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Magnetically Confined Plasmas*

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The propagation of high-velocity shock waves in an axial magnetic field generated by single-turn coils connected in parallel to a condenser bank is investigated. Time-resolved photographs show that the plasma behind the shock front is driven away from the tube walls by the magnetic pressure. This compression heats the ionized gas and maintains a high shock velocity during the transit of the front through the coil. The compressed plasma appears to be stable and undergoes radial oscillations that follow the current oscillations. The interpretation and significance of these observations in controlled thermonuclear fusion research are discussed.

I. INTRODUCTION

OBSERVATIONS of the magnetic compression of the plasma behind strong shock waves were extended to field strengths of 60 000 gauss with larger shock tubes and longer confinement times than in previous work.[1] The series of experiments reported in this paper are part of an investigation of methods for reaching thermonuclear temperatures by first preheating a tube filled with deuterium gas by means of high-velocity shock waves, and then compressing this plasma by a rising magnetic field along the axis of the shock tube. This paper is mainly concerned with the shock pre-heating and the initial stages of the compression. Experimental studies with still higher fields ($>2\times10^5$ gauss) and longer containment times will be discussed in subsequent publications, together with experimental results on an alternative method of pre-ionizing and pre-heating deuterium gas using a high-frequency ($\sim$10 Mc/sec), high-power, electrodeless condenser discharge ($\sim10^{10}$ watts). The plasma formed in this way can then be compressed by a rising axial magnetic field as discussed in this paper.

The general technique employed is to first accelerate a deuterium plasma by means of a high current discharge in a transverse magnetic field at one end of a T-shaped quartz tube[2] or at both ends of an H-shaped tube. Ion energies of $\sim$100 ev/ion can be achieved behind strong shock waves which propagate up the sidearm of the T (or H) tube. The sidearm is surrounded by single-turn coils connected in parallel to a large condenser bank. The bank is switched on when the shock wave enters the coil system. The currents which flow in the coils induce plasma currents which exclude magnetic fields from the interior of the high conductivity gas of ionized deuterium formed behind the shock front. In this way a boundary is established between the axial magnetic field and the plasma. If the magnetic pressure $H^2/8\pi$ exceeds the gas pressure $(N_i+N_i)kT$, the plasma moves radially inward from the walls of the tube. This compression results in an increase in the internal energy of the plasma and maintains the high shock velocity during the transit time of the shock wave through the coil array. In addition, energy is deposited in the plasma by Joule heating due to the high surface currents. The configuration of currents and fields used here is reversed with respect to those encountered in the "pinch effect" where there are θ-fields around a column of compressed plasma carrying a high axial current. The present experiments have shown that under certain circumstances there is no large scale instability of the compressed plasma

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[1] A. C. Kolb, Phys. Rev. **107**, 1197 (1957).

[2] A. C. Kolb, Phys. Rev. **107**, 345 (1957); Bull. Am. Phys. Soc. Ser. II, **2**, 47 (1957); A. C. Kolb, in *Magnetohydrodynamics*, edited by R. K. M. Landshoff (Stanford University Press, Stanford, 1957), p. 76. See also A. I. Morozov, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 305 (1957) [translation: Soviet Phys. JETP **5**, 215 (1957)], for theoretical considerations.

behind a high-velocity shock wave, while a pinched plasma without an internally trapped axial field is highly unstable.[3] This suggests that there is a possibility of reaching thermonuclear temperatures in plasmas with $\beta \sim 1$ (β= gas pressure/magnetic pressure) without the need for additional stabilizing fields.

II. SEMIQUANTITATIVE CONSIDERATIONS

Consider the behavior of a cylinder of plasma bounded at one end by a shock wave and subjected to a rising external magnetic field in the direction of shock propagation. The conductivity of the plasma is taken to be infinite so that we neglect the penetration of the field into the cylinder. Now, if the temperature is sufficiently high, then the magnetic field can be assumed to change slowly compared to the transit time of a sound wave across the cylinder of plasma and the compression will be essentially adiabatic. The field will rise to a certain value H_0 in a time t_0 until the magnetic pressure equals the gas pressure $2N_0kT_0$ (we take the ion density to be equal to the electron density for simplicity). Then radial compression takes place. The adiabatic compression of the cylinder can be computed by considering the coil and plasma cylinder to be elements in an electrical circuit with a time-dependent inductance. The appropriate circuit equation is

