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DIAGNOSTICS FOR THE MAGNETIC COMPRESSION
EXPERIMENT TO PRODUCE METALLIC HYDROGEN

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FOREWORD

This is a summer activities report prepared by the author, covering his investigations at Lawrence Livermore Laboratory from June 5 to August 9, 1974. His permanent address is:

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DIAGNOSTICS FOR THE MAGNETIC COMPRESSION EXPERIMENT TO PRODUCE METALLIC HYDROGEN

INTRODUCTION

The assigned problem was to look for and consider various diagnostic techniques for determining several of the experimental parameters in the magnetic compression experiment, as applied to producing the metallic phase of hydrogen. Possible techniques for obtaining sample chamber volume, pressure, and magnetic flux density were of interest, as were methods for ascertaining the attainment of the metallic phase and determining its resistance or superconductivity. In this report a number of possible measurement techniques are discussed; in some cases, it is suggested that the technique is impractical. In other cases, the technical implementation of the technique discussed may prove too difficult or costly. However, it is hoped that some of the diagnostic techniques considered may prove useful or at least lead to useful approaches. In some cases, even negative recommendations may be valuable in saving others time and thought. Finally, a few miscellaneous thoughts are introduced concerning various aspects of the subject.

SOME POSSIBLE TECHNIQUES RELATING TO SAMPLE-CHAMBER VOLUME MEASUREMENT

Volume Measurement Using Optically Transparent Anvils

In this scheme for determining the sample-chamber volume, sapphire anvils could be used. However, since the technique depends on the transmission of light through the sample tube, the anvils should either end abruptly (i.e., not be tapered), be step-tapered, or have a short, smooth taper as shown in Figs. 1a, 1b, and 1c, respectively. If the remainder of the tube containing the hydrogen is optically unobstructed (at least partially) and an argon flash illuminates one end of the tube, a high-speed framing camera (or a streaking camera) could be used to determine the minimum radius of the sample chamber, as long as the hydrogen (or other sample) remains essentially transparent. A smooth curve (determined partially by past experience or computer code) could then be drawn between points A-A on the anvils, through this measured minimum-radius point. Thus, the measured value of minimum radius could be used to determine the sample-chamber volume from a computer code or a previously calculated table.

Note that when the hydrogen reached the metallic transition, all light transmission would cease, and thus the relative volume of the phase transition would be known.

Fig. 1. Possible anvil configurations.

Fig. 2. Sample chamber, anvils, and coils.

The outer coil could be of gold or silver evaporated onto an anodized insulating coating on the interior of the sample tube, or it could be of copper wire initially held in place by a thin annular plastic form.

On the symmetry plane through the center of the chamber and perpendicular to the z axis, $\vec{B}$ will be uniform and in the z direction, provided there is reflection symmetry about this plane, as well as axial rotational symmetry. This may be proved simply by noting that, due to symmetry, $B_\phi = 0$ everywhere, and $B_r = 0$ everywhere

This procedure could be used with or without the center conductor discussed later in this report. Moreover, the smaller compression of the sapphire anvils could be determined (as the radiograph does the silver anvils) by affixing, e.g., gold marking lines or points to the sapphire anvils and following these in the framing-camera pictures, or possibly providing a one-time fix with the x-ray source. In the case of the step-tapered anvils, circles should automatically appear on the framing-camera photographs, so that gold markers would be unnecessary here.

Volume Measurement Using Two Coils

Consider the magnetic compression sample chamber arrangement shown in Fig. 2. Here a relatively incompressible dielectric rod (perhaps Al_2O_3 or possibly an even less compressible material, such as diamond) is fixed in the center of the sample chamber. It could be made the same diameter as the center conductor discussed in other sections to keep the experiment as similar as possible under the two sets of conditions. A coil of N_1 turns is wound about the dielectric rod at the center of the sample chamber (coil 1), and a second coil of N_2 turns is placed at the inner wall of the sample tube. The outer coil could be of gold or silver evaporated onto an anodized insulating coating on the interior of the

