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Laboratory*

CONTROLLED THERMONUCLEAR RESEARCH  
QUARTERLY REPORT

June, July, August 1960

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Processes (UC-20)  
TID-4500 (15th Ed.)

UNIVERSITY OF CALIFORNIA  
Lawrence Radiation Laboratory  
Berkeley and Livermore, California

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June, July, August 1960

September 10, 1960

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# CONTROLLED THERMONUCLEAR RESEARCH QUARTERLY REPORT

June, July, August 1960

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\*Preceding Quarterly Reports: UCRL-9243, UCRL-9106

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# CONTROLLED THERMONUCLEAR RESEARCH QUARTERLY REPORT\*

June, July, August 1960

Lawrence Radiation Laboratory  
University of California  
Berkeley and Livermore, California

September 10, 1960

## I. PYROTRON (MAGNETIC MIRROR) PROGRAM

### 1. INTRODUCTION AND SUMMARY

Richard F. Post

Among the more significant developments in this quarter were: the preliminary operation of the first stages of the three-stage magnetic compression experiment, additional results obtained in the investigation of compression-induced velocity-space instabilities, and an analysis of the trapped-particle confinement time in "BABY ALICE" as a function of decreasing confining magnetic field. This analysis appears to give a clear indication of the onset of losses owing to particle orbit effects, as soon as the particle orbit diameters exceed about 2 in. (central fields lower than 8000 gauss for 20-keV protons). Since the design is for operation at central fields up to 50,000 gauss, this particular loss mechanism should not be of concern in the full-scale ALICE experiment.

An additional check on the plasma density and temperature conditions previously determined to apply in the Table Top experiments has been provided by Ellis and Carlson. By using a pulsed electron beam to calibrate scintillators used in Ellis's earlier Table Top experiments, a lower-limit figure has been obtained for the space-averaged electron density in Table Top (at 1 millisecond after compression is begun). When corrected for the expected spatial distribution of the electrons, this gives a peak density and peak  $\beta$  value in approximate agreement with earlier determinations.

As an aid to understanding expected plasma confinement conditions in the multistage and the ALICE experiments, a theoretical calculation of plasma potential distribution has been made. In these experiments, and indeed in conceivable future "practical" mirror machines, the intrinsically difference in rates of escape of electrons and ions is balanced by the establishment of a positive potential. The magnitude and distribution of this

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\*This work was done under the auspices of the U. S. Atomic Energy Commission.

potential will then influence the confinement of the plasma. What has been found, as a result of a quantitative calculation for selected mirror ratios, is that the potential gradient is not uniform within the plasma itself, and indeed that in cases of interest much of the potential variation occurs outside the bulk of the plasma, so that relatively few of the ions feel the full potential. This result can be expected to somewhat diminish the correction for the "ambipolar" losses,<sup>1</sup> where, in effect, all particles were assumed to feel the full plasma potential. Ambipolar potentials may also play a role in plasma stability. For these reasons, the plasma in the multistage experiment and in ALICE may differ in stability, not necessarily favorably, from the stable Table Top plasmas.

## 2. MAGNETIC HIGH-COMPRESSION EXPERIMENTS

Frederic H. Coensgen

### Multistage Experiment

At this time, the effort of the Toy Top group is primarily concerned with the operation of the first two stages of the three-stage compression experiment described in previous reports. A number of difficulties have prevented us from taking data until recently.

First, mechanical and electrical failures in the transmission lines from the capacitor banks to the gating and transfer magnets have necessitated the replacement of these lines. Replacement of these rather complex lines has taken nearly two months (see Electrical Engineering Progress Reports for August 1960 by David R. Branum). The installation of the lines to the transfer coils has been completed, and in test operation they appear satisfactory.

The magnitude and distributions of the pulsed gating and transfer fields were measured and the total field distributions in the 9-in. section were computed at a number of points in the transfer cycle. After adjustment of the magnet position and elimination of a metal vacuum chamber from the 4-in. section, the fields appear satisfactory for plasma transfer from the 9-in. to the 4-in. section for injection fields up to 800 gauss in the 18-in. section.

Since the May report the vacuum chamber for the trapping, transfer, and heating measurements has been assembled. This system is nearly 40 ft. long, and its internal diameter varies from 9 to 36 in. It is an unbakable system of 1800 liters. There are more than 60 rubber gaskets, ranging in diameter from 2 to 38 in. Many of these are flat gaskets whose edges are exposed to the vacuum. Three 10-in. mercury diffusion pumps are in use on the main chamber and a 4-in. mercury diffusion pump is used

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<sup>1</sup>A. Kaufman, in Conference on Controlled Thermonuclear Reactions, Gatlinburg, Tennessee, June 4-7, 1956, TID-7520 - PT-2.

on the ion analyzer. The base pressure of the system is  $2 \times 10^{-7}$  mm Hg as measured by an untrapped gauge in the main volume. This base pressure is lower by an order of magnitude than that achieved in previous systems of similar construction but of smaller volume.

Absorption pumping by means of evaporated Ti films has been tested in the main chamber. The film is deposited on metallic walls of the chamber, which are maintained at 70°F or lower by means of water cooling coils. The evaporators are simply tantalum filaments on which titanium wire is wound. By outgassing these evaporators near the melting point of titanium before evaporation, the base pressure of the system has been reduced to  $2 \times 10^{-8}$  mm Hg upon deposition of the Ti film. With three plasma generators firing every 10 seconds, the pressure in the region of the Ti film returned to  $5 \times 10^{-8}$  mm Hg between shots. As the Ti pumping has proven effective, the number of evaporators and the area of cooled vacuum chamber wall are being increased.

Calibration of the ion analyzer under operating conditions is in progress. After several weeks of intensive effort the noise pickup in the detector circuits has been reduced by a factor of from  $10^3$  to  $10^4$ . The sensitivity has been increased by a factor of 10 since March 1960. Thus, smaller transmitted plasma samples are required, so that both polarization and space-charge effects in the analyzer should be reduced. Indeed, the resolution of the instrument has been improved by a factor of from 2 to 3.

Model magnets for the final compression stage have been built and the field distributions measured. It was possible to design a rather versatile final stage in which plasma can be compressed and contained or alternatively compressed and ejected. The plasma compression in the latter operation will be only half of that possible for compression and containment.

#### Plasma Generators

At the time of the preceding report we had just succeeded in limiting the arc current to one-half cycle, or crowbarring it at the end of the first quarter cycle. Upon investigation, the plasma output for these modes of operation is found to be essentially the same as that obtained with a ringing arc current.

As a result of a slight modification of the generator, most of the arc current now terminates on loaded titanium rather than stainless steel. With quarter-cycle operation, this change appears to have reduced the hydrogen contamination (relative to deuterium) by a factor of 5.

### 3. ELECTRON ENERGY DISTRIBUTION AND SCINTILLATOR--PROBE CALIBRATION

Robert E. Ellis and Norris W. Carlson

Calibration measurements have been made on the scintillator probe used to obtain some of the Table Top electron energy distribution data previously reported. The calibration used (described in the preceding progress report<sup>2</sup>) utilizes an electron beam with energies up to 50 kev. The results are shown below for a mirror-coil configuration on Table Top such that the mirror ratio was  $\approx 2.4$ . For injection into a 20-gauss dc magnetic field (the direction of the dc field being the same as the pulsed field) with a peak pulsed field of approx 21 kilogauss, a rise time to peak value of approx 600  $\mu$ sec, and a  $1/e$  decay time of about 12 msec, a mean density of  $4 \times 10^{12} \text{ cm}^{-3}$  was calculated for a time 1 msec after the magnetic field was pulsed on. At this time an appreciable number of particles have escaped, and the field has decayed somewhat. Thus, the particle density is appreciably less than its maximum value, which should occur at the peak of the compression cycle, i. e., at about 0.6 msec after initiation of the compression. Table I shows the calculated space-averaged plasma density and plasma electron mean energy as a function of time after initiation of the magnetic field as well as the corresponding temperature for a Maxwellian distribution and the mean energy of the escaping electron flux seen by the probe.

Table I

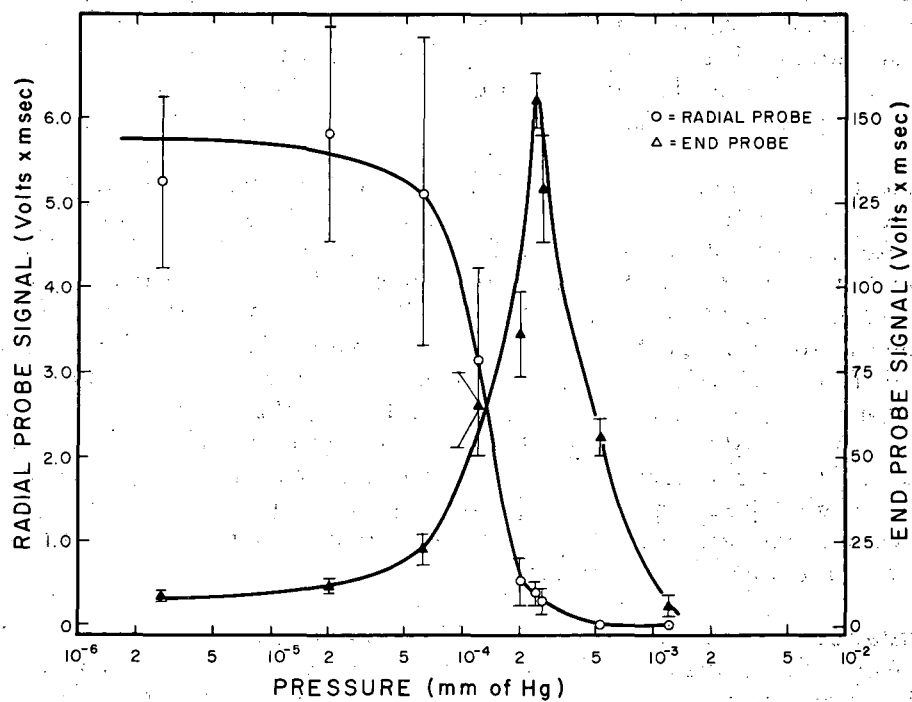
| Plasma properties as functions of time after initiation of the magnetic field |                                                                    |                                                            |                                                                                            |                                                            |
|-------------------------------------------------------------------------------|--------------------------------------------------------------------|------------------------------------------------------------|--------------------------------------------------------------------------------------------|------------------------------------------------------------|
| t<br>(msec)                                                                   | $\bar{n}$<br>averaged<br>plasma<br>density<br>( $\text{cm}^{-3}$ ) | $\bar{E}$<br>plasma<br>electron<br>mean<br>energy<br>(kev) | T<br>temperature<br>for a Max-<br>wellian dis-<br>tribution with<br>mean energy E<br>(kev) | Mean<br>energy of<br>escaping<br>electron<br>flux<br>(kev) |
| 1                                                                             | $4 \times 10^{12}$                                                 | 34                                                         | 23                                                                                         | 19                                                         |
| 2                                                                             | $3 \times 10^{12}$                                                 | 36                                                         | 24                                                                                         | 20                                                         |
| 3                                                                             | $2 \times 10^{12}$                                                 | 38                                                         | 25                                                                                         | 21                                                         |
| 4                                                                             | $7 \times 10^{11}$                                                 | 36                                                         | 24                                                                                         | 20                                                         |
| 5                                                                             | $2 \times 10^{11}$                                                 | 37                                                         | 25                                                                                         | 21                                                         |

<sup>2</sup> Controlled Thermonuclear Research Quarterly Report, UCRL-9243, August 1960.

It should be pointed out here that the voltage across the source washer stack was 10 kv for the particular run on which the above estimate of density is made. The effect of source voltage on plasma density was not investigated at that time, that source voltage being selected which provided steadiest operation and not necessarily the largest probe signals or highest plasma density. No correction was made for angle of entry of electrons into the absorber foils. Also, none was made for particles escaping through the opposite mirror; such particles obviously would not have been counted. Furthermore, the densities indicated are mean values averaged over radius and over the entire length between the mirrors. Thus, it is to be expected that the actual peak plasma density at the midplane would be at least roughly four times the values indicated, or about  $2 \times 10^{13} \text{ cm}^{-3}$  at 1 msec, in rough agreement with determinations obtained by other methods.

Comparisons have been made of the efficiency of a single-channel scintillator probe with and without a long small-diameter lucite rod light pipe. The plastic fluor used was 1/8 in. in diameter, coated with about 2000 angstroms of aluminum and mounted in a 1-in. -diameter stainless steel tube approx 4 ft long. The photomultiplier was about 5 ft from the fluor and there was no optical connection between them. The signal obtained by use of a 4-ft length of 1/8-in. diameter lucite rod light pipe was compared with that for a 4-in. length of the same rod. With a 0.3- $\mu$ a electron beam at 20 and 30 kev energy, the signal with the 4 ft light pipe was about 1/400 of the signal without the light pipe. Further tests are in progress using a 5-ft flexible glass fiber light pipe (made by American Optical Co.). (The lucite pipe was polished, but the surface smoothness could probably be improved by more careful polishing.)

The reason for these comparisons is to find the best arrangement of light pipes for a 21-channel scintillator probe to be used in making measurements of electron energy distribution and density on Table Top. With this probe it should be possible, in theory, to obtain the electron energy distribution and density with one machine pulse, utilizing 10 of the available channels. In addition, the radial distribution of escaping electron flux out to a radius of approx 3/4 in. may be obtained in one pulse by making use of the other channels. The probe is completed except for the ultimate selection of light pipes.



MU-21878

Fig. 1. Radial-probe and end-probe signals as functions of the pressure of the background gas.

#### 4. RADIAL SCINTILLATION-PROBE MEASUREMENTS ON TABLE TOP II

Walton A. Perkins

The experiments concerning the velocity-space hydromagnetic instability discussed in the preceding Quarterly Report have been continued. In that Quarterly Report (UCRL-9243) it was shown that the radial diffusion decreased abruptly at high density. This was interpreted as follows: at high plasma densities collisions become important during compression and they lower the ratio  $T_{\perp}/T_{\parallel}$  by diffusion in velocity space, so the plasma again becomes stable.

To study the effect of collision with the background gas, the vacuum chamber was filled with He to various pressures and then pulsed in the usual manner. The radial- and end-probe variations with background pressure are shown in Fig. 1. The end-probe signal increases in the  $10^{-4}$  region, probably because of ionization of the background gas during compression. Finally, at very high background pressures the plasma quickly dissipates its energy in ionizing the background gas. The radial diffusion decreases as the gas (and plasma) density is increased. Here collisions with the background gas and plasma cause the anisotropy of the electron velocity distribution to decrease and the plasma to become stable.

At very low electron densities the plasma should become stable again when its  $\beta$ --that is, (plasma pressure)/( $B^2/8\pi$ )--drops below the critical  $\beta$ . To obtain small trapped-plasma densities, the pulsed magnetic field is delayed relative to the source firing (i. e., mistiming the trapping field relative to the plasma injection). The effect of decreasing the density on the ratio of radial-probe signal to end-probe signal is shown in Fig. 2. This shows that the radial diffusion decreases and finally ceases at low plasma density.

#### 5. PLASMA DIAGNOSTICS IN TABLE TOP

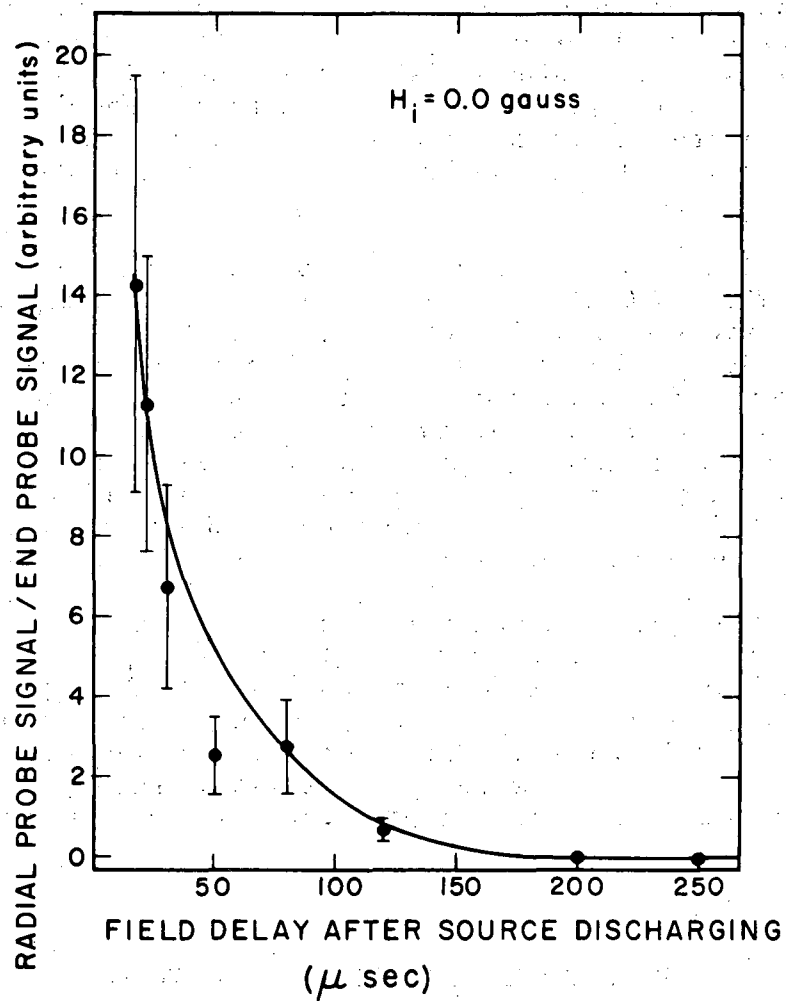
Thomas O. Passell\*

A second extended set of calorimetric measurements of the total energy of compressed plasma escaping Table Top has been completed. The same experimental conditions and variables were studied as for a previous set except for the electrical conductivity of the vacuum-system walls. The second set of data was taken with the vacuum-system walls made electrically conducting by coating with metal vaporized from a hot stainless steel wire in vacuo.

The most notable result obtained from the recent measurements is that the energy escaping transverse to the magnetic field in the plane midway between the magnetic mirrors is markedly less than that with non-conducting vacuum walls.

---

\*Stanford Research Institute, Menlo Park, California.



MU-21877

**Fig. 2.** Ratio of the radial-probe to end-probe signals as a function of the delay in pulsing the magnetic field after firing the source. The density of trapped plasma decreases as the delay is increased.

A report describing the development of calorimetry for plasma energy studies has been completed.<sup>3</sup> When the data from the above two extended runs have been reduced, they will be combined with the above preliminary report and published as a UCRL report.

Development continued on components necessary for measurements of electric fields extant during compression in Table Top. The fields are to be sensed by observation of the deflection of a stream of charged particles moving parallel to the Table Top magnetic axis. Deflection is due to the  $E \times B$  drift experienced by the particles, where  $E$  is the radially directed electric field due to the presence of the compressed plasma spindle. Both lithium ions and electrons will be used in the course of the experiments, electrons first in spite of lower deflection sensitivity to electric fields than the heavier lithium ions. Even if the electric fields are too weak for observation with an electron beam, the beam-deflection detection problem can be studied and (one hopes) solved.

It appears that the full output of the lithium ion gun ( $1.0 \text{ ma/cm}^2$  of anode surface) can be obtained in a focused beam only when the gun is immersed in magnetic fields  $> 10$  kilogauss. Thus, we are dependent upon the pulsed field of Table Top for focusing the beam, unless much smaller beam currents can be used, which is unlikely.

Final testing of the beam-focusing characteristics are expected to be performed on Table Top itself. Since no electrostatic focusing can be used without interfering with magnetic focusing, the gun will consist of merely a heated anode with a Pierce beam-extraction electrode. Many of the innumerable small problems of gun design have been solved. Those that remain should be solved before the gun is required for use on Table Top.

Beam-deflection detection mechanisms currently under test are (a) converting beam energy to light on the phosphor-coated terminus of several light guides and transmitting the light via the light guides (4 meters long) to photographic film or photomultipliers, (b) converting beam energy to heat in thermistor calorimeters of the same diameter as the beam and recording heat remotely, as has been done for plasma calorimetry. A 4-meter glass fiber light guide has been shown to transmit adequately the electroluminescence from the phosphor P-15 (the one we expect to use because of its sensitivity to low-energy electrons and positive ions). Adequate transmission is here defined as that which gives a current 10 times the dark current in a phototube at the other end. Tests of the thermistor-sensed beam-deflection detection are currently under way. If successful, mechanism (b) has the advantage of readability for many seconds after the pulse. The required heat sensitivities ( $0.1$  to  $1.0 \text{ millijoule mm}^2$ ) should be easily achieved.

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<sup>3</sup> "Plasma Calorimetry in Table Top," submitted as the final report on Project Agreement 23, Subcontract 122 between LRL and SRI.

## 6. TABLE TOP DIAGNOSTICS

James T. Mattingly

### Electron-Multiplier Rejuvenation

It has previously been shown that it is possible to rejuvenate an AgMg-MgO electron multiplier by gaseous discharges in argon and hydrogen.

This method was continued by using a CuBe-BeO structure in an argon atmosphere. After a drop in gain of two orders of magnitude had occurred by allowing the surfaces to "poison" in a poor vacuum environment, the rejuvenation process was commenced at low pressures and low currents for very short periods of time. After eight trials, the tube gain was almost back to the original measured gain.

The analysis of data indicated that the heating from the discharge was contributing to the rejuvenation of the structure. Another interesting note was that the discharge between the inner dynodes and the grounding plate at the front of the structure did not take place down the center through the dynodes, but around the structure on the periphery of the dynodes.

On the basis of the observation that heating is the factor for rejuvenation, an experimental structure was placed inside a ceramic cylinder heater in a vacuum. From a thermocouple on the insulation of the electron multiplier, the temperature of the structure could be observed and the heating controlled within 1 to 2 °C. From one observation, there is an indication that rejuvenation by this method can also be done, as observed by others.

## 7. PRELIMINARY BUILD-UP EXPERIMENT ("BABY ALICE")

James F. Steinhaus and Charles C. Damm

Operation of this experiment has been completed and a brief summary of the observations is presented here. Analysis of the data is proceeding and a complete report will be prepared.<sup>4</sup>

The beam of 20-kev hydrogen atoms had an intensity of 1.5 ma equivalent for most of the measurements, resulting in an estimated trapped-ion density of  $8 \times 10^5$  ions/cm<sup>3</sup>. Since the Debye length at this density is approximately equal to the machine size, we are dealing with essentially single-particle behavior.

<sup>4</sup>James F. Steinhaus and Charles C. Damm, The Trapping and Confinement of 20-kev Hydrogen Atoms in a Magnetic Mirror Machine, UCRL-6131 (in process).

The characteristic build-up and decay times for the trapped-ion density have been measured as a function of chamber pressure and magnetic field. For strong magnetic fields, the measured times are in reasonable agreement with the expected values based on a charge-exchange-dominated loss. Measurements were made in the pressure range from  $3 \times 10^{-6}$  to  $3 \times 10^{-5}$  mm Hg.

The variation of the observed decay rates with magnetic field intensity is shown in Fig. 3 for three pressures. The values expected from simple charge-exchange losses occur for field levels above about 8 kilogauss, but below this point a fairly sharp decrease in the decay period is recorded for all three pressures. The minimum value is governed by the turn-off time of the injected beam, which is about 4 or 5  $\mu$ sec. At 8 kilogauss, the proton orbit diameter is 2 in., and for the mirror spacing of 19.5 in. this yields a nonadiabatic parameter value ( $2\pi p/L$ ) of 0.32. Although a detailed theoretical computation has not yet been made for this case, it is not unreasonable to assume that nonadiabatic effects influencing the particle trajectories are responsible for the increased loss rates observed at lower fields.

The spatial distribution of trapped particles was sampled by means of the segmented detectors described in previous progress reports. Both radial and axial distributions were recorded, but the observations have not yet been adequately analyzed.

The neutralized fraction of total beam was found to be 0.70 at hydrogen pressures in the neutralizer between 0.4 and 3 microns. This is comparable to a predicted value of 0.80; the difference can probably be explained by re-ionization of beam atoms in the comparatively high-pressure region between neutralizer and trapping chamber. This region is not shielded magnetically, so that ionization results in prompt removal from the beam. Above 3 microns, the transmitted neutralized beam decreased sharply, probably due to Coulomb scattering in the neutralizer gas.

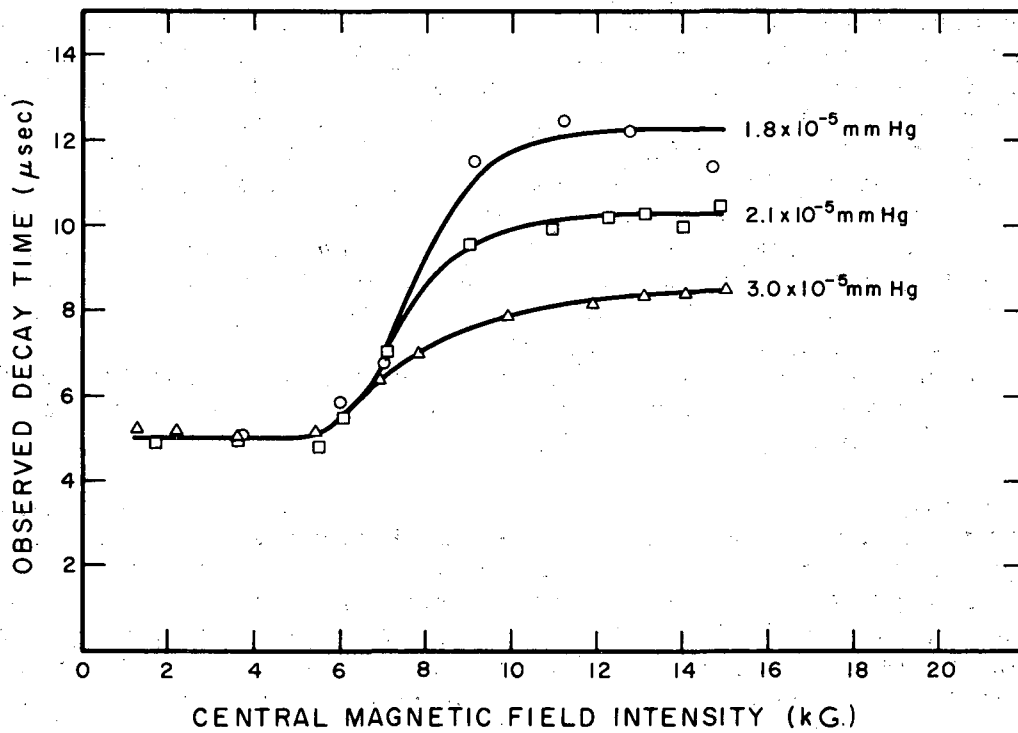
## 8. ALICE ION SOURCE

Frank J. Gordon

The new source, which was designed for mechanical compatibility with the rectangular magnetic-field coils, has now been assembled. In essence it is the same as the developmental source, but the engineering has been improved for ease in machining, assembly, and operation.

Beam trajectories based on the theoretical magnetic field configuration have been plotted, and appear satisfactory. Plots based on actual field measurements are under way. Final trajectories will have to be determined experimentally, and for this purpose adjustments are possible in such parameters as beam radius and exit angle, magnet separation, and source position.

Electrical and vacuum installations in the new building have progressed to near completion, so that operation of the source should be under way within a few weeks.



MU-21876

Fig. 3. Effect of magnetic field on observed decay time at constant pressures.

## 9. BEAM NEUTRALIZATION

Charles C. Damm and Archer H. Futch, Jr.

### Hydrogen Neutralizer

As was discussed in the preceding quarterly report (UCRL-9243), one of the difficulties associated with achieving the necessary vacuum in ALICE is the small component of thermal gas from the neutralizer that is directed straight through the beam tube. An earlier calculation had indicated that the molecular density in the trapping region of ALICE from this effect would be approximately  $10^8$  molecules/cm<sup>3</sup>. A more recent calculation based on the measured molecule-molecule scattering cross section indicates that this density may be reduced by at least one order of magnitude (to below the critical level) if adequate pumping speed is provided to adjust the pressure drop along the beam tube. In view of this possibility, attempts to devise a suitable discharge for shielding the plasma region from the directed thermal gas have been suspended. Neither of the two discharges tested<sup>5</sup> gave a measurable reduction of the transmitted D<sub>2</sub> thermal beam, indicating that more elaborate arrangements would be required to accomplish the shielding.

Since it seems advisable to have an early experimental measure of the effective gas density at the position of the magnetic axis of the ALICE mirror field, the hydrogen neutralizer and beam tube designed for ALICE are being assembled with the differential pumping chain including a simulated plasma chamber. The appropriate local density will be measured as a function of pressure distribution in the beam tube. A water vapor neutralizer will be tested in the same way at a later date.

### Water Vapor Neutralizer

The experimental apparatus to measure the efficiency of water vapor for neutralization of a low-energy ion beam (5 to 10 kev) has been completed. At present, the fraction of a proton beam neutralized as a function of beam energy is being measured. The data consist of both electrical and thermal measurements of the beam current. The thermal measurements are made by observing the rate of change in temperature of a small copper target as the beam is turned on or off. The charged component is deflected off the target by a transverse electric field in order to measure the neutral component.

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<sup>5</sup> Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960, p. 30.

## 10. VACUUM AND SURFACE STUDIES

Angus L. Hunt, Charles C. Damm, and Earl C. Popp

Recent work has been concerned with mass spectrometry, surface bombardment with energetic ions, and an oil-free experimental chamber for experiments on the gettering ability of evaporated metals.