$$V_0 - \frac{1}{C}\int_{t_0}^{t} I dt' = \frac{d}{dt}\{[L(t)+L_e]I\}, \qquad (1)$$
$$L(t) = (4\pi^2/c^2l)(R_c^2 - R_p^2),$$

where V_0 is the voltage at time t_0 across the external inductance L_e and the coil of radius R_c and length l, I is the current, C is the capacitance of the condenser bank, and $L(t)$ is the inductance of the coil-plasma system at time t. For an adiabatic radial compression we have $H^2/8\pi = NkT$ and $N/N_0 = (T/T_0)^{\gamma-1} = (R_0/R_p)^2$, where $\gamma = C_p/C_v$, R_0 is the plasma radius at time t_0, R_p is the plasma radius at time t, and N is the number density (ions and electrons)/cm^3 at time t. If the translational relaxation time is long compared to the compression time, then there are only two degrees of freedom and we may take $\gamma=2$ and obtain solutions of (1) in closed form. If the time of compression is long compared to the relaxation time, then $\gamma \sim 5/3$. However, for the present purpose, a 20% inaccuracy in γ is of little importance since we seek only rough estimates of the parameters which characterize the state of the compressed plasma.

For $\gamma=2$, one finds[4]

$$\frac{N}{N_0} = \frac{T}{T_0} = \frac{I}{I_0} = \left(\frac{R_0}{R_p}\right)^2 = \frac{1}{\mathcal{J}_0}\sin\tau + \cos\tau, \qquad (2)$$

with

$$\tau \equiv \frac{t-t_0}{[(L_0+L_e)C]^{\frac{1}{2}}},$$
$$t_0 = [(L_0+L_e)C]^{\frac{1}{2}} \sin^{-1}\left[\frac{I_0}{V_0}\left(\frac{L_e+L_0}{C}\right)^{\frac{1}{2}}\right],$$
$$I_0 = lc\left(\frac{N_0kT_0}{2\pi}\right)^{\frac{1}{2}},$$
$$\mathcal{J}_0 \equiv \frac{I_0}{V_0}\left(\frac{L_0+L_e}{C}\right)^{\frac{1}{2}}\left(1-\frac{I_0^2(L_0+L_e)}{V_0^2C}\right)^{-\frac{1}{2}},$$

where $L_0 \equiv (4\pi^2/c^2l)(R_c^2 - R_0^2)$ and R_0 are the inductance and plasma radius at the time t_0. If the coil radius and the plasma radius are nearly equal and if the external inductance is small, then it can be shown with (2) that the maximum temperature is approximately $T_{\max} = T_0 \times$(energy stored in the condenser bank/energy stored in the plasma at t_0)$^{\frac{1}{2}}$. Suppose, therefore, that one shock heats 200 cm^3 of deuterium at an ambient density of 10^{16} atoms/cm^3 to 10^6 °K. Then the plasma energy is $\sim$55 joules. For, say, 20 000 and 200 000 joules of stored energy, temperatures of $\sim 2\times10^7$ and 6×10^7 °K are energetically possible. These estimates are admittedly crude and serve only to guide the selection of experimental parameters in designing the apparatus. It can also be shown that the time t_0 before compression can be made quite small (<0.1 μsec) by using low-inductance circuits in the condenser discharge. This has been verified experimentally.

These considerations do not apply to the plasma immediately behind the shock front, because there one cannot use the adiabatic relations. Instead it is necessary to employ the Rankine-Hugoniot relations which govern strong shock waves.[5] The molecular deuterium ahead of the advancing front is nonconductive and therefore is not influenced by the pulsed magnetic field. After the passage of the shock wave, the magnetic pressure acts on the newly formed plasma and it begins to contract. We therefore expect that the compression will be greatest some distance behind the front and that the adiabatic formulas will have some degree of applicability in this region. It should also be pointed out that at very high velocities, i.e., $\sim 20\times10^6$ cm/sec, and for densities of the order 10^{16} cm^{-3}, the mean free path in the plasma starts to increase to the point where it is not correct to treat the front as if the shock thickness is small compared to characteristic lengths of the experimental apparatus.

