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Authors
Wilcox, John M.
DeSilva, Alan W.
Cooper, William S.
et al.

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ABSTRACT

In the 1956 Lockheed Symposium on Magnetohydrodynamics, William A. Newcomb presented a theoretical description of a hydromagnetic waveguide. Experimental results have been obtained for comparison with this theory. The hydromagnetic waveguide used is a cylindrical copper tube 15 cm in diameter and 86 cm long. It is filled with hydrogen to a pressure of 100 microns and immersed in a magnetic field of 15 kgauss. The plasma is produced by an interesting type of switch-on shock wave which produces almost 100% ionization. Ion densities have been measured with an accuracy of about ± 15% by observing with a monochromator the profiles of the first three Balmer lines and comparing with a careful theory of Stark broadening developed by Griem, Kolb, and Shen. The ion density decreases by a factor of three in 300 μsec because of recombination and diffusion losses. A hydromagnetic wave is induced by discharging a capacitor between the copper cylinder and a small coaxial electrode mounted in a pyrex insulator at one end of the tube, thus inducing the wave that Newcomb has labeled a principal mode. The integrated wave electric field is observed between coaxial electrodes, and the wave magnetic field and radial-current density are observed with probes.

The Alfvén velocity is $V_A = B/(\mu_0 \rho)^{1/2}$. Inserting the spectroscopic measurement of ion density and the known value of axial magnetic field into this expression yields a wave velocity in agreement with experiment. The wave velocity is observed to vary linearly with magnetic field, and the attenuation agrees roughly with theoretical predictions. The azimuthal magnetic field, b_θ, associated with the wave has been measured to be about 1% of the static axial field of 15 kgauss. The radial distribution of b_θ is described by a first-order Bessel function as predicted by theory. Wave reflections have been observed from a high-impedance boundary (a pyrex plate at the end of the

cylinder), a low-impedance boundary (a copper plate), and from a plasma -- neutral gas interface. In all cases, the change in phase of the electric and magnetic fields of the reflected wave agrees with theory.

EXPERIMENTS OF ALFVÉN-WAVE PROPAGATION[*]

John M. Wilcox, Alan W. DeSilva
William S. Cooper III, and Forrest I. Boley[†]

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In the 1956 Lockheed Magnetohydrodynamics Symposium, William A. Newcomb[1] presented a theoretical description of a hydromagnetic waveguide. Experimental results have been obtained for comparison with this theory.[2,3,4] We first review and extend the theory, next describe the method used for producing the plasma and for measuring its density by spectroscopic observation of Stark broadening, and finally describe the experimental results. Propagation of an Alfvén wave in a laboratory plasma is demonstrated, and measurements are reported of wave velocity as a function of magnetic field and ion density, of wave attenuation, and of reflections from a nonconducting boundary (a pyrex end plate), a conducting boundary (a copper end plate), and a plasma--neutral gas interface. The spatial distribution of the wave is also reported (modal analysis).

I. THEORY

Our theoretical discussion is indebted to unpublished notes of Newcomb (see also Reference 1).

We shall consider a torsional hydromagnetic wave propagating in a cylindrical plasma with finite conductivity. The geometry is indicated in Fig. 1. After the tube has been filled with plasma a hydromagnetic wave is induced by discharging a 0.2-μf capacitor between a small coaxial electrode mounted in the pyrex plate that seals one end of the tube and the copper cylinder (see Fig. 1), thus inducing the wave that Newcomb[1] labels a principal mode. The wave

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[*] Work done under the auspices of the U. S. Atomic Energy Commission.

[†] Visitor from Wesleyan University, Middletown, Conn.

velocity is along the static magnetic field lines in the axial direction, while the plasma velocity is in the azimuthal (θ) direction. Since the magnetic lines are "dragged" along the moving plasma, the oscillating magnetic field associated with the wave is also mainly azimuthal.

The wave frequency (0.5 megacycles) is assumed small compared with the ion cyclotron frequency (typically 25 Mc). The details of the calculations are available,[4] so we shall give here the fundamental equations and the pertinent results. We begin with the linearized form of Maxwell's equations, Ohm's law, and Newton's second law of motion (MKS units):

$$\nabla \times \underset{\sim}{b} = \mu_0 \underset{\sim}{j}, \tag{1}$$

$$\nabla \times \underset{\sim}{E} = -\frac{\partial \underset{\sim}{b}}{\partial t}, \tag{2}$$

$$\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B}_0 = \frac{\underset{\sim}{j}}{\sigma}, \tag{3}$$

$$\rho_0 \frac{\partial \underset{\sim}{v}}{\partial t} = \underset{\sim}{j} \times \underset{\sim}{B}_0, \tag{4}$$

where $\underset{\sim}{b}$ is the oscillating magnetic field associated with the wave, $\underset{\sim}{j}$ is the current density associated with the wave, $\underset{\sim}{E}$ is the wave electric field, $\underset{\sim}{v}$ is the plasma velocity, $\underset{\sim}{B}_0$ is the static axial magnetic field supplied by external coils, ρ_0 is the plasma mass density, σ is the plasma conductivity, and μ_0 is the permeability of free space.

The wave velocity can be computed from a dispersion relation. For our conditions the simple formula for the Alfvén velocity is accurate within 1 or 2%:

$$V_A = B_0/(\mu_0 \rho)^{1/2}. \tag{5}$$

The magnetic field b_θ associated with the wave is given by

$$b_\theta = \sum_{n=1}^{\infty} b_{\theta n} J_1(k_{cn} r) \exp\left[i(p_n z - \omega t)\right], \tag{6}$$

where $J_1(k_{cn} r)$ is the first-order Bessel function, and n (radial mode number) designates the mode of propagation. The $b_{\theta n}$ are constants determined by the form of the initial perturbation which induces the wave, and the k_{cn} are constants determined by a radial boundary condition. Also $p_n = k_n + i/L_n$, where k_n is the propagation constant and L_n is the attenuation length for the nth mode.

For the discussion of reflections we shall want the wave axial current density j_z and the wave radial electric field E_r:

$$j_z = \sum_{n=1}^{\infty} \frac{k_{cn}}{\mu_0} b_{\theta n} J_0(k_{cn} r) \exp\left[i(p_n z - \omega t)\right], \tag{7}$$

$$E_r = \sum_{n=1}^{\infty} p_n \left(\frac{V^2}{\omega} - \frac{i}{\mu_0 \sigma}\right) b_{\theta n} J_1(k_{cn} r) \exp\left[i(p_n z - \omega t)\right]. \tag{8}$$

For a nonconducting boundary such as a pyrex plate at the end of the tube one can derive the phase relations to be expected for the radial electric field E'_r and the magnetic field b'_θ of the reflected wave (primed quantities refer to the reflected wave). If surface charges are negligible then the axial current density must be zero at the boundary. Then, from Eq. (7), at the boundary $j_z + j_z' = 0$, and therefore $b'_{\theta n} = - b_{\theta n}$. Also $p_n' = - p_n$, since the reflected wave is traveling in the negative z direction. Inserting these relations in Eq. (6), we obtain $b_\theta' = - b_\theta$, and from Eq. (8) we obtain $E_R' = E_R$. Thus for a nonconducting boundary the wave magnetic field has a change of phase while the radial electric field does not. Similar considerations indicate that for a conducting boundary the radial electric field changes phase while the magnetic field does not.