on the transverse reflection symmetry plane. Thus, $(\partial B_r / \partial r) = 0$ and $(\partial B_\phi / \partial \phi) = 0$, also on this plane. Now

$$\nabla \cdot \vec{B} = \frac{1}{r} \frac{(rB_r)}{\partial r} + \frac{1}{r} \frac{\partial B_\phi}{\partial \phi} + \frac{\partial B_z}{\partial z} = 0, \quad (1)$$

$$= \frac{\partial B_r}{\partial r} + \frac{1}{r} B_r + \frac{1}{r} \frac{\partial B_\phi}{\partial \phi} + \frac{\partial B_z}{\partial z} = 0, \quad (2)$$

or

$$\frac{\partial B_z}{\partial z} = 0, \quad (3)$$

and

$$B_z (\text{center plane}) = \text{constant}. \quad (4)$$

The terminal voltage for coil₁ (the center coil) is then

$$V_1 = -N_1 \frac{d\phi_1}{dt} = -N_1 \frac{d}{dt} (A_1 B) = -N_1 A_1 \frac{dB}{dt}, \quad (5)$$

where for the present discussion A_1 is assumed to remain approximately constant. For coil 2 (the outer coil)

$$V_2 = -N_2 \frac{d\phi_2}{dt} = -N_2 \frac{d}{dt} (A_2 B) \quad (6)$$

$$= -N_2 \left(A_2 \frac{dB}{dt} + B \frac{dA_2}{dt} \right) \quad (7)$$

since the area A_2 will certainly vary with time in this case. Thus, the magnetic flux in the sample chamber may be determined, using a simple integrator, from Eq. (5) in terms of V_1 .

$$B(t) = -\frac{1}{N_1 A_1} \int_0^t V_1 dt. \quad (8)$$

Now, considering $B(t)$ as known from Eq. (8), the cross-sectional area (A_2) of the sample chamber at the center plane can be found from Eq. (6) in terms of V_2 .

$$A_2(t) = \frac{-1}{N_2 B(t)} \int_0^t V_2 dt. \quad (9)$$

From this the volume of the sample chamber could be found to a good approximation as discussed previously in the section on volume measurement with transparent anvils (p. 1).

The error introduced by assuming that A_1 (of the dielectric rod) remains constant could be eliminated by determining $A_1(t)$ by simple optical transmission during the shot, as recorded by a framing camera. Then $A_1(t)$ can be considered as a known quantity in Eq. (8), although not a constant.

Note that when the transition to metallic hydrogen occurs, the behavior of the coil voltages has very interesting aspects, depending upon whether the metallic hydrogen becomes superconducting or a normal conductor. If the transition were to a normal conductor of moderately high conductivity, one would expect the flux to be "frozen", for the short times of interest, and both voltages to become very small or zero. If the transition were to a superconducting state, then due to flux exclusion, one would expect the flux within coil 1 to increase and that in coil 2 to decrease. Thus V_1 would continue with the same sign (say negative), while V_2 would reverse sign.

It is interesting to speculate that too large a magnetic field within the sample chamber might exceed the critical field of the metallic hydrogen and prevent it from becoming superconducting (if it should have that tendency). Also, considering the combination of some critical field and the great disparity in flux densities at the inner and outer surfaces of the sample tube, it appears highly unlikely that any significant backpressure could result on the sample tube from interior flux buildup at the inner surface of the sample tube due to flux exclusion. Note that the two-coil system, as considered to this point, would allow the simultaneous optical probing experiments discussed on p. 2, but would probably preclude any high-frequency transmission experiments, with or without a center conductor. Coaxial-line TEM experiments involving only reflection, as used in the past, could probably still be performed, however.

An interesting extension of the two-coil method discussed above would involve extending the coils the length of the sample chamber. For purposes of discussion, assume that the anvils are sapphire and that the inner coil is continued in some manner up the tapered part of the anvils, as shown in Fig. 3. Let both the inner and outer coils have the same pitch and the same number of turns. Let V_1^m and V_2^m be the voltages produced by only the m th turn of coils 1 and 2, respectively, and let A_1^m and A_2^m be the cross-sectional area encircled by turn m of coils 1 and 2, respectively. Then

$$\frac{A_2^m(t)}{A_1^m(t)} = \frac{\int_0^t V_2^m dt}{\int_0^t V_1^m dt} \quad (10)$$

Fig. 3. Double-coil arrangement.