Mass Spectrometry

With the valuable advice of W. J. Lange and others in the ultrahigh-vacuum group at Westinghouse Research Laboratories, a CEC 620 mass spectrometer is in operation. The commercial instrument was modified for baking at temperatures as high as 450°C. Mass peaks are easily observable at total pressures as low as  $10^{-8}$  mm Hg. Some results are available on the residual contamination in the type-304 stainless steel system before baking and after moderate baking at 200°C for 4 hours. Results were as follows:

| Relative peak heights before and after baking |            |           |           |           |           |           |           |
|-----------------------------------------------|------------|-----------|-----------|-----------|-----------|-----------|-----------|
|                                               | Mass units |           |           |           |           |           |           |
|                                               | <u>15</u>  | <u>16</u> | <u>17</u> | <u>18</u> | <u>20</u> | <u>28</u> | <u>44</u> |
| before                                        | ...        | 1.5       | 15        | 53        | 2         | 2         | 1.5       |
| after                                         | 1          | 1         | 10        | 38        | 2         | 4         | ...       |

The significant result appears to be the reduction in the 17- and 18-mass-units peaks, which can be interpreted as a reduction in the water vapor in the system. Hydrogen was also present in the system, but comparable peak heights are not available because the change in magnetic field intensity required to observe this component results in an uncertain change in sensitivity of the spectrometer.

Because of the proximity of an ionization gauge to the mass spectrometer, some interesting results on changes in relative magnitudes of components during operation of the gauge are available. Additional components originated in the gauge elements or in the stainless steel walls enclosing the gauge. Or equally, they could originate from the interaction of the hot filaments with desorbed components from the stainless steel walls surrounding the gauge.

When the ionization gauge filament was turned off, the hydrogen peak at 2 was reduced, by a factor of about 3, from 10 to 3, and that at 28 was reduced to by about the same factor, from 7 to 2. The major remaining mass-unit peaks 17, 18, and 20 were practically unchanged in magnitude.

With the gauge degassing and with a hot Mo grid, almost all mass units in the mid-mass range were observed: 12, 13, 14, 15, 16, 17, 18, 20 and 28, indicating hydrocarbon contamination.

Careful measurements were made of the relative magnitudes of the 17, 18, and 28 peaks during outgassing of the gauge. The indicated pressure increased on outgassing from  $5 \times 10^{-8}$  to  $5 \times 10^{-7}$  mm Hg. The magnitude of the 17 component did not change except when the Mo filament in the gauge was initially heated; then a burst of about 10 times the initial peak height was observed. The sudden increase in 17 peak is probably associated with a sudden desorption from the Mo grid of the gauge. A momentary increase in the 18 peak to three times its initial value was also found as the Mo grid was heated. As with the 17 peak, the 18 peak returned to its initial value as the Mo grid reached a constant high temperature.

The behavior of the 28 peak was quite different from that of the 17- and 18-mass-unit peaks. The 28 peak increased to 20 times its initial value as the Mo grid was heated, and remained at this high value. It is possible to assume that almost all the steady pressure rise to  $5 \times 10^{-7}$  mm Hg on outgassing the ionization gauge was due to an increase in the mass-unit-28 component. The 28-mass-unit component is most likely associated with desorption of contamination from the stainless steel wall.

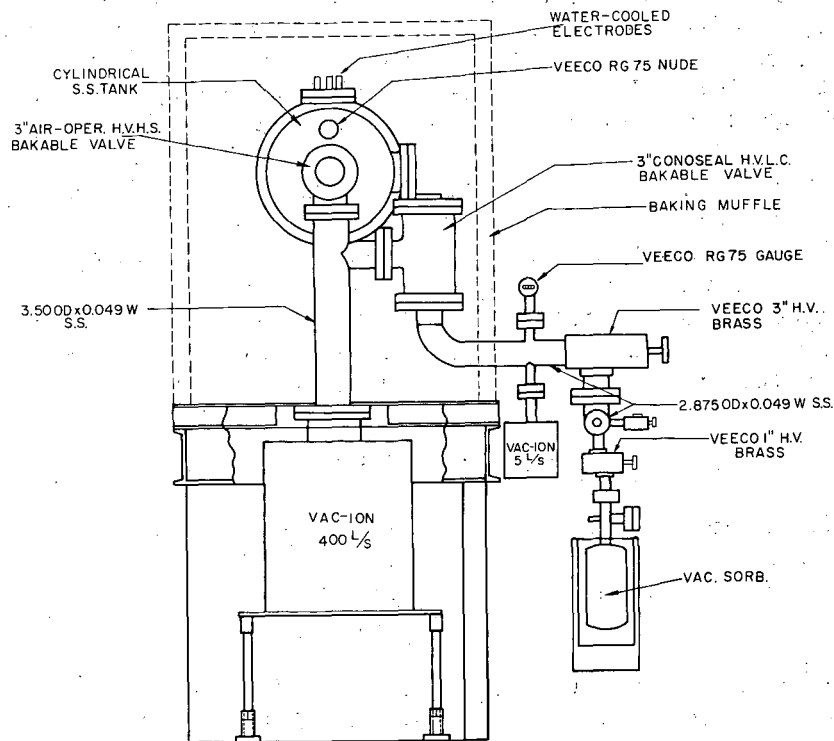
#### Surface-Bombardment Experiment

In the ALICE experiment, the number of molecules desorbed from the walls per incident fast neutral atom must be small if the background gas pressure is to remain low enough for exponential build-up of the plasma density.

From previous work it is known that hydrogen and deuterium molecules of thermal energies are efficiently adsorbed by deposit of evaporated molybdenum. It is not certain that neutral or ionic hydrogen and deuterium atoms of energies as high as 20 kev are as efficiently adsorbed by an evaporated deposit of molybdenum. It is also possible, if the wall surface is covered with a fraction of a monolayer of residual gas, that surface bombardment will desorb large numbers of residual gas molecules per incident high-energy particle.

It seems essential to obtain data on the effectiveness of molybdenum and various other wall materials as adsorbers for energetic hydrogen and deuterium atoms and on the components desorbed from these materials under vacuum conditions approximating those in the ALICE experiment.

A completely adequate experimental method appears difficult to achieve. One method is under development for determining the disposition of protons of energies up to 10 kev impinging on a target of molybdenum deposited on stainless steel. In this experiment, a mass-separated beam of a few micro-amperes traverses an ultra-high-vacuum region and enters the target chamber through a small defining orifice. The rate of pressure rise in the target chamber is recorded. If the rate of rise in the target chamber increases as the beam saturates the target, the target is initially effective in gettering the incoming beam. It is not known if this rate can be measured with the required precision, as reproducible results have not been obtained. A better experimental method, not dependent on a rate measurement, may be required.



MU-21881

Fig. 4. An experimental vacuum chamber free of all diffusion and forepump oil: left side view.

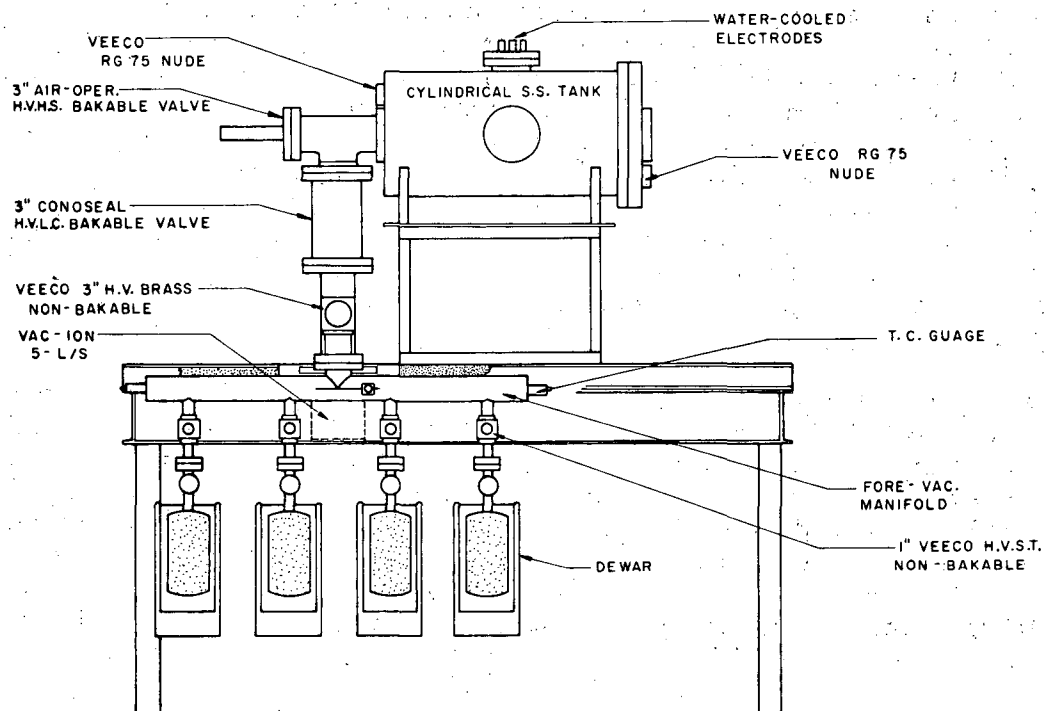
### Ionic and Sorption Pumping

To assure a cleaner substrate, free of all diffusion and forepump oil for molybdenum and other evaporated-metal deposits, an experimental chamber has been constructed using ionic pumping and low-temperature sorption pumps.

A stainless steel cylindrical cavity was carefully cleaned on the interior surfaces by solvents and sandblasting. The evacuating system consists of a Varian 400-liter/sec Vacion pump connected to the 70-liter cavity through a 3.402-in. i. d. stainless tubing, from which a foreline duct, 2.777 in. i. d., leads to a battery of four Varian 2-liter Vacsorb pumps operating as forepumps. This foreline can be isolated from the high-vacuum section by a 3-in. bakable valve. The Vacsorb manifold may, in turn, be isolated from the bakable valve by a 3-in. modified Veeco High-Vacuum valve. The section between these two valves is pumped by a 5-liter/sec Vacion pump. The arrangement of the system is shown in Figs. 4 and 5.

Filaments of the metal to be evaporated are supported in the cylindrical cavity by water-cooled electrodes. All gaskets in the bakable zone are single-pinch copper-nickel alloy, 90/10, except that on the large end flange, which is an experimental copper double-pinch design. This flange is equipped with energy-storing clamps to maintain pressure on the copper gasket when reannealing occurs during bake-out above 275°C. The zone between the two pinches is differentially pumped by the 5-liter/sec Vacion pump. Designs for the double-pinch flange, gasket, clamps, and the 3-in. bakable valve were by our Mechanical Engineering Support group.

The results of using two unbaked Vacsorbs with Type 5A Linde Microsieves, and operated sequentially, compare very favorably with our past experience using a Kinney KC 15 mechanical pump. The Vacsorbs pumped the experimental chamber, total volume about 80 liters, from atmospheric pressure to 5 microns in about 45 minutes, after which the Vacion pumps were started. After several days of operation, the pressure in the unbaked system, as indicated by two nude Veeco RG 75 ionization gauges, was  $1 \times 10^{-8}$ , while the ionization current in the 400-liter/sec Vacion indicated a pressure within the pump of  $6 \times 10^{-9}$  mm Hg. It was interesting to observe that one prebaked Vacsorb would hold the system at  $4 \times 10^{-5}$  mm Hg, with both Vacion pumps off, whereas an unbaked Vacsorb held the system at  $6 \times 10^{-4}$  mm Hg, indicating an improvement of more than a decade by baking the Vacsorb at 350°C for 2 hours.



MU-21882

**Fig. 5. An experimental vacuum chamber free of all diffusion and forepump oil: front view.**

## 11. AMBIPOLAR POTENTIALS IN A MIRROR MACHINE

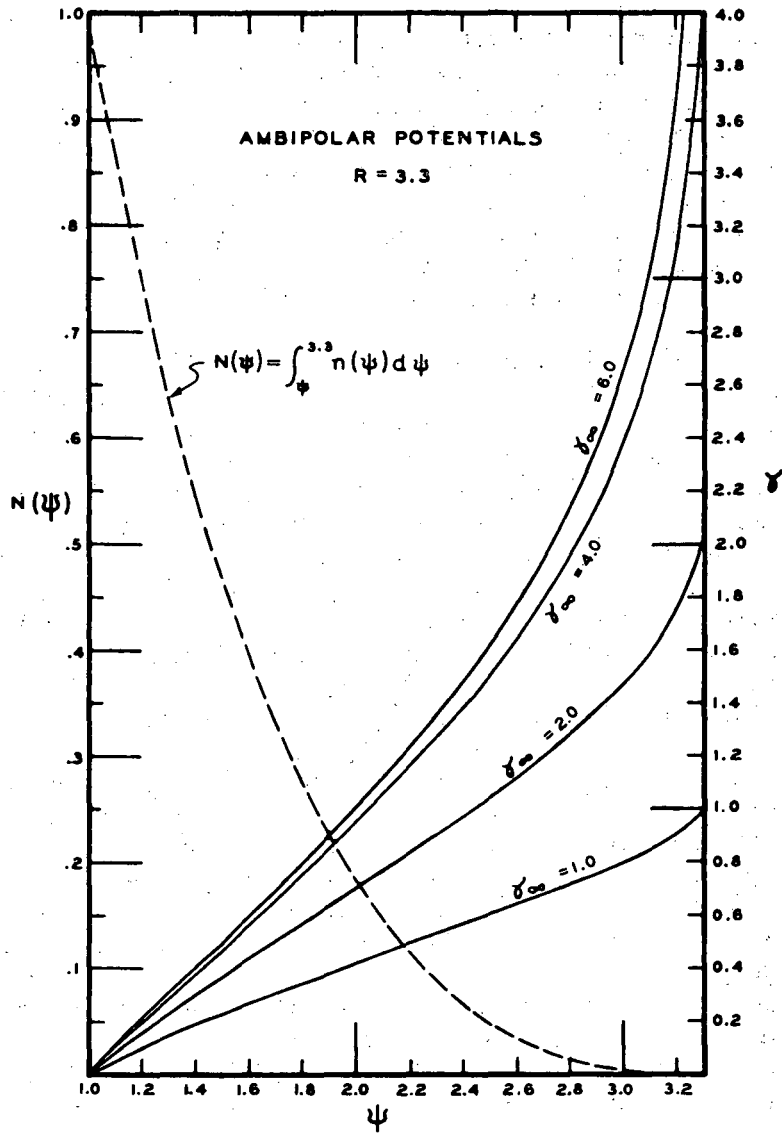
Richard F. Post

The plasma potential distributions in a mirror machine in which a high-energy group of ions and a lower-temperature electron component are confined are of interest in both the ALICE and the multistage compression experiment. In cases such as these experiments represent, it can be seen that the plasma will assume a net positive potential with respect to the chamber walls, so as to bring to equality the inherently more rapid loss rates of the electrons relative to the ions. The actual potential distribution attained may affect the stability proportions of the plasma, and will certainly have some effect on the rate of end losses.

A calculation of plasma potential which should apply in many cases of interest has been made. The method is to assume particle-distribution functions which are separately appropriate to the electrons and to the ions, from fundamental considerations, and then to find that potential distribution which yields a self-consistent particle-density variation in the region of the plasma between the midplane and the mirrors. In addition, it is assumed that the particle motions between the mirrors obey the adiabatic laws, i. e., small orbits and collision times long compared to a transit time. The distribution function of the electrons is then taken to be Maxwellian at the midplane, cut off at the plasma potential. The distribution function of the ions is fitted to the so-called "normal mode" solution of Judd, MacDonald, and Rosenbluth for the mirror diffusion loss problem.<sup>6</sup>

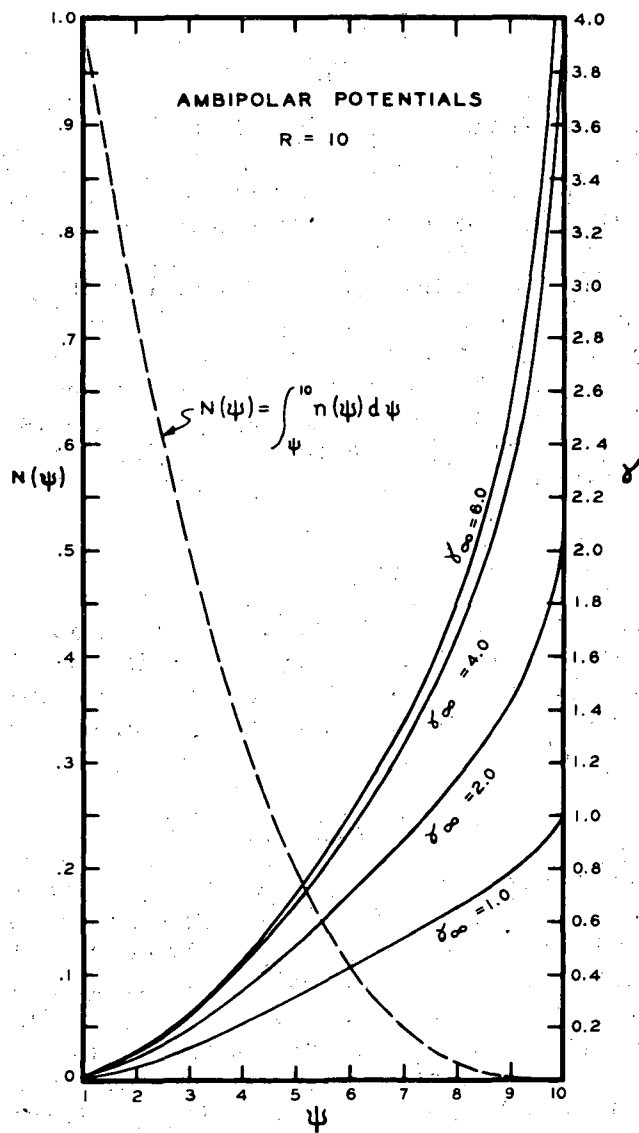
Figures 6 and 7 show the calculated potential distributions within the plasma for mirror ratios  $R = 3.3$  and  $R = 10$ . The potential is given in units of the electron temperature,  $\gamma = e\phi/kT$ , and  $\gamma_\infty$  on the curves refers to the total plasma potential. The potentials are plotted as a function of  $\psi = B/B_0$ , i. e.,  $\psi$  is a position variable which varies between 1 (at the midplane) and  $R$  (at the mirrors). The results are therefore plotted in a way which is independent of the actual field variation. It can readily be seen that for  $\gamma_\infty = 4$  or greater the internal potential distribution is relatively insensitive to the value of  $\gamma_\infty$ . Also plotted is the function  $N(\psi)$ , which is simply the total number of particles lying outside the point  $\psi$ . From these plots one can see that for  $\gamma_\infty = 4$ ,  $R = 3.3$ , for example, 80% of the particles feel a potential less than  $\gamma = 1$ , i. e., less than  $kT_e$ , and 99% feel a potential less than  $2.1 kT_e$ . For  $R = 10$ , the potentials felt by the average particle are an even smaller fraction of  $\gamma_\infty$ . The value of  $\gamma_\infty$  will depend on the value of the electron temperature relative to the ion energies, and should be about 4 to 5 in typical cases. If these calculated potential distributions are valid, they may be useful in interpreting the coming confinement experiments. They also appear to indicate that the correction to the end-loss formula arising from ambipolar effects may be substantially smaller than previously believed. The actual correction can be determined only by more detailed calculation, however.

<sup>6</sup>D. Judd, W. MacDonald, and M. Rosenbluth, "End Leakage Losses from the Mirror Machine," UCRL-2931, March, 1955 and Conference on Thermo-nuclear Reactions, Livermore, California, February 7-9, 1955, WASH-289.



MU-21874

Fig. 6. Theoretical ambipolar potentials. Mirror ratio  $R = 3.3$ .



MU-21875

Fig. 7. Theoretical ambipolar potentials. Mirror ratio  $R = 10$ .

## 12. P-4(STEADY-STATE PLASMA) SYSTEM

William L. Barr, Andrew L. Gardner, Laurence S. Hall,  
and Norman L. Oleson\*

Rotating Probe

Use of the rotating-probe assembly, with probes mounted in spoke fashion on a rotating axle, has permitted probing on the axis of the P-4 plasma column in a region where a stationary tungsten electrode would be evaporated even at floating potential. Preliminary measurements of ion density on the axis yield a value of  $1.5 \times 10^{13}$  per  $\text{cm}^3$ , in reasonable agreement with microwave indications of the range of electron density. Various measuring techniques for using the rotating probe will be tried. Besides allowing a probe to operate at a low duty ratio in the hot plasma, this device permits ready comparison of the characteristics of two probes so mounted on the same axle as to sample the same or adjacent regions of the plasma. It also provides an easy method of determining the extent to which a probe perturbs the operating characteristics of the system.

Probe Analysis

The theoretical analysis of the electrostatic probe problem is continuing, and a code for putting it on an IBM 709 is in the first stages of debugging. Progress on this problem is given in more detail elsewhere in this report (see L. Hall, D. Geesaman, R. Chazin, and J. Killeen in the report of the Theoretical Group, p. 67).

Hydromagnetic Waves

Some initial work has been done in the study of propagation of steady-state hydromagnetic waves along the plasma column of the P-4 system. Substantial care was found to be necessary in order to effect sufficient electrostatic shielding of a helical coil which surrounds the plasma column and magnetically couples to it for exciting or detecting the desired waves. Although the electrostatic shielding prevents pickup of much of the oscillation that is naturally present in the plasma, some modes couple magnetically to the pickup coil, and it will be necessary to detect the hydromagnetic waves in the presence of these oscillations.

Excitation Cross Sections of Lithiumlike Ions

Instrumentation is not yet completed for the lock-in amplifier arrangement to test the feasibility of these measurements in the P-4 system.

The problems of making such measurements in the P-4 system or by the use of crossed-beam techniques are discussed by R. L. Kelly in a final report of his work with the Pyrotron Program.<sup>7</sup> He points out that

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<sup>7</sup> R. L. Kelly, "Spectroscopic Pyrotron Diagnostics," Final Summary Report, Stanford Research Institute, Project No. SD-3116-2, July 15, 1960.

measurements with the crossed-beam technique are more likely to give unambiguous results. With the use of an ion-deceleration system it appears that Kelly's evaluation of the crossed-beam technique can be made more favorable by a factor of ten or so than he calculated, and the method would then seem to be feasible down to excitation energies of 10 to 50 ev. (The difficulty which then crops up is that of getting approx 10 ma of electrons over cross-sectional areas of approx  $1 \text{ cm}^2$  for lower electron energies.) If a suitable filter can be found to isolate the desired emission line, in the vacuum ultraviolet region, the increase in the detection sensitivity over that available by using a monochromator significantly relaxes this restriction, and measurements down to excitation threshold (about 8 ev) should be possible.

## II. ASTRON PROGRAM

### 1. INTRODUCTION

Nicholas Christofilos

During this quarter a small amount of work was done on the Dry Run Experiment, with most of the effort of the Astron group devoted to the testing of components of the Astron accelerator. The Astron program is now in the construction phase. Therefore no further experimental results of great interest can be expected until the facility is ready for experiments to test the Astron principle. In the interim any results will be of engineering interest only. Cores for the 5-Mev accelerator are being delivered and tested. Prototypes of the hydrogen thyratron modulators are being built. The 200-amp cathode has been successfully tested, and so on. The electrical engineering effort is described in more detail in the report of the project engineer, Vernon Smith.

The mechanical design of the mirror coils and the supporting structure has been completed. It is expected that all the mechanical components as well as the coils will be delivered on schedule.

During the construction phase physics experiments will be at a minimum, however, future results depend on the quality of the work done now and on the reliability of the components fabricated and tested. Therefore during the next 10 to 12 months the efforts and work of the group during this period will be extremely important, although not impressive in terms of any results on "plasma physics."

The remaining Astron theoretical problems are most difficult to handle unless drastic approximations are made and simplifying assumptions are employed to such an extent that the validity of the results would be questionable. Therefore any attempt to obtain valid solutions is bound to be very time-consuming. A characteristic example is the self-consistent equilibrium solution of the E layer, on which Dr. L. Tonks has spend more than two years. A similar but more difficult problem is to find a self-consistent solution of an E layer of finite length. Dr. Leslie Peck\* has been formulating this problem, recently, for a computing machine solution.

Professor C. C. Chang is working on the self-consistent solution of the E layer in the presence of a plasma. He has obtained, thus far, an exact solution in the simplified case of a straight electron beam traveling along the y or z direction, while beam electron density is a function of x only. The solution for the actual cylindrical layer appears to be extremely difficult. For these reasons, it does not appear that any substantial results of theoretical efforts will be available before the facility is ready for operation. However, a theoretical effort parallel with the experiment is always extremely useful in the preparation of the experiments and the interpretation of the experimental results.

Reports by Professor Chang and Dr. Thomas Lundgren, and also one by Dr. A. Saperstein, on different aspects of the Astron are included in the Theoretical Section of this Quarterly Report.

\*Consultant to Lawrence Radiation Laboratory, from Boston, Massachusetts.

## 2. DRY RUN EXPERIMENT

Ross E. Hester

During this period some work was done on beam trapping. The geometry was the same as reported previously, (UCRL-9245) with the addition of "A" coil. The A coil was located adjacent to the beam collimator; it was arranged so that the beam left the collimator, passed between turns of the A coil, and entered the tank. As the beam traversed the tank, reflected from B mirror coil and returned toward the injector, the A coil was pulsed on forming a magnetic mirror to trap the beam.

The injected beam was monitored by the grid located at the last collimating slot. This signal was calibrated by comparing it with signals obtained by collecting the total beam on a collector flag. The amount of charge trapped was determined by dumping the B coil, letting the trapped beam strike a beam collector located outside B coil.

The dump time for B coil was varied from 10  $\mu$ sec to several milliseconds after injection. Some delay was required in the dump time because the rf generated in the tank took from 2 to 3  $\mu$ sec to build up and be dissipated. Although the rf was too low to affect beam containment, it did prohibit the use of beam detectors during the first 2 or 3  $\mu$ sec after injection.

It was observed that under the conditions of the experiment an upper limit of  $10^{12}$  total particles was trapped. This number could be achieved with a very small injection current and good trapping efficiency, but was not exceeded as the injection current was increased. It was observed that coupling between A coil and the beam became too severe as the beam current was increased. An electrostatic shield helped but did not eliminate the problem. The A coil also oscillated too much after being pulsed. This oscillation allowed the mean life of the trapped particles to vary from 500  $\mu$ sec to several milliseconds, depending on the degree of oscillation.

It appeared that the limit of  $10^{12}$  particles could have been increased by redesigning A coil and its pulsed power supplies. Because the new Astron injection system does not use pulsed coils to trap the beam, and the laboratory space was needed to commence construction of the new Astron accelerator, this experiment was discontinued.

### III. LIVERMORE PINCH PROGRAM

Dale H. Birdsall, Edmund S. Chambers, Stirling A. Colgate,  
Harold P. Furth, Fred O. Halliday, Charles W. Hartman,  
and Ross L. Spoerlein

#### 1. SUMMARY

The construction of the 12-inch levitron has advanced to the point of vacuum testing, with the ring and liner in place. The electron beam is now functioning reliably as a pinch probe, and rough estimates of plasma resistivity are being made for the first time by this technique. Plasma acceleration in the conical pinch has been shown to depend purely on the formation of a local conical acceleration region near the exit orifice.

The liquid sodium experiment has permitted observation and freezing of highly stable free-floating equilibrium shapes in cusp geometry. With the same apparatus converted to mirror geometry, violent instability is observed. The experiment on ion heating by torsional waves in a mirror machine has continued to demonstrate the dominant role of rf sheaths. A number of theoretical studies have been made on plasma turbulence, hydromagnetic stability of pure- $B_\theta$  pinches, and the destabilizing influence of finite resistivity on sheet pinches. As part of a research project to develop new energy sources, a 3-megajoule unipolar generator has been put into operation, and a new scheme for inductive storage has been designed.

#### 2. ELECTRON BEAM PINCH

A thorough study of the effect of preionization on pinch centering has now been completed. Various techniques of preionization have been tried (see preceding Quarterly Report, UCRL-9243). Pinch operation down to  $1 \mu$  base pressure was found possible with a heated filament. The best technique for forming a symmetrical pinch, however, makes use of a ring of twelve triggers simultaneously fired in the cathode.

Accurate centering of the beam injected on axis is now obtained well into the pinch cycle, up to about the time of maximum current, when gross distortion of the plasma column begins to occur. If the beam is injected at radii other than zero, a constant-radius arc is traced which agrees roughly with what would be expected from the probe measurements. From the angle subtended by this arc the instantaneous pitch of the field lines is derived, and therefore the resistivity can be inferred for a given flux surface as it moves radially inward. Preliminary results indicate resistivity in the range  $10^{-2}$  to  $10^{-3} \Omega\text{-cm}$ .

### 3. CONICAL-PINCH PLASMA ACCELERATOR

The conical pinch has undergone a number of configurational changes in the past quarter, and an indication of the nature of the acceleration processes has been obtained. Modifications and their effects on acceleration, as measured by a piezoelectric probe 5 cm from the exit, are the following.