The attenuation caused by the finite conductivity of the plasma is given by

$$L_n = \frac{2\mu_0 \sigma k_n V_A^2}{\omega\left(k_{cn}^2 + \omega^2/V_A^2\right)} \tag{9}$$

where L_n is the attenuation length for the nth principal mode (i.e., the distance in which a wave amplitude decreases by 1/e). The higher modes attenuate more rapidly than the lowest mode, so that experimentally we shall be concerned for the most part with the lowest mode (n = 1). Neutral atoms cause a wave attenuation by charge exchange with ions; this attenuation has the same dependence on magnetic field as the attenuation caused by finite conductivity, and thus the two effects cannot be distinguished by varying the magnetic field.

For a discussion of the boundary conditions on the radial distribution of the wave magnetic field we shall want the form of the radial current density j_r,

$$j_r = - \sum_{n=1}^{\infty} \frac{ip_n}{\mu_0} b_{\theta n} J_1(k_{cn} r) \exp \left[i(p_n z - \omega t) \right]. \qquad (10)$$

By comparison with Eq. (6) we note that the wave magnetic field b_θ and the radial current density j_r have the same radial variation, namely $J_1(k_{cn} r)$.

II. PLASMA PREPARATION

Obtaining a suitable plasma with which to perform experiments is one of the most difficult problems to be faced. We have produced a hydrogen plasma that is highly ionized with a density of about 6×10^{15} ions/cm^3 and a temperature of the order of 10,000° K. The temperature has not yet been accurately determined. After the ionizing current has been turned off, the ion density falls to one-third the initial value in about 300 μsec, and the principal process involved in the loss of plasma seems to be volume recombination, since diffusion times have been estimated to be of the order of 10 msec. The ion density is measured[5] as a function of time with an uncertainty of about 0.7×10^{15} cm^{-3} by observing with a monochromator the profiles of the first three Balmer lines and comparing them with a careful theory of Stark broadening developed by Griem, Kolb, and Shen.[6] The amount of nonuniformity and turbulence of the plasma are important considerations which can be fully determined only by extensive measurements. However, the agreement of the experimental spectral line profiles with theory indicates that the light did not originate in regions of disparate ion density, and magnetic probes with a sensitivity of about a gauss immersed in the decaying plasma see no measurable turbulent fields.

The plasma is produced by a switch-on ionizing wave, which proceeds down the tube with neutral gas in front of it, and a highly ionized rotating plasma behind it. As shown in Fig. 1, the ionizing current is supplied by a lumped-constant pulse line, so that a constant current is supplied to the tube. Because of the 1-ohm series resistor in the circuit the voltage appearing across the tube is not necessarily the same as the pulse-line voltage. When the ignitron switch is closed a voltage of several kilovolts appears between the coaxial electrode and the copper cylinder. A local breakdown of the gas occurs at the end of the tube, and then a well-defined ionizing wave front proceeds down the tube at a velocity of about 5 cm/μsec. The front velocity can be increased by increasing the driving current. The thickness of the front (a plasma--neutral gas interface) as indicated by probe measurements is a few centimeters, which is short compared with our Alfvén wavelength. This fact is of importance in a later discussion of reflections.

The progress of the ionizing wave front down the tube can be observed with radial current probes which are shown in Fig. 2. A small area of the copper cylinder wall is isolated electrically. A radial current flowing to this isolated section produces an IR drop in the coaxial resistor that connects the isolated area to the main part of the cylinder. This radial current probe shows zero current until the front reaches it, and then a fast-rising current is observed. The position of the front as a function of time, as determined in this manner, is shown in Fig. 3. Note that the front proceeds down the tube at a constant velocity. This ionizing front is the subject of further theoretical and experimental study as an interesting type of switch-on wave, but for purposes of this paper we consider it just a means for producing plasma. If the ionizing current continues to flow after the front has reached the far end of the tube, impurity light is observed spectroscopically from atoms characteristic of the pyrex insulator. Therefore when the front has reached the far end of the tube the ionizing pulse line is short-circuited (crowbarred) with the ignitron shown in Fig. 1. This brings the rotating plasma to rest, and after 10 or 15 μsec the plasma is quiet enough for Alfvén-wave observations.

The plasma density as a function of time after the plasma has started to decay has been measured[5] by observing the profiles of the first three lines of the Balmer series, H_α, H_β, and H_γ. A monochromator is set at a given wavelength and six or eight shots are averaged to give the intensity as a function of time. The monochromator is then moved one or two angstroms and the process repeated; in this way the line profile is determined. The monochromator observes a cylinder of plasma along the axis of the tube. The results are compared with the theory of Griem, Kolb, and Shen,[6] who have improved the Holtzmark calculation of Stark broadening by including the effects of the local fields of electrons, electron collisions, electron shielding, and ion-ion correlations, as well as the local fields of ions. Typical results are shown in Figs. 4, 5, and 6, which show the measured profiles of H_α, H_β, and H_γ. These are taken at the same time delay after crowbar, and with an assumed ion density of 5.0×10^{15}/cc they all agree well with the theoretically predicted shape. The result of these spectroscopic observations is shown in Fig. 7, which shows the ion density as a function of time. The ion density extrapolates back to a value at the time of crowbar which would correspond to 85 to 100% ionization of the initial gas density.

The above discussion has concerned a switch-on ionizing wave which produces the plasma. We must carefully distinguish this phenomenon from the hydromagnetic waves that are discussed in the remainder of this paper.

III. RESULTS

Velocity

The Alfvén velocity V_A is equal to $B/(\mu_0\rho)^{1/2}$, where B is the constant axial magnetic field and ρ is the density of the material involved in the wave propagation. Although this equation is only an approximation to the true wave velocity as given by a dispersion relation, it is accurate within a few percent for our experiment. We consider first the absolute value of the velocity. The wave velocity is measured by observing the transit time between a magnetic probe near the driving end of the tube and a magnetic probe near the receiving end. The probes are 60 cm apart and a typical transit time is 1.2 μsec, which gives a measured wave velocity of 4.8×10^{7} cm/sec. The Alfvén velocity computed from Eq. (5) is 4.9×10^{7} cm/sec, where the strength of the static axial field is 16.0 kgauss and the ion density as measured from Stark broadening is 5.0×10^{15} ions/cm^3. The numbers agree within a few per cent, which is the size of the uncertainty in both the experimental and theoretical results. The Alfvén wave takes about 1 μsec for one transit of the tube, whereas the time for the ion density to change by a factor of two is more than 100 μsec; therefore during the time required for one wave transit the ion density is essentially constant.

