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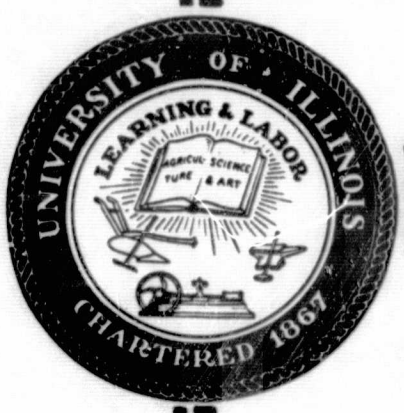
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COORDINATED SCIENCE LABORATORY

SUMMARY OF

PROGRESS REPORT FOR SEPTEMBER, OCTOBER, NOVEMBER, 1965

1. Space Sciences Group

The ionosphere program is now concerned only with rocket data reduction. For the general relativity satellite program, Baker-Nunn thresholds are discussed in relation to the problem of photographic observability, and the effect of micrometeorite cratering on determining the optimal diameter of the gyro satellite is discussed.

2. Surface Physics

Improvements in the electron source of the high-resolution electron spectrometer have resulted in a substantial increase in the sensitivity of the instrument. Preliminary measurements are reported that indicate the presence of low-energy loss peaks due to adsorbed gas. Progress on the construction of the apparatus for the measurement of the angular distribution of secondary electrons and on the instrumentation for the adsorption experiment is reported.

3. Computer

Operation statistics, new facilities for bubble-chamber data processing, and new display equipment are reported.

4. Control Systems

Several results were obtained in the continuing projects on the parameter-variation problem, stability of nonlinear systems, sub-optimal linear time-invariant control, and computer-oriented formulation and solution of the optimal control problem. Several new projects were initiated in the area of optimal control of plants which are subject to parameter variations.

5. PLATO

Student response data are being collected for the three university courses given for credit this semester using PLATO: Electrical Engineering 322, Library Science 195, and FORTRAN Programming for Business Students. The variables affecting the retention of conceptual materials are being analyzed. A man-computer interface study in order to optimalize keyset design is underway. Programming has also begun for three projects: a language-free test of interpersonal norms, an inter-nation simulation study and the system for instructional response analysis. Weekly seminars have been held this fall on subjects pertinent to PLATO research. During this quarter there have been thirty demonstrations of PLATO either in the classroom or by remote station. Transistor deflection circuitry replaces vacuum-tube types in the student-station circuitry completing the twenty-student-station classroom. Further progress has been made on the development and understanding of the plasma display tube.

6. Vacuum Instrumentation

Additional measurements on the pumping speeds of getter-ion pumps at low pressures have been made. These measurements and those on the effects of bakeout and processing of uhv systems in ultimate pressure are discussed.

7. Plasma Physics

In the calculation of the collision integral, it has been shown that the Monte Carlo error is reduced by a factor of 5 because of correlations predicted by Nordsieck. In the studies on beam-plasma interaction, anomalous diffusion has been observed during the beam instability together with intense radiation from plasma oscillations. Investigation of electron runaway in the linear plasma betatron has revealed an anomalous resistivity of the conduction current, which appears to stop the runaway current. Qualitative evidence has been obtained for a collisionless damping of the Tonks-Dattner modes.

8. Superconductivity Studies

Work is reported on a superconducting parametric amplifier (picovoltmeter), a study of the anisotropy of the energy gap in superconducting niobium and studies of flux flow in type II superconductors. Work is continuing on detection of microwave radiation from the ac Josephson effect in a superconducting bridge and the thermal conductivity of a type II superconductor in the mixed state, but no report of these activities is submitted at this time.

9. High Voltage Breakdown

When electrodes are gas-conditioned, the sharp protuberances on the cathode are blunted, thereby increasing the breakdown voltage by a factor of about 5 and the effective emitting area and prebreakdown current by about two and one orders of magnitude, respectively. The permanence or stability of the gas-conditioned surface is being investigated.

10. Thin Films

Continued work is reported on preparations for the size effect and Hall effect experiments. Development of the ionization-gauge deposition monitor has been continued to provide feedback control of the deposition rate.

11. Information Science

During the past quarter, several problems have been investigated. Results are obtained in the theory of residue codes for correcting multiple errors and the application of coding methods to information retrieval systems.

12. Switching Systems

Several new investigations were started during this quarter. These include computer aided design of structures, dynamic analyses of structures, and the propagation of errors in finite memory encoding-decoding schemes. Further progress is reported on the computer compiler and self-diagnosis studies.

13. Networks and Communication Nets

In studies of nonlinear networks, new conditions have been found such that transients decay to a unique periodic steady-state solution. These conditions permit a larger operating range of the nonlinear device (varactor) than is permitted by other solutions. In communication nets, studies include the overall reliability of nets with unreliable components, conditions for optimal flow in a net in which edge flow is limited, and nets with censors. In graph theory, studies are in progress on properties of biweighted graphs, and the determination of the minimum feedback arc set.

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PUBLICATIONS AND REPORTS

1. Journal Articles Published or Accepted

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Tang, D. T., and R. T. Chien, "[illegible]lic Product Codes and Their Implementation," Information a[illegible]ontrol (to appear).

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J. B. Cruz, Jr. and W. R. Perkins, "Sensitivity Comparison of Open-Loop and Closed-Loop Systems," Third Annual Allerton Conference on Circuit and System Theory (to appear), October, 1965.

Y. Ichikawa, "Ion-Oscillations in a Weakly Turbulent Plasma," Seventh Annual Meeting of the Division of Plasma Physics, APS (November, 1965), San Francisco.

C. Mendel and M. Raether, "Investigation of Electron Runaway in a Linear Induction Accelerator," Seventh Annual Meeting of the Division of Plasma Physics, APS (November, 1965), San Francisco.

Thomas E. Mueller, "Optimal Open-Loop Control of Linear Systems with Time Lag," Third Annual Allerton Conference on Circuit and System Theory (to appear), October, 1965.

A. Nordsieck and Bruce Hicks, "Non-linear Translational Relaxation, The Pseudo-Shock," Meeting of APS (October 1, 1965), Chicago.

W. R. Perkins, "Synthesis of Interconnected Linear Time-Varying Systems," Proc. NEC XXI, p. 694 (October, 1965).

G. S. Tahim, "Controllability of Time Lag Systems," Third Annual Allerton Conference on Circuit and System Theory (to appear), October, 1965.

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R-267 A Decoding Method for Bose-Chaudhuri Binary Codes Using an Error Counting Technique, W. Jack Bouknight, (October, 1965).

R-268 The Uses of PLATO: A Computer-Controlled Teaching System, D. L. Bitzer, E. R. Lyman, and J. A. Easley, Jr., (October, 1965).

R-269 Stochastic Flow of Messages and Its Efficient Transmission through Communication Nets, Kenji Onaga, (November, 1965).

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1. SPACE SCIENCES GROUP

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1.1 Ionosphere Program*

With the development of automatic data-processing methods for extracting Faraday rotation and differential absorption, CSL's role in the ionosphere program has shifted to analyzing the data from existing rocket shots and those which will be carried out by Dr. Sidney Bowhill's group in the Electrical Engineering Department. A final report, describing the novel system and operating techniques developed by CSL for measuring Faraday rotation and differential absorption in the D-region of the ionosphere with rocket probes, has been completed and is being published by CSL. It is designated as R-273, "High Resolution Radio Frequency Measurements of Faraday Rotation and Differential Absorption with Rocket Probes."

1.2 Orbiting Relativity-Gyro Experiment†

1.2.1 Photographic Observability. On a recent visit to the Smithsonian Astrophysical Observatory, it was learned that the observable energy flux for the Baker-Nunn camera is approximately 8×10^{-11} lumen second per square meter. This was quoted as producing a reliably observable image of a point source in competition with a one-second exposure

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to night sky, in that the night sky produces a photographic density 0.3 to 0.4 logarithmic density unit below the density produced by the point source. The energy flux is quoted for the input to the camera aperture, for a spectral distribution corresponding to the solar color temperature, as seen through the earth's atmosphere, and using red-extended Royal-X Pan film for reciprocity conditions favoring fractional-second exposure times.

This "threshold" corresponds to observing a solar flash near the zenith from a mirror facet of 60 square centimeters in projected area, at a range of 1000 kilometers, and for a flash duration of 7 microseconds. The duration is the time required for the satellite to rotate through 0.25 degree at a rotation rate of 100 Hz, to scan the half-degree width of the solar image. At this slant range, the orbital speed would correspond to an apparent speed of 0.4 degrees per second. At a flash rate of 500 Hz, the apparent flash spacing would be about three seconds of arc. Thus, within the optical resolution of the camera, some 12 seconds of arc, there would fall four flashes, producing an exposure above "threshold" by a factor 4. Actually observed resolutions involve some image spreading, resulting from light scatter within the film, so that a factor of 6 could be claimed. The method of data detection and analysis to be used, however, will involve correlation techniques exploiting the total energy in the flash pattern, involving some 400 flashes, so that the effective total exposure above "threshold" would be, allowing for the fact that not all flashes would be at the maximum intensity, nearer a factor of 200.

The detection and analysis of the flash pattern for an optimal determination of the center of the pattern will require correlation of the observed pattern with one derived from the pattern to be expected a priori. The derivation would reflect the nonlinearity of the photographic film together with a knowledge of the noise statistics of the film. For example, if the film were linear, and the noise statistics were gaussian with signal-independent parameters, then the optimal pattern would be the angular derivative of the expected brightness pattern, for the estimation of the pattern center.

It will then be important to develop accuract models of the photographic linearity and noise parameters in order to develop the estimation pattern for use in the correlation technique, and also, through computer simulations, to develop firm estimates of the accuracy that may be expected. Experimental work to this end will be started soon.

At the present time, however, a reliable accuracy estimation cannot be obtained, based on signal-to-noise considerations. It is not realistic, for example, to regard the Baker-Nunn "threshold", cited above, as equivalent to a noise level against which the optical brightness should be compared, in any literal sense. The density increment of 0.3 to 0.4 does correspond to a light transmission ratio of from a factor 2 to 2.5, but one does not know from this that the single-flash exposure, as described, is above the background by so small a factor. Typically, the density-vs-log-exposure curve would have a slope near 0.3 for exposures near the toe of the curve, so that the exposure ratio, corresponding to a density difference of 0.3, could be nearer the factor 10.

Questions relating to the noise level must also involve an estimate of the noise bandwidth, related to that needed to accomodate the signal. This noise arises from the random granularity of the photographic image. It was observed that a "point" image from the Baker-Nunn camera would be 10 or so grains wide, suggesting a bandwidth ratio of 10. Thus, a microdensitometer tracing using a very small aperture would show 10 times as much noise energy as a tracing using an aperture matched to a resolution width. The description of the "threshold" image as being "reliably observable" would be unusual for a signal presented at a signal-to-noise ratio of 2, for which the noise bandwidth matched that of the signal, but would be an eminently reasonable description at a signal-to-noise ratio of 10.

With some hope of realism, one could then estimate the "threshold" point-image signal-to-noise ratio as being of the order of 10, or even more if referred to exposure. In the same way, one could estimate the integrated whole-pattern signal-to-noise ratio to be 2000 or more, under the cited circumstances, with more reliable estimates to be obtainable after more study. Using these considerations, the accuracy for measuring the position of extended images should be estimated to be consistent with that usually quoted for the Baker-Nunn camera, namely 2 seconds of arc for laboratory measurements.

It will be noted that the number of flashes that will fall in a resolution element will increase with range, but that the brightness of each flash will decrease with the square of the range, so that the photographic effect will decrease with the first power of range, in a manner characteristic of line sources.

The sensitivity to other parameter variations is less severe. For example, a decrease in rotation rate will increase the exposure for each flash, but decrease the number within a resolution element, so that the net exposure would be the same. Similarly, an increase in the area of the facets, at the expense of reducing the number contributing to a given pattern, will result in no change in observability.

1.2.2 Micrometeorite Cratering. An investigation of the drift of the axis of the maximum moment of inertia due to micrometeorite cratering is being completed by Professor H. O. Barthel of the Department of Aeronautical and Astronautical Engineering and will be published as CSL Technical Report R274, "Effects of Micrometeorite Cratering on the Direction of the Axis of Maximum Moment of Inertia."

Since transfer of momentum by the meteoroids themselves is negligible, the investigation first determines the maximum angular effect on the gyro inertia tensor caused by the loss of a small mass removed from the surface. The angle of rotation of the body axes necessary to yield the principal moments of inertia are then computed from the inertia tensor. This angle is the displacement of the gyro symmetry axis (after damping) due to the mass loss and, in this study, is restricted to be one order of magnitude less than the total drift due to general relativity in one year. Next, the cratering mechanism is briefly examined and leads to a consideration of the velocity distribution of micrometeorites. Having obtained the velocity distribution, an estimate of the fraction of the total micrometeorite flux is made and used to calculate the number of hits per year, N, each of which could cause an angular disturbance

of the order of one-tenth the general relativity drift in one year. The results of this investigation are shown in Fig. 1.1, in which the number of hits per year, N, is plotted versus the quantity (C-A)/C for two conditions. One, an upper bound, is the case for which all of the kinetic energy of the impacting particle goes into melting (η=1). The second case is for only one quarter of the kinetic energy going into melting (η=1/4), a more reasonable estimate in view of the mechanism for melting. The results of Fig. 1.1 are computed for an earth-shielding factor of 0.75 (approximately 750-mile orbit) and a spherical gyro of one foot diameter.

In interpreting these micrometeorite-collision results, it should be kept in mind that each hit was assumed to produce a maximum effect. For purely random hits, 75 per cent of them will produce at least one half of the maximum possible angular shift. Furthermore, for N greater than 25, there is a 50 per cent chance of having a total effect of five times the maximum effect for a single hit. This result arises, because, in this number of hits, one hit will involve a mass which is an order of magnitude larger than the assumed mass. These considerations lead to the conclusion that the number of hits by masses which can cause an angular shift of 10 per cent of the relativity shift should not exceed approximately 10 per year.

The considerations of meteoroid statistics, along with the effects of gravity gradient and centrifugal deformation give rise to an optimal diameter. Departures from optimal diameter in the small direction cause increased gravity gradient torque, because of the larger (C-A)/C

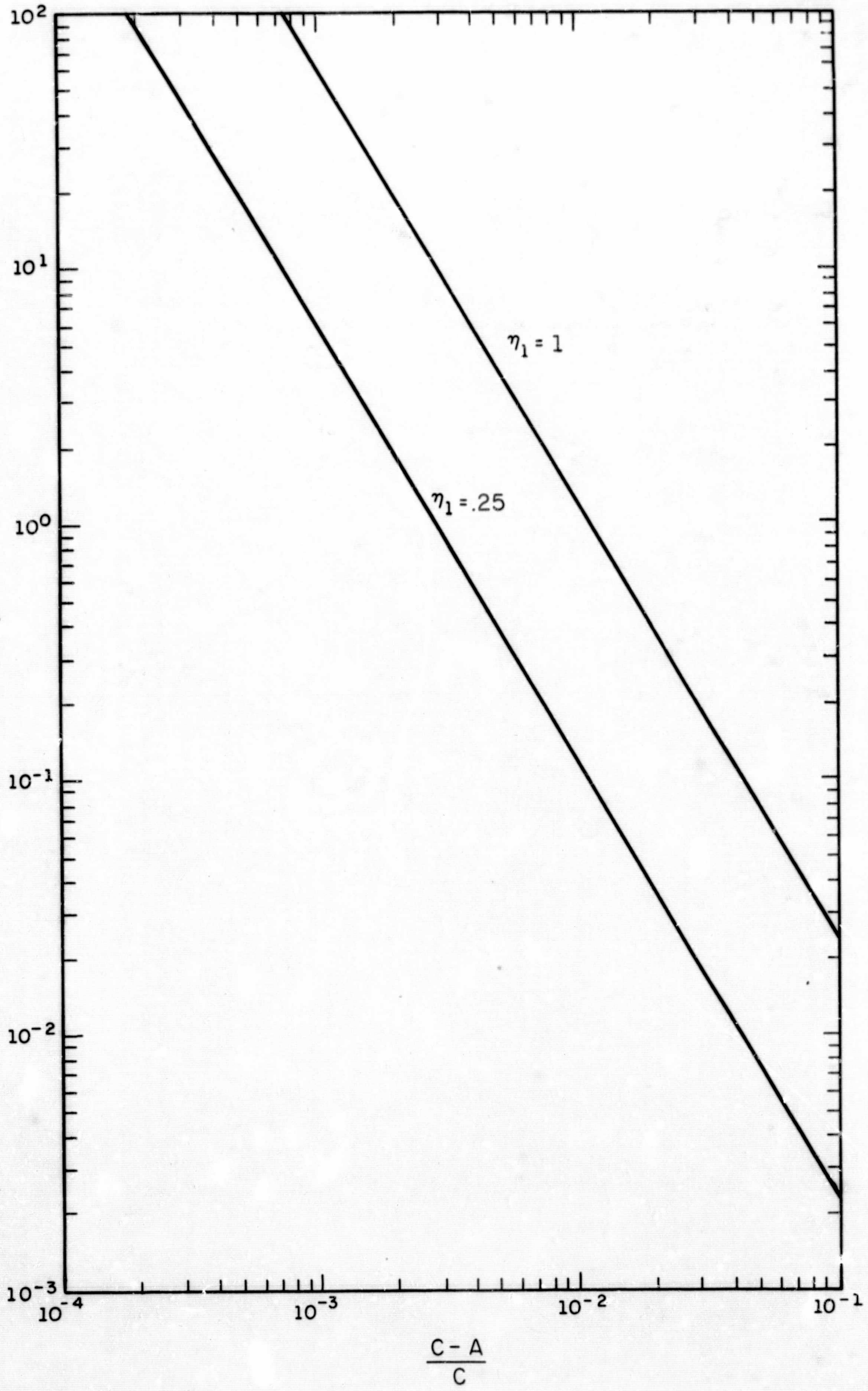


Fig. 1.1. The Number of Hits per Year, N, Each of Which Could Cause an Angular Disturbance of 0.6 arc sec, versus (C-A)/C.

ratio dictated by the micrometeorite-cratering effect on mirror orientations. In this case material strength limits the maximum speed. Departures in the large direction dictate (C-A)/C ratios which are smaller than those produced by the centrifugal deformation that would result from the employment of maximum angular speed. Therefore, the compromise of reduced angular speed, to prevent excessive centrifugal deformation, results in greater drift. Optimalization studies using various materials are now being conducted.

2. SURFACE PHYSICS

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2.1 Adsorption-Desorption Kinetics of Gases on Metal Surfaces†

The experiment for the study of gas-surface interactions by Auger ejection of metallic electrons by ions is continuing.

A feedback system has been constructed to hold the number of ions in the beam striking the target constant. A diagram of the apparatus is shown in Fig. 2.1.

The potential V_R of the electron-focus electrode controls the emission current from the filament F and the trajectories of the electrons into the ionization region; hence, it may be used to control the total ion current. A constant fraction of these ions moving toward plate A pass through its aperture and are focused onto the target. A plot of the relationship between V_R and I is shown in Fig. 2.2.

When the system is operating in the feedback mode, say at operating point P corresponding to an ion current I^o and an electron focus potential $V_R{}^o$, a momentary increase in ion current causes an increased electrometer-output voltage. Thus, a larger voltage is applied to the negative input of the operational amplifier, pushing the amplifier out of its balanced state and giving a negative instead of a zero output voltage. This negative voltage will drop the focus-electrode voltage

†Portions of this work were supported by the National Aeronautics and Space Administration undger Grant NsG 376.