Replacement of the conical insulator by a cylindrical one leaves the acceleration characteristics relatively unchanged. To demonstrate from what region of the pinch the accelerated plasma originates, a thin, movable metal diaphragm, with the same diameter as the exit orifice, has been inserted on axis and perpendicular to the pinch column. The acceleration process is unaffected so long as the diaphragm is more than a hole diameter from the exit. The time of arrival of plasma at the probe is independent of the axial position of the diaphragm, indicating that axial acceleration occurs in the immediate vicinity of the exit orifice.

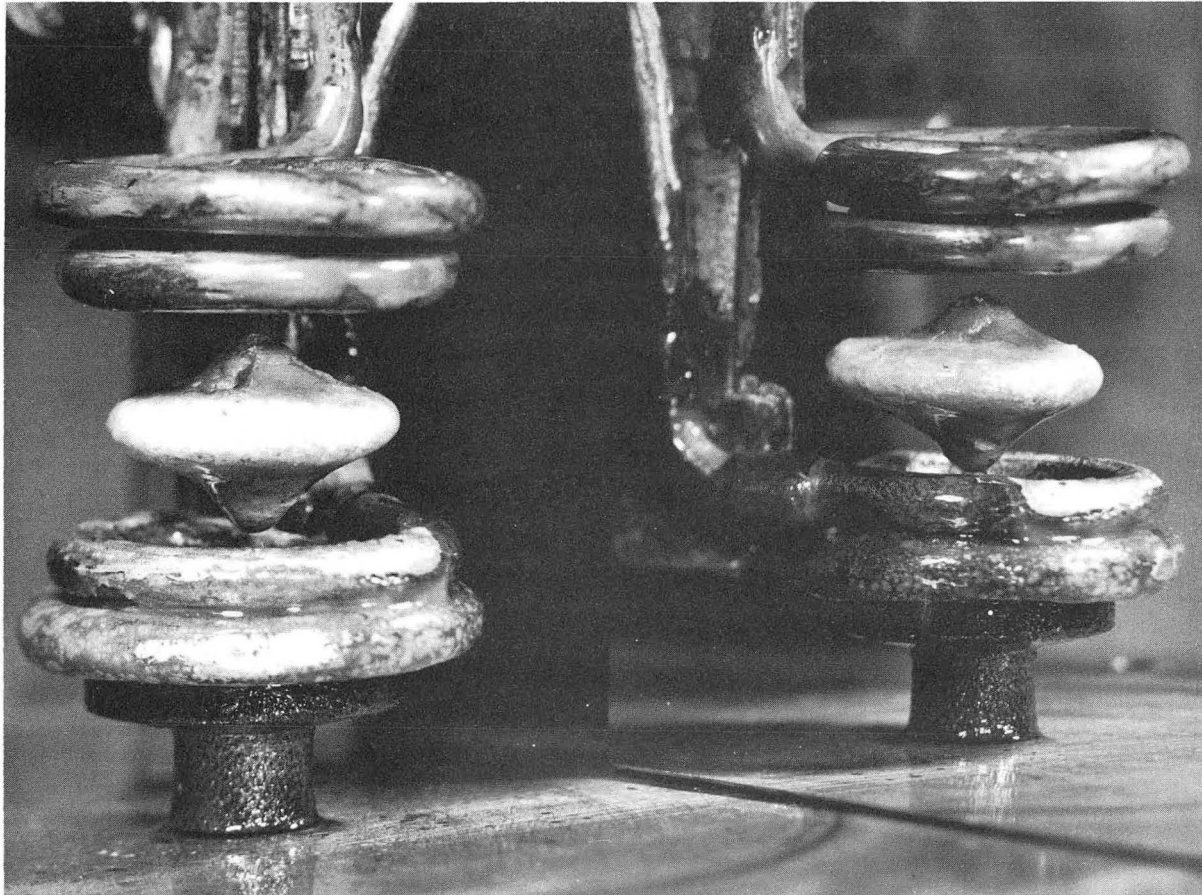
The conclusion that acceleration is localized at the exit region is further supported by the disappearance of acceleration when the exit is bridged by metallic conductors such as 50% transparent fine-mesh screen or a 95% transparent radial-spoke structure. If the same screen is located at a distance from the electrode, it does not stop the accelerated plasma.

The acceleration mechanism therefore appears to be the following: an ordinary pinch front moves radially inward with uniformity in the axial direction, except for a slight modification due to the conical structure, until the plasma diameter equals the exit orifice diameter. After this time the pinch current must flow to the rim of the orifice in the exit electrode, while compression continues. Thus a small "conical pinch" is formed in the exit region, which accelerates plasma as expected.

Probe measurements have shown that the current distribution near the exit orifice is much sharper when the exit electrode is the cathode. (This is consistent with anode-cathode asymmetry observed on the linear hard-core pinch.) Accordingly, the observed polarity dependence of acceleration (higher velocity when the exit electrode is negative) is most plausibly explained by the difference in hydromagnetic configuration near the exit, rather than by a direct electrostatic acceleration mechanism.

### 4. LIQUID SODIUM EXPERIMENT

A set of two vertically adjacent mirror or cusp (or both) field coils has been completed and has allowed the observation of hydromagnetic stability in the two geometries (see Fig. 8). With the coils in mirror geometry and a two-to-one mirror ratio, it was impossible to hold a sodium blob, either liquid or solid, even transiently within the field. As a consequence, only the  $m = 1$  instability was observed. In the cusp geometry, on the other hand, any pellet was stable, and liquid sodium could be frozen into its equilibrium shape by the simple expedient of squirting the hot liquid into the equilibrium location within a cold oil bath. The cusp shapes so formed, however, were determined in part by surface tension



ZN-2604

Fig. 8. Liquid sodium cusp experiment.

forces, so that the results cannot properly be compared with theoretical predictions for a hydromagnetic-hydrostatic equilibrium. In order to reduce the effect of surface tension forces, a larger model cusp (3-in. diam) is being made.

### 5. 12-INCH LEVITRON

The hard-core ring was assembled inside the inconel-x liner, and the liner completed and closed. The entire liner assembly was then fitted into the insulated copper shell and a first attempt was made at vacuum sealing. Unfortunately, the edge loading of the copper shells was great enough to cause a deformation of the shell lip under vacuum load, so that the vacuum seal proved imperfect. Roughly 50 microns was achieved, and the basic operation of the vacuum system was checked. The assembly was then dismantled in order to add a stainless steel H bar to strengthen the lips of the shell. It is expected that the H-bar support will be more than ample to hold the stress of vacuum, Mylar insulation, and z-field coils.

The four mechanical levitators have operated successfully through a few hundred cycles, without disrupting the positioning of the heavy core on the support rods. They are now being rigged in their final position for the operation of the core inside the levitron. The cribbing and iron are in place, ready for the levitron assembly. The insulation of the laminated iron has been checked and found sufficient.

The technique for winding the z-field coils has been planned and appears straightforward. Similarly, a Mylar taping machine has been developed to apply the principal insulation on the torus assembly.

The mass spectrometer power supply has been completely redesigned in order to avoid a filament modulation that was in turn modulating the primary output. This modulation destroyed the mass resolution for fast readout. Otherwise the mass spectrometer has performed satisfactorily.

An experimental plasma-injection facility has been assembled to measure the density and energy of the plasma that can be injected under the available conditions of magnetic field and voltage.

A liquid nitrogen finger trap has been assembled that can be inserted into the levitron to greatly increase the pumping speed of condensables.

The modifications of the main condenser bank have been completed.

## 6. ION HEATING BY TORSIONAL WAVES IN A MIRROR MACHINE

A number of different probes and loops were used to determine the time lag between a fast-rising driving pulse and the signal received at the far end of the machine. It appears that this lag is very short compared with that calculated from the equation for Alfvén velocity. Also, there is no appreciable change in velocity when the static magnetic field or the gas density is varied. The shape of the received pulse is dependent on the polarity of the driving pulse, especially when a load is attached at the receiving end. These results suggest that the mechanism of propagation is related to sheath formation rather than to hydromagnetic waves. This confirms earlier results on input impedance, etc.

A copper strip was placed with one edge about 5/8 in. outside the plasma, in a plane intersecting the machine axis. The deuterons accelerated by the driving field struck the copper and darkened it. Since the ions rotate in only one direction in the magnetic field, only one side of the strip was affected. The darkened area was about 1 in. deep (radially) at the center and tapered off to zero about 7 in. along the axial direction on either side of the mid-plane. When the neutral density was raised by a factor of 3, the axial extent of the darkened area was only half as great.

By evaporating 200 Å of  $\text{SiO}_2$  onto  $\text{MoO}_3$  "film," (see preceding Quarterly Report, UCRL-9243) practically all the warm neutrals resulting from charge exchange in the PIG discharge without rf were prevented from affecting the film. When the rf was applied, the resultant hot neutrals turned the film a darker color. However, no structure was observed. This is not surprising, considering the copper strip results.

Owing to the closing down of the present experimental area, the experimental effort on this project has not stopped, and a comprehensive report is to be written.

## 7. THEORY

A theory of plasma turbulence has been developed,<sup>1</sup> with a view to explaining anomalous resistivity and particle losses in the pinch. Large electric fields can occur, along magnetic lines of force, because of ion motion across field lines, the neutralizing electron current being limited by inductance. The local potential drops are proportional to  $(\lambda/r_i)^4$ , where  $\lambda$  is the wave length of the disturbance and  $r_i$  is the ion gyro-radius. On this model, very-short-wave-length disturbances do not contribute significantly to resistivity.

The hydromagnetic stability of various diffuse (infinite-conductivity)  $B_\theta$  pinches has been analyzed,<sup>2</sup> by using Kadomtsev's criteria for  $m = 0$

<sup>1</sup>S. A. Colgate, Turbulence in Plasma, UCRL-5888T, Aug. 1960.

<sup>2</sup>H. P. Furth, Hydromagnetic Stability of Diffuse  $B_\theta$  Pinches, UCRL-6107-T, Aug. 1960.

and  $m = 1$  stability in the absence of  $B_z$  field. The diffuse tubular dynamic pinch (Triax) is found unstable against  $m = 0$  and  $m = 1$  modes. (The instability growth rates, however, may be very small.) Hard-core pinches without nulls in  $B_\theta$  are stable against all modes, provided that

$\frac{\partial B_\theta}{\partial r} < -\frac{B_\theta}{2r}$  in the region where  $\frac{\partial p}{\partial r} < 0$ . Some general necessary criteria for  $m = 0$  stability are

$$\frac{\partial B_\theta}{\partial r} < \frac{B_\theta}{r}$$

and

$$\frac{\partial p}{\partial r} > -2\gamma \frac{p}{r}$$

in the region where  $\frac{\partial p}{\partial r} < 0$ .

The astrophysical concept of the "neutral point" instability has been applied to pinch-current layers.<sup>3</sup> It is shown that sheet pinches that would be stable for infinite conductivity are subject to "tearing" modes when finite resistivity is assumed. For sheet pinches resembling the current layer in the "stabilized pinch", the tear is expected to be helical. (This prediction is in accordance with results obtained on tubular sodium pinches.) A machine calculation is being started to investigate these processes in detail. A new type of plasma accelerator has been designed,<sup>4</sup> which makes use of the tearing instability to convert magnetic energy stored in a tubular (reverse-field)  $B_z$  pinch into axially directed kinetic energy of the pinched plasma.

## 8. ENERGY-SOURCE STUDIES

The unipolar generator has been "motored" up successfully, by using a 1600-amp-low-voltage supply, to a speed of 7000 rpm. The field-pulsing circuit has been installed so that a test of the high forced-field armature-voltage pulse can soon be made. The high-output-current test still awaits the completion of the resistive load and switch, but the initial successful operation gives promise of the achievement of easily controlled megajoule pulses delivered within 1/10 sec.

A new technique has been devised for making inductive storage more practical. The basic problem here is to interrupt the storage circuit without causing high-voltage transients or dissipating a large fraction of the energy in the interrupter switch. With an inductive load, the only solution is to use a shunt capacitor bank, but the peak storage in this bank amounts

<sup>3</sup>H. P. Furth, Resistive Relaxation of Perturbed Current Layers, UCRL-6071-T, July 1960.

<sup>4</sup>H. P. Furth, An Instability-Type Plasma Accelerator, UCRL-6118-T, Aug. 1960.

to half the energy stored in the inductance. It is now shown<sup>5</sup> that if  $N$  storage inductances are used in parallel, and are discharged successively, then the total energy transferred can amount to  $N(N+1)$  times the peak energy storage in the shunt capacitor bank.

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<sup>5</sup>H. P. Furth, Inductive Energy Storage Made Practical by Subdivision of the Storage Inductance, UCRL-6021-T, June 1960.

#### IV. BERKELEY PLASMA RESEARCH

##### 1. SHEET PINCH STUDIES

Oscar A. Anderson

###### Introduction

Most of the preceding quarter has been used to develop new equipment. The 100-kilojoule bank with its associated gear is now complete, and the  $8 \times 10$  Triax has been installed together with a redesigned preheating bank. (The latter was built after magnetic-probe measurements showed that the preheating current was still not sufficiently uniform.) A new tube, of 6-in. i. d. and 10-in. o. d., has been designed and constructed but not yet assembled in final form. The silicone gel insulation considered for this tube was tested for its properties in the event of a high-energy breakdown, and found to be hazardous.

###### $8 \times 10$ Tubular Pinch

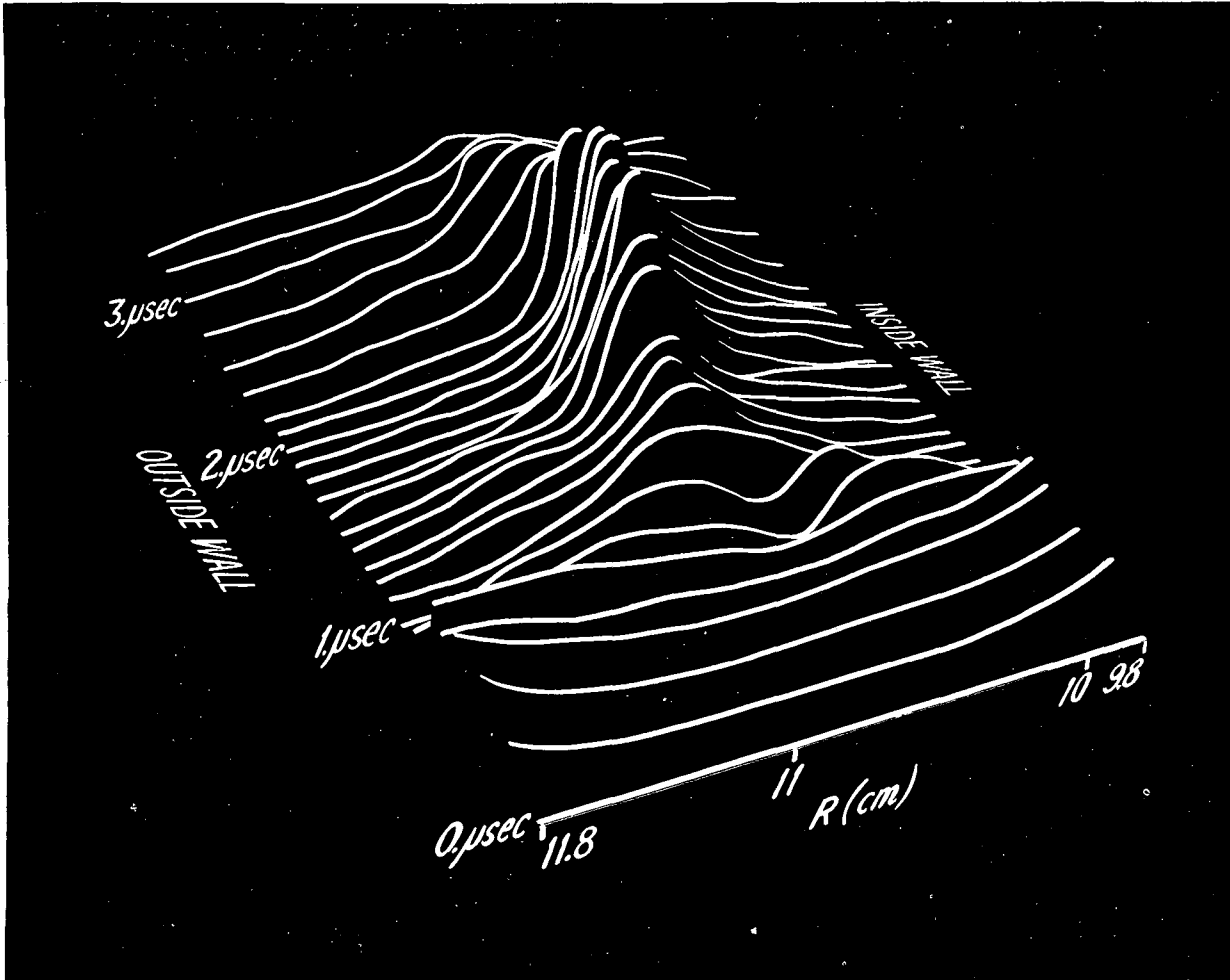
The magnetic-probe measurements made last quarter have been used to compute the current-density profiles shown in Fig. 9. The conditions were the same as for the streak photograph in UCRL-9106, Fig. 16. Because of occasional signal variations, it was necessary to use some selection and smoothing of the data; the results should be regarded as approximate. However, there is general agreement with the streak-photography data and further evidence that a well-defined pinch is maintained past the current peak.

The variations in the probe signals were investigated and found to originate in the preheating pulse, as shown by magnetic field measurements. A new preheating bank has been built which delivers  $10^5$  amp in less than 0.5  $\mu$ sec. This is fast enough so that the current distribution tends to depend on the tube geometry rather than irregular cathode effects. It is also fast enough to minimize the possibility of longitudinal rips, which can occur in cold plasma sheets over a period of time. Improved symmetry and reproducibility have been observed; experience will show whether any further modifications will be required. If the behavior is still unsatisfactory rf preionization, which was shown to promote initial symmetry in a stabilized-pinch experiment at Livermore, will be investigated. Measurements of resonance modes in the Triax system have already indicated that application of rf power will not be difficult.

The 200- $\mu$ f 100-kilojoule condenser bank has been assembled with all its associated control equipment. Four low-pressure switches with Venetian blind electrode apertures<sup>2</sup> are employed in parallel. The switches may be fired simultaneously, or with any desired relative time delays. The  $8 \times 10$  Triax has been removed from the 50-kilojoule bank (which will henceforth be used for cusp experiments) and installed on the new bank.

<sup>1</sup>Harold P. Furth, Eng. Note UCRL-6071-T(4506-41 CVL-23) and private communication.

<sup>2</sup>Oscar A. Anderson, in Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960, p. 66.



ZN-2602

Fig. 9. Current density as function of radial position and time in the  $8 \times 10$  Triax pinch. Peak current,  $1.2 \times 10^6$  amp. Initial deuterium pressure,  $830 \mu \text{ Hg}$ .

### Silicone Gel Insulation

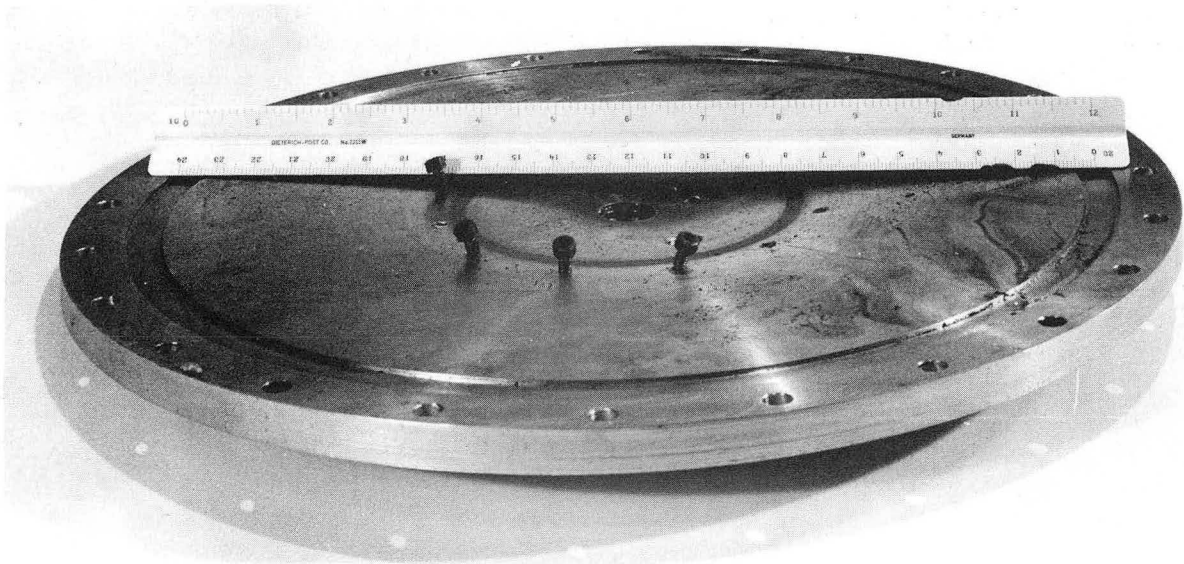
Some encouraging measurements on the electrical strength of Dow-Corning F-1 0042 dielectric gel were described in the preceding quarterly report.<sup>3</sup> This material was one of those considered for insulating the critical region where high voltage enters the Triax. A new tube, the  $6 \times 10$  Triax, was designed which allowed the use of either high-pressure gas, silicone gel, or other improved insulation materials which might be available in the future. The assembly problems with this tube have finally been solved and it should soon be ready for operation. Meanwhile a check has been made on an important property of the insulation, namely the mechanical pressure generated by an accidental breakdown. A test assembly was built which simulated the Triax terminal region except that the high-voltage clearance was reduced. The assembly vessel was filled with silicone gel and connected to a condenser bank. The vessel was a 4-in. cylinder made of 1/8-in. copper, with a 1/2-in. -thick brass lid. Only one-fourth of the 100-kilojoule bank was employed, and the breakdown occurred at a voltage corresponding to 15 kilojoules. Figure 10 shows the results; note particularly the deformation of the brass plate. The high pressure generated by the discharge is presumably due to gases evolved from the gel. Evidently the problem cannot be met by brute strength alone. One solution is to provide suitably located rupture discs. Another is to revert to gaseous insulation because of its lower destruction potential. Fortunately, the  $6 \times 10$  tube was designed with this possibility in mind, and without the gel it should still withstand twice as much voltage as the older Triax tubes.

### Future Plans

One of the first things to be learned with the 100-kilojoule bank is whether its longer-lasting current pulse will permit longer plasma containment times, as expected. This will first be studied at a temperature comparable to that obtained with the 50-kilojoule bank. The next step will be to observe the effects of higher energy. The well-known detrimental effects of impurities at energies above 100 volts will be avoided, it is hoped, by purifying the deuterium gas with a palladium filter at the inlet, and by using an improved pumping system now being designed. Oil migration will be low under all operating conditions. Most of the components for this system are now on hand.

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<sup>3</sup>Oscar A. Anderson, in Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960, p. 70.



ZN-2603

Fig. 10. Damage to fixture used for testing pressure of silicone gel discharge. Condenser-bank energy, 15 kilojoules.

## 2. HOMOPOLAR PROGRAM

G. Donald Paxson, William R. Baker, and Wulf B. Kunkel

Work on Homopolar IV, the Puffatron, has emphasized building, installation, and testing of the associated auxiliary equipment. A brief description of this work follows.

1. A Varian 75-liter "Vac Ion" pump has been purchased and put into operation on Homopolar IV, resulting in a pressure approximately  $7 \times 10^{-7}$  mm Hg without the aid of a liquid nitrogen trap. The improved vacuum enables the machine to withstand dc voltages of 120 kv, of either polarity between the electrodes, and also is responsible for a considerable increase in the intervening time between application of the high voltage and the voltage breakdown of the machine when this voltage is applied in the presence of the magnetic field. The breakdown time has been increased (at 80 kv and 20 kgauss) from a few hundred microseconds to more than 5 msec, thus greatly extending the useful time of the machine during each cycle of operation.

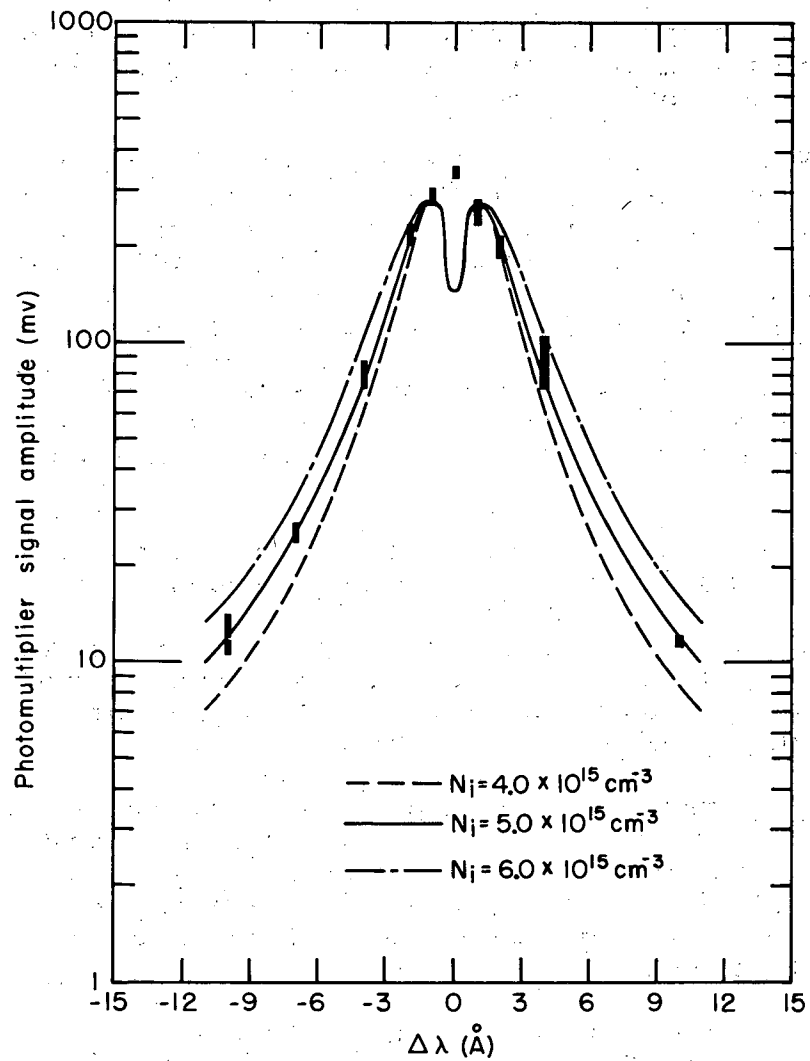
A new liquid nitrogen trap has been designed and constructed, and is currently being installed as an aid for the ion pump.

2. Two waveguide windows for microwave diagnostics have been installed, one in each end of the machine. The 8-mm klystron oscillator with its auxiliary equipment has been tested, and a signal has been transmitted successfully through the length of the machine.

3. The puff valve has been assembled and tested quite thoroughly. The tests included a life test, in which the valve was operated 450 times with no sign of wear or damage. The amount of gas delivered by the valve was measured, and the solenoid valves and check valves for operating the piston of the puff valve were assembled, and the complete cycling system was thoroughly tested.

A voltage signal from a coil in the puff-valve assembly is generated when the piston moves through the coil. This signal, after amplification, will trigger "on" the pulsed magnetic field. A second signal is produced by a barium titanate microphone button when the piston strikes the Lexan valve stem. This signal will trigger "on" the high-voltage Marx generator. These two signals have been tested for amplitude, duration, and reliability under actual operating conditions, and two transistor amplifiers for the signals have been built and tested. The pulse outputs from the two amplifiers are brought to ground potential through two carefully shielded isolation transformers which have been built and tested for 120-kv insulation, and also tested successfully for a maximum of 5-mv secondary signal when the primary winding is pulsed 100 kv with respect to ground.

Now that all associated equipment has been built and tested, the next few days will see the installation of the puff valve and the beginning of actual tests on the machine.



MU-21860

Fig. 11.  $H_\beta$  profile 30  $\mu\text{sec}$  after crowbar with three theoretical line profiles;  $T = 10,000^\circ\text{K}$ .