The measured wave velocity versus ion density in Fig. 8 was obtained by making measurements in the decaying plasma, i. e., by inducing the wave at successively greater time delays after the ionizing current was shorted out. The upper curve in Fig. 8 indicates a wave velocity proportional to the inverse square root of the ion density, while the lower curve indicates the constant velocity that would be expected if the sum of the ion density and the neutral density remained constant and if both ions and neutrals participated in the wave motion. From Fig. 8 we see that for waves induced soon after the plasma has started to decay good agreement with the upper curve is obtained, but in the later stages of the decaying plasma the situation is more complicated. The ions recombine and form neutral atoms, and the effect of these on the wave velocity must be considered. The neutral atoms are probably coupled to the ions, because of the large value of the charge-transfer cross section,[7] and so the mass density to be inserted in the Alfvén velocity formula would include the sum of the ion and neutral densities.

The experimental points fall in between the two curves, indicating that the total density of the decaying plasma is decreasing. The classical diffusion time for the neutral atoms is about 150μsec, and if one assumes that the atoms stick to the walls the results of Fig. 8 may be explained.

The measured variation of wave velocity with magnetic field is shown in Fig. 9. The predicted linear variation is observed. This measurement will be extended to both higher and lower values of magnetic field when new power supplies become available. The wave attenuation as a function of magnetic field is shown in Fig. 10. The solid line shows the variation predicted from Eq. (9). A more detailed examination of this equation will be possible after the plasma temperature has been determined.

Reflections

Hydromagnetic waves should reflect from a surface of abrupt discontinuity, such as the end of the discharge tube. We have predicted earlier that for a nonconducting boundary, such as a pyrex end plate, the wave magnetic field should change phase while the radial electric field should not, whereas for a conducting boundary the radial electric field changes phase while the magnetic field does not. The wave magnetic field is observed with small magnetic probes immersed in the plasma, and the integral over radius of the radial electric field is observed as the voltage between a coaxial electrode and the copper tube.

Figure 11 shows the wave reflected from a pyrex end plate. The top trace is the voltage appearing between the copper cylinder and the coaxial electrode at the end of the tube at which the wave was induced. The bottom trace is the wave magnetic field b_θ as observed with a magnetic probe (not shown in Fig. 1) at a radius of 4.6 cm and an axial distance of 13.3 cm from the driving end of the tube. The induced wave can be seen, followed at a time appropriate to the Alfvén velocity by the wave reflected from the far end of the tube. The reflected wave electric field (top trace) is in phase while the reflected magnetic field is out of phase, as predicted from theoretical analysis.

Next the receiving end of the tube was closed off with a copper plate, in order to observe reflections from a conducting boundary. When a wave was induced by using our standard procedure, a reflected wave appropriate to a nonconducting boundary was observed, as shown in Fig. 12, i.e., the electric field is in phase and the magnetic field is out of phase. Since the wave was induced after the ionizing current had been turned off (crowbarred), the plasma had no external currents flowing in it and was starting to decay. Under these circumstances a thin layer of neutral gas could conceivably form at the surface of the copper plate, thus insulating the plasma from the plate and presenting the wave with a high-impedance termination. To check this hypothesis the ionizing current was not crowbarred, but instead allowed to flow during the time of wave propagation. In this case a large current would flow from the plasma into the copper end plate which might tend to remove the insulating layer. Under these conditions the results shown in Fig. 13 were obtained which indeed indicate a low-impedance reflection (i.e., electric field, top trace, out of phase; magnetic field, bottom trace, in phase).

As mentioned in the section on plasma preparation, switch-on ionizing wave moves down the tube with a fairly well-defined front. If the ionizing current is crowbarred when the front is part way down the tube, the forward motion of the front almost stops. A rather abrupt boundary between a fully ionized plasma and a neutral gas should result. Preliminary measurements have indicated that this boundary is a few centimeters thick, which is small compared with the Alfvén wave length. Therefore it should be possible to reflect a hydromagnetic wave from this interface. The current driving the advancing ionizing front was stopped when the front had just reached a particular radial current probe. The location of the interface was then fairly well known.

Under these conditions the reflection shown in Fig. 14 was obtained. The phase relations indicate a high impedance boundary, as expected. The ionizing front was 58 cm from the end of the tube at which the wave was induced when the driving current was crowbarred. Using the transit time observed in Fig. 14 and the Alfvén velocity measured when the tube is full of plasma, one computes that the reflection occurred at a distance of 68 cm from the end of the tube. Since the plasma pressure would cause the interface to continue moving down the tube after the ionizing current was stopped, these numbers are in reasonable agreement. Also, a magnetic probe near the receiving end of the tube detected no signal under the conditions of Fig. 14. Thus the reflection from a plasma--neutral gas interface seems to be established. We observe that the wave reflected from this interface is smaller than the waves reflected from material boundaries, indicating that the loss on reflection is greater at the plasma--neutral gas interface.

Modes

Equation (6) in the theoretical section predicts that the wave magnetic field b_θ should have a radial dependence given by a first-order Bessel function,

$$b_\theta = \sum_{n=1}^{\infty} b_{\theta n} J_1(k_{cn} r) \exp\left[i(p_n z - \omega t)\right]. \tag{6}$$

The variation with radius of b_θ was observed with six magnetic probes disposed at various radii near the receiving end of the tube. Several modes of propagation are possible, depending on the radial wave number, but the lowest mode has the least attenuation and so should propagate for the greatest distance. The results are shown in Fig. 15, where the dashed curve describes the lowest-order axially symmetric principal mode. The wave magnetic field b_θ is observed to go to zero near the outer boundary. Since the radial variation of the wave radial current density is the same as b_θ (compare Eqs. (6) and (10), the radial current density should also go to zero at the outer radius. This was confirmed by the fact that hydromagnetic wave signals were not observed on the radial current probes described earlier and shown in Fig. 2. (To repeat and, we hope clarify: the radial current probes "see" the switch-on ionizing wave but do not see the Alfvén wave). Since the conductivity of the copper tube is much better than the conductivity of the lukewarm plasma it is surprising that the radial current density should be zero at the boundary. However, as discussed above in connection with reflections, it is possible that the decaying plasma forms a layer that insulate it from the walls. In this regard we can observe in Fig. 15 that the theoretical curve fitted to the experimental points goes to zero at a position a few millimeters inside the radius of the copper tube. If the conclusion drawn from these observations is correct we can visualize a plasma immersed in a magnetic field with a density of 5×10^{15} ions/cm^3 and a temperature of about 1 ev with no external currents flowing in it. It is isolated from its copper and pyrex walls by a layer of neutrals and slowly decays, probably by a volume recombination process. This neutral layer can be pierced by a high-density current such as would appear at the driving end of the tube.