[3] Artsimovich, Andrianov, Bazilevskaia, Prokhorov, and Filippov, Atomnaya Energiya **1**, No. 3, 76 (1956) [translation: Soviet J. Atomic Energy **1**, No. 3, 367 (1956)]; M. A. Leontovich and S. M. Osovets, Atomnaya Energiya **1**, No. 3, 81 (1956) [translation: Soviet J. Atomic Energy **1**, No. 3, 371 (1956)]; L. C. Burkhardt *et al.*, J. Appl. Phys. **28**, 519 (1957); O. A. Anderson *et al.*, Phys. Rev. **109**, 612 (1958). See also the series of articles in Nature (January, 1958).

[4] A. C. Kolb, Proceedings of the Geneva Conference on Peaceful Uses of Atomic Energy, Vol. 31, P/345, 1958 (to be published).

[5] See, for example, reference 2.

III. EXPERIMENTAL ARRANGEMENT

The shock tubes used in this work were 3 cm i.d. and the coils around the tube were 3.6 cm i.d. with a 1-cm rectangular cross section. The coils were connected in parallel to a condenser bank and had a 1-cm spacing. Both "T" tubes and "H" tubes were used. In an "H" tube there are a pair of electrodes at both ends of the tube as shown in Fig. 1. The back straps which carry the return current provide the magnetic field which causes the electromagnetic acceleration of the plasma into the sidearm. By striking a discharge simultaneously at both ends of the tube, shock waves are generated which strike one another at the center of the tube. This shock collision brings the plasma to rest and transforms the energy of the ordered motion into thermal energy.

The high current between the electrodes at one or both ends of the tube is generated by switching a 50-kv, 0.5-μf, 700-kc/sec condenser.[6] The switch consists of a pair of electrodes in a helium atmosphere with a gap spacing sufficient to hold off the discharge voltage. It is triggered by a second trigger gap mounted inside the switch. The trigger condenser is operated at $\sim$65 kv with 0.01 μf and 1.3 Mc/sec. The delay time after triggering is less than 10^{-7} sec. In this experiment, the coils are energized by a 20-kv, 100-μf bank of 100 condensers connected in parallel. These condensers are enclosed in a steel cabinet immediately behind the tube. The condensers are arranged in four columns of 25 condensers and are connected by flat copper plates separated by 0.021 mil of Mylar. The total inductance of the external circuit, including the air gap switch, is 0.022 μh so that $(dI/dt)_{t=0}$ is $\sim 10^{12}$ amp/sec. The calculated and measured external inductance agree within 25%, the major uncertainty being the switch inductance.[7] The inductance of the coil may be estimated from the formula $L_c = 3.95\times10^{-2} R_c^2 l^{-1}$ μh for a single-turn coil whose length is large compared to the radius. For $l=20$ cm and $R_c=1.8$ cm (these dimensions are typical), one finds that $L_c=0.006$ μh. The total measured inductance, including the coil and connections to the bank, is 0.03 μh and is also in good agreement with the calculated value. These figures were obtained from an analysis of current oscillograms. The effective resistance of the circuit can be found from the damping and is $\sim$0.004 ohm. This resistance is due primarily to the air-gap switch. The time to maximum current calculated from the resistance, inductance, and capacitance is 2.6 μsec and is in accord with the observed time. The maximum current at full voltage is 950 000 amperes so that with $H \cong 0.4\pi I/l$, the maximum field for the 20-cm coil array is $\sim$60 000 gauss. The coil shown in Fig. 1 is 30 cm long so that the attainable fields in this tube are somewhat lower. It should be remarked here that much higher fields have been obtained in other experiments. Our purpose in the series of experiments reported here was not to obtain very high fields and extreme temperatures but to study the acceleration, confinement, and hydromagnetic stability of high β plasmas and to utilize this information in the design of our present high-energy devices.

