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CONTROLLED THERMONUCLEAR RESEARCH QUARTERLY REPORT

December 1959, January, February 1960

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December 1959, January, February 1960

Lawrence Radiation Laboratory
University of California
Berkeley and Livermore, California

March 17, 1960

GENERAL INTRODUCTION

C. M. Van Atta

In this issue of the Quarterly Report some changes in organization of the material have been made and the section on High-Energy Injection has been eliminated. Basic experimental plasma experiments carried out directly by members of the major program groups are included in the sections reporting their respective activities, even when the basic research is relatively unrelated to the major objectives of the group. The section on theoretical and basic experimental plasma research now includes only those experimental activities carried out independently of the major groups.

It may be helpful to point out some of the more significant accomplishments of the past three months.

1. Machine calculations on ion-density build-up by energetic neutral atom injection (Alice) indicate that charge exchange between already trapped atomic ions and the incoming neutral beam results in a significantly faster increase in plasma density near the axis as long as the size of the orbit for the ion in the confining field is an appreciable fraction of the width of the injected beam.

2. An analysis of the energy transfer from 200-kev deuterons to cold electrons (10 to 1000 ev) shows that the energy-transfer rate is appreciably less than the value predicted by the quasi-equilibrium theory.

3. Analysis of the stability of the Tubular Pinch leads to the conclusion that conditions for stability are much more easily satisfied in the Tubular Pinch than in a columnar pinch. The condition which ensures stability is that $|rB_\theta|$ is a decreasing function of r, which can be satisfied in a tubular pinch but not in a columnar pinch.

4. A technique has been found for finding sufficient theoretical conditions for hydromagnetic stability in diffuse linear pinches and applied to the hard-core type of pinch. It is found that plasma "β's" of the order of 0.5 are compatible with hydromagnetic stability if the configuration corresponds to the "maximal force" regime.

5. In Table Top significant results are now being obtained on the limits of stability for plasmas of highly anisotropic velocity distribution. Highly anisotropic conditions are produced by high magnetic-field compression ratios with low plasma density such that collision processes do not occur fast enough to maintain approximate isotropy.

6. Experiments with plasma jets injected axially into cusp geometry under conditions which have been said to ensure a high trapping efficiency show no evidence for trapping of the plasma, which either is immediately lost out the cusp or penetrates the stronger mirror on the far end of the cusp adjusted to a value which is predicted to prevent penetration. In related experiments on colliding plasma jets previously reported it has been shown that the predicted violent interaction between colliding plasma jets does not seem to occur.

7. A modified technique for utilizing evaporated molybdenum films in vacuum gettering has been unexpectedly effective in reducing the pressure in an unbaked vacuum system to the range of 10^{-9} mm Hg. This technique was developed in the Alice project and has been applied to the Table Top machine with remarkable success.

8. The method of inductance balancing, discussed in the preceding report as a possible means of correcting the unbalanced magnetic forces in the Tubular Pinch that throw the plasma against the inner wall of the annular space, has been tried out with very favorable results. Streak-camera pictures now show the plasma clearly remaining near the center of the annular space with no tendency to hit the walls.

Early in the present report period the first meeting of the Plasma Physics Division of the American Physical Society was held at Monterey. The LRL Controlled Thermonuclear Research Group was well represented at the meeting and made a creditable contribution to the program of research papers. These papers and other publications presented or appearing during the past three months are listed at the end of the report.

I. PYROTRON (MIRROR MACHINE) PROGRAM

INTRODUCTION AND SUMMARY

Richard F. Post

During the quarter the "Baby Alice" fast-atom-injection experiment was brought into operation, final construction and assembly of the multistage compression experiment got under way, and the studies of confinement in the Table Top facility were directed toward finding and investigating conditions under which theoretically predicted instabilities could be observed. In addition, encouragement that the demanding vacuum requirements of the Alice experiment can be met was found in the latest results of molybdenum evaporation experiments.

Returning to the question of stability of confinement, it should be noted that the final analysis of all the data taken with the Table Top magnetic-compression experiment had convinced us that plasma conditions are attainable in this experiment in which the plasma is stably confined and remains for long times, times that are in agreement with the expected rate of loss by simple collisional diffusion. These conclusions, together with tentative theoretical explanations, have been published.[1] Encouraging though these results may be, they still leave unanswered many questions. One is whether the stability is in any way dependent on the relative temperatures of the electrons and ions. Although hydromagnetic theory seems to indicate that stability should not depend on the relative temperatures, more subtle effects may be present. As we now see the problem, an answer to this first question will require evidence from either the multistage experiment (Toy Top) or the Alice facility, both of which should make possible the creation of a plasma with ion energies much higher than the electrons, i.e., the inverse of the present plasma conditions in Table Top. However, there are other important questions which may be answered with the present Table Top plasmas. One has to do with the role of the conducting coating in providing a stabilizing effect. A second question, of considerable interest, revolves around the following circumstances: It is predictable that magnetically confined plasmas that are highly anisotropic in velocity space should exhibit a "velocity-space" instability, even at very low β values. In the Mirror Machine magnetic-compression experiments, such anisotropic distributions can be deliberately created by the use of large compression ratios, and by compression at rates and initial plasma densities such that collisional effects do not destroy the anisotropy. Theoretical predictions, based on a formula[1] derived by Newcomb, can be used to predict the onset of these instabilities. We have performed some preliminary experiments on Table Top in which the conditions required by the theory (relatively low initial density, very high magnetic-compression ratio) should be satisfied, and have observed evidence of instabilities, i.e., enhanced diffusion across the magnetic field. This enhanced radial diffusion can be lessened or increased by control of initial conditions or the compression ratio. We feel these results may be of considerable help in planning new experiments and may assist in interpreting the results of other confinement experiments, such as the Oak Ridge DCS.

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[1] R. F. Post, R. E. Ellis, F. C. Ford, and M. N. Rosenbluth, Phys. Rev. Letters 4, 166 (1960).

MAGNETIC HIGH-COMPRESSION EXPERIMENTS

Frederic H. Coensgen

Multistage Experiment

The design and construction of the multistage magnetic-compression experiment has been the major occupation of the Toy Top group during the past quarter. The vacuum chamber will contain the following three sections: (a) an 18-in. -diameter injection and drift section approximately 2 meters long, (b) an intermediate 9-in. section about 1.5 m long, (c) a 4-in. final compression chamber about 60 cm long, (d) a large coupling section about 2 m long, and (e) the momentum-energy analyzer.

A dc guiding field will be provided for the system which will allow the use of injection fields as high as 600 gauss.

As the plasma ions from the generators have large forward momenta, they will drift into the 9-in. section without the necessity (at this time) of an 18-in. transfer field. Here they will be trapped by a narrow fast-rising field (6 μsec). Then the plasma will be transferred by means of two-pulsed fields. The transfer time will be about 70 μsec. The final compression should reach fields of the order of 10^5 gauss.

At this time the dc field system is being assembled. Direct-current field measurements and final shimming of the dc fields should be completed within a week. All mechanical parts are being fabricated. The necessary capacitor banks are under construction (see Electrical Engineering Development section of this report).

The trapping, transfer, and containment by the dc field in the 4-in. section will be studied before the high-compression coils are installed.

Plasma Generators

A gas-fed generator similar to that developed by John Marshall at LASL has been built and has been in operation for four weeks. Some reworking of the fast valve and electrical circuits has been necessary. At present, the plasma is being analyzed by the methods previously developed for analyzing the Toy Top generators. We are interested in the operation of the generator in the presence of longitudinal magnetic fields.

Injection

The plasma that penetrates into a magnetic field from a zero field has been analyzed. From these data and the earlier data (taken in November) a more accurate determination of $B_c = 12\pi\rho v^2$ has been made.

The data for plasma injection into a simple cusp have been reduced for earlier times. No evidence of trapping has been found. It is known from magnetic-probe data that no sharp boundary between the plasma and the magnetic field is developed in these experiments.

The time separation between the impurities and the D^+ ions was studied. From the data it appears possible to select a reasonably pure (90% or greater) deuterium plasma in the multistage experiment.

Reports

The following two reports have been written during this quarter:

W. E. Nexsen, W. F. Cummins, F. H. Coensgen, and A. E. Sherman, Collision of Two Plasma Streams, UCRL-5824, December 1959.
and
F. H. Coensgen, A. E. Sherman, W. E. Nexsen, and W. F. Cummins, Plasma Injection into a Magnetic Cusp, UCRL-5894-T, February, 1960.

DETECTION AND ANALYSIS OF PLASMA ELECTRONS

Robert E. Ellis and Walton A. Perkins

Electron Energy Distribution

Some of the results obtained from the previously reported IBM 709 computer analysis of electron energy distribution data[1] are presented here. The data were obtained with a single-channel scintillator probe (and aluminum foil absorbers) located from 1.5 to 3 in. from the plane of one of the magnetic mirrors of the Table Top machine. The electron flux escaping from the mirror entered a 1/8-in. collimator in front of a plastic fluor after passing through the absorber foil, and the signal produced in the fluor was detected by a Du Mont 6292 photomultiplier tube at the end of a 1.5-in.-diameter hollow stainless steel light piper. The magnetically shielded photomultiplier tube was about 5 ft from the fluor. Peak pulsed magnetic field values, in the median plane between the mirrors, ranged from 16 to 32 kilogauss, with mirror ratios of 1.67 and 2.4 for the two sets of coils used during the experiments. Absorber thicknesses ranged from 0.29 mil to 3.4 mils with about 2000 angstroms aluminum coating on the fluor to make it lighttight.

Typically, five to fifteen machine pulses were taken at each absorber setting. Axial or radial sources were used as noted in the accompanying figures. Time was measured from the initiation of the magnetic field, the field rise time being typically $\approx$ 500 μsec, with field decay times of $\approx$ 12 to 15 msec.

Approximately 150 distributions were computed in two machine runs. Half of the curves represented the energy distribution of the electron flux escaping through the mirror. For each distribution of the escaping electrons a corresponding energy distribution of the plasma electrons was calculated, based on the assumption that Coulomb scattering of electrons on ions is the mechanism that causes electron leakage through the mirrors.

Six different sets of data for different experimental conditions were analyzed. For each of these sets, distributions were calculated for t = 1, 2 and 3 msec (t = time elapsed after magnetic field is pulsed). Data for t = 4 and 5 msec are also available in several instances, but have not yet been analyzed.

Parameters that were varied in the analysis were (a) the "cutoff" energy E_c, which represents the minimum energy an electron may have (after penetrating the absorber) and still produce a significant signal in the fluor; (b) the angle of entry, θ, of an electron into the absorber, which is a function of the ratio of the magnetic field at the absorber to the field at the mirror plane, and which is presumed to determine the effective absorber thickness for a given actual thickness; and (c) the energy interval ΔE and the number M of such intervals used in the numerical solution of the integral equation that defines the measured oscilloscope pulse height Q

[1] Robert E. Ellis and Walton A. Perkins, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 11.

as a function of absorber thickness, electron flux, electron energy, fluor scintillation efficiency and other experimental parameters represented by the constant K in Ref. 1.

In the following figures, some of the results are graphically displayed. The so-called angle of entry θ (in degrees) is sometimes given, signifying that the electron is assumed to have passed through the absorber along a path which is at an angle θ with the normal to the absorber surface because of the helical trajectory of the electrons as they spiral along magnetic field lines. Since the mean energy for a given distribution, determined by taking the first moment of the distribution, is increased by a factor of 1.7 to 1.8 for θ = 54 deg as compared to θ = 0 deg for example, it is planned to ascertain experimentally whether this large correction should be made. A possible way of checking this is to take distribution runs with the probe at various distances from the mirror plane. If such a correction is required, the same distribution should be obtained with different probe positions under identical operating parameters. Until such verification is possible, we feel that we can bracket the electron mean energy between the results for θ = 0 and calculated θ values. Also, with improved probe sensitivity, such a correction can be minimized by operating at greater distances from the mirror.

The parameter E_c is set equal to 5 kev for all the curves shown. It is found that typically if E_c is varied from 0 to 10 kev, the mean energy changes by about 1 to 2 %. Preliminary measurements of E_c for the probe used in these experiments, with the monoenergetic electron beam facility mentioned elsewhere in this report, indicates that E_c will be within this range.

Figures 1 through 6 show the energy distributions for plasma electrons.

Figure 1 shows curves obtained by drawing a "best fit" curve through the data points, and two extremum curves, obtained by drawing smooth curves through the extremes of the indicated uncertainties so that maximum variation occurs in the corresponding solutions for the energy distribution. In this case, the maximum variation in mean energy caused by selection of the Q values for the analysis is ± 10% from the "best fit".

Figure 2 shows the variation of the distribution with time.

Figure 3 shows the effect of initially injecting plasma into different dc magnetic fields. If the injected plasma were completely trapped in the initial dc magnetic field and adiabatically compressed, the plasma compression ratios in these two cases should be 2100 and 210, respectively, and the corresponding values of $\bar{E}$ should vary by a factor ≈ 10 for an adiabatic compression. This result might indicate that compression of the plasma does not occur immediately upon application of the pulsed field, when low dc mirror injection fields are used, but occurs only when the magnetic pressure of the confining field exceeds the initial plasma pressure. Taking $n_e = 10^{12}$ and T_e = 10 ev as a crude estimate of the initial plasma parameters, this corresponds to an initial plasma pressure of about 16 dynes, which implies that the pulsed magnetic field would have to substantially exceed 20 gauss before compression could occur.

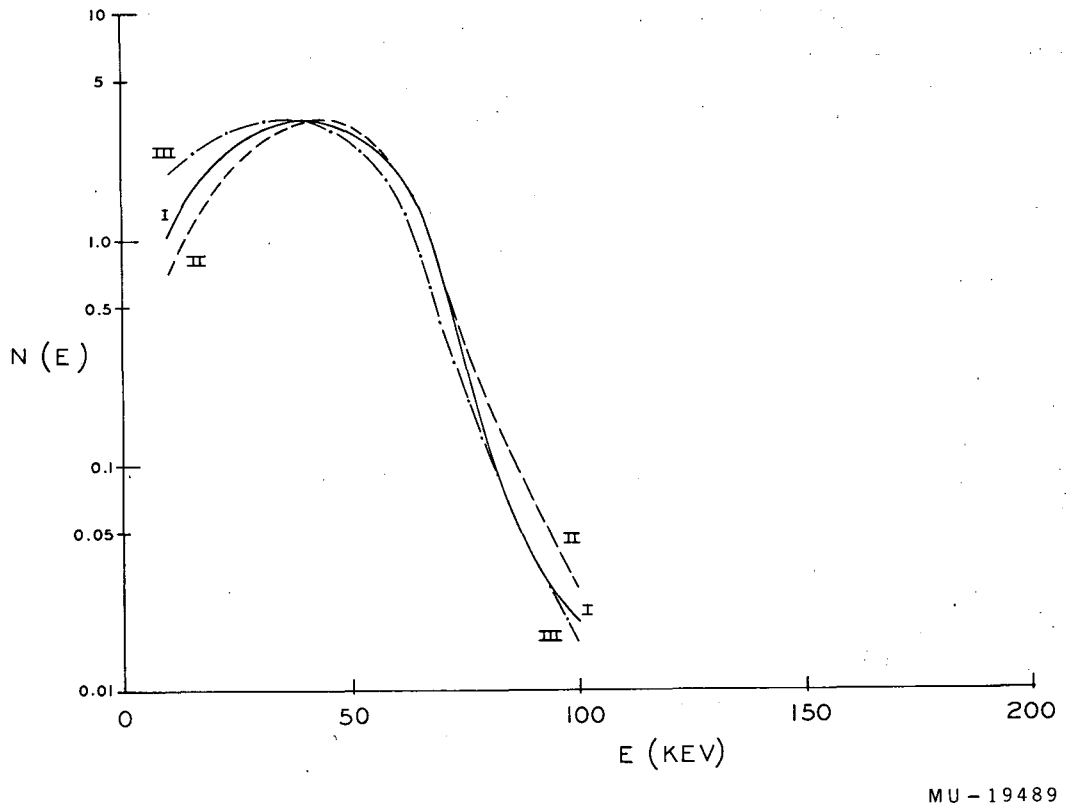

Fig. 1. Plasma electron energy distributions obtained with a "best-fit" curve (I) and two extremum curves (II and III) drawn through experimental data points.
Axial source; B_0 = 16 kG; t = 1 msec; θ = 54.3 deg assumed.

I: best fit, $\bar{E}$ = 39.9 kev

II: drawn low at low E_0, high at "high E_0"; $\bar{E}$ = 43.4 kev

III: drawn high at low E_0, low at high E_0; $\bar{E}$ = 35.7 kev

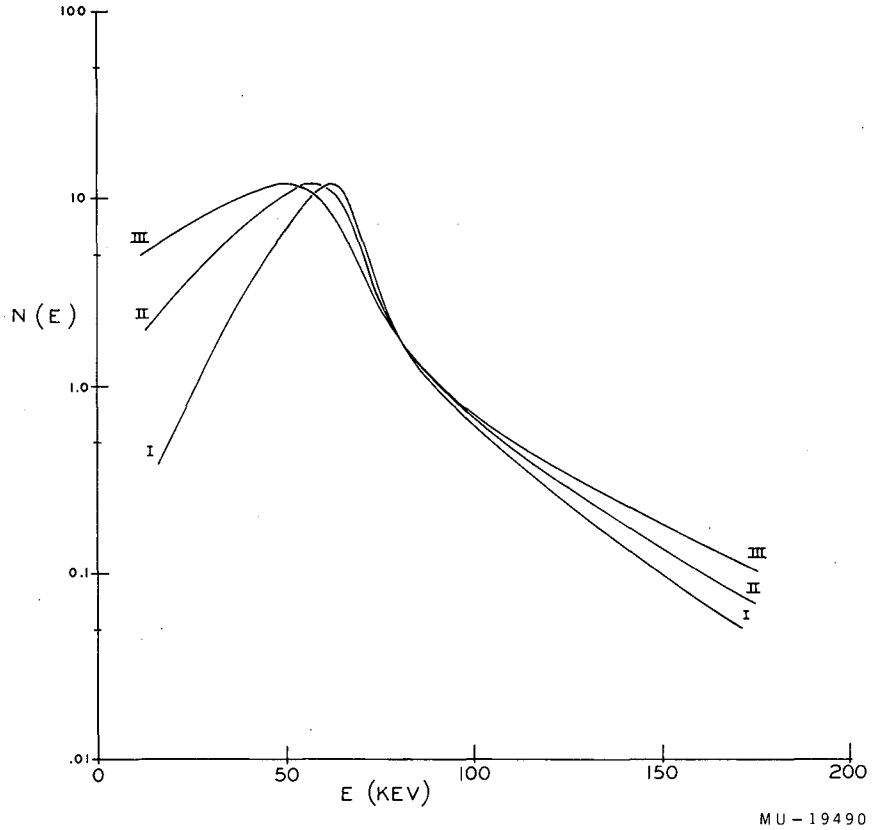

Fig. 2. Plasma electron energy distributions showing variation of the distribution with time.
Axial source; B_0 = 32 kG; θ = 54.3 deg assumed
I: t = 1 msec; $\bar{E}$ = 63.3 kev
II: t = 2 msec; $\bar{E}$ = 55.3 kev
III: t = 3 msec; $\bar{E}$ = 48.2 kev

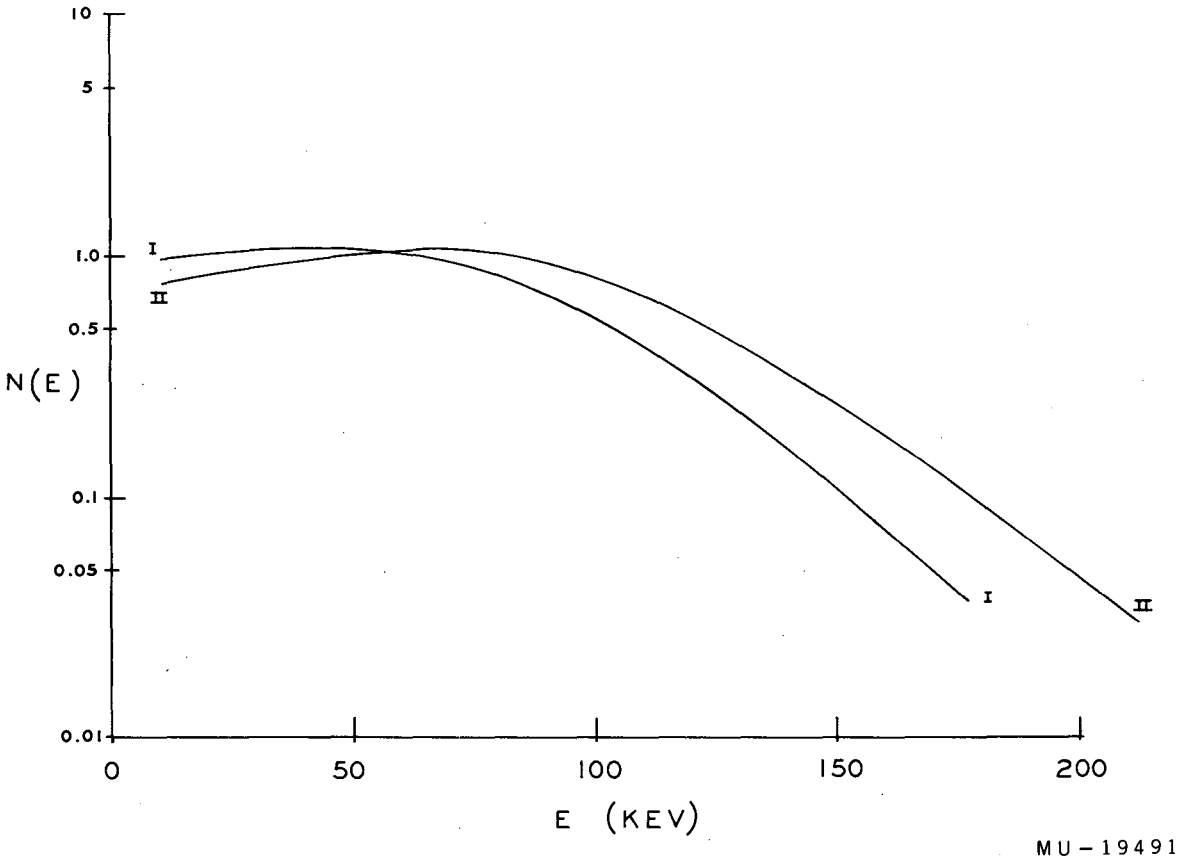

Fig. 3. Plasma electron energy distributions showing effects of initially injecting plasma into different dc magnetic fields.
Radial source; B_0 = 21 kG; t = 1 msec; θ = 66.9 deg assumed.
I: field = 100 gauss; $\bar{E}$ = 60.8 kev
II: field = 10 gauss; $\bar{E}$ = 74.0 kev

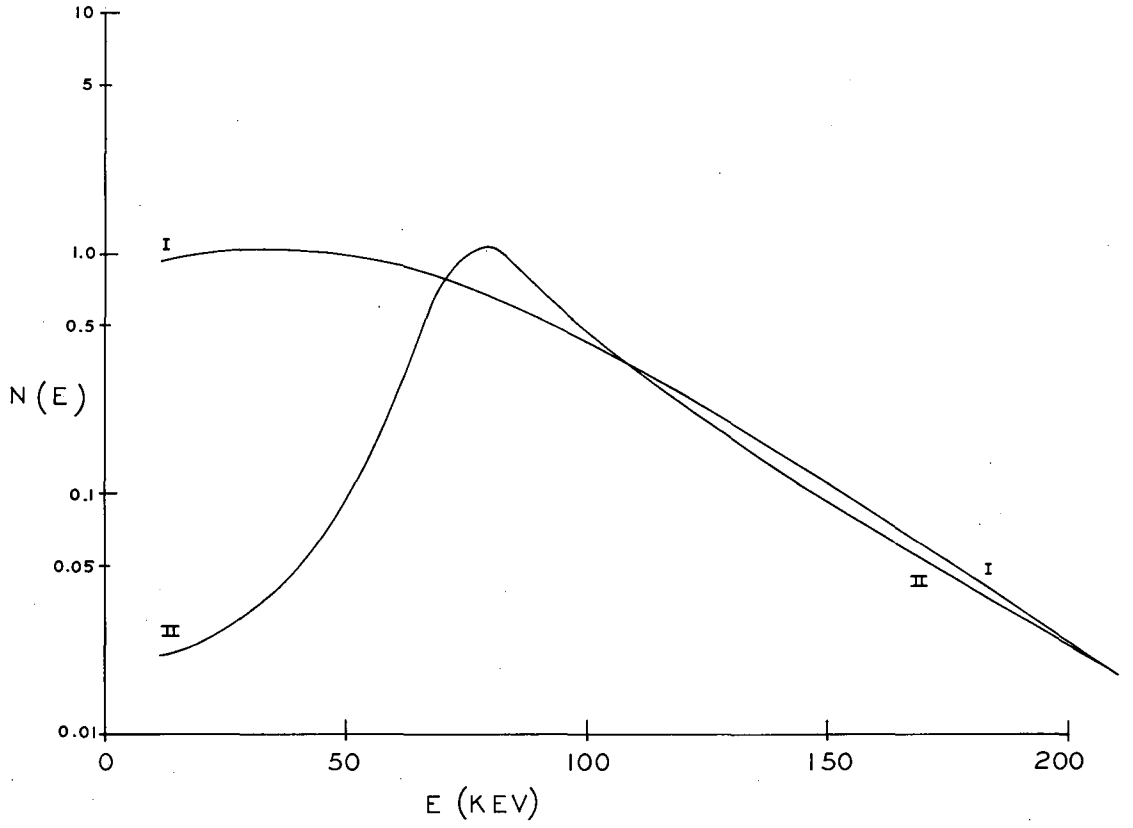

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Fig. 4. Plasma electron energy distributions showing effects of argon background gas.
Radial source; B_0 = 21 kG; t = 1 msec.
I: no argon (base pressure = 1.6×10^{-6} mm Hg); $\bar{E}$ = 62.1 kev
II: with argon (base pressure $\approx 8.5 \times 10^{-5}$ mm Hg); $\bar{E}$ = 94.4 kev

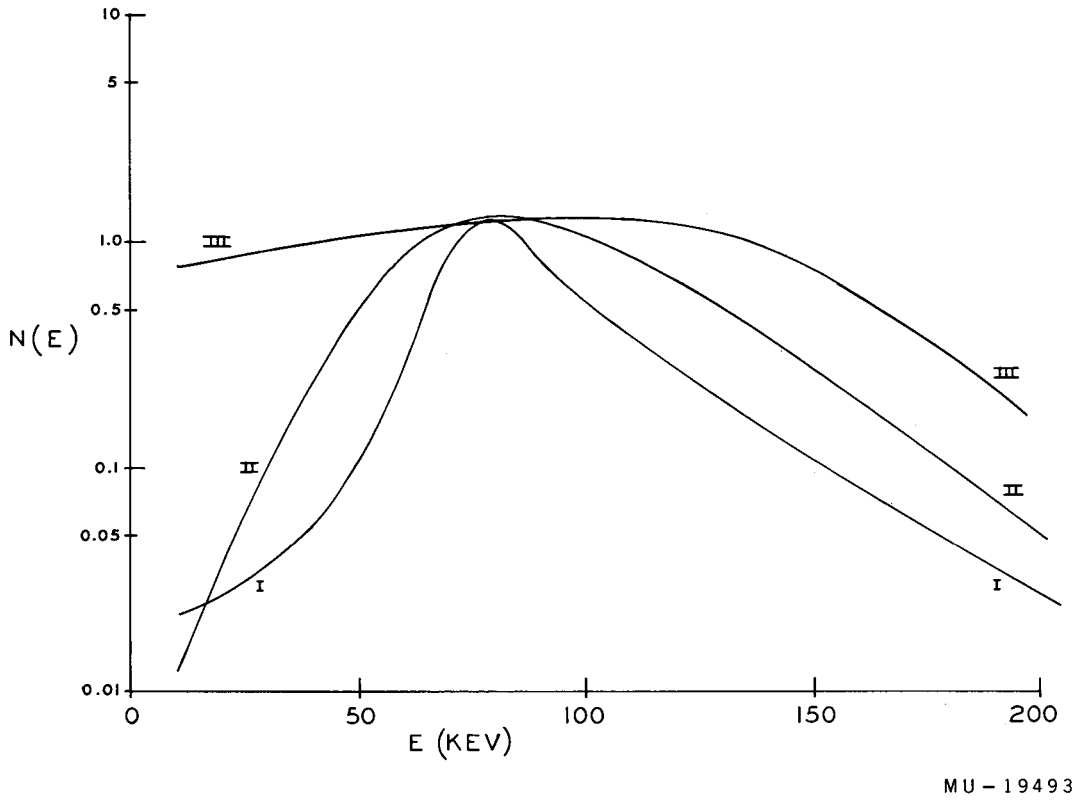


Fig. 5. Plasma electron energy distributions showing variation of the distribution in time when argon is present as background gas.
Radial source; B_0 = 21 kG; base pressure = 8.5×10^{-5} mm Hg of argon; θ = 66.9 deg.

I: t = 1 msec; $\bar{E}$ = 94.4 kev
II: t = 2 msec; $\bar{E}$ = 94.4 kev
III: t = 3 msec; $\bar{E}$ = 92.6 kev

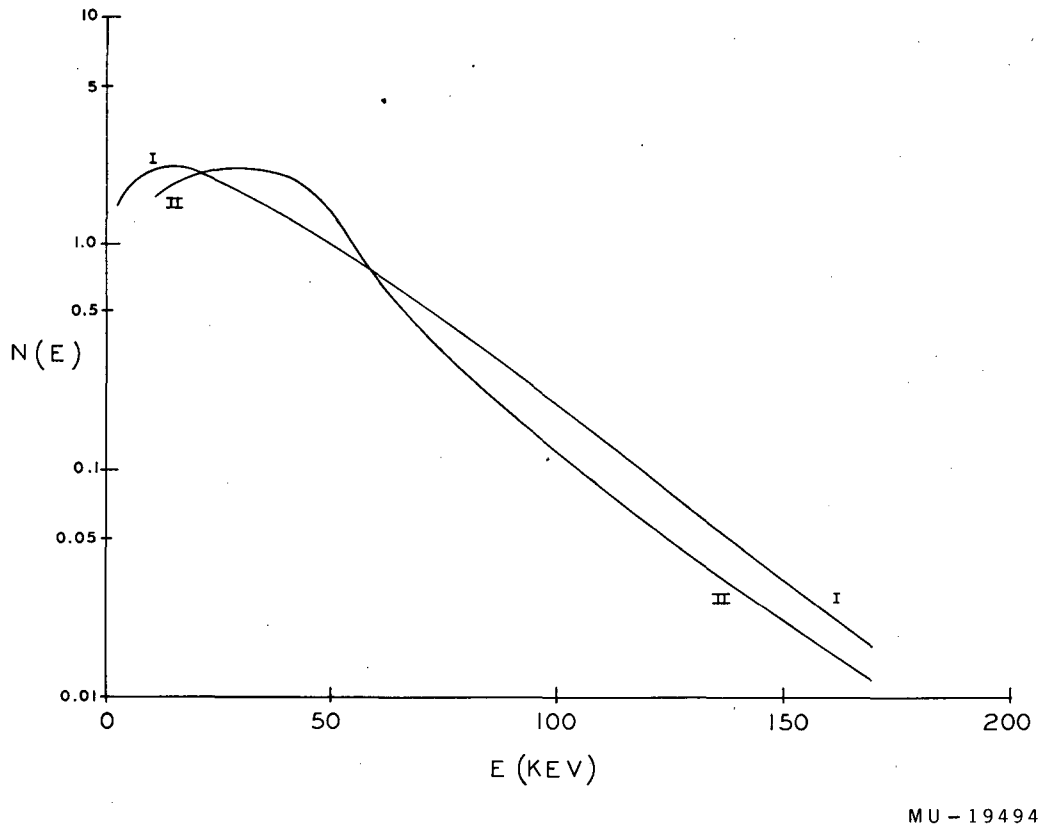


Fig. 6. Comparison of measured plasma electron energy distribution (Curve II) with a Maxwellian distribution of the same mean energy $\bar{E}$ (Curve I).
Axial source; B_0 = 32 kG; t = 1 msec; θ = 0 deg.
I: $\bar{E}$ = 38.4 kev, kT = (2/3)E = 25.6 kev
II: $\bar{E}$ = 38.4 kev

In Fig. 4 is shown the effect on the electron energy distribution of the introduction of a high-Z background gas into the compression cycle. Note the depletion of the low-energy electrons. Figure 5 represents variation of distribution with time in the presence of argon.