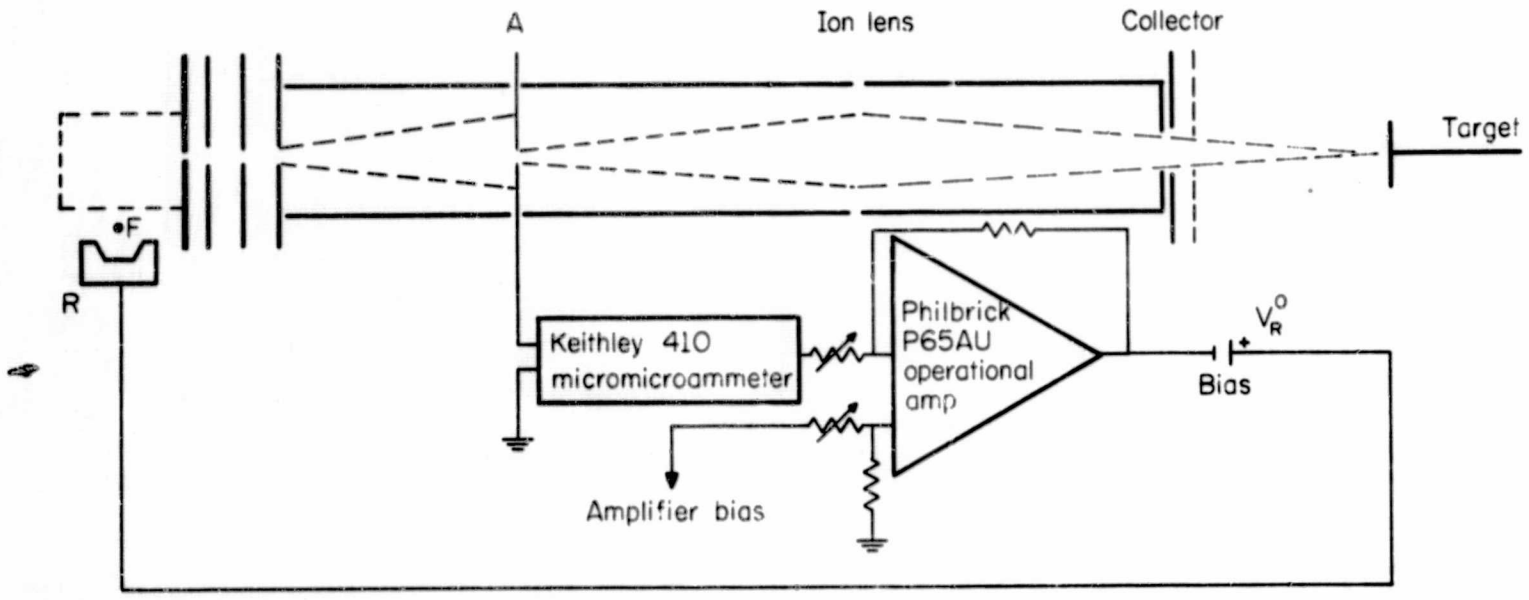


Fig. 2.1. Ion-Current Control System.

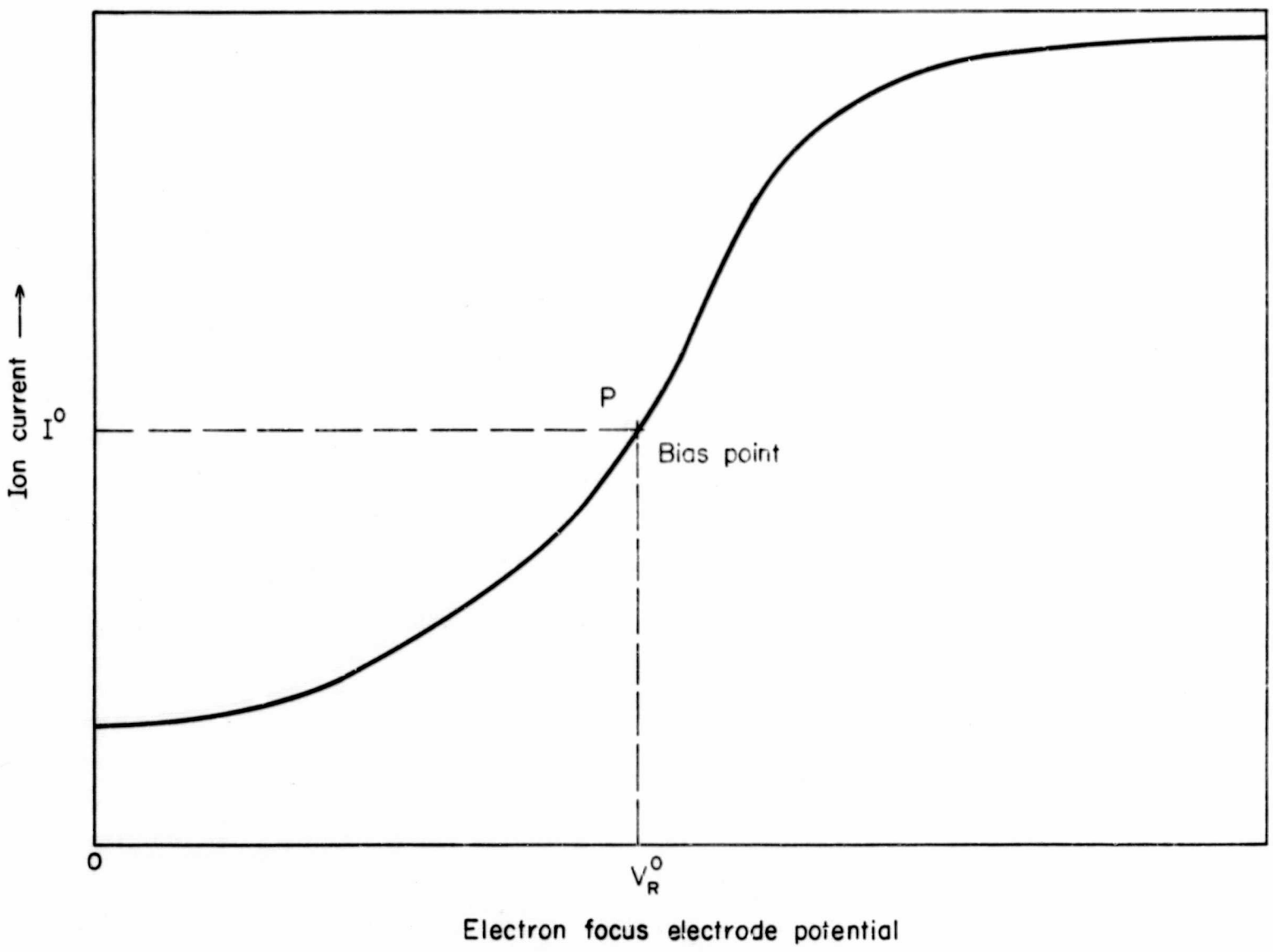


Fig. 2.2. Ion Current <u>versus</u> Electron Focus-Electrode Potential.

from its steady-state value, thereby reducing the ion current and bringing the amplifier back into balance. A momentary decrease in ion current produces the converse result.

Using this system, we have observed runs of many hundreds of seconds during which the ion current was constant to better than 1%.

We spent much of this quarter attending to the vacuum system itself. One of the glass-molybdenum feedthroughs in the bottom of the target-cooling liquid-nitrogen reservoir began leaking, probably due to stresses set up when the trap was filled. The feedthrough was replaced with some difficulty.

A quadrupole mass analyzer was used to obtain partial-pressure measurements of the residual gases in the system. Fig. 2.3 shows a typical spectrum taken after a light bakeout (250°C) and an outgassing of both the Bayard-Alpert gauge and the analyzer. The peaks at 18 due to H_2O^+, at 28 due to CO^+ and N_2^+, and at 44 due to CO_2^+ are apparent. Background pressure was about 3×10^{-9} Torr. Since our system is pumped with DC-705 oil, it is possible that the peak at 78 is due to C_6H_6, as observed by Gosselin and Bryant.[1]

After removing the mass analyzer and baking to 450°C, the system pressure went down to less than 8×10^{-10} Torr in a few days. After some weeks of operation, the pressure dropped to below 4×10^{-10} Torr.

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[1] C. M. Gosselin and P. J. Bryant, J. Vac. Sci. Tech., 2, 293-297 (1965).

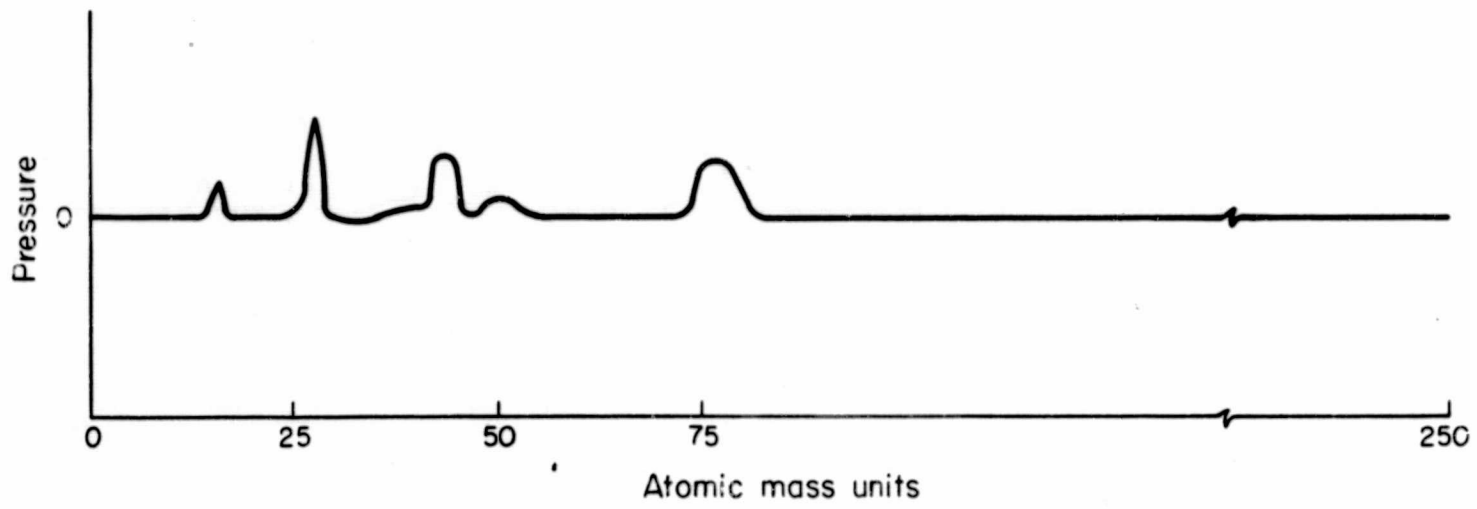


Fig. 2.3. Typical Mass Spectrum of Residual Gases.

2.2 High Resolution Study of Secondary Electron Emission[†2]

The current passing through the monochromator-target-analyzer system has been increased substantially. At 1.35 eV pass energy (giving a beam incident on the target of 30 millivolts width at ½ height), about 7.5×10^{-9} A pass through the monochromator to the target. At 2.70 eV pass energy, about 45×10^{-9} A reach the target. Note that the ratio 45/7.5 = 6.0 is approximately equal to the product of the factor of 2 increase in transmission and the factor of $2^{3/2}$ due to space-charge-limited flow from the cathode, $2^{5/2} \approx 5.7$. The counting rate at the analyzer output for the analyzer centered on the elastic peak (for 3.0 eV primaries and a total energy resolution of 55 millivolts) is about 5×10^{4}/sec. At lower energy primaries, this elastic counting rate increases somewhat, and, at higher energy primaries, it decreases considerably.

Structure has been observed in the region just below the elastic peak. Figure 2.4 shows a 2.0 eV range in this region for 4.0 eV primaries. The loss peaks shown are multiples of about 0.38 eV from the primary peak (which is not shown). This curve was obtained with the target as-is, after the system cooled from both baking the vacuum system and simultaneously heating the target by electron bombardment. Thus, the target was not clean. The location of the structure relative

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[†]Portions of this work were supported by the National Aeronautics and Space Administration under Grant NsG 376.

[2]See the previous four progress reports.

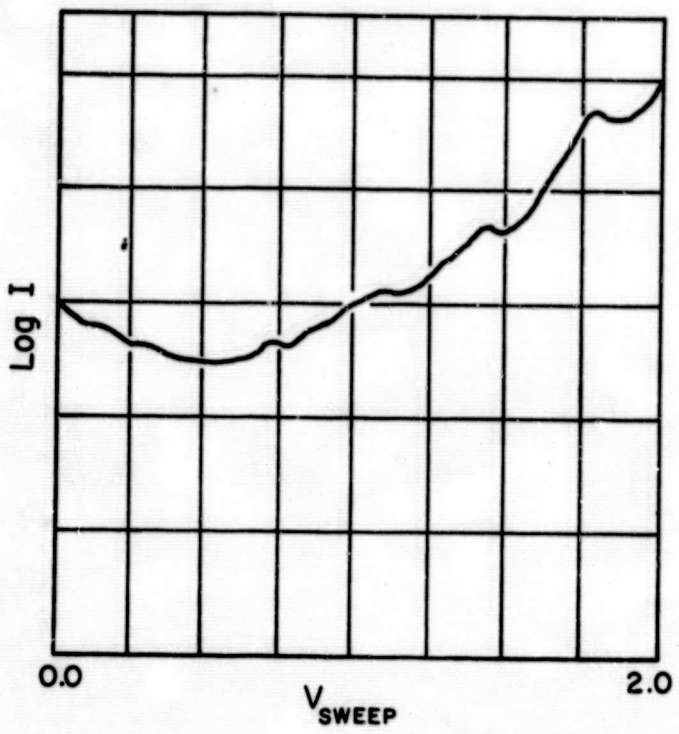


Fig. 2.4. Discrete Loss Peaks Just Below the Elastic Peak.

to the elastic peak was independent of the primary energy. It was more evident for primaries in the range 2.0 to 5.0 eV.

Fig. 2.5 shows, in the dashed curve, the primary peak (at 3.0 eV) and two loss peaks. The smaller sharper peak is 0.38 eV below the elastic peak and is the same as the right-hand peak in Fig. 2.4. Peaks at further multiples of 0.38 eV are not in the region displayed. The second loss peak is at about 0.080 eV below the primary. However, no other peaks at multiples of 0.080 eV have been observed. The solid curve is for the same region as in the dashed one, but taken after the target had been flashed clean. No evidence of the 0.38 eV loss peaks could be seen in this curve. Thus, the peaks at 0.38, 0.76, 1.14, and 1.52 eV below the primary peak are associated with adsorbed gas.

2.3 Angular Distribution of Secondary Electrons†

Work is continuing on the vacuum system[3,4] for the angular distribution experiment. Ovens have been constructed from Marinite[5] and Titan type D heating coils. Marinite appears to be a cheap and convenient material for ovens. It does, however, warp severely during bakeout. In order to minimize the possibility of cracking, heating coils may be attached to either side of the oven panels, and either side of each panel can be used as the inside. Thus by reversing the oven panels, the direction of warp can be changed.

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†Portions of this work were supported by the National Aeronautics and Space Administration under Grant NsG 376.

[3] CSL QPR, March-April-May, 1965.

[4] CLS QPR, June-July-August, 1965.

[5] Johns-Manville product.

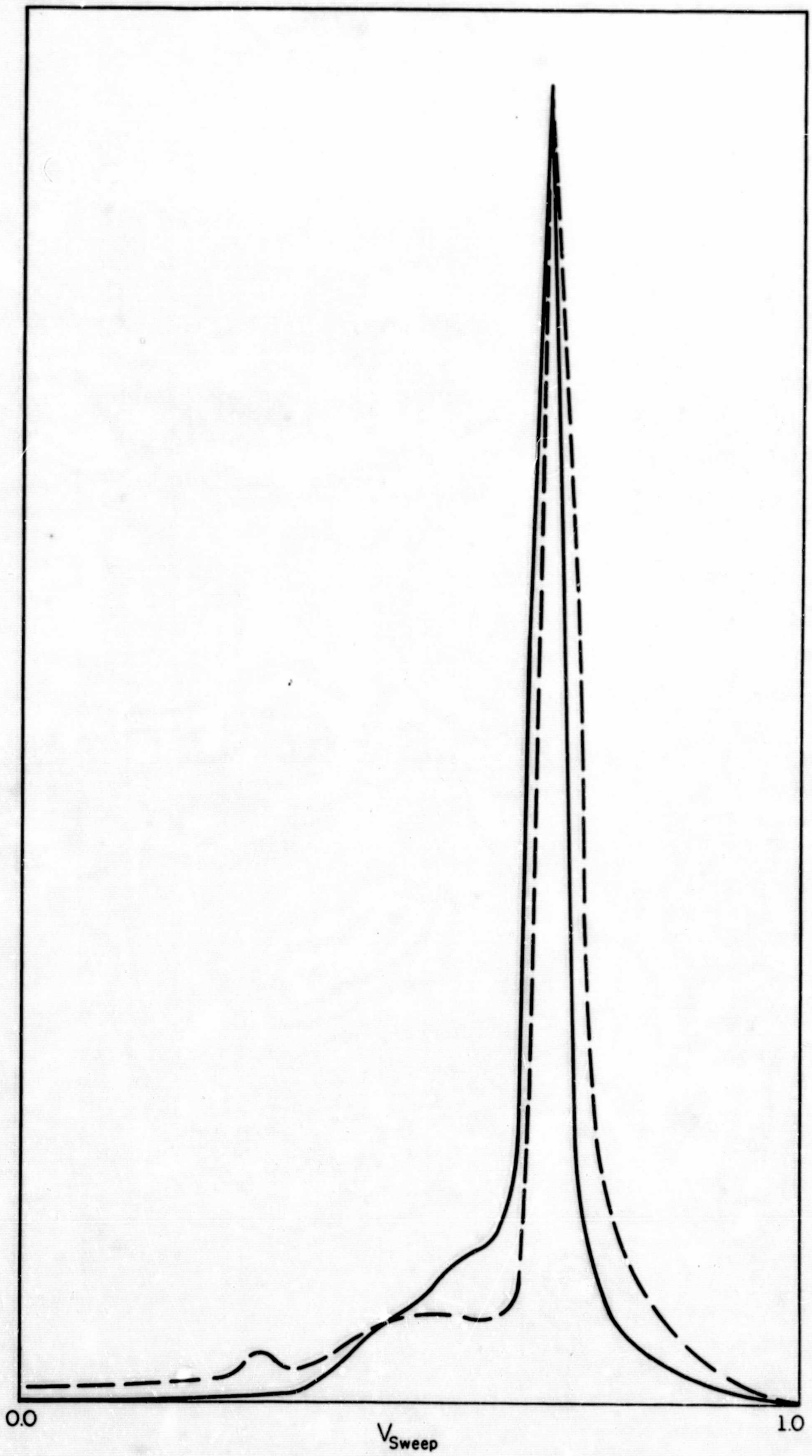


Fig. 2.5. Gas-Covered Surface Showing Discrete Loss Peaks (Dashed Curve) and Clean Surface Showing No Discrete Peaks (Solid Curve).

After two bakeouts, a pressure of 5×10^{-9} Torr was obtained. The rubber O-rings that join the main diffusion pump to the baffle, and baffle to the lower cold trap were replaced by aluminum O-rings. The system then attained a pressure of about 3×10^{-10} Torr after a mild bakeout.

After the system had run for about ten days, a leak appeared in at least one of the aluminum O-rings. This leak was caused by mercury amalgamating with the aluminum. Amalgamation had never been a problem with aluminum O-ring seals on another mercury system, and it was felt that the aluminum oxide layer was sufficient protection for unbaked O-rings. However, the different flange geometry on this system exposes the O-ring to a much higher mercury contamination. To overcome this difficulty, O-rings will be made from a 5% silicon alloy of aluminum. This material has been used successfully by others.[6]

A guarded coaxial feedthrough has been constructed, using the high-temperature-glass-to-metal-sealing techniques developed by Nick Vassos, and is being tested. The feedthrough shown in Fig. 2.6 is made from molybdenum and Corning 1720 alumina-silica glass; all materials are non-magnetic. Although testing has been insufficient to insure reliability, this feedthrough appears to be usable on ultrahigh-vacuum systems for low current measurement.

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[6]Edwards High Vacuum, Inc. Research Report No. 213, March 21, 1963.