### 3. HYDROMAGNETIC WAVE AND CYCLOTRON HEATING

#### Hothouse I

William S. Cooper III, Alan W. DeSilva, and John M. Wilcox

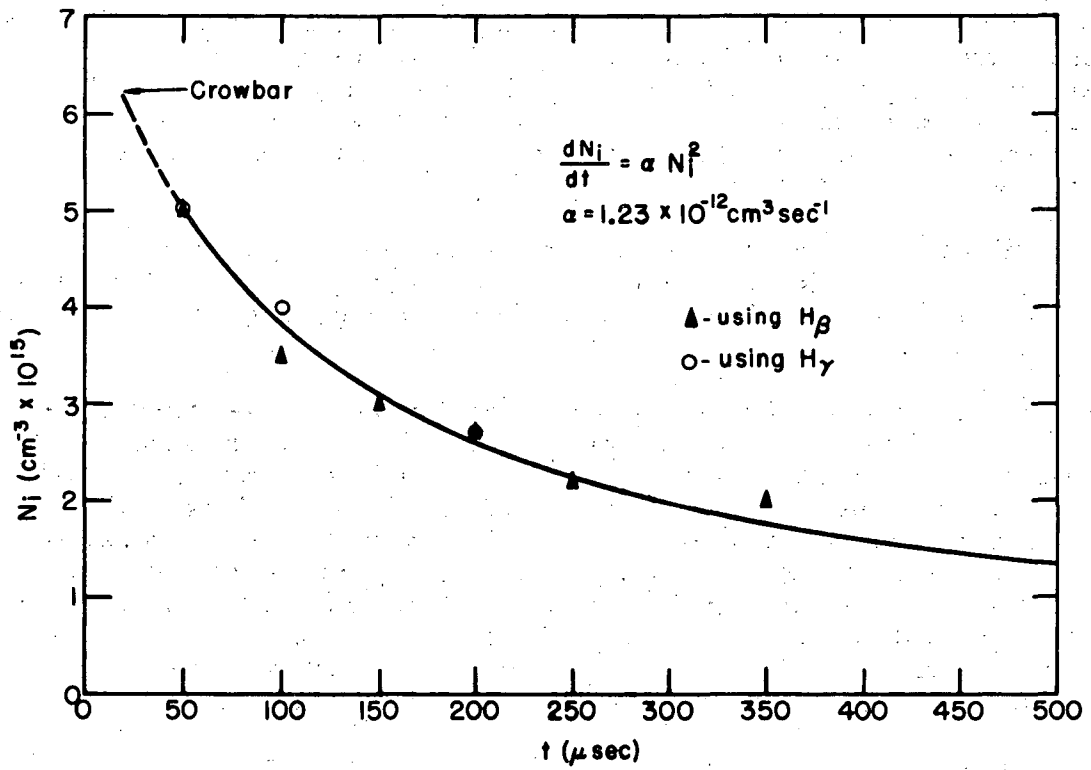
The spectroscopic diagnostic work begun during the preceding quarter was continued. The impurity lines that appear in the spectrum if the bank is not shorted as soon as the ionizing front reaches the end of the tube were identified. The profiles of three of the hydrogen Balmer lines,  $H_\alpha$ ,  $H_\beta$ , and  $H_\gamma$ , were determined as functions of time after crowbar by using a monochromator, and the ion density determined as a function of time from the observed Stark broadening of these lines.

A Hilger-Watts constant-deviation prism spectrograph was used with Eastman Type 103F glass plates in the spectroscopic work. The lines that appear in the spectrum if the machine is not crowbarred were identified as due to Si II, Si III, Si IV, O I, O II, Na I, and C II.

Two Jarrell-Ash Model 82-000 monochromators were set up to permit simultaneous observation of two spectral lines. The monochromators were used with a beam splitter in the optical system so that both observed light from a column of plasma about 2 in. in diameter lying along the axis of the tube. With the use of these monochromators the profiles of the first three lines in the Balmer series,  $H_\alpha$ ,  $H_\beta$ , and  $H_\gamma$ , were measured as functions of time. The line profiles were determined by measuring the intensity at 11 points, spaced 0, 1, 2, 4, 7, and 10 Å on each side of the line center. A number of shots were taken at each point (usually 6), and the results averaged. Cross plots then gave the line shape as a function of time.

The observed line profiles were then "best-fitted" by eye to theoretical curves taken from Griem, Kolb, and Shen,<sup>4</sup> and the corresponding ion densities noted. A sample  $H_\beta$  profile, for 30  $\mu$ sec after crowbar, is shown in Fig. 11. The errors shown for the intensity at each point represent the standard deviation of the mean for all the shots taken at that point. Errors in  $\Delta\lambda$  are estimates. Three theoretical curves are drawn for ion densities of 4.0, 5.0, and  $6.0 \times 10^{15} \text{ cm}^{-3}$ . These curves were arbitrarily matched at their maximum values. The temperature at this time was estimated (by observed damping of Alfvén waves and relative intensities of Balmer lines in the recombination spectrum) as 1 to 3 eV. The theoretical line shapes are fairly insensitive to temperature in this range, and all three curves are drawn for  $T = 10,000^\circ \text{K}$ . The theoretical dip in the center of the  $H_\beta$  line was not observed. It may have been filled in by Doppler broadening or Zeeman splitting (both amounting to about 0.5 Å), or by light from regions of much lower ion density near the pyrex endplate.

<sup>4</sup>H. R. Griem, A. C. Kolb, and K. Y. Shen, Phys. Rev. 116, 4 (1959);  
idem NRL Report 5455, March 4, 1960.



MU-21861

Fig. 12. Ion density as a function of time.

Ion densities determined in this way ranged from  $5.0 \times 10^{15} \text{ cm}^{-3}$  at 30  $\mu\text{sec}$  after crowbar to about  $2 \times 10^{15} \text{ cm}^{-3}$  at 330  $\mu\text{sec}$  after crowbar. The ion density as a function of time is shown in Fig. 12, using data from the  $H_\beta$  and  $H_\gamma$  profiles. A volume-recombination curve has been fitted to these data, using the volume-recombination coefficient  $\alpha$  as a fitting parameter. The value of  $\alpha$  thus determined is  $1.2 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$ . This is about twice the theoretical value for hydrogen, as calculated by Zanstra,<sup>5</sup> for  $T = 10,000^\circ\text{K}$ . It must be noted, however, that the volume-recombination coefficient  $\alpha$  is a function of the temperature, which must be changing with time. It is surprising that a curve calculated for constant  $\alpha$  fits the data as well as it does.

Errors in  $N_i$  in Fig. 12 are estimated at about  $\pm 0.5 \times 10^{15} \text{ cm}^{-3}$ . The curve of ion density versus time extrapolates back to a value of  $6.2 \times 10^{15} \text{ cm}^{-3}$  at the time of crowbar, corresponding within the experimental errors to 100% ionization of the neutral hydrogen initially in the tube. Line profiles before this time (while the ionizing front is still proceeding down the tube) do not fit the theoretical curves for a single density. This is to be expected, as the ion density must vary through the front.

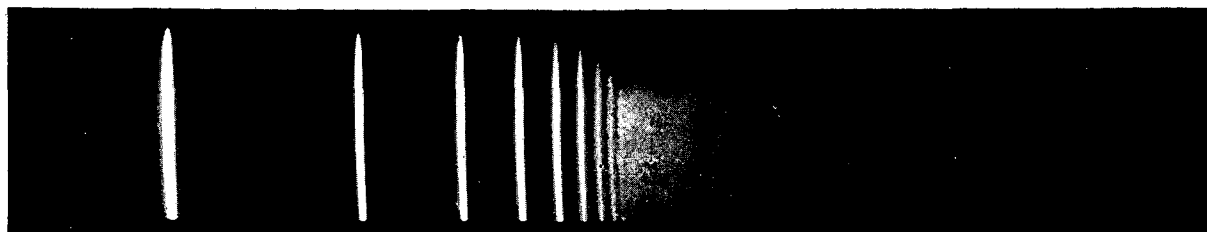
One independent check of the ion density was carried out. A plate taken with a small spectrograph with quartz optics showed nine members of the Balmer series distinctly before the discrete spectrum merged with the continuum. A calculation based on the Inglis-Teller method<sup>6</sup> gave a time-averaged ion density of  $3.5 \times 10^{15} \text{ cm}^{-3}$ . A print of this plate, showing a pure Balmer spectrum and the continuum, is shown in Fig. 13.

Several improvements have been made in the experimental setup. The vacuum system was overhauled and a diffusion pump added, which reduced the base pressure of the system from about  $0.5 \mu\text{Hg}$  to  $0.03 \mu\text{Hg}$ . A new "fast bank" was designed and built in anticipation of further Alfvén-wave studies. This bank rings at almost twice the ringing frequency of the old "fast bank," and when used with a damping resistor, gives a single pulse with a length of 0.8  $\mu\text{sec}$ . This should eliminate troubles previously encountered with reflections from the end of the tube which interfered with observations of the incoming Alfvén wave.

One report was written during this quarter: Alan W. DeSilva, William S. Cooper III, and John M. Wilcox, Experimental Observations of Alfvén-Wave Modes and Reflections, UCRL-9258, June 8, 1960.

<sup>5</sup>H. Zanstra, Proc. Roy. Soc. (London), A186, 236 (1946).

<sup>6</sup>A. Pannekoek, Monthly Notices Roy. Astron. Soc. 98, 694 (1938).



ZN-2601

Fig. 13. Hydrogen spectrum showing the first nine members of the Balmer series and the continuum.

#### 4. ION CYCLOTRON RESONANCE

Peter R. Forman, James C. Glass, Gordon W. Hamilton,  
C. N. Watson-Munro,\* and John M. Wilcox

The Berkeley ion cyclotron resonance experiment known as Hothouse II was designed to examine the possibilities of ion cyclotron heating by resonant absorption of an Alfvén wave launched at a magnetic field above ion cyclotron resonance.

##### Experiment

The equipment consists of these items (indicated in Fig. 14):

(a) The plasma tube, which is a copper cylinder of 8 in. i.d. and 37 in. long. The ends are terminated in quartz discs, each supporting molybdenum electrodes 2-1/2 in. in diameter and 3 in. long. Indium seals are used in all places where organic contamination could occur.

(b) A  $B_z$  magnetic field along the axis of the tube, which is supplied by eight water-cooled coils of 9 in. i.d. and 20 in. o.d. Two coils at each end are independently fed to provide mirror fields. Sensitivity is about 9 gauss per ampere, and fields of up to 20,000 gauss are available with the present dc supplies.

(c) A vacuum system consisting of two 10-in. diffusion pumps complete with liquid air traps and mechanical backing pump. Background pressure is of the order of  $5 \times 10^{-7}$  mm Hg.

(d) Two rf oscillators, each capable of operating at a peak power of 1.2 Mw for a 30-kv 2-msec pulse to the plate. The oscillators can also be run on CW at 15 kv. Their efficiency has been measured calorimetrically into an artificial load at 60%.

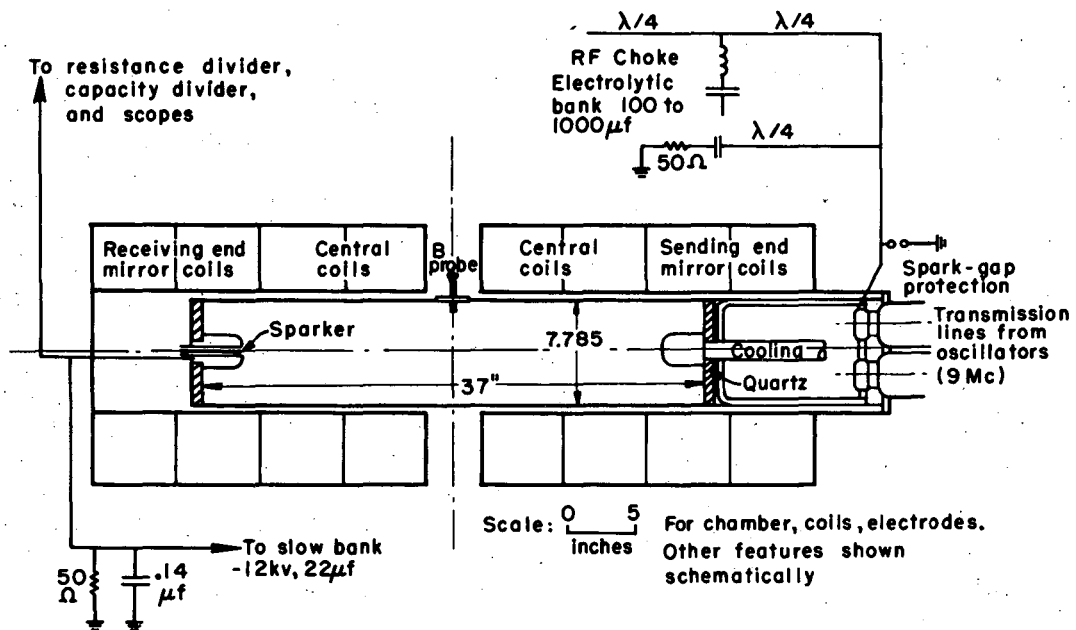
In the present set of experiments the oscillators have been used in push-pull and fed via quarter-wave 50-ohm pressurized transmission lines to the machine. The transmission lines are shortened by terminating at the oscillator end with condensers; by unbalancing the value of these condensers it is possible to provide voltages at the machine up to 1400 volts rms.

(e) A "slow bank" of eight 7.5- $\mu$ f condensers capable of providing up to 18 kv positive and negative pulses for plasma preparation. A "crowbar" ignitron is also contained in the slow bank.

(f) Diagnostic facilities include an 8-mm microwave interferometer, a monochromator, and facilities for viewing and for insertion of probes at the center of the machine.

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\* Visitor from University of Sydney, Australia.



MU-21862

Fig. 14. Schematic drawing of Hothouse II (on Sept. 15, 1960).

Theory

It can be shown that the application of an  $E_r$  field to the cylindrical plasma with a  $B_z$  axial magnetic field can give rise to two waves of phase velocities given by<sup>7</sup>

$$U^2 = \frac{c^2}{1 - \omega_p^2 \frac{1}{(\omega \pm \omega_{ce})(\omega \mp \omega_{ci})}}, \quad (1)$$

where  $\omega$  = plasma frequency,

$\omega_{ce}$  = electron cyclotron frequency,

$\omega_{ci}$  = ion cyclotron frequency,

$\omega$  = frequency of  $E_r$  wave =  $5.7 \times 10^7$  radians/sec.

The  $(\omega - \omega_{ci})(\omega + \omega_{ce})$  term refers to the ordinary hydromagnetic wave and gives an imaginary solution for  $\omega_{ci} = Be/m_i < \omega$ , the condition in which a magnetic "beach" occurs and the energy is transferred to the ions.

The hydromagnetic impedance of the plasma cylinder for the ordinary wave is given, for  $\omega_p^2 \gg \omega_{ci}\omega_{ce}$  or  $nm_i c^2 \gg B^2/\mu_0$  (always satisfied here), by

$$Z_{or} = 60 \epsilon_{or}^{-1/2} \ln \frac{r_2}{r_1} \text{ ohms} \quad (2)$$

$$= 60 \left[ \frac{\epsilon_0}{ne} B \left( \frac{Be}{m_i} - \omega \right) \right]^{1/2} \ln \frac{r_2}{r_1}, \quad (3)$$

where  $\epsilon_{or}$  = relative dielectric constant for the ordinary wave,  $r_2$  and  $r_1$  are the radii of the outer and inner electrodes, and  $n$  = ion or electron density. Since the impedance is expected to be so low, any electrode sheath, which would represent an effective series impedance, must be taken into consideration.

If we neglect the effects of collisions to calculate the thickness of any electron sheath that may be formed, we have, from Poisson's equation, thickness

$$d = \left( \frac{2\epsilon_s V}{n_s e} \right)^{1/2}, \quad (4)$$

<sup>7</sup> Thomas H. Stix, Absorption of Plasma Waves, Phys. Fluids 3, 19 (1960) (also MATT-3, June 1959).

giving a sheath impedance (mks units used throughout)

$$Z_s = \frac{1}{\omega A} \left( \frac{2V}{\epsilon_s n_s e} \right)^{1/2}, \quad (5)$$

where  $A$  = area of sheath,  
 $V$  = applied voltage, zero to peak,  
 $\epsilon_s$  = dielectric constant of sheath,  
 $n_s$  = electron density in sheath.

It can be shown<sup>8</sup> that  $\epsilon_s$  is given by

$$\epsilon_s = 1 + \frac{n_s m_e}{\epsilon_0 B^2},$$

giving a sheath impedance of the form

$$Z_s = \frac{1}{\omega A} \left[ \frac{2V}{\left( 1 + \frac{n_s m_e}{\epsilon_0 B^2} \right) n_s e} \right]^{1/2}, \quad (6)$$

where  $m_e$  = mass of electron.

Assuming 50% of the oscillator energy is fed into the plasma, at maximum energy dissipation, we have, for two tubes,

$$\frac{(V/\sqrt{2})^2}{Z_p} = \frac{V^2}{2Z_p} = W_p = 1.2 \times 10^6 \text{ watts}, \quad (7)$$

where

$$\begin{aligned} Z_p &= \text{total plasma impedance} \\ &= Z_s + Z_{or}, \end{aligned} \quad (8)$$

neglecting the extraordinary wave impedance which is higher than  $Z_{or}$  and in parallel with it. The energy converted to ion motion will be inversely proportional to the number of ions,

$$\text{i. e., } W_i \propto 1/n, \quad (9)$$

and it is Eqs. (3), (6), (7), and (9) that determine the optimization of the operating conditions.

<sup>8</sup>C. L. Longmire, private communication.

### Experimental Results

Although the Hothouse II machine was assembled by February 1960, a number of problems with rf insulation (associated with the necessity to pulse the oscillator at 30 kv) and dc power supplies delayed regular operation for several months.

A 3-msec pulse line is nearing completion; in the experiments so far completed the oscillators have been pulsed with two 1- $\mu$ f condensers charged to 25 to 30 kv (625 to 900 joules).

#### Initial Experiments with rf Only

It was found just possible to achieve microwave cutoff at a neutral pressure of 2.8 microns ( $n = 1.8 \times 10^{14}$  per  $\text{cm}^3$ ). At 8 mm wavelength this represented about 10% ionization only. Some plasma preparation seemed necessary.

#### Slow-Bank Plasma Preparation

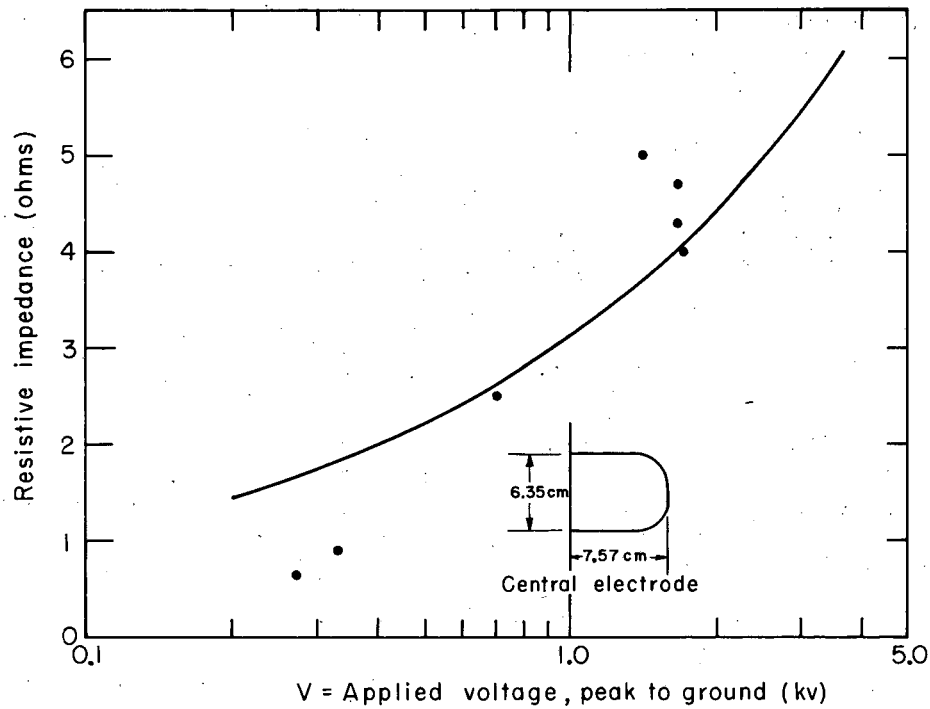
The slow bank was applied to the end of the machine opposite to the rf feed, and with rf loading used as a guide, it was found that 20  $\mu$ f at 13 kv of slow-bank energy gave adequate plasma preparation. The oscillator was turned on 20 to 50  $\mu$ sec after the slow bank had been crowbarred.

#### Sheath Studies

The high impedances encountered and the absence of a strong Alfvén wave at high magnetic fields suggested that the bulk of the energy was being absorbed in an anode sheath forming alternately, at each half cycle, on the central electrode and on the outer wall of the copper cylinder.

Experimental support was obtained for this argument from these observations:

- (a) The impedance varied as the square root of applied rf volts [Eq. (6) and Fig. 15];
- (b) By the application of a negative bias to the central electrode, the bulk of the sheath voltage drop and hence impedance was moved to the larger-area outer electrode (Fig. 16).
- (c) The use of a long electrode in the center also reduced total impedance (Fig. 16). This electrode had the disadvantage of its length, representing several hydromagnetic quarter waves.
- (d) The use of a multirod tungsten electrode of about four times the surface area of the short electrode provided the greater area without increasing the length (Fig. 16).



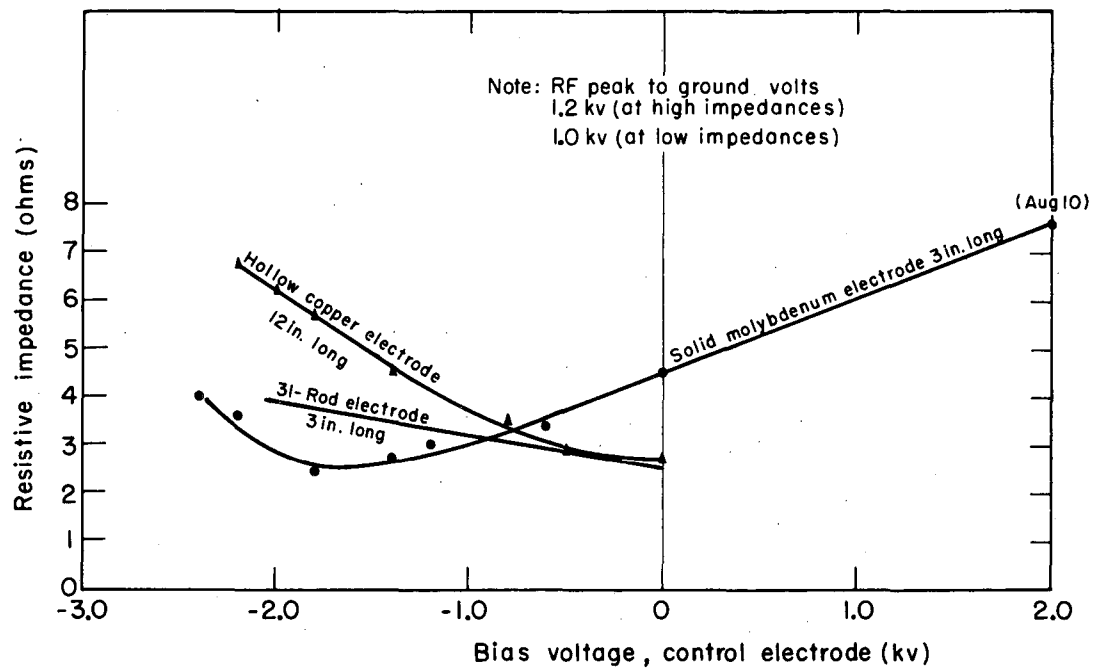
MU-21863

Fig. 15. Hothouse II. Variation of total plasma impedance with applied rf volts. Resistive impedance obtained as shown in Fig. 16.

Curve:  $Z = \frac{1}{\omega A} \sqrt{\frac{2V}{\epsilon_0 n_s e}}$ . Best fit for  $Z \approx \sqrt{10 V}$ ,

$\therefore A \sqrt{n_s} \approx 4.75 \times 10^{-9} \text{ (meter)}^{1/2}$ . For  $n_s \approx 6.4 \times 10^{-9} \text{ m}^{-3}$ ,

$A = 262 \text{ cm}^2$ . Actual areas: sides,  $130 \text{ cm}^2$ ; end,  $35 \text{ cm}^2$ .

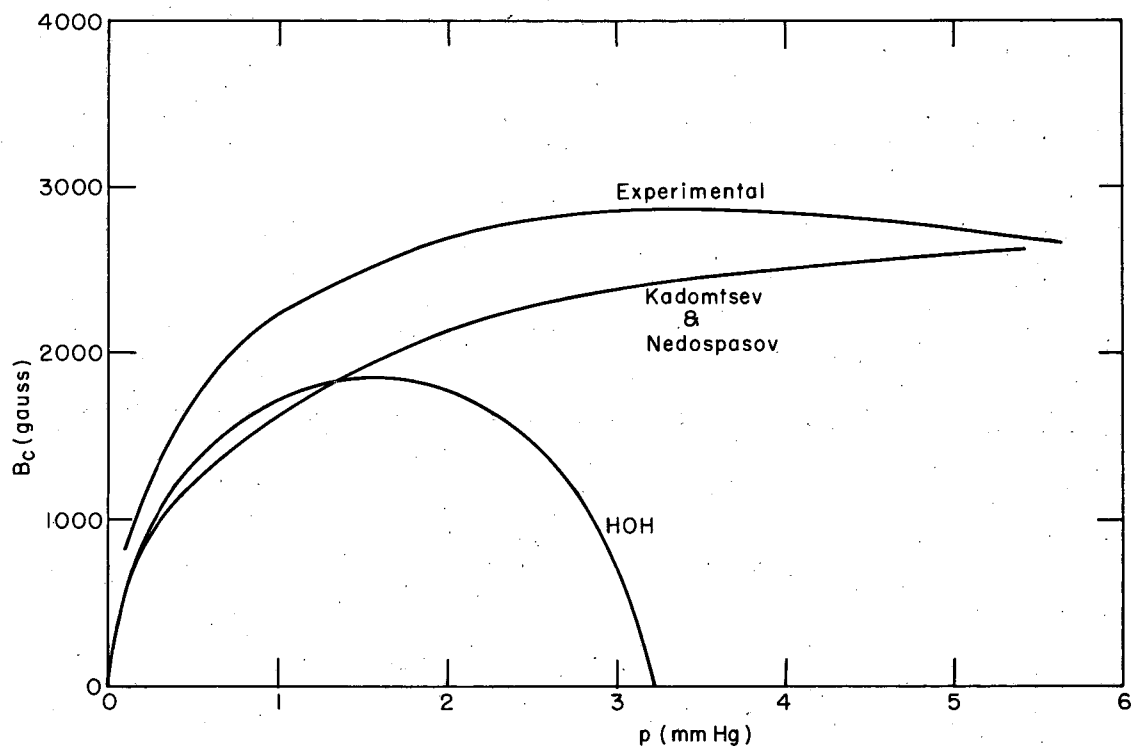


MU-21864

Fig. 16. Resistive impedances measured in Hothouse II =

$$\frac{(\text{rms volts})^2 (\text{into machine})}{50\% (\text{dc volts} \times \text{dc amps})(\text{into oscillator})} ;$$

rf peak to ground is 1.2 kv at high impedances, 1.0 kv at low impedances.



MU-21865

Fig. 17. Critical field,  $B_c$ , as a function of pressure. He gas in a 0.9-cm-radius tube. The magnetic field is 200 cm long.  $T_{ion} = 400^\circ K$ .

This increase of the effective area of the sheath enabled the total plasma impedance to be reduced to about 2.5 ohms at 25,000 gauss and  $1 \mu$  pressure ( $6.4 \times 10^{13}$  ions/cm<sup>3</sup>). As the hydromagnetic impedance for the ordinary wave is about 1/2 ohm under these conditions, it would be expected that about one-fifth of the energy would be fed to the wave and, under magnetic "beach" conditions, to the ions.

Preliminary reconnaissance observations of (a) voltages (allowing for attenuation) received at the capacity-terminated end of the machine, (b) indications of time-dependent Doppler broadening of the  $D_\beta$  spectral line, and (c) effects of ion resonant magnetic fields support these arguments. However, it is necessary to measure the variation of velocity with  $B_z$  and the amplitude of magnetic fields before a clear identification of ordinary, extraordinary, or sheath waves can be made. Spectral measurements will need verification and considerable extension.

## 5. PLASMA PHYSICS AND MICROWAVE DIAGNOSTICS

Donald B. Hopkins, M. C. Horton, George A. Paulikas,\*  
Robert V. Pyle, Henry F. Rugge, and J. Warren Stearns

### Enhanced-Diffusion Experiment

Recently, Hoh<sup>9</sup> and Kadomtsev and Nedospasov<sup>10</sup> have produced theories pertaining to the enhanced losses from a positive column in a magnetic field. Hoh makes use of Bohm's criterion for the stability of a wall sheath, and shows that it is no longer satisfied when the magnetic field,  $B$ , exceeds a critical value  $B_c$ . The actual manner in which the failure of the sheath-stability criterion affects the discharge is not discussed. Kadomtsev and Nedospasov, on the other hand, show that perturbations of this discharge column can grow when oscillations driven by the volume forces,  $j \times B$ , can no longer be stabilized by local adjustments in the rate of diffusion to the walls. Their results can be used to predict  $B_c$ , the frequency and the wave length of the oscillation, and the growth rate.

We have showed that the enhanced losses at  $B_c$  are caused by the transition to a helical discharge, and the empirical effects of changing gas, pressure, tube diameter, etc. have been given in a separate paper.<sup>11</sup> The above theories have been applied to the experimental conditions described therein, and results of the type shown in Fig. 17 are found. The agreement between the experiments and the theory of Reference 10 are rather good.

\*National Science Foundation Fellow.

<sup>9</sup>F. C. Hoh, Phys. Rev. Letters 4, 559 (1960).

<sup>10</sup>B. B. Kadomtsev and A. V. Nedospasov, J. Nuclear Energy, Part C, 1, 230 (1960). We are grateful to the authors for a prepublication copy of this paper.

<sup>11</sup>T. K. Allen, George A. Paulikas, and Robert V. Pyle, Instability of a Positive Column in a Magnetic Field, UCRL-9110, May 1960.

Further measurements of frequency, wave length, and growth rate are continuing. In all cases to date, the measured and calculated values are in reasonably good agreement. Hoh's theory is the less satisfying of the two in that it predicts nothing about the behavior of the discharge, nor does it match our curves for  $B_c$  vs  $p$ . It should be noted that we are unable to obtain a calculated curve that matches the example given by Hoh,<sup>9</sup> our curve being compressed by a factor of nearly 2 along the pressure scale.