The radial distribution of magnetic fields has also been measured for a wave that has been reflected from the receiving end of the tube and then reflected from the driving end, i.e., the wave has made three transits of the tube. The result is shown in Fig. 16, where the dashed line again describe the lowest-order principal mode.

We have briefly described some of the fundamental properties of Alfven waves that have been investigated experimentally in our Laboratory. Other experiments at several laboratories will continue these investigations. Further studies of the velocity and attenuation of Alfvén waves as functions of ion and neutral densities and electron temperature should eventually permit the use of Alfvén waves as nonperturbing probes to determine these important plasma properties. The process of absorption of energy from Alfvén waves by the ions of the plasma when the wave frequency is near the ion cyclotron frequency is being investigated as a possible means of heating the plasma. All these experiments provide experimental checks of theories that are important also in astrophysics and the physics of the upper atmosphere, the realms of naturally occurring Alfvén waves.

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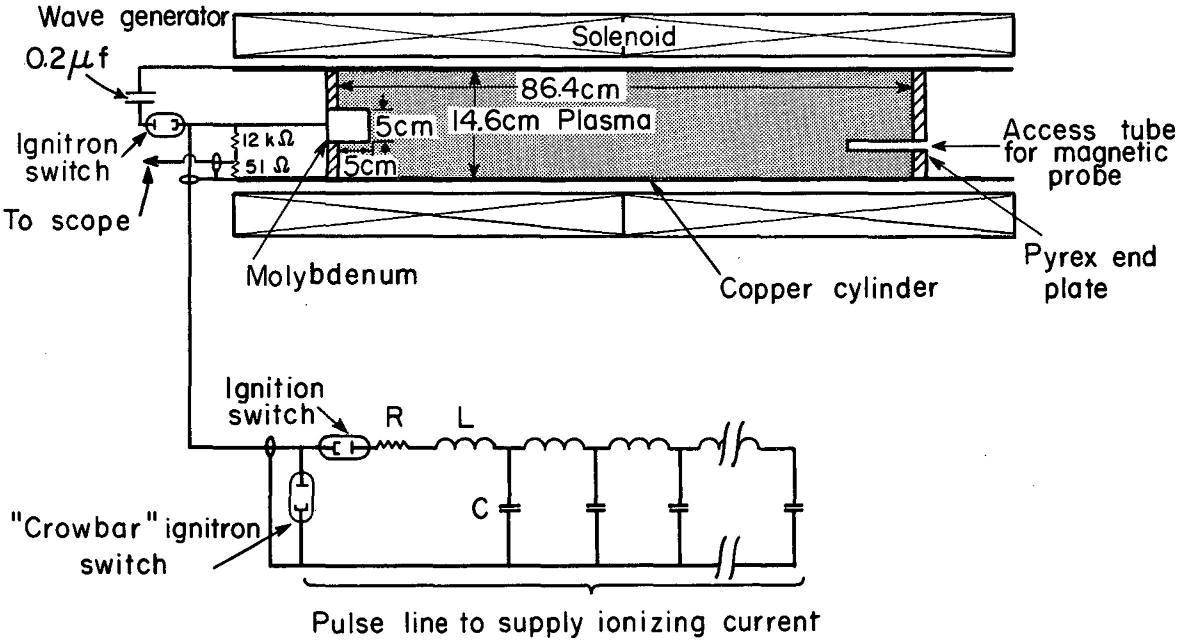

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Fig. 1. Experimental geometry.

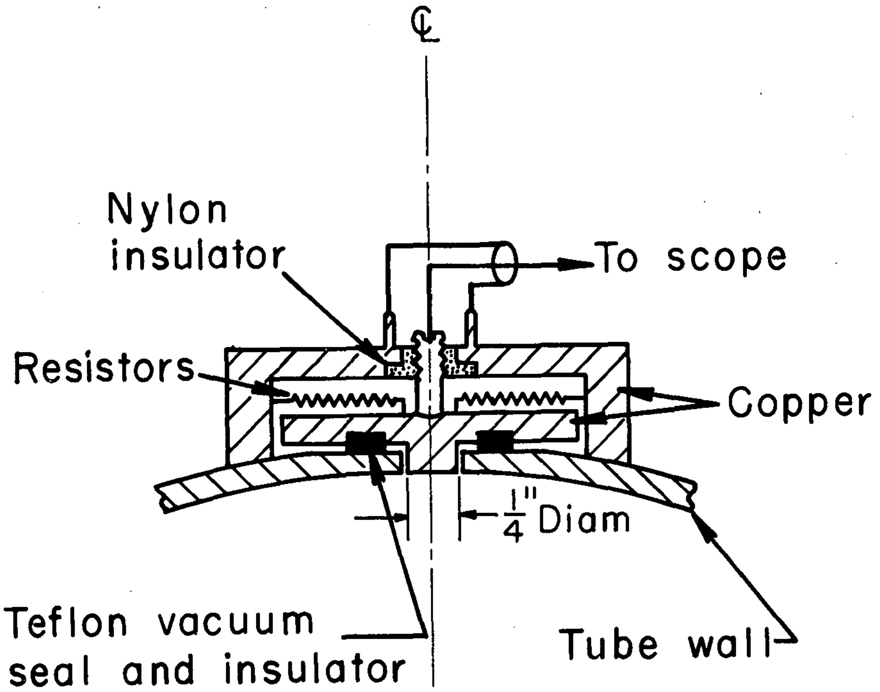

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Fig. 2. Geometry of the radial-current probe. A radial current flowing to the 1/4-in.- diam button is returned to the tube wall through coaxial resistors. The resulting IR voltage is observed on an oscilloscope.