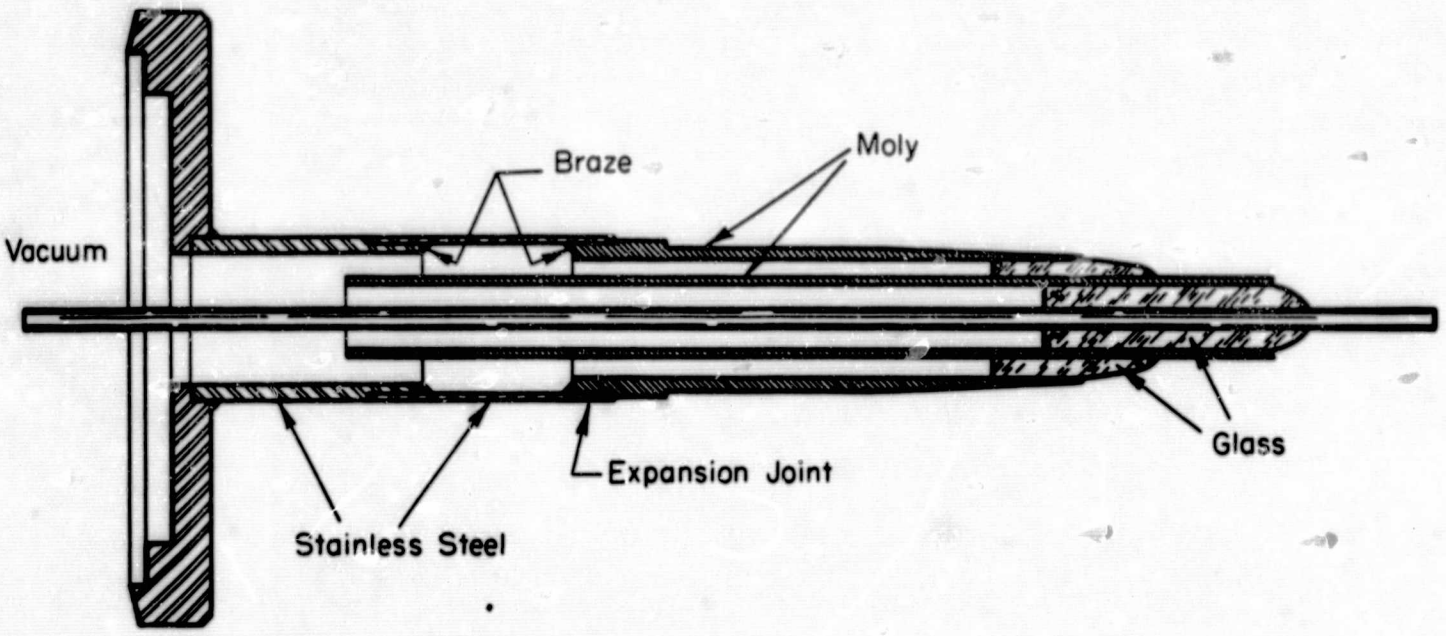


Fig. 2.6. Nonmagnetic Guarded Feedthrough.

3. COMPUTER

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E. Neff
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3.1 Introduction

This group is responsible for the development and maintenance of the CSL computing facility.

3.2 CSX-1 Computer

3.2.1 Operations.

Period: September 1 to December 1, 1965

Total Running Time	2183.3	hours
Average Per Day (7 day week):	23.99	hours
Operational Time: 99.96%	2183.3	hours
Scheduled Maintenance Time: 0%	0.0	hours
Emergency Maintenance Time: .04%	0.7	hours

L. Hedges

3.2.2 Bubble Chamber Data Processing. Two features of the SMP-CSX-1 system have become operational in the last three months. These are the point-measuring technique and equipment, and the semi-automatic control by the CSX-1 of the list of material to be measured.

In order to allow measurement of distinct points, a second mode of electronic operation has been introduced into the SMP digitizing system. In this second mode the leading and trailing edges of the pedestal

in the photomultiplier output, caused by traversal of the periscope mask over a bench mark, are used to trigger reading of the angular orientation of the mask at the two times. The leading- and trailing-edge orientation may then be used to construct a bisector of the mask, which, in the ideal case, would extend through the center of rotation of the mask. During a single revolution of the periscope, the mask may be expected to cross five to eight bench marks, allowing five to eight lines to be intersected to determine a "best" intersection point. The data indicates that this "best" intersection is found to an accuracy better than that of a least count on an individual reading of the sine and cosine of the angle or orientation. The spread in measurements of a single point is about 20 to 30 microns in both the x and y directions.

Also in regular use at this time, is an input tape to the CSX-1, containing the list of material to be measured by an SMP. This tape is prepared from cards obtained directly from the scanning sheets, and also from a feedback on previous measurement failures. The SMP operator signifies that he wishes to receive measuring information from the CSX-1, whereupon the computer reads a record from the input tape and relays this information to the operator, and at the same time, stores the information for later output along with the measured data. The system serves to increase both the efficiency of measuring and the associated bookkeeping.

Projected uses of the CSX-1-SMP system rely upon the additional CSX-1 memory to be installed in January. At that time, a third bubble-chamber-film-format measuring capability will be added to the program.

This will allow simultaneous measuring of film produced at Lawrence, Argonne, and Brookhaven National Laboratories. With the arrival of the new memory, further research will also be done in the area of automatic ionization measurement of bubble chamber tracks as an aid in identification of reactions.

D. Mortara
W. Stolte

3.3 CDC 1604 Computer

3.3.1 Operations.

Period: September 1 to November 30, 1965

Total Running Time:		1234.30 hours
Average Per Day (7 day week)		13.56 hours
Operational Time:	94.29%	1163.80 hours
Preventive Maintenance Time:	3.25%	40.17 hours
Engineering Time:	2.46%	30.33 hours
Emergency Maintenance Time:	0.00%	0.00 hours

E. Neff

3.3.2 New Equipment. The two 12 bit digital-to-analogue converters for the display system were completed in this quarter. These circuits are accurate to better than .02%, but their ability to separate nearby points on a cathode-ray tube are better than this figure implies. Measurements have shown that with an array of 4096X4096 addressable positions on the face of a cathode-ray tube, the deviation of a spot from its expected position is less than 9% of the normal distance between two adjacent points. It is expected that with a more stable power supply this figure will drop to less than 7%.

These converters couple a 16" cathode-ray tube through a temporary interface to the CDC 1604 computer. The system, at present, operates in a point-plotting mode, and all images are composed of an appropriate series of points. In the next six months, however, the system will include circuits for generating characters and lines.

J. Stifle
L. Hedges

4. CONTROL SYSTEMS

J. B. Cruz, Jr.
W. R. Perkins
M. Sobral, Jr.
S. D. Agashe
M. S. Davies
J. P. Herner
R. A. Hoyt
T. J. Killian
M. Schoenberger
R. Werner

4.1 Survey of Sensitivity Theory†

A survey of various approaches to sensitivity theory is in preparation. A significant feature of the report will be the inclusion of an extensive bibliography. The paper will be published jointly with Dr. Petar Kokotovic of Yugoslavia.

J. B. Cruz, Jr.
W. R. Perkins

4.2 Optimal System Design in the Presence of Plant-Parameter Variation†

An investigation of the problems of design of linear, time-invariant control systems in the presence of plant-parameter variation[1-4] is being undertaken. The problem is first dealt with by considering what

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

[1] R. A. Rohrer and M. Sobral, Jr., "Sensitivity Considerations in Optimal System Design," IEEE Transactions on Automatic Control, AC-10, 43-48; January, 1965.

[2] W. R. Perkins and J. B. Cruz, Jr., "The Parameter Variation Problem in State Feedback Control Systems," J. Basic Engineering (Trans. ASME, Series D), 87, 120-124; March, 1965.

[3] D. D. Siljak and R. C. Dorf, "On the Minimization of Sensitivity in Optimal Control Systems," presented at the Third Allerton Conference on Circuit and System Theory, October 20-22, 1965, Urbana, Illinois.

[4] P. Dorato and A. Kestenbaum, "Application of Game Theory to the Sensitivity Design of System with Optimal Controller Structures," Presented at the Third Allerton Conference on Circuit and System Theory, October 20-22, 1965, Urbana, Illinois.

seems to be a reasonable extension to partially known plants of the well-defined optimal-control problem. When the extension is made, many new questions arise and some answers for these questions are proposed. Some game-theoretic concepts will be used in order to formulate the new problem better. Also, some interrelation between game theory and invariance will be briefly discussed. Recent results obtained by several authors are used in the definition of the problem. Finally, it is hoped that meaninful comparisons between an optimal closed-loop solution and the optimal open-loop solution can be made using the above definitions and concepts.

M. Sobral, Jr.

4.3 Synthesizing Comparatively Insensitive Linear Systems[†]

The problem, briefly stated, consists of relating a sensitivity criterion to performing the optimization of a linear regulator problem. That is, given a linear time-invariant plant described by the state equations

$$\dot{\underset{\sim}{x}} = A\underset{\sim}{x}+B\underset{\sim}{u} ,$$

then for what W and R matrices does performing the minimization of

$$\int_o^\infty \{\underset{\sim}{x}^t W\underset{\sim}{x}+\underset{\sim}{u}^t R\underset{\sim}{u}\}dt$$

yield a feedback solution

$$\underset{\sim}{u} = F\underset{\sim}{x} ,$$

[†]Portions of this work were supported by the Air Force Office Office of Scientific Research under Grant No. AFOSR 931.65

such that the sensitivity requirement

$$[S^*(s)S(s)-I]_{s=j\omega} < 0,$$

for all real ω, is necessarily satisfied, where S(s) is defined as

$$S(s) = [I-(sI-A)^{-1}BF]^{-1} .$$

At present, work is being done on finding the matrices Q for which the condition

$$[S^*(s)QS(s)-I]_{s=j\omega} < 0$$

is satisfied for all real ω, given W, R, and F. Solution of this problem, it is hoped, will suggest sufficiency conditions on the W and R matrices for solution of the primary problem.

J. P. Herner

4.4 Optimal Control and Sensitivity Considerations†

Investigation continues into the problem of finding optimal or near-optimal control laws for plants with uncertain parameters. Although this usually leads to an approximate solution, a greater lower bound does exist which can serve as a guide to the adequacy of the approximation. Work at present is concentrated on determining a means for finding the greatest lower bound and using this for obtaining satisfactory controls.

T. J. Killian

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

4.5 Constrained Optimal Control†

Research has continued in the solution of optimal control problems in which the control configuration is a priori constrained. The optimal control problem is, then, to determine the parameters of this configuration such that a performance index is minimized. Two types of regulator problems have been solved.

The first is described by

$$\dot{\underset{\sim}{x}} = \underset{\sim}{f}(\underset{\sim}{x})+B\underset{\sim}{u} \ ,$$

$$\underset{\sim}{x}(t_o) = \underset{\sim}{x}_o \ ,$$

with the constraints

$$\underset{\sim}{u} = c\underset{\sim}{x} \ ,$$

$$\dot{c} = 0 \ ,$$

and the performance index

$$J = \underset{\sim}{x}^T(T)P\underset{\sim}{x}(T) + \int_o^T [\mathcal{L}(\underset{\sim}{x})+\underset{\sim}{u}^T R\underset{\sim}{u}]dt \ ,$$

where R and P are diagonal positive-definite matrices. Although the condition for minimizing J is the satisfaction of a 2-point boundary-value problem, an iterative technique has been developed which converges quite rapidly. If one has $\underset{\sim}{f}(\underset{\sim}{x})=A\underset{\sim}{x}$, and $\mathcal{L}(\underset{\sim}{x})$ is the sum of quadratic and quartic terms, the procedure appears to converge very rapidly. For a fourth-order system with initial values of the parameters quite far from the optimal, convergence in eight iterations was obtained for the single-input case.

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

The second problem, the fixed point linear regulator problem has been the center of a good deal of attention during the past few years. Kalman has determined that the optimal control is linear, time-varying feedback of the state variables. Rekasius has shown that in order for $\underset{\sim}{x}(T)=\underset{\sim}{0}$, the gains in the feedback must approach infinity as t approaches T. He has proposed an alternate solution to the problem in which $\underset{\sim}{u}=(\underset{\sim}{c}')^T\underset{\sim}{x}+f(t)$ where $\underset{\sim}{c}'$ is the solution to the infinite time problem and f(t) is some time-varying open-loop control. Also considering implementation problems, I have constrained $\underset{\sim}{u}$ such that

$$\underset{\sim}{u} = c\underset{\sim}{x} + \underset{\sim}{d} ,$$

where the elements of c and $\underset{\sim}{d}$ are constant. An iterative procedure which results in rapid numerical convergence has also been developed for this problem.

M. Schoenberger

4.6 Plant-Parameter Sensitivity in Optimal Regulators†

Preliminary studies are being carried out on the problem of plant-parameter sensitivity in optimal linear regulators. Investigations are being made into the effects upon a quadratic performance index of large variations of plant parameters. It is expected that the results of this investigation will lead to synthesis techniques for relatively parameter-insensitive linear regulators.

Integral to this study is a choice of a "meaningful" measure of the sensitivity of the performance index. Two of these which are

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

believed very good prospects are

$$E\{[J(a,u)-J(a,u_o)]/|J(a,u_o)|\}$$

and

$$E\{J(a,u)\}.$$

In the above, E is the expected value, J is the quadratic performance index, a is the variable plant paramter, u is the control, u_o is the optimal control for paramter value a. These sensitivity indices are, of course, not original in this work.

R. A. Hoyt

4.7 Computer-Oriented Formulation and Solution of the Optimal Control Problem: Constructive Aspects of Mathematics†

Investigation continues about the computer-oriented formulation of the optimal control problem discussed in the previous Progress Report.

It was observed that because of the algorithmic character of computations on a digital computer, the algorithmic character of various mathematical theories may need to be examined in detail. This led to the development of a new constructive theory of mathematics. This theory will be described in detail in a forthcoming technical report. We may mention here briefly that this new theory involves the notion of a "sequential construction."

According to this viewpoint, mathematics is supposed to consist in the writing of new statements--ordered collections of symbols--from old statements, using given statements and given patterns of construction

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

(axioms of a theory), and in the recognition of new patterns of construction. The notion of "conjunction" is seen to be merely a shorthand for writing a collection of statements "in a single line." The notion of "negation" corresponds to a statement not being allowed in a given theory. Finally, the notion of "disjunction" is completely eliminated.

This theory has been applied to an elementary theory of sets, groups and ordered structures. Of course, the application of this theory to a computer-oriented formulation of the optimal control problem may be a formidable task.

S. D. Agashe

4.8 Stability of Control Systems†

Work continues on the stability of systems containing a number of nonlinearities. For the case of a single nonlinearity, a convenient frequency-domain criterion was derived by Popov using the techniques of functional analysis. Kalman showed that the methods of Lyapunov could be applied to the problem and by these means obtained an equivalent criterion. It is hoped that the Lyapunov approach will yield a frequency-domain criterion, analogous to that of Popov, for systems which include a number of nonlinearities. Commencing with a generalization of the Lure-type Lyapunov function which includes the nonlinearities,

$$V = x'Px + \Sigma_i \ell_{ij} \int_0^{\sigma_i} f_i(\sigma_i)d\sigma_i \quad ,$$

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

it is possible to proceed formally to a generalization of the Popov criterion

$$\mathrm{Re}\{(\Xi + E j\omega G(j\omega))\} > 0 \ , \quad \text{for all } \omega \ ,$$

where $G(j\omega)$ is a matrix frequency response. However, this criterion has not yet been established rigourously.

Aggarwal and Jackson[5] have recently noted that for nonlinear systems with linear parts of a certain form, stability may be ensured if the nonlinearity is confined to a sector of the form $f(\sigma)/\sigma > K$. A convenient graphical method of finding the lowest value of K consistent with the Popov criterion has been found.

M. S. Davies

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[5] J. K. Aggarwal and E. K. Jackson: Univ. of Texas, Bureau of Eng. Research; Techn. Report No. 6.

5. PLATO

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5.1 Introduction†

The purpose of the PLATO project has been to develop an automatic computer-controlled teaching system of sufficient flexibility to permit experimental evaluation of a large variety of ideas in automatic instruction including simultaneous tutoring of a large number of students in a variety of subjects. The PLATO system differs from most teaching systems in that the power of a large digital computer is available to teach each student, since one such computer controls all student stations. The project work has fallen into three categories, no two of which are wholly separate from each other: (1) development of the tools for research; (2) provision of a prototype for multi-student teaching machines; (3) learning and teaching research. Under the first category has come the development of three successive versions of the PLATO equipment with PLATO IV, which includes an audio facility, now under construction. The twenty-student-station classroom provides the prototype for multi-student teaching machines mentioned in the second category.

†Portions of this work were supported by the Advanced Research Project Agency through the Office of Naval Research under Contract Nonr - 3985(08).

The learning and teaching research, the third area of PLATO research, has covered curriculum studies, college teaching, and behavioral science research. Cooperative work with the University of Illinois Committee on School Mathematics is now in its fourth year. Professor W. E. Montague of the Department of Psychology is a half-time member of the PLATO group and is directing two behavioral-science studies. Cooperative work with three university departments (electrical engineering, library science, and business administration) has resulted in three credit courses offered this semester. Other interactions of the PLATO group with various disciplines at the University have suggested experiments and studies in negotiation (Guetzkow), health education (Creswell), evaluation of teaching materials in many fields (SIRA), language analysis (Myers), comparative psycholinguistics (Osgood), and many other areas. The demands on the PLATO staff and the computer facility have resulted in the gift of the use of a 1604 computer from the Control Data Corporation which will be installed by January 1, 1966, and which will be for the sole use of PLATO research.

The plasma display discharge tube research, another important part of research in category one, is offering definite promise for the possibility of a less expensive PLATO display. Small display holes of approximately ten-thousandths of an inch in diameter have been constructed and tested. The light from these holes was sufficiently bright to be clearly visible in a lighted room. It was shown that the display spot can be turned on, erased, or read, to see if it is on or off, all within two microseconds. The light emitted from the hole occurs in bright pulses, each of which lasts less than twenty nanoseconds.

5.2 PLATO III System Equipment

During this quarter work continued in the development and construction of circuitry required for the realization of a 20-station teaching system.

Student-station circuitry constructed to date includes all that required for the full operation of 10 student stations. Construction of the remaining to complete the 20-station system continues and is expected to be complete and ready for installation and check out during January 1966. Check out is expected to be accomplished before the beginning of the spring semester (February 9, 1966). Included in the soon-to-be-completed equipment will be transistor deflection circuitry that will feature reliability and efficiency with respect to presently used vacuum-tube types, and compatibility with respect to presently-used deflection yokes and power-supply components.

Developmental circuitry required to update the present system or to provide new system facilities continues to be under study. Included are transistor deflection circuits that will replace vacuum-tube types operating in existing flying-spot scanner equipment, and audio storage to provide for random-access audio readout capability for all student stations in the PLATO system.

B. Voth

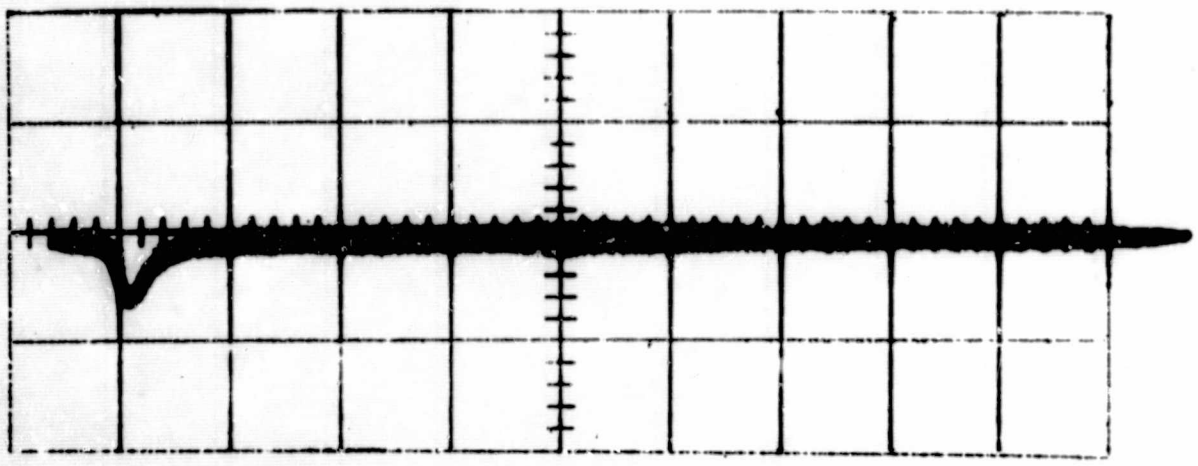
5.3 Plasma Display Discharge Tube

A rectangular array of gas-discharge cells can, in principle, provide a simple, effective display for the PLATO teaching system, and for the many other multiple-access systems now under development. These

cells provide adequate light, they can be separately addressed, and because the firing voltage can be made larger than the sustaining voltage they possess a memory. Unfortunately, when many cells are fired to form a pattern, the discharges can couple the selecting electrodes together in a way that makes addressing of the cells ambiguous.

