitetto and L. H. Fisher
New York University
New York 53, New York

Townsend's second ionization coefficient, γ, has been previously measured at pressures as high as half an atmosphere in air, nitrogen, and hydrogen.(1, 2, 3) Ionization currents in strongly attaching gases have been shown to depend on an attachment coefficient, η.(4) Thus to determine γ in an attaching gas, current-voltage measurements must be analyzed to yield three coefficient, γ, η, and the first Townsend coefficient, α. The equation for current simplifies enormously when $\alpha = \eta$, allowing an unambiguous determination of γ. This has been carried out for oxygen at an E/p of 35.4 (at which we find $\alpha = \eta$) yielding a value of γ of approximately 0.045 at a pressure of 300 mm Hg. This is more than an order of magnitude larger than the values of γ previously found in hydrogen and nitrogen for the same nickel cathode.(3)

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* Supported by the U. S. Office of Naval Research.

(1) F. Llewellyn Jones and A. B. Parker, Proc. Roy. Soc. (London) A213, 185 (1952); Dutton, Haydon, and Llewellyn Jones, Proc. Roy. Soc. (London) A213, 203 (1952).

(2) Wilkes, Hopwood, and Peacock, Nature 176, 837 (1955); Crompton, Dutton, and Haydon, Proc. Phys. Soc. (London) B69, 2 (1956).

(3) D. J. DeBitetto and L. H. Fisher, Phys. Rev. 100, 1227 (1955).

(4) M. A. Harrison and R. Geballe, Phys. Rev. 91, 1 (1953).

THE BREAKDOWN MECHANISM OF THE LONG LABORATORY SPARK*

F-7

E. Howard Holt
Electrical Engineering Research Laboratory
University of Illinois
Urbana, Illinois

The work of Allibone and Meek(1) and of Norinder and Salka(2) on the mechanism of long-gap spark breakdown of air at atmospheric pressure using the laboratory impulse generator has been extended. A catadioptric camera of nominal aperture f/1.85 and with the transparency of a quartz lens(3) enabled photographs of partially developed discharges to be taken containing significantly more detail than those obtained in previous work. The simultaneous recording of oscillograms showing the growth of current in the test gap enabled a close correlation to be made between the interpretations of the photographs and the oscillograms. A time resolution of the discharge development in the 3 feet, 6 inches rod gap was obtained by "chopping" the impulse generator output by a parallel sphere-gap after a predetermined time. In addition to electron avalanches and positive and negative streamers, whose roles have been previously established, "threads" of discharge associated with positive streamers were photographed and their role of aiding the growth of conduction current in the gap before the main stroke occurs was established by the interpretation of the current oscillograms.

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* Work done at the Research Laboratory of Associated Electrical Industries Ltd., Aldermaston, England.

(1) T. E. Allibone and J. M. Meek, Proc. Roy. Soc. A166, 97 (1938) and A169, 246 (1938).

(2) H. Norinder and O. Salka, Ark. f. Fysik 3, 347 (1952) and 5, 493 (1952).

(3) J. Dyson, J. Sci. Instr. 32, 272 (1955).

Saturday, November 3

9:00 a.m.

SESSION G

IONIZATION AND AFTERGLOW

Chairman, L. H. Fisher
New York University

MICROWAVE DETERMINATIONS OF THE FREQUENCY OF IONIZATION AND THE COEFFICIENT OF FREE DIFFUSION IN HYDROGEN[*]

M. P. Madan, S. J. Buchsbaum, and E. I. Gordon
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

Microwave breakdown experiments yield, apart from other parameters, the ratio ν_i/D_-, in which ν_i is the ionization frequency and D_- is the coefficient of free diffusion for electrons. This paper describes a method for a direct determination of ν_i and D_-, utilizing an additional experimental parameter tp, where p is the pressure and t is the time for the build-up of electron density. In addition, the steady-state breakdown fields can also be predicted. The experiment has been performed, using two TM_{010}-mode resonant cavities of different sizes. The results have been compared with the theory of Allis and Brown. By properly accounting for the space-charge effect and the nonuniformity of the electric field, the results are in substantial agreement with the theory.

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[*] This work was supported in part by the Army (Signal Corps), the Air Force (Office of Scientific Research, Air Research and Development Command), and the Navy (Office of Naval Research).