Thus, for a moderate number of equally spaced turns

$$\frac{\text{vol}_2}{\text{vol}_1} = \frac{\int_0^t V_2 dt}{\int_0^t V_1 dt}, \quad (11)$$

where vol_1 is the volume within coil 1, vol_2 is the volume within coil 2, and the sample-chamber volume is given by

$$\text{Chamber vol} = \text{vol}_2 - \text{vol}_1. \quad (12)$$

If the coils were connected in series subtracting, a voltage proportional to the sample-chamber volume would be produced.

Suggestion for Possible Improvement in Accuracy of Sample-Chamber Volume Determination by Radiograph

The position of the sample-chamber walls as determined from the radiograph is somewhat uncertain due to blurring of the edges. This blurring results from several factors, among which are: (1) the tube edges may often be moving as the exposure is made, and (2) the thickness of the sample-tube wall which the x rays must penetrate does not increase and decrease sharply (see Fig. 4) but, instead, changes, gradually, giving rise to more gradual changes of exposure level.

The first source of blur can be reduced by choosing the time of the x-ray flash to coincide as nearly as possible with the turnaround time of the sample tube. This may or may not be desirable, depending upon the desired volume point and the particular measurement desired.

The second source of blur could perhaps be reduced by plating the sample tube (of copper or silver) with a thin layer of lead or gold inside and out. Alternatively, the picture might be further sharpened if two narrow lines of lead or gold were plated on the inner and outer surface of the sample tube; the lines would lie in the same plane through the axis of the tube

Fig. 4. X rays passing through cylinder.

Fig. 5. Lead lines on sample chamber.

and perpendicular to the x-ray beam (see Fig. 5). These lines might tend to delineate the edges of the sample tube on the x-ray picture. For this particular consideration, a large contrast in material atomic number would probably be most desirable. Thus for this case, a copper tube would appear more desirable than silver. The use of a single line of absorptive material has the possible disadvantage that it introduces some circumferential asymmetry, which could give rise to some asymmetry in the radial movement of the sample tube.

ELECTROMAGNETIC WAVE REFLECTION AND TRANSMISSION EXPERIMENTS

The method which has been used thus far to determine the transition point to metallic hydrogen uses a train of electromagnetic pulses at 16.45-MHz repetition rate, reflected from the material in the sample chamber. The transition from the molecular to the metallic state can then be observed as a change from a near +1 reflection coefficient for an open circuit to a near -1 reflection coefficient for a short circuit. Although it appears that this is a satisfactory technique to indicate the occurrence of the transition, it can give only a very rough upper limit of the resistivity of the metallic state. Thus it may be desirable to have some corroborating data from one or more slightly different techniques. Some possibilities are discussed below. These may be divided on the basis of whether a center conductor through the sample chamber is required or not.

Diagnostics with a Center Conductor in the Sample Chamber

In this configuration a center conductor would pass through both anvils and the sample chamber. This can be done in two different ways: (1) the anvils themselves could be made of dielectric material (e.g., Al_2O_3), or (2) the anvils could be constructed of conducting material (e.g., silver) and a dielectric sleeve placed around the center conductor, separating it from the anvil. In both cases, during the course of the implosion, there will be a difference in dielectric constant, as well as a difference in outer conductor diameter between the anvil region and the sample-chamber region of the transmission line. Also, both the diameters and the dielectric constants will change during the implosion. Thus, for each of these two cases, a large fraction of the incident signal will be reflected. However, a portion of the incident wave will also be transmitted until the metallic phase of the hydrogen is reached. At the time of phase transition the transmitted signal will drop to zero or nearly zero, depending on the conductivity of the metallic phase. Since the most important diagnostic period occurs around this transition time, it appears that the second configuration (i.e., the metallic anvils) is more appropriate when viewed in terms of this electromagnetic wave diagnostic alone. This results from the fact that the maximum transmitted signal can be expected at the time of minimum sample chamber diameter for this configuration, before the metallic phase is reached. At the time of phase transition, the transmitted signal would suddenly approach zero.