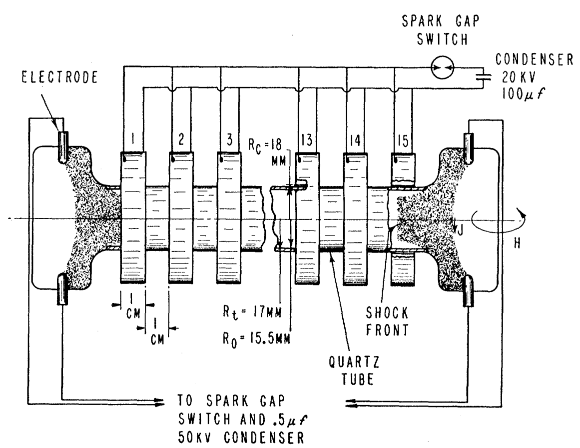


FIG. 1. Schematic illustration of the H-tube and coil arrangement.

[6] All of the data discussed in this paper were obtained at 50 kv although the condenser used can be charged to 125 kv.

[7] Since switching is a major problem in working with million-ampere discharges, the high-current switches used with large condenser banks at NRL will be described in more detail elsewhere.

IV. T-TUBE EXPERIMENTS

Studies of the dynamic stability of the radially compressed plasma behind high-velocity shock waves were carried out with T-tubes. When the large condenser bank was discharged just after the shock entered the first turn of the coil system, it was found that shock velocities of $(10\text{–}20)\times10^{-6}$ cm/sec could be maintained during the transit through the coil. Typical streak camera photographs which compare the velocity with and without an axial magnetic field are shown in Fig. 2. In the no-field case one observes a rapid attenuation due to both wall cooling and the progressive heating of deuterium gas as the shock moves along the tube. The

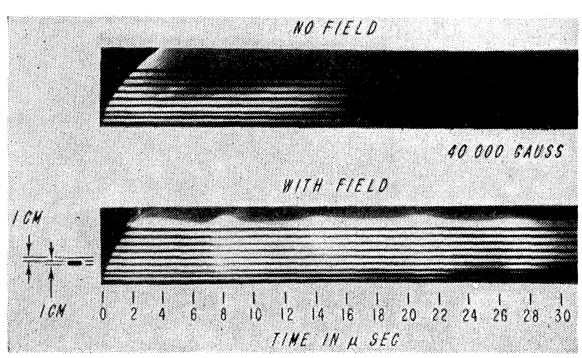


FIG. 2. Smear camera photographs of the propagation of strong shocks in deuterium (200 microns ambient pressure) with and without a confining axial field. The dark shadows are from the coils used to generate the axial field. The maximum field here was 40 000 gauss. The high initial velocity is maintained by the action of the confining field.