PHYSICAL PRINCIPLES UNDERLYING VERY-HIGH-OUTPUT FLUORESCENT LAMPS

G-2

John F. Waymouth
Sylvania Electric Products Inc.
Salem, Massachusetts

Francis Bitter
Massachusetts Institute of Technology
Cambridge, Massachusetts

Fluorescent lamps generate light by the conversion of ultraviolet radiation from a mercury-rare-gas discharge into visible light by a phosphor on the walls of the tube. With present-day phosphors, the factor limiting the maximum light output obtainable is the amount of ultraviolet radiation per unit length which can be produced by the discharge. Two factors limit the amount of ultraviolet radiation. First, the efficiency of production of uv decreases for mercury vapor pressures above 6-10 microns and, hence, the condensed mercury temperature must be kept low (40° C). In the past, this has meant that total lamp power input was limited to about 10 - 15 watts per foot, to keep the bulb-wall temperature at 40°C. Second, even at constant mercury vapor pressure, the ultraviolet radiation approaches a saturation value (which is determined by the electron temperature) as the power input is increased.
In order to produce high output, therefore, it is necessary to have the electron temperature as high as possible. The factors influencing the electron temperature are discussed, and a practical way of increasing it is described. A simple means of providing the correct mercury vapor pressure is described.

MICROWAVE CONDUCTIVITY MEASUREMENTS IN NEON CONTAMINATED WITH ARGON*

Aldo L. Gilardini*
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

The method used by Gould and Brown(1) for determining the electron collision probability for momentum transfer in helium by measuring the microwave conductivity of a decaying plasma as a function of the electron energy, controlled by a microwave heating field, has been used for determining the same parameter in neon. In this case, due to the smaller value of the electron collision probability and the bigger atomic mass of neon as compared to helium, energy gradients produced by the heating field nonuniformities are very important in determining an energy redistribution inside the plasma. The conditions required for having a pressure independent ratio of the real to the imaginary part of the complex conductivity and for reaching steady state electron energy conditions are theoretically investigated. From the measured microwave conductivity in neon contaminated with argon, the electron collision probability in neon has been computed as a function of the electron energy; the curve joins Ramsauer and Kollath's(2) measurements for higher electron energies.

Some measurements of the diffusion constant in neon contaminated with argon are also discussed. They show the increase in diffusion due to the ambipolar-free diffusion transition as a function of the proper variables,(3) and the formation of molecular ionized argon.

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* This work was supported in part by the Army (Signal Corps), the Air Force (Office of Scientific Research, Air Research and Development Command), and the Navy (Office of Naval Research).

* National Science Foundation Foreign Fellow on leave from Instituto Superiore PP. TT., Rome, Italy.

(1) L. Gould and S. C. Brown, Phys. Rev. 95, 897 (1954).

(2) C. Ramsauer and R. Kollath, Ann. Physik 12, 529 (1932).

(3) W. P. Allis and D. J. Rose, Phys. Rev. 93, 84 (1954).

G-4

ELECTRON LOSS IN THE XENON AFTERGLOW

R. Lowell Fey[*] and Walter J. Graham
U. S. Naval Research Laboratory
Washington, D. C.

Studies of electron loss in the afterglow of a microwave (∼ 9000 mc) discharge in xenon reported previously(1) have been continued. Measurements were extended to a lower electron density limit of about $10^8/\text{cm}^3$. Behavior as a function of pulse length has been studied, using pulse lengths ranging from several hundred microseconds down to 1/4-microsecond. Results support Persson and Brown's hypothesis of impurity removal from the quartz discharge bottle during the discharge.(2) At higher pressures electron removal rates depended on impurity concentration, while at lower pressures (∼ 1 mm Hg) the decay rates indicated the occurrence of both atomic and molecular xenon in the afterglow.

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[*] Now at National Bureau of Standards, Boulder, Colorado.

(1) R. L. Fey and W. G. Graham, Bull. Am. Phys. Soc. 30, 32 (1955).

(2) K. B. Persson and S. C. Brown, Phys. Rev. 100, 729 (1955).