At CSL, the direction of research on this device stems from the idea that if these electrodes are separated from the gas discharges by glass walls, the discharges can still be controlled by alternating voltages, but they will be isolated from each other by the capacitive reactances through the glass. With this arrangement, however, the behavior of each gas cell is entirely different from that of a direct-current discharge. In an efficient discharge, transfer of charge to the walls rapidly reduces the exciting field and completely extinguishes the discharge. Figure 5.1 shows, for example, that in a neon-nitrogen gas the discharge extinguishes only 20×10^{-9} seconds after it begins. The upper trace shows the current pulse on a time scale of 50×10^{-9} seconds per division. The lower trace shows the same pulse superimposed on the displacement current, in this case, on a time scale of 0.5×10^{-6} seconds per division. The driving signal in each case is a sinusoidal voltage with a frequency of 100 kHz. Although the duty cycle for light output is only 1/250, the discharge provides enough light for the display.

The memory in these cells actually resides in the charges which remain on the wall from pulse to pulse. To ignite a cell with wall charges, the driver need apply a voltage that may be as small as one-half the voltage needed to fire the cell in the absence of the wall charges.

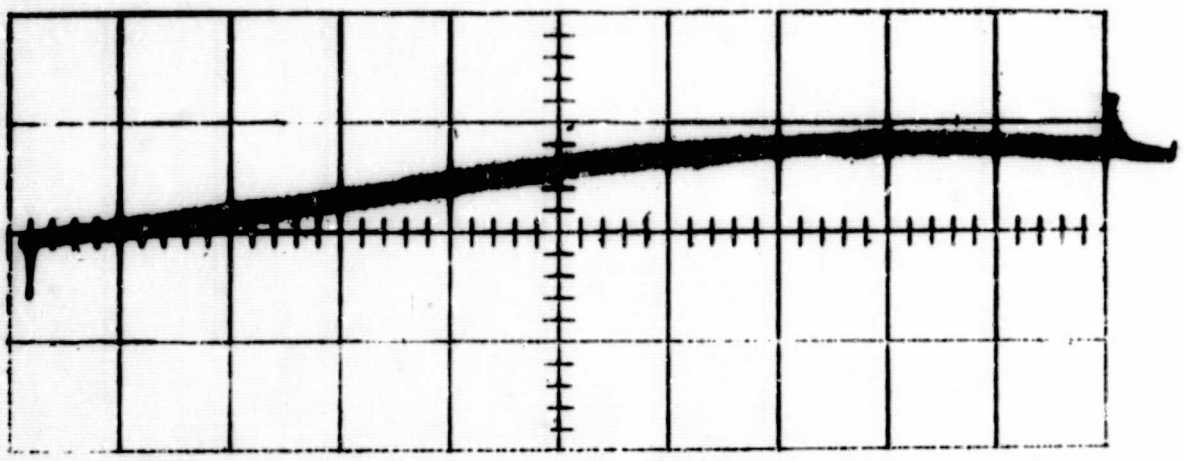


Amplitude Scale

10^{-3} amps/div

Time Scale

50×10^{-9} seconds/div



Amplitude Scale

10^{-3} amps/div

Time Scale

0.5×10^{-6} seconds/div

Fig. 5.1. Discharge Current in the Gas Discharge Display Cell.

Unlike the dc discharge whose "memory" is inherent in the distribution of charged particles in the volume, the discharge functions simply as a switch to transfer charge to the cell walls.

Fig. 5.2 shows an equivalent circuit in which C is the capacitance across the unfired cell, C_1 is the capacitance between an electrode and the adjacent cell wall, and G is a spark gap which represents the discharge itself. With a signal V' between the electrodes A and B, the voltage across C consists of two components, a voltage V_d proportional to V', and a voltage V_o proportional to the charge Q on the cell walls. More precisely

$$V' = V_d + V_o \quad ,$$

$$V_d = C_1 V/(C_1+2C) \quad ,$$

and

$$V_o = Q/C \quad .$$

Whenever the gas breaks down, charge flows to the walls to change V_o. Between firings, however, the cell "remembers" the value of V_o.

To initiate a discharge, V must exceed the firing voltage V_f. When the cell walls are uncharged, the external signal must supply the entire voltage and V_d must exceed V_f. With charged walls, however, the external signal need supply only the difference between V_f and V_o.

Assume now that the amplitude of the sinusoidal sustaining voltage is such that V_d does not exceed the firing voltage V_f.

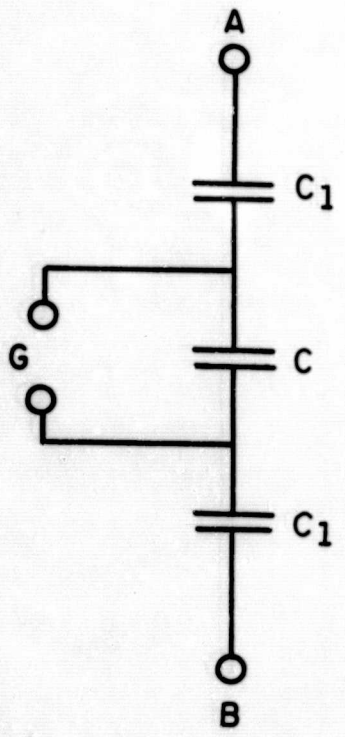


Fig. 5.2. Equivalent Circuit of Gas Discharge Display Cell.

In the "0" state $V_o = 0$ and, since V_d never exceeds V_f, the cell cannot fire. No charge is transferred and the cell remains in the zero state. In the "1" state, on the other hand, the cell fires when V_d just exceeds (V_f-V_o). In this case, V_o is equal to one-half the voltage change V_c produced by the transfer of charge,

$$V_o = \tfrac{1}{2}V_c.$$

After the discharge

$$V_o = -\tfrac{1}{2}V_c.$$

On the negative excursion of V_d the cell fires again when $V_o=-(V_f-V_o)$. The charge transfer this time restores V_o to its original value, and the cell remains in the "1" state.

R. H. Willson
H. G. Slottow
D. L. Bitzer

5.4 PLATO Learning and Teaching Research

5.4.1 University Courses

5.4.1.1 Electrical Engineering 322 - Circuit Analysis. The PLATO EE 322 teaching sequence described in a previous report is being used during the fall semester, 1965-1966, to supplement a regular class section of EE 322. Selected students receive instruction on the PLATO system during one class period each week. The lesson material presented by the teaching sequence parallels that material which the student would have received in class. The responses of the group are being used to improve the EE 322 teaching sequence and to acquire some indication of the effectiveness of the existing lesson sets. Much of the information gained will also be used to aid in the preparation of a lesson sequence

on circuit analysis to be presented to a class section in the spring semester of 1965-1966. The proposed lesson sequence will be combined with various testing procedures so that comparative data on two types of teaching logic can be obtained.

The group presently receiving instruction consists of nine volunteer students. These students attend one PLATO teaching session per week but remain as participants in the regular class section (i.e., the PLATO students take the same exams and receive the same assignments as the rest of the class). The student responses are recorded and are analyzed to gain information concerning lesson length, lesson errors, student progress, participation, etc.

R. L. Johnson

5.4.1.2 FORTRAN Programming for Business Students. During the current semester, nine students are being processed using the logic for teaching FORTRAN computer language developed during the summer of 1965. These students are also being given traditional classroom lectures dealing with the rules of the FORTRAN II language. A similar group receives only the traditional lectures. Comparative measurements are being obtained with respect to (1) the ability of the students to identify incorrect statements, (2) the ability to compose correct statements, and (3) the average number of attempts made by the students before their programs run successfully.

Plans are being made for two modifications in the project. One modification will allow for the fact that students make more keying errors as they proceed through the lessons. The errors have been traced

to a difference betwen the PLATO keyset and the ordinary keypunch keyboard which is being used simultaneously for the preparation of programs. The other modification will involve the incorporation of on-line compilation capabilities into the PLATO logic. This will provide immediate feedback to the student regarding the grammatical validity of the individual statements and the logical validity of the program as a whole.

M. Uretsky

5.4.1.3 Library Science 195. Since the beginning of the fall semester, twenty-five students have been enrolled in the course "Introduction to the Use of the Library" (L.S. 195) of which twelve have been taking the instruction on the PLATO system. To date, both the experimental and control groups have completed ten of the fourteen units which cover the entire course. A mid-term examination given to both groups revealed about the same results from each.

Each student has completed seven problem sheets, the answers to which were to be found by using the library facilities. No difference has been seen between the experimental and control group.

A final examination will be given at the end of the semester, and each student will be asked to fill out a rating sheet for the course. All data derived will be analyzed during the next semester.

M. Axeen

5.4.2 Mathematics Instructional Projects. Work is continuing on coding the latest versions of PROOF. ARITHDRILL is undergoing final debugging.

J. Gilpin
T. Smith
B. Wilson

5.4.3 Behavioral Science Projects

5.4.3.1 Retention of Conceptual Materials Research. Efforts have continued to be directed during this quarter to the investigation of variables affecting the retention of conceptual materials begun during the last quarter. Another study involving sixty subjects was completed concerning the retention of concepts over a one week period. These data are being analyzed. In addition, the basic program has been revised and made completely general. This provides considerable flexibility in examining the learning and retention of lists of verbal materials.

W. E. Montague
H. Smoker
A. Wearing
C. E. Webber

5.4.3.2 Man-Computer Interface Study. A study has been started concerning the man-computer interface. In tasks where the presentation time of learning materials is an important variable, students must type their responses on the typewriter within the time period provided. This requirement often produces errors which are not inherent in the difficulty of the learning material, or in miscalculations made by the student, but can be attributed to the organization of the input keyboard and the student's inexperience with it. Since it is preferable

not to have to select expert typists as students, information must be obtained regarding the error frequencies of inexpert typists inputting information to the computer. During this quarter a program has been written to instrument an experiment investigating these errors. Three groups of students will type letters, consonant-vowel-consonant syllables, and words; their error rates will be observed. Two of the groups will be given two different keyset configurations: the regular typewriter layout and an alphabetized keyboard. These groups will be compared to reveal the effect of layout on the errors, and any difference may indicate which layout provides superior performance for relatively inexpert students. These groups will also be compared to a control group in which students merely print their responses on paper. This comparison allows the assessment of errors produced by the keyset requirements. At best, the study is exploratory, and further work is necessary to optimize keyset design which will minimize data entry errors and maximize entry speed.

W. E. Montague
H. W. Smoker
A. Wearing
C. E. Webber

5.4.3.3 A Language-Free Test of Interpersonal Norms. One of the two additional research groups outside the Coordinated Science Laboratory, which have started to prepare PLATO programs to carry out research in cooperation with the PLATO groups, is headed by Professor Charles Osgood of the Department of Psychology and the Institute of Communications Research. Professor Osgood and his coworkers will use

PLATO in experimental production and testing of symbolic animated films, designed for a language-free test of interpersonal norms. Programming for the first animation trials is in progress.

B. L. Hicks

5.4.3.4 Inter-nation Simulation Studies. The second new research project cooperating with the PLATO group is an Inter-nation Simulation Study. Professor Harold Guetzkow and his coworkers of Northwestern University will enlarge the scope of their Inter-nation Simulation Studies by using the PLATO system. Initial meetings have been held to plan the overall strategy using the PLATO classroom as the communication center for a six-nation negotiation study and to outline flow diagrams for the logic of the program.

B. L. Hicks

5.4.3.5 Other Potential Uses in Behavioral Science Research. The potential uses in survey research and in studies of industry-labor bargaining and negotiation have been outlined in PLATO memos for files.

B. L. Hicks

5.4.4 Project SIRA (System for Instructional Response Analysis). A preliminary design has been drawn up for a language permitting retrieval of instructional responses and instructional response information. Programming this language is expected to begin shortly. Explorations are underway in the adaptation of the PLATO system (with a retrieval language) to author-evaluator search behavior. Investigations are also being made

into a storage format which will permit faster retrieval time than does the existing dope tape.

The TEXT-TESTER logic has been completed, but new problems have been encountered in adapting it to serve the BRAILLE logic which may require major reprogramming. TEXT DOPE, a simple retrieval program that works from the existing dope tape, is nearing completion and will be tried soon with lessons controlled by TEXT-TESTER.

J. Easley, Jr.
W. Golden
T. Hastings
B. Hicks
J. Kraatz
R. Stake
B. Wilson

5.5 PLATO Seminars

The PLATO group has held a series of weekly seminars this fall. The topics have been those pertinent to the research in progress with the PLATO system. The seminars have been given in conference rooms in the Illini Union and have included on-line demonstrations of PLATO programs using the PLATO remote-station facility. The seminars presented during this quarter were:

"The Nature of Present and Future PLATO System Equipments," Mr. Brian Voth, Research Engineer, Coordinated Science Laboratory.

"Use of PLATO for Verbal Learning and Memory Experiments," Professor William E. Montague, Assistant Professor of Psychology.

"SIRA, System for Instructional Response Analysis," Professor J. A. Easley, Jr., Associate Professor of Education, Research Director, University of Illinois Committee on School Mathematics.

"A Possible Solution to Remote Storage and Display Problems," Dr. H. G. Slottow, Senior Research Engineer, Coordinated Science Laboratory; and Dr. D. L. Bitzer, Director, PLATO Project, Coordinated Science Laboratory.

"The Use of PLATO in the Course on 'Computer Programming' for Students of Business and Commerce," Professor M. Uretsky, Assistant Professor of Accountancy.

"A PLATO Program Designed to Optimize Paired Associates Learning in Humans; The Current Subject Matter: Arithmetic Number Pairs," Mr. John Gilpin, Research Associate in Education, University of Illinois Committee on School Mathematics.

"CIRCE - What is it and its Relation to PLATO?" Professor Thomas Hastings, Director of CIRCE (Center for Instructional Research and Curriculum Evaluation), Professor of Education.

E. R. Lyman

5.6 PLATO Demonstrations.

The PLATO system has been demonstrated this year to many visitors: technical, lay, interested colleagues, teachers, etc. Groups varying from two to a thousand people have been shown the system. The large groups, such as the University of Illinois Foundation members, or the members of the Illinois Junior Academy of Science, have been handled in large auditoriums by the remote PLATO student station using data transmitted over telephone lines. Remote demonstrations have been given at many places on the University of Illinois campus and as far away as the Congress-Circle campus in Chicago. As of December 1, 1965, eighty demonstrations had been presented in 1965 in contrast to twenty nine in 1964, and nineteen in 1963.

E. R. Lyman

6. VACUUM INSTRUMENTATION

F. Propst D. Alpert F. Steinrisser

6.1 Pumping Speed of Getter-Ion Pumps[†]

Measurements of the pumping speeds and discharge currents of a diode and a triode getter-ion pump have continued. Measurements with N_2 have been finished for both pumps, and with H_2 for the diode pump. The pressure varied from 3×10^{-7} to 1×10^{-10} Torr. Earlier measurements have been confirmed, and no unexpected results were found. The variation of discharge current, I, as a function of pressure, P, was measured with the diode pump. The pressure range was 3×10^{-7} to 2×10^{-12} Torr for the gases He and N_2. Below a certain pressure (10^{-8} to 10^{-9} Torr), which depends upon the gas, the quantity I/P deviates from a constant and follows a power law: $I = cp^n$, $n>1$. This was also observed by Redhead[1] for magnetron gauges.

During one of the pumping-speed measurements, a large increase in pump current was observed. The current saturated at about 10μA, when the pump was running with N_2 at a pressure of 5×10^{-10} Torr. With the pump magnet removed and varying the pump voltage, the current was found to obey the Fowler-Nordheim relation, i.e., we were observing field emission. To remove the whiskers responsible for field-emission currents, a high voltage (25 kV instead of the normal 7 kV) had to be applied with

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[†]Portions of this work were supported by the National Aeronautics and Space Administration under Grant NsG 376.

[1]P. A. Redhead, Can. J. Phys., 37, 1260 (1959).

the magnet still removed. In addition, the presence of gas at a pressure of 10^{-5} to 10^{-6} Torr was necessary to reduce the field-emission currents at 7kV to below 10^{-10} A.

6.2 Processing of UHV Systems[†]

Work described previously[2] was continued. One vacuum system was used to study the dependence of H_2, He, and CO partial pressures upon the processing method. A similar system was used to study CO production after O_2 admission into the system, and as a function of the processing method. Both systems were equipped with a GE magnetic deflection type mass spectrometer. Although the measurements are not yet finished, the following conclusions can be drawn:

1. By processing an UHV system with a valve between the system and trap, as described in (2), the lowest pressures obtainable are in the low 10^{-12} Torr range. This is about 10 times lower than pressures obtained previously without a valve and appropriate procedure.
2. When a system and its trap are baked at the same time, the main residual gas is H_2. The evolution of H_2 is substantially decreased if hot-filament ionization gauges are switched off. This also reduces the He influx considerably.
3. CO production under admission of O_2 is much smaller in systems where a valve separates trap and system during bakeout.

[†]Portions of this work were supported by the National Aeronautics and Space Administration under Grant NsG 376.

[2]Progress Report, March-April-May, 1965.

7. PLASMA PHYSICS

M. Raether
H. Bohmer
W. Carr
J. Chang
W. Bernhard
B. Hicks
R. Hosken
Y. Ichikawa
T. Lie
R. Huggins
C. Mendel
K. Saul
H. G. Slottow
M. A. Smith

7.1 Boltzmann Equation

The study of Monte-Carlo errors in the evaluation of the Boltzmann collision integral has been completed and was reported in CSL Report I-131. A large part of the systematic error appears to be due to quadrature error and amounts to about 1 percent. The random errors are reduced, as Nordsieck originally predicted, because of correlation of the errors of the two parts of the collision integral, the reduction being by a factor of five. The random error, for a sample size of 44,000, is 2 percent.

During the past quarter, several new calculations have been planned, some of which will be described at the International Gas-Dynamics Symposium in July 1966 in London. One set of calculations will extend our tests of velocity distribution functions to include not only tests of Mott-Smith functions for shock waves but also tests of Yen's functions that have been derived by moment methods. These tests are possible only because of the development in CSL of Nordsieck's Monte-Carlo method of evaluating the collision integral. Other new calculations visualized are: correction of the Monte-Carlo estimates of the collision integral by the use of three rather than two conserved moments (see CSL Report R-236); and solution of the Boltzmann equation for the relaxation

of a gas whose initial velocity-distribution function has an asymmetric bimodal shape rather than the symmetric shape studied in R-236.

In preparation for these new calculations, it is appropriate to update the control parameters and the input-output sections of the computer program. A more flexible output is being programmed which will be easier to modify in the future as the use of the program changes.

B. Hicks

7.2 The Linear Plasma Betatron

The linear plasma betatron has given a considerable amount of data in the last period. It has been found that the peak runaway current drops rapidly with increased pressure, but does not seem to depend on the applied electric field. (Fig. 7.1)

The conduction current near the axis of the discharge levels-off a short time after conduction begins, to a value too small to be explained by ion-electron collisions. (Fig. 7.2) The resistivity of 0.02 ohm-cm would indicate an electron temperature of 2 eV, which we expect is too small by an order of magnitude. This leveling off occurs about the same time the runaway stops and large high-frequency oscillations are found.

Electric-probe measurements will be tried shortly to investigate the conduction further.