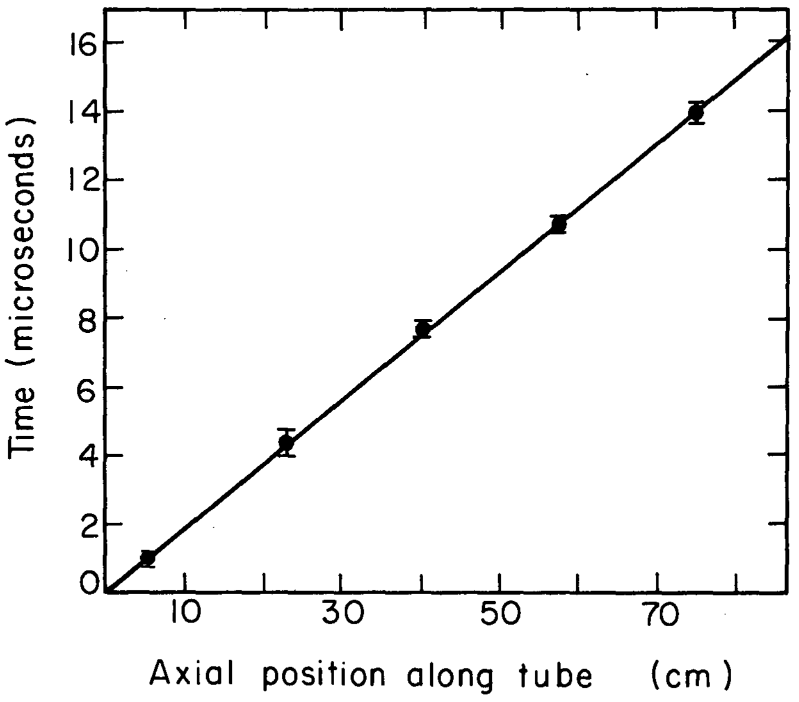

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Fig. 3. Position of the switch-on ionizing wave front vs time, as measured with radial current probes.

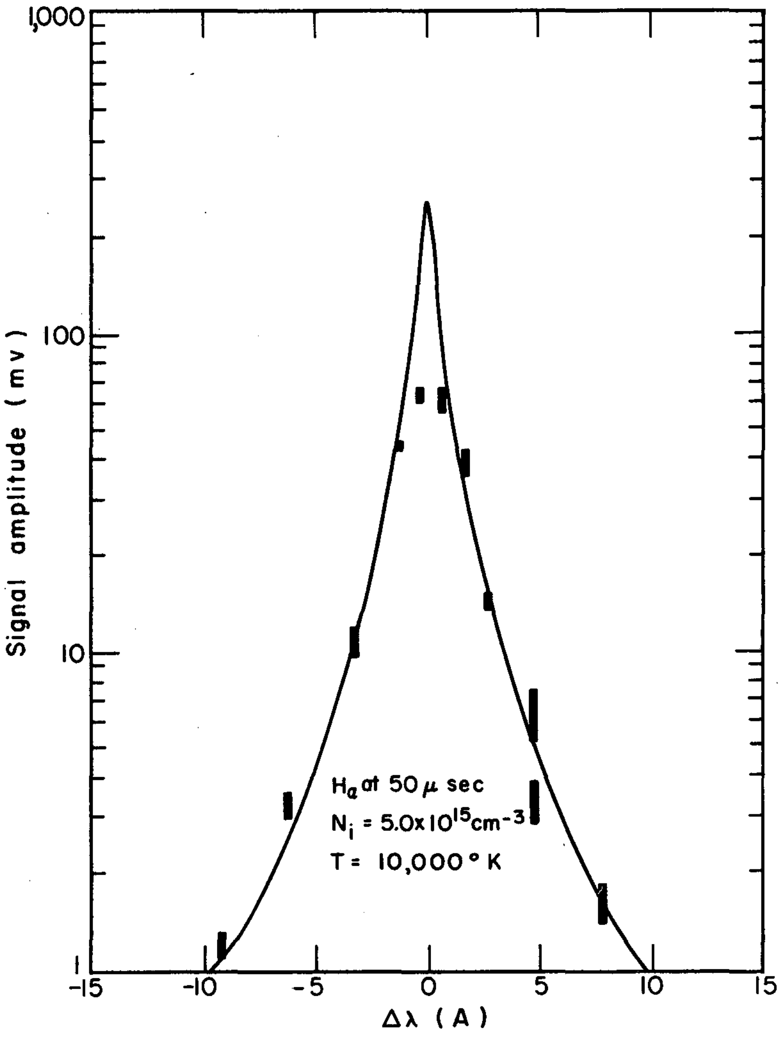

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Fig. 4. Measured H_α profile. Solid curve is theory of Griem, Kolb, ahd Shen[5] for ion density of 5.0×10^{15} cm^{-3} and temperature of 10,000° K.

