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LABORATORY OBSERVATIONS OF MAGNETOHYDRODYNAMIC SHOCK WAVES

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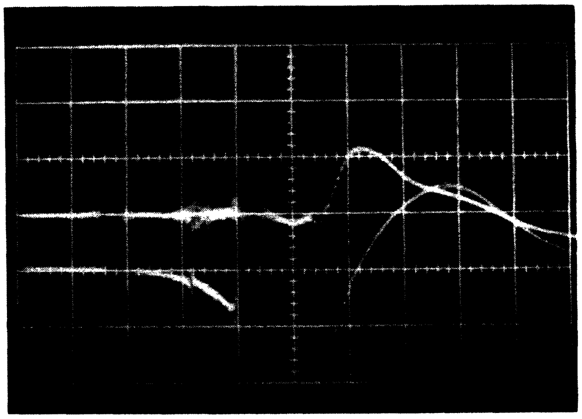
Observations in a magnetically driven shock tube of the inverse pinch type have confirmed the basic differences predicted in an earlier paper[1] between the flow when the gas is initially cold (nonconducting) and when it has been rendered appreciably conducting by some type of preheating. To our knowledge, these are the first experiments in which these differences have been verified.

When a discharge is initiated in an inverse pinch tube and the gas is initially highly conducting, the magnetic piston will produce a true magnetohydrodynamic shock wave whose propagation speed is greater than or equal to the "combined speed" for infinitesmal disturbances, $(a_0^2+b_0^2)^{1/2}$, where a_0 and b_0 are respectively the ordinary acoustic and Alfvén speeds in the ambient fluid. For the case where the driving current increases linearly with time and the conductivity approaches ∞ (i.e., $Re_m \rightarrow \infty$), an exact simularity solution can be found.[2] It is found that for a given condenser bank voltage and initial pressure the shock speed increases as the ambient axial magnetic field B_{z_0} is increased. There is a jump in B_z at the shock front followed by a decrease at the piston.

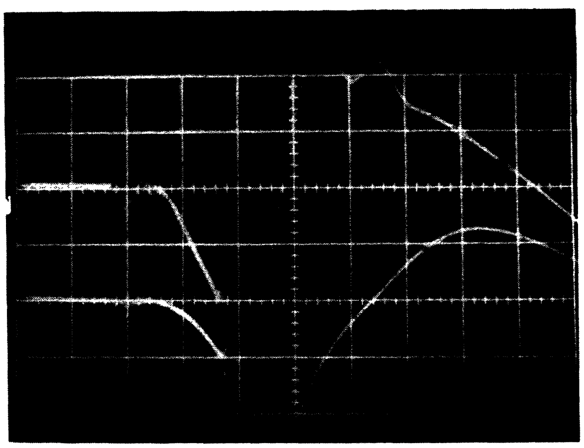
If, however, the discharge is initiated without preheating the gas, the flow is quite different. The shock wave then propagates into a cold gas, and for the limit where the magnetic diffusivity is larger than either the thermal or viscous diffusivities throughout the shock region, there is no compression of the field across the shock, and the jump conditions are given by the familiar Rankine-Hugoniot relations.[3] The effect of increasing the ambient field is to slow the piston and hence also to retard the shock, in contrast to the corresponding case for real magnetohydrodynamic shocks.

In previously reported experiments[1] the gas was not preionized and the flow was found to be as described above. Preheating was accomplished in the present experiments by discharging a preionization bank into the chamber, operating as an inverse pinch. The preheating current oscillates through several cycles and sends out a series of shocks which heat the gas by a combination of Ohmic and shock heating. It has been found by crude time and space resolved spectroscopy that after about 100 μsec, argon at initial pressures of from 0.1 to 1 mm Hg has relaxed to a fairly uniform state with a temperature of approximately 15 000°K. At this time the main bank is fired, sending out the wave which is studied.

Theoretical studies[4,5] of collision-dominated[6] shock structure indicate that the magnetic Reynolds number based on shock thickness should be about 1 for shocks with Alfvén Mach numbers near 5. Thus, in the present experiments we expect a "shock thickness" of the order of two or three cm which is not negligible compared to the radius of curvature. Hence, there exists a compression zone rather than a real shock, and, while the flow is qualitatively the same as that for infinite conductivity, it differs quantitatively.