G. Ecker<sup>12</sup> has calculated the effects of the flare in the magnetic field at the end of the magnet, and the manner in which the large perturbations introduced by a probe in the discharge can be unfolded from probe measurements to give the true radial variation of the floating potential. These results have not yet been compared with experiment, and will be included at a later time.

### Cesium Plasma

Calculations have been made of the spatial distribution of a highly ionized cold Cs plasma in a magnetic field for various boundary conditions. The experiment has been rebuilt with indirectly heated ionizing surfaces so that the plasma does not see any externally applied voltages, and probe measurements are in progress.

### Microwaves

Miscellaneous diagnostic engineering and calculations pertaining to electrostatic wave propagation in the Cs plasma are continuing.

## 6. CROSSED ELECTRIC AND MAGNETIC FIELD BREAKDOWN STUDIES

Melvin J. Bernstein

Work has continued on the steady-state measurement of the ionization coefficient of hydrogen across a magnetic field,  $B$ .

It was erroneously stated in the preceding quarterly report that the height of the electrode structure was 10 cm; this should have read 6.3 cm for the total height. Since then the total height has been increased to 8.8 cm, tripling the height of the middle collecting anode ring. This was necessary to reduce problems of diffusion along the magnetic field. A series of removable inner cathode rings was made to give gap widths of 2, 4, 5, 6, 8, and 10 mm. Thus for any given setting of  $E$ ,  $p$ , and  $B$  the current collected by the middle anode may be plotted as a function of electrode spacing and the ionization coefficient  $\alpha/p$  can be evaluated. Electric fields used varied from 75 to 1000 v/cm. Pressures ranged from 1 to 8 mm Hg and the magnetic field was varied between 0 and 8000 gauss.

A theory is given by Blevin and Hayden<sup>13</sup> on how  $\alpha/p$  should be reduced as a function of magnetic field. They use the parameter  $B/p$ . Their theory

<sup>12</sup>Consultant to LRL, at the Institute of Theoretical Physics, University of Bonn.

<sup>13</sup>Blevin and Hayden, Australian J. Phys. 11, 18 (1958).

is based on the fact that in hydrogen the electrons have an almost constant mean free time between collisions, independent of their energy.

Preliminary runs have not given data satisfactory enough either to prove or disprove the above theory. The geometry of the system is now being more accurately aligned in the hope of obtaining more reliable data.

## 7. MAGNETIC CUSP STUDIES

Arthur R. Sherwood, Oscar A. Anderson, and William R. Baker

A magnetic cusp program in Berkeley was initiated by William R. Baker in September 1959.<sup>14</sup> Equipment was built and ready for experimental work by the end of that year. Shortly afterward Jean-Paul Watteau, on a six-month visit from France, joined this program. The pinch-cusp experiment that he performed is described in the last quarterly report.<sup>15</sup> Mr. Watteau has now returned to France, but the cusp experiments will be continued.

Several revisions and redesigns have been made in order to increase the mechanical and electrical reliability of the experiment, and an effort has been made to reduce electrical noise. A larger cusp field condenser bank has been installed so that the results can be extended for longer times. As a first step towards improving and extending the diagnostics a magnetic probe has been designed and built.

<sup>14</sup>W. R. Baker and H. P. Furth, Eng. Note UCRL-5714-T (4506-41 CVL-15) Sept. 29, 1959.

<sup>15</sup>William R. Baker and Jean-Paul Watteau, in Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960, p. 83.

## 8. ANALYSIS OF THE IONIZING HYDROMAGNETIC "SWITCH-ON" SHOCK WAVE

Robert A. Gross\* and Wulf B. Kunkel

The Hothouse experiments require plasmas with electron densities between  $10^{14}$  and  $10^{16}$   $\text{cm}^{-3}$  inside metal tubes in the presence of strong axial magnetic fields. It was found that a very convenient and interesting way of producing such plasmas consists of simply passing a fairly large radial current transiently between some central electrode at one end of the machine and the cylindrical metal wall. This current seems to cause a complete electrical breakdown of the entire gas volume by driving an ionizing front in the manner of a "switch-on" shock wave<sup>16</sup> which propagates at uniform velocity along the magnetic field.<sup>17</sup> The propagation velocity, the current, and the voltage between the electrodes are readily observable and seem to be rather simply related to the gas density and to the initial magnetic field. The most striking feature is the approximate proportionality between the voltage or the front velocity and the initial magnetic field for given current and gas density. The situation invites analysis.

So far, a simplified plane two-dimensional model has been studied theoretically, assuming the existence of equilibrium conditions behind as well as in front of a steady ionizing wave which may have a finite but constant thickness. In this case the equations of motion may be directly integrated to give the familiar conservation laws relating the conditions behind the wave to the propagation velocity, the current, and the conditions ahead of the wave. The model is, of course, not realistic even if cooling losses and viscous drag between the walls and the moving gas behind the wave could be ignored. The reason is that it can be shown that the wave must be compressive, i. e., the plasma behind the wave must have a forward longitudinal velocity which leads to a rarefaction at the driving end of the tube and a resulting nonsteady flow.

The general treatment even of the simple two-dimensional model leads to fairly complex algebraic relations which are to be presented and discussed in a separate report. In case most of the energy is shared between ionization, dissociation, and the transverse mass motion--i. e., if the thermal and the longitudinal kinetic energy can be neglected--some simple expressions may be derived of which the most important ones are quoted here. Let the initial magnetic field be denoted by  $B_0$ , the field due to the current flowing in the front by  $B_{\perp}$ , and the initial gas density by  $\rho$ . Let, furthermore, the change of the internal energy per unit mass (ionization energy and dissociation energy) in going across the wave be denoted by  $\Delta e$ . Then for  $B_0 \gg B_{\perp}$ , the wave velocity is given by

$$U = \frac{B_0 B_{\perp}}{\mu_0 \rho (2\Delta e)^{1/2}} \quad (1)$$

\*School of Engineering, Columbia University, consultant to LRL.

<sup>16</sup>K. O. Friedrichs, "Nonlinear Wave Motion in Magneto-Hydrodynamics," Los Alamos report No. LAMS-2105; written 1954, distributed as NYO-6486, 31 July 1958.

<sup>17</sup>A. W. DeSilva, William S. Cooper III, and J. M. Wilcox, Experimental Observations of Alfvén-Wave Modes and Reflections, UCRL-9258, June 1960.

The transverse flow velocity behind the wave is

$$u_{\perp} = (2\Delta e)^{1/2}, \quad (2)$$

and the electric field is

$$E = B_0(2\Delta e)^{1/2}. \quad (3)$$

The quantity  $\Delta e$  in these expressions must be computed for the assumed equilibrium from the temperature and pressure conditions behind the wave. Unfortunately, the relationships explicitly involving the temperature are much more complex and will not be given here. In many cases of interest, however, the gas is fully dissociated and ionized but not exceedingly hot, so that the value of  $\Delta e$  is rather insensitive to temperature.

Similarly the expression for  $u_{\parallel}$ , the longitudinal flow velocity, is rather complex, since it involves the temperature directly.

It is interesting to note that the transverse flow velocity  $u_{\perp}$  in this limit becomes independent of the initial magnetic field, and both the transverse velocity and the electric field are independent of the gas density. These quantities vary only slowly with the current and are primarily dominated by the ionization energy of the gas. These properties are reminiscent of the voltage and velocity limitations observed in "rotating plasma" devices, and it should be emphasized at this point that they are derived purely from conservation laws and have no bearing on the ionization mechanism. The ionization mechanism determines only the ionization rate and in this way the wave structure, but neither the fields and gas flow conditions behind the wave nor the wave-propagation velocity. The thickness of the ionizing front in the Hothouse I experiment appears to be only a few centimeters, indicating that the ionization occurs in only a very few microseconds. The details of this mechanism are not yet clear.

It is encouraging that the expressions (1) and (3) are in fair agreement with observations in spite of the extreme simplifications in the model analyzed here. A somewhat more refined treatment is in progress, and some experiments to compare theory and practice over a range of conditions are planned.

## V. THEORETICAL AND BASIC EXPERIMENTAL PLASMA PHYSICS

### 1. CONVECTIVE INSTABILITY

William A. Newcomb

Tserkovnikov has recently investigated the convective instability induced by gravity in a perfectly conducting plasma with a frozen-in magnetic field.<sup>1</sup> Restricting his attention to motions that do not involve any bending of the magnetic field lines (pure interchange modes), he obtains the following expression for the growth rate of the fastest instability:

$$p^2 = \frac{g}{\rho} \left( \frac{\rho^2 g}{\gamma P + B^2} - \frac{d\rho}{dz} \right), \quad (1)$$

where  $1/p$  is the e-folding time,  $g$  is the acceleration of gravity,  $\rho$  is the plasma density,  $\gamma$  is the ratio of specific heat,  $P$  is the plasma pressure, and  $B$  is the magnetic field intensity. The acceleration of gravity is in the positive  $z$  direction, and the magnetic field is perpendicular to it. The stability criterion resulting from Eq. (1) is obviously

$$\frac{d\rho}{dz} > \frac{\rho^2 g}{\gamma P + B^2}, \quad (2)$$

which must be satisfied for all values of  $z$ . The plasma is therefore stable against interchange motions if and only if the density gradient exceeds a certain critical value depending on the magnetic field intensity.

I have extended Tserkovnikov's analysis to include motions that distort the field lines in an arbitrary way.<sup>2</sup> Using the hydromagnetic energy principle,<sup>3</sup> I obtain the following stability criterion:

$$\frac{d\rho}{dz} > \frac{\rho^2 g}{\gamma P}, \quad (3)$$

in which the critical density gradient is independent of the magnetic field. It follows that the rigidity given to the plasma by the frozen-in field is never sufficient to completely stabilize the plasma if it is unstable in the absence of a field. The magnetic field does, however, slow the instability down. I have found that the growth rate of the fastest instability is still given by Eq. (1) whenever  $B < B_0$ , where

$$B_0^2 = \gamma P \left[ \left( \frac{\rho^2 g}{\gamma P} \right)^{1/2} \left( \frac{d\rho}{dz} \right)^{1/2} - 1 \right]. \quad (4)$$

<sup>1</sup>Yu. A. Tserkovnikov, Convective Instability of a Rarefied Plasma, Report No. T-2, Division of Theoretical Physics, Mathematical Institute of V.A. Steklov, Academy of Science of the USSR, Moscow, 1960.

<sup>2</sup>W. A. Newcomb, Convective Instability Induced by Gravity in a Plasma with a Frozen-In Magnetic Field, UCRL-6034, July 1960.

<sup>3</sup>I. B. Bernstein, E. A. Frieman, M. D. Kruskal, and R. M. Kulsrud, Proc. Roy. Soc. (London) A 244, 17 (1958).

This means that the fastest instability is a pure interchange when  $B < B_0$ . But if  $B > B_0$ , the fastest instability involves bending of the field lines, and the maximum growth rate is given by a different expression:

$$p^2 = \frac{\rho g^2}{B^2} \left[ 1 - \left( \frac{dp}{dz} \right)^{1/2} \left( \frac{\rho^2 g}{\gamma P} \right)^{-1/2} \right]^2 \quad (5)$$

It follows that the maximum growth rate is inversely proportional to  $B$  when  $B$  is sufficiently large.

I have not yet completed my paper on the transverse adiabatic energy principle, which was briefly discussed in the preceding quarterly report (UCRL-9243, page 101).

## 2. STABILITY DIAGRAMS FOR THE LINEAR PINCH

Daniel Z. Freedman

Stability curves for linear pinch devices were plotted on the basis of stability criteria derived by W. A. Newcomb and A. N. Kaufman.<sup>4</sup> The stability of both the tubular and columnar pinches was investigated.

The field geometry of the pinch is essentially expressed by the function

$$\phi = \tan^{-1} (B_\theta / B_z),$$

the angle between the magnetic field and the axis of the pinch. In the tubular pinch, where the plasma is assumed to occupy a thin layer of thickness  $\delta$  at a distance  $r_0$  from the axis, the stability depends on the parameters  $\phi_i$  and  $\phi_e$ , the values of  $\phi$  at the inner and outer boundaries of the plasma, and on the dimensionless parameters  $\alpha_i = a_i/r_0$  and  $\alpha_e = a_e/r_0$ , where  $a_i$  and  $a_e$  are the radii of the inner and outer conductors. In the columnar pinch there is no central conductor and the plasma consists of a uniform central region surrounded by a thin transitional current shell of radius  $r_0$ . The critical parameters are  $\alpha_e$ ,  $\phi_e$ , and  $P_i$ , the plasma pressure in the central region. For the tubular pinch the minimum and maximum plasma pressure compatible with stability were determined for  $\alpha_i = 1/2$  and  $\alpha_e = 2$ , and for various values of  $\phi_i$  and  $\phi_e$ . For the columnar pinch the minimum and maximum pressures were determined for  $\alpha_e = 2$  and various values of  $\phi_e$  and  $P_i$ . The report on this work (UCRL-6084) is in preparation.

<sup>4</sup>W. A. Newcomb and A. N. Kaufman, Hydromagnetic Stability of a Tubular Pinch, UCRL-5434, May 1960.

### 3. STUDY OF THE STABILITY OF ASTRON E LAYER

Alvin M. Saperstein

A study of the stability against longitudinal bunching of the self-consistent solution of the infinitely long Astron E layer given by Lewi Tonks was undertaken. It was assumed that charge neutrality was maintained in the perturbed motion of the E layer, such that the perturbed electric current had only an azimuthal component. Thus the vector potential also has only an azimuthal component.

In order to avoid the difficulty of expansion about the singularities which determine the boundaries of the equilibrium state, an adiabatic first-order solution was assumed. The resulting equations then related the first-order corrections to the adiabatically varied currents and vector potential. The change in the transverse velocity of the electrons was solved for in terms of the vector potential, which, when substituted into Ampere's equation, resulted in an inhomogeneous linear integral differential equation of the Volterra type. A further relation is obtained by relating the perturbed axial velocity to the axial variation of electron density.

These resulting equations yield a well-defined eigenvalue problem for the perturbation frequency as a function of wave number. It is, however, an extremely complicated problem; and so far no approximations have been found that would lead to tractable equations. An attempt is now being made to examine the energy approach to stability in the hope that a variational method may be found which may lead to a more tractable problem.

### 4. EQUILIBRIUM SOLUTIONS OF INFINITELY LONG E LAYER IN ASTRON

Chieh-Chien Chang and Thomas S. Lundgren

Some preliminary analytic investigation has been made for the equilibrium case of an infinitely long Astron E Layer and for a simplified model consisting of a plane sheet of streaming electrons. For the time being, equilibrium solutions are obtained with the continuum concept of three fluids, one of relativistic electrons, the second of plasma electrons, and the third of plasma ions (which include the ions that neutralize the beam).

For the case of a plane sheet of relativistic electrons, the distribution of the self-induced magnetic and electric fields (so-called self-consistent fields) are studied. The mechanical and magnetic pressures across the width of the beam are also plotted. A number of interesting properties are obtained. The above is based on the assumption of uniform velocity and temperature of the beam.

For the case of an applied uniform axial magnetic field, the beam is bent into a rotating cylindrical sheet as the Astron E Layer. The centrifugal term can be evaluated as a perturbation of the plane-sheet beam.

If the temperature distributions of plasma electrons and ions are not uniform but are similar to the distribution of number density of the beam, some solutions for the beam number density are also obtained.

## 5. STRUCTURE OF THE COLLISIONLESS ELECTROSTATIC SHOCK

Paul J. Kellogg

When two clouds of plasma collide, they cannot pass through each other even when collisions are negligible, because electrostatic oscillations grow and destroy the relative motion. But the problem of the structure of the shock front, where the streaming motion of incoming plasma is destroyed and converted to random motion, is unsolved. It can easily be seen that this shock is different from most shocks in that the motion must be time-dependent even in the shock frame, otherwise--since particle energy is conserved in a time-independent electrostatic field--all particles gain or lose exactly the same amount of kinetic energy and the streaming motion cannot be made random. It is conjectured that the shock structure is probably as follows in the shock frame. An electrostatic, oscillatory wave is generated at the shock front and travels back into the shocked region, and is attenuated as it goes. Particles crossing the shock front either gain or lose energy to the wave, depending on the phase of the oscillatory wave at the time they cross the front. An essential feature of the structure is the interpenetration of small bunches of plasma, and so such a structure could not be treated in a hydrodynamic approximation.

In order to check this conjecture, the problem of two colliding plasmas has been set up for the 709 computer in Buneman's sheet approximation.<sup>5</sup> It is hoped that this problem will be run in the near future.

## 6. MAGNETIC SHOCKS

Stanley A. Zwick

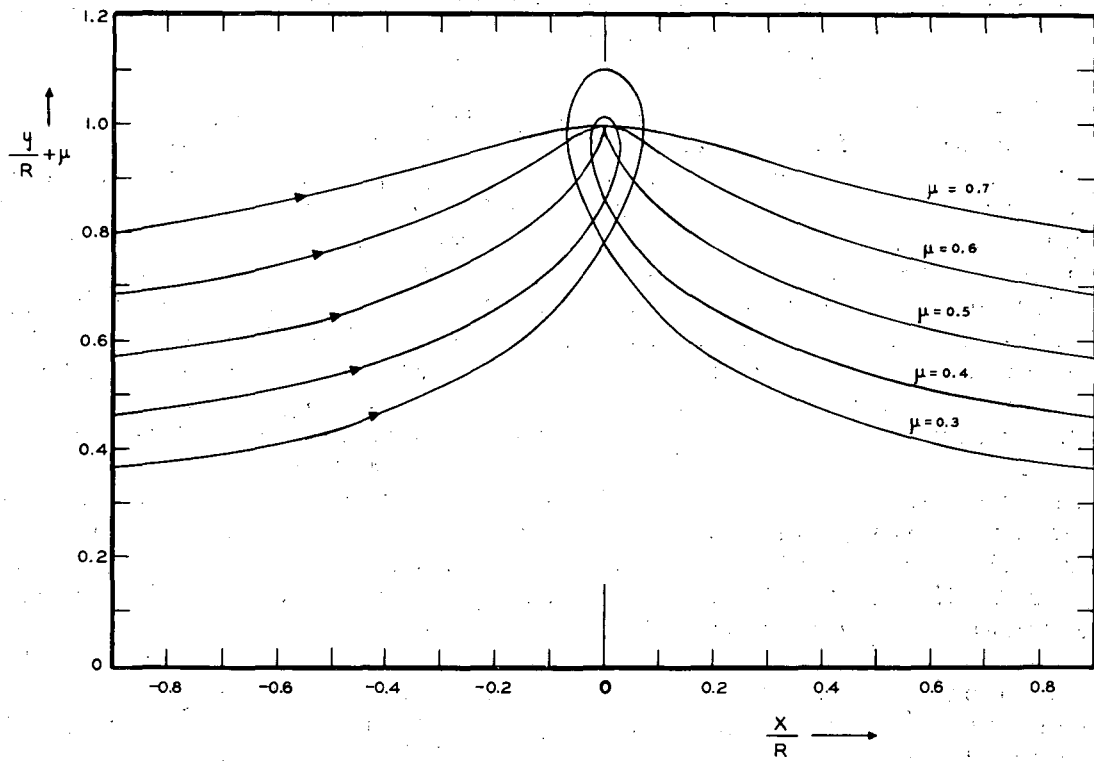
Numerical solutions for the high-speed magnetic pulse have been obtained. Particle trajectories for various pulse speeds are compared in Figs. 18 and 19 for respective frames moving with the pulse, or at rest in the plasma. The effect of "crossovers" (i. e., a diamagnetic loop) on the magnetic field, in the case of the high-speed pulse, is shown in Fig. 20.

The parameter  $\mu$  used to label trajectories in Fig. 18 represents the reciprocal of the Alfvén-Mach number,

$$\mu = a_0/V, \quad a_0^2 = B_0^2/4\pi nN,$$

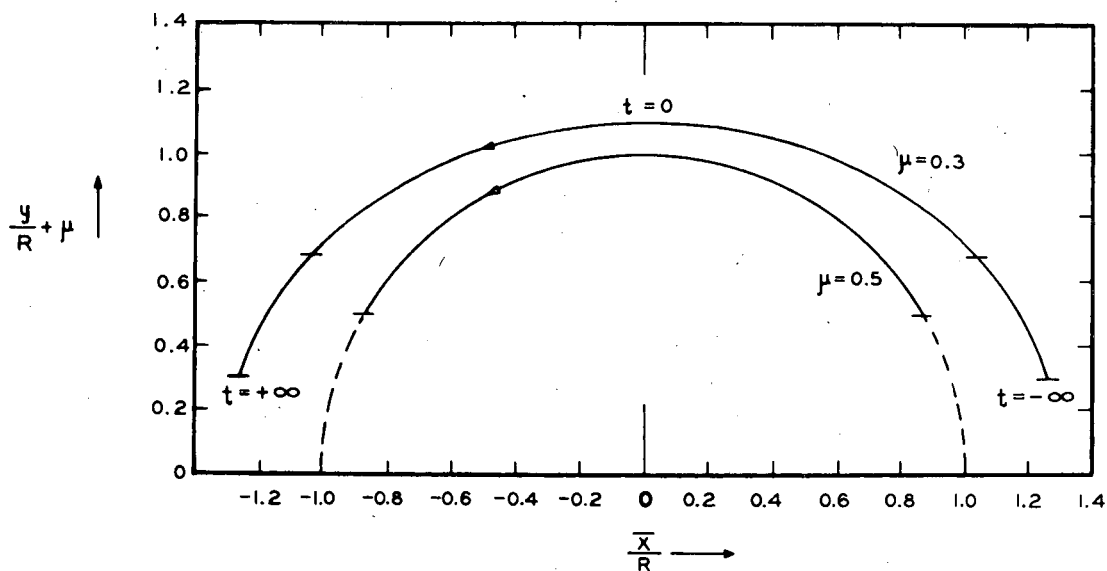
where  $V$  is the pulse speed,  $B_0$  is the applied magnetic field, and  $N$  is the

<sup>5</sup>O. Buneman, Phys. Rev. 115, 503 (1959).



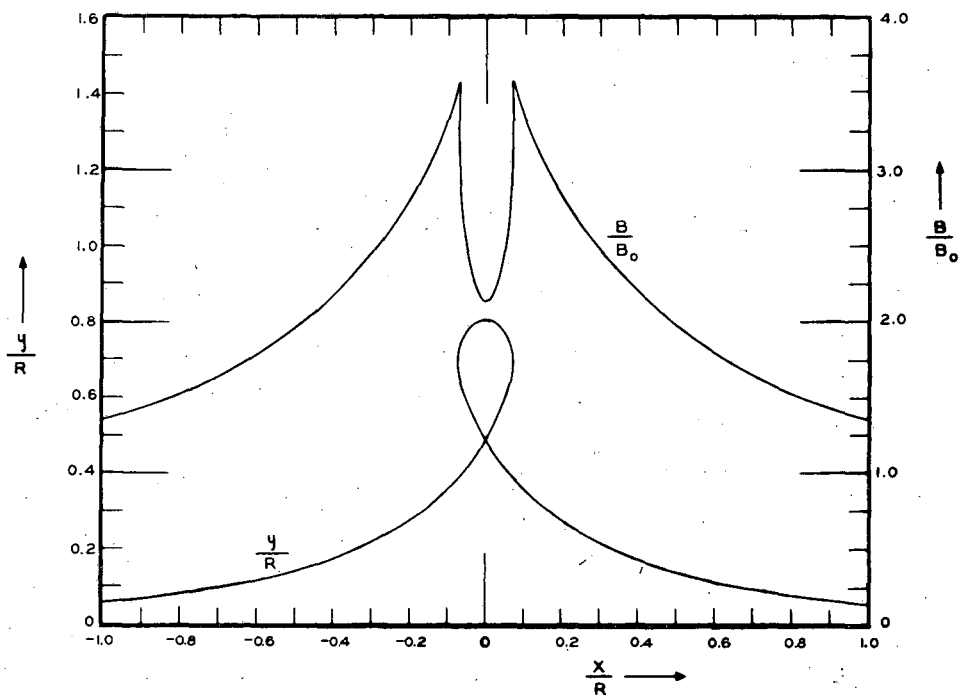
MU-21870

Fig. 18. Particle trajectories for various values of  $\mu$ , as seen (in each case) in a frame moving with the magnetic pulse.



MU-21869

Fig. 19. Particle trajectories in the initial rest frame of the plasma. For  $\mu = 0.5$  or larger, the particle moves on a circle of radius  $R$ . The path for  $\mu$  less than 0.5 deviates from a circular trajectory in its central portion.



MU-21868

Fig. 20. Loop trajectory  $y/R$  and corresponding magnetic field ratio  $B/B_0$ , for  $\mu = 0.3$ .  $B$  reaches  $3.57 B_0$  at the edge of the loop ( $x = \pm 0.07 R$ ).

total number of particles per  $\text{cm}^3$  in the undisturbed plasma. (Here  $\mu = 1/\sqrt{1+a^2}$ , in terms of the parameter  $a$  used in the preceding report.<sup>6</sup>) For clarity, each trajectory in Fig. 18 has been displaced upward by its value of  $\mu$ ; i. e., the representative (positive) particle starts at ordinate  $\mu$  at  $x = -\infty$  and returns to this ordinate at  $x = +\infty$ . For  $\mu = 0.5$  the trajectory has a cusp, while for  $\mu < 0.5$  it has a loop. (Loop solutions have been found, thus far, over the range  $0.25 \leq \mu < 0.5$ .) The length unit is given by  $R = \sqrt{mc^2/\pi Nq^2}$ , where  $m$  is the mass and  $|q|$  the numerical charge of both the positive and negative particles assumed to compose the plasma.

In the initial rest frame of the plasma, particle trajectories for  $\mu \geq 0.5$  are segments of a circle of radius  $R$ . These may be superimposed if in each case the trajectory is assigned the initial ordinate  $\mu$  (as in Fig. 18). For  $\mu < 0.5$  the trajectory starts as a portion of a circle of radius  $R$ , but expands in the crossover region to form a roughly elliptical segment having a radius of curvature everywhere greater than  $R$ . The loop trajectory for  $\mu = 0.3$  in Fig. 19 has a crossover region for  $|\bar{x}/R| \leq 1.038$ .

## 7. THEORY OF AN ELECTROSTATIC PROBE IN A PLASMA

Robert L. Chazin, Donald P. Geesaman,  
John Killeen, and Laurence S. Hall

An improved analysis has been made of the behavior of an electrostatic (Langmuir) probe immersed in an infinite plasma composed of electrons and a single species of ion. The development is based on the simultaneous solution of Poisson's equation and the collisionless Boltzmann equation. The formal analysis is similar to that of Bernstein and Rabinowitz,<sup>7</sup> but differs in the boundary conditions and the method of solution. In particular, a Maxwellian distribution and distinct temperature are assumed for each type of particle in the undisturbed plasma. Although this leads to a more cumbersome equation than the monoenergetic ion-velocity distribution of the Bernstein-Rabinowitz theory, arguments can be made which indicate that the energy spread is an essential and probably critical feature of a correct analysis in the touchy transition region between the sheath and the relatively large region of nonvanishing potential in which the plasma is very nearly neutral. As in the Bernstein-Rabinowitz theory, an a priori division into "sheath" and "plasma" regions is not found to be necessary.

The problem, as presently formulated, is separated into two parts: (a) the determination of the self-consistent potential distribution about the probe in the presence of the plasma, and (b) the subsequent determination of the collected probe current. This division avoids the difficulty of relating the density and the current explicitly--a procedure which, in general, can be carried out exactly only with a complete knowledge of the potential around the probe. The exception is the case studied by Bernstein and Rabinowitz.

<sup>6</sup> S. A. Zwick, in Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960, p. 103.

<sup>7</sup> I. B. Bernstein and I. N. Rabinowitz, Phys. Fluids 2, 112 (1959).

The most important result of part (a), and the central feature of the development, is the determination of the curve in energy-momentum phase space which separates the attracted-particle orbits that intersect the probe from those orbits which do not. This curve enters functionally in the expression for the density of attracted particles, and an iterative procedure has been devised for its determination. At present a code is in preparation for putting this portion of the problem on an IBM 709.

Once the phase-space curves are numerically determined, they will be cast into a certain approximate analytic form and the results tabulated. This will allow the collected current, which is an integral over the phase space of those orbits intersecting the probe, to be expressed in terms of probe potential and system parameters in such a way that a simple iterative procedure can be applied in the laboratory to obtain temperatures and densities from the probe voltage-current characteristic. This last feature, almost wholly missing in most previous analyses with the notable exception of the original work by Langmuir and Mott-Smith,<sup>8</sup> is felt to be a necessary ingredient of a useful theory.

## 8. CYCLOTRON RADIATION FROM A PLASMA

Donald P. Geesaman

A calculation is being made of the energy loss from a hot plasma due to the escape of cyclotron radiation. The work assumes the conclusions of Drummond and Rosenbluth,<sup>9</sup> and of Trubnikov and Bazhanova.<sup>10</sup> Expressions for the absorption coefficients are taken from the derivation of Trubnikov.<sup>11</sup> The energy-loss integrals are currently being programmed for evaluation by machine integration. Representative plasmas are to be considered for slab and cylindrical geometries with reflectors, and the critical dimensions of the systems are to be obtained on the assumption that all the thermonuclear energy that goes toward heating the ions will be transferred to the electrons by collisions.