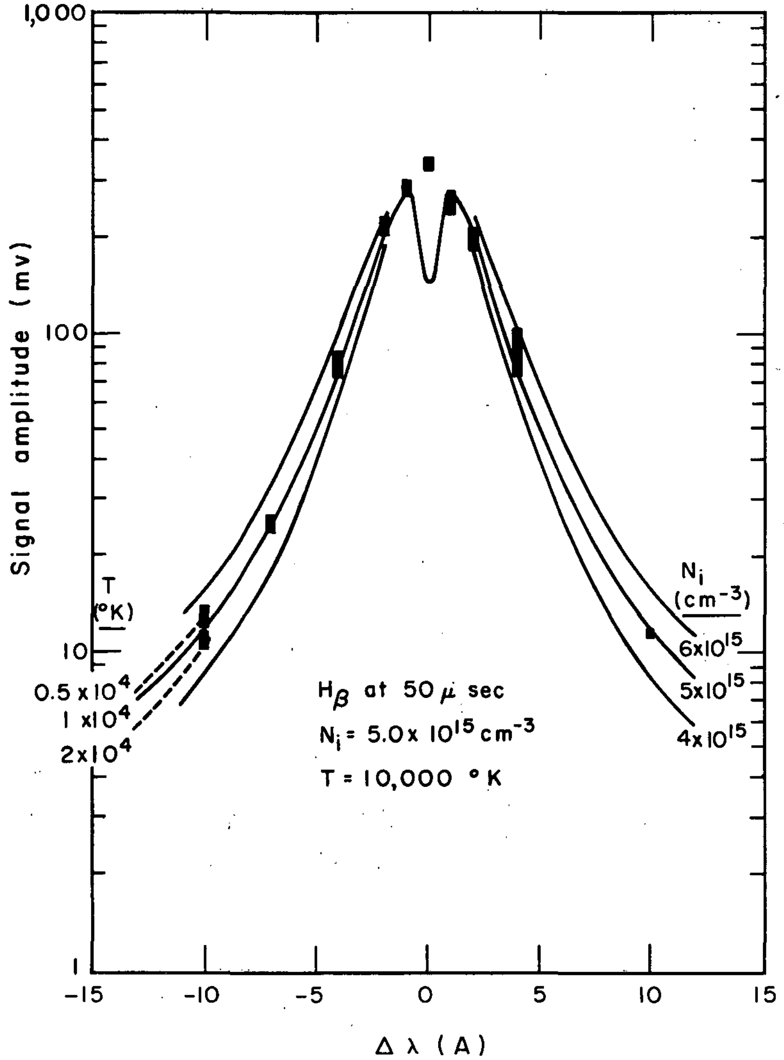

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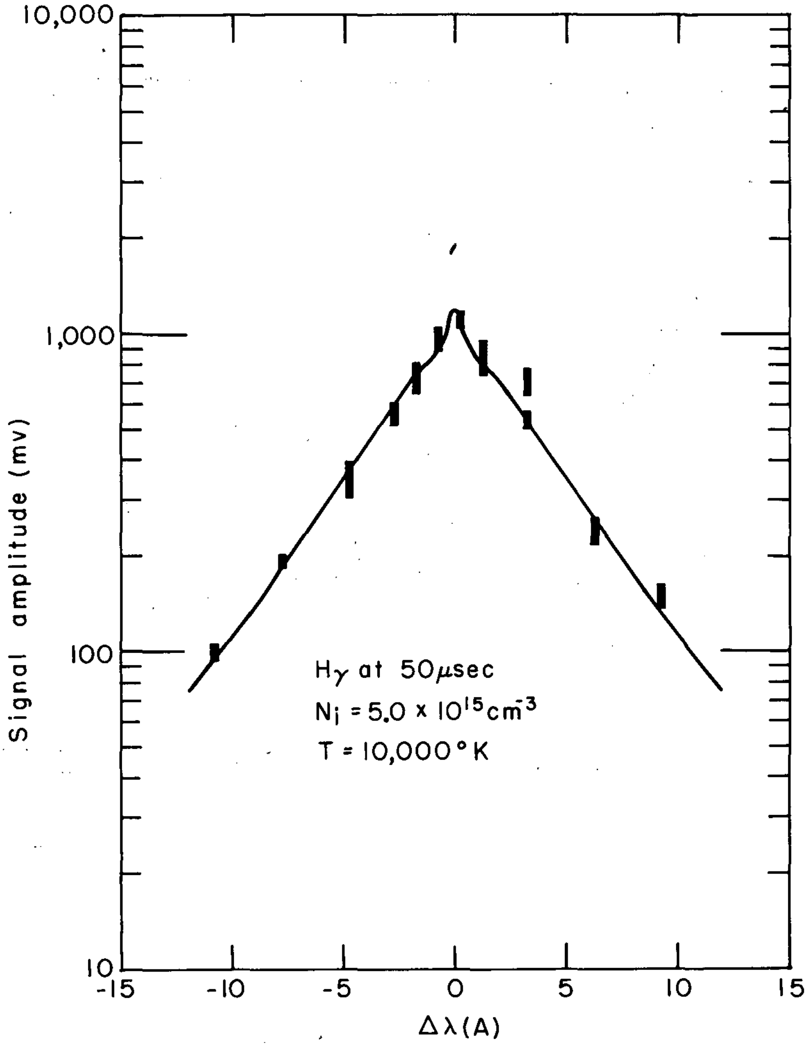
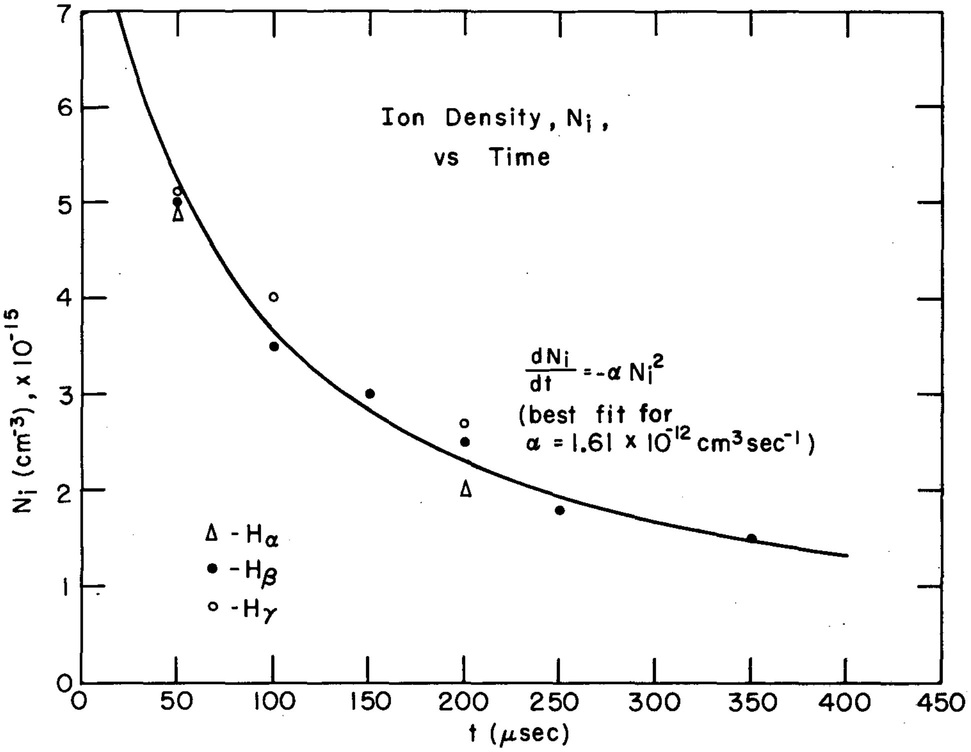
Fig. 5. Measured H_β profile. Solid curves are theory of Griem, Kolb, and Shen[5] for indicated plasma parameters.



MU-21661

Fig. 6. Measured H_γ profile. Solid curve is theory of Griem, Kolb, Shen[5] for ion density of 5.0×10^{15} cm^{-3} and temperature of $10,000^\circ$ K.



MU-21665

Fig. 7. Ion density vs time, as determined from profiles of H_α, H_β, H_γ. The solid curve is a least-squares fit assuming the recombination rate to be proportional to the square of the ion density.