C. Mendel

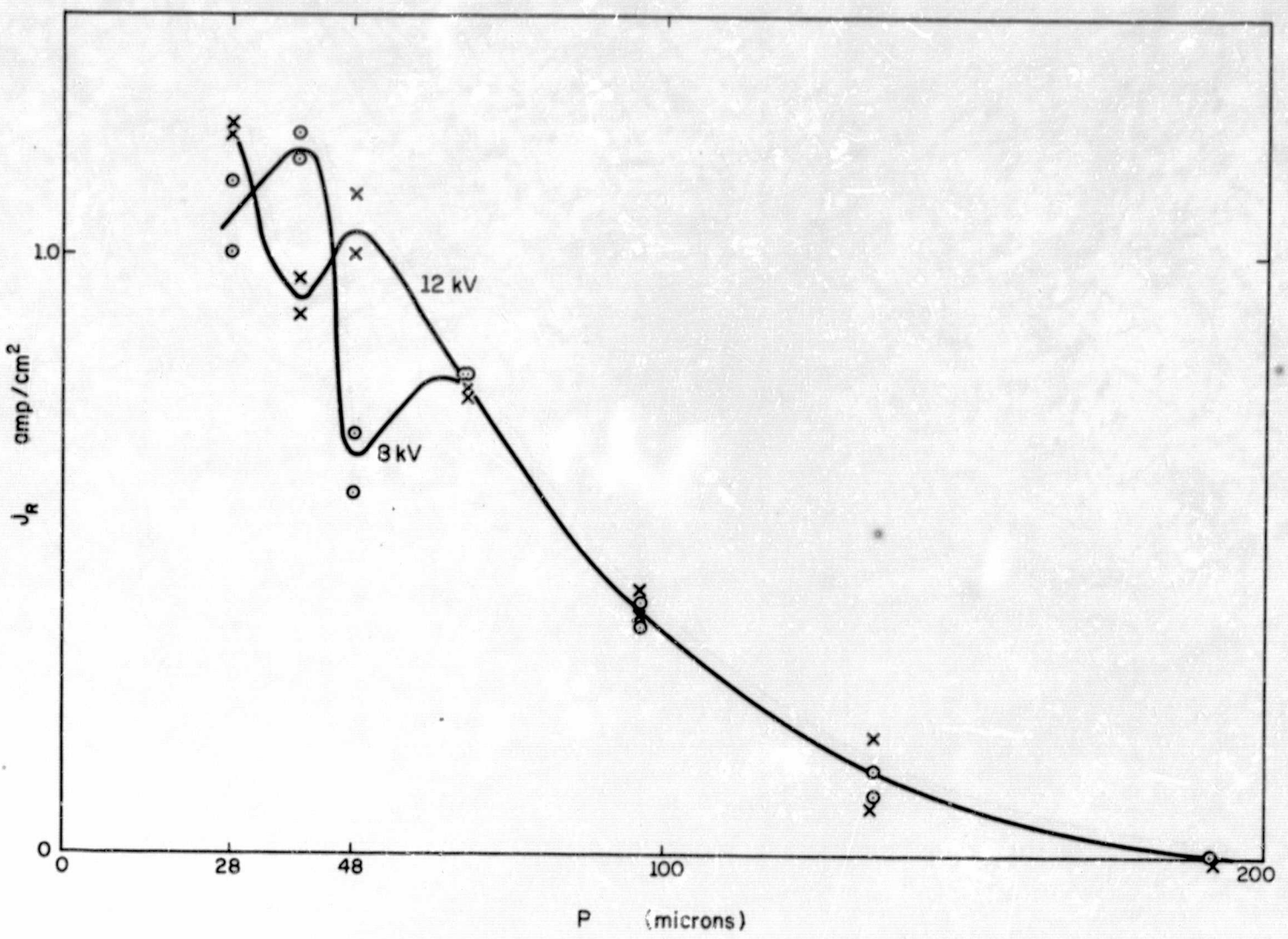


Fig. 7.1. Run-away Current versus Pressure.

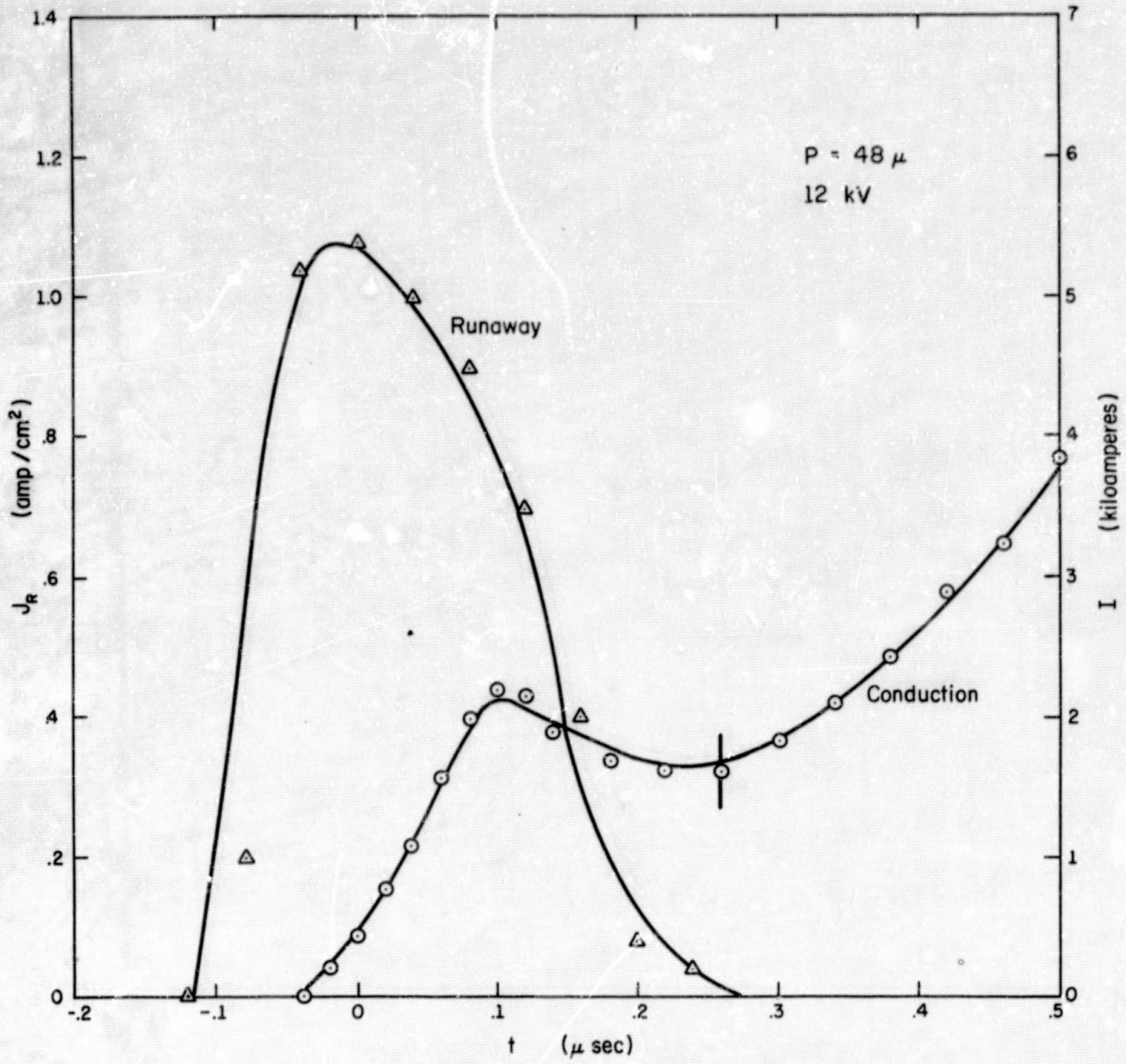


Fig. 7.2. Run-away and Conduction Current versus Time.

7.3 Landau Damping in an Inhomogeneous Plasma

Collisionless or Landau damping of logitudinal electron waves in a finite temperature (warm) plasma was predicted by Landau[1] from his solutions of the Vlasov equation, but it is only recently that collisionless damping has been deomonstrated experimentally. Since 1962, several workers have demonstrated Landau damping[2], the most recent being that of Malmberg, Wharton and Drummond[3] who deomonstrate damping of an electrostatic electron wave in a cylindrical plasma column immersed in an axial magnetic field, and Grimes[4] (1965) who demonstrates Landau damping of helicon waves in a solid state plasma. Recently, Jackson and Raether[5] have calculated the collisionless damping rate in Tonks-Dattner resonances in a one-dimensional inhomogeneous plasma state, and it appears that experimental verification should not be difficult. Work has been proceeding for three months on this project, and, although no quantitative verification has yet been shown, qualitative verification has been demonstrated.

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[1] L. D. Landau, J. Phys. (U.S.S.R.) 10, 25 (1946).

[2] Caulton, Herstenov, and Paschke, J. Appl. Phys. 33, 800 (1962); Stover, and Kino, Bull. Am. Phys. Soc. 9 336, (1964); Hirshfield and Dennis, Proceedings of the Sixth International Conference on Ionization Phenomena in Gasses, 1963, Dolgapolov et. al., Soviet Phys., J.E.T.P. 18, 866 (1964); Wong, Motley and D'Angelo, Phys. Rev. 133, A436 (1964).

[3] Malmberg, Wharton and Drummond, to be published.

[4] Grimes, 7th Annual Meeting of the Plasma Physics Division of the American Physical Soc. (1965).

[5] Jackson and Raether, C.S.L. Report R-239.

7.3.1 Experimental Conditions for the Observation of Landau Damping. The experimental conditions must first confirm the assumptions made by Landau when formulating his theory. These assumptions were: the electron collision frequency with either neutral atoms or ions should be small and not contribute to the damping, the ratio of the Debye length to the plasma container dimensions should be small, and the electron velocity-distribution function is Maxwellian. In addition, the theory of Jackson and Raether requires the plasma to be inhomogeneous, and the ratio of plasma diameter to Debye length $L/\lambda D$ should be smaller than 200. As well as conforming to the above conditions, it should be possible to vary the electron temperature and hence the Debye length, and also to measure both the electron temperature and density. Such an experiment has been devised and will be described together with preliminary results in this report.

7.3.2 Experimental Apparatus. Tonks-Dattner resonances have been observed in both dc discharges[6] and pulsed discharge afterglows[7]. A pulsed-discharge afterglow was chosen in preference to a dc discharge because the electron density varies approximately exponentially with time (a diffusion-controlled plasma) and it is relatively easy to vary the electron temperature without seriously affecting the electron density. In a dc discharge, the electron density can be varied quite easily, but

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[6] Dattner, A., The Plasma Resonator, Ericsson Technics 13, 309 (1957).

[7] Schmitt, Meltz, and Freyheit, Phys. Rev. 139, A1432 (1965).

the temperature can be varied only by changing the pressure and/or the tube diameter. It should, however, be pointed out that much higher temperatures are attainable in a dc discharge.

In this experiment, the gas used is neon on account of the low electron-neutral collision frequency. The Tonks-Dattner resonances are observed by passing the discharge tube through a waveguide parallel to the long dimension, and perpendicular to the direction of energy propagation (the E field vector is normal to the tube axis). The discharge is pulsed, and, at the same time, the time base of an oscilloscope which displays either the power transmitted by the waveguide or the power reflected by the discharge, is triggered. The waveguide used is L band ($6\frac{1}{2}$"X$3\frac{1}{4}$"), with a microwave frequency between 1,000-1,600 MHz. The frequency used is fixed by the highest electron density that can be tolerated; the first resonance occurs when $(\omega p/\omega)^2 \approx 2$ or when the electron density is $n \approx 2 \times 10^{10}$ cm^{-3}. At densities much higher than this, the damping due to electron-ion (coulomb) collisions[8] becomes comparable to the estimated Landau damping, which in turn is reduced by the increase of the ratio of the plasma container dimensions to the Debye length. The highest frequency that can be used is therefore indirectly fixed by the plasma diameter.

A block diagram of the apparatus is shown in Fig. 7.3. To facilitate the simultaneous measurement of either the electron temperature or density with the observation of the resonances, two identical tubes,

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[8] Chen, C. L., Phys. Rev. 135, A627 (1964).

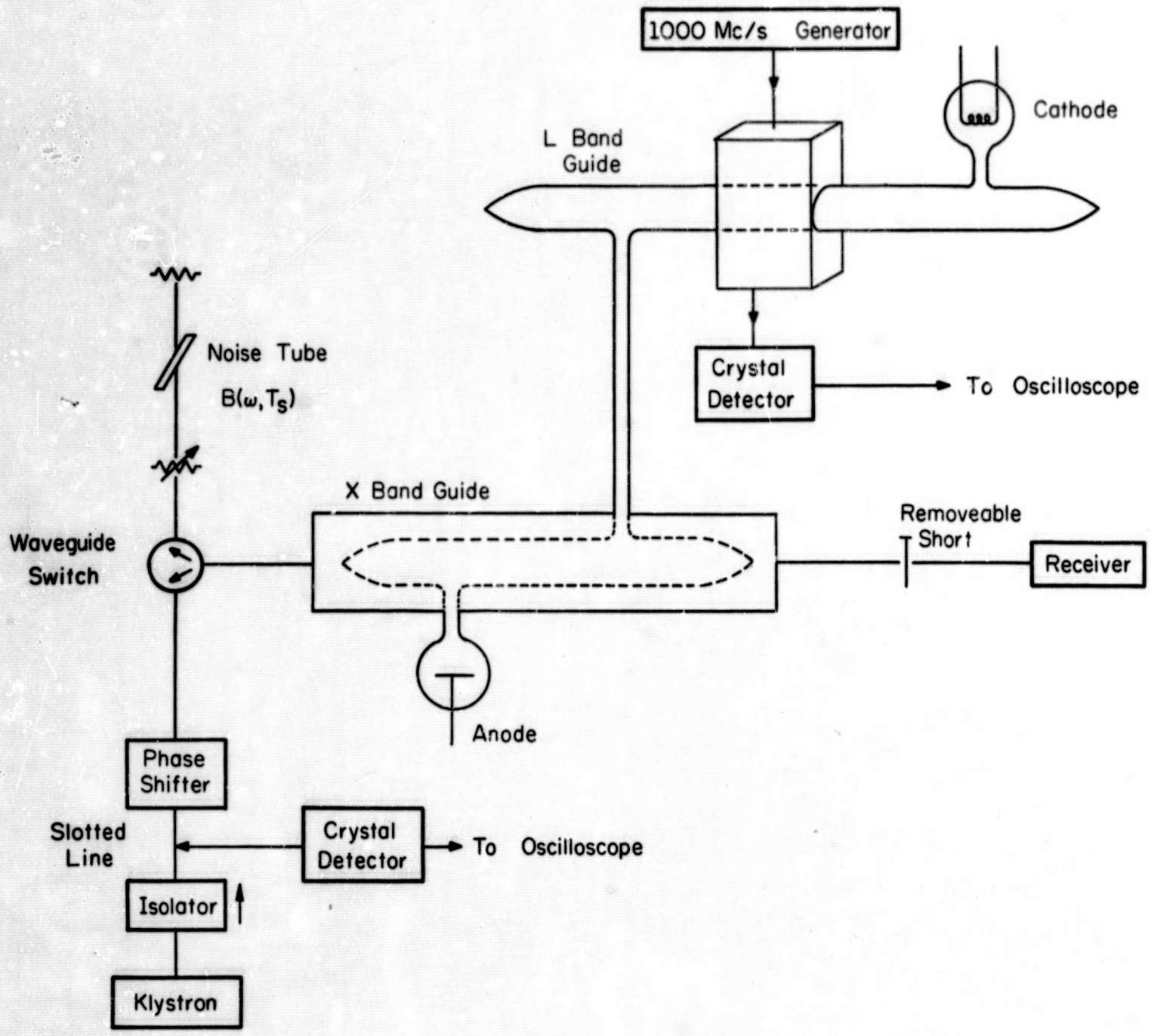


Figure 1 Diagram of the Apparatus

Fig. 7.3 Block Diagram of the Experiment.

one connected to a heated cathode, and the other to an anode, are connected in series by a small tube. During the active discharge, the positive column fills both tubes, and the afterglows may therefore be assumed to be identical. One tube is located in an X-band waveguide and the other passes through the L-band waveguide. The X-band waveguide can be connected either to a reflection interferometer for the electron-density measurement, or to a receiver and noise tube for temperature measurement. In the electron-density measurement, the microwave signal passes through the plasma twice, once before, and once after reflection by the short, and sets up a standing wave which is detected by a slotted line. The phase shifter is initially set for 0^{o} phase shift and the slotted line adjusted for a minimum. Phase shifts of less than 90^{o} resulting from one transveral through the plasma can be compensated for by the phase shifter and the phase shift read off directly. For larger phase shifts, the integral number of π phase shifts per double traversal must first be counted. When the Tonks-Dattner resonances occur at phase shifts greater than π, the cw interference pattern is displayed on the oscilloscope together with the Tonks-Dattner resonances and the two signals photographed. The positions of the maxima and minima in time are then plotted against the corresponding electron density and the width and position of the resonances can easily be found. If information about the electron density corresponding to less than one interference peak or total phase shift of less than π is required, the klystron is pulsed at a variable time in the afterglow, and the phase shift adjusted to minimize the pulsed

signal. The calculation of the electron density from the phase shift is discussed elsewhere[9] and will not be described.

When the electron temperature is too measured, the short is removed, and the klystron and phase shifter replaced by a noise tube and attenuator. Time resolution of the temperature is obtained by an extension of the method described by Bekefi and Brown[10] and is as follows: The receiver first samples the blackbody radiation at some time in the afterglow from the plasma, when it is being illuminated by blackbody radiation of known temperature T_s' from the noise tube. After the plasma has completely decayed, the radiation from the noise tube is again sampled. If the emission from the plasma is $B(\omega,T_x)$ where T_x is the plasma temperature, and a fraction A_ω (the absorptivity of the plasma) of the emission from the noise tube $B(\omega,T_s')$ is absorbed by the plasma, then the total noise power observed by the receiver is

$$P_T = (1-A_\omega)B(\omega_1 T_s') + A_\omega B(\omega_1 T_x)$$

The power from the noise tube alone observed by the receiver is $P_R=B(\omega_1 T_s)$. If the two powers are compared and T_s' adjusted until they are equal, then

$$P_R = P_T \text{ or } B(\omega_1 T_s) = (1-A_\omega)B(\omega_1 T_s') + A_\omega B(\omega_1 T_x)$$

$$\text{or } B(\omega_1 T_s) = B(\omega_1 T_x) \text{ and } T_s' = T_x.$$

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[9] L. Goldstein, Advances in Electronics and Electron Physics, Acad. Press (New York) Vol. 17, (1955) 399.

[10] Bekefi and Brown, J. Appl. Phys. 32, 25 (1961).

irrespective of the value of the absorptivity of the plasma. In practice, the temperature of the noise source is varied by changing the attenuator which also radiates noise power and for which a correction must be applied. The final expression for plasma temperature is

$$T_x = \alpha T_s [1-(1-\alpha)T_o/\alpha T_s](1+K)$$

where α is the fraction of the noise tube power transmitted by the attenuator, T_s is the specified noise temperature of the noise tube, T_o is the room temperature, and K is a constant which takes into account the energy loss between the attenuator and the plasma.

The instrumentation for the temperature measurement is shown in Fig. 7.4. The plasma is assumed to decay in less than half the time between discharge pulses and the receiver is gated on at twice the pulse repetition rate. A pulse from the master pulse generator (100 Hz) triggers a Tektronics 162 saw-tooth generator which turn triggers a Tektronics 163 pulse generator. The length of the output pulse from the latter unit is equal to half the repetition time and is a square wave. This square wave serves as a reference for the phase-sensitive detector; it is also differentiated, and the negative spike is inverted to give 200 positive pulses per second. A second Tectronics 163 unit shapes these pulses which then gate the receiver i.f. amplifier on. The sampling time (typically 10 μsec) is controlled by the second 163 unit, and the 162 and first 163 units serve as a variable-delay network. After integration and amplification, the receiver output is fed into the signal input of the phase-sensitive detector.

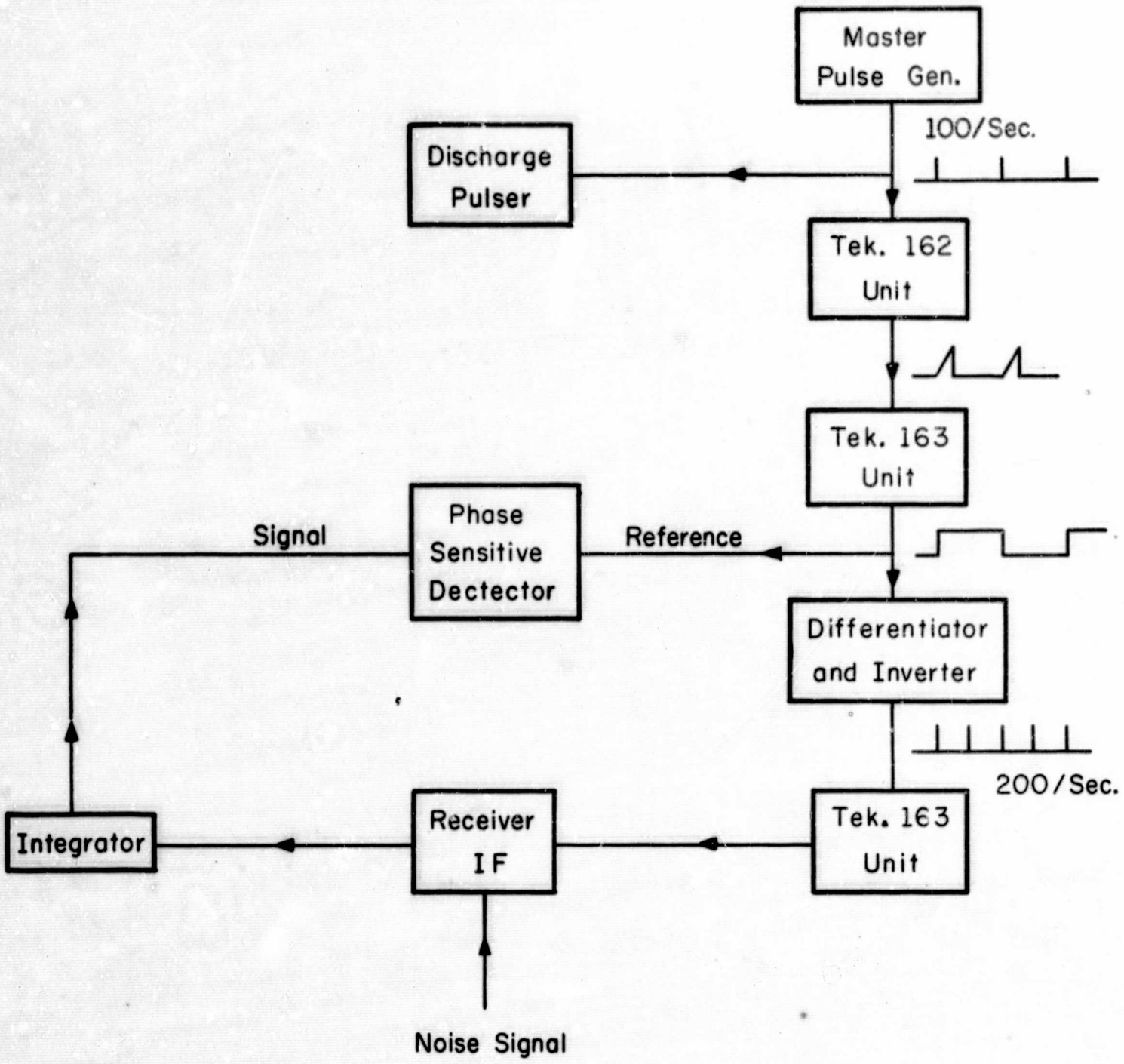


Fig. 7.4. Instrumentation for Noise Temperature Measurement.