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<sup>8</sup>I. Langmuir and H. Mott-Smith, GE Review 27, 449, 538, 616, 762, 810 (1924).

<sup>9</sup>W. E. Drummond and M. N. Rosenbluth, Phys. Fluids 3, 45 (1960).

<sup>10</sup>B. A. Trubnikov and A. E. Bazhanova, Physics of Plasma and Problems of Controlled Thermonuclear Reactions 3, 131 (1958).

<sup>11</sup>B. A. Trubnikov, On the Angular Distribution of Cyclotron Radiation from a Hot Plasma (to be published).

## 9. PENETRATION OF CHARGED PARTICLES THROUGH THE PICKET-FENCE AND RELATED FIELDS

N. W. Hetherington and C. H. Woods

The picket-fence magnetic field (the so-called cusp magnetic field is a special case of the picket fence) is produced by currents flowing in a set of straight, parallel, equidistant wires lying in a plane, the direction of current flow being the same in alternate wires, and opposite in adjacent wires. Plasma interacting with such a field is generally considered to be stable. The extent to which single particles penetrate the magnetic barrier is a separate question, and is the subject of a separate report.<sup>12</sup>

Whether or not a particular particle will penetrate the barrier depends in a complex way on the initial conditions for that particle, because these conditions ultimately determine whether the particle arrives near a "picket" or near a "slot." The particle energy and the angle of arrival are of course relevant, and are implied in the initial conditions.

Although it is possible to express the vector magnetic potential of the field, and to derive a mechanical potential for the particle (which can be used to calculate the distance of closest approach to the wires), no analytic method of answering the question of penetration has been developed. We have resorted to machine-calculated trajectories for answering this question. Before the results are given, it is necessary to describe briefly the types of trajectories one finds possible.

(a) Particles projected perpendicular to the barrier and straight at a wire bounce away in a relatively simple curved path that lies in a plane, and may or may not cross itself once.

(b) Particles projected perpendicular to the barrier and straight at a slot continue in a straight line and penetrate the barrier.

(c) Particles not near a penetration zone in phase space generally execute a relatively simple trajectory in three dimensions.

(d) Particles that are projected near a slot, and that do not penetrate, usually develop a helical trajectory similar to ones found in the conventional magnetic mirror. The helix has a variable radius which comes to a minimum at the point where the particle is nearest the plane of the picket fence. For trajectories of this type, the motion may be adiabatic for several revolutions.

(e) Particles started as in (d) which penetrate the picket fence simply pass through the mirror in the same way as a particle is lost from a mirror machine. The minimum radius of the helical part of the trajectory occurs at the plane of the picket fence, and has the value  $R$  for trajectories passing halfway between the wires.

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<sup>12</sup> N. W. Hetherington and C. H. Woods, Penetration of Charged Particles Through the Picket Fence and Related Fields, UCID-4198, October 1960.

There is only one parameter in the whole problem, namely, the ratio  $R/D$ , where  $D$  is the distance between wires. Preliminary results based on fifty specially chosen trajectories indicate that the probability of penetration for a single collision with the barrier is roughly 0.30 for  $R/D = 0.1/\pi = 0.03183$ . For smaller particle energy,  $R$  is smaller and the probability of penetration is smaller, but not proportional to  $R$ . For  $R/D = 0.01/\pi = 0.003183$  the probability of penetration is 0.17.

If all the currents in the picket fence are made to flow in one direction, and a sheet current flowing in the opposite direction is placed some convenient distance behind the fence, a novel situation results. The mechanical potential associated with a particle is such that the particle can never penetrate the whole system. However, the space in which the particle moves is no longer simply connected, because the particle must be allowed, in certain cases, to circumvent a wire. Some applications are discussed in the report<sup>12</sup> for which this topological feature is not a difficulty.

## 10. SCYLLA SPECULATIONS

Harold P. Furth and Lewi Tonks

One of us (H. P. F.) suggested about June 1 that the high-temperature ions which are seemingly responsible for the neutron production in Scylla might, at an early stage of their speed-up, find themselves in a magnetic field configuration closely resembling the E layer (of Astron) configurations that the other (L. T.) has been concerned with. The reversal region of the magnetic field, the existence of which experiment had shown was necessary for neutron production, would constitute a guiding trough with strong focusing action and an accelerating electric field from the changing flux. This action could furnish an initial energy increment which would then be multiplied by the subsequent adiabatic compression.

The initial deuteron acceleration due to the vanishing of the reverse flux is readily estimated on the basis of experimental numbers. We have just  $V \approx e\Delta\phi/2\pi rmc$ , where  $V$  is the velocity to which a deuteron can be raised when starting from rest, and  $\bar{r}$  is the mean radius of the tubular region of zero field. If one takes for  $\Delta\phi$  twice the typically trapped reverse flux in Scylla, estimated at  $10^4$  gauss cm<sup>2</sup>, and if  $\bar{r}$  is 0.5 cm, then  $V = 4 \times 10^7$  cm/sec. The experimental observation of little Doppler shift in the neutron spectrum is not inconsistent with the runaway explanation. Since the reverse flux has vanished at about the time when neutron production begins, all ions are then forced into small gyro-orbits, and even ions with a runaway history produce a neutron spectrum without any marked Doppler shift.

A highly idealized model has been studied so far to develop some feeling for the basic phenomenon. The tubular zero-field region is assumed to be at rest, which is a fair approximation during the interval between arrival of the shock on axis and the onset of the neutrons. The plane geometrical approximation is used. Collisions and other multiparticle phenomena are ignored.

The equations of motion of a charged particle in a model configuration,  $B_z = -B'y$  with  $B'$  constant,  $E_x = \text{constant}$ ,  $B_x = B_y = E_y = E_z = 0$ , were written down. The trajectories were seen to constitute a family of essentially two parameters, energy and phase. The trajectory would have three stages. State I is a gyration about a guiding center which moves in an oblique straight line toward the  $x$  axis. The  $y$  component of the motion arises from the  $E \times B$  drift. The  $x$  component arises from the  $\nabla B \times B$  drift, and causes the particle to lose energy. Stage II begins when the guiding-center concept breaks down because the gyration radius approaches equality with the distance between the guiding center and the  $x$  axis. (The guiding-center speed also increases indefinitely.) Stage II is the trapping stage, and marks the transition between motion toward the  $x$  axis and confinement to its neighborhood. Stage III is the runaway stage in which the electric field accelerates the particle in the  $B \approx 0$  zone. Figure 21 shows one trajectory. Unfortunately, the  $x$  and  $y$  scales are unequal, and this gives the appearance of elliptical, instead of circular, gyrations in Stage I.

## 11. SCATTERING OF CHARGED PARTICLES BY ATOMS

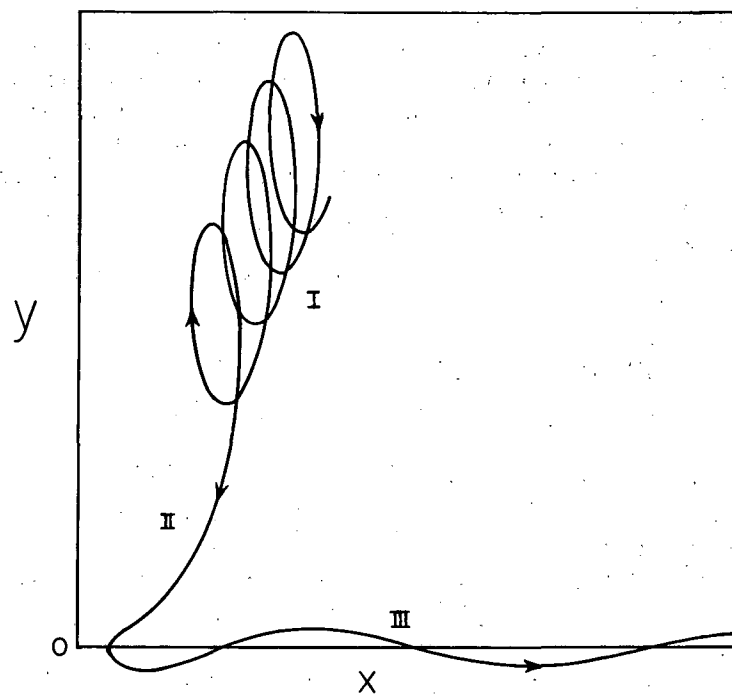
Marvin H. Mittleman

The code mentioned in the preceding report<sup>13</sup> for the calculation of the electron-neutral atom elastic-scattering cross section is now operating. We are calculating the phase shifts for hydrogen and argon at the moment. Results are not yet available. The code can be used to describe scattering from any atom for which Hartree-Fock wave functions are available.

The problem of charge exchange in the system of proton plus atom is now being investigated. Helium is being used as an example. A method for calculating the scattering of an electron from atomic hydrogen exactly is being developed in cooperation with M. Rotenberg. We contemplate the use of the LARC for the actual calculation.

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<sup>13</sup>Marvin H. Mittleman, in Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960, p. 113.



MU-21871

Fig. 21. Typical particle trajectory in reverse-field layer.

## 12. CONTAINMENT OF POSITRONS IN A MIRROR MACHINE

Gordon Gibson,\* Willard C. Jordan,<sup>†</sup> and Eugene J. Lauer

This experiment has been described in earlier Quarterly Reports and also in *Physical Review Letters*, along with a brief presentation of some of the results.<sup>14</sup> In this report the mean containment times observed with the counter located on axis are summarized and analyzed in some detail.

Figures 22 and 23 show curves for fast-empty counting rate vs time taken with neon as the scattering gas and with the single-channel pulse-height analyzer set for  $0.5 \pm 0.05$  Mev (counter resolution = 19% half width at half maximum) and for  $1.0 \pm 0.1$  Mev (counter resolution = 13%). Similar data have been obtained with argon, krypton, and xenon as scattering gases. In each case the pressure was chosen to give containment times of the order of seconds, the range of containment times for which it is possible to make the most accurate comparison of measurement and theory. The pressure was varied by a factor of four within this range. For all these data the coil separation was 64 inches center to center, the coils were coaxial, the central field was 1300 gauss, and the current bias<sup>15</sup> was 13%.

Table II lists the observed mean containment times (time for an e-fold decrease of the straight lines, which were fitted by eye to the data) along with theoretical time constants. For 0.5-Mev positrons in neon, two sets of data taken about two months apart are shown. These give an indication of the degree of reproducibility of the measurements. Repeated measurements of the containment time yield maximum deviations of  $\pm 10\%$  from the average values. Part of this is due to the uncertainty in adjusting the scattering gas pressure. Also, repeated calibrations of the ion gauges vary by  $\pm 5\%$ .

The theoretical (single-energy) containment times listed are obtained from the formula<sup>16</sup> for the multiple scattering of an electron in passing through a thin foil, where  $\pi/2$  minus the half angle defining the loss cone is substituted for the projected root-mean-square angle on a plane, i. e.,

$$\tau = \frac{2(\beta^3) \left[ \frac{\pi}{2} - \sin^{-1} \left( \frac{1}{\sqrt{R}} \right) \right]^2}{8\pi N_0 (Z+1) Z R_0^2 c \ln(\delta/\Delta) (1-\beta^2)} \quad (1)$$

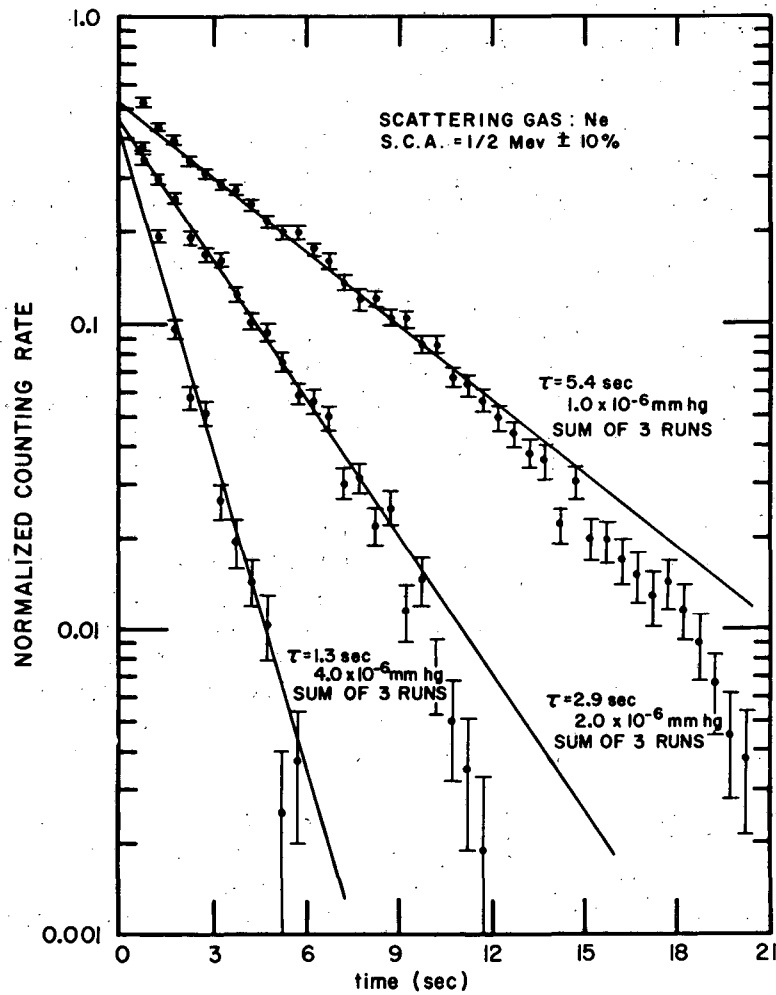
\* Westinghouse Electric Corporation.

<sup>†</sup> Bendix Corporation.

<sup>14</sup> Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, *Phys. Rev. Letters* 5, 141 (1960).

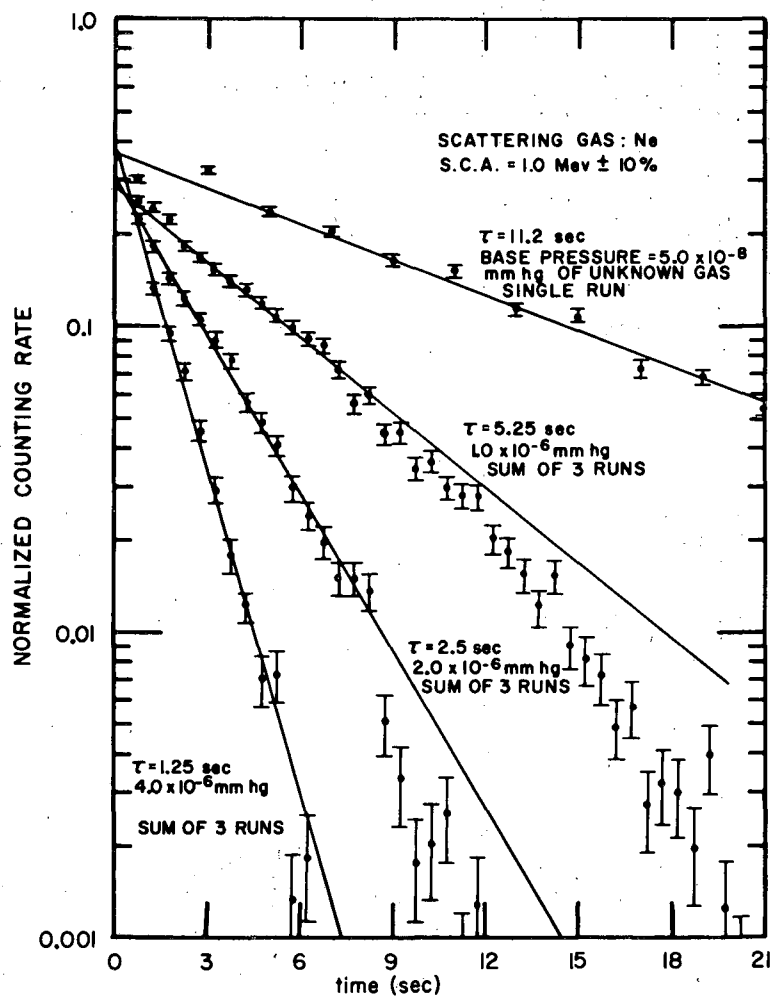
<sup>15</sup> Defined as  $2(I_F - I_N)/(I_F + I_N)$ , where  $I_F$  and  $I_N$  are the currents in the coils which are far from and near to the counter respectively.

<sup>16</sup> E. Fermi, *Nuclear Physics* (University of Chicago Press, Chicago, 1950), page 37.



MU-21872

Fig. 22. Counting rate vs time after opening fast valve. Single-channel analyzer set for  $0.5 \pm 0.05$  Mev.



MU-21873

Fig. 23. Counting rate vs time after opening fast valve. Single-channel analyzer set for  $1.0 \pm 0.1$  Mev.

Table II

Observed mean containment times ( $\tau$ ) compared with the predictions of gas scattering theory; coaxial 60-inch (mean diameter) coils separated 64 inches, 1300-gauss central field, + 13% bias,  $R = 1.68$ .

| Scattering gas | Z  | Single-channel analyzer (Mev) | Pressure at 25°C (10 <sup>-6</sup> mm Hg) | $\tau$ (sec)                |                          |          |
|----------------|----|-------------------------------|-------------------------------------------|-----------------------------|--------------------------|----------|
|                |    |                               |                                           | Theoretical (single-energy) | Theoretical (corrected)  | Observed |
| Neon           | 10 | 1.0 ± .01                     | 1.0                                       | 7.0                         | 5.5                      | 5.2      |
|                |    |                               | 2.0                                       | $\frac{1}{2} \times 7.0$    | $\frac{1}{2} \times 5.5$ | 2.5      |
|                |    |                               | 4.0                                       | $\frac{1}{4} \times 7.0$    | $\frac{1}{4} \times 5.5$ | 1.2      |
|                |    | 0.50 ± .05                    | 1.0                                       | 2.8                         | 6.0                      | 5.4, 4.6 |
|                |    |                               | 2.0                                       | $\frac{1}{2} \times 2.8$    | $\frac{1}{2} \times 6.0$ | 2.9, 2.6 |
|                |    |                               | 4.0                                       | $\frac{1}{4} \times 2.8$    | $\frac{1}{4} \times 6.0$ | 1.3, 1.3 |
| Argon          | 18 | 1.0 ± .01                     | .31                                       | 8.7                         | 8.5                      | 5.5      |
|                |    |                               | .62                                       | $\frac{1}{2} \times 8.7$    | $\frac{1}{2} \times 8.5$ | 2.9      |
|                |    |                               | 1.24                                      | $\frac{1}{4} \times 8.7$    | $\frac{1}{4} \times 8.5$ | 1.8      |
|                |    | 0.50 ± .05                    | .31                                       | 3.5                         | 5.8                      | 4.8      |
|                |    |                               | .62                                       | $\frac{1}{2} \times 3.5$    | $\frac{1}{2} \times 5.8$ | 2.6      |
|                |    |                               | 1.24                                      | $\frac{1}{4} \times 3.5$    | $\frac{1}{4} \times 5.8$ | 1.4      |
| Krypton        | 36 | 1.0 ± .01                     | .075                                      | 12                          | 13                       | 5.9      |
|                |    |                               | .15                                       | $\frac{1}{2} \times 12$     | $\frac{1}{2} \times 13$  | 3.6      |
|                |    |                               | .30                                       | $\frac{1}{4} \times 12$     | $\frac{1}{4} \times 13$  | 2.0      |
|                |    | 0.50 ± .05                    | .075                                      | 5.2                         | 7.2                      | 5.8      |
|                |    |                               | .15                                       | $\frac{1}{2} \times 5.2$    | $\frac{1}{2} \times 7.2$ | 3.2      |
|                |    |                               | .30                                       | $\frac{1}{4} \times 5.2$    | $\frac{1}{4} \times 7.2$ | 1.6      |
| Xenon          | 54 | 1.0 ± .01                     | .043                                      | 12                          | 13                       | 6.4      |
|                |    |                               | .086                                      | $\frac{1}{2} \times 12$     | $\frac{1}{2} \times 13$  | 3.3      |
|                |    |                               | .172                                      | $\frac{1}{4} \times 12$     | $\frac{1}{4} \times 13$  | 1.9      |
|                |    | 0.50 ± .05                    | .043                                      | 5.2                         | 7.0                      | 5.1      |
|                |    |                               | .086                                      | $\frac{1}{2} \times 5.2$    | $\frac{1}{2} \times 7.0$ | 2.6      |
|                |    |                               | .172                                      | $\frac{1}{4} \times 5.2$    | $\frac{1}{4} \times 7.0$ | 1.3      |

V.

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UCRL-9393

This agrees quite well with the fundamental time constant obtained from a simple model of a Lorentzian gas in a mirror machine<sup>17</sup> where the following assumptions are made: The positrons behave adiabatically; there are sinks corresponding to the loss cones in velocity space; the loss cones are independent of position; particles enter the loss cones because of elastic multiple Coulomb scattering.

There are many limitations to this theory when comparing it with the experimental results. The magnetic field is not uniform in a mirror machine, of course, and the spatial dependence of the distribution function must be considered in a rigorous treatment. In this manner the importance of the higher harmonic terms, which represent particles that escape more promptly, has been estimated.<sup>18</sup> Another approximation is the use of the Coulomb potential. Shielding of the nucleus has been accounted for only in the manner in which the cutoffs have been chosen. (Neglect of the shielding is a more serious limitation for the gases having the larger nuclear charges.) A further complication is that positrons do not have a single energy during their confinement, but degrade in energy, mainly because of inelastic collisions and radiation due to their gyration in the magnetic field. Hence, the probability of a given scattering event's occurring for a given positron is a function of time. The effect of energy degradation also complicates the interpretation of the results, since the containment time observed experimentally becomes a function of the energy distribution of the positrons.

The energy lost by a positron of a given initial energy due to the ionization of a given scattering gas during a mean containment time is independent of the pressure. (The rate of energy loss is directly proportional to the pressure, while the containment time varies as the inverse of the pressure.) However, this energy loss varies with different scattering gases approximately as  $1/(Z+1)$ . The energy loss due to radiation varies directly with the containment time, assuming a uniform magnetic field and neglecting the variation of rate of loss with energy. Hence by utilization of a high enough pressure the effects of radiation can be made negligible. This is an advantage in treating the energy-degradation effects theoretically, since the energy loss per unit path length due to ionization is independent of the pitch angle of the velocity vector, the magnitude of the magnetic field, and--to a good approximation--the energy of the positron over the energy range of interest. However, we are limited experimentally to pressures that give containment times greater than the pumpout time of about 0.3 sec, so that radiation effects are negligible for only some of the data presented here.

From Tables II and III it can be seen that a 1-Mev positron loses approx 0.37 Mev because of ionization of the scattering gas during a calculated mean containment time when the scattering gas is Ne, and that a 0.5-Mev positron loses approx 0.15 Mev. A 1-Mev positron whose velocity vector is normal to a 650-gauss field loses approx 0.0058 Mev during a mean containment time when the Ne pressure is  $4 \times 10^{-6}$  mm Hg, and approx 0.022 Mev

<sup>17</sup> Gordon Gibson and Eugene J. Lauer, UCRL-5696 (1959).

<sup>18</sup> David Berkowitz, private communication. It has been estimated that the observed time constants in this experiment would be approximately 10% shorter than that given by Equation (1).

Table III

Rates of energy loss for various operation conditions. The radiation loss is obtained by assuming that the velocity vector is normal to the field. The relative importance of the radiation loss to the ionization loss is also given.

| Gas | H = 650 gauss                                      |                                              |                                                           |                                              |                                                           |            | H = 1300 gauss                                     |                                                           |                                                   |                                                           |
|-----|----------------------------------------------------|----------------------------------------------|-----------------------------------------------------------|----------------------------------------------|-----------------------------------------------------------|------------|----------------------------------------------------|-----------------------------------------------------------|---------------------------------------------------|-----------------------------------------------------------|
|     | E = 0.5 Mev                                        |                                              |                                                           | E = 1.0 Mev                                  |                                                           |            | E = 0.5 Mev                                        |                                                           | E = 1.0 Mev                                       |                                                           |
|     | $\left(\frac{dE}{dt}\right)_{\text{ion}}$          | $\left(\frac{dE}{dt}\right)_{\text{rad}}$    | $\frac{(\Delta E)_{\text{rad}}}{(\Delta E)_{\text{ion}}}$ | $\left(\frac{dE}{dt}\right)_{\text{rad}}$    | $\frac{(\Delta E)_{\text{rad}}}{(\Delta E)_{\text{ion}}}$ |            | $\left(\frac{dE}{dt}\right)_{\text{rad}}$          | $\frac{(\Delta E)_{\text{rad}}}{(\Delta E)_{\text{ion}}}$ | $\left(\frac{dE}{dt}\right)_{\text{rad}}$         | $\frac{(\Delta E)_{\text{rad}}}{(\Delta E)_{\text{ion}}}$ |
|     | $\left(\frac{\text{Mev}}{\text{sec}}\right)$       | $\left(\frac{\text{Mev}}{\text{sec}}\right)$ |                                                           | $\left(\frac{\text{Mev}}{\text{sec}}\right)$ |                                                           |            | $\left(\frac{\text{Mev}}{\text{sec}}\right)$       |                                                           | $\left(\frac{\text{Mev}}{\text{sec}}\right)$      |                                                           |
| Ne  | $0.052 \frac{P}{1.0 \times 10^{-6} \text{ mm Hg}}$ |                                              | $0.023 \frac{1.0 \times 10^{-6} \text{ mm Hg}}{P}$        |                                              | $0.062 \frac{10 \times 10^{-6} \text{ mm Hg}}{P}$         |            | $0.092 \frac{1.0 \times 10^{-6} \text{ mm Hg}}{P}$ |                                                           | $0.25 \frac{1.0 \times 10^{-6} \text{ mm Hg}}{P}$ |                                                           |
| A   | $0.027 \frac{P}{3.1 \times 10^{-7} \text{ mm Hg}}$ | .0012                                        | $0.044 \frac{3.1 \times 10^{-7} \text{ mm Hg}}{P}$        | .0032                                        | $0.12 \frac{3.1 \times 10^{-7} \text{ mm Hg}}{P}$         | $4 \times$ | $0.18 \frac{3.1 \times 10^{-7} \text{ mm Hg}}{P}$  | $4 \times$                                                | $0.48 \frac{3.1 \times 10^{-7} \text{ mm Hg}}{P}$ |                                                           |
| Kr  | $0.011 \frac{P}{7.5 \times 10^{-8} \text{ mm Hg}}$ |                                              | $0.11 \frac{7.5 \times 10^{-8} \text{ mm Hg}}{P}$         |                                              | $0.29 \frac{7.5 \times 10^{-8} \text{ mm Hg}}{P}$         |            | $0.44 \frac{7.5 \times 10^{-8} \text{ mm Hg}}{P}$  |                                                           | $1.2 \frac{7.5 \times 10^{-8} \text{ mm Hg}}{P}$  |                                                           |
| Xe  | $0.010 \frac{P}{4.3 \times 10^{-8} \text{ mm Hg}}$ |                                              | $0.12 \frac{4.3 \times 10^{-8} \text{ mm Hg}}{P}$         |                                              | $0.32 \frac{4.3 \times 10^{-8} \text{ mm Hg}}{P}$         |            | $0.48 \frac{4.3 \times 10^{-8} \text{ mm Hg}}{P}$  |                                                           | $1.3 \frac{4.3 \times 10^{-8} \text{ mm Hg}}{P}$  |                                                           |

when the pressure is  $1 \times 10^{-6}$  mm Hg. For 0.5 Mev this loss is approx 0.00084 Mev at  $4 \times 10^{-6}$  mm Hg and approx 0.0034 Mev at  $1 \times 10^{-6}$  mm Hg. When the field is 1300 gauss the energy loss due to radiation is four times as great. This indicates that the energy loss due to ionization is the dominant loss mechanism over these ranges of the parameters when Ne is the scattering gas. However, for Xe, the gas having the largest nuclear charge, the relative effect of radiation becomes more important and, in fact, at a pressure of  $4.3 \times 10^{-8}$  mm Hg, a positron energy of 1 Mev, and a field of 1300 gauss, it is larger than the loss due to ionization. In this case the total energy loss (0.26 Mev) during a mean containment time is approximately 1/2 of that for the comparable Ne case. Actually the radiation loss is somewhat greater in a mirror machine than is indicated in Table III if the fields that are given are taken as the minimum field on axis. For an adiabatic particle the instantaneous rate of radiation varies as the cube of the magnetic field. As a consequence, in this experiment, the rate, averaged over a longitudinal period of the motion for a particle whose center of gyration remains on axis and whose velocity vector has a pitch angle of 55 deg as it passes through the midplane, is about 1.5 times that indicated in the tables.