Fig. 6. (a) Sample chamber with center conductor; (b) equivalent circuit.¹

Consider first the case of metallic anvils (case 2), as shown in Fig. 6. For the moment assume only continuous-wave (cw) sinusoidal excitation. The characteristic impedance in the anvil region is given by

$$Z_0 = \frac{1}{2\pi} \frac{\eta_0}{\sqrt{\epsilon_{r1}}} \ln \frac{b}{a}, \quad (13)$$

where η_0 is the intrinsic impedance of free space; i.e.,

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377 \, \Omega \quad (14)$$

and ϵ_{r1} is the relative permittivity of the dielectric sleeve. In the sample-chamber region between the anvils (length ℓ)

$$Z_0 = \frac{1}{2\pi} \frac{\eta_0}{\sqrt{\epsilon_{rH}}} \ln \frac{d}{a}, \quad (15)$$

where ϵ_{rH} is the relative permittivity of the molecular hydrogen. The equivalent circuit for this configuration is shown in Fig. 6b. If the anvils were not tapered but ended abruptly at the sample-chamber interface, the susceptance B would be capacitive, with the capacitance as given in Ref. 1. For the more complicated situation of the tapered anvils, the susceptance B can be determined experimentally by letting the sample chamber length ℓ be $\lambda/2$, thus producing the same reflection as from a susceptance of $2B$. Note that as implosion occurs, the difference in coaxial line diameters at the sample-chamber interface will decrease, thus reducing the susceptance B . This would indicate that as implosion takes place, the reflected signal should diminish and the transmitted signal increase until the metallic phase transition occurs. At this point the reflected signal should approach the amplitude of the incident signal, and its phase should correspond to the 180° phase shift of the reflection coefficient. The transmitted wave should fall to zero or nearly zero. Any nonzero value of the transmitted signal at this time could be used to roughly determine the conductivity of the metallic phase. However, it seems very unlikely that any transmitted signal will be detectable if the metallic phase is truly reached. The propagation constant in the sample chamber for the metallic phase would be

$$\gamma = \sqrt{j\omega\mu_0\sigma} \quad (16)$$

if $\omega\epsilon \ll \sigma$ and if it is assumed that the metallic phase is nonmagnetic. Here σ is the conductivity of the metallic hydrogen.

The depth of penetration for the highest resistivity commensurate with past experiments ($\rho = 0.047 \Omega \cdot \text{cm}$) and a frequency of 10 MHz (the lowest frequency which seems practical here) would be found from

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \quad (17)$$

to be only about 0.35 cm. This, together with a transmission coefficient into and out of the sample chamber of 0.01, would yield an attenuation of about 105 dB. Thus, with the noise levels produced by the experiment and the short time durations available for measurement, even for the largest transmission which can be expected for an input of say 100 mW, measuring the transmitted signal could present some difficulty. Significantly lower resistivities would completely preclude this measurement. Thus, actual resistance measurement by this configuration does not seem feasible, except possibly for the higher resistance range. The difficulties in resistance measurement anticipated here for the metallic anvil would appear to be more severe in the case of the dielectric anvil, where the difference in outer diameters at the time of phase transition would be greatest.

If a pulse train were used instead of a sinusoid, some information concerning the way the sample chamber implodes could be obtained by the way the pulse is distorted upon reflection, as in time-domain reflectometry.² However, most of this information would be lost if a narrowband filter were used, as has been done in the past, to reduce the effects of experiment noise. Also, any pulse transmitted through the metallic hydrogen phase would be badly distorted, making it difficult to estimate attenuation.