Maxwellian and measured distributions are compared in Fig. 6. The fit to a Maxwellian distribution is probably within experimental or computational error, over two decades of density.

Scintillator Probe Measurements

For the past month we have been using a scintillator probe which protrudes radially into the vacuum system midway between the mirror coils. The plastic scintillator, which is coated with 0.06 mil of aluminum, monitors the electron flux at positions from the axis to the wall of the 12-in. -diameter chamber. In conjunction with the radial scintillator, we are using an axial scintillator to monitor the electron flux that escapes through one of the mirrors and an x-ray monitor mounted outside the vacuum chamber in the center of the machine. Data are being taken simultaneously by these three scintillators as the machine parameters are varied. The results have not been analyzed yet.

Plasma Source

A fast-acting gas valve, which is to be used as a component of a plasma source, has been tested for

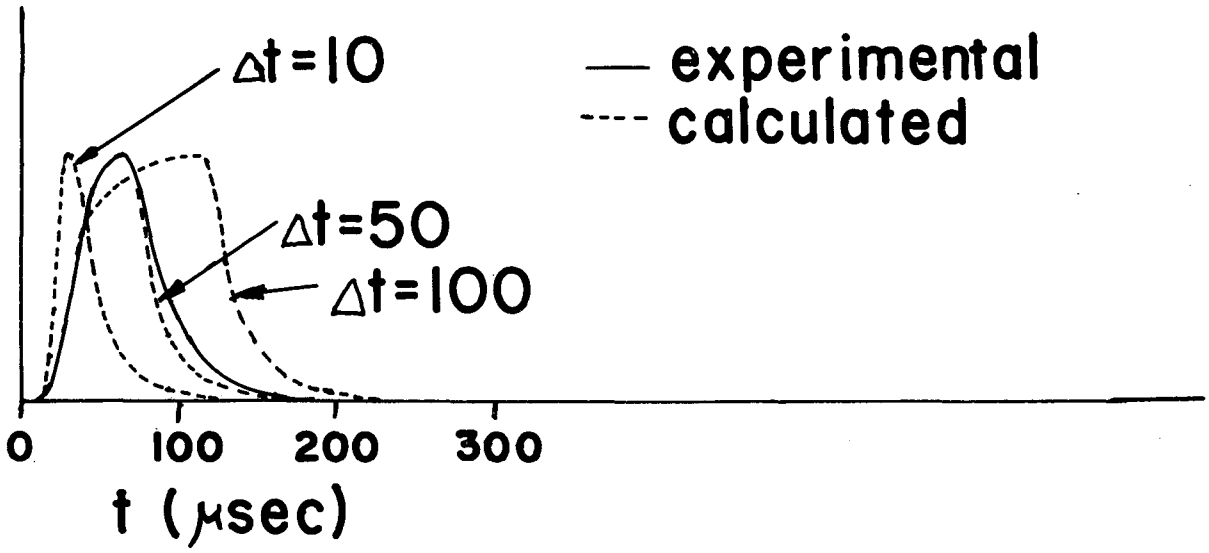
(a) duration of time that valve is open,
(b) reproducibility,
(c) number of molecules emitted as a function of the gas pressure in the pocket behind the valve seat.

The gas valve is a slight modification of an electromagnetic valve designed by Orrin Twite. A rapidly changing magnetic field stretches an aluminum disk, which unseats a teflon washer. Part of the gas in a gas pocket behind the teflon seat is emitted into a vacuum.

The duration of time that the valve is open, Δt, was measured by employing a nude Veeco ion gauge and photographing the output signal. For the ion gauge placed 4 cm from the valve, the experimental pulse shown in Fig. 7 below was obtained. Pulses calculated for opening times of 10, 50, and 100 μsec are also shown. The best fit with the experimental pulse was obtained for $\Delta t = 58$ μsec. This is in reasonable agreement with the value Twite obtained by a switch method.[2]

The short-time reproducibility was found, by a comparison of oscilloscope traces, to be very good. When first pulsed after a several-hour rest, the valve emits a large amount of gas. The gas bursts then decrease to a steady value after about fifty pulses. This change is apparently caused by the deformation of the teflon seat.

[2] Orrin A. Twite (Lawrence Radiation Lab., Livermore, Calif.) private communication.



MU-19495

Fig. 7. Gas pulse from fast-acting gas valves. The ordinate is the ion gauge reading.

A curve is shown in Fig. 8 of the number of gas molecules emitted per pulse as a function of the gas pressure in the pocket. This is just one of a set of curves that can be obtained by varying the voltage on the capacitor that discharges into the coil. Notice that the slope of the curve increases as the gas pressure increases, indicating that collisions between the molecules enhance their emission.

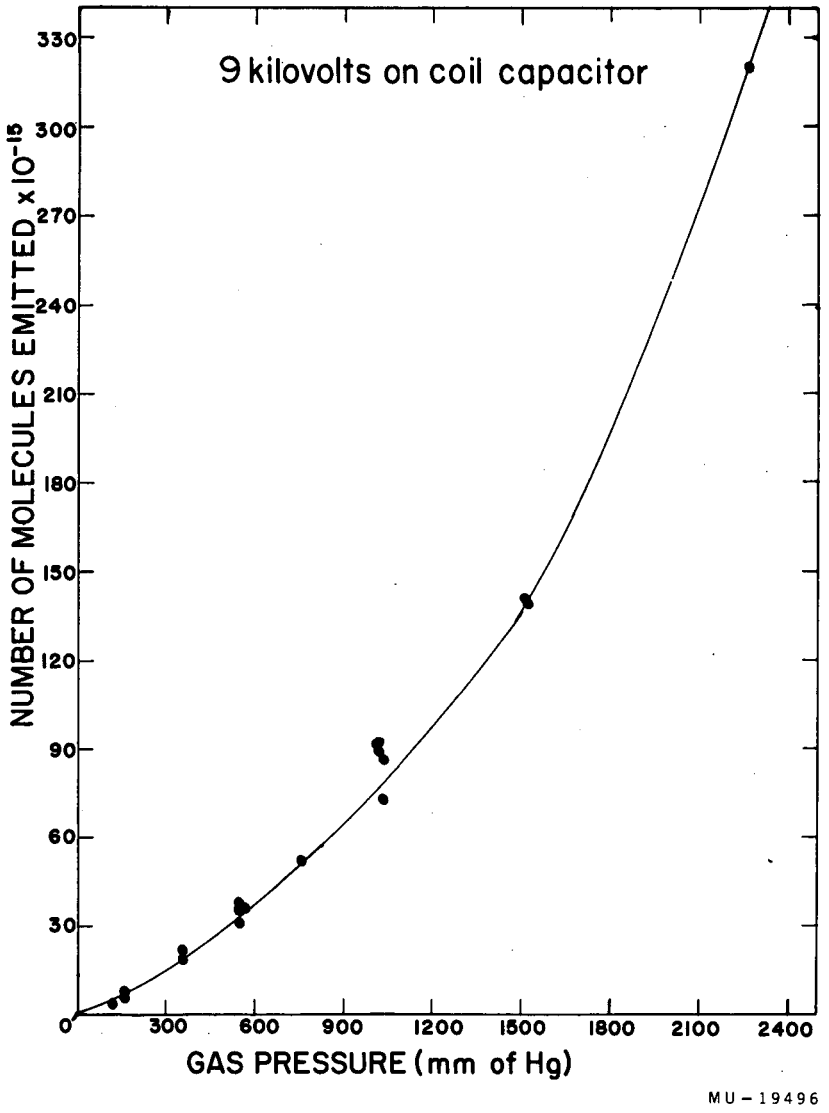


Fig. 8. Number of molecules emitted as a function of the gas pressure in the pocket.

50-kev ELECTRON ACCELERATOR (FOR FLUOR CALIBRATION)

Norris W. Carlson and Robert E. Ellis

Preliminary measurements of the parameter E_c (cutoff energy), mentioned elsewhere in this report, have been made for the single-channel probe with which most of the electron energy distribution measurements were run on the Table Top machine. Although a 1-msec pulse of approx. 1 ma of electrons at an energy of approx 4 kev evidently produces a detectable signal in the probe, further investigation of the effects of beam energy, beam current, condition of the aluminum coating on the fluor, and secondary emission from the Faraday collector must be made before E_c is determined. The complete calibration of the probe will not be accomplished until a reliable curve of signal versus beam energy flux is made.

TABLE TOP DIAGNOSTICS I

Thomas O. Passell*

Equipment is being built or developed for measurement of plasma electric fields during the compression pulse in Table Top. The only device requiring development for this work is a surface-ionization source of Li^+ ions. The Mark I version of this source is ready for emission and life tests. Electric field will be measured by observation of the $E \times B$ drift deflection of the axially directed beam.

Concurrently with the above project, a calorimeter for the total energy in the leakage plasma of Table Top has been developed and is now ready for diagnostic work on that device. In its present form, it is a sheet of shiny aluminum, 5 in. in diameter by 0.010 in. thick, with a 32A2 thermistor (2000 ohms at 25°C) attached near the edge. A resistor for adding known quantities of energy is placed at the end of a diameter opposite the thermistor. With the thermistor as one leg of an equal-arm Wheatstone bridge and a 0-to-10 mv 15,000-ohm input impedance recorder in the galvanometer position, a reproducible calibration of 1.0 mv per joule has been measured. Eddy-current heating has been found to follow the expected B^2 dependence and to be approximately 0.1 joule per pulse at > 1 kilogauss maximum field strength.

The above calorimeter is designed for placement 16 to 20 in. from the center of the nearest mirror coil with its center coincident with the magnetic field axis. At 16 in. mild "blowout" forces are experienced, so it is unlikely that this design will be used at distances less than 16 in.

*Stanford Research Institute, Menlo Park, California

TABLE TOP DIAGNOSTICS II

Norris W. Carlson and James T. Mattingly

Electron Multiplier Studies

In an electron multiplier used as a particle detector, the gain is modified, for a given applied voltage and detected particle, by contamination from the surrounding medium and the counting-rate deterioration of the dynode structure. The gain of the electron multiplier structure, for a given applied voltage, is the output current from the anode divided by the input current on the first dynode. A curve for each applied voltage can be determined for the gain vs input electron current. These curves are parallel and are in effect as long as the gain remains constant. This constitutes a comparison test for gain and thus for the useful lifetime of the electron multiplier structure.

A gradual deterioration of the dynode structure is accompanied by a gradual loss in gain. A poisoning by its medium may be detected by a drop in gain. In general, the dynode structure erosion can be kept to a minimum by low output currents. The poisoning continues, for high or low currents, as long as the structure is subjected to the poisoning. Therefore, an attempt to poison the structure and rejuvenation by electron bombardment or gaseous discharge is planned. An erosion of the structure by high currents and rejuvenation is also planned.

ADIABATIC LOW-ENERGY INJECTION AND CAPTURE EXPERIMENT (ALICE)

Preliminary Build-Up Experiment ("Baby Alice")

James F. Steinhaus and Charles C. Damm

The apparatus has now been assembled and placed in operation and signals from the two diagnostic probes have been observed.

The proton beam, variable from 15 to 20 kev, is neutralized in a hydrogen gas cell and the neutral beam detected after traversal of the 16-kilogauss mirror field. An optimum neutralizing gas pressure* of 1.5 μ at the center of the neutralizer (7.5×10^{-5} mm Hg* in confinement chamber) gives a fractional neutralization of 0.7. This compares with an expected maximum value of 0.8 as determined from the charge-exchange and ionization cross sections. A fraction of 0.4 was neutralized in the system at base pressures with no additional neutralizing gas introduced.

A neutral beam of 10 ma has been calorimetrically measured on the target located beyond the confinement chamber, approximately 9 feet from the source.

Even at pressures* of 7×10^{-6} mm Hg in the confinement chamber, strong signals are observable on the radial and axial distribution probes which measure respectively the charge-leakage rate through one mirror, and the fast-atom flux to the chamber walls.

The radial probe consists of a set of 19 equal-area segments (0.1 in.^{2} each) uniformly spaced along a 3-in. radial line and shielded by a high-transmission grid. Each segment, or channel, is connected to a capacitor that stores the collected charge. Display of the capacitor voltage occurs through a stepping switch to an oscilloscope.

The axial probe presently consists of 20 copper plates (3 in.^{2} each) slanted at 45 deg to the radial plane. These are grounded and provide secondary electrons to 20 similar but vertical collectors which are scanned in the same manner as just described for the radial probe. The axial probe extends approximately 9 in. to either side of beam centerline.

The quantitative interpretation of the probe signals, as well as better pressure measurements in the confinement region, must await refinement of beam collimation at the entrance to the chamber.

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*Pressures given have not been corrected for hydrogen gas.

GRID SOURCE DEVELOPMENT

Frank J. Gordon

An insulated and water-cooled electrode, which was built into the arc chamber of the Alice grid source, has been found to be of very little value. Elimination of this electrode allowed a major simplification in source-cooling-water channels. Eight vacuum-to-water O-ring seals were eliminated along with the associated insulators that had given outgassing problems. The resulting source is nearly trouble-free.

The Baby Alice machine was connected to the source and all elements aligned. Approximately 20 ma of proton beam traverses the Baby Alice confinement chamber and impinges on a target which is about 9 ft from the source.

The Mechanical Engineering Section made a very nearly exact mathematical analysis of the magnetic field associated with the rectangular coils designed for the Alice source. The numbers were tabulated by the 650 computer, and beam trajectories are being plotted on the mechanical-particle analogue. Results obtained from our mock-up were verified, but many more parametric variations are possible. Coil design is frozen and construction has started.

The new source facility for Alice--including source tank, vacuum system, and coil support--is all under construction, and electrical engineering is well advanced.

A new source body is indicated, designed to fit through the rectangular coils and incorporating beneficial changes made since the original design.

THEORETICAL CONSIDERATIONS

Archer H. Futch and Charles C. Damm

Preliminary numerical solutions of the build-up equations for neutral-atom injection have been obtained. The numerical results show that, at least for the values of the parameters listed in Table I, the process of charge exchange of the trapped ions with neutral beam atoms increases the ion density in the plasma core and results in less stringent conditions for the formation of a high-energy plasma.

The spatially dependent differential equation for the ion density was discussed in a previous progress report (UCRL-8775). This equation has been modified to include the process of charge exchange of the beam atoms with trapped ions. In addition, the code for machine calculation will include two equations for the neutral-gas density. These equations include the effect of the thermal gas flux resulting from wall bombardment by fast atoms, the neutral-gas "burn-out" in the core, and the neutral-gas pumping by the ions. Two equations result from the two-region model for the neutral density. The neutral density is assumed spatially constant for each region.

Numerical Results

Figure 9 shows the build-up of the trapped-ion density for a point near the center of the plasma as a function of time. Two curves are shown. Curve 1 gives the ion density calculated from the equation without including the terms for charge exchange with the beam. Curve 2 is the ion density calculated from the complete equation. The neutral-gas density is assumed to be constant for both cases. Table I gives the values for certain parameters used for these calculations. It is obvious that for this geometry and beam width the effect of charge exchange with the beam increases the trapped-ion density. Figure 10 shows the radial distribution of the trapped ions for Curve 1 at 3 sec.[1]

The writers wish to express their appreciation to Lloyd E. Mish, who programmed the equations for numerical solution.

[1] For further discussion see "Plasma Build-Up for Neutral Injection" by Warren Heckrotte, p. 74 in this report.

Table I

Parameters used in calculation of trapped-ion density (Fig. 9).

Deuterium neutral gas density	1×10^8 molecules/cc
Injected neutral atom current	9.7×10^{16} atoms/cm^2/sec
Energy of injected deuterium atoms	20 kev
Magnetic field	50,000 gauss
Radius of curvature of a 20-kev deuteron	0.575 cm
Beam width	2.54 cm
Position of beam center	0.575 cm above the magnetic axis
Direction of magnetic field	from left to right if viewing the plasma from the direction of the source

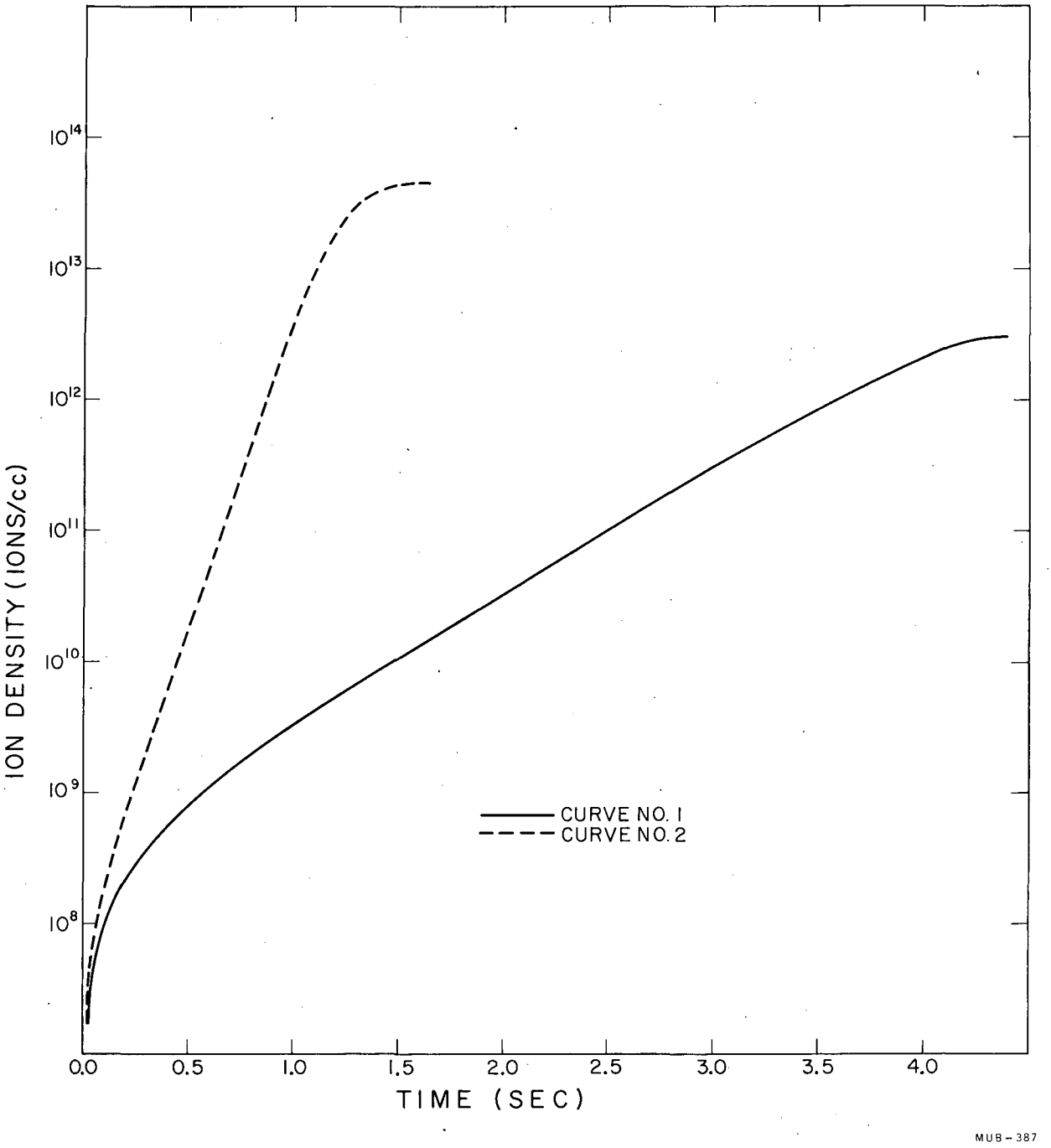

Fig. 9. Calculated ion densities for plasma core. Curve 1: without including charge-exchange terms. Curve 2: using complete equation.

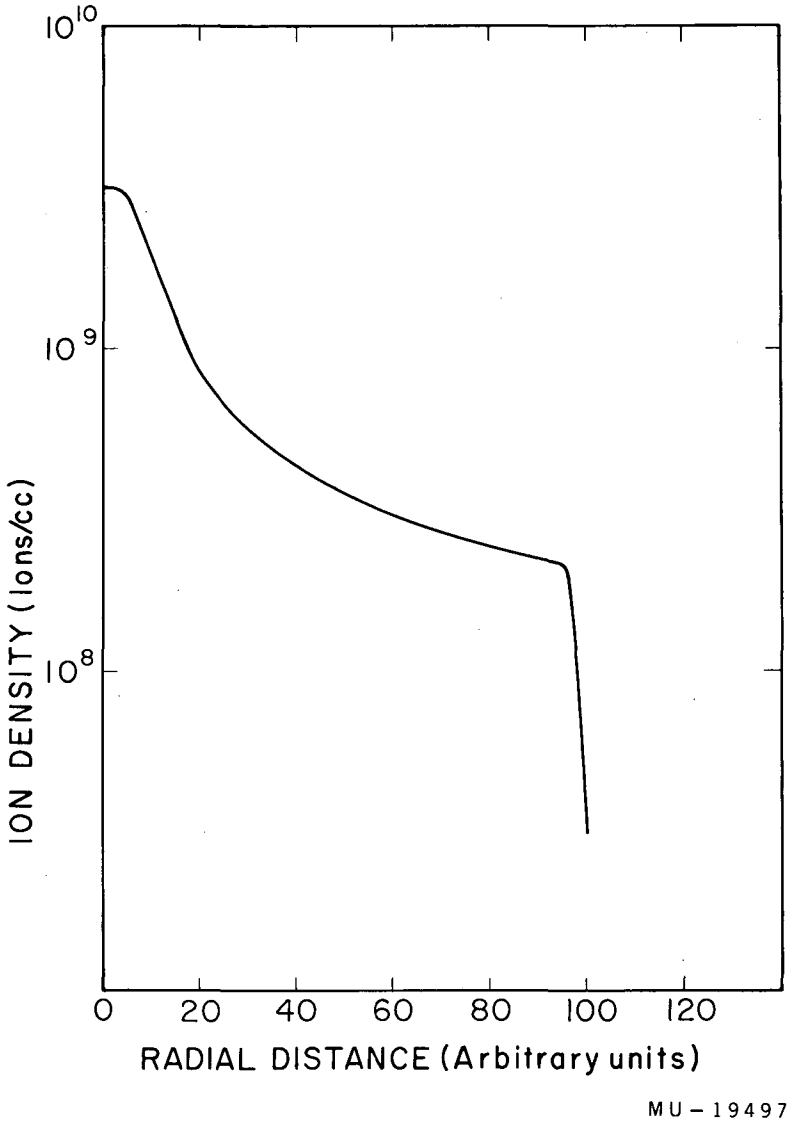

Fig. 10. Distribution of trapped ions in plasma at 3 sec.

VACUUM AND SURFACE STUDIES

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

Getters and Getter-Pump Development

The experiments on deposition of evaporated molybdenum in unbaked, stainless steel vacuum systems have been continued.

Deposition of molybdenum by vaporization from simple hairpin filaments has been found to reduce the indicated pressure in an unbaked stainless steel system to as low as 4×10^{-10} mm Hg. A different vaporization procedure has given a lower ultimate pressure than that previously reported. In this new procedure the filament is repetitively pulsed with 500 watts for 1 min at 5-min intervals. The maximum pressures attained decrease with each successive pulse until, near the end of the filament life, they are within the range 10^{-9} mm Hg. The minimum pressures between pulses decrease to the range 10^{-10} mm Hg. After fusion of the filament, the pressure falls to its ultimate value.

The reason for the lower pressure with this procedure is not clear. It may be attributable to the lower wall temperature associated with the pulse technique. If the wall temperature remains lower, a structural change in the molybdenum deposit, as well as a lower degassing rate from the walls, may be expected. The pulse technique also may reduce the contamination evolved from the filament supports.

The molybdenum deposit appears to be a grey powder. The deposit has little metallic luster except where the substrate was not cooled. Photomicrographs of samples removed from the cooled walls show the deposit to consist of two classes of particles. The first class consists of large particles, 100 to 300 μ in diameter, which are almost spherical. The second class consists of smaller particles which are about 30 μ in largest dimension, but their wide size range as well as irregular appearance suggests they may be aggregates of much smaller particles.

A more quantitative measurement of the minimum pumping speed for hydrogen was made. The initial hydrogen pumping speed of a molybdenum deposit of about 300 mg on a substrate of 8×10^{3} cm^2 area is at least 4×10^{4} liters per second. It was found that the measured pumping speed decreased from 39×10^{3} l/sec to 22×10^{3} l/sec over a 20-min period under a constant hydrogen influx of 1.1×10^{16} molecules per second. Before hydrogen admission, the pressure was 7×10^{-10} mm Hg. During hydrogen admission, the hydrogen pressure in the tank increased from 8.7×10^{-9} mm Hg to 1.6×10^{-8} mm Hg. For our gauges, a factor of 2.5 times the indicated gauge readings gave the hydrogen pressure. Because the tank walls were at various distances from the filament and portions of the tank were completely shielded from the molybdenum vapor, the deposit was nonuniformly distributed.

The major impurity in the hydrogen source was 0.5% argon by a mass-spectrometric analysis. Since it can be shown that the presence of any argon reduces the measured pumping speed, it appears that the pumping speeds reported here for hydrogen must be conservative.

P-4 (STEADY-STATE PLASMA) SYSTEM

William L. Barr, Daune M. Gall,* Andrew L. Gardner,
Laurence S. Hall, Raymond L. Kelly,** and Norman L. Oleson*

Another rupture in the anode liner occurred during the past quarter. The anode section has since been modified to improve its cooling and a further modification is being prepared which will allow the dissipation of still greater heat flux.

Probe Analysis

Much of the probe data has been re-analyzed in view of an improved understanding of the probe as used in the P-4 system. Although the results do not differ appreciably from those obtained previously, they are better justified and some features indicate greater internal consistency.

A report is being prepared by Laurence S. Hall which will discuss various aspects of probe theory.

The rotating probe assembly has been fabricated and tested for mechanical performance. Although frequent maintenance will be required, further testing will be done under operating conditions in the P-4 system.

Profiles of Emitted Light

A technique has been developed for obtaining the radial profile of the beam in the light of the various spectral lines. The light from a given small volume of plasma cannot be observed separately because the monochromator accepts all the light from a horizontal slice through the beam. However, the desired profiles can be obtained from the observed intensities. Unfortunately the profile obtained is very sensitive to the method of analyzing the data.

The technique developed here consists in the fitting, by a least-squares method, of second-degree polynomials to each of the parts of the observed intensity profiles. This has two advantages. First, the least-squares method performs the necessary smoothing of the data; and second, the resulting integration can be performed analytically, thus avoiding some of the tedious numerical work.

Diffusion Study

The determination of the total rate of ion diffusion out of a section of the plasma beam will be made indirectly by observing the equilibrium pressure of the neutral gas and measuring the effective speed at which it is pumped away.

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*U. S. Naval Postgraduate School, Monterey, California.
**Stanford Research Institute, Menlo Park, California.

A method has been developed for introducing a small known flow of gas into a side port of the P-4 system and measuring small changes in neutral pressure in order to ascertain the effective pumping speed of the plasma beam itself. Previous checks showed that an auxiliary gas input of about 10% of the total flow caused undue perturbation of the plasma.

Excitation Cross Sections

Instrumentation is being assembled at P-4 for measurement of excitation cross sections in the lithium-like ions, C(IV), N(V) and O(VI). The problem of introducing the electrons into the beam has yet to be solved.

II. ASTRON PROGRAM

INTRODUCTION

N. C. Christofilos

In the past quarter the most important activity of the Astron Group was completion of the design of the 200-amp electron gun and the 2-Mev electron accelerator. Although all the detailed designs are not yet ready the design is well enough advanced to allow the ordering of most of the hardware.

The review committee under the chairmanship of Professor Kenneth M. Watson submitted its recommendations. In view of the recommendations the laboratory decided to proceed with the Astron program as follows:

a. Complete the 200-amp Astron gun
b. Construct the 2-Mev electron accelerator
c. Complete the Astron facility, including the injection systems.

In accordance with this decision we started placing orders for hardware as soon as final parameters had been selected. Sample cores for the accelerator have been tested and the order for the cores was placed as soon as the results of the tests were available.

The findings of the Review Committee more specifically are:

a. The new injection system is considered adequate to handle the quantity of electrons required to achieve reversal of the magnetic field.
b. There is no indication of instability of the E layer nor a rigorous proof of stability.
c. Provided that the E layer is stable, it would be possible to confine some plasma up to certain critical β; the value of this β is not known at this time.
d. The Astron is in no way inferior to any of the other Sherwood concepts.

Hence, the recommendation to proceed with the program as planned by the Laboratory. It is hoped that the detailed design of both the accelerator and the facility will be completed within the next three months. The completion of the facility as well as the "running in" of the accelerator is expected by late spring 1961.

Some activity continued in the dry-run experiment. A new plasma switch was installed on the Astron electron gun. A prototype Marx generator is being developed for the testing of the 10-inch cathode for the 200-amp electron gun. These activities are described in more detail in the following section.

Dr. Lewi Tonks continued his calculations on the self-consistent solution of the E layer. He now has some results on the requirements for field reversal in the presence of a dynamical friction (energy loss of the

E-layer electron by Coulomb scattering). Although there are indications of instability and irregularities in the solution, such irregular points are outside the useful range of parameters. Consequently it appears that the field reversal is feasible. Dr. Tonks's work is described in this report.

ASTRON EXPERIMENTAL PROGRAM

William A. S. Lamb and Robert E. Wright

During this period a new switch was installed on the Astron electron gun to replace the eight spark gaps used previously. This was done to improve the reproducibility of the beam pulse and to allow more quantitative measurements. In addition, experiments were started to enable one to operate the machine with energy spreads in the injected pulse of electrons which could be controlled by changing slot widths in a collimating system.