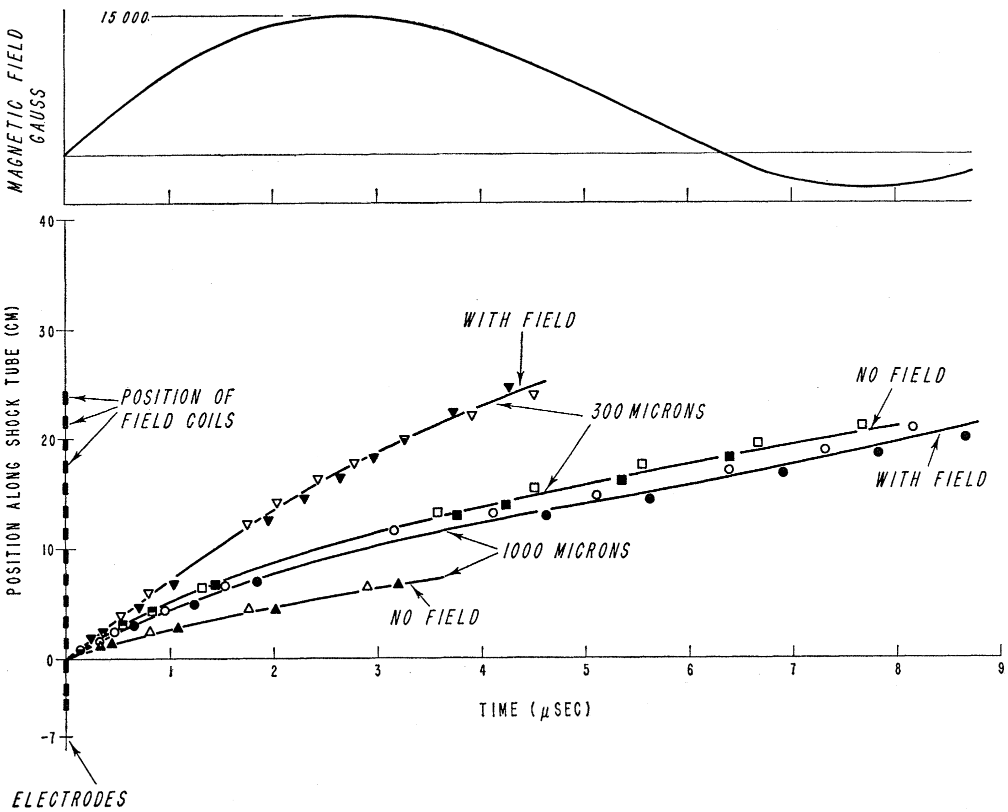


FIG. 3. Position *versus* time plot of the position of the luminous front for two ambient pressures. The open and solid data points are from two different experiments under the same conditions.

periodic bursts of luminosity when the axial field is present is due to the successive compressions and expansions of the plasma caused by the current oscillations in the 100-μf condenser bank.

In Fig. 3 we have plotted the position of the shock front as a function of the time for two different ambient densities. The black and white data points represent the degree of reproducibility that can be obtained for two different experiments under the same conditions. If the electrodeless discharge due to the pulsed axial field is delayed, then one observes that at the time the large bank is switched there is an abrupt acceleration of the front. This behavior is illustrated in Fig. 4 where a smear camera photograph shows this acceleration 5 μsec after the shock passes the first coil. On this photograph one can also observe the radial compression of the plasma at two points on the tube (denoted there by "image rotator"). At these points the abscissa is the plasma radius. A T-tube with coils and two image rotators, photographed in its own light, is shown in Fig. 5. The compression here is approximately $\frac{1}{3}$ of the tube radius. The compressed plasma is remarkably stable. There is no evidence here of any instability of the plasma column. An examination of the original negative shows that there is apparently a sharp boundary established between the luminous plasma and the external magnetic field. The plasma radius is observed to follow the periodic oscillations of the field. The radial compression also appears to be adiabatic on the first compression since radial shock waves are not observed. This is in accord with the expectations outlined previously in II.

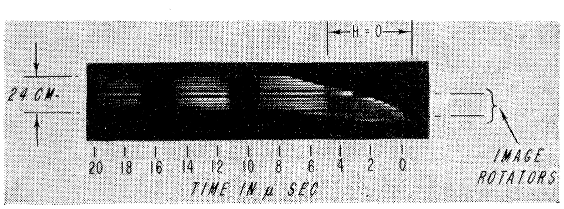


FIG. 4. Acceleration of a deuterium plasma as a result of the compression due to a rising axial field delayed 5 μsec. The radial compression can be observed at two positions along the tube by using image rotators (see Fig. 6).

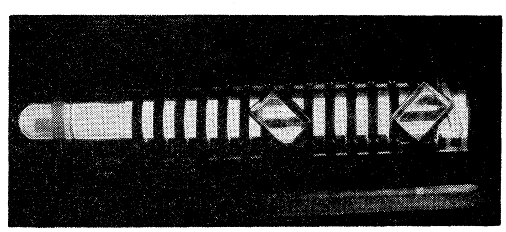


FIG. 5. T-tube and field coils photographed in its own light showing position of image rotators. The initial acceleration occurs at the right of the figure.

The compression, radial stability, and high velocity during the compression cycle are also illustrated in Fig. 6. In this case the external field was switched approximately 1 μsec after the shock entered the coil. After the time of maximum compression (at maximum current) the shock velocity begins to decrease as the plasma column starts to expand. For purposes of comparison, a smear camera photograph of the propagation of a shock wave without a confining field is also shown in Fig. 6. In order to observe the plasma as it leaves the far end of the coil when the axial field is large, an 8-turn coil was used. There is a sharp deceleration after the plasma leaves the magnetic channel as can be seen in Fig. 7 for a shock wave in deuterium.