No Center Conductor in the Sample Chamber

A diagnostic technique similar to that described above but without a center conductor would employ a cw microwave signal, probably the TE_{11} (transverse electric) mode in a circular waveguide in this case. This signal could be introduced into the sample chamber through a dielectric (e.g., Al_2O_3) cylinder in a metallic anvil. For the initial unimploded structure, the combination of the large change in radius and dielectric constant at the sample chamber would again reflect most of the wave incident upon the sample

Fig. 7. (a) Waveguide arrangement; (b) equivalent transmission line circuit.

chamber. Neglecting the "reentrant" tapered part of the cavity, the transmission-line equivalent circuit would be as shown in Fig. 7 (see Ref. 3). In spite of the large reflection, a small signal would be transmitted through the cavity, and this signal and the reflected signal would be detected and recorded. As the sample chamber implodes, the difference in diameters between the lead-in waveguide and the sample chamber becomes less, and the reflected signal should decrease while the transmitted signal should increase. When the metallic phase transition is reached, the reflected signal should suddenly jump to an amplitude near that of the incident signal, while the transmitted signal should vanish. Note that for a microwave signal, the guided-wave propagation constant in a conducting material is given by

$$\gamma_g = \sqrt{\mu\epsilon\omega_c^2 - \mu(\epsilon - j\frac{\sigma}{\omega})\omega^2}, \quad (18)$$

where ω_c is the cutoff radian frequency for the mode propagating. Previous measurements indicate that for metallic-phase hydrogen under the conditions here, the conductivity σ will be greater than 2.13×10^3 mho/m. Thus

$$\frac{\sigma}{\omega} \gg \epsilon \text{ and } \mu\omega^2\left(\frac{\sigma}{\omega}\right) \gg \mu\epsilon\omega_c^2 \quad (19)$$

for the TE_{11} mode over the entire microwave range. Thus

$$\gamma_g = \sqrt{j\omega\mu_0\sigma}, \quad (20)$$

just as for a TEM (transverse electromagnetic) wave in a good conductor and also

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}}. \quad (21)$$

However, ω is now in the microwave range. Thus, no transmission whatever would be observable for conductivities in the expected range.

PHASE TRANSITION AND RESISTANCE MEASUREMENT BY STATIC VOLTAGE

Perhaps the simplest way to detect the time of the phase transition to the metallic state would be to use dielectric anvils and a small electrode in contact with the hydrogen sample, as shown in Fig. 8. A dc voltage would be established between the two probes, and the current flow would be monitored. The current

Fig. 8. Direct-current probe configuration.

should be negligible until the metallic phase transition is reached, at which time conduction will occur.

Resistance measurement would be difficult, however, since it is expected that the resistivity of the metallic hydrogen will be small. Consider, however, the equation for the resistance between two concentric hemispheres of radii a and b (see Fig. 9),

Fig. 9. Concentric hemispheres.

$$R = \frac{\rho}{2\pi} \left(\frac{1}{a} - \frac{1}{b} \right). \quad (22)$$

If $b \gg a$, this may be approximated by

$$R = \frac{\rho}{2\pi a}. \quad (23)$$

Thus the resistance is almost entirely determined by ρ and a . Now if the two electrodes of Fig. 8 are made to be small hemispheres, the major contribution to the resistance of the metallic hydrogen will be due to the regions very close to the contacts. A rough approximation to the total resistance would be

$$R = \frac{\rho}{\pi a}. \quad (24)$$

Note that in the absence of an insulating barrier, the sample tube itself would conduct some of this current. This current path could possibly be eliminated by an insulating film (plastic or oxide) on the inner surface of the sample tube, thus increasing somewhat the (small) value of the total resistance between contacts. However, for contact diameters much smaller than the minimum inside diameter of the sample tube, which should be possible, Eq. (24) still remains a satisfactory "rough" approximation. For the geometry of the Road Runner experimental series and an electrode diameter of 0.1 mm, Eq. (24) should be accurate to better than 30% and, for the maximum expected resistivity $\rho = 0.047 \Omega \cdot \text{cm}$, yields a resistance of about 3Ω . Of course, more accurate determinations of resistance could easily be obtained by computer code or more thorough analysis.