Plasma Switches

This switch, which was developed several months ago (and is to be described in a separate report), consists of a pair of electrodes in a vacuum which are triggered by the injection of a ball of plasma between them. The plasma gun is essentially a Bostick plasmoid source.[1] On the test bench the switch operated with jitter times of less than 10^{-8} sec and carried up to 10^5 amp. Its duty cycle is limited to several pulses per second because of the need for pumping to remove the resulting gas. (See Fig. 11.)

This unit was operated successfully on the Astron electron gun and markedly improved the uniformity of the beam pulses.

Beam Energy Analyses

In order to inject electrons of a controllable spread in energy an analyzer is being installed on the injection system. This consists of a pair of slits installed at the focal point of the beam and 180 deg away around the perimeter of the tank. Preliminary operation of the system shows encouraging results and it is hoped that we may pass nearly full current with quite small energy spreads obtained by narrowing the slits.

[1] W. H. Bostick, Phys. Rev. 106, 404 (1957).

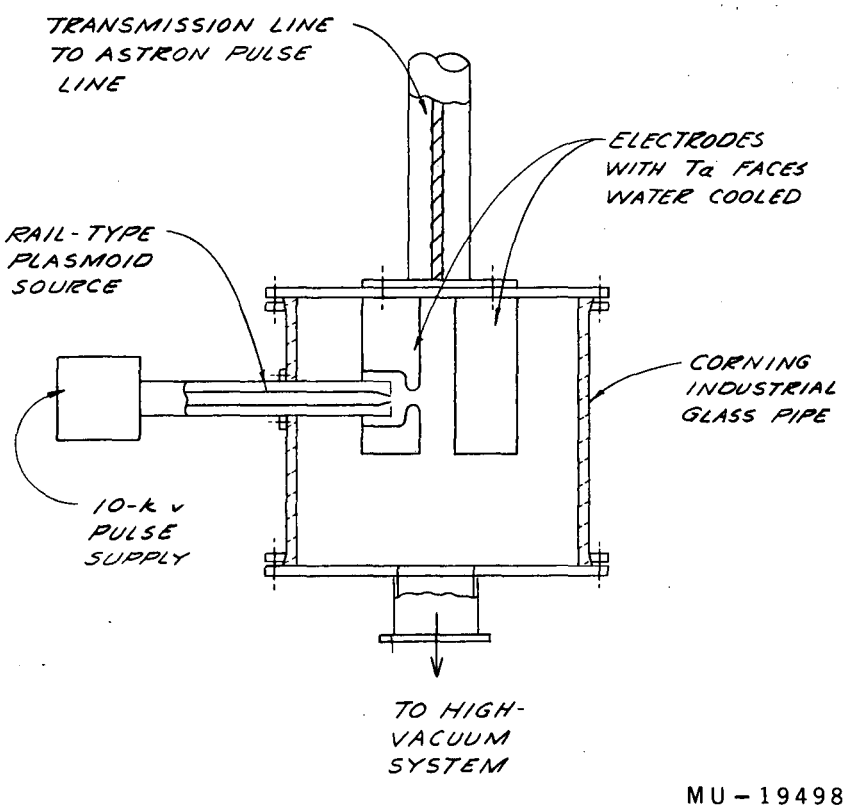

Fig. 11. Schematic of plasma switch.

10-INCH CATHODE TEST FACILITY

D. D. Reagan and R. E. Wright

A prototype six-stage cable Marx generator has been built. It produces pulses which are flat-topped to better than 5%. They are 0.2 μsec long, with 1.5×10^{-8} sec rise and decay times. At present it supplies about 56 kv to a 300-ohm load. To test the 10-inch Astron cathode a somewhat less crude eight-stage device is being put together which should deliver 160 kv into a 200-ohm load.

ASTRON E-LAYER CALCULATIONS

Lewi Tonks*

I. The three parameters that determine the E layer in the presence of dynamical friction but no scattering are (a) the initial momentum of the electrons, P_0, in m_0c units, (b) the ratio, G, of the radius of the injection circle to the radius of gyration of the virgin electrons in the vacuum field, and (c) a quantity

$$S = 2\, r_E\, N/\nu, \tag{1}$$

which is a measure of the electron injection rate, r_E being the classical electron radius, N being the rate of injection of electrons per cm length of layer per second, and ν being the rate of loss of electron energy defined by

$$d\gamma/dt = -\,\nu/\beta. \tag{2}$$

Here γ is the relativistic mass ratio and β is the usual v/c.

The E layers that are of probable interest to the Astron program lie within a three-dimensional region in the "space" of these parameters. This region has been thought to include the transition through zero field and to extend through a thinning of the layer to where it occupies approximately one-sixth of the injection-circle radius, and it has been judged to cover a range of energies up to 50 Mev. In agreement with N. Christofilos the energies chosen for exploration were approximately 5, 15 and 40 Mev--actually P_0 = 10, 30, and 80. Values of G of 1.3, 1.7, and 2.0 or 2.1 cover the range from small to fairly strong reversal without encountering marked pathological effects. A few calculations with G equal to 2.5 or 4.0 have been made just to observe the pathology. S served as the independent variable, its increase carrying the field through reversal and to thinner and thinner E layers. Almost all curves showed some minor indication of pathology in the form of an abrupt change of slope or a very steep slope or a cusp in some range, but the major pathological manifestations indicative of instability did not occur in the range of S from 0.6 to 4.6 within which reversals up to 0.75 occurred (1.00 would be exact reversal). A significant result is that following reversal with increasing S, the internal reversed vacuum field changed little as S increased over a considerable range, the main effect being the thinning of the layer.

Figures 12 and 13 summarize two features exhibited by the more than 115 systematic calculations that have been made. In Fig. 12 the range of S for which an almost constant reversed field exists is plotted against G. The points corresponding to all three energies are seen to define a common area. The larger S value of each pair is for a layer 1/6 the injection radius in extent and the smaller S value is for the knee of the curve which initiates the approximately constant region of reversal.

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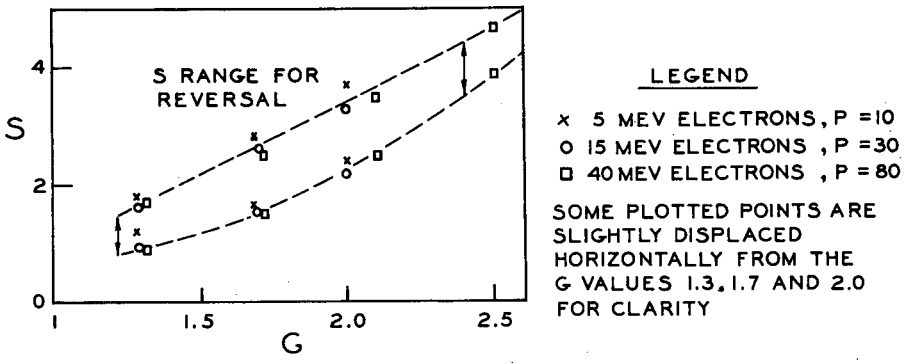
*Consultant to Lawrence Radiation Laboratory from General Electric Vallecitos Atomic Laboratory, Pleasanton, California.



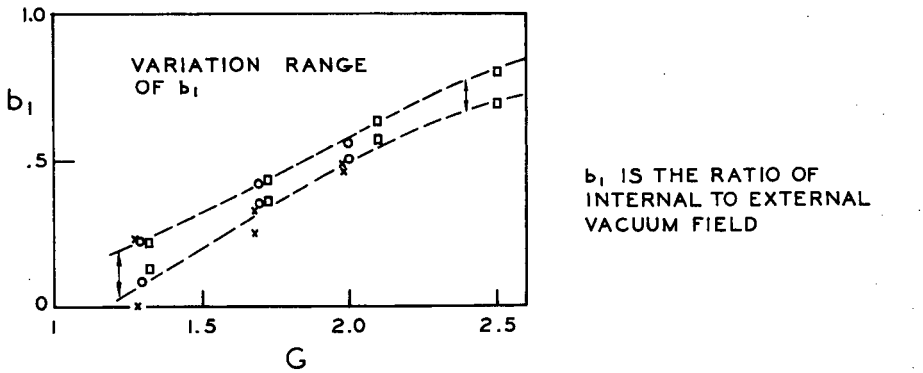


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Fig. 12. (above) Range of "injection rate" versus ratio of injection-circle radius to gyration radius.

Fig. 13. (below) Ratio of reversed to impressed field versus ratio of injection-circle radius to gyration radius.

Figure 13 shows the magnitude of reversal as a function of G and includes the range of variation as S is changed between the limits shows in Fig. 12. Again there is a remarkable independence of injection energy.

II. The magnitude of the dynamical friction has almost certainly been grossly overestimated by using a simple-theory Coulomb-shielding distance. A ready-made treatment applicable to relativistic electrons is being sought in order to avoid the need for an original investigation. It can be reasonably expected that the correction will affect only the ν in Eq. (2) above (reducing it) and not the form in any important way. A more important consequence will probably be the need to recognize radiative loss as the predominant effect. Although this is directly amenable to the machine method now in use, the complexity of the calculation would be markedly increased. A happy consequence would be stronger justification for the neglect of scattering.

The present basis of calculating ν gives a value of 500 sec^{-1} for a plasma containing 10^{15} electrons cm^{-3}. For S = 2 (see figures)

Eq. (1) predicts an injection requirement of 300 μa of E electrons per cm length of layer, or 0.09 amp for a 10-ft length. At 50 Mev this is 4.5 Mw. A markedly smaller ν will reduce this power requirement somewhat.

III. A question of some interest but little urgency is: what happens if the injection rate is increased beyond that value of S for which the layer thickness becomes zero? The answer is now seen to be -- on a steady state basis, as always -- that the E-layer transforms smoothly, expanding so that the virgin electrons now enter on the pericenters of the virgin-electron trajectories instead of on the apocenters. The new E-layer lies, therefore at least partially outside the injection circle. Results in hand can easily be reinterpreted to cover this circumstance.

III. LIVERMORE PINCH PROGRAM

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

ELECTRON BEAM PINCH

An electron beam has been fired through a 4-in.-diameter 18-in.-long linear "stabilized pinch" and observed at the exit electrode. The electron beam (400 kev, 0.1 amp, and 0.1-μsec duration) enters the linear pinch at the axis of one electrode. With no pinch, but with an initial axial magnetic field, it can be observed (by the light from a phosphor screen) at the opposite pinch electrode, after traversing a 0.002-in.-thick Be-copper foil, and is found to arrive on axis. When the beam is fired during a pinch discharge, the beam is observed to move radially off axis at the very beginning (0.1 μsec) of the pinch current, and then circle back toward the axis during the rise (9 μsec) of the main B_θ field, which compresses the entrapped B_z flux. The displacement of the beam from the axis occurs independently of (a) polarity (the displacement merely being reversed); (b) initial ionization (high- and low-frequency initial current); (c) density (50 to 500 microns pressure); (d) pinch ratio (B_z initial/B_θ final), (e) tubular extension of the beam entrance electrode, to shield out any distorting magnetic field at the entrance slit. The radial displacement of the beam is being determined as a function of length along the pinch. After the completion of present magnetic-probe measurements and a consequent understanding of the tracking of the beam, we hope to measure the enhanced diffusion of the beam when it traverses a turbulent pinch current layer. Already, even under conditions of high density, some local beam movements during the 0.1-μsec duration of the beam pulse have been found to be at least 10 times as fast as the average velocity $(E/B)c$ of the field. The pattern of the small movements observed is circular, and of a size (~ 1/2 cm) that is suggestive of the expected interchange instability.

*U. S. Naval Postgraduate School, Monterey, California.

CONICAL PINCH PLASMA ACCELERATOR

The conical pinch plasma gun now consists of a quartz cone 22 cm long, with 10-cm largest diameter and 7-cm smallest diameter. The cone is placed between two normal electrodes, the large end electrode having a 3.5-cm central hole for plasma expulsion.

Use of the quartz cone, pulsed gas input, and a pre-ionization heating cycle allows sharp pinch boundary formation. Pulsed gas input also allows the accelerated plasma to be projected into a high-vacuum region. Pinch current is supplied by a two-stage Marx surge generator, each stage consisting of two 14-μf 20-kv capacitors in parallel. Major emphasis up to now has been placed on reliable detection of the accelerated plasma, time-of-flight determination of velocity, and variation of pinch parameters for optimization. Detection is accomplished by diamagnetic probes, and charged-particle collection with a biased Faraday cup.

With peak pinch current roughly constant at about 150 ka (1.5 μsec rise time), average plasma velocity is observed to increase from 1.5×10^7 cm/sec to 4×10^7 (200 to 1600 ev) as gas pressure is decreased from 650 to 150 μ of D_2. Rough indications of accelerated plasma density show little change with pressure down to 100 μ. Below 100 μ pressure, density rapidly falls off.

Very preliminary examination of the fine structure of the plasma pulse collected under optimum pressure conditions (175 μ D_2) indicates that two principal bursts of plasma are ejected; an 800-ev burst, prior to the first bounce; and a second burst, mainly at 3.5 kev, and with some component up to 50 kev, near the first bounce. A weak axial magnetic field (250 gauss) appears to alter some of the acceleration mechanisms.

More extensive variation of pinch conditions will be carried out, along with plasma density measurements.

12-INCH LEVITRON CONSTRUCTION

Evaluation of the epoxy-Kanigen method of fabricating pinch tubes has been completed. The method has been found unsuitable for the levitron, because of difficulties in obtaining a good vacuum seal between the two coatings.

The status of various components of the levitron is as follows:

Inconel-x liners. Fabrication of the six 60-deg sections is essentially complete and ports are being attached. The approximate delivery date is March 14.

B_θ coil windings. These windings have been made demountable and are complete except for insulation.

Torus shells. The epoxy coating (Epocast 275) is 75% complete on one shell and the process appears satisfactory. The second shell is ready for application of the coating.

Mechanical levitator. A combination magnetic and pneumatic levitator has been developed, which promises to provide a satisfactory backup for the magnetic levitating scheme. The levitator withdraws a support rod through a distance of 5 in. and returns it in approx. 40 msec. The dwell at the bottom is sufficient for completion of the pinch cycle.

Klunker switch. An isolating switch designed to disconnect the ac levitating supply during the pinch cycle is well along and appears feasible. The switch carries 60,000 amp successfully for 10 ac cycles, and can be opened for 40 msec with what is presumably an adequate gap. High-voltage tests are not yet completed.

Vacuum and diagnostic port components. These are 90% complete; a satisfactory technique for attaching them is being worked out.

Gamma bank. Fusing of the capacitor bank is complete and bank modifications for the levitron are 40% complete. The bank is being upgraded to operate at 20 kv.

Electrical system. Details have been worked out for the entire levitron electrical and diagnostic system. The welding control for magnetic levitation has been received and checked. Modifications are under way for the desired programming.

SODIUM PINCH

The sodium pinch experiments have been completed, using both the hard-core and standard stabilized pinch configurations.

The hard-core pinch is formed by passing the pinch current first up along a central copper rod or "hard core" (3 cm diam by 55 cm long), then down along a solid sodium tube (3-mm-thick wall, 7-cm diameter), then back up a helical B_z coil, and finally back down to the condenser bank. The B_θ field formed around the hard core is bounded by the sodium tube (tubular pinch), which also bounds the external axial B_z field, formed by the helical external coil. Since these elements are in series, the radial equilibrium position of the sodium under the magnetic pressure does not vary with the pinch current, provided, of course, we consider times that are short compared with the leakage time of the B_z field into the sodium.

The pinch current used (approx 500,000 amp from a 0.5-farad condenser) resulted in an effective pinch time of 1 msec, which was 30 times the long Alfvén wave transit time over the pinch layer, but was short compared with the leakage time of the B_z field to the inside of the sodium tube.

Figure 14 shows the sodium tube, which had developed a helical slot instability after nine successive pinches. Hydromagnetic theory (assuming perfect conductivity) predicts unequivocal stability for the configuration. The disagreement is probably ascribable to the finite conductivity of the sodium. The layer itself is sufficiently thin so that the current density is always uniform (resistively dominated current distribution) during the time of the pinch. One notes at the end of the helical slot (Fig. 14) the "tearing" action of the magnetic field. Such a "tearing" could not occur in a perfectly conducting medium, but can be predicted on rather elementary grounds for a resistive sheet current conductor.

Figure 15 shows the incipient helical instability modes of the sodium tube after nine successive pinches in standard "stabilized pinch" geometry (B_z inside, B_θ outside) for the same current wave form but lower magnetic field, so that the slot instability had not yet formed.

The general conclusion is that hydromagnetic phenomena are grossly different for perfectly conducting and poorly conducting media, even though time scales are chosen for which gross trapping of fields takes place in either case. As a consequence, one worries about the application of hydromagnetic theory to steady-state configurations. This conclusion is further strengthened by some of the liquid sodium experiments.

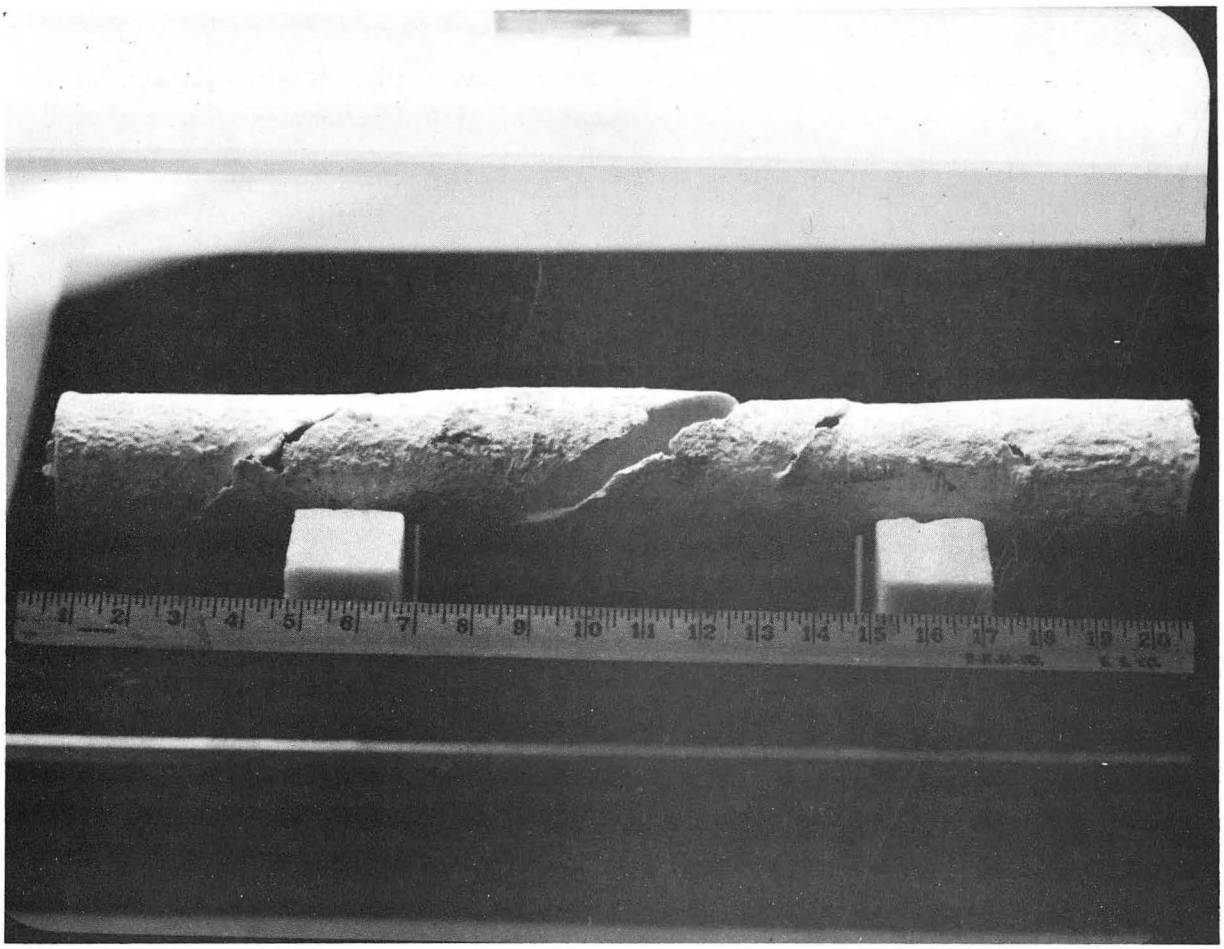

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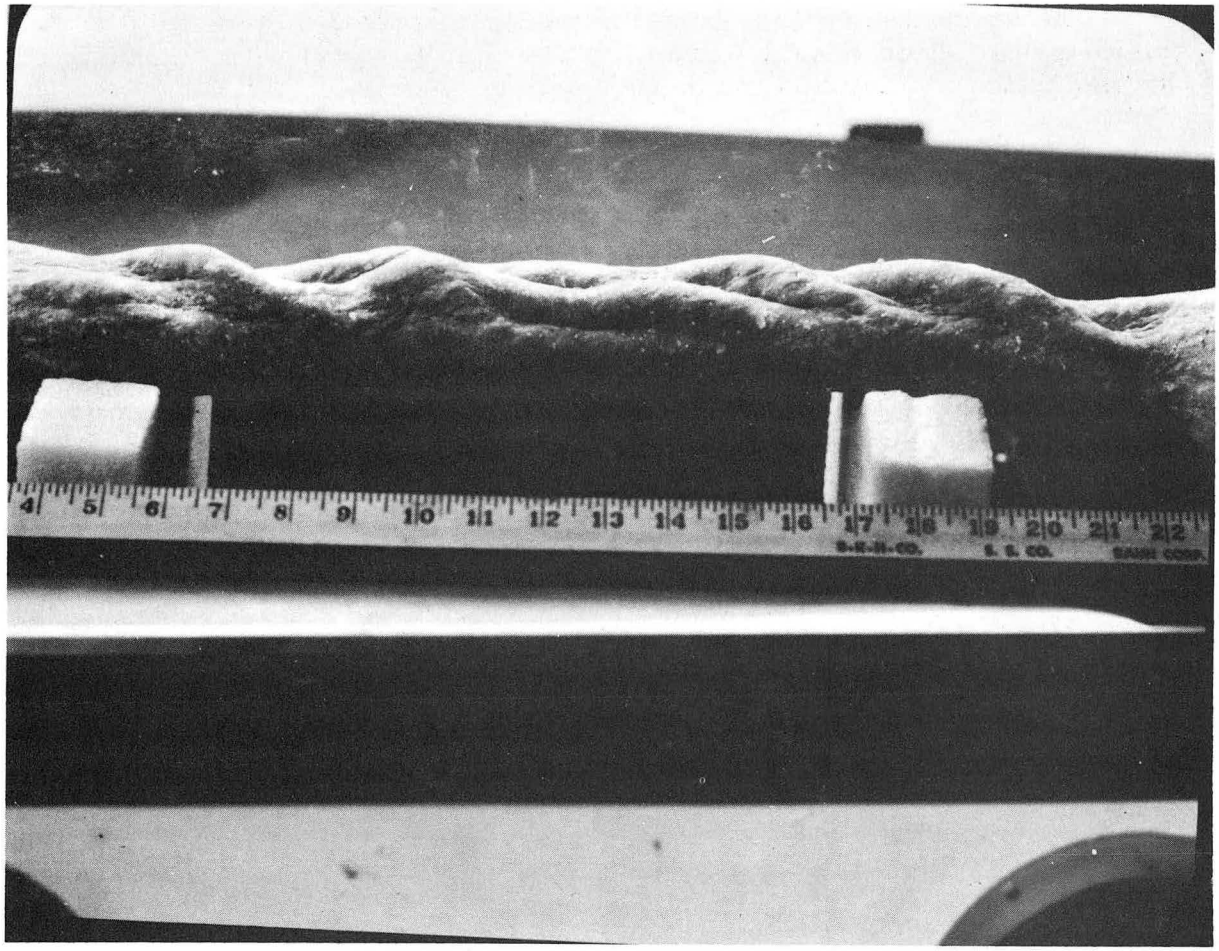
Fig. 14. Sodium tube after nine successive hard-core pinches.



ZN-2352

Fig. 15. Sodium tube after nine successive stabilized pinches.

LIQUID SODIUM EXPERIMENT

The study of magnetic containment geometries, with rf field and "diamagnetic" fluid (liquid sodium),[1] has been pursued with emphasis on the magnetic -mirror and magnetic-cusp geometries.

A mirror geometry was constructed by securing two half mirror coils parallel to each other and perpendicular to a conducting plane. Surface tension permits the sodium to remain initially in the mirror field, but as the applied field strength is increased, the central mass is displaced laterally (m = 1 instability). The pieces of sodium left behind are ejected from the ends of the mirror.

A cusp geometry was built, consisting of a single current loop held horizontally above the surface of a pool of liquid sodium. A concentric micarta tube served to confine the sodium radially. Magnetic pressure exerted by the current loop caused the sodium surface to peak in the cusp region. The sodium could be made to rise through the cusp, thus entering a region where the magnetic pressure was weak compared with surface tension. The sodium column then formed a "mushroom" on the top. Alternatively, a micarta block could be inserted to block off the sodium at the cusp. Most of the equilibrium surfaces were investigated under these conditions. Marked stability was observed.

A direct-current experiment was also undertaken to observe possible instabilities which might be traced to finite resistivity. A coaxial electrode arrangement very similar to the hard-core pinch geometry was chosen, primarily because it had been investigated previously[1] with rf fields and found to be stable.

The first successful dc run showed a large-scale asymmetry in the equilibrium position of the sodium. In two other dc runs the accuracy of the electrode geometry was improved, and the asymmetry was not so obvious.

Further studies are being made of the dc experiment. A new machine for the more detailed study of the mirror geometry is also being designed.

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[1] S. A. Colgate, H. P. Furth, and F. O. Halliday, Hydromagnetic Equilibrium Experiments with Liquid and Solid Sodium [UCRL-5752], to be published in Revs. Modern Phys.

ION HEATING BY TORSIONAL WAVES IN A MIRROR MACHINE

Radio-frequency torsional waves have been excited in a hollow cylinder of plasma by applying an alternating radial electric field at one end of the cylinder. The method and apparatus have been described.[2] When the waves alternating at the applied radio-frequency propagate to a region where the static magnetic field is adjusted to ion-cyclotron resonance, energy is transferred from the waves to the ions of the plasma. Recent experiments have been performed to study this transfer.

Heated D^+ ions, gyrating in a field of 4300 gauss, charge-exchanged with D neutrals (at a density of $6 \times 10^{13}/cm^3$). The hot D^0's resulting were measured by secondary-electron emission from a stainless steel target (2 cm^2). Electron currents as high as 30 μa were measured. If the secondary-emission ratio is taken as 0.1, which may correspond to a neutral energy of roughly 1 kev, the calculated hot neutral flux was 10^{15}/sec cm^2. This neutral flux measured by the detector depended strongly on the position of the resonance region in the machine; it was at a maximum when the resonance region was adjacent to the detector target.

At lower pressure, 10^{13} D^0/cm^3, at which the total charge-exchange cross section would be lower, a positive current was detected which peaked at resonance. This was interpreted to be positive ions reflected at the target to the collector.

Victor Garner noticed that a copper shield placed around the D^0 detector became darkened on one side but not the other. The darkened side corresponded to the direction from which ions gyrating in the static magnetic field would strike the shield. Following this clue, a hot ion detector was made, using a 0.5-in.-diam shield with a 0.125-in.-diam hole, through which azimuthally directed ions could strike a collector. Even when the detector was 2 in. from the plasma, a positive current of 6 μa was obtained. An energy analysis was performed by applying a positive voltage to the collector. About half the ions overcame 1000 volts. The results of later experiments, during which the positive current first declined and then increased with increasing bucking potential, are not yet understood. As expected, when the D^+ detector was rotated 180 deg, there was only a small positive current, which became a negative current when the positive bucking potential exceeded 10 volts. The hot D^+ current increased rapidly with decreasing pressure. This was expected from the decreasing total charge-exchange cross section.

The electrical impedance of the plasma was measured. The impedance decreased with increasing rf voltage to about 1 ohm at 200 v; then it increased to about 10 ohms at 500 v. The rf level at the impedance minimum depended on the pressure, increasing with increasing pressure. The three-dimensional plot resembled a V-shaped valley. Hot D^0 production followed a similar curve, peaking near minimum impedance. Hot D^+ current was low up to the point of minimum, impedance, then increased sharply.

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[2] Edmund S. Chambers, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 103.

The current, light output, and pressure of the reflex discharge increased when the rf voltage was turned on. At 0.2 μ pressure the increase in discharge current increased linearly with the rf voltage. At higher pressures this curve was displaced to higher rf voltages.

HIGH-MAGNETIC-FIELD RESEARCH

Technological development has been halted during this quarter, in favor of increased activity on the levitron. The existing-300 kilogauss magnet has been made available to other groups for the testing of semiconductor field-sensing devices and the forging of metal parts. The industrial potential of high-field metal forging is being studied.

About half the emulsion stacks obtained at the Bevatron have now been analyzed by the Livermore Nuclear Emulsion Group. The technique of using a 200-kilogauss field with emulsion has proved entirely satisfactory. Significant new results on K^--meson interactions in heavy nuclei have been found, and will be reported at the Washington meeting of the American Physical Society.

A 125-kilogauss magnet of 5 in. i. d. is being designed for Donald Glaser, to be used with a bubble chamber. Parts for a submillimeter microwave generator, to be operated in conjunction with the 300-kilogauss magnet, are being prepared for C. K. Birdsall.

Several review articles on high-field research have been requested and written.[3, 4]

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[3] H. P. Furth and R. Waniek, High Magnetic Fields and Their Applications [UCRL-5863], to be published in Kelvin Scale.

[4] H. P. Furth, High Magnetic Field Research [UCRL-5881], to be published in Science.

THEORY

A technique has been developed for finding sufficient conditions for hydromagnetic stability in diffuse linear pinches.[5] This technique has been applied to study the stability of that class of hard-core pinches where current flows everywhere orthogonal to the magnetic field ("maximal-force" pinches). It is found that "β's" of order .5 are compatible with hydromagnetic stability. Since there is no current component parallel to magnetic field in "maximal-force" pinches, one does not expect any of the undesirable electron-runaway effects and current-flow instabilities peculiar to "stabilized pinches" and ohmically heated stellarators. Present theory therefore indicates that the use of a "maximal-force" regime in the levitron will permit perfectly stable containment of high-pressure plasma, even if pinches that are merely hydromagnetically stable should turn out to be unsatisfactory.

The theory of the shock origin of cosmic rays in the explosion of supernovae is awaiting a machine calculation of the nonrelativistic hydrodynamics. This code is now available and has been checked by calculating a known similarity solution. The relativistic hydrodynamics has been rederived and leads to agreement with the observed cosmic-ray spectrum.

Present theory concerning the resistivity of a turbulent plasma predicts a resistivity only 1/100 of that observed in pinches, provided one assumes (a) no first-order charge separation and (b) a frequency spectrum like that actually observed with the limited band width of magnetic probes. Obviously, one or both assumptions must be substantially incorrect.

A full report has been prepared on hard-core pinch experiments, their interpretation, and future prospects.[6]

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[5] H. P. Furth, Sufficient Conditions for Hydromagnetic Stability of a Diffuse Linear Pinch [UCRL-5865] to be published in Physics of Fluids.

[6] S. A. Colgate and H. P. Furth, Stabilization of Pinch Discharges [UCRL-5862], to be published in Physics of Fluids.