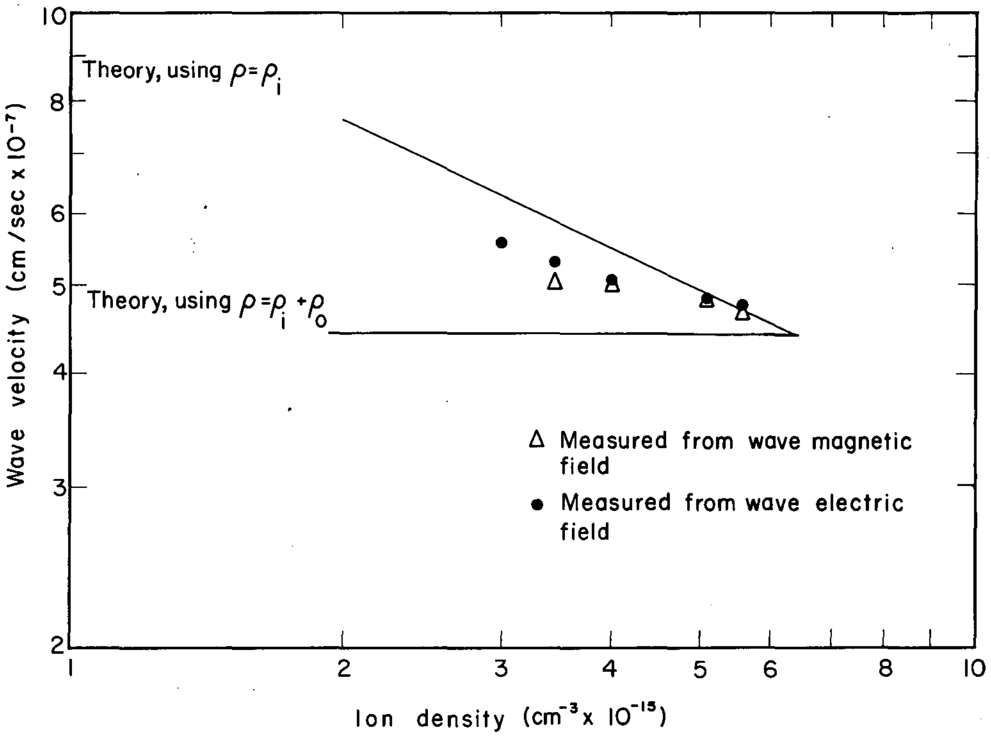


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Fig. 8. Alfven wave velocity vs spectroscopically determined ion density. These measurements were made in the decaying plasma by inducing the wave at various time delays after the plasma started to decay. Axial magnetic field strength 16.0 kgauss.

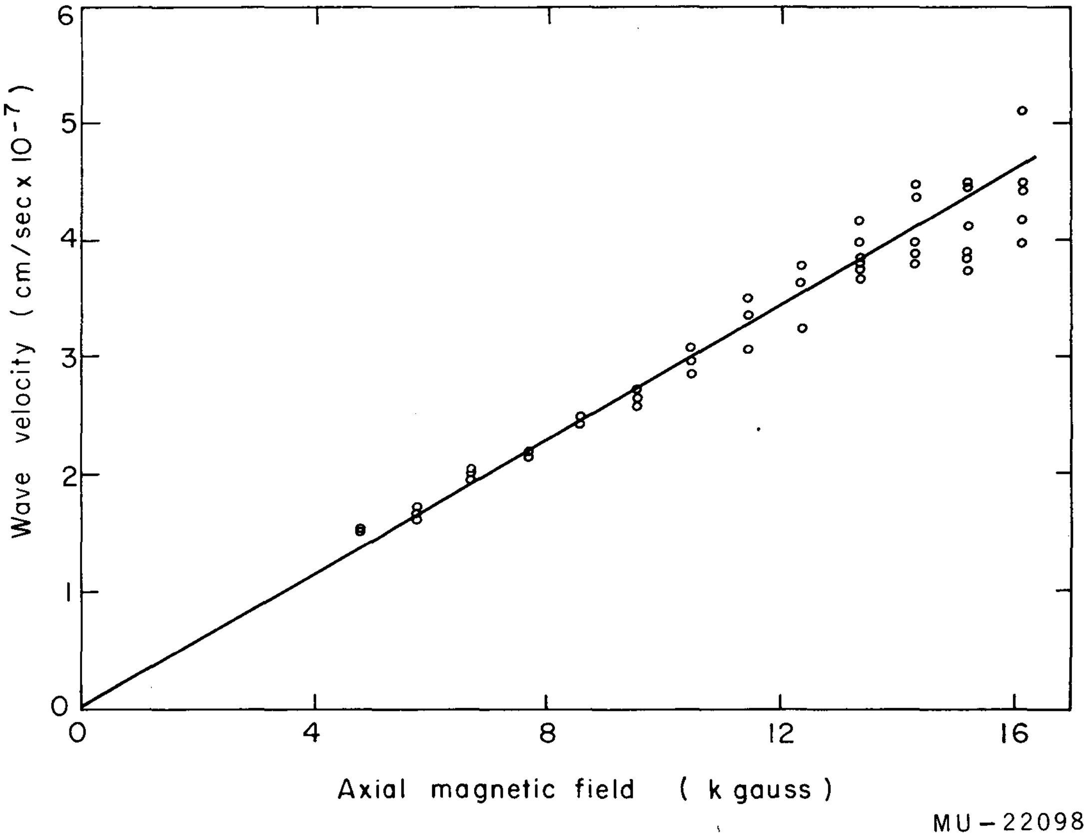


Fig. 9. Alfvén wave velocity vs magnetic field; the solid line indicates linear dependence on the magnetic field.