SPECTRAL LINE WIDTH AND DISSOCIATIVE RECOMBINATION IN A HELIUM AFTERGLOW

W. A. Rogers and M. A. Biondi
Westinghouse Research Laboratories
Pittsburgh 35, Pennsylvania

The width of the λ5876 line of atomic helium has been studied as a function of pressure in the afterglow of a pulsed microwave discharge. If the afterglow radiation is the result of dissociative recombination of diatomic helium ions with electrons, it was predicted(1) that the afterglow line width must exceed that of the active discharge because of the kinetic energy imparted to the excited atom in the act of dissociation. Although this prediction was corroborated, the pressure dependence of the afterglow width did not appear to fit the dissociative recombination hypothesis. Helium molecular bands, if present, would distort the interferometer fringe pattern causing an apparent increased line width which increased with pressure. Spectrometric analysis shows that this effect is not large enough to explain the excess afterglow width in the pressure range 1 to 7 mm Hg. The observed behavior might result if the upper state of the transition were populated largely by cascading from higher atomic states rather than directly by dissociative recombination or if the recombination rate of the atomic ion is high enough to contribute appreciably to the observed light intensity. The probable importance of these effects is estimated.

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(1) W. A. Rogers and M. A. Biondi, Phys. Rev. 99, 1657A (1955).

THE FREE ELECTRONS IN ACTIVE NITROGEN*

W. B. Kunkel
University of California
Berkeley 4, California

It has been proposed that the free electrons usually found in active nitrogen are generated by ionization of nitric oxide molecules(1) either in binary collisions with metastable nitrogen molecules or in triple collisions with two nitrogen atoms. The required reaction rate constants seemed reasonable (of the order of 10^{-32} cm^6 sec^{-1} for the three-body collisions). Attempts were made to distinguish between recombination and ambipolar diffusion loss of the electrons by injection of known amounts of nitric oxide into the active gas at various pressures and simultaneous measurement of the increased electron density. The results confirmed the theory qualitatively. Unfortunately, it is not possible to separate the two removal mechanisms if their rates are comparable. Quantitative discrepancies might be ascribed to the fact that nitric oxide molecules may also be destroyed in part by non-ionizing reactions.

So far, attempts to detect the nitric oxide ions directly in a mass spectrograph have been unsuccessful.

Incidentally, it was shown that the emission of the nitrogen afterglow is not induced by free electrons since minute traces of benzol vapor injected into the glowing stream removed all free electrons while the afterglow was enhanced.

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* Work supported by Wright Air Development Center.

(1) W. B. Kunkel and A. L. Gardner, Phys. Rev. 98, 558 (1955).

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SHORT DURATION AFTERGLOW OF NITROGEN[*]

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In the afterglow of a low pressure discharge through nitrogen the spectrum and the intensity of the light emitted were observed with a "shutter speed" of 100 microseconds through a period of 1500 microseconds. The data were correlated with the decay of the electron-ion concentration. The spectrum is essentially identical with that of Kaplan's "auroral afterglow." It contains most of the prominent band systems, including N_2^+ bands. The Herman bands between 7000 and 8000A appear with considerable intensity. The spectra are excited only to a minor extent by electron-ion recombination, but largely by the recombination of two active particles, some of them metastable.
In oxygen under the same conditions very little light is emitted.

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THE EARTH'S RESIDUAL RING CURRENT

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If the earth were standing still in the highly ionized very low density medium filling interplanetary space, the earth's magnetic field would not prevent the velocity distribution of the charged particles of the medium from becoming Maxwellian except for some distortions near the earth's surface due to particles becoming absorbed in the earth's atmosphere.

The motion of the earth in its orbit about the sun produces a motion of the ambient medium relative to the earth's magnetic field at about the earth's orbital speed. Each particle in the medium executes a Stőrmer orbit in the earth's field except for the effects of collisions with other particles which are slow in so low density a medium. The Stőrmer orbits are of two types: the free orbits in which the particle approaches the earth from a great distance and after approaching the earth, moves away indefinitely; and the captive or periodic orbits in which the particle moves back and forth past the equatorial plane in rather complicated orbits coiled about magnetic lines of force which are steadily advancing in longitude about the magnetic axis. Particles in these periodic orbits are held in the ring containing all such captive particles and the ring moves with the earth through the ambient medium.