IV. BERKELEY PLASMA RESEARCH

SHEET PINCH STUDIES

Oscar A. Anderson

Introduction

The study of the dynamical behavior of the tubular pinch has continued. Streak photography has been used to observe plasma confinement, and attention has been devoted to some technical problems associated with streak-camera diagnostics, switch development, and high-voltage insulation.

Diagnostics Program

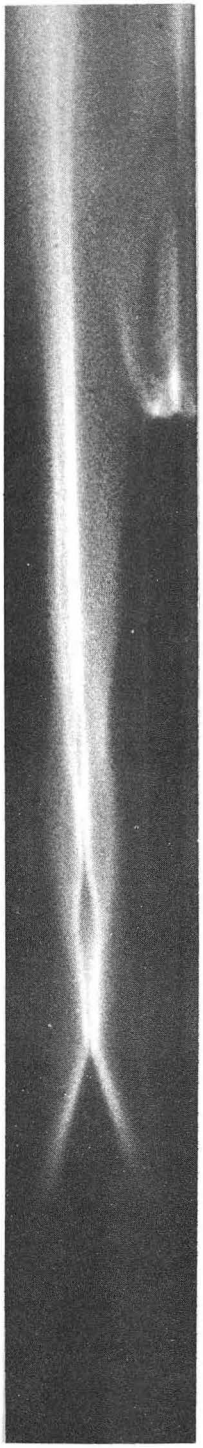
A model 100A streak camera (similar to the camera described in the preceding report) was assembled and installed under the supervision of Willis C. Goss for permanent use in the Berkeley pinch program. John M. Stone has given valuable assistance in solving the optical alignment problems.

In certain streak photographs (such as Fig. 16) interesting events occurred for which it was desired to pinpoint the time involved. That is, a method was needed for coordinating the time scale of these photographs with that of other information, such as the tube voltage signal. A light-pulse generator was devised for this purpose and was recently completed. In operation, a pair of kiloampere pulses of 0.03 μsec duration, spaced by 5 μsec, is passed through a discharge tube aligned with the optical slit. (This tube is 1 mm in diameter and length, and is supplied from a reservoir of hydrogen at 10 mm Hg pressure.) At the same time that the light signals arrive at the camera image plane, the beams of all the oscilloscopes being used in the experiment are intensified. Later, photographic enlargements are made in which the bright spots on the oscillograph traces are put into exact register with the dense, clearly defined lines at the edges of the streak photographs.

8 × 10 Tubular Pinch

While the new streak camera was under construction, the light from the radial slit in the end electrode of the tube was scanned with a monochromator. It was found, as expected, that the D_β line from the pinch region was greatly broadened at the pinch time. Once again, no appreciable impurity lines were found. In another experiment a correlation was noticed between the tube breakdown-delay time preceding the preheating cycle and the amplitude of the pinch oscillations during the main discharge cycle. When the delay was 0.5 λsec, normal oscillations appeared, but when by chance the breakdown was immediate, the oscillation amplitude was cut in half. This effect needs more investigation.

Streak photographs were made under a wide range of conditions. One of these is shown in Fig. 16, which was obtained by using deuterium at a pressure of 500 μ. Several unexplained effects may be noticed: the shock motion seems to be arrested at certain times; the dark region between the



ZN-2347

Fig. 16. 8×10 tubular pinch streak photograph.

two shock fronts never disappears; and there is a sudden onset of luminosity between the pinch plasma and the wall after about 4 μsec. These phenomena are worthy of study but further work with the 8×10 tube was postponed so that the modified 4×10 tube could be evaluated.

4×10 Tubular Pinch

The inductance-imbalance problem has been previously discussed. Figure 17 shows the changes that were made to the 4×10 tube; the original version may be found in UCRL-8682. A comparison of the pinch behavior before and after the inductance change is shown in Fig. 18. It is seen that the tendency for the plasma to strike the wall has been avoided. But note that the pinch nevertheless breaks up at about the same time (1.5 μsec after the current peak).

It is important to determine why the plasma confinement is shorter in the 4×10 tube than in the 8×10 tube, since in the former tube there is the advantage of more space between the plasma and the wall. Several possible explanations for the shorter confinement time are being considered. One is that the modification reduced the coupling between the two flux regions and may have introduced a destabilizing effect. It is also possible that although the tube with the smaller core has more room for the plasma, this benefit is canceled by the reduction in wall stabilization.

High-Current Switch

Four switches, according to plan, are being modified to accept Silastic rubber insulation, but only one has been assembled; there has been difficulty with the vulcanizing process. Meanwhile a program of reducing the switch jitter time is in progress. The following changes were made:

(a) In order to provide a more powerful trigger spark the inductance of the trigger pulse-generating system was reduced by a factor of 15.

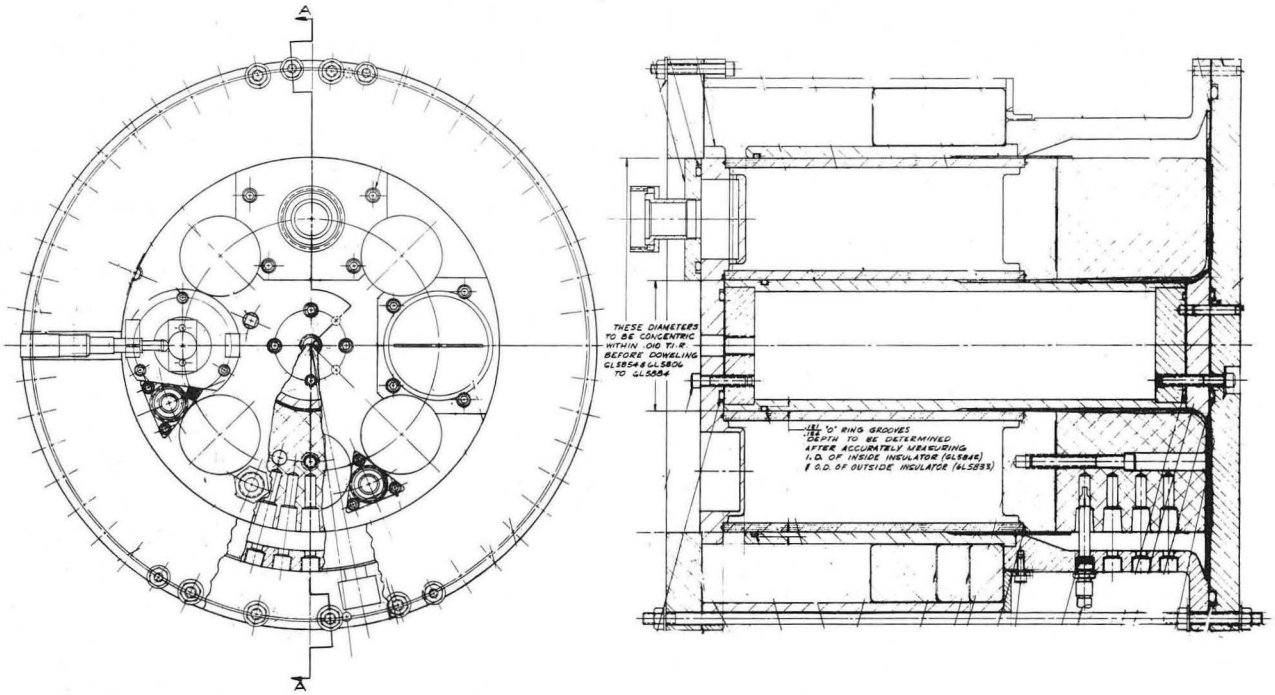
(b) Electrode holes were moved to line up with the trigger spark and the shape of the holes was changed.

(c) The spark plug electrode and insulator arrangement was redesigned.

These changes had the following effect: at pressures around 10 μ the delay was reduced from about 0.8 to 0.2 μsec, while jitter decreased from the order of 0.5 to 0.05 μsec. The effect of raising the initial pressure was also studied. It was found, for example, that at 50 μ the delay time was reduced to 0.03 μsec with negligible jitter. However, the problem at high pressure is that a switch may break down before it is triggered. The shape of the electrode holes will be further revised in an attempt to improve this situation.

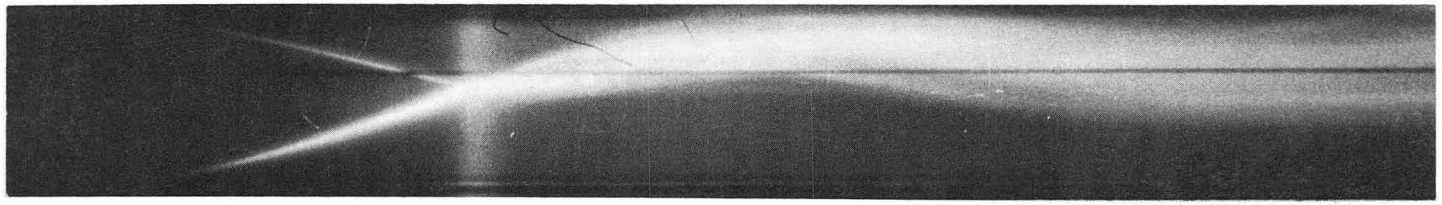
Future Plans

In the next quarter emphasis on streak-camera diagnostics will continue. Among the problems of a technical nature the most pressing is the unreliable insulation system of the tubular pinch tubes themselves. For example, most of the operation with the 4×10 tube has been limited to 15 kv rather than 30 kv as originally intended. Because of the design of the tube it is not practicable to use the Silastic rubber insulation which has been so successful in the switches. Other insulating materials, such as silicone gel, are being evaluated.

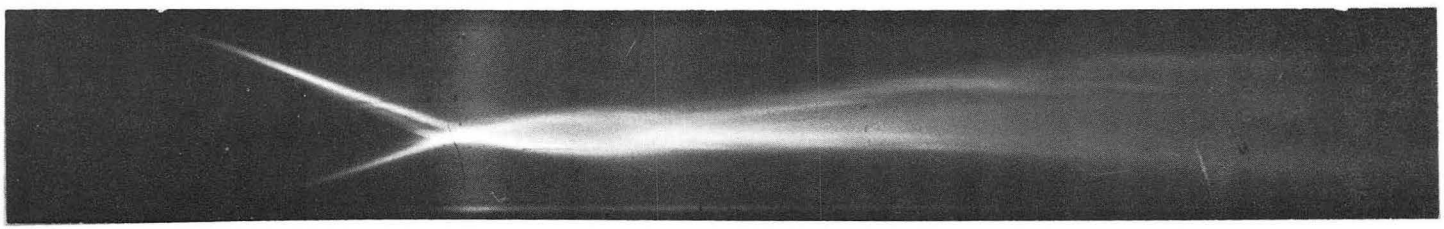


MUB-394

Fig. 17. 4×10 tubular pinch with balanced inductances.



(a) unbalanced



(b) balanced

ZN-2373

Fig. 18. 4×10 tubular pinch streak photographs: (a) unbalanced, (b) balanced.

HOMOPOLAR PROGRAM

Alexander Bratenahl, Wulf B. Kunkel, William R. Baker,
John W. Blamey,* and Didier Veron†

Introduction

There appears to be growing evidence in certain types of crossed-field plasma devices that the drift velocity of the plasma tends to be limited to several times 10^6 cm/sec by some unknown mechanism.[1] Alfvén has a rather elegant theory of the formation of the solar system[2] that depends in a very intimate way on a postulated ionization process which, if applied to the homopolar or other devices under the assumption that neutral gas is present, would result in limiting the velocity to the order of magnitude observed.

Alfvén postulates that in a region where plasma is colliding with a neutral gas the latter is ionized by a direct process if the plasma velocity exceeds $v_c = \sqrt{2V_i/M}$, where V_i is the ionization potential for the neutral gas and M is the mass of the plasma ion.[3] This implies that plasma cannot drift through stationary neutrals at a velocity greater than v_c.

Some experiments by Fahleson and Bloch in Sweden, using their recently constructed homopolar device, have demonstrated velocity limitation in a very clear-cut way under conditions whereby the plasma was incompletely ionized.[4] At present the actual mechanism, if it exists, is not understood at all, but the role of neutral gas present, particularly near the walls, may quite possibly be the cause of limitation in the homopolar. The application of these ideas to the energy balance in the homopolar meets with difficulties; the effect is likely to be dominant at the boundaries. It should be emphasized that it is by no means clear at this time that Alfvén's mechanism is actually operative in the homopolar, nor even that it exists at all. It may only be regarded as a clue.

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*Visitor from the Research School of Physical Sciences, The Australian National University, Canberra, Australia.

†Visitor from Centre d'Etudes Nucléaires de Fontenay-aux-Roses, France.

[1] William R. Baker, Alexander Bratenahl, William S. Cooper, and Wulf B. Kunkel, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 73.

[2] H. Alfvén, On the Origin of the Solar System (Oxford University Press, 1954). These ideas were first published in Stockholms Observatoriums Annalen, 1942, 1943, and 1946.

[3] H. Alfvén, Ionic Heating and Confinement of a Magnetized Plasma, invited paper, January 1960 meeting of the American Physical Society, New York, N. Y.

[4] This work was reported by Alfvén, reference 3.

Homopolar III

Homopolar III has been overhauled in preparation for an investigation of velocity limitation, and in particular a study will be made of neutrals present and conditions in the boundary flow at the walls. To this end the technique of disconnecting the source condenser bank, developed for Ixion at Los Alamos, has been attempted--but so far unsuccessfully.

One new observation is interesting. The main bank is divided and the two sections fired at different times. During the current pulse of the first section, when most of the ionization takes place, the internal circuit impedance is a very complicated function of time. After the plasma is thus prepared, the current pulse from the second section can be interpreted as a constant impedance similar to conditions at crowbar, and the velocity limit may be somewhat relaxed. The data have not yet been analyzed in detail. It is hoped that shortly it will be possible to disconnect the first bank before firing the second so that there will be no coupling between the two.

Homopolar IV

Homopolar IV (see Fig. 19) sometimes called "Puffatron", is under construction, and with a little luck may be in operation in a month. The philosophy behind this device is an attempt to leap over the two principal hurdles encountered in previous homopolars. As reported previously,[1] the insulators have always been a very serious weakness and quite possibly the chief source of voltage, and hence of velocity limitation. The operative voltage of previous machines has never been large enough to test thoroughly the existence of a speed barrier, if any. Homopolar IV should have a short but finite operating time during which the insulators and insulator boundary conditions are eliminated entirely. In addition, it will be operated at up to ten times the present voltages.

This device consists of an 8×56-in. solenoid pulsed to 20 kilogauss. The electrodes are 2-in.- and 6-in.-diameter coaxial metal pipes. The insulators are pyrex pipes extending out of the ends. In operation the system will be pumped to 10^{-6} mm Hg, or better. Four Tobe-Deutsch 100-kv 0.8-μf condensers will be connected directly across the electrodes. At the center of the inner electrode a fast valve, opening in 15 μsec, will introduce a puff of neutral gas radially. It is hoped that the breakdown of this gas and its subsequent motion as a homopolar will take place in a time short compared with the spreading time towards the insulators at the ends. It will be noted that the device serves as its own switch.

Fast Impact Valve

Release of about 10 micron-liters of neutral deuterium into the vacuum in 20 μsec is a tentative requirement for Homopolar IV described above. Several designs for such a valve have been considered, and the opening speed of one was measured as typically more than 100 ft/sec developed within 7 μsec, maintained for 20 μsec, and thereafter reduced in speed to give closure in 400 μsec.

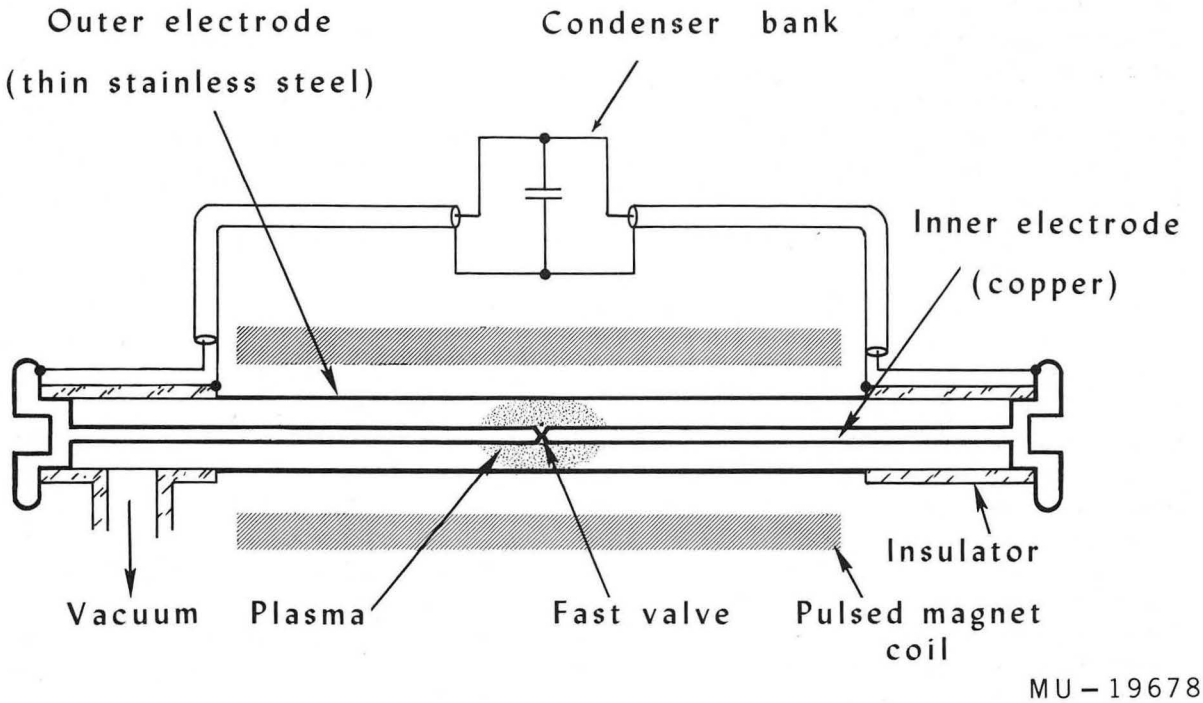

Fig. 19. Homopolar IV.

As shown in Fig. 20, an aluminum alloy piston is accelerated by atmospheric pressure along an initially evacuated tube to strike the stem of a nylon poppet valve at about 160 ft/sec. The impact pressure, transmitted through the nylon at sound velocities, opens the valve, and the deuterium stored in the annular cavity A escapes radially.

The following relationship derived by John W. Mark[5] for an earlier design gives approximately the fraction of deuterium remaining in the cavity of assumed constant cross-sectional area, A ft^2, after time t (in sec) for a uniform opening velocity of v ft/sec ($T\ ^{o}K$ is the initial gas temperature):

$$\frac{m}{m_0} = \left\{ 1 + \frac{7.5\ vt^2 \sqrt{T_0}}{A} \right\}^{-5} .$$

The effective value of A cannot be made very small, therefore v must be large. In the earlier design the valve action compressed the gas to give a high T, small A, and large v, but some practical difficulties could not be overcome.

The transmission of velocity and stress through a body is characterized by the relationships

$$\Delta v = \frac{\Delta p}{\sqrt{E\rho}} , \qquad c = \sqrt{\frac{E}{\rho}} ,$$

where Δv and Δp are the velocity and stress changes at a point as the front passes at sound velocity c through material of elastic modulus E and density ρ. Thus the velocity v that may be achieved in a time short compared with double transit times is limited by allowable compressive and tensile strengths, the elastic moduli and the density, except in the case of body forces. Nylon is superior to metals in this respect.

According to a more accurate theory involving dispersion, the several elastic moduli and reflections from boundaries (e.g. the cylindrical surface),[6,7] there may be several discrete pulses and attenuation in magnitude and time. The time taken to develop the full velocity change for an initial step pulse is of the order of d/c, where d is the diameter of the rod. For the valve described this is tolerable.

Some theoretically attainable speed has been sacrificed for practical considerations and convenience. An opening speed of 200 ft/sec should be reasonable for nylon. There is also evidence that the stress may safely exceed the accepted static strength.

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[5] John W. Mark, Puff Valve, Engineering Note 4507-41 M2, Aug. 20, 1959.

[6] Julius Miklowitz, Third U. S. National Congress of Applied Mechanics, 1958, p. 215.

[7] H. Kolsky, Stress Waves in Solids (Oxford University Press, 1953).

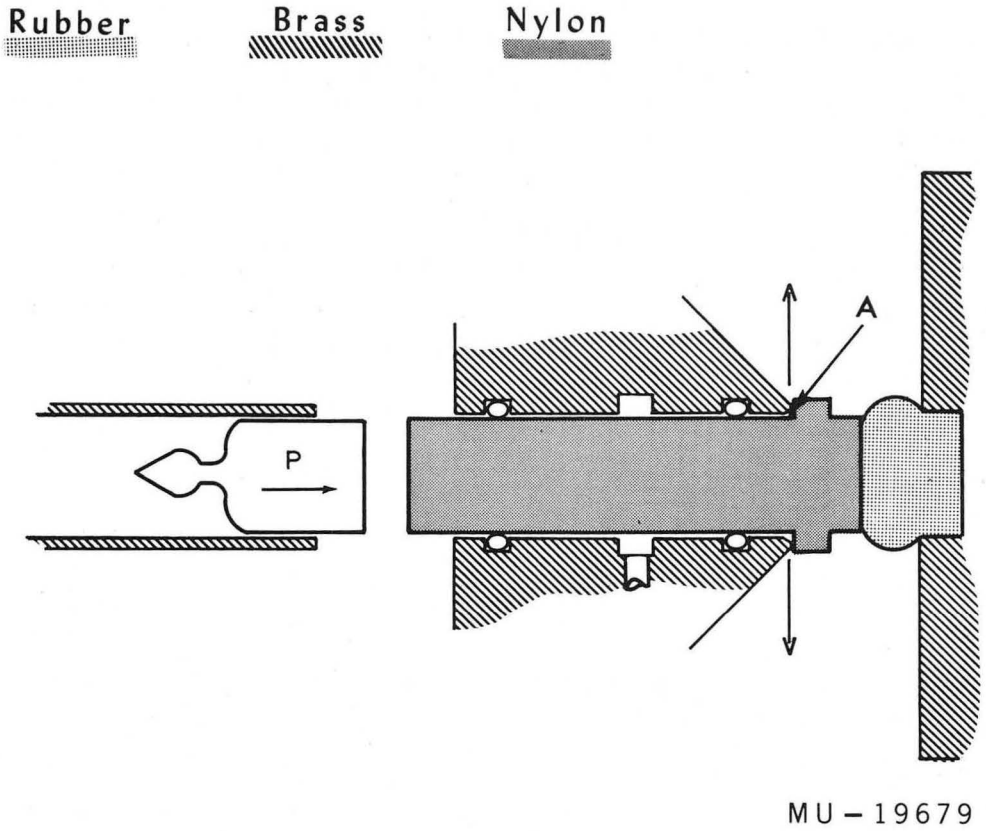


Fig. 20. Fast impact valve.

The axial dimensions of the aperture versus time were recorded (Figs. 21a and 21b) by means of an optical system. The ordinate is non-linear for the first few thousandths of an inch.

For this valve the difference in results for nylon and aluminum pistons was not great, so the aluminum piston was preferred for other practical reasons. Of length 0.5 in. plus holding lug, and 0.499 in. in diameter, it was accelerated through the 0.500-in. tube with negligible frictional losses. By variation of the length and material of the piston and use of pressure other than atmospheric the opening characteristics of the valve may be varied.

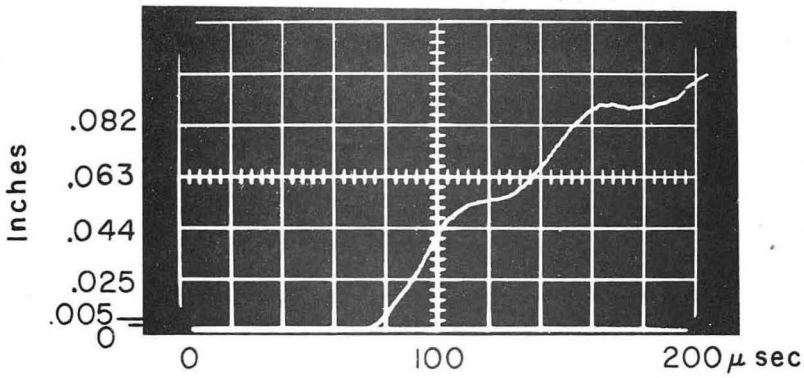
The rapid lateral expansion and contraction of the valve stem, as given by Poisson's ratio, necessitates the use of two and possibly three O-ring seals with a pump-out space between them. It is possible to design a valve to make positive use of this type of leak.

The method of refilling the cavity A with deuterium (by a slow leak) is omitted from Fig. 20 for clarity. The stationary valve seat is detachable. A material softer than metal may be necessary to avoid too great a pressure on the rubber buffer which provides both sealing and restoring forces. The complete system fits inside a tube of 1.75-in. bore, and is retractable.

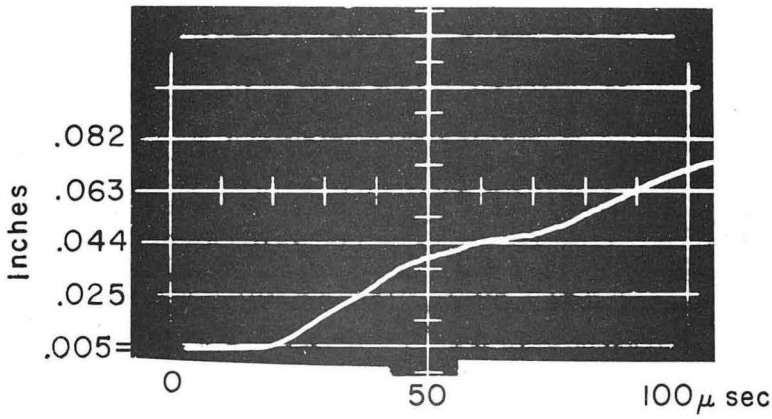
Acoustic Probe

An attempt was made to calibrate the acoustic (pressure) probe (developed by DeSilva[8]) in a shock tube. The shock tube was made available in the Chemistry Department on the campus through the kindness of Prof. Harold S. Johnston. The attempt was only qualitatively successful owing to some mechanical difficulties and the short time the shock tube was available. It may be briefly noted qualitatively that the probe is linear, and has a sensitivity of ≈ 0.3 v/atmosphere and a rise time probably less than 2 μsec. The theoretical rise time is about 0.2 μsec.

[8] Alan W. DeSilva, in Controlled Thermonuclear Research Quarterly Report, UCRL-8887, Sept. 1959, p. 81.



(b) Nylon piston



(a) Aluminum

MU-19677

Fig. 21. Valve opening versus time.

PLASMA PHYSICS AND MICROWAVE DIAGNOSTICS

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

Enhanced-Diffusion Experiment

An understanding of our extension of Lehnert's experiment concerning "enhanced diffusion" from a positive column most likely will come from detailed measurements of the fields in the plasma (with which one can compare possible mechanisms) and from the amassing of sufficiently good data that reliable empirical relationships can be developed. We are proceeding in both ways. Shortly after the radial potential measurements shown in Fig. 31 on page 94 of UCRL-9002 were obtained, Dr. Gunter Ecker† developed theoretical expressions from which one can deduce the presence of enhanced diffusion. This theory applies at magnetic field strengths for which the discharge is still azimuthally uniform.

In the usual theory of the positive column it is assumed that only charged-neutral collisions need to be considered. However, if charged-charged interactions exist, perhaps owing to small-scale collective effects, then a new resistive term is introduced and the radial potential curves will show minima over some range of magnetic fields. Such a situation appears to exist at 425 to 568 gauss in Fig. 31 of UCRL-9002. It should be added that radial field measurements are much more sensitive indicators of the presence of enhanced diffusion than are longitudinal electric field or electron density measurements.

It is therefore important to understand what trust can be put in the measurements made with radial probes, such as those of Fig. 31, UCRL-9002. The answer is still in doubt; this is based on asymmetries that appear as the probe tip is moved across the centerline of the tube. The probe apparently disturbs the local radial potential distribution much more than any other parameter. It is felt that this problem can be avoided by using a dog-leg probe with the region near the tip aligned parallel to the magnetic field. A considerable improvement occurred when the tip was removed in this way to 3 cm from the radial part of the probe. Measurements with probes with even longer axial extensions are in progress.

Careful spectroscopic measurements are being made, and known impurities are being added to the discharges, in an attempt to understand the role that impurities can play.

A report (UCRL-9110) summarizing the experimental results is in preparation.[1]

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*National Science Foundation Fellow.

†Visiting Professor of Physics, Naval Postgraduate School, Monterey, Calif., on leave from the University of Bonn, and consultant to Lawrence Radiation Laboratory.

[1] T. K. Allen, George A. Paulikas, and Robert V. Pyle, Instability of a Positive Column in a Magnetic Field [UCRL-9110, March 1960], to be submitted for journal publication.

Plasma Oscillations

The experiment to observe the growth and decay of large-scale electrostatic oscillations in a beam has been completely rebuilt and is in operation again.

Cesium Plasma

A device to produce thermally a highly ionized column of Cs plasma for diffusion and electrostatic-wave-propagation experiments has been constructed but is not yet in operation.

Microwaves

Dielectric-coated-wire waveguides (Goubau lines) are being tested for diagnostics and electrostatic-wave launching. Sixty-mil-diameter aluminum wires, hard-anodized to a depth of 2 mils, are currently being used at 8-mm wavelengths. Such lines have most of their energy concentrated within a wavelength of the guide and, in plasmas that can tolerate them, provide better localized density measurements than does free-space propagation. Much cleaner phase-shift presentation near cutoff densities in a PIG discharge are observed when such a line is used in one leg of the microwave interferometer. Simultaneous density measurements with Langmuir probes are in progress. The losses from this type of line at right-angle bends with radii of curvature of 3 cm are low enough ($\approx$ 2 db) that the signal can be introduced into the PIG radially but transmitted parallel to the magnetic field lines, thus allowing another type of spatial localization not possible with a radiated signal.

The microwave instrumentation of other Sherwood devices is proceeding simultaneously.

HYDROMAGNETIC WAVE AND CYCLOTRON HEATING

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

Much of this quarter has been occupied with the details of plumbing and wiring incidental to the final installation of the ion-cyclotron heating experiment. When the experiment was placed in operation a silicon rectifier supply which provides the magnet current burned out and caused a further delay of several weeks. A replacement has been borrowed from Livermore and installed, and the experiment is now ready to proceed. Microwave interferometer and spectroscopic equipment have been installed to aid in the diagnosis of this experiment.

Theoretical analysis has continued of the hydromagnetic wave experiment. The spatial distributions of the wave quantities, such as induced magnetic field, have been calculated. One of the authors (Alan DeSilva) has passed his qualifying (oral) examination for Ph. D. candidacy and will now devote his full time to extending the hydromagnetic wave observations for his thesis. Equipment necessary for extensive magnetic-probe measurements in the hydromagnetic waveguide has been designed, constructed and installed.

Some work has been started to examine and extend recent results from Bloch[1] in Stockholm, which are related to the limiting velocity of rotation which is encountered in rotating-plasma experiments and elsewhere. This may be related to a crucial assumption required for a theory of the origin of the solar system which was proposed by Alfvén.[2] Hydromagnetic wave propagation can be used as a probe to measure the properties of the rotating plasma.