If the two gated noise samples from the receiver are unequal, there will be a 100 Hz component in the signal and it will produce a deflection of the phase-sensitive detector. However if the two samples are equal, there will be no such component and a null reading will be observed. When the attenuator between the noise tube and the plasma is adjusted for a phase-sensitive-detector null reading, the two noise samples will be equal, and the plasma temperature may be found from the attenuation. The temperature as a function of time in the afterglow is measured by varying the delay time (up to 100 μsec) between the discharge pulse and the gating pulse. At high electron densities where the plasma frequency is comparable to the receiver, the plasma is 'black' and the accuracy of the measurement is of the order of $\pm$ 50°K. At lower electron densities, where the plasma is somewhat tenuous, the accuracy falls to $\pm$ 300°K.

7.3.3 Results. Preliminary results of a qualitative nature are shown in Fig. 7.5. For these resonance photographs, the afterglow temperature was progressively increased by increasing the discharge pulse length and therefore the number of metastable states. Metastable states in the afterglow can be lost by superelastic electron collisions which elevate the electron temperature for several hundred microseconds.

The heating of electrons by superelastic collisions is, however, somewhat unpredictable, and the validity of the assumption that the electron-distribution function is Maxwellian may be questioned. With this in mind, other forms of electron heating are under investigation; at present, a small percentage of hydrogen is being added to the neon

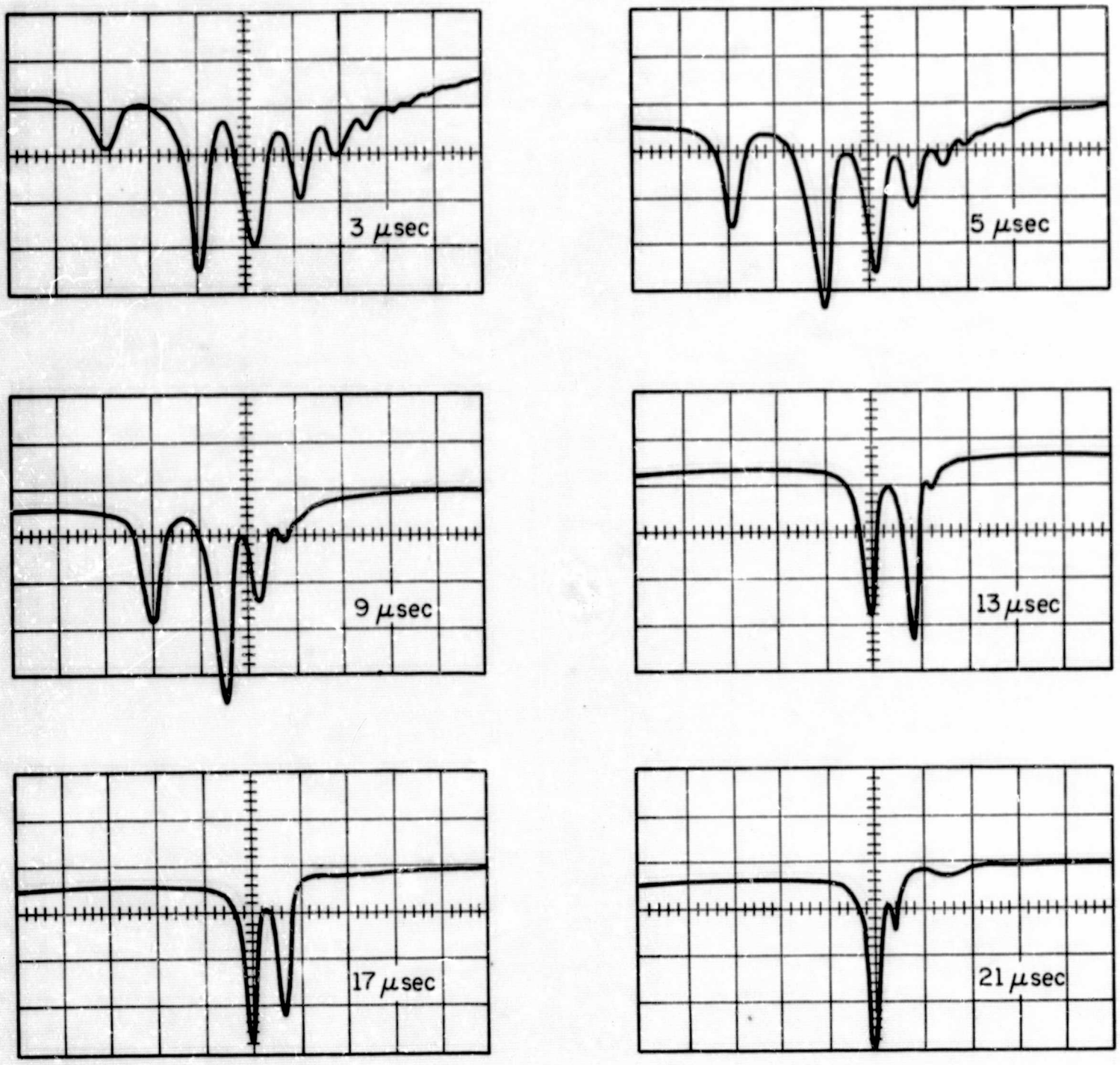


Fig. 7.5. Tonks-Dattner Resonances for Different Plasma Temperatures. Notice that the higher resonances, which are most sensitive to Landau damping, die out rapidly as the temperature increases.

to enhance metastable destruction and heating carried out either by superimposing a dc voltage across the discharge tube, or by microwave heating.

R. Huggins
M. Raether

7.4 Electron Beam-Plasma Interaction

During the period covered by this report (preliminary) measurements were performed on the system describe in the previous progress report. Specifically, the electron density in the neon-afterglow plasma and the noise radiation from the beam-plasma instability were measured.

Fig. 7.6 shows a block diagram of the 8mm microwave bridge constructed for the density measurements. With the 27GHz klystron on cw, the bridge could be balanced using the attenuator and choosing a minimum in the standing wave pattern of the slotted line. Insertion of a plasma between the microwave horns results in a phase shift of the microwaves and in a signal at the pickup probe of the slotted line. An oscilloscope display of the probe output versus time for a decaying plasma is shown in Fig. 7.7a. Counting from the zero phase shift at the right-hand side of the picture, the minima correspond to phase shifts of 2π, 4π, 6π. Knowing the length of the plasma the microwaves have to traverse, the average electron densities can be easily calculated. In order to get a more accurate measurement, the klystron was pulsed on for 2 μsec at various times after the plasma pulse and the phase shift was measured in fractions of the wavelength, using the slotted line. With this method, it is possible to measure the density over more than two orders of magnitude.

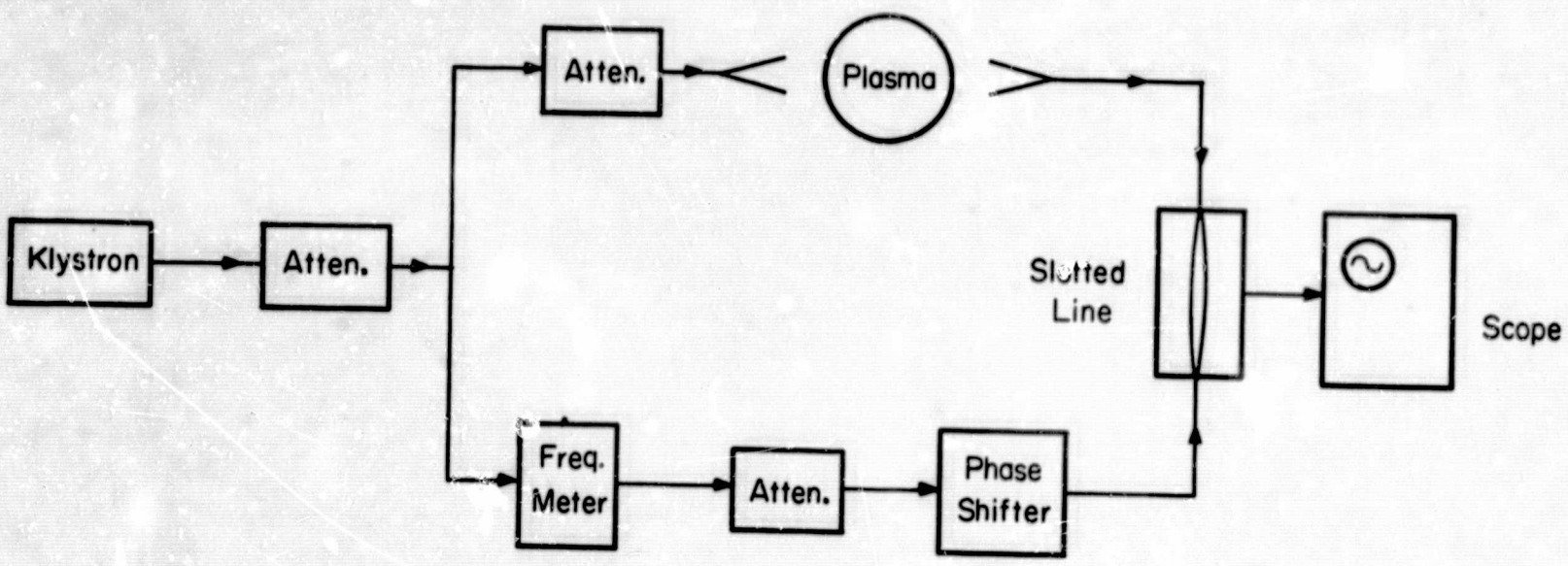
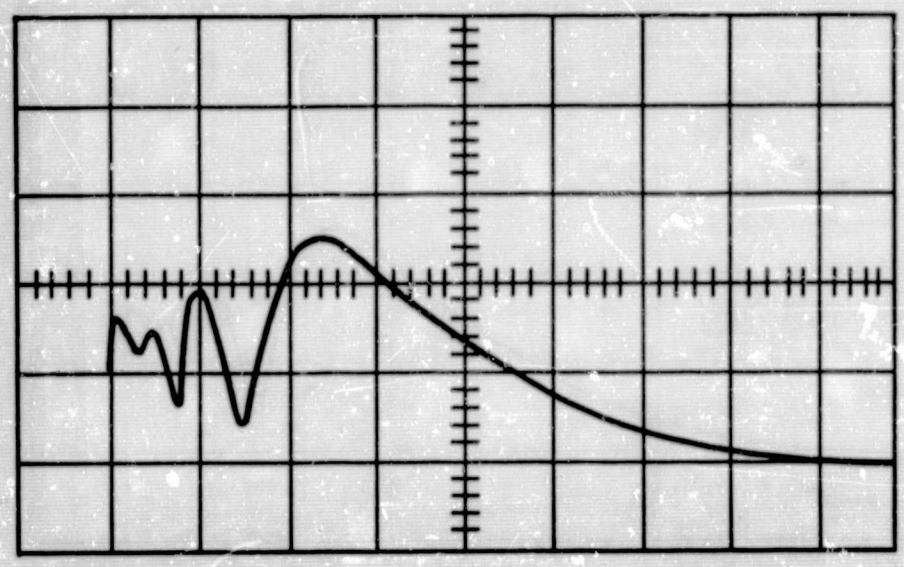


Fig. 7.6. 8 mm Microwave Interferometer for Plasma Electron Density Measurement.



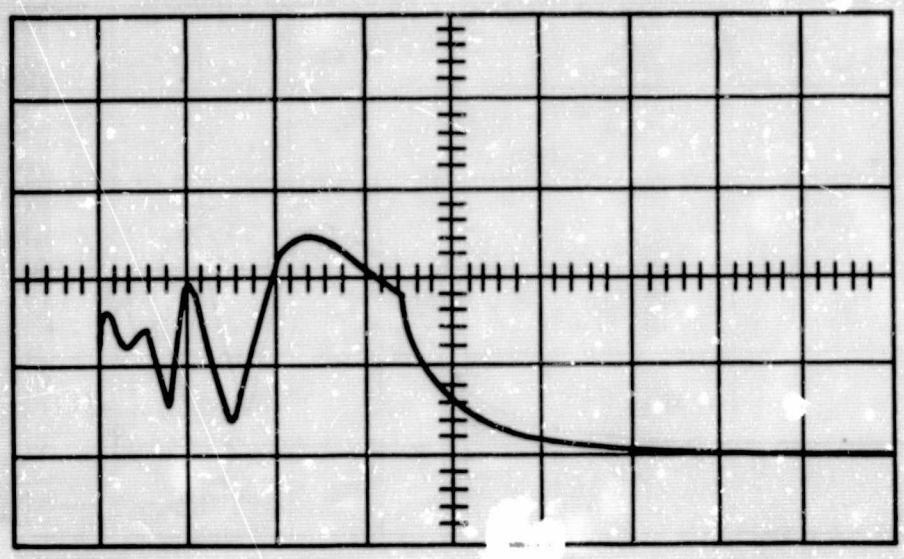


Fig. 7.7. a) Oscilloscope Display of Fringeshift Pattern, Time Base: 50 μsec/cm.

b) As Fig. 7.7 a), showing the Influence of the Beam on the Phaseshift.

Fig. 7.8 shows how the electron density depends on the decay time for three different gas pressures. Obviously, the plasma decays by two different modes, depending on the density range. At densities smaller than 10^{12} el/cm^3 the slope of the curves depends on the gas pressure. Therefore, the decay must be due to a diffusion to the walls, dominated by electron-neutral collisions. Above 2×10^{12} el/cm^3 the slope is independent on the gas pressure. Recombination is probably an important loss mechanism in this regime.

One would expect that a high-density electron beam would raise the electron density, because of direct collisions of beam electrons with neutrals. Besides, plasma electrons which gained energy above the thermal level from the beam-plasma instability could ionize further neutrals. Surprisingly, a sudden drop in the plasma density was observed. Fig. 7.7b shows an oscilloscope display of a "fringe-shift" pattern observed under the same conditions as the one in Fig. 7.7a, except that here at the time indicated by the arrow an electron beam of 400 mA, 21 keV, and 2 μsec duration was shot into the plasma. Apparently the phase shift and therefore the density goes more rapidly to zero than in Fig. 7.7a. From the slope of the oscilloscope trace, one can roughly calculate that the ratio of the diffusion coefficients, before and after the time the beam was shot in, is 1:7.

It is shown in the next section of this report, that under the conditions of Fig. 7.7b, the electron beam drives the plasma into a high-frequency instability. Therefore, the sudden rise in the diffusion coefficient is either due to anomalous diffusion, or is the result of randomization of the plasma oscillations, and subsequent heating of the plasma.

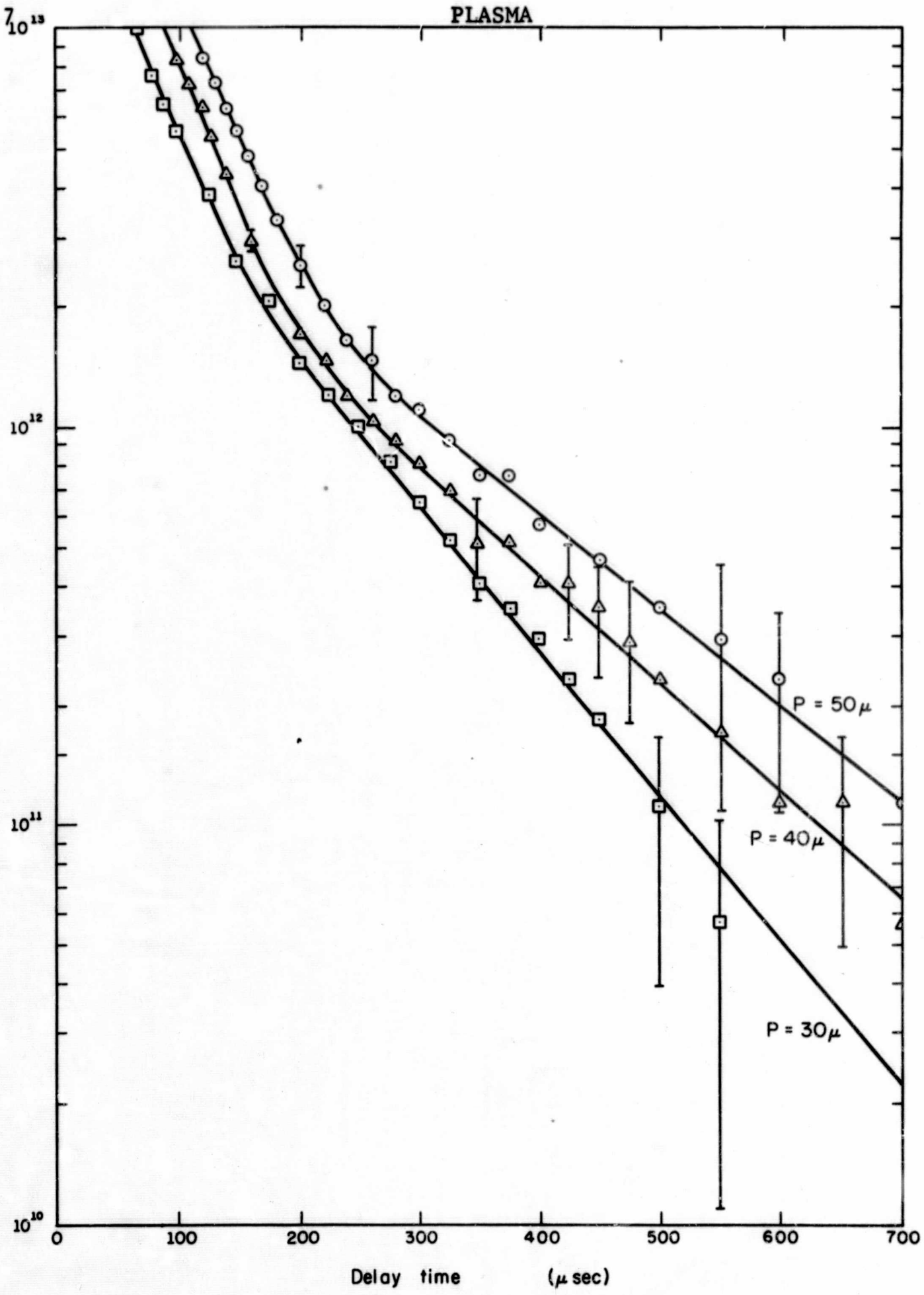


Fig. 7.8. Average Electron Density in the Afterglow for 3 Megawatt Pulse Power.

The first explanation appears to be more likely, because the change in the diffusion coefficient takes place within a few microseconds. In that case, we have an example for a weakly turbulent plasma and it might be possible to check some of the theories developed recently for weakly turbulent plasmas. We therefore intend now to study this effect more closely by time resolving the transition between the normal and abnormal diffusion and by varying parameters such as plasma density, beam current, and gas pressure.