The various observations have demonstrated that high shock velocities in deuterium (~Mach 100) can be maintained by driving a shock-heated plasma radially away from the walls of the shock tube. The compression raises the internal energy of the plasma and this markedly influences the velocity. We also have the interesting result that in this geometry the compressed plasma column is stable in the center of the tube in contrast to the unstabilized pinch discharge.

V. H-TUBE EXPERIMENTS

The electrodes at both ends of an H-tube are connected in parallel to a high-voltage condenser of the type described in Sec. III. It is possible to fire the parallel gaps simultaneously with an electrode separation of 2–3 cm because of the low ambient pressures (0.1–1.0 mm Hg). This result is in accord with recent studies of the ignition of high-voltage discharges in hydrogen.[8] The two shock waves are observed to strike one another very nearly at the center of the tube from smear camera photographs (Fig. 8). A comparison of the film blackening with and without an axial containing field shows that there is considerably more light if there is no containment. This is due to influx of silicon and oxygen from the tube walls which are responsible for most of the radiation. The magnetic insulation reduces the impurity level and consequently less light is emitted. At temperatures above 30 000 °K the deuterium is fully ionized so that there is no line

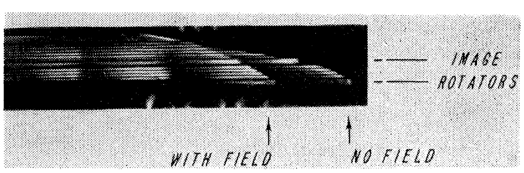


FIG. 6. Smear camera photographs with and without confining field (double exposure) showing radial compression and the stability of the confined plasma. The time and distance scale are the same as in Fig. 5. The velocity falls off rapidly as the field decreases in magnitude. The ambient pressure was 400 microns deuterium with a maximum field of 15 000 gauss.

[8] A. S. Pokrovskia-Sobeleva and B. N. Kliarfel'd, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 993 (1957) [translation: Soviet Phys. JETP **5**, 812 (1957).

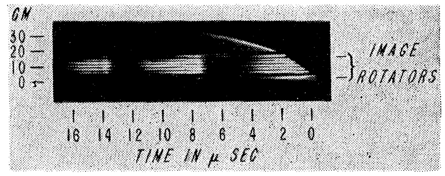
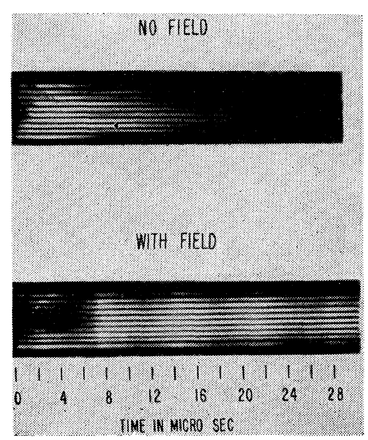


FIG. 7. Smear camera photograph showing the sharp deceleration of the luminous front as the plasma leaves the magnetic channel. The ambient pressure was 200 microns deuterium and the maximum field is 30 000 gauss.

spectrum and the radiation is mainly due to bremsstrahlung and recombination in the ionized gas. The greatly increased radiation intensity after the first half-cycle of the axial field is also caused by impurities picked up from the walls during the time that the field is near zero. One also observes that the velocity of the reflected shock after collision at the tube center is much greater due to the greater sound speed in the compressed plasma relative to the sound speed when the plasma is not magnetically contained. The interval between the time that the primary shock enters the coil and the time that reflected shock leaves is ~3 μsec. During this time the effect of end losses should not be serious. To extend this time interval it is necessary to use correspondingly longer tubes or to trap the plasma in the coil by magnetic mirrors[9,10] at the tube ends.