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[1] H. Alfvén, invited paper, January 1960 meeting of the American Physical Society.

[2] H. Alfvén, On the Origin of the Solar System (Oxford University Press, 1954).

ION MAGNETRON

Robert W. Layman

In the preceding report there is a description of an experiment, called the ring experiment, to measure the cathode power dissipation and ion current as a function of axial position at various magnetic field shapes. This experiment was interrupted by magnet power-supply failure and later by breakdown of the experimental setup. A second experiment was started while repairs were being made, therefore the ring experiment has not yet been resumed.

The second experiment is designed to test the possibility of reducing the loss of circulating ions through charge exchange by ionizing neutrals returning to the discharge region from the wall. To do this a ring filament 7 in. in diameter and made of 60-mil tungsten wire was installed concentric with the anode at the same axial position as the north iron end piece. The electrons from the filament follow along field lines to the opposite end of the machine to be reflected back. Thus an electron screen is inserted between the liner wall and the discharge. A neutral detector, which consists of a 1-in.-wide 7-in.-diameter copper ring equipped with a thermocouple, was placed in the axial center of the machine.

As in the ring experiment, this experiment was interrupted owing to equipment failure. Compensation for thermal expansion of the filament was not sufficient. Several supports broke, shorting out about 99% of the filament. However, even with only a point source of electrons, a 20% increase in neutron counting rate was observed.

The apparatus for both the ring and filament experiments have been repaired. The filament experiment will be completed first and will be fully reported in the next quarterly report.

V. THEORETICAL AND BASIC EXPERIMENTAL PLASMA PHYSICS

ENERGY TRANSFER FROM HOT IONS TO COLD ELECTRONS IN A PLASMA

Warren Heckrotte and John Killeen

The study of the energy transfer from hot ions to cold electrons by means of the numerical solution of the Fokker-Planck equation described in an earlier report[1] has been continued. We have completed the problem proposed in the preceding progress report,[2] i.e., in the beginning we neglect the energy loss of the ions and solve the Fokker-Planck equation for the electron-distribution function, keeping the ion-distribution function fixed in time. The case presented is for deuterons at approximately 200 kev, and the electrons are initially at 10 ev and heat up to 1 kev.

The equation for the electron-distribution function was given in the preceding report.[2] In that equation let

$$f_- = \frac{n_-}{I_2^-(0)\, v_0^3} F_-, \qquad f_+ = \frac{n_+}{I_2^+(0)\, v_0^3} F_+,$$

$x = \frac{v}{v_0}$, where n_+ is the ion density, n_- is the electron density, v_0 is some characteristic speed (a constant determined by the initial mean electron energy), and

$$I_2(t) = \int_0^\infty x^2 F(x,t)\, dx,$$

$$I_2(0) \int_0^\infty x^2 F(x,0) dx.$$

[1] Warren Heckrotte and John Killeen, The Slowing Down of Fast Ions in a Plasma, in Controlled Thermonuclear Research Quarterly Report, UCRL-8887, Sept. 1959, p. 86.

[2] Warren Heckrotte and John Killeen, The Heating Up of Electrons in a Plasma, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 80.

In addition we introduce the new time variable,

$$\tau = \frac{\Gamma e}{2}\left(\frac{n_-}{I_2^-(0)v_0^3}\right) t ,$$

where

$$\Gamma e = \frac{4\pi e^4 \ln\Lambda}{m^2} .$$

With these substitutions, the equations to be solved using the IBM 709 code, DION,[1] are the following:

$$\frac{\partial F_-}{\partial \tau} = \frac{\partial^2 F_-}{\partial x^2}\left[A(F_-, x, \tau) + KA(F_+, x)\right]$$

$$+ \frac{\partial F_-}{\partial x}\left[B(F_-, x, \tau) + KB(F_+, x) + K\,\frac{m-M}{M}\,\frac{2}{x^2}\int_0^x F_+(y)y^2\,dy\right]$$

$$+ 2F_-\left[F_- + K\,\frac{m}{M}\,F_+\right] ,$$

where

$$K = \frac{n_+ I_2^-(0)}{n_- I_2^+(0)} ,$$

$$A(F, x, \tau) = \frac{2}{3}\left[\int_x^{x_J} F(y, \tau)\, y\,dy + \frac{1}{x^3}\int_0^x F(y, \tau)\, y^4 dy\right] .$$

$$B(F, x, \tau) = \frac{4}{3x}\left[\int_x^{x_J} F(y, \tau) y\,dy + \frac{3}{2x}\int_0^x F(y, \tau) y^2 dy - \frac{1}{2x^3}\int_0^x F(y, \tau) y^4 dy\right].$$

The quantity I_2^- is proportional to the electron density and should remain constant. It is calculated at each time step and provides a check on the numerical solution. In addition, for each time step we calculate

$$I_4^- = \int_0^\infty x^4 F_-(x, \tau)\, dx = \int_0^{x_J} x^4 F_-(x, \tau) dx.$$

(The value x_J in the above integrals must be taken large enough so as not to affect the value of I_4^- and I_2^-.) The mean electron energy is given by

$$E_- = \frac{3}{2} k T_- = \frac{1}{2} m v_0^2 \frac{I_4^-}{I_2^-} .$$

The quantity $I_4^-(\tau)$ is then proportional to mean electron energy. In the case presented we let the problem run until I_4^- increased by a factor of about 10^2 over its initial value. If the initial value corresponds to 10 ev then the mean energy when the calculation is stopped is about 1 kev. The electron distribution function, $F_-(x, \tau)$, at a time τ corresponding to this energy gain, is given in Fig. 22. The energy gain given by $I_4^-(\tau)$ is presented in Fig. 23. In the case calculated the initial electron-distribution function was Maxwellian, with mean energy 10 ev. This determines v_0 by the previous equation. The ions are assumed to be all at the same speed, taken to be $3v_0$. This corresponds to a deuteron energy of about 200 kev given by

$$E_+ = \frac{1}{2} M (3v_0)^2 .$$

In this case we have taken $n_+ = n_-$. At any value $I_4^-(\tau_1)$ we can compare the solution $F_-(x, \tau_1)$ with the Maxwellian distribution of the same average energy given by

$$F_M(x, \tau_1) = 4\pi I_2^- \left(\frac{3}{2\pi} \frac{I_2^-}{I_4^-(\tau_1)} \right) e^{-\frac{3}{2} \frac{I_2^-}{I_4^-(\tau_1)} x^2} .$$

In Fig. 22 the corresponding Maxwellian is presented.

We can compare the energy gain $I_4^-(\tau)$ to the gain calculated by using the energy-transfer rates given by Spitzer.[3] From Spitzer we have

$$\frac{dE}{dt} = \frac{1}{\sqrt{2ME_+}} (4\pi e^4 n_- \ln\Lambda) \left(1 + \frac{M}{m}\right) [\phi(x) - x\phi'(x)] ,$$

where

$$x = \frac{3}{2} \sqrt{\frac{m}{M} \frac{E_+}{E_-}}$$

and

$$\phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy .$$

[3] Lyman Spitzer, Physics of Fully Ionized Gases (Interscience Publishers, Inc. New York, 1956) p. 79.

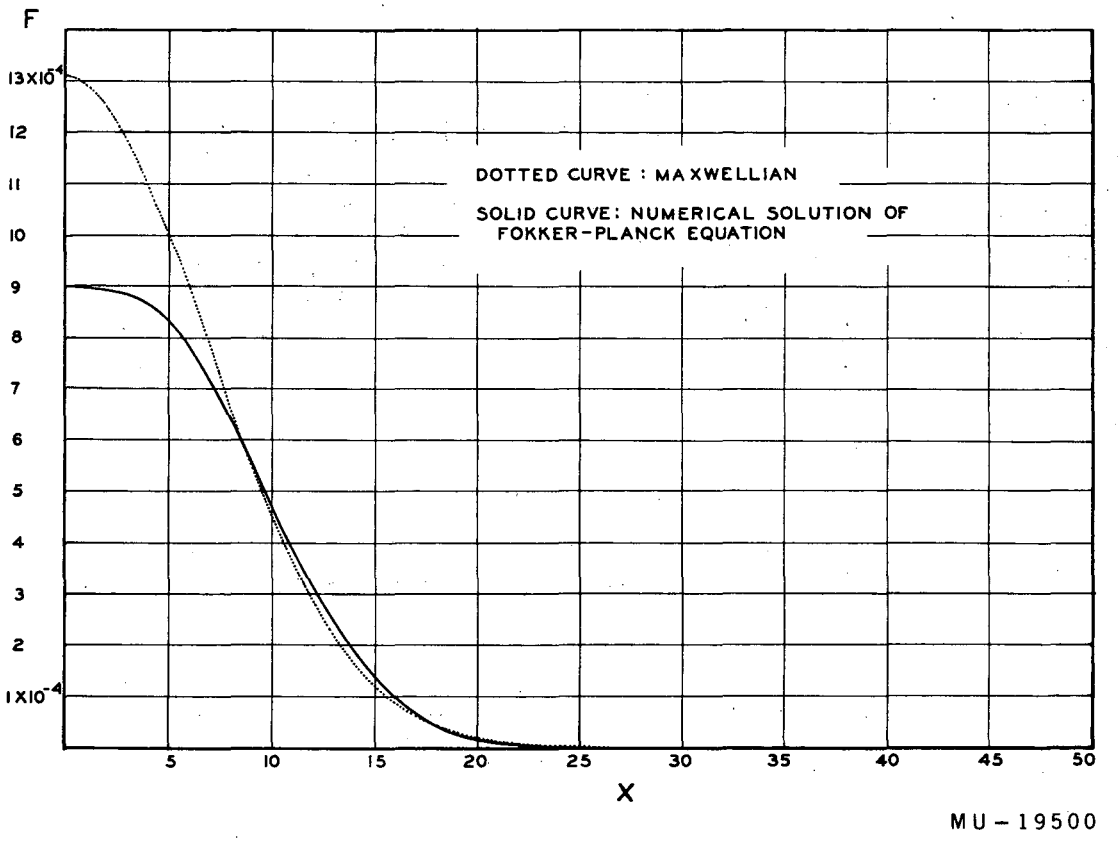

Fig. 22. Electron-distribution function at a time corresponding to an average electron energy of 1 kev.

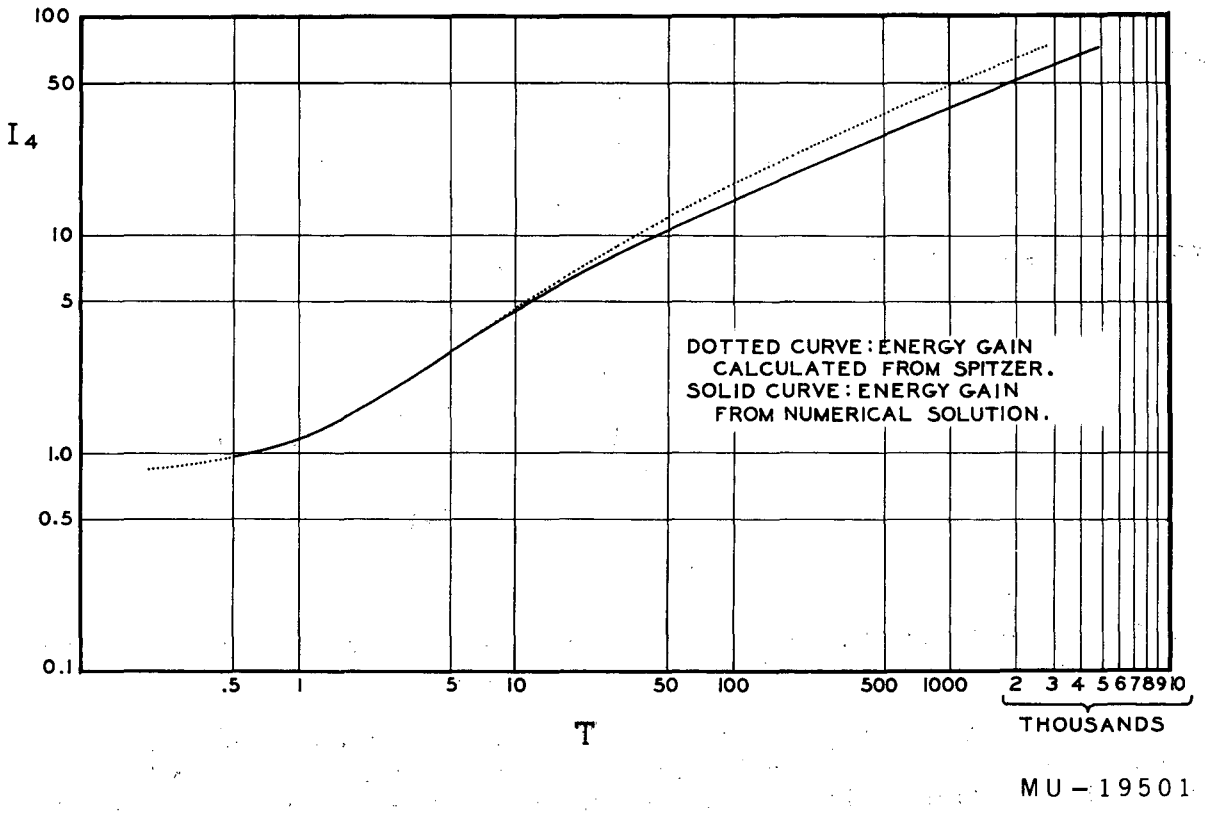

Fig. 23. Average electron energy as a function of time.

In our variables this becomes

$$\frac{dI_4^-}{d\tau} = \frac{4}{3} (I_2^-)^2 \left(\frac{m}{M} + 1\right) [\phi(x) - x\phi'(x)] = P(I_4^-)$$

and

$$x = 3 \sqrt{\frac{3}{2} \frac{I_2^-}{I_4^-}} .$$

We can then calculate

$$\tau(I_4^-) = \int_{I_4^-(0)}^{I_4^-} \frac{dI_4}{\left(\frac{dI_4}{d\tau}\right)} = \int_{I_4^-(0)}^{I_4^-} \frac{dI_4}{P(I_4)} .$$

The $I_4^-(\tau)$ calculated, as above, from the Spitzer transfer rate is compared to the $I_4^-(\tau)$ from the numerical solution in Fig. 23.

It is of interest to note that the time required for the electrons to reach 1 kev differs considerably (by nearly a factor of 2) from the two calculations. This indicates that the energy transfer rate is less than the value predicted by the quasi-equilibrium theory.

The programming of the DION code for the IBM 709 was done by Mr. Garret Boer.

PLASMA BUILD-UP FOR NEUTRAL INJECTION

Warren Heckrotte

The equations for the build-up of a plasma in a mirror machine for neutral and molecular-ion injection are well known and have been rather extensively studied by many people. These considerations have been generalized to take into account the finite Larmor radius of the trapped ion. It is assumed that a trapped ion precesses about the axis of the mirror machine in a time short compared with an e-folding time. Furthermore, any longitudinal spreading or diffusion of the trapped ions across the magnetic field is neglected. The resulting equations are too difficult to solve analytically and make a numerical approach necessary. Even general conclusions are difficult to extract for cases of practical interest. An approximate form of these equations for neutral injection has been solved numerically by Archer H. Futch, in Richard F. Post's group, with the interesting result that an enhanced build-up is realized by virtue of the charge exchange of the trapped ions with the neutral beam (and the finite Larmor radius of the ions). An examination of the build-up equations does tend to confirm this result. Because of the finite size of the beam the charge exchange of the trapped ions with the beam does represent a gain. This is a purely geometrical effect. This is offset to some degree by a diffusion of the trapped ions resulting from the charge exchange with the neutral beam. If the density variations are not too large, then, the net effect will be to enhance the build-up. It is hoped that these conclusions can be made somewhat sharper without recourse to lengthy machine calculations such as undertaken by A. H. Futch.

THEORY OF THE SCATTERING OF CHARGED PARTICLES BY ATOMS

Marvin H. Mittleman

The investigation of the scattering of electrons by atoms is continuing. The theory as set out by Lippman, Mittleman, and Watson[1] has been applied to the high-energy scattering.[2] It is also being applied to low-energy scattering for specific atoms (argon and potassium). This necessitates the use of fast computing machines for the solution of the resultant integro-differential equation. The effect of the Pauli principle has been included and its importance will be investigated.

Hydrogen has been treated as a special case.[3] The elastic scattering of slow electrons is being treated by numerical methods similar to those mentioned above. Excitation scattering will be possible once the elastic-scattering wave functions are obtained. This is contemplated.

The scattering of protons by atomic hydrogen is being investigated with consideration of all the various final states. The exchange scattering to the metastable 2s state has been proposed as a new and interesting experiment. The high-energy (Born-approximation) calculation of this and similar cross sections has been performed. This leads to a slightly different theoretical interpretation of the existing experiments by Fite, and may make for an agreement between Born approximation and experiment at energies lower than approximately 250 kev, which is the lower limit now.

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[1] Bernard A. Lippman, Marvin H. Mittleman, and Kenneth M. Watson, The Scattering of Electrons by Neutral Atoms, UCRL-8774, May 1959.

[2] Marvin H. Mittleman and Kenneth M. Watson, Effects of the Pauli Principle on the Scattering of Electrons by Atoms at High Energies, UCRL-8976, Nov. 1959.

[3] Marvin H. Mittleman, The Scattering of Electrons by Atomic Hydrogen, UCRL-5711, Dec. 1959.

MAGNETIC SHOCKS

Stanley A. Zwick

The collision-free, plane magnetic shock is being studied from a microscopic (kinetic-theory) point of view, with the objective of learning about the possible structure of such a shock.

A pure magnetic shock in a plasma differs from an ordinary shock, in that the change in conditions across the front is assumed due to a coupling between the magnetic field and electric currents in the plasma, rather than to the effect of collisions between plasma particles. To make sure the assumption will apply, one excludes particle interactions, as such, from the mathematical model. However, there is as yet no clear evidence that the resulting model will actually lead to a shock-type transition; or if it does, that the transition will have any constant identifying characteristics. Finally, if in theory a steady-state magnetic shock could exist, there is the question of what collisions might do to disrupt the picture.

It is hoped that by a suitable extension of the adiabatic approach, or by the use of iterative techniques, it will be possible to arrive at some significant conclusions.

STABILITY CALCULATION FOR A DIFFUSE LINEAR PINCH

Donald P. Geesaman

A numerical calculation was recently initiated based on William A. Newcomb's hydromagnetic stability criteria for a diffuse linear pinch.[1] Following a suggestion of Harold P. Furth, field configurations were taken to satisfy the condition

$$B \cdot j = 0,$$

or equivalently

$$rB_\theta = \lambda B_z ;$$

and the pressure gradient was tentatively represented by

$$\frac{dP}{dr} = \begin{cases} A & \text{for } a < r < 1, \\ -\frac{\ell}{2r}\left(\frac{r^2+\lambda^2}{1+\lambda^2}\right)^{\ell/2} & \text{for } 1 < r < b. \end{cases}$$

Work is currently in progress to determine the relationship of the parameters λ, ℓ, A, a, and b to the stability of the system.

[1] William Newcomb, Hydromagnetic Stability of a Diffuse Linear Pinch, UCRL-5447, Aug. 1959.

HYDROMAGNETIC STABILITY OF A TUBULAR PINCH

William A. Newcomb

The stability analysis of a tubular pinch, which was described in the last quarterly report (UCRL-9002, p. 25), has now been completed. The virtual displacements are divided into two categories, Type I and Type II, according as they are continuous or discontinuous across the current layer. Type I stability was discussed in UCRL-9002, and the Type II criterion has the form

$$P_{min}(\phi, \phi_i, \alpha_i) < P < P_{max}(\phi, \phi_e, \alpha_e), \qquad (1)$$

where P is the plasma pressure at any given point in the current layer, ϕ is the angle between the magnetic field and the z axis at that same point, ϕ_i and ϕ_e are the values of ϕ at the inner and outer edges of the layer, α_i is the radius of the inner conductor in units of the layer radius, and α_e is the radius of the outer wall in the same units. The necessary and sufficient condition for Type II stability is that this inequality should be satisfied at every point in the layer. Taking $B^2/2$, the magnetic pressure holding the layer together, as the unit of pressure, we have plotted the functions P_{min} and P_{max} in Fig. 24 for two representative pinch configurations, both of which are Type I stable. The stability criterion is that the pressure profile should stay out of the shaded regions, with the vertical line-segment counting as a shaded region. (Attention is restricted to values of P less than unity, since any higher values would be incompatible with static equilibrium.) Note that stability is more easily achieved when ϕ_e is small, in which case the field in the outer region is mostly axial. It is also desirable that ϕ_i be in the same quadrant as ϕ_e, so that ϕ will never go through $\pi/2$; there is a special instability at $\phi = \pi/2$, and P_{min} is positive near the inner edge if $\phi_i > \pi/2$.

The columnar pinch, in which there is no axial conductor and in which the plasma occupies the entire region interior to the current layer instead of being restricted to the current layer itself, has also been analyzed. The Type II stability criterion has the form

$$P_{min}(\phi, P_i) < P < P_{max}(\phi, \phi_e, \alpha_e), \qquad (2)$$

where P_i is the plasma pressure in the column and P_{max} is the same as in (1). This criterion is plotted in Fig. 25 for a representative case.

The general conclusion is that the tubular pinch is easier to stabilize than the columnar pinch for the following reasons:

(1) Any pinch is stable if $|rB_\theta|$ is a decreasing function of r, but this condition cannot be satisfied in a columnar pinch.

(2) A columnar pinch is always unstable for Type I displacements if α_e is larger than a certain critical value, although stable tubular pinches exist even with $\alpha_i = 0$, $\alpha_e = \infty$. This means that the stabilizing effect of a conducting wall is indispensable in a columnar pinch, and that there is a definite limit on the compression of the plasma column, since the compression ratio is equal to α_e^2.

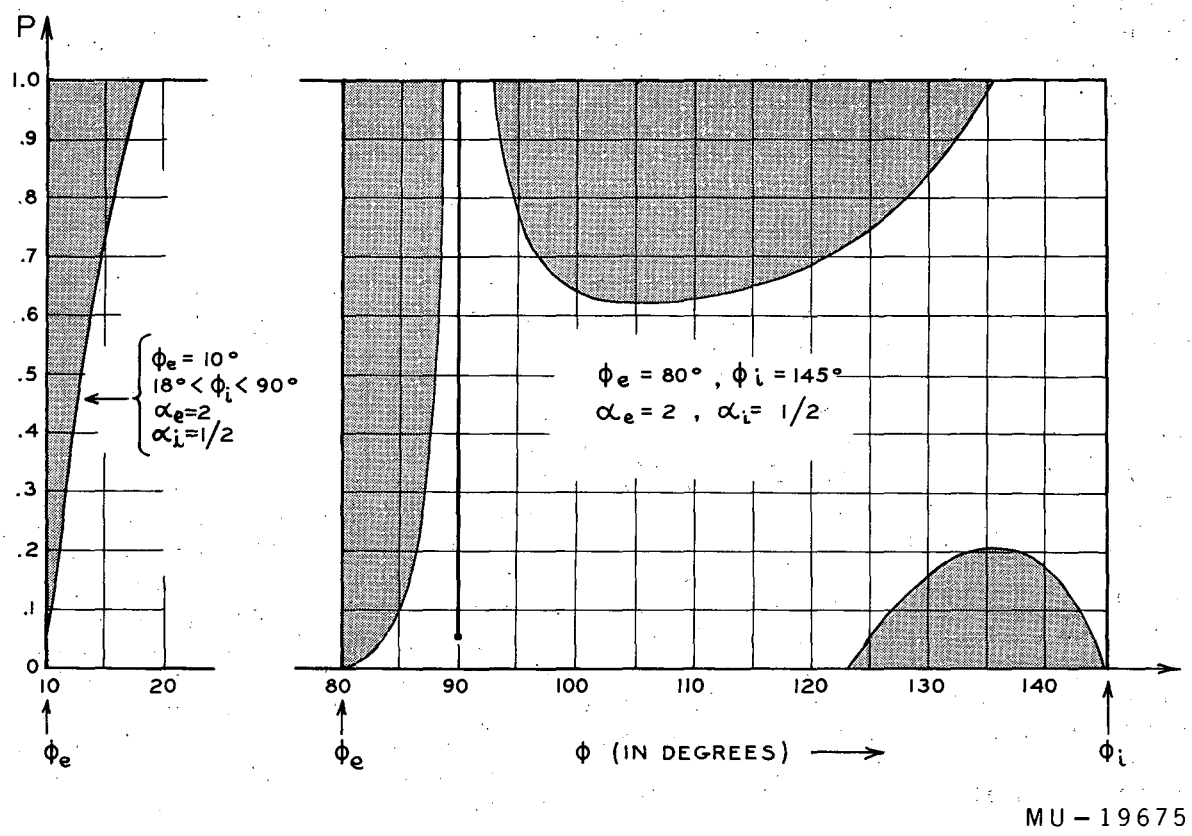

Fig. 24. Maximum and minimum pressures for two illustrative tubular pinch configurations.

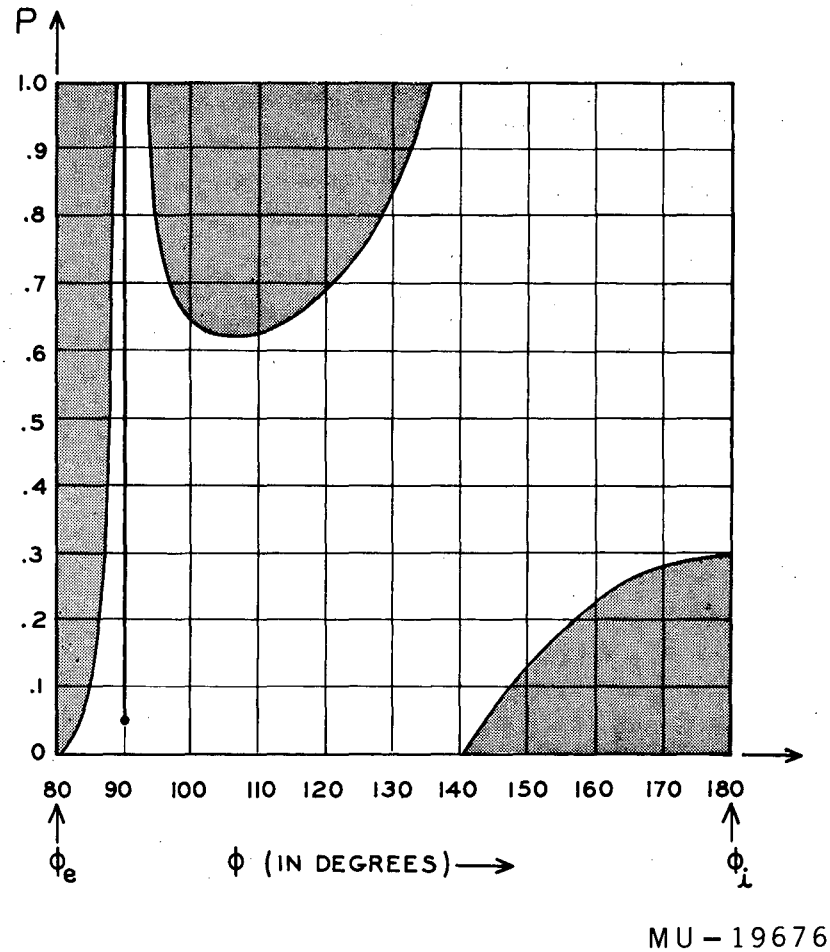

Fig. 25. Maximum and minimum pressures for a columnar pinch with $P_i = 0.3$, $\phi_e = 80^o$, and $\alpha_e = 2$.

(3) Type I stability of a columnar pinch requires a large value of ϕ_e, which we have seen to be unfavorable for Type II stability. In a tubular pinch, on the other hand, small values of ϕ_e are favorable for both types of stability.

(4) There exists a tubular configuration (i. e., $\phi_e = 0 < \phi_i < \pi/2$) in which $P_{min} < 0$ and $P_{max} > 1$ at every point; this configuration is stable for all attainable values of P. But in every columnar pinch there are points where $P_{min} > 0$ and points where $P_{max} < 1$. (The limiting case $\phi_e = 0$, where $P_{max} > 1$ at every point, cannot be approached without violating the Type I stability condition.)

(5) In a columnar pinch there must always be a point in the layer where $B_z = 0$ ($\phi = \pi/2$); otherwise P_{max} will be negative near the outer edge. This point, as is clear from Fig. 25, has an especially small P_{max}. We have seen, however, that there need not be any such point in a tubular pinch.

The work summarized here will be presented in detail elsewhere.[1]

[1] William A. Newcomb and Allan N. Kaufman, UCRL-5434 (in preparation).

SPACE-CHARGE EFFECTS IN A BEAM NEUTRALIZER

C. H. Woods

Molecular ions created in a gas-type neutralizer for proton or deuteron beams represent a space charge, and together with the original protons or deuterons produce a transverse electrostatic field. This field helps to accelerate the ions to the wall, but also scatters the original beam. Recombination can play a major role in the process if a thin plasma is present, and can reduce or even eliminate the space charge that would otherwise ultimately accumulate. However, it is important to understand what will happen if electrons are not carried inward from the wall at a sufficient rate to make recombination effective, and a calculation based on this assumption has been carried out in a separate paper[1] to determine the self-consistent field of the positively charged particles involved and the angle of scattering which it produces.

The results have been applied to a particular numerical example in which 20-kev protons are neutralized in a hydrogen-gas neutralizer 3×10 cm in cross section and 50 cm long. The result is that, for 20 ma of proton current being neutralized, the maximum scattering angle α is 0.12 radian, and the potential at the center of the neutralizer is 37.5 volts, which is 2.6 times the potential that would be caused by the proton beam if the neutralizer were not present. The scattering angle and potential are proportional to the beam current, so that for 200 ma the angle would be 1.2 radians and the potential 375 v. The distribution of scattering angle among the protons is triangular in shape, as shown in Fig. 26, so that three-quarters of the protons are scattered less than $\alpha/2$ radian.

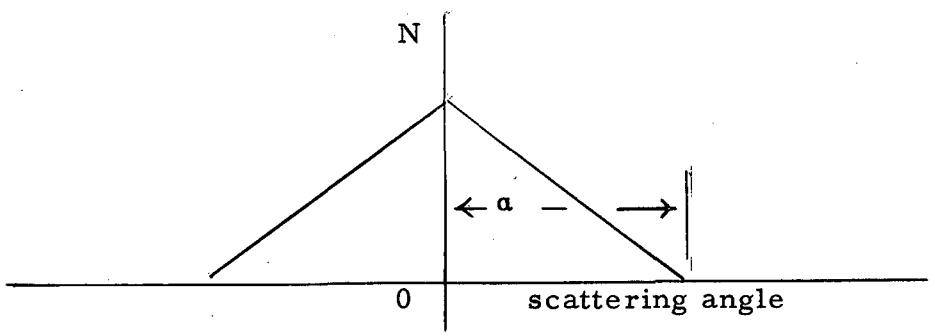

Fig. 26. Distribution of scattering angle.