If radiation is neglected, the density  $D$  of the trapped positrons as a function of energy and time (under the assumptions of our model which have been discussed) is given by

$$\frac{dD}{dt} = \frac{\partial D}{\partial t} + \frac{\partial D}{\partial E} \frac{dE}{dt} = S_0(E) S(t) - \frac{D}{\tau_s(E)},$$

where

$$\frac{dE}{dt} \approx -\alpha (\text{constant over the energy range of interest}),$$

$S_0(E)$  is the beta energy spectrum of the positrons from Ne<sup>19</sup>,

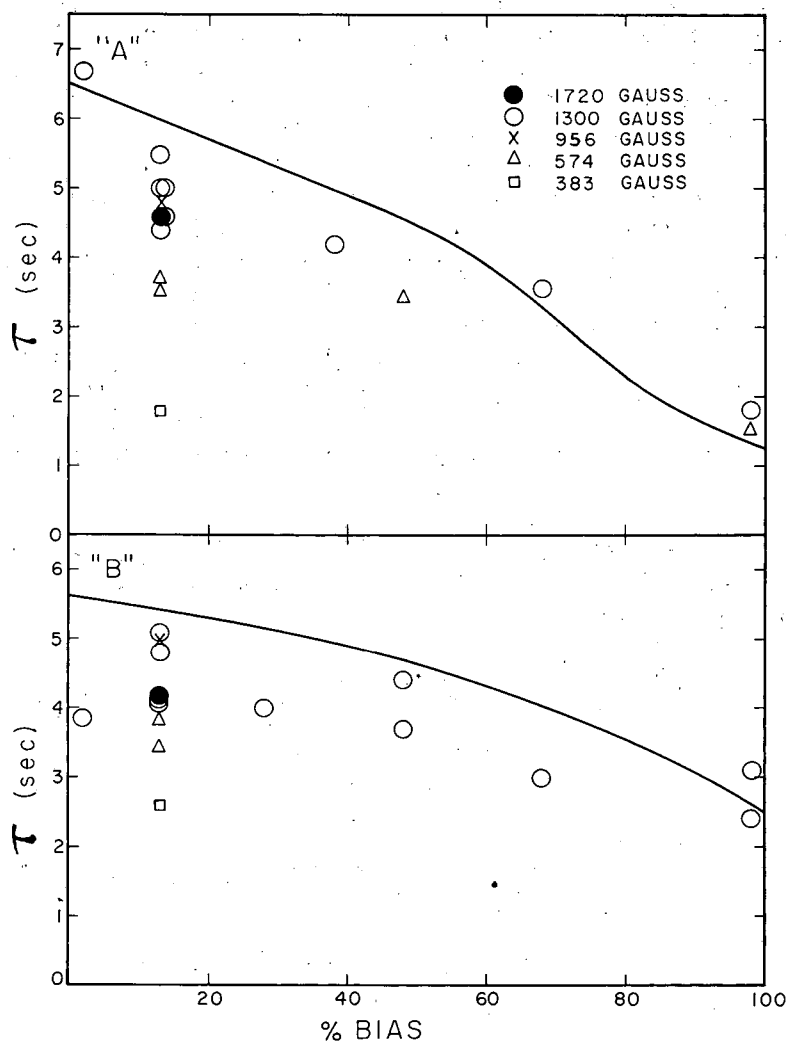
$$S(t) = \text{constant for } t < 0,$$

$$S(t) = e^{-t/\tau_p} \text{ for } t > 0,$$

$\tau_s(E)$  is the mean containment time given by Eq. (1).

This equation has been solved numerically to obtain a more refined theoretical prediction of the observed results for the steady state and for  $t \gg \tau_p$ . In addition, the effects of the finite width of the single-channel analyzer plus the resolution of the counter have been folded in to give a theoretical counting rate as a function of time. These are the "corrected" theoretical results given in Table II.

The observed containment times vary with the pressure, nuclear charges, and energy, as they should--which allows one to conclude that the particles behave adiabatically and escape because the velocity vector enters



MU-21880

Fig. 24. Comparison of measured and theoretical mean containment times with mirror coils having 60-in. mean diameters. "A": Analyzer set to accept  $0.5 \pm 0.05$ -Mev particles. "B": Analyzer set to accept  $1.0 \pm 0.1$ -Mev particles. The solid lines are theoretical values with  $1.0 \times 10^{-6}$  mm Hg of neon as the scattering gas. Experimental data were obtained at various pressures of neon and reduced to  $1.0 \times 10^{-6}$  mm Hg by assuming the times scaled inversely with pressure. Each point represents the average of several runs at a particular field strength and bias setting as indicated. Where duplicate points are plotted the data were obtained on different dates.

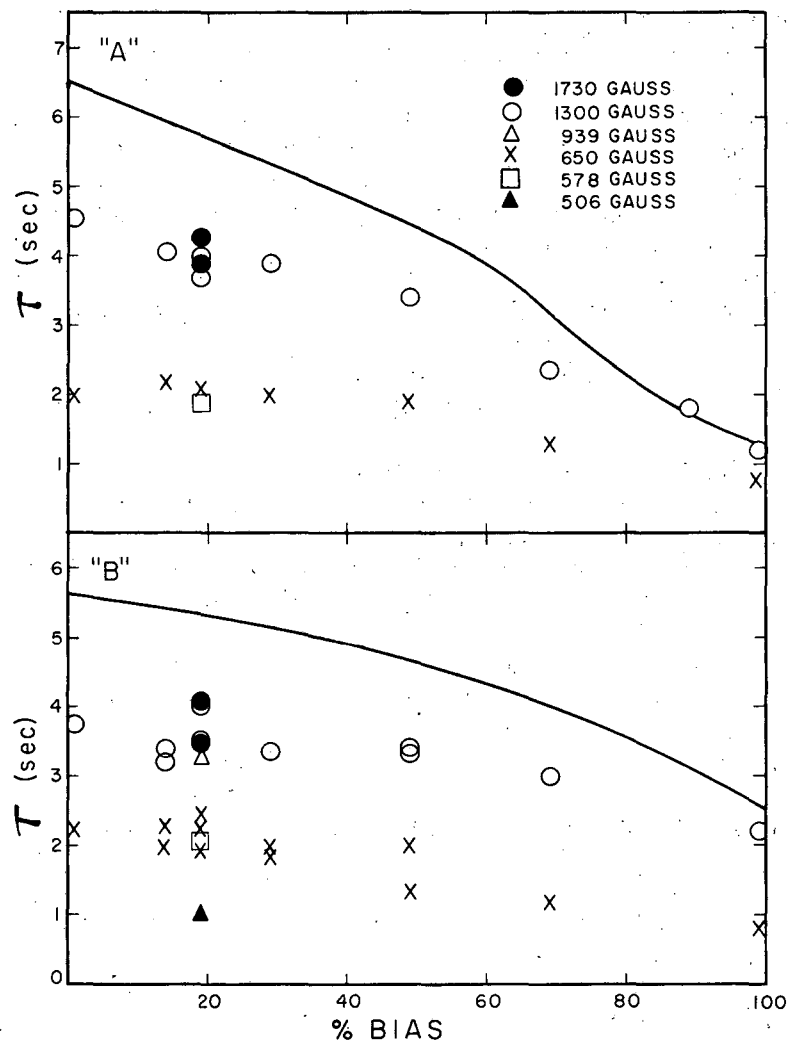
the loss cone as a result of multiple scattering,<sup>19</sup> with a mean containment time as given by Eq. (1). That the times agree as well in magnitude as they do with those predicted by Eq. (1) is fortuitous. Certainly a factor of 2 or so would not be too alarming considering the numerous effects that must be considered. For example, a different choice of the smaller impact parameter would slightly alter this agreement. The calculated time constants are not very sensitive to the choice of cutoffs which appear in the argument of a log term in the usual way. When the counter is set for 0.5 Mev and 1 Mev the measured containment times are roughly the same. This is as predicted for neon; the effect of the decrease in the scattering cross section with increasing energy is compensated by the effects of energy degradation. The more rapid drop-off of counting rate observed at long times (see Figs. 22 and 23) is expected from the theoretical treatment of the energy loss. As we go to other gases we see that the observed containment times vary with the nuclear charge about as predicted. The measured times at 1 Mev are about 1/2 of the predicted times when the scattering gas is Xe or Kr. However, this is just where the radiation effects are important, and because of its complexity this effect has not been folded into the theoretical results.

Although radiation limits the lowest pressure we may use and still make reasonable comparisons with theory, the experimental limitation is the base pressure of the system. For most of the data given in Table II the base pressure was about  $1 \times 10^{-7}$  mm Hg. This was subsequently improved to about  $1 \times 10^{-8}$  mm Hg, and containment times were measured with neon pressures as low as  $10^{-7}$  mm Hg. To within about 30% these scaled as they should. In Fig. 23 a base-pressure run ( $5 \times 10^{-8}$  mm Hg of unknown gas) at 1 Mev is shown. At 0.5 Mev the time constant at this pressure is about 30 sec. At the improved base pressure, containment times have been observed that are more than an order of magnitude greater. However, because of the various effects that have been described, it is impossible to ascribe a mean containment time to any of the base-pressure runs.

The effect of the bias on the time constants is shown in Figs. 24 and 25. The theoretical curve has been obtained by taking into account the energy-degradation effects. The smaller mirror ratio at a particular bias is used in Eq. (1) for the containment time. In addition, the time constants has been measured as a function of the field strength. If the particles behaved adiabatically the containment time should be independent of the magnitude of the field, and depend only on its shape. However, as the field is decreased the orbits get larger, and for a given set of coils and coil spacing the particles should tend to become more "nonadiabatic". Decreasing the coil size for a given field shape and intensity should have this effect also, since the field gradients are increased. The results in Fig. 24 were obtained with the same coils and coil spacing as were used

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<sup>19</sup>The rapid increase in the detected trapped fraction as we go from negative to positive bias is additional verification. e. g., See reference 14.



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Fig. 25. Comparison of measured and theoretical mean containment times with mirror coils having 30-in. mean diameters. Other parameters as in Fig. 24.

in obtaining the data given in Table II. In Fig. 25 a new set of coils was used which had a mean diameter of 30 in. instead of 60 in. The spacing in this case is 32 in., which gives about the same field shape and mirror ratio as for the larger coils. In addition, the diameter of the vacuum can between the coils was increased from 20 to 44 in.

Within the experimental uncertainty the containment times decrease with increasing bias about as expected. The experimental points near zero bias and at very large bias are more uncertain than those near 20% bias, since the number of trapped particles that leave at the counter end is smaller and hence the statistics are not as good.

Changing the field from 1720 gauss to 956 gauss with the large coils does not appreciably change the containment time. The measured times at 574 gauss are slightly smaller; however, there may be some wall effects due to diffusion across the field. The measured times are considerably shorter at 393 gauss, but there definitely are wall effects in this case.

With the small-coil-large-vacuum-chamber setup, the wall loss is expected to be negligible at 650 gauss. This has been confirmed by observing the effects of inserting probes radially into the containment region in the mid-plane. At 650 gauss for the smaller set of coils the measured containment times are about  $1/2$  of those for fields from 939 to 1730 gauss. Many of the data shown in Fig. 25 were obtained by first taking a run at 650 gauss then one at 939 gauss, then 1300 gauss, and then repeating this sequence. Doubling the pressure at 650 gauss decreases the measured containment time by a factor of 2, just as it does at the higher fields. The positrons apparently behave adiabatically during most of their time of confinement. However, there is an effectively larger loss cone at 650 gauss. This observation is in agreement with some theoretical results<sup>20</sup> obtained for this degree of adiabaticity.

Containment times have been measured for counter positions off axis also. Correspondingly long containment times have been observed there for particles that could not encircle the axis. These results will be presented in a future report.

At present the effects of tilting the coils are being studied. By the use of probes the precessional surfaces as predicted by adiabatic theory are being investigated as well as the new type of diffusion that may result.<sup>21</sup>

<sup>20</sup>A. Garren, et al., in Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy, Geneva, (United Nations, Geneva, 1958), 1958, Vol. 31, p. 65.

<sup>21</sup>Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, Phys. Rev. Letters 4, 217 (1960).

### 13. ATOMIC-BEAM AND MOLECULAR-BEAM RESEARCH

Forrest S. Baker, Gilbert O. Brink, and Edmund S. Chambers

During the last quarter the crossed-beam machine has been essentially finished and is being set up to start the experimental program. An oven loader is being added to the machine to permit the changing of beam sources without the necessity of taking the machine up to air. An electron gun has been developed which is useful in its present form down to about 200 volts. In order to go to lower energies it will be necessary to shield the electron beam from stray magnetic fields.

An improved ion source is being built to produce  $H^+$  and  $H_2^+$  ions to study cross sections of interest to the Sherwood program. This source is similar to one being used at the Stanford Research Institute and should have less energy spread than the previous one.

An experimental program is being planned to investigate the electron ionization and electron excitation cross sections of the alkalis. The alkali atoms are particularly suited to atomic beam experiments because they are detectable on a surface ionization detector. There is also considerable theoretical interest in these cross sections.

#### Total Ionization Cross Section of Potassium

For practical reasons the first of these cross sections that will be measured is the total cross section for production of positive ions by electrons on potassium atoms. This cross section is of interest because it can be used to normalize cross sections that will be measured later. The measurement will be done in two parts.

#### Relative Measurements

Measurements of a quantity related to this cross section can be made directly on the crossed-beam machine. If one meets the conditions that the entire electron beam passes through the atomic beam, and that all ions produced are collected, the ion current collected will be given by

$$S(E) = \frac{INlQ_T(E)}{e\bar{v}} f(E),$$

where

$S(E)$  = ion current collected,

$I$  = total electron current passing through the atomic beam,

$Q_T(E)$  = total cross section for ionization,

$l$  = path length of the atoms in the electron beam,

$e$  = charge on the electron,

$\bar{v}$  = average velocity of the atoms in the beam,

$f(E)$  = a function of the electron energy that depends on the ionic species produced,

$N$  = atomic-beam flux in the interaction region.

Here  $f(E)$  can be thought of as the average charge per ion produced. We have

$$f(E) = \frac{\sum_i n_i(E) q_i}{\sum_i n_i(E)},$$

where

$n_i(E)$  = number of ions of the  $i$ th species produced per second,

$q_i$  = charge on an ion of the  $i$ th species,

$$n_i(E) = \frac{INQ_i(E)l}{e\bar{v}},$$

where the quantities are as defined above and  $Q_i$  is the partial cross section for the production of the  $i$ th species. The above treatment is true as long as the incoming beam consists only of monatomic species, i. e., no  $K_2$ .

In the intended experiment all the quantities in the expression for  $S$  can be measured except  $N$  and  $f(E)$ ;  $f(E)$  could be measured only if a method of measuring charge-to-mass ratio were included in the experiment. This measurement will be saved for a later experiment.

From the expression for  $S$  we have

$$Q_T f(E) = \frac{e\bar{v}}{INl} S(E).$$

Hence from a measurement of the total ion current produced as a function of electron energy the quantity  $Q_T f(E)$  may be deduced. The measurement will be relative, however, since  $N$  will not be known, but may be kept constant during the experiment. In a later experiment the quantity  $f(E)$  will be measured and then the true relative total ionization cross section will be known.

### Absolute Measurement

In order to measure the total ionization cross section absolutely it is necessary to know the atomic-beam flux in the interaction region. This cannot be measured easily in the above experiment. It can be measured, however, in a separate experiment that uses radioactive  $K^{42}$  as a tracer.

Suppose that an atomic beam of  $K^{42}$  is crossed by an electron beam under the above conditions and a method is provided to collect all the ions formed and at the same time to collect all the atoms in a given area of

the direct beam. The total number of ions formed per second (assuming no polymers in the beam) would be

$$A(E) = \frac{INQ_T(E)l}{e\bar{v}},$$

where the quantities are as defined above and  $A(E)$  is the total number of ions produced per second. It can be shown that we have

$$Q_T(E) = C \frac{R_s(E)}{R_B(E)},$$

where

$C$  = an apparatus constant,

$R_s(E)$  = counting rate of ion sample in a given counter,

$R_B(E)$  = counting rate of direct beam sample in the same counter, and the two samples are collected for the same length of time and counted at about the same time.

Thus by counting samples obtained under the same conditions at various values of the electron energy, several absolute values may be obtained for  $Q_T$ . These may be used to normalize the relative values obtained in the previous section. Both the above experiments will have to be corrected for the polymer content of the beam.

Equipment for both of the above measurements is being set up and further details will be reported later.

#### 60-kev Hydrogen Ion Source

In order to study hydrogen atom and molecule reactions with the crossed-beam apparatus, a 60-kev hydrogen ion source is being developed. At present an rf source with canal extraction is being studied. This is similar to the one described by Moak et al.<sup>22</sup> About 1 ma has been obtained.

Peterson et al. have found that an rf ion source, in which the ions are extracted directly from an aperture at the surface of the plasma, gives ions with a much smaller energy dispersion.<sup>23</sup> Such a source is similar to the Livermore MTA source. A small model is under construction for our use.

The Varian V2200A magnet has now been mounted on an adjustable cart. It will be used as the energy selector for the ions. The closely regulated power supplies for the ion source have been received from Sorensen.

<sup>22</sup>C. D. Moak, H. Reese, Jr., and W. M. Good, *Nucleonics* 9, 18 (1951).

<sup>23</sup>J. R. Peterson, C. J. Cook, and O. Heinz, SRI Tech. Report 720-1 (1960).

## VI. ENGINEERING AND TECHNOLOGICAL DEVELOPMENT

### 1. ULTRAHIGH-VACUUM DEVELOPMENT

Norman Milleron and Leonard L. Levenson

#### Introduction

Pursuing our goal of optimizing diffusion pump systems,<sup>1</sup> we worked on

- (a) measurement of oil backstreaming from an unbaffled pump,
- (b) conductance measurements,
- (c) pumping-speed measurements,
- (d) large bakable valve design,
- (e) contamination analyzer.

#### Results

##### Unbaffled Backstreaming of Oil

Small amounts of Naroil-40 oil backstreaming from the modified 10-in. diffusion pump previously reported<sup>2</sup> were measured while the pump was starting, stopping, and running.

The procedure used was to catch oil on a cold surface, warm the surface, wash off the oil with acetone into a weighing boat, and evaporate the acetone. Not more than 0.003 g of oil was lost during each washing and rapid evaporation.

Results were as follows:

- (a) Starting the pump with jet cap preheated yielded  $2.0 \times 10^{-4}$  g/cm<sup>2</sup> of oil.
- (b) Running the pump with jet cap hot yielded  $5 \times 10^{-6}$  g/cm<sup>2</sup>/hr.
- (c) Stopping the pump, boiler cooled first, yielded  $1.8 \times 10^{-4}$  g/cm<sup>2</sup>.

##### Conductance Measurements

The results of the conductance measurements are given in two UCRL reports.<sup>3, 4</sup>

<sup>1</sup>Norman Milleron and Leonard L. Levenson, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 115.

<sup>2</sup>Norman Milleron and Leonard L. Levenson, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 119.

<sup>3</sup>D. H. Davis, L. L. Levenson, and N. Milleron, Theoretical and Experimental Studies of Molecular Flow Through Short Ducts, UCRL-5972, July 1960.

<sup>4</sup>L. L. Levenson and N. Milleron, Optimization of Molecular Flow Conductance, UCRL-6014, Aug. 1960.

### Pumping-Speed Measurements

The modified 10-in. N. R. C. pump<sup>2</sup> was hooked up directly to a 2400-liter chamber. Pumping speed runs using both steady-state and  $dP/dt$  measurements agreed within 15% over the pressure range  $1 \times 10^{-4}$  to  $1 \times 10^{-6}$  mm Hg.

A nitrogen speed of 2000 liters/sec for the modified, low-back-streaming pump agreed well with the manufacturer's claim for an unmodified pump. A helium speed of 2500 l/sec is probably due to too much space between first and second jets. A full report of this work is in progress.

### Large Bakable Valve Design

A method of expanding and contracting pressure-actuated valve seals is being examined.

### Contamination Analyzer

Work has progressed on a combination surface-desorption-mass-spectrometer analyzer. Perhaps this instrument will see a minimum of 100 molecules desorbed per  $\text{cm}^2$ .

## 2. MECHANICAL ENGINEERING DEVELOPMENT

Thomas H. Batzer

### Toy Top

John R. Benapfl

A titanium pumping system is being developed for the source end of the Toy Top machine. The titanium is evaporated by resistance heating; about 1500 watts is required to heat the titanium to just below the melting point. The evaporator is constructed of a core of 100-mil tantalum rod 24 in. long wound with 31-mil titanium wire. The rod dimensions are chosen on the basis of an impedance match with the power supplies.

The evaporation or plating chamber is a cylinder 3 ft in diameter and 3 ft long. The periphery and one end are water-cooled to about 60°F. The results of a typical run are as follows: the evaporator is switched on for about 15 min and the pressure measured with a nude ion gage. During this time the pressure drops from  $4 \times 10^{-7}$  mm Hg to  $1.5 \times 10^{-8}$  mm Hg. After the evaporator is turned off the system returns to its original base pressure, in about 4 hr. The systems leak and outgassing rate is approximately 0.04 micron liter per second, giving an over-all system speed of about 2700 liters/sec at the lowest pressure reached. The plan is to use several evaporators over the entire length of the system. It must be noted that the above test is on a static system.

Table Top

James F. Ryan

The mechanical crowbar relief switch is in place and ready for use when required by the experimental program.

Low-Energy Neutral Beam Experiment

William S. Neef, Jr. and Eugene T. Bradley

The installation of utilities to the experimental area is nearly complete. The liquid nitrogen supply system was tested and found satisfactory. Installation of the vacuum forelines was completed and leak testing has begun. Cooling-water supply lines are nearly finished; compressed-air line installation is complete.

The 20-kv ion beam source is about 95% complete. Parts for water-cooled internal shields are being fabricated, and the exit port is being modified to provide a beam target. Testing should begin about the first of September.

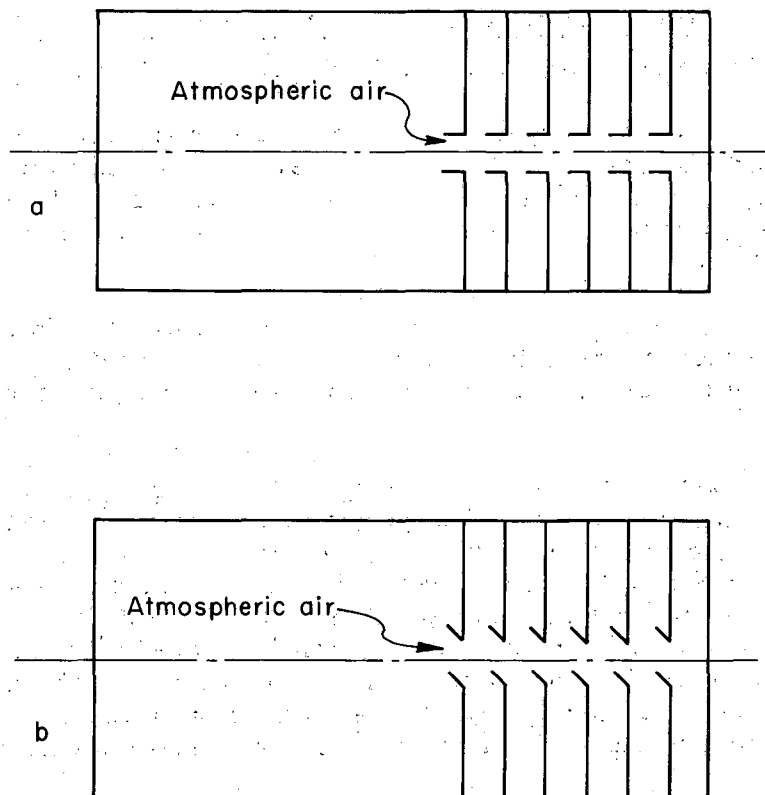
The second attempt at impregnating and potting the first 12-pancake mirror coil section was made and appears successful; however, upon cooling to 80°K a single circumferential crack appeared on one face of the coil. Subsequent electrical and cooling tests will determine the seriousness of this crack. A second coil composed of only two pancakes was tested at 80°K and showed intermittent circumferential cracks which are probably of no consequence. It is felt that a second 12-pancake coil should be fabricated and tested at liquid nitrogen temperature while fabrication of 2-pancake sections is continued. Electrical pulse tests are scheduled for about September 1.

All parts needed for the beam-tube pumping test have been fabricated and are being assembled. A new rotating plug for the beam control valve has been fabricated of stainless steel. The first aluminum plug had vacuum leaks at several welds which could not be repaired.

Several of the new elbow traps designed for cooling by circulating liquid nitrogen have been assembled. Conductance measurements will be made while the traps are in use on the beam-tube pumping test and source test.

A special clamp to be used in conjunction with the double-pinch seal on the reaction chamber has been fabricated and is being stress-analyzed at elevated temperatures. The test is about 50% complete. Several components of the reaction chamber are being redesigned to utilize the double pinch seals.

The Sanctus hardware is being moved from Bldg. 124 to Bldg. 180. A location has been established for the installation, but actual erection of equipment may be delayed several months. The Felix pumping tank is to be used as a beam-source development vacuum system. A location has also been chosen for this equipment and it will be installed at the same time as Sanctus.



MU-21866

Fig. 26. Schematic representation of multi-orifice chamber (a) with Borda tubes parallel to beam direction, (b) with Borda tubes inclined at 45 deg to beam direction.

Astron

Charles A. Hurley, James F. Ryan, James E. Blades,  
David C. Holten, and Edward G. Scarlett

The over-all mechanical design of the 720-kv electron gun is essentially complete, except for the refining, debugging, and normal engineering follow-up during the fabrication, assembly, and testing phases.

The only major component outstanding is the 12-in. -diameter ceramic-insulated accelerating column being fabricated by Coors Porcelain Company. However, the mechanical assembly of the gun can continue, using an alternate accelerating column, which is built up with O rings in place of the furnace-brazed joints. This column has been assembled and vacuum-tested and hydrostatically tested satisfactorily.

The building modifications noted in the preceding Quarterly Report are very nearly on schedule and should be completed by the middle of October.

Assembly of a full-scale accelerator unit has been delayed because of the inability of the vendor, Gladding, McBean and Company, to supply vacuum-tight ceramic electrode assemblies. We plan to buy six of the leaky assemblies at a reduced price. These will be sealed with a silicon varnish and assembled with O rings to allow assembly of one full-scale accelerator unit. This can then be used to test all the details of construction, electronic power and pulse forming elements, and heat dissipation.

An order for 30 additional modular assemblies is being placed. The most likely vendor is the General Electric Company.

Some design and testing work has been done on the hardware for beam diagnostics, including an analyzing magnet, target, and pressure transition section.

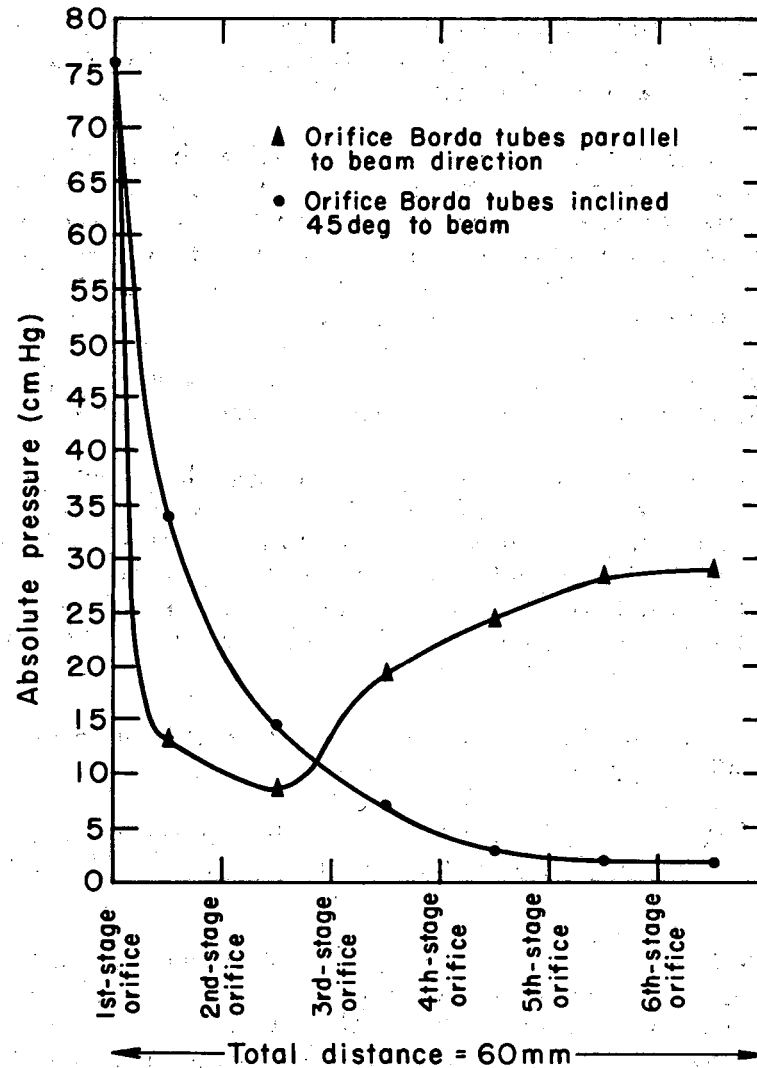
The studies of a differentially pumped transition section have continued through this reporting period. An experimental apparatus similar to Fig. 26a was constructed,<sup>5</sup> and a number of test runs were made to determine the pressure characteristics of the device. The tests were performed by using four Roots-Connerville rotary blowers<sup>6</sup> and five mechanical vacuum pumps,<sup>7</sup> in various combinations.

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<sup>5</sup>See Section VI in Controlled Thermonuclear Research Quarterly Report, UCRL-9243, June 1960.

<sup>6</sup>Roots-Connerville rotary blowers, Models 24, 33, 36, and 59.

<sup>7</sup>Kinney mechanical vacuum pumps, Models KC-47, KC-47, KC-110, KC-110, and KC-130.



MU-21867

Fig. 27. Pressure-distance characteristics for a differentially pumped transition section.