The experimental setup described in Fig. 7.7 of the previous progress report was used to detect noise radiation from the beam-plasma instability and to perform a microwave scattering experiment. To this end, the linear gate was pulsed open during the time the electron beam tranversed the plasma, so that only microwave signals resulting from the beam-plasma interaction were detected. The output of the lock-in amplifier was fed into a x-y plotter. A voltage proportional to the time elapsing between the plasma and beam pulse was applied to the carriage of the plotter. In changing the delay time, one gets the noise radiation as a function of plasma density as shown in Fig. 7.9.

From the appearance, shape and abundance of the resonances one can draw the following conclusions:

a) The electron beam excites plasma oscillations.

b) The first large resonance occurs at a delay time of 270 μsec which corresponds to a plasma frequency at the center of the plasma tube of about 10kHz. Since the receiver was set on 10.150kHz, this resonance corresponds to a radiation at the plasma frequency.

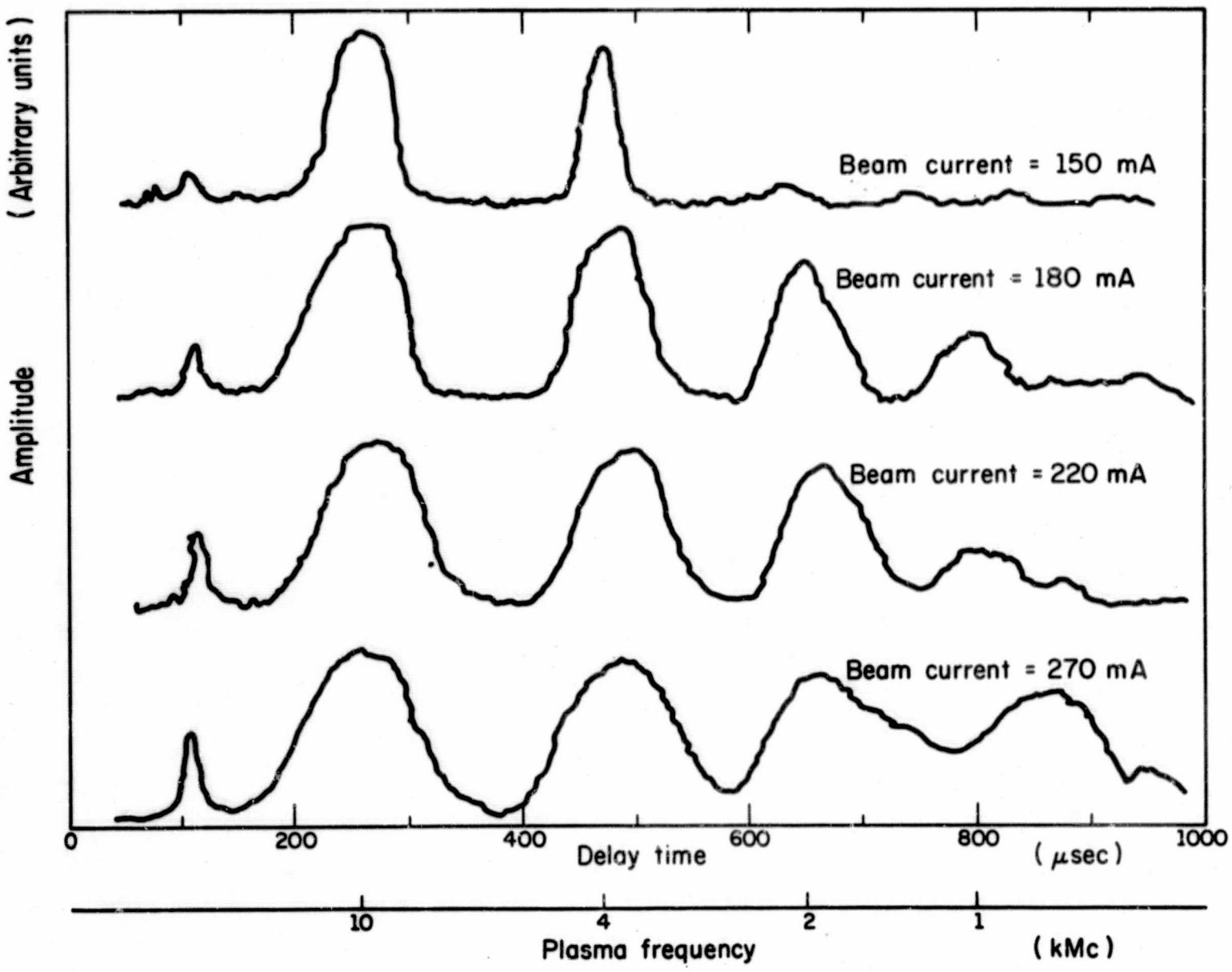


Fig. 7.9. Noise Radiation as a Function of Delay Time, Amplitude in Arbitrary, Nonlinear Units.

c) With increasing beam current, higher resonances appear and the lines broaden.

The origin of these resonances is not yet understood. In the case of Tongs-Dattner resonances, the fundamental resonance should occur at a much higher density. If the resonances were due to wave-wave coupling, then the plasma frequencies corresponding to the peaks should be multiples of the fundamental frequency, which is not the case.

Scattering of microwaves from the beam-plasma instability was not observed yet. In the present arrangement the plasma frequency must be 1.5kHz (density approximately 3×10^{10} el/cm^3) in order to be able to detect the scattering. At this density the number of scattering electrons is small, and the plasma is not very unstable compared with higher densities. Furthermore the high power microwaves have to couple to a small k vector, which again makes the detection of the scattering difficult. In order to make the experimental conditions more favorable, a K-band microwave receiver was constructed.

H. Böhmer

8. SUPERCONDUCTIVITY STUDIES

C. B. Satterthwaite
M. G. Craford
J. R. Carlson
B. K. Moore
I. Toepke
R. P. Ries
D. Gutman

8.1 Introduction

The work of this group included (a) studies of thin-film superconductors and effects in superconductors observable by thin-film techniques (in collaboration with its Thin-Film Group), (b) studies of type-II superconductors, and (c) a device application of superconductors.

8.2 Superconductive Tunneling in High Purity Single Crystal Niobium

The anisotropy of the superconducting energy gap in a pure niobium single crystal (resistivity ration, $R_{300}/R_{4.2} \approx 300$) was measured using dc tunneling techniques. Preliminary data indicated that the gap was isotropic to within the experimental accuracy of about 1 per cent.

Anisotropy should be present if the crystal is of sufficient purity. Attempts are being made to increase the purity of the crystal by means of outgassing in high vacuum.

The apparatus necessary to make ac measurements on the junctions is presently being built. These measurements will make it possible to measure the density of states and the phonon spectrum of the crystal.

G. Craford

8.3 Superconducting Parametric Amplifier (Picovoltmeter)

The spurious noise level in the newest version of the picovoltmeter is slowly being reduced as various noise sources are identified and eliminated. Several runs have had rms noise levels of less than 0.5×10^{-12} volts. This sensitivity was obtained with a source resistance of 6×10^{-6} Ω with a time constant of 16 seconds, and is roughly the same as that obtained during the very best run of the first version, but does not yet approach too closely the sensitivity anticipated for this newer version. At the present time, the main source of excess noise appears to be spurious vibration of the output coil in the weak residual magnetic field of the various magnetic shields.

R. P. Ries

8.4 Flux Flow in Type-II Superconductors

It has been postulated that the apparent resistive behavior of type-II superconductors in magnetic fields between H_{c1} and H_{c2} results from viscous flow of magnetic flux transverse to the current. In order to detect this flux flow we have tried to prepare structures consisting of two thin films of In separated by an insulating layer of about 100 Å of SiO. With a magnetic field perpendicular to the structure, both films behave like type-II superconductors; i.e., the field penetrates the superconductor as an array of flux quanta with their associated supercurrent vortices. If flux motion is induced in one film (the primary) by a transport current, as indicated by a voltage drop, a similar motion should be induced in the secondary producing an emf across the secondary.

While our attempts to observe this effect have been unsuccessful, due primarily to faulty insulation, Giaever[1] have recently observed just this effect.

Improvements in our film techniques have encouraged us to continue this work and to study flux flow in some detail.

I. Toepke
D. Gutman

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[1] Ivar Giaever, Phys. Rev. Letters 15, 825 (1965).

9. HIGH VOLTAGE BREAKDOWN

D. Alpert
E. M. Lyman
D. Lee
T. Casale

9.1 Effect of Gas in Conditioning Tungsten Electrodes

In the previous quarter, it was reported that the breakdown voltage could be raised by as much as a factor of 5 for plane parallel tungsten electrodes in ultrahigh vacuum by subjecting the electrodes to a gas-conditioning process. It was shown that the improvement results as a consequence of the blunting of the electron-emitting protuberances or whiskers on the cathode.

In this quarter, the properties of the gas-conditioned surfaces have been studied in more detail. It was found, for example, that when a tungsten surface is gas-conditioned so that its voltage breakdown point is increased, there is a large increase in the emitting area (by as much as two orders of magnitude) and an accompanying large increase in the emission current. If the emitting area had remained unchanged, there would have been no increase in the emission current since the critical field at the emitter tips is not changed by gas conditioning. The increase in emitting area may be due either to the blunting of the tips or to an increase in the number of tips which contribute to the emission at the higher average field, or to both effects.

At the high currents near the breakdown voltage, a new phenomenon was encountered for the gas-conditioned surfaces. Spots on

the anode opposite emitter points on the cathode became incandescent, emitting first red, then brilliant white light, as the voltage was raised. Weaker incandescence at the cathode was also observed. In the region of incandescence, the plot of log i/V^2 vs $1/V$ was reproducible but the current exceeded that predicted by the Fowler-Nordheim straight line established at lower voltages by one to two orders of magnitude. The relative importance of thermal emission and ion exchange in explaining this increase in current has not yet been established. The very high currents often prevented the voltage-breakdown point from being reached because of power-supply limitation, or because of red-hot heating of the entire anode (cooled by liquid nitrogen).

An attempt was made to establish a most important property of the gas-conditioned surface, namely the long-time stability of the conditioning. Preliminary experiments seem to indicate that a gas-conditioned surface, with its improved voltage-breakdown properties, tends to revert, with time, toward its former unconditioned state. To provide a definitive answer concerning the degree of stability, or the rate of reversion, our experimental conditions need to be much more carefully controlled than in the past. The equipment is now undergoing modification to permit an extensive run (over a period of a week, instead of a day) with controlled conditions of temperature, gap spacing, applied voltage and residual gas pressure.

E. M. Lyman

10. THIN FILMS

R. N. Peacock
M. G. Craford
J. T. Jacobs

K. G. Aubuchon
W. P. Bleha
T. A. O'Meara

10.1 Size Effects

Efforts in the work with size effects in the electrical conductivity of metallic thin films have been divided between a study of the basic questions and construction of apparatus. Consideration of the background research in this area indicates that it is very important to measure both the temperature coefficient of resistivity and the effects of varying the thickness of samples. Calculations show that the changes in resistivity must be made to an accuracy of 0.01 to 0.001%. Various methods of achieving this accuracy are under consideration.

The ion-pumped vacuum station described in the previous progress report has achieved pressures in the mid 10^{-10} Torr range. The cryopump, which is also to be part of this system, is under construction. Transfer of brazing and electropolishing to the recently-constructed portion of the laboratory has delayed assembly of this pump. It is expected that the pump and liquid-helium facilities for its use will be ready by January 1, 1966, and tests of the complete vacuum system can start. When the basic system is complete, preliminary experiments on the size effect will be started.

10.2 Hall Effect

Work has continued on the stainless-steel vacuum system to be used for deposition and measurement of the Hall effect on thin-film

materials. After the initial tests of the system reported in the previous quarter, disassembly showed considerable quantitites of oil on the liquid-nitrogen trap. To help in preventing contamination by oil vapor, a water baffle has been designed and is now near completion in the machine shop. Without this baffle, the lowest pressure observed up to the present has been 2.6×10^{-9} Torr. This is very good, considering that the bakeout temperature was limited by the use of Viton O-rings in the valve.

J. T. Jacobs

10.3 Ionization-Gauge Evaporation Rate Monitor and Rate Control

Further development of the ionization-gauge evaporation-rate monitor has been directed toward a circuit to provide control of the deposition rate of the films.

The circuit uses the signal from the double ionization gauge described in the last report to operate a silicon-controlled rectifier in a feed-back loop with the source transformer. Maximum controlled power is 2.5 kV. The circuit has been tested, and is now being built in final form by the electronics shop.

W. P. Bleha

11. INFORMATION SCIENCE

R. T. Chien
R. B. Ash
J. T. Barrows
D. Chow
H. T. Hsu
V. Lum
R. J. Tracey

11.1 Introduction

The purpose of this research is to develop information-theoretic methods for the design and optimalization of digital systems for data transmission and data processing. During the past quarter, several problems in this area have been investigated in depth. Particularly significant results are obtained in (1) the theory of residue codes for correcting multiple errors, and (2) the application of coding methods to information retrieval systems.

11.2 Algebraic Theory of Bose-Chaudhuri-Hoquenghem Code

We have concentrated in investigating the application of step-by-step decoding procedures to the known nontrivial cases of perfect codes, namely the Golay (23,12) code over GF(2) and the Golary (11,6) code over GF(3).

Peterson has shown a cyclic-code version of the Golay (23,12) code. However, according to the BCH bound, the minimum distance of this code in its cyclic version is only five. By another algebraic technique Mattson and Solomon were able to prove that the minimum distance of the cyclic Golay (23,12) code is indeed seven. A similar situation exists for the Golay (11,6) code over GF(3). According to the BCH bound, the minimum distance of the cyclic version of this code is only four. By extending,

to non-binary cases, the Mattson-Soloman technique we have recently proved that the true minimum distance of the cyclic Golay (11,6) code over GF(3) is five.

The step-by-step error-correction procedure described in the previous progress report is applicable to both of these two perfect codes. It should be noted that that particular procedure is the first algebraic procedure ever discovered to be capable of fully utilizing the true minimum distances of these perfect codes for error correction. Known algebraic procedures are all based on the BCH bound and hence cannot correct more errors than are derived from the bound. On the other hand, threshold types of correction circuits are usually combinatorial in nature and hence are usually not practical for large t. Although, for all practical purposes, the discovery is more or less limited to perfect codes, its potential implications are of a much broader nature.

V. Lum

11.3 Coding Methods for Information Retrieval

11.3.1 Retrieval by Algebraic Coding. In the previous progress report, an information-retrieval procedure based on coding was described in detail. Progress has been made in two directions.

First, an alternative procedure was conceived. With this alternative procedure, one first computes $t_1=f(s_d)-f(s_q)$. We then consider $|M_{t_1}|$. If $|M_{t_1}|=0$, then d does not cover q. If $|M_{t_1}|\neq 0$, then we can determine $f(s_{d+q})$ by solving a set of simultaneous equations. It is estimated that the efficiency of this alternative procedure is not far from that of the main procedure.

Secondly, after studying thoroughly the complexity of this procedure, it became clear that storage requirements as well as computational labor can be greatly reduced by going into a variable-length structure. In the variable-length structure the length of the synchrome of a document vector (query vector) is related to its weight $w_d(w_q)$ in that it is

$$[S_1, S_3, \ldots, S_{2w_d-1}].$$

Hence the syndrome length can be used to calculate immediately the weight of the vector. For any query of weight w_q, it is only necessary to consider documents d such that $w_d \geq w_q$. The power sums

$$S_{2w_q+1}, S_{2w_q+2}, \cdots, S_{2w_d-1}$$

can be easily calculated through the application of Newton's Identities.

It is clear that with this variable length structure the following is true:

a. The length of the syndrome of each document is minimized.

b. The amount of computation required to determine whether a document d covers the query q is also greatly reduced.

c. The system achieves addition flexibility as no particular code need be chosen and the representation does not change when the number of attributes are increased.

R. T. Chien

11.3.2 Retrieval by Using Multiple Copies of the Same Code.

Using ℓ codes, the ratio of the number of the parity-check bits required is $\ell(m-n)/n$ where n is the least positive integer such that $2^n \geq \ell$.

The percentage amount of work required by using ℓ codes compared with that required by using one code for each different weight of documents is

$$\ell^{-2D} \Sigma_k C_k^2$$

where D is the weight of the document, and the C_k's are the coefficients of the terms in the expansion of $(x_1+x_2+\ldots+x_\ell)^D$. To illustrate, for D = 10, the reduction ratio by using four copies is 100.

D. Chow

11.3.3 Retrieval by Permutations that Leave the Code Invariant. Let G_1 be a weight-preserving automorphism on S, the set of r-tuples, or the set of all syndromes. The following lemma is important to the information retrieval process.

Lemma 1: Let the transpose H^T of the parity check matrix be a column matrix with entries I_r and R. If there is a syndrome in the orbit of G_1 with norm (the number of 1's) equal to t_o which is less or equal to total number of descriptors t, then the weight of cosets which corresponds to these syndromes is t_o. Other syndromes in this orbit must have norm either equal to t_o or greater than t.

The process of determining the weight of the document plus query is based on the evaluation of the norms of syndromes in the orbit of the syndrome of the document plus query. We also have a table which contains indications for the orbits of G_1, if the permutation group which leaves the code invariant is large. The implementation of the r-stage shift register to perform weight-perserving mapping become simple if the mapping is a permutation on the natural basis of S.

The following lemmas provide a method for searching these permutations.

Lemma 2: Let M_p be a permutation matrix corresponding to the permutation on the natural basis of S, the set of all syndromes. If H^T is the transpose of the parity-check matrix as above, the necessary and sufficient condition for M_p to be a weight-preserving permutation is that RM_p can be obtained from the row permutation of R where R is as defined in H^T.

Lemma 3: If M_p is a weight-preserving permutation matrix then (a) M_p can permute only columns of R which have same number of 1's in the column among themselves and (b) the row permutation of R corresponding to RM_p must permute the rows with same number of 1's in the rows among themselves.

The proof these lemmas follows from the fact that M_p corresponds to weight-preserving atomorphism of S if and only if M_p corresponds to the row permutations of the transpose of the parity-check matrix.

D. Chow

11.4 Coding for Compound Channels

The method of computing L_t has been extended to the case of $t = 3$. To test the efficiency of the general procedure, L_t $(t = 1,2,3)$ has been determined for BCH codes listed in Peterson. The method proved to be quite efficient.

H. T. Hsu

11.5 Linear Residue Codes

Early in this quarter, it was discovered that the recursive relation

$$2^{\alpha_i} x^i = x^{i-1} + \lambda_i B \qquad (1)$$

due to Euler might be the key to the construction of multiple-error-correcting linear residue codes. This fact has now been verified. With the judicial use of (1), coupled with the representation of numbers in nonadjacent form, it appears that a general theory of linear residue codes for multiple-error correction is possible.

A typical method for construction is as follows: Given an integer B, we use the recursion formula (1) to derive a set of x_i's such that

$$2^{\alpha_i} x_i = x^{i-1} + \lambda_i B$$

and $\lambda_i = \pm 1$ and $\alpha_i \geq 2$. Suppose after m steps $x_m = x_o$, then

$$2^m x_o - x_o = B\left[\sum_{i=1}^{m} \lambda_i 2^{\sigma_{i-1}}\right]$$

where $\sigma_i = \sum_{j=1}^{i} \alpha_j$ and $\sigma_o = 1$. As it turned out, we can usually construct, with the process just illustrated and letting $x_o = 1$, a code of distance m and length σ_m. Details of the general method are being investigated. A technical report covering the discovery will be prepared shortly.

J. T. Barrows

11.6 Coding for the Time-discrete Gaussian Channel

The problem of constructing explicit codes for the time-discrete Gaussian channel is being investigated. The inputs to such a channel are sequences of real numbers, and the output sequence is formed

from the input sequence by the addition of a sequence of independent Gaussian random variables. A constraint such as an average-power limitation is placed on the allowable input sequences.

The capacity of the time-discrete Gaussian channel with average-power limitation was found by Shannon in his 1948 paper. However, very little is known about the properties of specific coding schemes for this channel. Since the channel may be described analytically in a convenient way, it is perhaps reasonable to expect the existence of easily implemented codes with desirable error-correcting properties. Another hopeful sign is that for the time-continuous Gaussian channel with average power limitation (here the inputs are time functions and the output is formed by adding to the input a sample function of a Gaussian noise process), an orthogonal coding technique may be used to maintain any transmission rate below channel capacity with an arbitrarily low probability of error.