The term scattering rather than deflection is used because the effect includes the randomness of where along the neutralizer a proton is converted to a neutral atom, and the effect cannot be corrected by electric or magnetic focusing devices. Laminar flow becomes nonlaminar on passing through the neutralizer.

[1] C. H. Woods, Space-Charge Effects in a Beam Neutralizer, UCRL-5902-T, March 1960.

THE BUMPY TORUS

Gordon Gibson,* Willard C. Jordan,† and Eugene J. Lauer

Single-particle motion in the Bumpy Torus has been discussed in earlier reports.[1, 2] These reports presented the results of machine calculations of the action integrals and magnetic fields for the case of N (number of coils) = 16 and R/r (ratio of major to minor radius) = 5.44.

Figure 27 presents some calculations for N = 4×16 or 64 and R/r = 4×5.44 or 21.76. As expected, the new curves are more nearly "axially" symmetric than the old. This tends to decrease the rate of loss of particles due to the diffusion process previously described.[1] More than three sudden 45-deg changes of direction would be required for a particle starting at $\rho = R$ to diffuse onto a J, μ surface which passes through a region in which the field is 1/3 of the maximum value in the median plane. Hence it is expected that the mean time for this diffusion would be approximately 3^2 or 9 times as long as would be required for a single 45-deg change of direction.

*Westinghouse Electric Corp.

†Bendix Aviation Corp.

[1] Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, in Controlled Thermonuclear Research Quarterly Report, UCRL-8887, Sept. 1959, p. 32.

[2] Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, The Bumpy Torus, UCRL-5738, Oct. 1959.

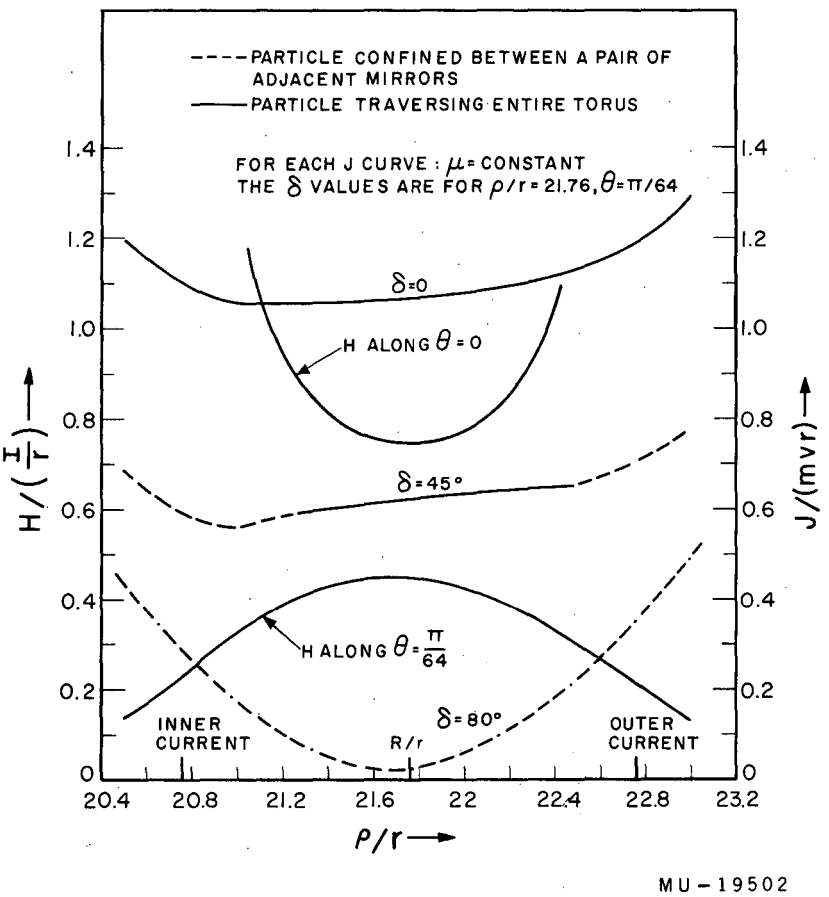

Fig. 27. Adiabatic invariants in the median plane and field magnitudes in the median plane and in the plane of a coil for a Bumpy Torus with N = 64 and R/r = 21.76.

CONTAINMENT TIME OF POSITRONS IN A MIRROR MACHINE

Gordon Gibson,* Willard C. Jordan,† and Eugene J. Lauer

In previous progress reports experimental containment times (e-fold) were given as a function of the type of scattering gas, the gas pressure, the energy of the escaping positrons, and the strength of the magnetic field. The results were compared to theory and agreed to within a factor of 2.5. This agreement is as good as could be expected for our simplified theoretical model; however, a disturbing fact is the dependence of the observed containment times on the positron energy. It was observed that positrons escaping with a kinetic energy of 1/2 Mev had a longer "containment time" than those escaping at 1 Mev. Since the scattering cross section decreases with increasing energy this result is unexpected. The discrepancy is largest for Ne (the scattering gas having the smallest nuclear charge).

However, under the assumption of adiabatic behavior, the effects of energy degradation on the energy distribution of the trapped positrons have been studied theoretically. This was studied earlier[1] for the steady-state situation in order that the bias curves could be properly normalized. It was found that the energy distribution of trapped particles was dependent on the mirror bias and the z of the scattering gas, but independent of the scattering-gas pressure p, since the containment time varies as 1/p and the rate of energy loss varies as p. This calculation has been improved by taking into account the counter resolution, and also extended to determine the effects on the time-analysis experiment. Theoretical results have been obtained for various positron energies and neon scattering gas for a single bias of the magnetic mirrors. It is found that the energy-degradation effect removes the discrepancy of the energy dependence of the observed containment times. The theory also provides a correction to the intercept (a measure of the fraction of the positrons trapped[2]) at time zero of the "exponential" decay curves. A code is being debugged which will give the correction factors for all z and all bias values of interest.

Much experimental equilibrium and time-analysis data have been obtained as a function of mirror bias for various scattering gases (Ne, A, Kr, Xe). These data will be presented in a future progress report along with the theoretical corrections.

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*Westinghouse Electric Corp.

†Bendix Aviation Corp.

[1]Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, in Controlled Thermonuclear Research Quarterly Report UCRL-8775, Sept. 1959, p. 20.

[2]Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, in Controlled Thermonuclear Research Quarterly Report, UCRL-9002, Dec. 1959, p. 21.

ATOMIC-BEAM AND MOLECULAR-BEAM RESEARCH

Gilbert O. Brink

The vacuum system for the crossed-beam machine has been completed and is undergoing vacuum tests. The best vacuum that has been obtained to date is 1.5×10^{-6} mm of Hg. This is adequate for beam work, but further modifications are being considered which should improve the ultimate vacuum and pumping speed. The system does not have any measurable leaks and the above pressure seems to be the base pressure with the present pumps. At present one of the mercury diffusion pumps is being modified to incorporate refrigerated coils, in order to see if this will improve the ultimate vacuum.

The oven support and chopping wheel are being assembled and appear to be satisfactory. The electronic detection system is being tested and steps are being taken to optimize its performance.

During the last quarter a time-of-flight mass spectrometer of the type described by Wiley and McLaren[1] has been constructed and tested. It appears to be very satisfactory for a crossed-beam experiment. It is capable of resolving adjacent mass numbers up through mass 40; the resolution falls off above that. Its transmission seems to be quite high, especially if focusing electrodes are placed inside the drift tube. The spectrometer is now being redesigned in a form that can be used in the crossed-beam machine.

Some thought has been given to the design of an experiment to measure the absolute value of the cross section for production of positive ions by electrons on hydrogen molecules. Although this cross section has been measured before, it is of interest to measure it again by a crossed-beam technique. This will probably be the first experiment attempted with the crossed-beam machine.

[1] W. C. Wiley and I. H. McLaren, Rev. Sci. Instr. 26, 1150 (1955).

VI. ENGINEERING AND TECHNOLOGICAL DEVELOPMENT

ULTRAHIGH-VACUUM DEVEOPMENT

Norman Milleron and Leonard L. Levenson

Introduction

Pursuing our goal reviewed last quarter, we worked on:

(a) reducing oil backstreaming,
(b) measuring trapping efficiency of 13x zeolite in an elbow,
(c) motion seals through rubber "O" rings trapped by activated alumina,
(d) conductance measurements.

Results

Oil Backstreaming

To recapitulate, we are trying to eliminate the need for a water baffle (UCRL-9002, p. 115).

Two oil pumps were tested. The first, type H-10P, 10-1/2-in. i. d., made by NRC, using Narcoil-40, is now deemed satisfactory. That is, oil collected on a Plexiglass cover plate over the pump mouth at 15°C can be evaporated, thus rendering the cover dry, at 23°C. The second pump, type PMC720, made by CVC, using Octoil "S" is still being worked on.

Hugh Smith of this Laboratory measured approximately 8% decrease in pumping speed for the PMC720 without its top jet. Previously we noted much of the oil backstreaming from the PMC was from a source other than the top jet. Relying on Smith's results, we removed the first PMC jet, heated and covered the second jet, and observed a great reduction in backstreaming rate; however, too much oil still was backstreaming. We are now testing to see if the second jet stream is rebounding from the third jet surface.

Trapping Efficiency of Zeolite

Artificial zeolite, type 13x, retained by a wire mesh in an elbow trap, has been described.[1] Tests so far are inconclusive, but it is worth noting that:

(a) the ion gauge reading rose to a plateau at 1 to 2×10^{-8} mm Hg in 4 months:
(b) the gauge filament was left "off" for 30 days and pressure recovered to 1 to 2×10^{-8} without outgassing the gauge.

[1] N. Milleron and L. Levenson, in Controlled Thermonuclear Research Quarterly Report, UCRL-8775, June 1959, p. 80.

Motion Seals

Liquid metal seals are tricky. Perhaps activated alumina can be used as a trap between a clean system and a rubber seal running in Octoil S. Four such O-ring seals are nearly ready for testing.

Conductance Measurements

Conductance measurements have been made on many geometries since an earlier Quarterly report.[1] A summary of results is presented in Chart I. The theoretical values of P were calculated by Donald H. Davis.[2]

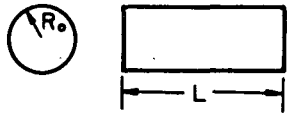
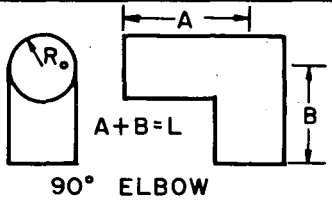
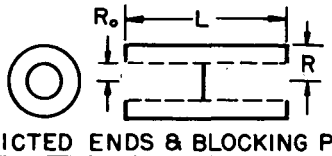
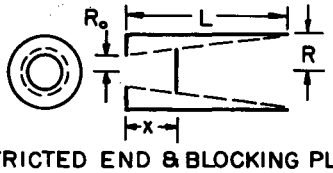
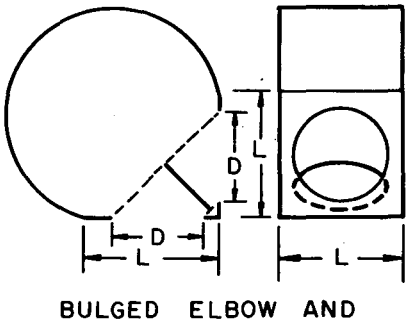
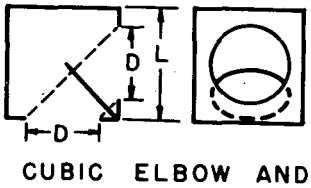
The conductance F of any geometry is given by

$$F = P\,F_0,$$

where F_0 is the conductance (in liters/sec) of the orifice to which P applies when the obstructing baffle system is removed.

Figures 28 and 29 illustrate the possible practical applications of some of these geometries.

[2] Donald H. Davis, A Monte Carlo Calculation of Molecular Flow Rates Through a Cylindrical Elbow and Pipes of Other Shapes [UCRL-5821-T] J. Appl. Phys. (to be published).

GEOMETRY	L/R_o	EXPERIMENTAL P		THEORETICAL P
 STRAIGHT CYLINDER	0.993	0.70		0.69
	2.05	0.52		0.51
	2.38	0.45		0.47
	3.75	0.37		0.37
	4.84	0.31		0.32
	6.05	0.27		0.28
 A+B=L 90° ELBOW	2.19	0.52		0.51
	3.06	0.42		0.42
	4.06	0.34		0.36
	4.88	0.31		0.32
	5.88	0.27		0.27
 RESTRICTED ENDS & BLOCKING PLATE	2	$\frac{R}{R_o}=1.5$	P=0.38	0.39
	3	$\frac{R}{R_o}=1.5$	P=0.38	0.39
 ONE RESTRICTED END & BLOCKING PLATE	2.0	$\frac{x}{L}=0.16$	P=0.29	0.35
	2.0	$\frac{x}{L}=0.27$	P=0.33	0.38
	2.0	$\frac{x}{L}=0.31$	P=0.35	0.38
	2.0	$\frac{x}{L}=0.60$	P=0.29 SMALL END	0.30 SMALL END
	L/D			
 BULGED ELBOW AND ELLIPTICAL BLOCKING PLATE	1.0	0.45		—
	1.5	0.40		—
	2.0	0.32		—
 CUBIC ELBOW AND CIRCULAR BLOCKING PLATE	1.5	0.38		—

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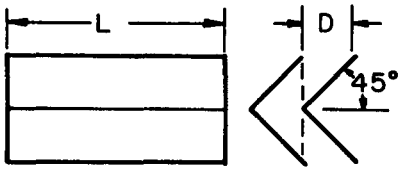
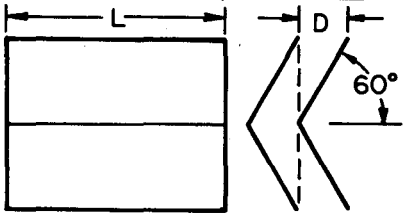
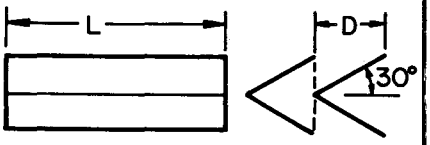
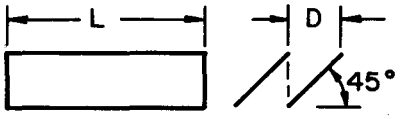
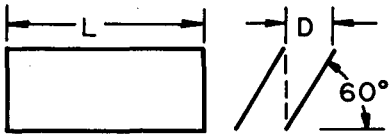
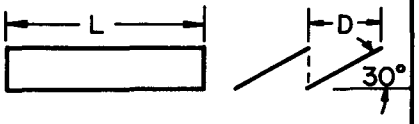
GEOMETRY	L/D	EXPERIMENTAL P	THEORETICAL P
 45° CHEVRON	1.0	—	0.19
	3.77	0.17	—
	5.0	—	0.23
	11.3	0.19	—
	∞	—	0.25
 60° CHEVRON	1.0	—	0.19
	4.61	0.20	—
	5.0	—	0.26
	∞	—	0.28
 30° CHEVRON	1.0		0.16
	2.67	0.13	
	5.0		0.19
	∞		0.19
 45° LOUVER	3.77	0.39	—
	11.3	0.40	—
 60° LOUVER	4.61	0.41	—
 30° LOUVER	2.67	0.26	—

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Chart I. Geometrical factors for molecular flow.

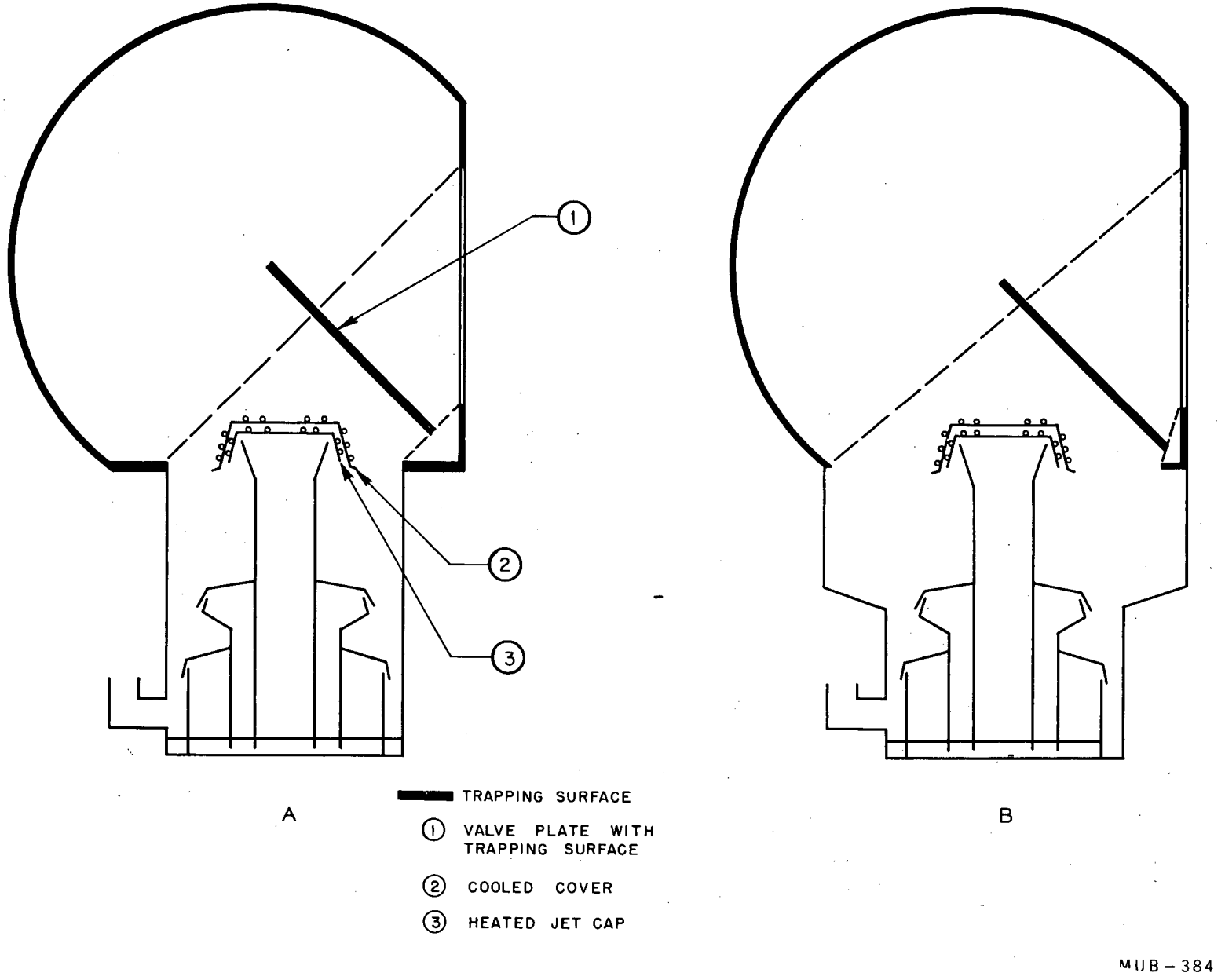


Fig. 28. Possible schemes for pumping on vertical orifice.

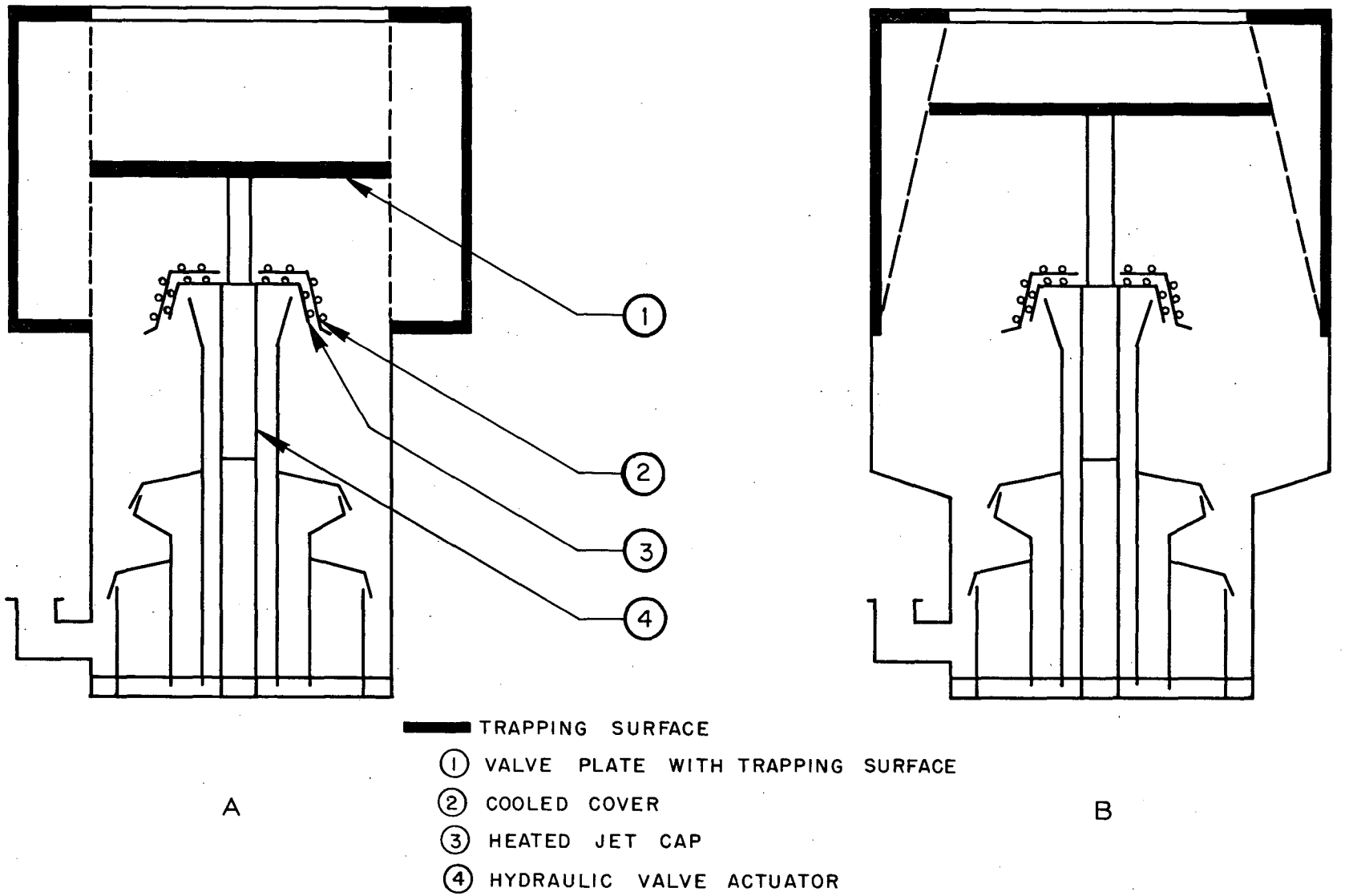


Fig. 29. Possible schemes for pumping on horizontal orifice.

MECHANICAL ENGINEERING DEVELOPMENT

Thomas H. Batzer

Beta-Ray Experiment

J. Ralph Ullman

An yttrium probe assembly, Part No. 8NL8814, has been designed to investigate high-density-electron containment times.

P-4 Probe Rotator

J. Ralph Ullman

The probe rotator has been assembled. Preliminary tests indicate that the maximum speed approaches the 1800 rpm specified. However, the differentially pumped teflon labyrinth seal drags, to the extent of overheating the drive motor. The seal components are being modified to reduce this drag and the result should be a usable probe. The seal has held pressure in the range of 10^{-7} mm Hg with the probe rotating and static.

Hard-Core Torus

Raymond E. Keyes

The attempt to substitute a Kanigen nickel plate in place of the Inconel "X" liner in the hard-core torus (see Fig. 30) has been abandoned. A trial run using the Kanigen nickel plating on a 2-ft-long linear mock-up showed that the porosity of the nickel plating made it impossible to attain suitable vacuum.

Four of the six 60-deg elbow sections of the 0.007-in.-thick corrugated liner are complete with ports. Two more 60-deg sections will complete the first assembly. The first of two assemblies is scheduled for March 1 completion. Figure 31 shows a linear corrugated tube set up in the bending fixture. Figure 32 shows the elbow after bending. Note the small buckling dimples on the corrugation peaks at the outer periphery. Masonite diaphragms rimmed with insulated cable and mating with the inside of each corrugation proved successful in preventing the dimpling. In Fig. 32, two corrugations on the left side were cable-reinforced and show no dimples after the bending.

Figure 33 shows a jig for checking the elbows and final 180-deg assemblies. The elbow section came out a little long on the inner periphery. This will be remedied by pinching the corrugations with a special tool.

The vendor made a mock-up of the weld connection joining the elbow sections. The joint proved acceptable without need for prior stress relieving. Generally, for Inconel "X", stress relieving is recommended before welding of parts that have been cold-worked.

The top and bottom 20-turn θ coils have been fabricated on the copper shell halves.

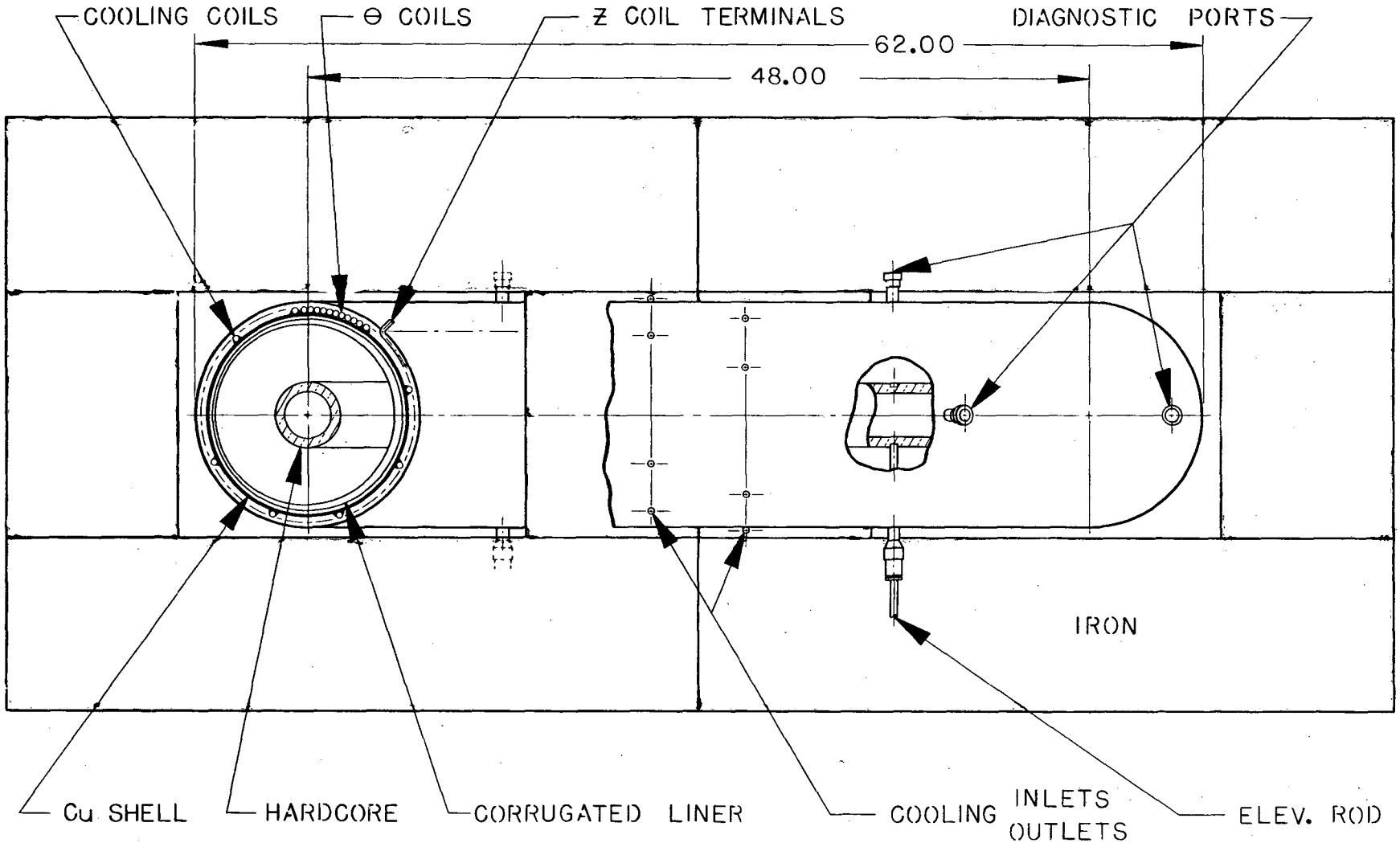
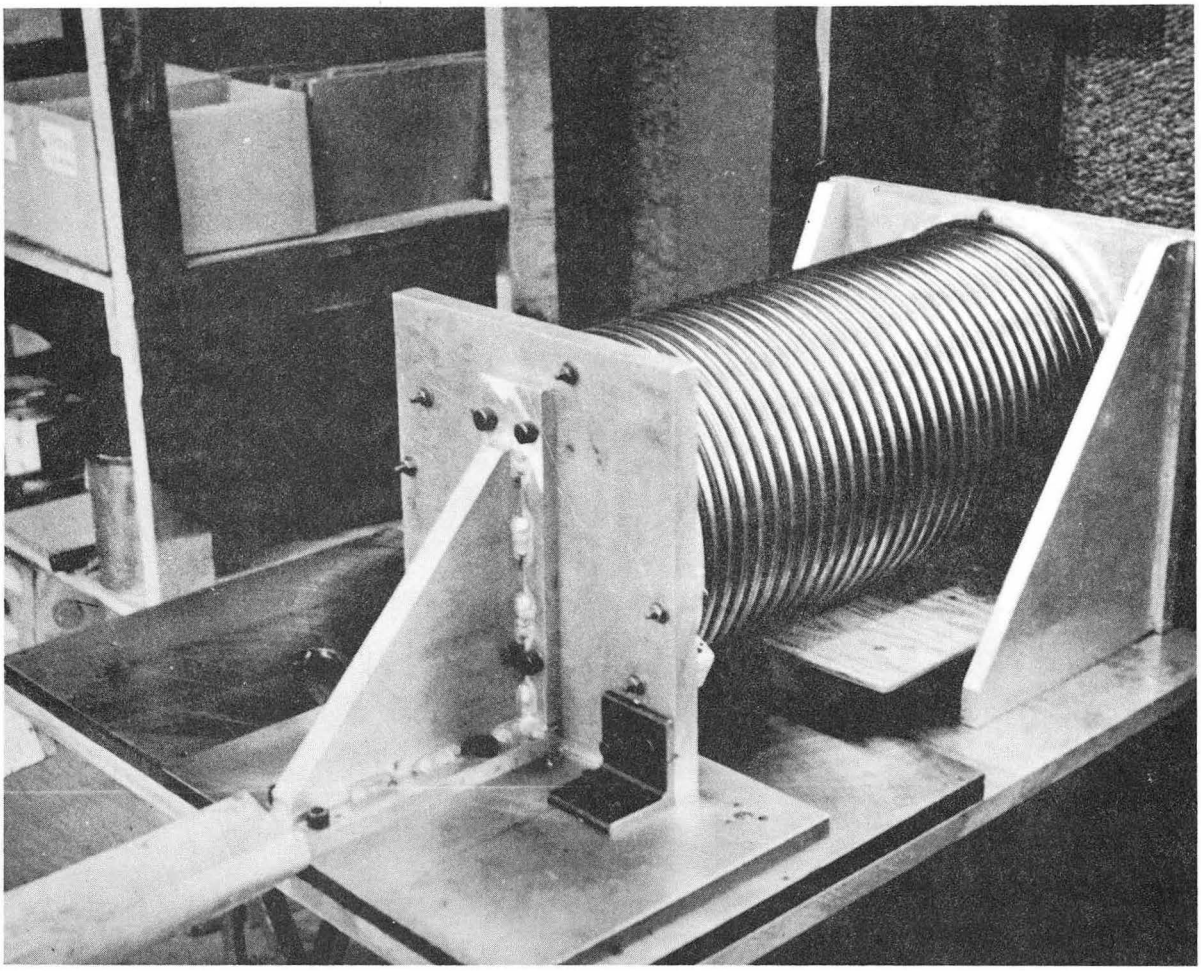
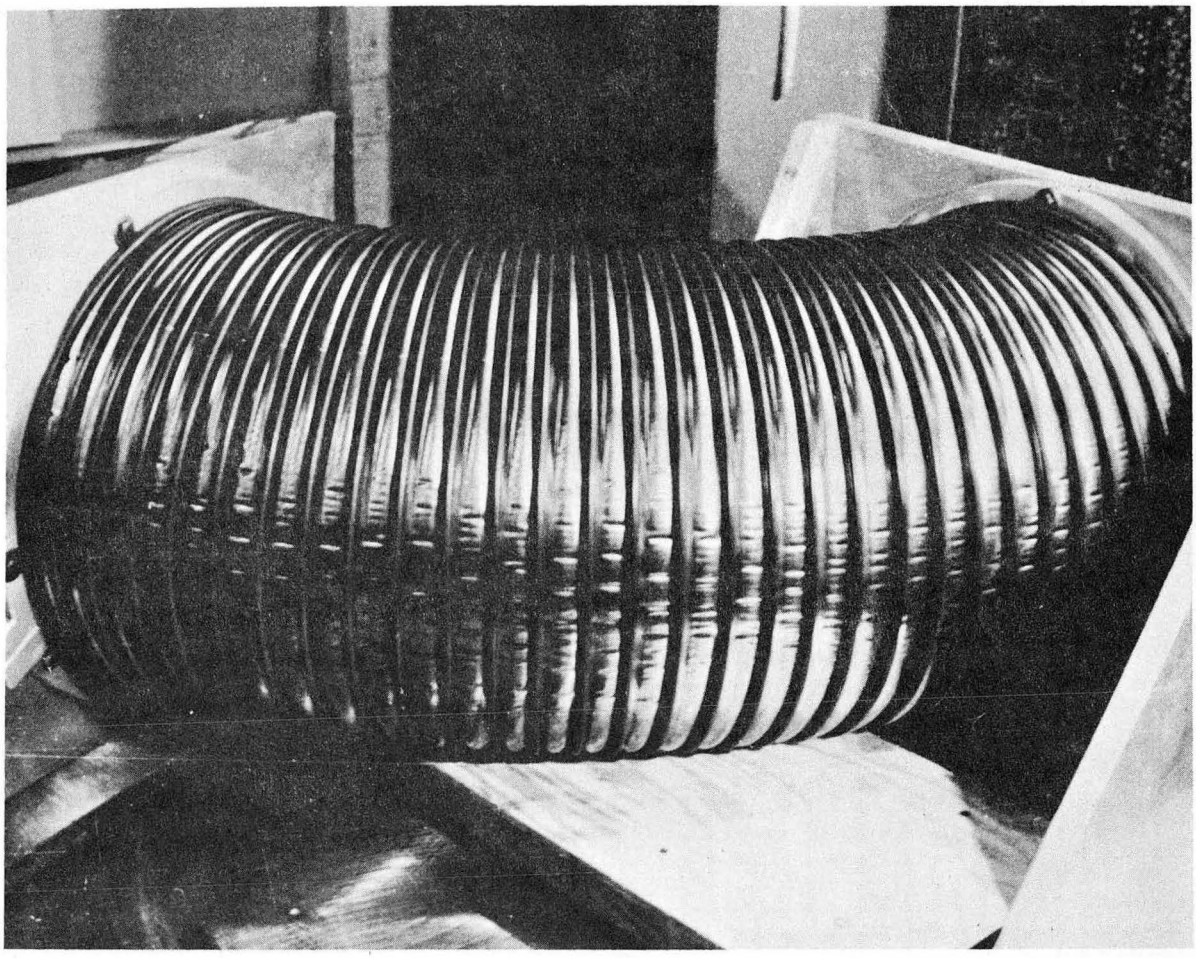


Fig. 30. Levitron.