The magnetic field of this ring weakens the dipole field inside the ring and strengthens it outside with the result that high energy (300 kev) protons in streams from the sun can reach the earth at the observed lower magnetic latitudes (67° and less) than the simple Stőrmer latitudes (79°) for single protons.

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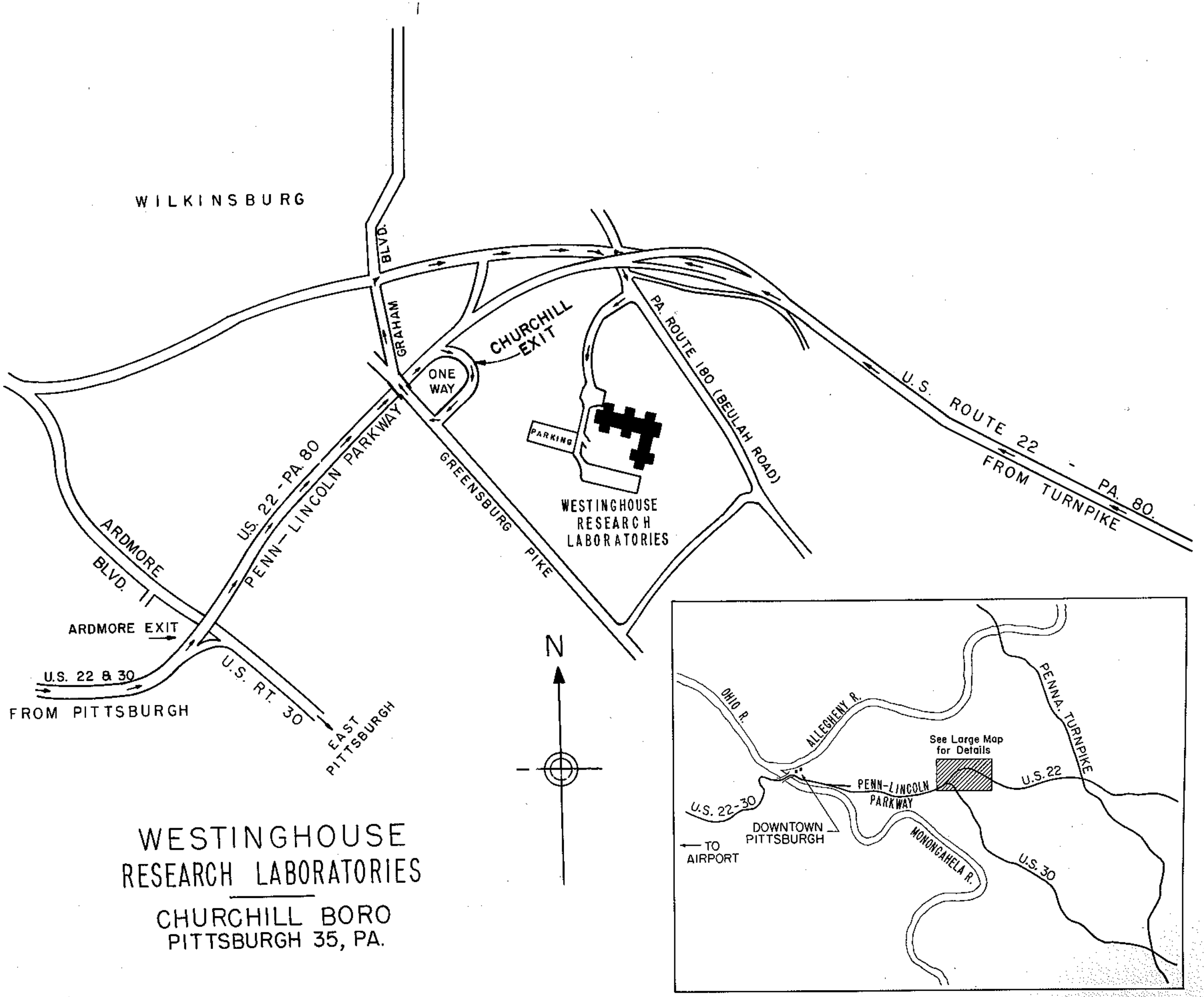

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