By these general methods and by utilizing higher magnetic fields with longer containment times, there are now experimental indications that temperatures in the thermonuclear range are feasible. Experiments with this object are now in progress that employ a 285 000-joule condenser bank rated at 20 kv with 1430 μf. There are 99 Tobe-Deutschmann capacitors connected in parallel by large copper plate transmission lines. The total external inductance is ~0.003 μh. This figure is somewhat variable and depends on the switch inductance. The short circuit

FIG. 8. Shock collision in a 20 cm H-tube with 200 microns deuterium and $H_{\max}=60\,000$ gauss. The reduced luminosity after collision is due to lower impurity concentrations from wall vaporization with a confining field. Radiation from silicon and oxygen produces most of the light in the no (axial) field case and in the bursts of light from the ringing of the field coil.



[9] R. F. Post, Bull. Am. Phys. Soc. Ser. II, **3**, 196 (1958).
[10] L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956), pp. 11, 12.

current capability is $\sim 15\times 10^6$ amperes in 2.8 μsec with $dI/dt \sim 6\times 10^{12}$ amp/sec. With this apparatus, fields of 100 000–500 000 gauss have been generated with magnetic pressures up to $\sim$10 000 atmospheres in a single-turn coil with magnetic mirrors, producing high-energy radiation at the time of maximum current as observed through 2 cm Pb on a scintillation counter.[4,11]

[11] *Note added in proof.*—A similar apparatus (Scylla) has been assembled at the Los Alamos Scientific Laboratory and measurements of neutron production have been reported by Boyer, Elmore, Little, and Quinn, Proceedings of the Geneva Conference on Peaceful Uses of Atomic Energy, Vol. 32, P/356 (1958); Elmore, Little, and Quinn, Phys. Rev. Letters **1**, 32 (1958).

ACKNOWLEDGMENTS

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Absorption Spectrum of KCl:Tl at Low Temperatures

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The ultraviolet absorption spectrum of thallium in single-crystal potassium chloride has been accurately measured down to 187 mμ at 295°, 77°, and 4°K. The asymmetry apparent in both major bands at room temperature disappears at low temperature. The existence of two kinds of singlet thallium centers in slightly different crystalline environments is suggested as a possible explanation.

THE general structure of the optical absorption spectra characteristic of thallium in alkali halide crystals has been known for some time. It consists of two principal bands called the A and C bands and a much weaker B band ($\lambda_A > \lambda_B > \lambda_C$). These absorptions and two emission bands associated with them have been ascribed to a center composed of a substitutional thallium ion and its chlorine nearest neighbors. A "configuration coordinate diagram," which gives the energy levels of the center as functions of a distance parameter, has been proposed by Seitz and developed quantitatively for KCl:Tl by Williams to explain the center's behavior. Inherent in the model is the assumption that the absorption and emission bands are simple and Gaussian in shape. Recent excitation data[1] have indicated that another more complex center is active in the A-band region and is responsible for the visible emission band. The present absorption data show further complexity in both A and C bands. The absorption measurements were made with a Cary model 14M recording spectrophotometer with which considerably greater accuracy and detail can be obtained than has been previously available, particularly in the short-wavelength C band. The data were taken at 295°, 77°, and 4°K using a Dewar described elsewhere.[2] The single crystal used was grown by the Kyropolous technique and had a Tl concentration in the crystal of about 19 ppm. Results of identical runs without samples were subtracted from the data before plotting.

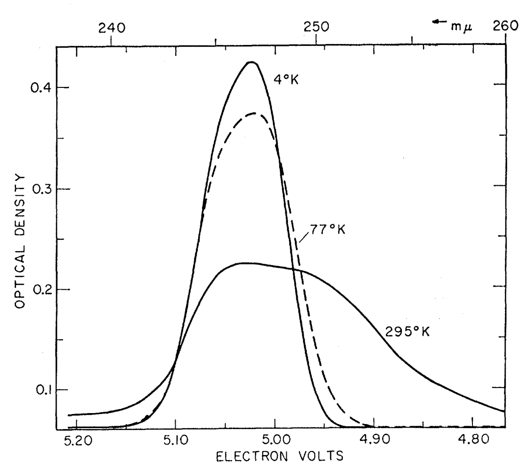


FIG. 1. The A-band absorption in KCl:Tl.