(a) Without Preheating
Sensitivity: .5 v/cm., upper & lower
Sweep: 1 μ sec/cm



(b) With Preheating
Sensitivity: .2 v/cm., upper; .5 v/cm., lower
Sweep: 1 μ sec/cm

FIG. 1. Magnetic probe signals.

Figures 1(a) and 1(b) show the output of magnetic probe traces without and with preionization, respectively. The upper trace in each picture is the output of a $\dot{B}_z$ probe, where negative deflection corresponds to positive $\dot{B}_z$. The lower trace is the output of the $\dot{B}_\theta$ probe, again with negative deflection indicating a positive signal. These traces were obtained with 10 turn, 1 mm diameter coils encased in a 3 mm diameter glass envelope inserted radially into the chamber. The probes were positioned 1.8 in. from the chamber center in both cases and the ambient gas was argon, whose pressure at room temperature was 1 mm.

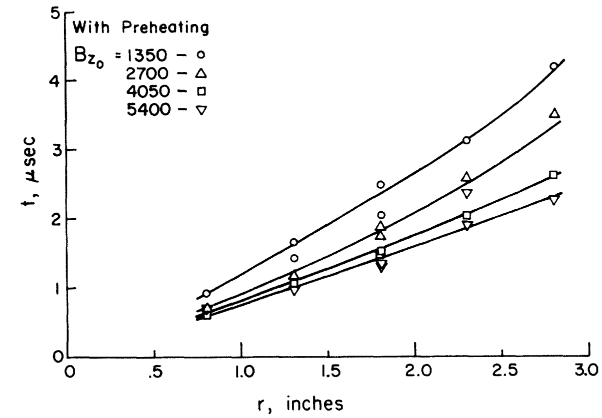


FIG. 2. Trajectory of $\dot{B}_z$ peak as a function of initial axial magnetic field in gauss.

Open loop probes of the type described by Camac et al.[7] were tried and gave identical results. The important feature in these photographs is that in 1(a), without preheating, there is no compression of the axial field; rather the only change in B_z occurs when it is swept away by the advancing current sheet. However, when the gas is initially conducting, a definite compression of the axial field occurs before it is swept away by the piston [Fig. 1(b)]. If the traces are integrated, the compression is found to be only 1/3 to 1/2 of that predicted by the infinite conductivity theory; this is not surprising, however, for the reasons given above.

The substantial width of the "shock region" is actually somewhat beneficial as it makes possible crude measurements of shock structure. The use of pressure probes[8] in conjunction with $\dot{B}_z$ probes shows a sharp pressure jump occurring at the back of the region of magnetic compression for low initial fields. At higher B_{z_0} the sharp pressure jump disappears completely. This change-over from a "shock within a shock" to a smooth transition is in qualitative agreement with the shock structure described by Marshall.[5]

Figure 2 shows the trajectory of the point of maximum $\dot{B}_z$, which corresponds very closely to the point of steepest B_z compression, for experiments in argon at 1/2 mm Hg initial pressure. It is seen that the "wave speed" thus defined increases with ambient axial field in accordance with theory. The steep pressure pulse at the back of the wave, in cases where it exists, does not speed up with increasing B_z, indicating that the thickness of the transition region grows continuously during its traversal of the chamber.

Therefore the wave is not fully formed during this time, which is quite reasonable.

Experiments have been run at several pressures in argon and helium and qualitatively similar behavior is obtained.

In conclusion, in the presence of strong preheating the compression zone displays true magnetohydrodynamic characteristics with strong coupling between the gas and electromagnetic fields, as distinct from the ordinary shocks which are observed in the absence of preheating.

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[1]G. C. Vlases, J. Fluid Mech. 16, 82 (1963).

[2]C. Greifinger and J. D. Cole, Phys. Fluids 4, 527 (1961).

[3]A. G. Kulikovskii and G. A. Lyubimov, Rev. Mod. Phys. 32, 977 (1960).

[4]Z. O. Bleviss, Heat Transfer and Fluid Mechanics Institute Preprints of Papers, 1959 (unpublished), p. 27.

[5]W. Marshall, Proc. Roy. Soc. (London) A233, 367 (1955).

[6]The parameters in these experiments are such that the mean free path is smaller than the Larmor radius.

[7]M. Camac et al., Suppl. Nucl. Fusion, Pt. 2, 423 (1962).