A sketch of the actual multi-orifice chamber is shown in Fig. 26a. When this configuration was used, a serious streaming problem between interstage orifice chambers became evident, as shown in Fig. 27. It was felt that this was because the discharge vena contracta of one orifice was transmitted almost completely to the inlet of the next orifice, thereby creating a high-pressure vena contracta ram through the center of the device, with air backflow along the periphery of this ram. The apparatus was then reworked as shown in Fig. 26b, where the Borda tube of each orifice was tilted 45 deg with respect to the longitudinal axis of the chamber. Testing was then resumed, and pressure characteristics as shown in Fig. 27 were obtained.

These data indicate that an orifice inlet deflection of this type would eliminate any backflow problem. It was also evident that the smoothest pressure distribution is obtained when the mechanical vacuum pumps are arranged in order of increasing capacities from the first (atmospheric-pressure) orifice. The rotary blowers used in the testing proved ineffective for the pumping loads encountered.

Design work on the main chamber of the Astron experiment is nearly complete except for the injection tank and the beam inflector. The latter waits for further specifications. The E-Layer tank and the 20-ft resistor tank are in fabrication on outside contract. The 12 split magnet coils for use around the tank flanges have been received. These coils are designed to permit an unperturbed field across the tank flanges and yet allow access for unbolting the flanges.

A section of coaxial leads for the internal coil has been assembled with commercial nylon tubing and fittings for voltage isolation and return water path. Resistance of 50,000 ohms was obtained and the assembly was leak-tight at 300 psi. Further tests to check the ability of the nylon fittings to stand hot water are being made.

Resistor elements using 1-mil and 8-mil wire have been made as a possible replacement for the thin-film glass-backed passive circuit resistors. The tooling for the external solenoids on the Astron experiment are being made in our Coil Shop. The 43-in. -diameter 2.5-ft-long coil will be made to determine feasibility of fabrication; the rest will be let out to contract.

### Component Development

J. Ralph Ullman

The differential-area air-drive piston (UCRL Drawing Number L19C-3824) used to drive the fast plug valve for the ALICE beam tube has been assembled and a preliminary run made. An indicator chart recorded on a rotating drum for the 3-in. stroke showed a travel time of 8 msec. Actuating and balance air pressures were 90 psi and 30 psi, respectively.

A 6-in. bakable valve, a descendant of the 4-in. bakable valve (UCRL Drawing Number 8ML-1176), has been designed and is being detailed. It is to be used on the ALICE reaction chamber on the beam-exit side.

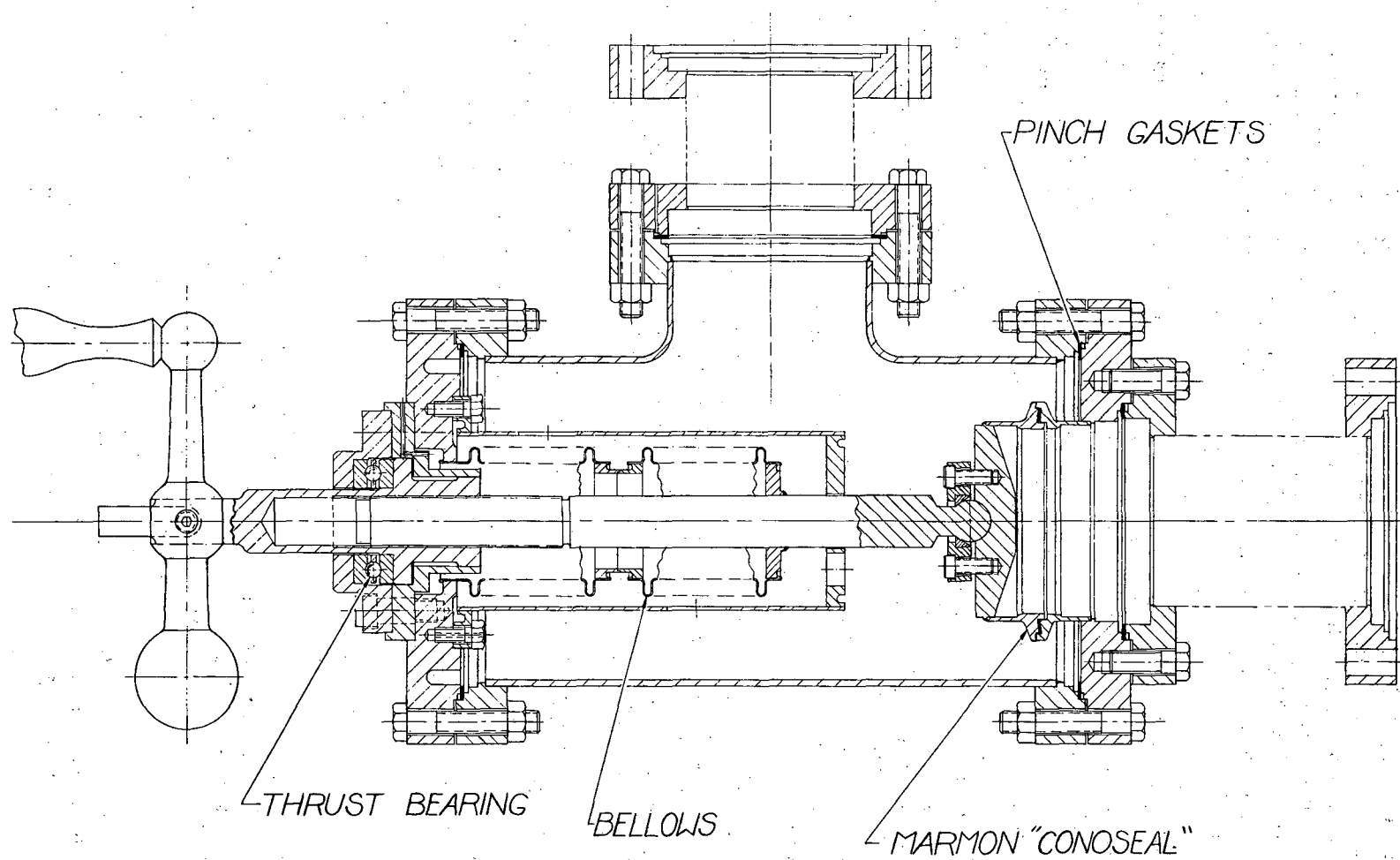


Fig. 28. Three-inch angle valve.

MUB-489

Modification of the large flange for the Mopu Number 2 tank to take a bakable double pinch gasket has been completed. Also, a bakable liquid nitrogen circulating coil has been designed and is in fabrication for insertion into the Mopu Number 2 tank. It will permit metal evaporation studies with condensation on a low-temperature substrate.

The 3-in. bakable angle valve (UCRL Drawing Number L19C-7524) has been assembled and installed on the Mopu Number 2 manifold. It isolates the vacuum tank from the roughing line leading to the VacSorb pumps. A Marmon Conoseal has been used as the valve and seat. Tests to date indicate this to be a simple, inexpensive, and effective way to make a bakable angle valve. Figure 28 shows the valve assembly.

### Cryogenic Project

Clyde E. Taylor, Robert L. Nelson, and David C. Holten

Most of the engineering work on this project is concerned with the design of the low-temperature helium blow-down system. This system will remove, during 1-min pulses, 3 kw from an 8-in. i. d. sodium magnet coil. Helium gas at 7°K and at 5 to 10 atmos pressure is the cooling fluid. One pulse every 30 min to 1 hr will be possible. The major components not yet under construction are the two low-temperature valve boxes (all low-temperature valves are on order), the magnet container, connecting piping, support stands, and instrumentation.

Two 10,000 ft<sup>3</sup> plastic helium-recovery balloons have been installed, with a fence for wind protection. Twelve type-MLA reconditioned submarine battery cells have been obtained to power the sodium coil.

A large sodium sample was distilled and cast into a tube, 1/2 in. o. d. by 20 ft long, wrapped into the form of a coil 2 in. o. d. × 14 in. long. The magneto-resistance of this coil at liquid helium temperature was measured up to 18,000 gauss. These results will be published separately.

A model of a low-temperature high-current-capacity switch was tested for contact resistance at liquid nitrogen temperature. The 24 contacts have less than 0.1 micro-ohm total resistance, and the switch is being incorporated into the magnet coil chamber. Its purpose is to thermally isolate the solenoid from the warm electrical leads when the solenoid is not energized. This switch will not open or close under electrical load.

An Arthur D. Little helium liquefier has been installed and is now operating in the Cryogenics Laboratory. A modification incorporated in this machine makes it possible to pipe the helium gas to and from an external heat load, bypassing the Joule-Thompson expansion system. This permits external experiments to be continuously refrigerated at temperatures down to 8°K.

Low-Temperature Refrigeration

Clyde E. Taylor

Experiments were completed on the three-stage F-22-ethylene-methane cascade refrigeration system using two-stage compression. One rotary compressor, in the methane stage, was damaged, apparently because of improper lubrication. Before this compressor was removed, temperatures below  $-300^{\circ}\text{F}$  were reached in the dummy baffle used as a heat load. The system operated very satisfactorily at  $-260^{\circ}\text{F}$  using single-stage compression in the methane system and two-stage compression in the F-22 and ethylene stages. The remaining two Leiman rotary compressors, used as low-pressure compressors in the F-22 and ethylene stages, performed very satisfactorily for about 2 months of operation.

Experiments were done on mixing methane and ethylene as a refrigerant gas and were very encouraging. Therefore the cascade system was modified and is now operating using single-stage hermetically sealed compressors only.

Typical heat loads and dummy baffle temperatures are:

| <u>Watts</u> | <u>Inlet temperature</u> | <u>Outlet temperature</u> |
|--------------|--------------------------|---------------------------|
| 0            | $-244^{\circ}\text{F}$   | $-223^{\circ}\text{F}$    |
| 100          | $-242^{\circ}\text{F}$   | $-217^{\circ}\text{F}$    |

Tests at higher heat loads are now in progress.

### 3. ELECTRICAL ENGINEERING DEVELOPMENT

Vernon L. Smith

Pyrotron

David R. Branum

Table Top II

The machine has been operated a total of 7,241 times at an average bank level of  $\pm 10$  kv.

One of the pulse coils was replaced when an internal water leak developed. The new coil was tested up to a bank level of  $\pm 16$  kv.

Since the machine is now in constant use, a preventive maintenance schedule had to be established to reverse the polarity on the acid-water type charge resistors. The reversal is done after every 1,000 bank operations, thereby preventing excessive resistor electrode erosion.

During the past quarter there have been several chassis component failures, and one "arc-over" in the control circuits caused a 1-day shutdown.

The mechanical crowbar relieving switch has been modified and is being installed on the machine.

The gas valve experiment by Dr. Walton Perkins now requires a higher operating voltage on its capacitors, thereby greatly over-rating the present ignitron switches. A six-section "green river" type of capacitor bank for the main shock coil is now under construction. An additional 2- $\mu$ f 30-kv capacitor bank for the initial shock coil is also under fabrication.

A safety interlock system was installed and checked out for the electron gun experiment. A 250-kv 1-ma dc supply was added to the experiment so that either the original 50-kv supply or the new 250-kv supply could be used as the over-all gun energy supply.

A 0- to 3-kv 200- $\mu$ sec pulse width linear-sweep generator is under development for the experiments of Dr. Robert Ellis.

A 0- to 1-kv 10- $\mu$ sec pulse width square-wave generator is under development for the experiments of Dr. R. Perkins.

A relay-control scanning system that has to scan the outputs of 200 separate thermistors is now under development for the experiment of Dr. Thomas Passell.

A 0- to 10-kv 1- $\mu$ sec pulse width square-wave generator is under development for the experiments of Dr. Thomas Passell.

### Toy Top III

The 300-kw dc magnet supply designated Perkins No. 10 was completely installed and is now in use.

A completely new bank-to-load-coil transmission line was constructed for the two sections of bank No. 4. This line consists of 12 heavy double copper flexbraids in parallel, 6+ and 6-. The insulation consists of two layers of transflex tubing over each flexbraid. The line was arranged into a 2 $\times$ 6 configuration and encapsulated with fiberglass tape and epoxy resin. The finished line has a resistance of 0.64 milliohm and an inductance of 0.1 microhenry. The first line made up of coax cables had a resistance of 7 milliohms and an inductance of 0.03  $\mu$ h. The gain that resulted by decreasing the transmission losses resulted in a 25% higher field at the same bank levels, thereby allowing a bank operation at  $\pm 15$  kv for normal operation with desired fields instead of  $\pm 20$  kv.

The inductance of the crowbar section of bank No. 4 was too high and was thereby causing a bank-crowbar-field modulation after peak field. Since the bank can be operated at  $\pm 15$  kv instead of full-level  $\pm 20$  kv, a crowbar ignitron was removed from each crowbar chain, leaving only two ignitrons in series and two sets in parallel per bank. Since the peak operating current per tube is 150,000 amperes, a modification to add another two chains in parallel is under design. This modification should further decrease the crowbar chain inductance and resistance and result in a smoother crowbarred field with a longer  $1/\epsilon$  decay.

Work is continuing on bank No. 3C. The controls and metering sections are being installed. A 24-conductor transmission line patterned after the bank No. 4 is now under design.

A bank No. 4 type of transmission line will be constructed from banks 3A and 3B to their respective load coils.

In all the banks for Toy Top III a long L/R field delay is desired, therefore an efficient transmission line-crowbar switch is needed.

A signal-powered pulse stretcher was designed for the diagnostics effort of Toy Top III. It consists of a fast-recovery diode, a transistor clamp, and a pulse transformer-coupled delay line. The diode stretches a 10-nsec input signal. The transistor clamp collector voltage is the pulse voltage of the stretched signal. The input signal is passed through a delay line--1  $\mu$ sec in the model made. This delayed signal is then transformer-coupled to the base of the transistor clamp to turn it on and clamp the stretched voltage. The output signal is thereby a 1- $\mu$ sec square wave for every 10-nsec signal on input. This is a useful device for finding a random fast signal in a long time base.

A video-frequency filament supply for a Veeco ion gauge is under design. The filament will be powered by a 20-kc signal source and the final model will be self-regulating.

#### P-4

A mercury relay signal chopper that was synchronized to a mechanical wheel light chopper was designed and constructed, and is now in use on the experiment.

### Pyrotron--Miscellaneous

H. W. Van Ness

#### Baby Alice

The rapid beam turn-on and turn-off system and other diagnostic circuitry required for the completion of this experiment were completed and operated satisfactorily during this period. All experimental work on the Baby Alice machine was concluded on July 29.

The machine has since been dismantled and the main vacuum system has been moved to Bldg. 180 for use in future source-development work.

#### ALICE

Design of the electronics installation for Bldg. 180 continues. The thyrite discharge resistor assembly for dissipating the energy stored in the cryogenic cooled coil has arrived and is awaiting installation. A general specification was written regarding the requirements for dissipating the inductively stored energy. This specification was sent out to industry with requests for proposals on specific components and methods for accomplishing

the desired performance. A 300-kw Perkins dc power supply has been temporarily put into operation in the ALICE main bay area. It is being used to initially energize the ALICE ion source field coils and for preliminary tests on the first completed modular section of the ALICE cryogenics coils, and dc current-interruption tests using this supply and a presently available switch are planned.

### Source Development

Design work on the ALICE ion source installation in Bldg. 180 is essentially complete except for the 0.1% magnetic-field regulator and 0.2% high-voltage regulator. All other required chassis and components are on hand and are being installed. The source will be initially operated without the regulators mentioned above.

A promising solution to the close field regulation requirement now seems possible, using a rotating-coil fluxmeter produced by the J. C. Carter Company of Costa Mesa, California. This fluxmeter is stated to have an accuracy of one part in  $10^4$ . It also produces an error signal proportional to the deviation from a preset field value. It appears that this error signal could conveniently be used in a closed-loop system to regulate the 400-kw motor generator set. Contact has been made with the Engineering Department of the J. C. Carter Company and this system is being studied.

### Sanctus

The beam-scattering experiments were performed in Bldg. 124 with negative results. For this reason and also because theoretical calculation now indicates that this feature may not be required in the ALICE experiment, there are presently no plans for continuing these experiments in Bldg. 180. The Sanctus vacuum system and field coils have been moved to Bldg. 180 for possible future use in other experimental work.

### Pinch and Collapse

H. W. Van Ness

### Gamma Bank Area

Operational tests of the bank sections disclosed a total of 32 defective capacitors, which were replaced. These units were open-circuited internally. At voltages above 16 kv occasional faults and misfires in the bank are obtained. These faults are not well understood at this time, and future testing of a bank section is desirable if 20-kv operation is eventually desired.

A 40-kw 450-kc oscillator is being installed for use in inductively heating the inconel liner in the forthcoming "Levitron" experiment.

### Electron-Beam Experiment

A 50-kw pulsed oscillator operating at 5 Mc has been developed. It will be used to supply the electron gun anode-cathode potential in the near future.

### Fast-Scan Mass Spectrograph

Electronic circuitry has been developed for output amplification and scanning of a C. E. C. Diatron 20B mass spectrograph tube. A hyperbolic-waveform scanning system is being employed to produce a linear display of mass numbers on a conventional linear time base oscilloscope. Scanning rates from  $10^{-3}$  to  $10^{-1}$  sec to cover the mass range 2 to 100 will be provided.

### Energy-Storage System Investigation

The unipolar generator was received within the 1960 fiscal year. It is now being installed and initial starting is planned for the week of August 21.

A design of a resistive load for the generator has been decided upon.

Tests on prototype sections for the  $1.5 \times 10^6$ -amp switch look promising. Individual switch sections appear to be capable of conducting 17,000 amp for 0.2 sec without damage.

### Switch Development

David B. Cummings

### Mechanical Switching

The addition of a saturable reactor to the fast mechanical crowbar relief switch is completed. It will be tested as soon as the longer L/R decay time is needed.

### Ignitron Development

#### Tube Tests

Some of each of five different types of experimental ignitrons have been tested. These have been single- and double-pantleg anode seals in glass and ceramic with different kinds of vacuum-melted metal anodes. These tests have tentatively established:

a. The single-pantleg anode seal appears to accomplish the same thing as the double pantleg, that is, inhibit breakdown in the throat of the tube. Single-pantleg tubes appear to hold 20 kv as well as double-pantleg tubes.

b. The single pantleg appears to be as effective with a ceramic anode seal as with a glass anode seal. In addition, the ceramic tube appears to be much cleaner. An unglazed shield over the ceramic ignitor seal appears to have ended the wetting problem at that point.

c. A higher ignitor impedance appears to resist wetting in a metal anode tube.

d. Vacuum-melted mild and stainless steel anodes appear to hold voltage as well as vacuum-melted molybdenum. However, they may be slightly more susceptible to ignitor wetting.

### Miscellaneous

A report by D. B. Cummings, Ignitron Discharge Growth During  $10^8$ -Watt Pulses, UCRL-5687, June 1960, has been distributed.

Tests of a 2-in. pulse-type ignitron and a 5-in. tetrode high-voltage ignitron as a pulse line shorting switch have been completed. This was to establish the limitation on current rise time. The results are being prepared as a UCRL report.

### Atomic and Molecular-Beam Experiment

David R. Branum

The initial tests on the cross-section experiment have been completed. A number of changes in the machine and associated electronic equipment have been made in an effort to improve the machine operation.

The units to be used in a test mass spectrometer have been installed. Gain measurements will be taken on the photomultiplier section.

The 6-kv and the 15-kv dc power supplies for the ion-source portion of the experiment have been received. A 60-kv dc supply is still on order.

### Cryogenics Coil Experiment

J. W. Savage

Basic system design is complete. Present efforts are directed toward detailing the refrigeration system, liquid hydrogen, nitrogen, and "cold storage" valve control systems.

The  $4 \times 10^8$ -joule energy-storage bank (submarine batteries) is here but not permanently installed. The main switch for the 45,000-amp coil circuit is ordered, and problems of current control and battery-charging supply are in process of solution.

The microvolt bridge and other instrumentation for the bulk sodium resistivity determination is beginning to arrive and should be complete by October 1, 1960.

### Astron System Engineering

C. D. Nail

### Main Field Power Supplies

An engineering note, LE 404-1, has been written to describe the present thinking on the design of main field supplies. This has been submitted with a letter, EPS-181, to fifteen potential suppliers of large power supplies. Considerable interest has been shown in the letter, and firm proposals are expected very shortly. From the proposals and further engineering data we expect to receive, definite specifications will be written and the supplies put out for bid.

### Thyratron Pulser Design

The decision has been made to use hydrogen thyratron pulsers for the bulk of the cores. The most promising tubes is the Kuthe 6587, of which 200 have been received.

Several of these have been tested, and the rest will be checked as rapidly as possible in Bldg. 170. Tests and conditioning of the tubes (spot knocking) are conducted to 35 kv.

Design problems are being worked out for the pulser module. The pulser for each core will be constructed in a standard chassis, probably 7 in. high, and will plug into the rack. All the connections to the pulse-forming line, load cables, and control cables will be made automatically in the plug-in operation.

The preliminary results from an operating model of the pulser have given a 40-nsec rise time into resistive loads. This chassis has a fully coaxial tube housing with the above plug-in features. Filament power is from a specially-low-capacitance transformer. This method will be compared with results using a similar structure and the filament method suggested by D. O. Kippenhan. His method induces heater power into the load-transmission cables. A second chassis is being built by use of this technique.

Several companies have been interested in constructing the pulser chassis or the tube housing, and discussions are continuing.

### Core Bias Methods

Comparison studies have been made on the preferred method for biasing the magnetic cores. Both ac and dc bias have advantages and disadvantages. No decision has been reached so far.

### Timing Monitor

A system for monitoring the timing of as many as 500 separate pulsers seems imperative in order to get the system into operation. Consequently, considerable planning is in progress toward an inexpensive monitoring system which can indicate, by visual means, the malfunction of individual pulser units. Separate adjustments of the trigger timing at each pulser chassis are contemplated to compensate for variation in firing time in individual chassis and for variation in cable lengths.

### System Trigger Pulser

The 500-core pulsers will require trigger pulses of 500 to 600 volts into terminated cable. The total pulse energy is similar to that produced by one core pulser. It may be possible to use a design similar to the core modules as a system trigger if voltage-distribution and impedance-matching problems can be worked out.

Astron Research and Development

Kris Aaland

Pulse Generators

The system now in use has an 867-kc/sec crystal oscillator. A frequency tripler and two doublers provide 10-Mc/sec repetition rate. One hundred 867-kc/sec cycles are counted to provide a gate of 1200-10 Mc/sec pulses.

Pulse Amplifiers, Kilowatt Level

A single-pulse amplifier was designed for magnetic pulse permeability-measuring purposes. Description and performance are found in report No. LE 407-1 by G. A. Reeser.

Efforts are focused on amplifiers that can handle a train of pulses.

Two "channels" are needed: start-pulser and stop-pulser or single signal channel and gate channel for turn-on of certain stages.

Pulse Amplifiers, Megawatt Level

To achieve tube economy the plate voltage must be high. The high pulse duty cycle (120  $\mu$ sec) dictates a thoriated tungsten type of cathode.

We have two Machlett DP11 and DP11L tubes on hand. These were "high-potted" at the factory to their equipment limit--125 kv. Consequently we are designing facilities to go to a possible 150 kv operation. Coupled with the problem of insulation, we have heat dissipation. So far, we have assembled two complete oil heat-exchanger high-voltage facilities. Both power supplies are of 20 kw rating and have silicon diode type rectifiers. Detailed tube performance will be available in report No. LE 413-1 (JN 292-M) by B. M. Loth.

Accelerator Core Acceptance Tests

Twenty-five samples out of 150 cores received were tested with a 30-Mw unit.

Pulse permeability varied as expected. See B. M. Loth's report LE 409-1 (JN 293-M).

Magnetic Materials

Investigation at 30-nsec pulse width is complete. High permeability is obtained with 1/4-mil 50% Ni-Fe and Philips 4H type ferrite. Refer to report LE407-1 (JN289-M) by G. A. Reeser.

Other Reports Issued

G. A. Reeser, Timing System of Pulsed Machine LE 402-1. This is last year's work, intended for present "Astron" construction.

G. A. Reeser, Magnetic Core Tests for Pulsed Operation at 30 Nanoseconds Pulse Width, UCRL-6121-T. This paper is intended for presentation at the Sixth Annual Conference on Magnetism and Magnetic Materials to be held in New York City, November 14-17, 1960.

Kris Aaland, Accelerator Beam Pulsing System with Extremely Wide Range of Pulse Lengths and Pulse Repetition Rates, UCRL-5430-T, Rev. 2. This paper was presented at the Pacific General Meeting of the A. I. E. E. in San Diego, California, August 8-12, 1960.

## VII. TALKS AND PUBLICATIONS

Purdue University Summer Institute in Nuclear Engineering, June 13-July 18  
and July 25-August 5, 1960, sponsored by the AEC

C. M. Van Atta, Recent Progress in Controlled Thermonuclear Research,  
invited lecture (June 20).

American Physical Society Meeting, Montreal, Canada, June 15-17, 1960

C. C. Chang, Feasibility Study of Transient Version of Astron Thermo-  
nuclear Reactor (UCRL-5942-T Abst., April 1, 1960).

N. Christofilos, High-Current Pulsed Electron Accelerator (UCRL-5951-T,  
June 1960).

John Killeen and Warren Heckrotte, Energy Transfer from Hot Ions to Cold  
Electrons (UCRL-5948-T Abst., April 5, 1960).

C. W. Hartman, S. A. Colgate, and R. H. Munger, Conical Pinch Plasma  
Accelerator (UCRL-5950-T Abst., April 5, 1960).

W. A. Perkins and R. F. Post, Experimental Observation of a Velocity-  
Space Instability (UCRL-5953-T Abst., April 5, 1960).

R. F. Post and W. A. Perkins, Velocity-Space Plasma Instabilities Ob-  
served in a Mirror Machine--Theory and Interpretation (UCRL-5954-T  
Abst., April 5, 1960).

R. V. Pyle, G. A. Paulikas, H. F. Rugge, and J. W. Stearns, Thermally  
Ionized Cesium Plasma (UCRL-9154 Abst., April 1960).

Institute for Atomic Energy im I. V. Kurchatov of the Academy of Sciences,  
Moscow, USSR; Physico-Technical Institute, Leningrad; Institute of  
Electronic Physics, Sukhumi; Physico-Technical Institute, Kharkov

C. M. Van Atta, Selected Topics of Controlled Thermonuclear Research at  
the Lawrence Radiation Laboratory, invited lectures, July 9, July 12,  
July 16 and July 19, 1960.

The Danish AEC International Summer Course in Plasma Physics, Riso,  
Denmark, August 1-12, 1960

R. F. Post, Some Aspects of the Economics of Fusion Reactors (UCRL-6077,  
July 1960), invited lecture.

R. F. Post, Fast Neutral Particle Injection into a Mirror Machine  
(UCRL-6078, July 22, 1960), invited lecture.

R. F. Post, Impurity Radiation Losses from a High-Temperature Plasma (UCRL-6130, September 1960), invited lecture.

C. B. Wharton, Plasma Waves I. Theory of Wave Propagation in Plasma, invited lecture.

C. B. Wharton, Plasma Waves II. Experiments Using Waves in Plasma, invited lecture.

C. B. Wharton, The Space-Charge Waves in Plasma, invited lecture.

C. B. Wharton, The Plasma Probe, invited lecture.

C. B. Wharton, General Plasma Diagnostic Survey, invited lecture.

AIEE Pacific General Meeting, San Diego, Calif., Aug. 8-12, 1960.

Kris Aaland, Accelerator Beam Pulsing Systems with Extremely Wide Range of Pulse Lengths and Pulse Repetition Rates (UCRL-5430-T Rev. 2).

An Introduction to Thermonuclear Plasma Physics Symposium, Gatlinburg, Tennessee, August 22-26, 1960.

H. P. Furth, The Pinch. II, invited paper.

E. J. Lauer, Test of Mirror Confinement Using Positrons from Radioactive Gas, invited lecture.

F. H. Coensgen, Experiments on Cusp and Mirror Confinement and Compression, invited lecture.

Lewi Tonks, The Astron Thermonuclear Machine and Its Field-Reversal Problem, invited lecture.

Second International Symposium on Rarefied Gas Dynamics, Berkeley, Calif., August 3-6, 1960.

D. H. Davis, Norman Milleron, and L. L. Levenson, Theoretical and Experimental Studies of Molecular Flow through Short Ducts (UCRL-5972, July 1960).

Atomic and Molecular Gas Beams Symposium, Denver, Colorado, June 2-22, 1960.

M. H. Mittleman, The Proton-Hydrogen Scattering System (UCRL-5941-T Abst., April 28, 1960).

PublicationsThe Physics of Fluids

A. N. Kaufman, Plasma Viscosity in a Magnetic Field, 3, 610 (1960).

The Physical Review Letters

G. Gibson, W. C. Jordan, and E. J. Lauer, Containment of Positrons in a Mirror Machine, 5, 4 (1960).

Il Nuovo cimento Serie X

Alfredo Banos, Jr. and Russell Vernon, Large-Amplitude Waves in a Collision-Free Plasma. I. Single Pulses with Isotropic Pressure, 15, (1960).

International Atomic Energy Agency, Review Series No. 4, Vienna 1960

C. M. Van Atta, Recent Developments in Controlled Thermonuclear Fusion Research at the University of California.

John Wiley and Sons, Inc., New York

A. N. Kaufman, Plasma Transport Theory in the Theory of Neutral and Ionized Gases (De Witt and Detoenf, editors), 1960.

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