The A band is shown in Fig. 1. The general behavior with temperature is similar to that of the excitation spectrum for ultraviolet emission[1] and to previously published absorption data.[3] The absorption half-width at room temperature (0.202 ev) matches Johnson and Studers'[3] value very well. The low-temperature half-widths however are about 15% lower, with measured values of 0.107 ev at 77° and 0.094 ev at 4°K. In addition, the band at low temperatures is very nearly symmetric, in contrast to the obvious asymmetry found at room temperature. Thus it is apparent that the room-temperature absorption half-width must not be used to compute or check the simple configuration

[1] D. A. Patterson and C. C. Klick, Phys. Rev. **105**, 401 (1957); K. H. Butler, J. Electrochem. Soc. **103**, 508 (1956).
[2] G. A. Russell and C. C. Klick, Phys. Rev. **101**, 1473 (1956).
[3] P. D. Johnson and F. J. Studer, Phys. Rev. **82**, 976 (1951).

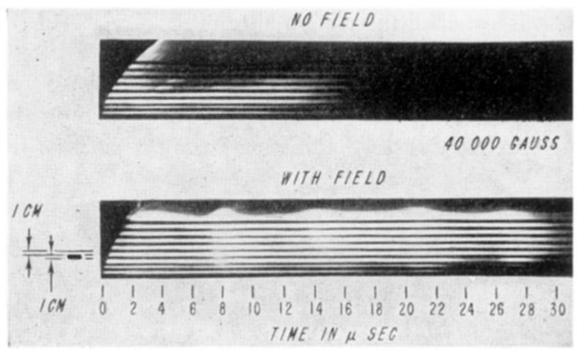
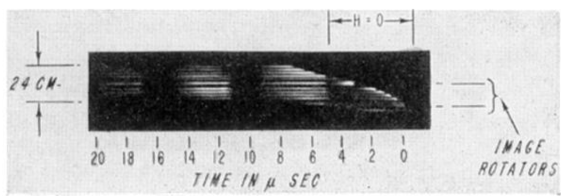


FIG. 2. Smear camera photographs of the propagation of strong shocks in deuterium (200 microns ambient pressure) with and without a confining axial field. The dark shadows are from the coils used to generate the axial field. The maximum field here was 40 000 gauss. The high initial velocity is maintained by the action of the confining field.



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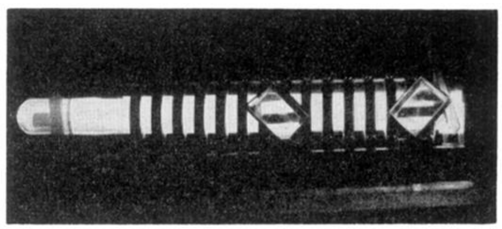

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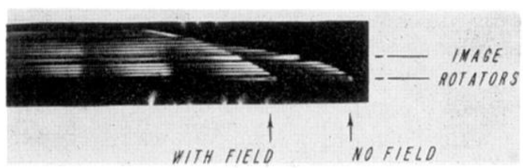

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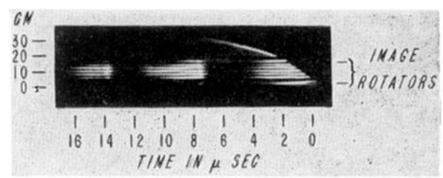

FIG. 7. Smear camera photograph showing the sharp deceleration of the luminous front as the plasma leaves the magnetic channel. The ambient pressure was 200 microns deuterium and the maximum field is 30 000 gauss.

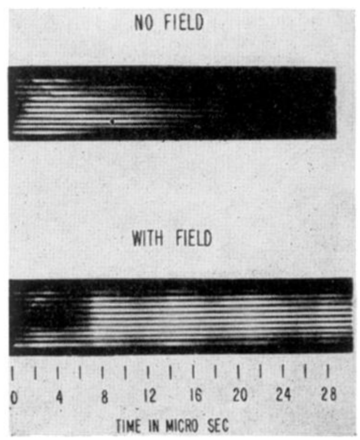

FIG. 8. Shock collision in a 20 cm H-tube with 200 microns deuterium and $H_{max}=60\,000$ gauss. The reduced luminosity after collision is due to lower impurity concentrations from wall vaporization with a confining field. Radiation from silicon and oxygen produces most of the light in the no (axial) field case and in the bursts of light from the ringing of the field coil.