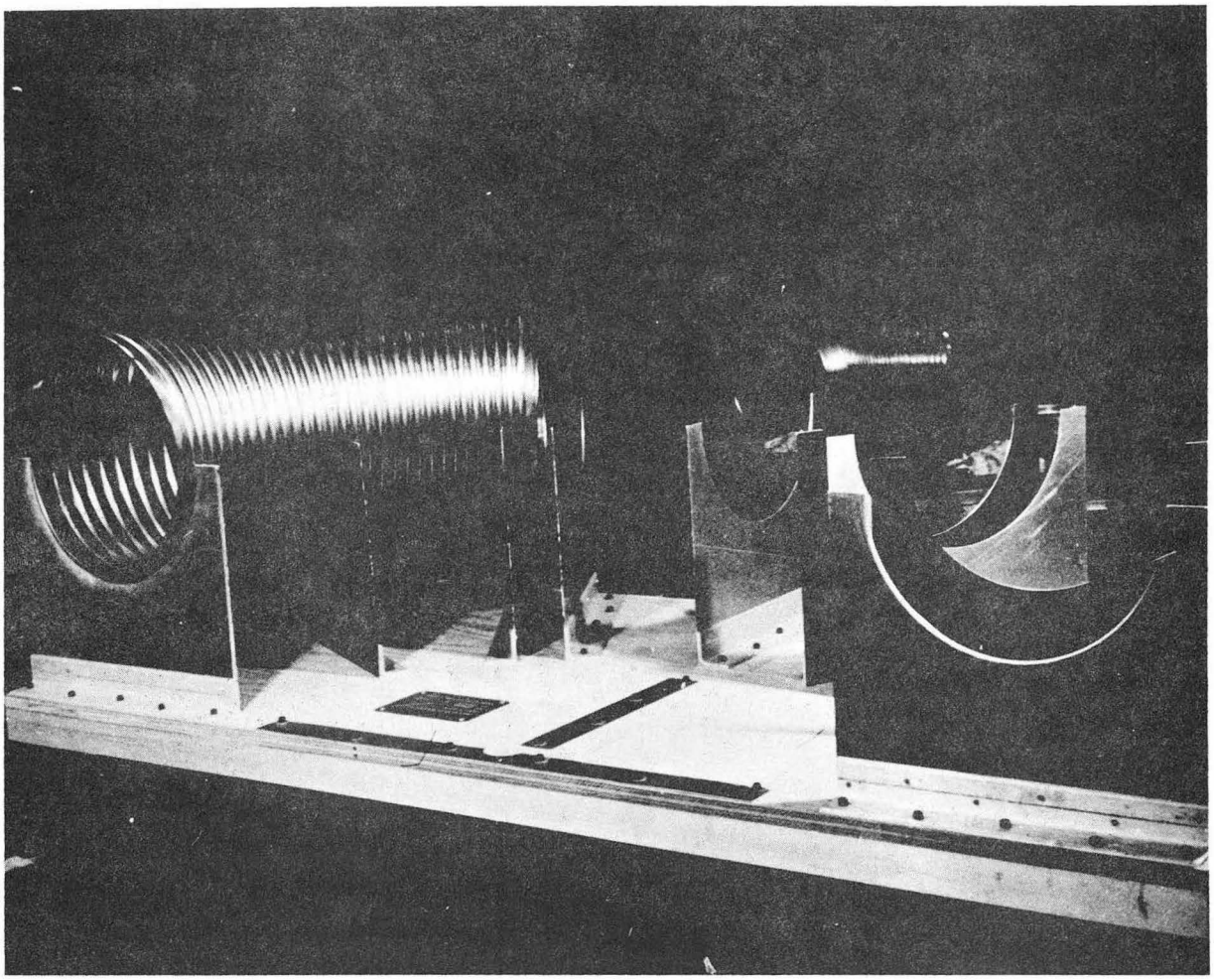
ZN-2349

Fig. 31. Linear corrugated tube set up in the bending fixture.



ZN-2351

Fig. 32. Elbow after bending.



ZN-2348

Fig. 33. A jig for checking the elbow.

A mechanical means of back-up for the electromagnetic levitation of the core is being studied and developed. The basic scheme is for four elevator rods to support the core. The four are to be triggered simultaneously by pulsed coils. Each is to be withdrawn pneumatically from inside the liner and returned to catch the core at a position 1 cm lower. The pinch is to be executed while the rods are in dwell position. Experience with a fast-acting pneumatic switch confirms the feasibility of this approach.

A Klunker switch for the electromagnetic levitating circuit is being developed jointly with Electronics Engineering. It is a pneumatically operated switch triggered by a pulsed coil. A contact attached to a diaphragm is held closed by air pressure on the top side. The pulsing coil lifts the contact from the bottom side. The contact is also a shut-off valve. When lifted, it opens the low-pressure side of the diaphragm to high-pressure air reservoir. The throttling-control setting on the inlet and another leak-off control are intended to provide the desired cycling time for the switch.

Toy Top

John R. Benapfl

A new three-stage compression experiment, which is tentatively scheduled to be in operation by April 1, is under construction. Most of the structural parts and vacuum-system components have been fabricated.

The peculiar shape of the pulsed coils has necessitated a departure from the conventional epon-and-glass methods of fabrication. Instead, the single-turn coils will be mechanically held together by bolts through the current feed tabs and strengthened by metal rims around their peripheries. Electrical insulation will be provided by a 0.030-in. -thick coat of nylon. Techniques for applying this nylon coat are now being worked out and the results so far indicate its feasibility.

Figure 34 shows a cutaway view of a plasma generator currently being used at Los Alamos and also being evaluated by the Toy Top group. The plunger of the air cylinder (1) is connected to a pawl (5) which engages the hammer (4). The hammer moves along the valve stem (2) until the pawl is tripped by the release (6). The hammer is then accelerated by the accelerating spring (9) and strikes the anvil (3). A compression wave is set up which lifts the valve off the seat (17). The seating spring (8) provides approximately 200 pounds closing force. Deuterium gas is fed into the tube (7) through the storage chamber and into the 1-cc volume in the tip of the valve stem. After the gas is released through the port (16) a voltage is applied between the inner electrode (13) and outer electrode (14), ionizing the gas.

The hammer and anvil are electrically insulated; however, when the blow is struck their contact initiates a time delay of from 400 to 700 μsec before 20 kv stored in two 15-μf capacitors is applied to the electrodes. The valve itself opens 150 μsec after contact. Gas pressure in the valve tip ranges between 1/2 and 1 atmosphere.

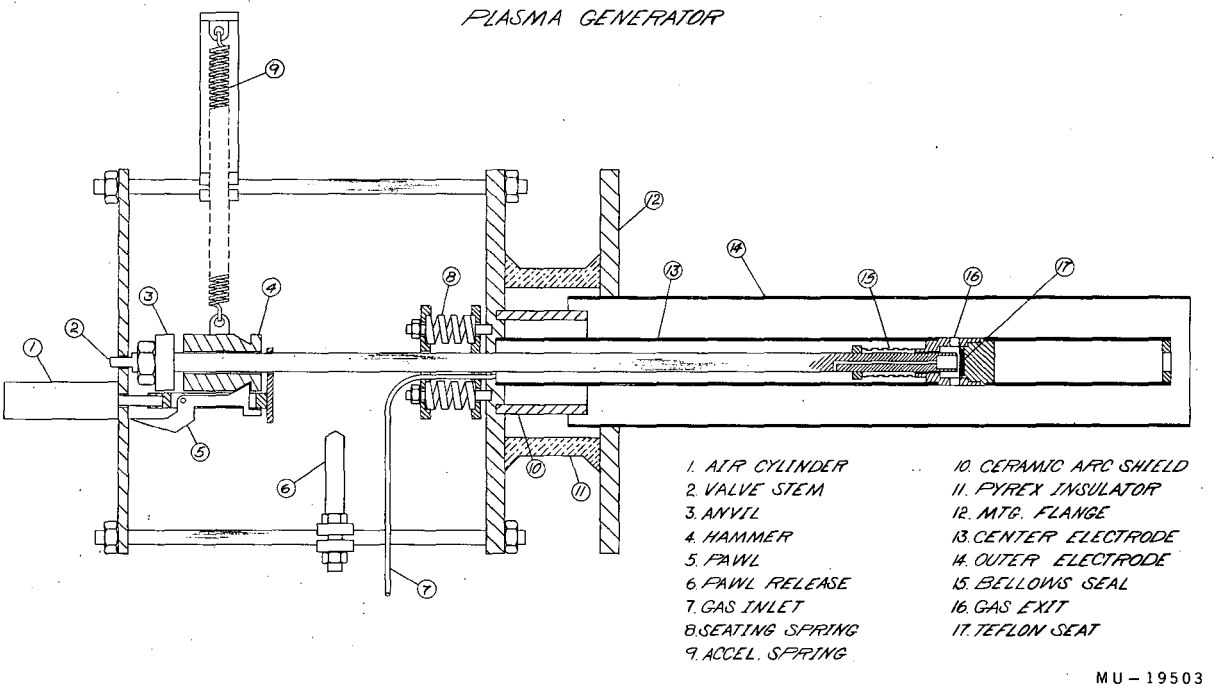


Fig. 34. Plasma generator.

Table Top

James F. Ryan

The new copper-tungsten cylinder for the mechanical crowbar relief switch[1] was examined after about 750 closures under load. Arc erosion is visible over the first 3/8 in. of contact surface. About half of this service was at indicated bank voltage of plus and minus 12 kv.

The switch is out of service until a saturable reactor can be designed and installed to limit the rate of current build-up during the first 500 to 700 μsec of switch contact--that is, about 1/4 in. to 3/8 in. of travel.

The fast shutter for the vacuum spectrograph has been assembled and is undergoing mechanical tests. Alteration of some parts will be required before correct performance can be obtained.

Low-Energy Neutral-Beam Experiment

William S. Neef, Jr., Eugene T. Bradley, and J. Ralph Ullman

The design of the liquid nitrogen supply system for the Alice[2] area in Building 180 was completed and released for fabrication. Branch lines to the cryogenics laboratory were included.

Floor beam tracks were installed, coil-support carts were assembled, and the auxiliary support frame has been fabricated and erected in Building 180.

All pancakes for the first Alice coil section are wound, electrically connected, and in the potting fixture ready for vacuum impregnation with resin. Electrical resistance measurements show that one short may exist, and the assembly is being oven dried to determine whether the short is due to moisture or a foreign particle.

A mathematical analysis of the magnetic field to be produced by the rectangular coils in the Alice beam source was completed. The 650 computer was utilized to get a wealth of field-plot data for various coil geometries and spacing. Mechanical-particle plots from this information are being made and studied at present.

The new beam source was designed and the source cavity and pumping cavity have been released for construction by the Berkeley Machine Shop. A coil drawing has been made and some tooling has been started toward the fabrication of the two rectangular coils for the source.

The mechanical equipment for the Baby Alice Experiment was completed and the experiment has produced useful information. Some engineering follow-up has been required to provide miscellaneous hardware to aid the experimenters.

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[1] Shown as Fig. 32, in Controlled Thermonuclear Research Quarterly Report, UCRL-8887, Sept. 1959, p. 127.

[2] Refer to Fig. 21, in Controlled Thermonuclear Research Quarterly Report, UCRL-8775, June 1959, p. 89.

The differentially pumped double-pinch gasket[3] system shown in Fig. 35, utilizing 90-10 cupronickel gaskets with an annealed hardness of 15 to 16 on the Rockwell B scale, has been baked out six times for a total of 126 hours to temperatures exceeding 400°C without leaking. Ultrahigh vacuum was attained after the sixth bakeout--8×10^{-10} mm Hg. After the sixth bake the two cupronickel gaskets on the side arms of the cross were replaced with stock sheet-copper gaskets. The system was then baked three more times for a total of 126 hours to 450°C; again there were no leaks. The leak checking was done with a Veeco helium mass-spectrograph leak detector, which has a sensitivity on the order of 1×10^{-10} atm-cc per sec leak rate.

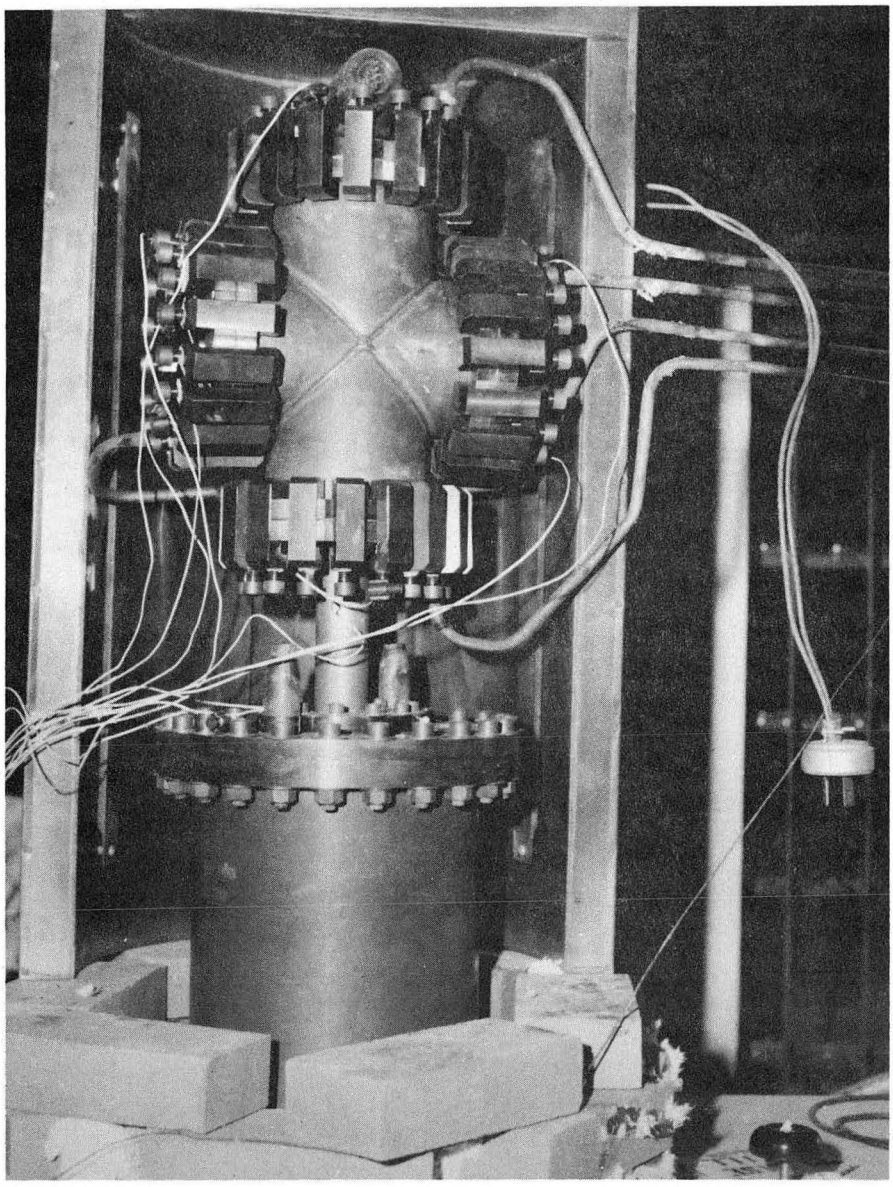
A Marman conoseal, Fig. 36, was also tested, but results were inconclusive. Slight damage to the flanges incurred during fabrication has caused erratic results. The first seal leaked after a mild bakeout. The second gasket gave zero leakage through a full bakeout cycle. The third gasket never gave a seal. Careful inspection has revealed the source of the trouble and Marman is repairing the damage. Testing will be continued on this commercial design to determine reliability.

The 90-deg-angle baffle for Alice's 4-in. diffusion pumps has been received and is being tested for efficiency of trapping and conductance.

A cylindrical sheet tungsten filament assembly 10 in. in diameter by 12 in. long, L19C 1925, has been designed to be mounted in the Movac tank. It will be outgassed by resistance heating to 2600°K. The filament, upon cool-down, should have a good potential for adsorption on the clean surfaces. Such a filament may be feasible for pumping neutral gas from the Alice reaction chamber.

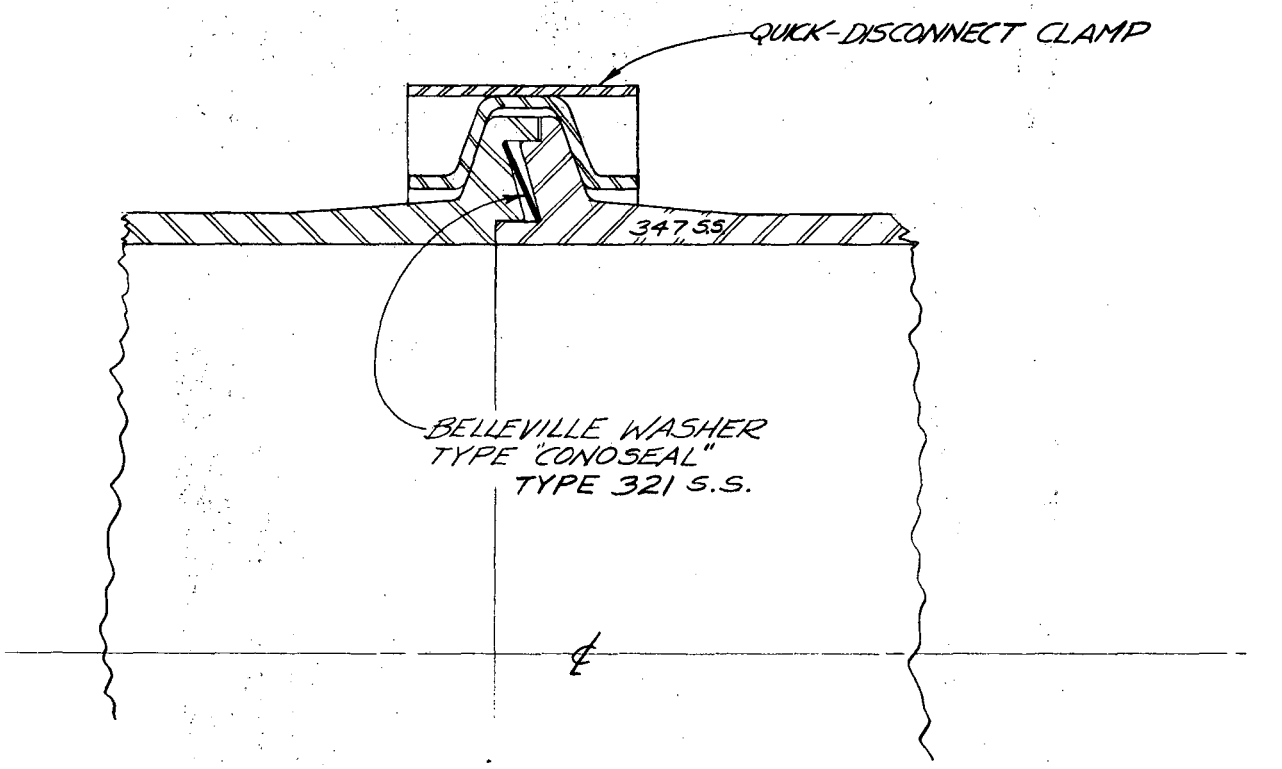
A switch assembly, L19C 1935, has been designed to operate in ultrahigh vacuum within the Movac tank. It would permit selective evaporation of molybdenum filaments. The filaments are 0.05 in. in diameter by 6 in. long. Operating time with the total filament array has been estimated to be on the order of months.

[3] Refer to UCRL-9002, Fig. 42, p. 127.



ZN-2350

Fig. 35. The differentially pumped double pinch gasket system.



MU-19488

Fig. 36. Marman conoseal joint.

Atomic and Molecular-Beam Research

Charles A. Hurley and Alfred R. Taylor

A large part of the hardware has been delivered and the apparatus (shown as Fig. 23, p. 95 of UCRL-8775) has been approximately 75% assembled. Machining difficulties have been encountered with the very precise beam-chopper mechanism. The rotating section of the analyzer chamber is also being modified to reduce leakage and torque.

A Stern-Pirani detector for measuring the pressure of the neutral beam has been designed, and fabrication is about 75% complete.

A gear drive with suitable protractor strips for position indication has been designed for the rotating analyzing chamber cover, and fabrication is approximately 90% complete.

The design has been completed for a precision platform that is to be used inside the vacuum chamber. This is a precision support table for mounting instruments that are optically aligned.

Astron

Charles A. Hurley, James F. Ryan, and Edward G. Scarlett

Although it had been indicated in the preceding Quarterly Report (UCRL-9002, p. 130) that oil would probably be used as an insulating medium for the pulsed electron gun (200 amp, 720 kev), this has been changed to a gas having a dielectric constant of approximately 1. The purpose is to reduce the capacitance between the transformer secondary sheets. The dielectric constant of the transformer oil is approximately 2 to 3. The gas will be Freon or nitrogen at 30 psig. For this pressure it is necessary to design the tank as a pressure vessel.

The gas-to-vacuum separation is made by a 12-in.-diameter ceramic column, as originally planned.[4] However, two different fabrication schemes will be tried because of the very difficult assembly and maintenance problem. One method is to fabricate the column with the accelerating plates soldered to the ceramic, thus making the vacuum seal. The other is to build the column up at assembly, using Hycar O rings to make the seal.

The over-all mechanical design of the gun is approximately 50% complete. Requests for bids have been released for the soldered ceramic accelerating column and for the pressure vessel. The 10-in. matrix cathode is being fabricated by Semicon of California, Inc. Six have been ordered.

The equipment necessary to test the cathode is approximately 50% designed and 25% fabricated. This includes the vacuum system, vacuum vessel, accelerating column, and cathode-support hardware. The Marx generator requires additional design, including a pressure-vessel high-voltage bushing design, spark gap, and coil.

[4] Refer to Fig. 45, UCRL-9002, p. 131.

The design layout for the 48-core 768-kev induction accelerating unit has been completed.[5] Two such units are to be built. Samples of secondary plates and rings have been delivered to Electrical Engineering for test with sample cores. Details for holding the core will be checked before plates and rings for the complete unit are ordered.

The ceramic-metal accelerating column is now awaiting return of quotations. Bids have been recieved from four suppliers so far. Prices range from approximately $19,000 to $26,000 for two columns plus one spare.

The layout is complete for the main Astron solenoid coils. They will be made up of modular coils on a fibrous-glass sleeve of 43-in. inside diameter, using 1/2-in. -square copper conductor in a single layer. The sections will be 2.5 ft long (50 turns). Water connections at the quarter points will allow field strengths up to 1280 gauss. Maximum current capability will be 1560 amp.

The mirror-field coils are similar to the main solenoid, but have separate electrical circuits for each 6 in. of length (10 turns). The current capability is 1900 amp, giving 1560 gauss. A mandrel has been designed on which these and the main solenoid coils will be formed.

A preliminary layout has been completed on the injection section on the cantilever and internal mirror coils. Approximately 16,000 ft of 1/4-in. copper conductor will be required for these coils. Coils will be two-layered, of 39 turns, and 6 in. long.

Cryogenic Coil Development

Clyde E. Taylor, Robert L. Nelson, Richard Mallon,[6] Arturo Maimoni, and David Cummings

Electrical resistivity measurements have been made on aluminum of the highest purity now commercially available in large quantities.[7] They show that after annealing at 400° C (the optimum annealing temperature) for 24 hr it is possible to obtain a ratio of room-temperature resistivity to liquid-helium-temperature resistivity, ρ 273°K/ρ 4.2°K, of 1900. Distilled sodium gave a resistivity ratio of 1830, which increased to 2160 after standing for 22 days at room temperature. Sodium distillation is continuing.

Coil design is nearly complete and fabrication has begun. The coil-test system is about one-half designed. Switch-gear tests of components for the 20-ka 6-v requirements are proceeding. A no-load switch for thermal isolation of the coil has been designed, and the actuation mechanism, consisting of helium-gas-actuated bellows, is being tested.

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[5] Refer to UCRL-9002, Fig. 46, p. 132.

[6] Consultant from ASTRA, Inc., Raleigh, North Carolina.

[7] "Super Raffinal," produced by Aluminum Industrie A. G., Neuhausen am Rheinfall, Switzerland, distributed by United Mineral and Chemical Corp., 16 Hudson St., New York.

ELECTRICAL ENGINEERING DEVELOPMENT

Vernon L. Smith

Pyrotron

David R. Branum

Table Top II

The machine has been used by Dr. Walton A. Perkins in his scintillation-photomultiplier probe experiments.

For this operation there were 3,650 bank pulses at an average bank level of + 10 and - 10 kv. Approximately a hundred pulses were at a level of + 15.5 and - 15.5 kv. The total of bank pulses to date is 57,980.

During the last part of December, the mechanical crowbar relieving switch was installed on the machine and operated satisfactorily up to bank voltage levels of ± 15.5 kv. After 756 operations at an average bank level of ± 10 kv, the mechanical switch elements started to stick with the switch in a closed position. The switch assembly was removed from the system and is now undergoing modifications to eliminate the initial-contact-arc pitting that caused the switch malfunction.

Early in January one of the pulse coils developed fracture cracks and was removed for repairs. A new coil was then installed and tested up to bank levels of ± 15.5 kv.

The four special General Electric type 5555 ignitrons that had been installed in December were removed in January after 1,172 pulses at an average bank level of ± 10 kv. The ignitor resistance had fallen below reliable triggering value with the pulse circuits of the Table Top system. The four tubes were replaced with Westinghouse type 5555 ignitrons. The Westinghouse ignitrons in the rest of the chain have been in service since January 1958 with a total pulse operation of 27,000 pulses and they still show good ignitor resistances of 50 to 200 ohms dc and still ac "hipot" to above 24 kv rms.

During the past three months there have been no capacitor bank problems. A few pulse-signal chassis have been repaired or replaced for component failure. Nearly all the components on the machine have been in more or less continuous service for more than 4-1/2 years. This extended use is showing up in the types of failure that have been happening, i. e., power-transformer shorts, filter-capacitor shorts, deterioration of insulation on high-voltage wiring, etc.

Additional pulse-capacitor-bank sections consisting of one Tobe Deutschmann 15-mf 20-kv capacitor and one type A ignitron in a coaxial housing each were built for the side experiment on gas valve sources. They have not been connected to the shock ionization coil.

An additional side experiment was added in December by Richard F. Post for the study of high-vacuum production; it required various source pulsers, vacuum-gauge power supplies, and control circuitry. A complete dc floating power-supply system for Veeco-type vacuum gauges is now under construction.