R. B. Ash
R. J. Tracey

12. SWITCHING SYSTEMS

S. Seshu
G. Metze
F. Preparata
S. J. Fenves
R. duPreez
R. Marlett
S. C. Chang
G. Martens
D. Crockett
W. J. Bouknight

12.1 Computer Compiler†

The system compiler is approximately one-half completed. Initial studies have been completed on one particular implementation of the hardware compiler. It is expected that these two compilers will be operational at the end of the next quarter.

S. Seshu
G. Metze

12.2 Failure Behavior

The behavior of sequential machines under failure is being investigated. Attention is focused on synchronous deterministic quasi-linear sequential machines. It has been shown by means of examples that cycle lengths of machines are neither preserved or monotone under failure. It has also been shown by means of an example that unreachable states may remain unreachable under input failures, thus contradicting a conjecture of Manning.

S. C. Chang

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†Portions of this work were supported by the National Science Foundation under Grant NSF GK-36.

12.3 Diagnosable Computers†

Computer design principles have been established which allow checkout programs to be algorithmically derived without the use of the details of the logic. The procedure depends on the micro-order flow diagrams for the instructions of the machine to be diagnosed and at present will produce checkout programs which detect approximately 80% of all solid, single failures. Methods for choosing operands to detect data-dependent failures have also been considered. For example, eight particular additions have been shown to be sufficient to check an n-bit ripple-carry adder which uses n full-adder stages.

The validity of these principles and procedures will be tested by an experiment. The CSX-1 computer will be redesigned according to certain criteria, and a checkout program will be manually generated. Th completeness of this program will be determined by simulation, using Professor Seshu's sequential analyzer program.

R. Marlett

12.4 Algebraic Network Synthesis†*

Given a realizable state model, a transfer function matrix can be obtained. However, given a realizable transfer function matrix, there is no known method for obtaining a realizable state model. Presently, node insertion is being investigated as a possible method for solving this problem.

G. Martens

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†Portions of this work were supported by the National Science Foundation under Grant NSF GK-36.

*Portions of this work were supported by the AF-AFOSR Contract Number AF-AFOSR 931.65.

12.5 Synthesis of Sequential Networks†

An investigation of modular decomposition of sequential machines is being conducted. Consideration is given to the general description and construction of special classes of sequential machines with basic sequential modules. With the advent of integrated circuitry, it is felt that such a study is more meaningful than the problem of state assignment to minimize the number of diodes in a switching circuit.

E. D. Crockett

12.6 Computer System Evaluation†

A simulator program, Console Timing Simulator System, was completed along with various "dirty work" programs to be used in the investigation of time-shared console-input computer systems with respect to blocking, saturation and degeneration effects.

Emphasis for the next quarter will be on specific problems in time-shared systems with an eye toward gaining information on simulation usage and techniques in this area as well as possible solutions.

W. J. Bouknight

12.7 Structural Design

Two activities were begun during this quarter. The first one deals with the application of symbolic transfer functions to structural problems. It is planned to investigate both static and dynamic analysis, as well as the use of the method for generating

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†Portions of this work were supported by the National Science Foundation under Grant NSF GK-36.

coefficients for structural-parameter optimalization. The problem is considerably more complex than in the case of electrical networks, because the network variables are vector quantities and, therefore, the branch impedances are defined by submatrices.

The second activity deals with computer-aided design, and is intended to make use of the graphical output facilities being implemented on the CDC 1604 computer. The actual problem being considered is the generation and display of shear, moment, rotation, and deflection diagrams for structural members. The computer program, making extensive use of list processing, will be used as part of the new problem-oriented language being written, but primary emphasis at the present is to gain experience in graphical data display for engineering problems.

S. J. Fenves
R. duPreez

13. NETWORKS AND COMMUNICATION NETS

M. E. Van Valkenburg
W. Mayeda
T. Kamae
T. Murata
J. A. Resh
G. H. Stumpff
S. Toida
T. N. Trick
N. Wax*

13.1 Stability of Nonlinear Networks†

The network being considered is linear time-invariant, with a nonlinear element embedded in it, along with periodic sources of period T. The nonlinear element can be resistive, inductive (without hysteresis), or capacitive, and its function is defined only within a certain range of operation of the nonlinear device; i.e., a varactor diode burns out if the voltage across it becomes too great. If the nonlinear element is capacitive, then the network can be described by the equation

$$e(t) = \int_a^t z(t-\tau)i(\tau)d\tau + v(q(t)), \qquad (1)$$

where z(t) is the impulse response of the linear time-invariant part of the networks, and v(q(t)) is the nonlinear function. A similar equation can be written in the nonlinear inductive or resistive problem. In previous work[1] conditions were given on the source amplitudes such that there existed a steady-state solution, $q_p(t)$, to this equation for

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*On leave.

†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

[1]Trick, T. N., "Lower Bounds on the Thresholds of Subharmonic Oscillations," Ph.D. Thesis, School of Electrical Engineering, Purdue University, 1966.

$a = -\infty$, which was unique in the space of bounded measurable functions of period T, and under these conditions the nonlinear device always operated in its allowable dynamic range. Unfortunately, the existence of a unique solution in the space of bounded measurable functions with period T does not guarantee that another solution will not exist.[2] Thus, in order to show stability, in the sense that only a unique bounded periodic solution of period T can exist, we must show that all transients decay to this desired steady-state solution. In the past few months, conditions on the above network have been determined such that all transients decay to the unique periodic steady-state solution of period T. These conditions should be better (in the sense that a larger operating range of the nonlinear device is permissible) than another stability criteria[3], since our results do not estimate the rate of transient decay, but show only that the transients do decay to the desired response. At the moment, some examples are being solved to show that this is indeed the case.

T. N. Trick

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[2]Trick, T. N. and Anderson, D. R., "Lower Bounds on the Thresholds of Subharmonic Oscillations," Third Annual Allerton Conference, University of Illinois, 1965.

[3]Leon, B. J. and Anderson, D. R., "The Stability of Pumped Nonlinear Reactance Circuits," IEEE Trans. on Circuit Theory, CT-10, p. 468 (December, 1963) [A correction appears in CT-12, p. 143, (March, 1965).]

13.2 Reliability Studies of Communication Nets

In the present study we define an R net as follows[4]: An R net is a connected, nonorientated linear graph with each edge ij assigned a weight (component reliability) $r_{ij} \in [0,1]$. Since a nonexisting edge between any given pair of nodes can be considered as an existing edge with weight zero, and since if more than one edge exists between any pair of nodes we can combine the r_{ij}'s into a single r_{ij}, we can, without loss of generality, consider an R net as a complete graph with edge weights on [0,1]. A net so defined may also be considered as a probabilistic net or a generalized switching network, in which each switch has a certain probability of closing (opening) or alternatively is only partially open (closed).

If we define R_{ij} to be the total or overall reliability between nodes i and j, then by using properties of linear graphs combined with probability theory (e.g., Bayes' Theorem) it is not difficult to show that R_{ij} has the following properties:

1. R_{ij} is a linear, non-decreasing function of any given $r_{k\ell}$, and further, if the R net is strongly connected, (i.e., each edge is contained in some path i to j), then R_{ij} is strictly increasing. Also one has

$$\partial R_{ij}(r_{k\ell})/\partial r_{k\ell} = R_{ij}(1) - R_{ij}(0)$$

2. R_{ij} is bounded above by the value of the reliability obtained by assuming each path ij independently and taking the parallel

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[4] Y. Fu, "Applications of Topological Methods to Probabilistic Communications Networks," IEEE Trans. on Comm. Tech. COM-13, 301, Sept. 1965.

combination of all such path reliabilities.

3. R_{ij} is bounded below by the product of the reliabilities of all cut sets separating i and j when such cut sets are considered to act independently. (The reliability of a cut set is one less the product of unreliabilities of the edges in the set.)

4. R_{ij} can be written as an alternating series of sums of progressively increasing unions of individual path products of r's over all k paths;

$$R_{ij} = \sum_{s=1}^{k} p_s - \sum_{\substack{s,t=1 \\ s\neq t}}^{\binom{k}{2}} p_s Up_t + \sum_{\substack{s,t,u=1 \\ s\neq t\neq u \\ s\neq u}}^{\binom{k}{3}} p_s Up_t Up_u + \ldots + (-1)^{k-1} \sum_{1}^{\binom{k}{k}} p_1 Up_2 U \ldots Up_k$$

where p_s equals the product of r's contained in the s path.

5. Since the existence of any cut set between i and j assures the non-existence of any path i to j (and conversely), R_{ij} may also be written as one minus the alternating sums of progressively increasing unions of individual cut set products of unreliabilities over all cut sets separating i and j.

6. Properties 4 and 5 imply that if the R net is planar and we consider i and j as "input" terminals, then R'_{ij} of the dual R net is in fact the unreliability $(1-R_{ij})$ of the original R net, when we assign as edge weights in the dual graph $1-r_{ij}$ from the original graph.

By property 4 we see that each term of R_{ij} will be a path product or combination of path products only. This fact allows one to write the terms of R_{ij} directly from the net by inspection. Unfortunately, however, a significant amount of cancellation and addition of terms occurs

in the expression as given in 4, hence there are some coefficients other than unity. A simple means of determining these non-unity coefficients is presently still being sought in order that R_{ij} can be written directly and completely by inspection.

G. Stumpff

13.3 Optimum Flow in a Communication Net†

The study is concerned with the problem of obtaining a set of edge flows which result in maximum terminal flow in a communication net. The methods for accomplishing this stem from the work of Ford and Fulkerson which relates maximum terminal flow to the cut set separating the terminals. A new set of cut sets, the "set of M-cut sets" is introduced which make it possible to improve some edge flows while maintaining maximum terminal flow. The details of the method are given in Report No. R-270.

W. Mayeda
M. E. Van Valkenburg

13.4 Communication Nets with Censors

We have begun a study of communication networks for which the admissible patterns of information flow are subject to certain topological constraints suggested by the requirements of censors in a public information system: en route from origin to destination, all information must be processed by a censor.

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At present, two models are being considered, both of which are modifications of the Ford and Fulkerson model which has received so much attention in the literature of the past decade, that a communication net is a weighted linear graph whose vertices and edges represent the stations and channels and whose edge weights are the channel capacities; information flow from station v to a distinct station v' is represented as a weighting of the edge sequences joining v to v' -- the weight of an edge sequence is the average information rate along that particular route in the net. Both of our kinds of "communication nets with censors" entail the following two modifications of the model just described:

(1) We distinguish between two types of stations: "users" and "censors"; primary interest centers about communication among the users, but this is conditioned by (2).

(2) The only admissible information routes are those which begin and end on distinct users, and which pass through exactly one censor.

These complete the description of what we shall call "type-1" communication nets with censors; the definition of "type-2" nets (the simpler of the two kinds) includes the following additional modifications:

(3) We distinguish between two types of channels: "open" and "guarded"; and require of the admissible information routes that all channels preceding the censor be guarded and all channels following the censor be open.

Most of the results to data concern type-2 nets, containing an arbitrary number of users but only one censor. In this case we can

define three terminal capacity matrices: $T^o = [t^o_{ij}]$, $T^g = [t^g_{ij}]$ and $T = [t_{ij}]$ of orders n+1, n+1 and n respectively, where n is the number of users in the net: Denoting by $v_1,\ldots,v_n,v_{n+1}$ the stations of the net, with v_{n+1} being the sole censor, the definitions are:

t^o_{ij} = maximum attainable information rate from station v_i to station v_j $(i,j = 1,\ldots,n,n+1;\ i \neq j)$ in the open subnet, with no restrictions on information routes;

t^g_{ij} = same as above, but for the guarded subnet;

t_{ij} = maximum attainable information rate from user v_i to user v_j $(i,j = 1,\ldots,n;\ i \neq j)$ in the net with censors, admissible information routes being constrained by (2) and (3).

Clearly, t^o_{ij} and t^g_{ij} are given by Ford and Fulkerson's max-flow, min-cut theorem; thus the analysis problem is completely solved by our first

Theorem: $t_{ij} = \min\{t^g_{i,n+1},\ t^o_{n+1,j}\}$.

It is a corollary that one can always rearrange the rows and columns of T to obtain a new matrix $T' = [t'_{ij}]$ whose characteristic property is that for any pair i,j $(i,j = 1,\ldots,n)$, either $t'_{ij} = t'_{i,j+1} = \ldots = t'_{in}$ or $t'_{ij} = t'_{i+1,j} = \ldots = t'_{nj}$.

Our second main result is the solution of the realizability question:

Theorem: The corollary just described states a necessary and sufficient condition for a given real, nonnegative constant matrix to be the terminal-capacity matrix T of a single-censor type-2 communication net.

The sufficiency proof of this condition is a synthesis procedure. Two such procedures are given, both of which we have shown to yield realizations with the minimum possible total channel capacity.

The study of type-1 nets has, as yet, produced no results comparable to those described above for type 2; the best we have accomplished is in the direction of constructing a linear programming formulation which is well tailored to the structure of the problem. In the single-censor case, type-1 nets present an interesting special case of the simultaneous-flow problem in ordinary nets; when the channels are nonoriented, Hakimi has solved the latter problem in a way that shows promise of yielding an analysis theorem like Theorem 1 above, but so far this has not been accomplished.

13.5 Theory of Biweighted Graphs†

A topological solution of the matrix equation[5]

$$A_{\alpha} Y (A^{+})^{T} X = 0$$

of a biweighted graph (a linear graph with two different kinds of weights, y and α assigned to each edge) has been investigated. The solution is given in terms of a new subgraph called the S-subgraph having the following definition and properties:

Suppose that a graph G under consideration is a directed

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

[5] T. Murata, "Analysis of Lossy Communication Nets by Modified Incidence Matrices," Proc. of the 3rd Annual Allerton Conference on Circuit and System Theory, October 1965.

linear graph with v vertices which is more than or equal to v-1 edges. An S-subgraph of G is defined as one which consists of v vertices and v-1 edges such that the number of outgoing edges is exactly one at every vertex except for a particular (reference) vertex. From this definition, the following properties can be derived:

1. Each vertex in an S-subgraph must be an initial vertex to exactly one edge except for the reference vertex.
2. The reference vertex cannot be an initial vertex of any edge in an S-subgraph.
3. If an S-subgraph is connected, it must be a directed tree.
4. If an S-subgraph is separated, there is at least one circuit.
5. All circuits in an S-subgraph are directed circuits.
6. There do not exist more than one circuit in each connected part in an S-subgraph.
7. All edges (or trees) connected to a circuit in an S-subgraph must be directed toward the circuit.
8. The reference vertex cannot be a vertex of a circuit in an S-subgraph.

It has been shown that the determinant of the coefficient matrix of the aforementioned equation with the reference-vertex removed is the summation over all S-subgraphs, i.e.,

$$\det[A_{\alpha r} Y (A_r^+)^T] = \sum_{j=1}^{\ell} \prod_{k=1}^{v-1} y_{jk} \prod_{p=1}^{S_j} \left(1 - \prod_{q=1}^{M_{jp}} \alpha_{pq}\right)$$

where y_{jk} : the y weight of the kth edge in the jth S-subgraph

α_{pq} : The α weight of the qth edge of the pth circuit in an S-subgraph

ℓ : the number of S-subgraphs in G

v : the number of vertices in G

S_j : the number of circuits in the jth S-subgraph

and M_{jp} : the number of edges in the pth circuit in the jth S-subgraph

(if there is no circuit, $S_j = M_{jp} = 0$, then we define $\prod_{0}^{0} (1 - \prod_{0}^{0} \alpha_{pq}) = 1$).

The above result is a basis for topological analysis of systems which the biweighted graph represents, e.g., active networks. Note that if all the α's are unity, the above determinant is reduced to a classical result, i.e., the summation of y (admittance) products over all directed trees.

T. Murata

13.6 Minimum Feedback Arc Sets†

An interesting problem in the theory of directed graphs is to determine a minimum set of arcs (directed edges) whose removal leaves the resulting graph free of directed circuits.[6] This set is called a minimum feedback arc set. Younger[7] proposed an algorithm to list all

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†Portions of this work were supported by the Air Force Office of Scientific Research under Grant No. AFOSR 931.65.

[6]This is also among a list of research problems in Seshu and Reed, Linear Graphs and Electrical Networks, Addison-Wesley, 1961.

[7]D. H. Younger, "Minimum Feedback Arc Sets for a Directed Graph," IEEE Trans. on Circuit Theory, CT-10, June 1963.

minimum feedback arc sets. He regarded this as a problem of numbering of all vertices of a given graph. Therefore his way of attacking is not graph-theoretical. The graph-theoretical properties of a minimum feedback arc set have been investigated. Several interesting properties and bounds on the order of a minimum feedback arc set have been obtained which will be given in a later report.

T. Kamae

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13. ABSTRACT

The ionosphere program is now concerned only with rocket data reduction. For the general relativity satellite program, Baker-Nunn thresholds are discussed in relation to the problem of photographic observability, and the effect of micrometeorite cratering on determining the optimal diameter of the gyro satellite is discussed.

Improvements in the electron source of the high-resolution electron spectrometer have resulted in a substantial increase in the sensitivity of the instrument. Preliminary measurements are reported that indicate the presence of low-energy loss peaks due to adsorbed gas. Progress on the construction of the apparatus for the measurement of the angular distribution of secondary electrons and on the instrumentation for the adsorption experiment is reported.

Operation statistics, new facilities for bubble-chamber data processing, and new display equipment are reported.

Several results were obtained in the continuing projects on the parameter-variation problem, stability of nonlinear systems, sub-optimal linear time-invariant control, and computer-oriented formulation and solution of the optimal control problem. Several new projects were initiated in the area of optimal control of plants which are subject to parameter variations.

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ABSTRACT (continued)

Student response data are being collected for the three university courses given for credit this semester using PLATO: Electrical Engineering 322, Library Science 195, and FORTRAN Programming for Business Students. The variables affecting the retention of conceptual materials are being analyzed. A man-computer interface study in order to optimalize keyset design is underway. Programming has also begun for three projects: a language-free test of interpersonal norms, an inter-nation simulation study and the system for instructional response analysis. Weekly seminars have been held this fall on subjects pertinent to PLATO research. During this quarter there have been thirty demonstrations of PLATO either in the classroom or by remote station. Transistor deflection circuitry replaces vacuum-tube types in the student-station circuitry completing the twenty-student-station classroom. Further progress has been made on the development and understanding of the plasma display tube.

Additional measurements on the pumping speeds of getter-ion pumps at low pressures have been made. These measurements and those on the effects of bakeout and processing of uhv systems in ultimate pressure are discussed.

In the calculation of the collision integral, it has been shown that the Monte Carlo error is reduced by a factor of 5 because of correlations predicted by Nordsieck. In the studies on beam-plasma interaction, anomalous diffusion has been observed during the beam instability together with intense radiation from plasma oscillations. Investigation of electron runaway in the linear plasma betatron has revealed an anomalous resistivity of the conduction current, which appears to stop the runaway current. Qualitative evidence has been obtained for a collisionless damping of the Tonks-Dattner modes.

Work is reported on a superconducting parametric amplifier (picovoltmeter), a study of the anisotropy of the energy gap in superconducting niobium and studies of flux flow in type II superconductors. Work is continuing on detection of microwave radiation from the ac Josephson effect in a superconducting bridge and the thermal conductivity of a type II superconductor in the mixed state, but no report of these activities is submitted at this time.

When electrodes are gas-conditioned, the sharp protuberances on the cathode are blunted, thereby increasing the breakdown voltage by a factor of about 5 and the effective emitting area and prebreakdown current by about two and one orders of magnitude, respectively. The permanence or stability of the gas-conditioned surface is being investigated.

Continued work is reported on preparations for the size effect and Hall effect experiments. Development of the ionization-gauge deposition monitor has been continued to provide feedback control of the deposition rate.

During the past quarter, several problems have been investigated. Results are obtained in the theory of residue codes for correcting multiple errors and the application of coding methods to information retrieval systems.

Several new investigations were started during this quarter. These include computer aided design of structures, dynamic analyses of structures, and the propagation of errors in finite memory encoding-decoding schemes. Further progress is reported on the computer compiler and self-diagnosis studies.

In studies of nonlinear networks, new conditions have been found such that transients decay to a unique periodic steady-state solution. These conditions permit a larger operating range of the nonlinear device (varactor) than is permitted by other solutions. In communication nets, studies include the overall reliability of nets with unreliable components, conditions for optimal flow in a net in which edge flow is limited, and nets with censors. In graph theory, studies are in progress on properties of biweighted graphs, and the determination of minimum feedback arc set.

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