[8]H. W. Liepmann and G. Vlases, Phys. Fluids 4, 927 (1961).

FARADAY ROTATION FOR THE F BAND IN KCl†

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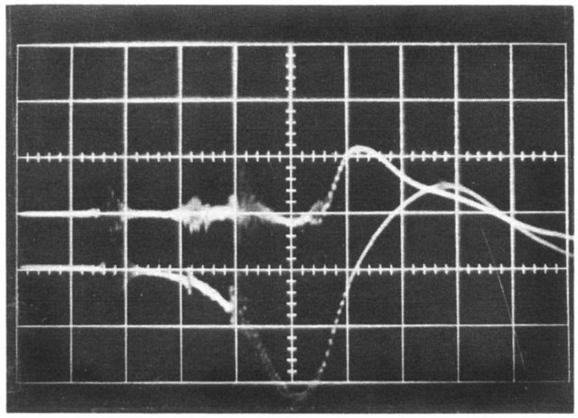
Although measurements with electron spin resonance[1] and electron nuclear double resonance[2] have provided accurate information about the magnetic splitting of the F-center ground state, there is a complete lack of corresponding knowledge about the excited state of this center. Zeeman experiments in absorption offer a means of investigating the magnetic splitting in the unrelaxed excited state; however, the expected splitting of about 10^{-4} eV would be difficult to detect in the presence of a F-band width of about 0.2 eV.

Faraday rotation, on the other hand, is a sensitive means of detecting small changes in the dispersive properties of crystals in a magnetic field. Dexter[3] calculated the extra dispersion introduced into a KCl crystal by the presence of F centers. With certain assumptions about the magnetic energy levels involved, he predicted the spectral dependence for Faraday rotation. A quantitative comparison with earlier experimental work[4,5] proved impossible because of experimental uncertainties and lack of detail.

In our experiment a dynamical method of measurement is used. Light from a Leiss double monochromator is plane polarized and focused onto the sample which is located at the center of a 50-kilogauss superconducting solenoid in a liquid helium Dewar. The transmitted light passes through a rotating polarizer and is detected by a photomultiplier. The resulting alternating signal is compared in phase with a reference signal of the same frequency by means of an amplitude-independent phase meter. Any rotation of the plane of polarization of the light as it passes through the crystal is directly observed as a phase shift between the two alternating voltage signals.

After a measurement of the Faraday rotation in the uncolored KCl crystal, F centers are introduced either by additive coloration or by room-temperature x irradiation of KCl doped with H^- ions.[6] Both coloration techniques produce essentially the same Faraday rotation results. The optical density as a function of wavelength is measured to insure that only F centers are present. With a crystal at 4.2°K the rotation is recorded as a function of magnetic field for different wavelengths in the F-band region. A linear variation of rotation with applied magnetic field up to the highest field of 50 kilogauss is observed so that a meaningful Verdet constant can be defined. Figure 1 shows the wavelength dependence of the rotation at 4.2°K and 65°K for a typical KCl crystal containing F centers. A study of the temperature dependence of the rotation shows clearly that two distinct contributions to the rotation are involved. At temperatures exceeding about 40°K the magnitude of the total effect is



(a) Without Preheating
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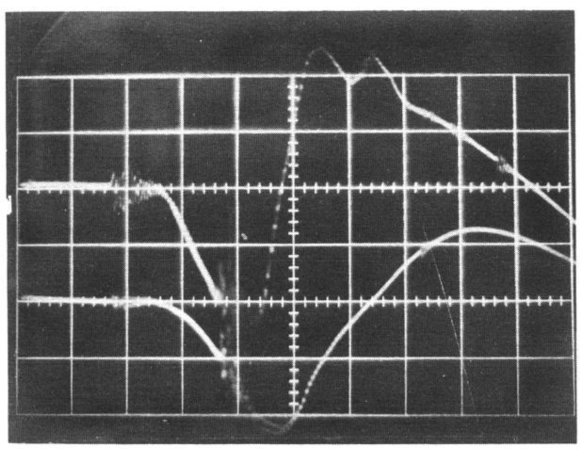

(b) With Preheating
Sensitivity: .2 v/cm., upper; .5 v/cm., lower
Sweep: 1 μ sec/cm

FIG. 1. Magnetic probe signals.