A "breadboard" of the output stage of the deflection pulser for the 50-kv electron gun experiment has been installed and used. The complete system will drive the deflection plates at the end of 15 feet of RG-8/U coax cable to peak voltages of 2.7 kv and pulse widths of 10 μsec, 100 μsec, 1 msec, and 10 msec. A complete pulser power-supply system in an isolated cart is now under construction. The present "mock-up" system uses battery supplies on top of the 0- to 50-kv accelerating power supply.

The six special 3/4-in. photomultiplier detector probes were checked and found to be very satisfactory; therefore six more are being constructed for a 10- to 12-unit detector. The detector uses RCA type C7204 gain-of-200,000 3/4-in. photomultipliers, and a transistorized preamplifier emitter follower. All components (with the exception of the main high-voltage supply and the main battery supply for the amplifier) are contained in a 1-in. o. d. thin-wall brass tube. The bases are linear to 40 v and have a noise output of 10 mv. The response time is from 0.5 μsec to 20 msec with less than 1% differentiation at the long pulse width.

Toy Top III

The new experimental setup in this area is now known as Toy Top III; formerly the experiment was known as Toy Top II phase B.

There has been much electronics engineering effort in the past three months. The two 300-kw dc power supplies known as Perkins #9 and #10 are complete, and only the final control connections to the control centers of the experiment remain to be finished.

The two 20-kv 2-amp bank-charging supplies are complete in themselves, and their control-metering connections are now being installed in the experimental control console.

Bank No. 1 is approximately 90% complete. The work that remains to be done is the installation of the ignitrons and their respective pulse circuitry, and the connection from the bank output bus to the load coil in the machine.

Bank No. 4 is now under construction, and the capacitor racks are near completion. The work remaining on bank No. 4 includes all the controls, pulse circuitry, ignitron switch mounts, the transmission line up through the floor to the experiment above, and the connection from the transmission-line terminations to the two load coils.

Banks No. 2 and 3 have been delayed until banks No. 1 and 4 are tried out on the experiment.

Several fast-capacitor ignitron switch sections were constructed and used in the experimental study of the Lawrence Radiation Laboratory version of the Los Alamos Marshall gas-fed source. The rise time of the current into the source was 2 to 3 μsec at 15 kv on a 15-mf capacitor. At this level, a peak current of approximately 180,000 amp, the WE4242 ignitrons held up fairly well, lasting for several hundred shots until their anode seals became so hot that corona discharge noise caused false circuit triggering. The average pulse rate was one pulse every 30 sec. At a capacitor voltage level of 10 kv the ignitron switches last for 2,000 to 3,000 pulses before developing excessive jitter and misfires.

The single-channel data-handling system has been installed. The system has an average error (from pulse heights read on a Polaroid picture of a 5-in. oscilloscope trace) of ± 2%. The output versus input is linear from 10 to 190v, and falls off to 2% from 10v to 1 v input. For smaller signals a gain-of-1,000 amplifier is inserted ahead of the analyzer. A second channel is under construction and further work is planned to increase the linearity.

Pyrotron

H. W. Van Ness

Baby Alice

Electronics installation has been debugged and the experiment is in progress.

Alice

Design of the electronics installation in Building 180 is in progress. A major problem under consideration is the removal of stored electrical energy from the cryogenically cooled coils at the end of each pulse. Several possible energy-transfer schemes are being considered.

Sanctus

The arc-current limiter has been put into operation successfully.

Source Development

Design for the source development effort for Building 180 is in progress.

Pinch and Collapse

H. W. Van Ness

Gamma Bank Area

A 1.5-farad electrolytic bank has been constructed and is operational for use in the Levitron experiment.

The gamma bank is being reconnected for operation at 20 kv in the Levitron experiment. Charging-circuit fusing has been added throughout the bank. Tests are under way to devise a "safety crowbar" system to prevent damage of capacitors in the event of prefiring of ignitrons when the bank is operated near 20 kv.

Operating tests of an electromechanical isolating switch for the Levitron experiment appear to be successful. This switch is required to conduct up to 60,000 amp when closed. It must open rapidly (in a few milliseconds) and remain open for 10 to 50 msec and then reclose rapidly. During the open time it must withstand up to 20 kv applied. Operational-life tests will be run to determine if a useful life of 1000 operations can be obtained.

A Diatron 20B mass-spectrograph tube has been purchased for use in a "fast-scan" system to be used with the Levitron. Design investigation for the associated components and circuitry required is in progress.

Electron-Beam Experiment

Tests are in progress to develop circuitry to provide multiple pulses from the 300-kev electron gun. It is hoped that five pulses spaced over a 2.5-μsec interval can be obtained.

Plasma-Acceleration Experiment

Material to construct the fast bank is currently being received. Construction will start within 2 weeks.

Sodium Radio-Frequency Analog Experiment

Tests of a variable-frequency ignitron inverter (100 to 2000 cycles) will be run shortly. If successful, this equipment could have possible use in other experiments, such as the Levitron.

300-kv Marx Bank Area

To date, no written response has been received from Cornell-Dubilier concerning test and replacement of the unsatisfactory capacitors which prevented completion of the bank.

Energy-Storage-System Investigation

Owing to budgetary restrictions, effort has been kept to a minimum on this program. The latest delivery-date promise on the machine is March 21.

Switch Development

David B. Cummings

Mechanical Switch

The fast mechanical crowbar relief switch with silver-tungsten contact assembly was operated on Table Top for 756 pulses. These were at up to 14 kv or a peak current of 120 ka. At this point some contact erosion was noticed and the switch removed. Apparently enough current can build up during arcing for contact to cause the gradual erosion of even silver-tungsten. A saturable reactor is being made to inhibit current build-up prior to contact.

Ignitron Development

Tube Tests

Five ignitrons have been tested with ceramic anode and ignitor seals and vacuum-melted moybdenum anodes. These tubes have established that

(a) such tubes can be made with copper brazing,
(b) they are very clean and can withstand crowbar arc-back currents,
(c) the anode seal geometry is susceptible to mercury droplets or wetting and is not reliable at 20 kv,
(d) Westinghouse ignitors are less susceptible to molybdenum-mercury wetting,
(e) the ceramic ignitor seals are more susceptible to wetting than glass and must be shielded or glazed.

Tests were performed at 17 and 20 kv on tubes with 1/4-in.-radius throats. These appear to be suitable for operation at 17 kv and are better by several kv than previous designs. These tubes had graphite anodes. Acceptance tests at 10 kv have been performed on a number of regular graphite ignitrons. During these tests the inductor failed. A new one was designed and built in the Coil Shop.

Ignitron Mechanisms Investigation

By taking Kerr-cell photographs of glass ignitrons with two ignitors it has been established that two ignitors work in parallel whether fired from the same or separate circuits. The report on previous work is completed and is being reviewed.

Microwave Diagnostics

Harlin L. Bunn

Pencil Beam Antennas

Work has been conducted on designs for pencil-beam antennas. Certain experiments are using magnetic fields that constrict the plasma column to such a size that the radiation from conventional electromagnetic horns scatters around the column instead of propagating through it. This introduces large errors which render the method useless. The designs being considered include metallic lens, dielectric lens, parabolic dielectric lens, and optical glass lens. These have been fabricated and are ready for testing. Consultations have been held with members of the Electrical Engineering Staff at Berkeley on methods of measurements.

Low-Loss Waveguides

a. TE_{01} Waveguide

The new design for the resonant slot transition, centered at 69 kMc, has been evaluated. It did not give the same results as the first design, centered at 34.5 kMc. The reason for this failure has not been evaluated. The Bell Laboratories and Marie' designs have not been completed.

b. H Guide

A scaled version of the mode launcher designed for the 34.5-kMc band failed to give the results expected at 69 kMc. Consequently the original model was tested at 69 kMc by providing a tapered waveguide section from RG-96/U to RG-98/U. The measured loss per horn at 69 kMc was about 1.2 kv, as compared with 0.6 db for 34.5 kMc. The measured loss per foot of the H guide proper was apparently 0.05 db, a considerable reduction from that of RG-98/U. Further studies remain to be done on an optimum design for a mode launcher.

Pulsed Interferometers

No active work has been conducted on this project. However, studies are to be conducted by the writer on a similar type of work in a project not related to Sherwood. The idea will be to see if a low-power CW source can be used as a "tickler" for controlling the frequency of a pulsed source. Indications are that this can be achieved with extremely low power, the power appearing to the pulsed oscillator as a noise with a definite phase. This noise, being what starts oscillations, in turn controls the frequency of the pulsed oscillator. Should this prove successful, one should be able to use one of the proposed pulsed devices of Coleman's group at the University of Illinois or some other pulsed source in the low millimeter range for interferometer work. The low-power CW for controlling the frequency can be provided by conventional multiplication schemes from low frequencies or from the gas-discharge device being investigated by J. R. Baird of the University of Illinois.

Atomic and Molecular-Beam Experiments

David R. Branum

The system is being installed in Building 180, and almost all the electrical vacuum requirements are now complete.

Several chassis have been designed and some are still under design for the mass-spectrograph analyzer, the chopper wheel and the photomultiplier and ion-electron detectors.

Astron

Kris Aaland

Induction Accelerator

Magnetic Cores

1-mil 50% Ni-Fe was selected for core material. 100 toroids of 8-in. i.d. by 24 in. o.d. by 1/2 in. thickness were ordered.

More information on 50% Ni-Fe is therefore presented here.

Figure 37 shows magnetizing current shapes (proportional to oersteds) at different voltage levels (expressed in gauss, since pulse width is constant). Each operating point has optimum dynamic bias.

Measurements done on "low" level (see LE report 361-1) extrapolated agree very well with points checked on full-size samples from G. L. Electronics and Magnetics Metals Company.

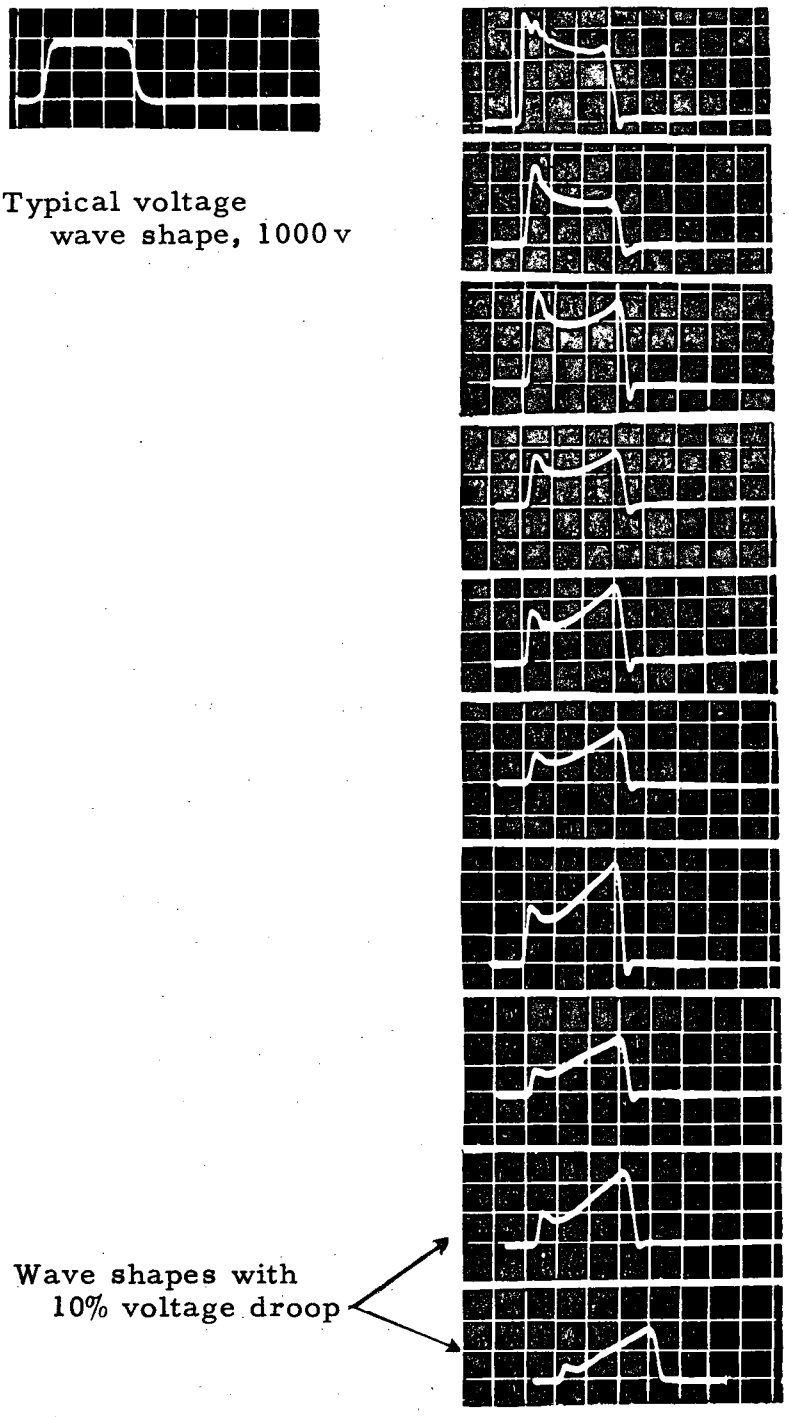
The graph, Fig. 38, was plotted by G. A. Reeser from wave shapes in Fig. 37. This method of presentation was suggested by C. H. Woods of Lawrence Lab. Reference to this work is to be filed in the Electronics Engineering Department under LE 379-1.

Pulser

Of first consideration is the switching element. When the other problems involved are isolated, a spark gap or a thyratron seems preferable. Thus, tests were performed earlier on three basic different thyratrons.

A small 5C22 tube has successfully been operated with 8000-volt 1600-amp 250-nsec pulses in a resistive load for 700 hours at 60 pps. Rise time is 50 nsec, with 2-nsec short-time jitter. Long-time firing-delay variations are not known.

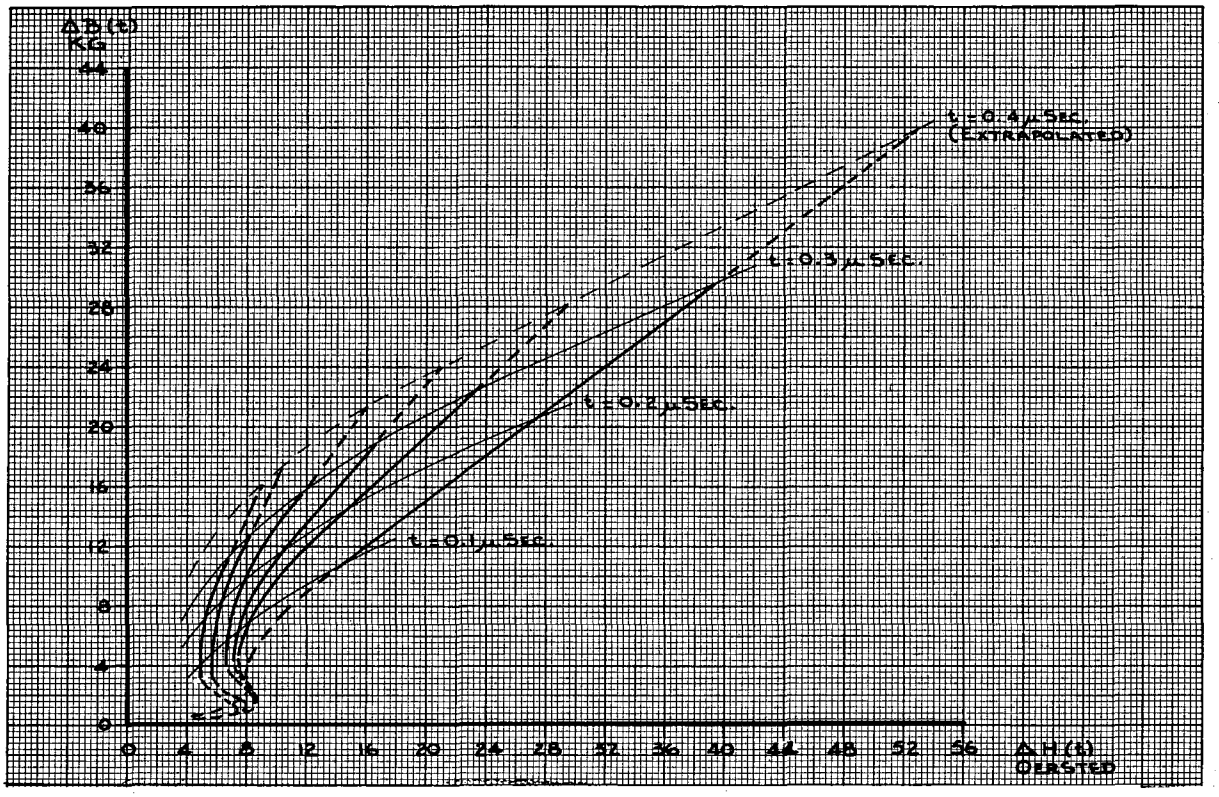
A glass 1257 and a ceramic GL7390 delivered a maximum of 20,000 v and 2400 amp at 250 nsec pulse width, 20 pps. The rise time for 1257 is about 100 nsec with 4-ohm lines. In a pulse-forming network the GL7390 yielded about 50 nsec rise time.



Peak excitation (gauss)	Peak excitation (oersteds)
5,580	2.9
7,450	3.5
11,200	6.8
13,000	8.1
14,900	12.1
18,600	16.1
18,600	16.6
22,300	23.2
22,300	22.7
29,800	40.3

MUB-390

Fig. 37. Excitation-current wave shapes; 1-mil 50% Ni-Fe, GL Electronics #2324; t_p = 0.3 μsec.



MU-19504

Fig. 38. Minimum-excitation and dynamic ΔH-ΔB curves for 1-mil 50% Ni-Fe core, GL Electronics #2324.

A triggered spark gap is presently used for checking arc-down in the sample cores. From a 30-nf capacitor charged at 25,000 v we observed a voltage rise time of about 10 nsec across the core load.

One observes in Fig. 37 that the load is quite nonlinear with amplitude and time. This, of course, calls for a low-impedance source so as to obtain good voltage regulation during the pulse.

A line pulser would have to be shunted or compensated and the switch asked to carry the extra current.

A capacitor provides a low-impedance source; however, a disconnecting-switch element is required. This brings into the picture electron tubes.

When considering the use of hard tubes, one may just as well introduce the use of feedback circuits. (See Fig. 39.) Extensive work is going on along these lines.

Tubes such as the Eimac 4PR60 are found to handle 60-amp apiece, and deliver 25 kv (1.5 megawatt). (See LE 371-1.) A unit of 16 tubes in parallel was built that delivered 1200 amp. With feedback connected, about 800 amp was delivered in the load. Ringing frequency is 330 Mc. Preliminary wave shapes are shown in Fig. 40 and superseded by Fig. 41.

Decelerator

Metal film resistors were successfully checked at 600-kv electron bombardment. (Refer to Bernard M. Loth's report LE 373-1.)

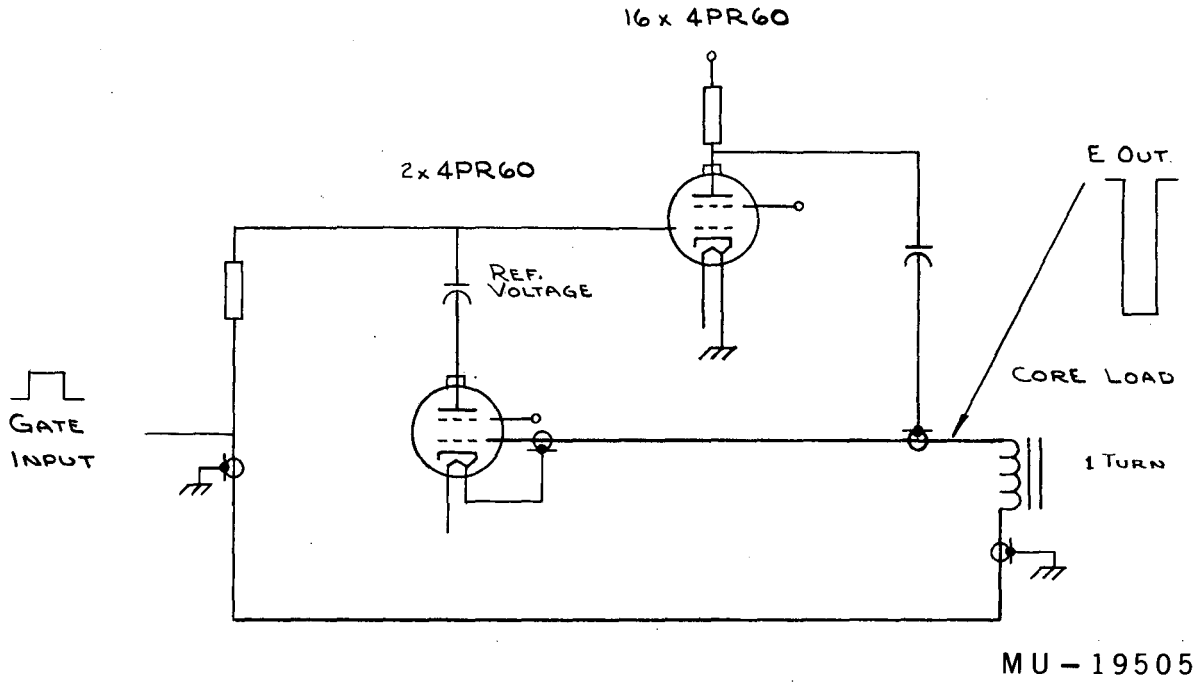
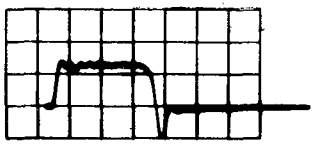


Fig. 39. Basic pulser.

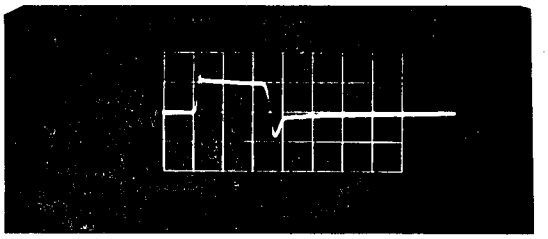


Average impressed voltage: 10 kv

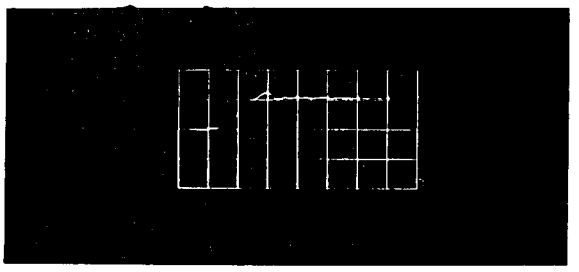
Peak core load current: 800 amp
(Damping-resistor current: 100 amp)

MUB-392

Fig. 40. Voltage-regulated modulator output into sample core and 100-ohm damping resistor. Pulse width: 0.3 μsec.



0.1 μsec/cm
(vertical: 7 kv/cm)



.01 μsec/cm
(vertical: 7 kv/cm)
Leading edge
showing 10-nsec rise
and 330-Mc ringing.

MUB-391

Fig. 41. Voltage wave shapes.

TALKS AND PUBLICATIONS

Meeting of the Division of Plasma Physics of the American Physical Society, Monterey, Calif., Dec. 3-5, 1959.

William L. Barr and Raymond L. Kelly, Spectroscopic Measurements in P-4 (UCRL-5726 Abstract, Oct. 1959).

H. P. Furth and F. O. Halliday, A Two-Stage Plasma Accelerator (UCRL-5732-T Abstract, Nov. 1959).

Lewi Tonks, Self-Consistent Field and Motion of Electrons Which Slow down in a Uniform Impressed Magnetic Field (UCRL-5733-T Abstract, Nov. 1959).

S. A. Colgate, Enhanced Diffusion Due to Magnetohydrodynamic Turbulence (UCRL-5734-T Abstract, Nov. 1959).

T. O. Passell, Ion Beam Space Potential Measurement with an Electron Beam (UCRL-5735-T Abstract, Oct. 1959).

A. L. Gardner, L. S. Hall, W. D. Kilpatrick, and D. E. Edwards, P-4--A Steady-State Plasma System (UCRL-5736-T Abstract, Oct. 1959).

N. O. Oleson and D. M. Gall, Probe Measurements in P-4 (UCRL-5737-T Abstract, Oct. 1959).

W. F. Cummins, F. H. Coensgen, A. E. Sherman, and W. E. Nexsen, Study of an 800-ev Plasma Generator (UCRL-5742-T Abstract, Oct. 1959).

R. F. Post, Acceleration of a Plasma by Time-Varying Magnetic Fields. (UCRL-5744-T Abstract, Nov. 1959).

A. E. Sherman, F. H. Coensgen, W. E. Nexsen, and W. F. Cummins, Determination of Ion Rotational Energy Distributions of Plasma in a Uniform Magnetic Field (UCRL-5748-T Abstract, Nov. 1959).

F. H. Coensgen, W. E. Nexsen, W. F. Cummins, and A. E. Sherman, Plasma Injection into a Magnetic Cusp (UCRL-5749-T Abstract, Nov. 1959).

W. E. Nexsen, W. F. Cummins, F. H. Coensgen, and A. E. Sherman, Collision of Two Plasma Streams (UCRL-5750-T Abstract, Nov. 1959).

E. S. Chambers and H. P. Furth, Direct Electrical Excitation of Ion Cyclotron Waves (UCRL-5751-T Abstract, Nov. 1959).

F. O. Halliday, S. A. Colgate, and H. P. Furth, Liquid Sodium Hydromagnetic Equilibrium Measurements (UCRL-5752-T Abstract, Nov. 1959).

D. H. Birdsall, S. A. Colgate, and H. P. Furth, Instability of a Hydromagnetically Stable Pinch Configuration (UCRL-5753-T Abstract, Nov. 1959).

R. L. Spoerlein, S. A. Colgate, H. P. Furth, L. E. Sandy, and O. A. Twite, Small Levitron (UCRL-5754-T Abstract, Nov. 1959).

W. Heckrotte and J. Killeen, A Numerical Solution of the Fokker-Planck Equation for a Plasma (UCRL-5755-T Abstract, Nov. 1959).

H. W. Bandel, Space-Charge Effects in an Ion Energy Analyzer (UCRL-5759-T Abstract, Nov. 1959).

R. F. Post, R. E. Ellis, and W. A. Perkins, Studies of Plasma Confinement in a Mirror Machine: The Effect of Impurities and Other Perturbations (UCRL-5760-T Abstract, Nov. 1959).

R. E. Ellis, W. A. Perkins, and R. F. Post, Electron Energy Distribution and Temperature of the Plasma in a Mirror Machine (UCRL-5761-T Abstract, Nov. 1959).

W. A. Perkins, R. E. Ellis, and R. F. Post, Radial Distribution of Plasma in a Mirror Machine (UCRL-5762-T Abstract, Nov. 1959).

J. Killeen and G. Boer, Densities of Particles Trapped by the Geomagnetic Field (UCRL-5763-T Abstract, Nov. 1959).

A. W. DeSilva, F. I. Boley, and J. M. Wilcox, Plasma Alfvén Waves: Velocity and Attenuation (UCRL-8958 Abstract, Oct. 1959).

J. M. Wilcox, F. I. Boley, and A. W. DeSilva, Plasma Alfvén Waves: Power Transfer and Impedance (UCRL-8959 Abstract, Oct. 1959).

T. K. Allen, G. A. Paulikas, and R. V. Pyle, Apparent Enhanced Diffusion in Plasma in a Magnetic Field (UCRL-8960 Abstract, Oct. 1959).

A. Bratenahl and W. B. Kunkel, Some Studies of Current Flow and Boundary Effects in Homopolar III (UCRL-8962 Abstract, Oct. 1959).

Alfredo Banos, Jr. and Russell Vernon, Large-Amplitude Plasma Waves: I. Scalar Pressure (UCRL-8989 Abstract, Oct. 1959).

Russell Vernon, Large-Amplitude Plasma Waves: II. Non-Isotropic Pressure Tensor (UCRL-8990 Abstract, Oct. 1959).

Sylvan Katz, The Configuration of a Fully Ionized Plasma in an Axially Symmetric External Magnetic Field (UCRL-8991 Abstract Oct. 1959).

Kenneth Schwartz, The Stability of a Diffuse Linear Pinch with an Almost Isotropic Pressure Tensor (UCRL-8992 Abstract, Oct. 1959).

International Symposium on Magneto-Fluid Dynamics, Williamsburg, Virginia, January 18-23, 1960.

S. A. Colgate, H. P. Furth, and F. O. Halliday, Liquid Sodium Hydromagnetic Equilibrium Measurements (UCRL-5752-T Abstract, Nov. 1959).

Project Matterhorn, Princeton University, Princeton, New Jersey, Colloquim, January 25, 1960.

S. A. Colgate, Hard-Core Pinch, invited paper.

General Electric Company, Schenectady, New York, January 26, 1960.

S. A. Colgate, Plasma Physics, invited paper.

Fourth Sherwood Vacuum Conference, Princeton University, Princeton, New Jersey, January 26-27, 1960.

T. H. Batzer, Demountable Bakable Fields, invited paper.

C. C. Damm, Ultrahigh Vacuum without Bakeout, invited paper.

L. L. Levenson, Optimization of Diffusion Pump Systems, invited paper.

Norman Milleron, Review of Vacuum Objectives and Progress at Livermore, invited paper.

J. R. Ullman, Cryogenic Pumping with Liquid Helium, invited paper.

American Physical Society Meeting, New York, N. Y., January 27-30, 1960.

R. C. Jopson, W. A. S. Lamb, and R. E. Wright, Injection and Trapping of High-Current Electrons (UCRL-5731-T Abstract, Oct. 1959).

N. C. Christofilos, Injection and Trapping of High-Current Electron Beams, (UCRL-5743-T Abstract, Oct. 1959).

M. H. Mittleman, An Optical Potential Including the Pauli Principle (UCRL-5579-T Abstract, Nov. 1959).

American Society for Metals, Golden Gate Metals Conference, San Francisco, Calif., February 4, 1960.

Norman Milleron, Degassing of Metals in Ultrahigh Vacuum, invited paper.

A. I. E. E. Symposium on Engineering Aspects of Magnetohydrodynamics, University of Pennsylvania, Philadelphia, Pa., February 18-19, 1960.

Harlin L. Bunn, Microwave Diagnostic Systems and Techniques for Use in Controlled Fusion Research (UCRL-5721 Abstract, Oct. 1959).

W. M. Wells, Jr., Experimental Determination of Pressure Drops for the Flow of Mercury through a Nonuniform Field (UCRL-5725 Abstract, Oct. 1959).

Journal Publications

Physical Review Letters

R. F. Post, R. E. Ellis, F. C. Ford, and M. N. Rosenbluth, Stable Confinement of a High-Temperature Plasma, 4, 166 (1960).

Gordon Gibson, Willard C. Jordan, and Eugene J. Lauer, Bumpy Torus, 4, 217 (1960).

The Physical Review

B. A. Lippman, M. H. Mittleman, and K. M. Watson, Scattering of Neutral Atoms, 116, 920 (1959).

The Physics of Fluids

John M. Wilcox and Forrest I. Boley (Letters to the Editor) 3, 141 (1960).

John M. Wilcox, Forrest I. Boley, and Alan W. DeSilva, Experimental Study of Alfvén-Wave Properties 3, 15 (1960).

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