POSSIBLE PRESSURE MEASUREMENT STUDIES

Hawke has suggested using the pressure-induced shift of a fluorescent ruby line to measure pressure. This would be "calibrated" by measuring the magnetic field outside the sample tube with an optical Faraday-effect experiment. The magnetic pressure on the outer wall of the sample tube is then given by $B^2/2\mu_0$ (in SI units).

Note that this technique neglects the inertia of the sample tube, which could be significant, especially near turnaround. Also, the magnetic flux inside the sample tube is not taken into account. The importance of both of these effects could be well approximated by computer code.

Another possibility which might be worthy of investigation is the pressure dependence of the resistance of several types of wire, such as manganin or gold-chrome.⁴ Such wire could be wound in a noninductive coil around either a center conductor or a dielectric mandrel and calibrated through the Faraday effect, as above. Difficulties could develop here in connection with the response time of the resistance, as well as in other areas.

A second effect which would be interesting to explore is the anomalously high voltage produced when thermocouples are subjected to shock compressions.⁵ It would be interesting to see if this anomaly persisted at high pressures not produced by shock, such as the isentropic compression believed to occur here. In addition to being a scientifically interesting experiment, the study could possibly lead to a high-pressure transducer. This investigation could be carried out simultaneously with other programs.

The hardness of the liner or sample tube material could be tested before and after (if it could be found) the experiment. In shock-wave experiments, changes in hardness can be related to shock pressure.⁶ Perhaps a similar relation exists in this isentropic case and could corroborate other maximum-pressure data (although it certainly could never be expected to be a primary source of data).

Vereshchagin' and Arkhipov⁷ suggest that the determination of sonic velocity in the compressed material appears to be the most realistic method of measuring ultra-high pressures. Although this is certainly worth investigation, the difficulties here also appear very formidable.

MISCELLANEOUS COMMENTS

Improper Use of the Inductance Definitions in Several Theoretical Papers

In several papers on the subject of creating large magnetic flux densities by imploding cylindrical "liners," several authors (see, for example, Refs. 8 and 9) appear to use the definition of inductance incorrectly. They consider a conducting cylinder having one value of longitudinal magnetic flux density inside the cylinder and another value outside the cylinder. They then define the inductance of the cylinder by $L = \Phi/I$, where I is the current flowing in the liner and Φ is the magnetic flux enclosed by the liner. Note that although this appears to be the usual definition for inductance, there is a restriction on the definition that the enclosed flux must be produced by the current I , or vice versa. For the conditions considered in the references cited, this is not the case. The flux is produced by an external source and diffuses into the cylinder, creating a current. As implosion occurs, a larger current flows to contain the flux within the cylinder. Initially, however, the flux within the cylinder is not

"created" by the current in the cylinder, and thus the definition is incorrectly used. Consider, for example, the case where the initial flux is created by a dc current solenoid around the liner, rather than by a pulsed source. In this case the flux will reach a steady value, the liner current will decay to zero, and the inductance as defined by these authors would become infinite. Certainly one can define a symbol L in any way he wishes, but in this case the L defined is not simply a constant dependent only on the geometry of the configuration and the material parameters as is the usual case. However, as the cylinder shrinks and the flux density inside becomes very large compared with that outside, the expression for L becomes a valid approximation for the true inductance. Because of the above problems, it is suggested that some caution be exercised if the concept of inductance is to be used in an analysis of this problem.

Possibility of Liner with Slits

It is noteworthy that several of the experiments for the implosive production of high magnetic fields have used a liner with a slit. At some future time, should it appear that it is desirable to create higher pressures than are currently attainable, it may be of value to consider this technique.

The use of a slit would yield a larger initial flux within the liner and may thus increase the pressure transferred to the sample tube by the implosion. The slit could be made in the form of a "V" for greater stability when it closed (see Fig. 10). An outer liner of Lucite* might give added stability and provide a closed container for maintaining a vacuum.

Fig. 10. Liner with V-shaped slit.

* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Energy Research and Development Administration to the exclusion of others that may be suitable.

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