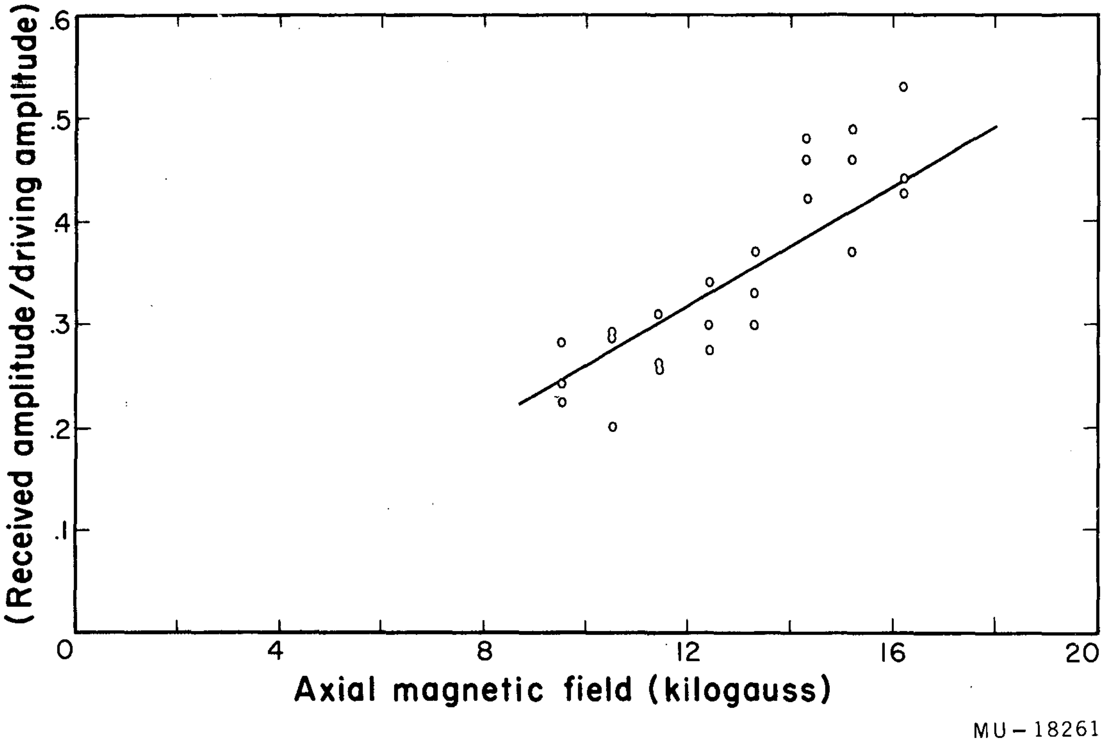
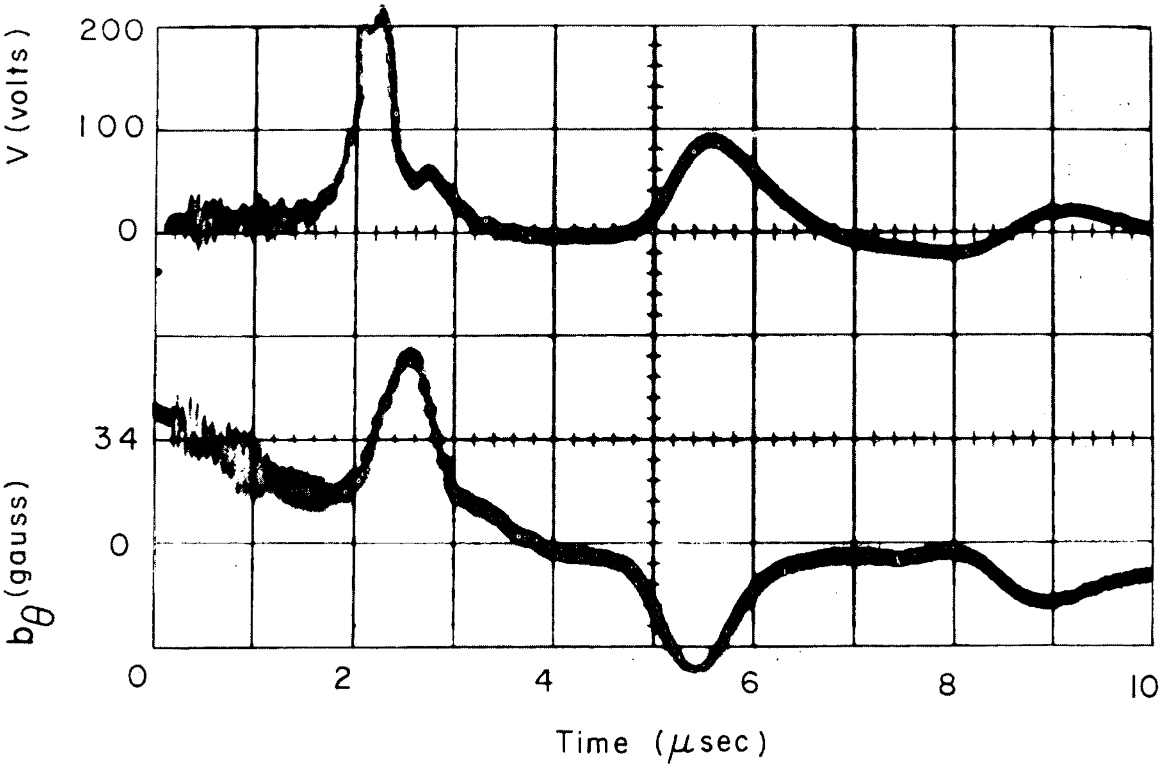
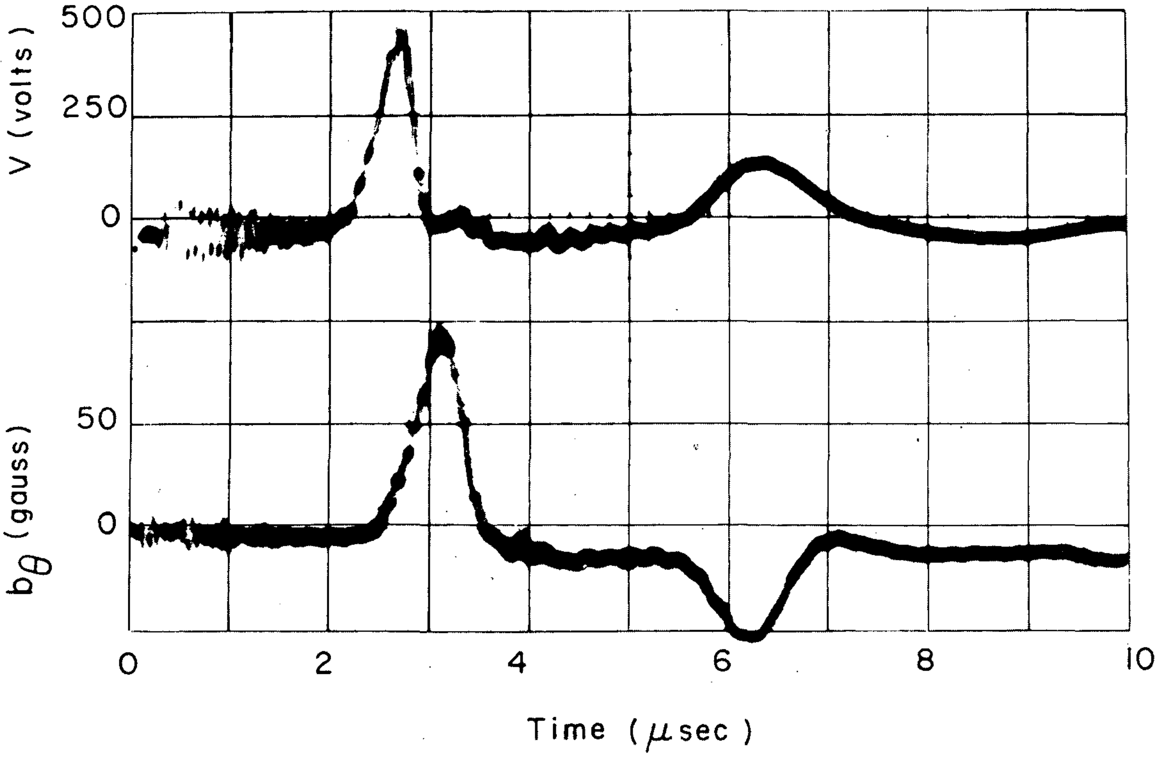


Fig. 10. Received amplitude/driving amplitude vs axial magnetic field. Solid curve is a plot of Eq.(9) normalized at 12 kgauss.



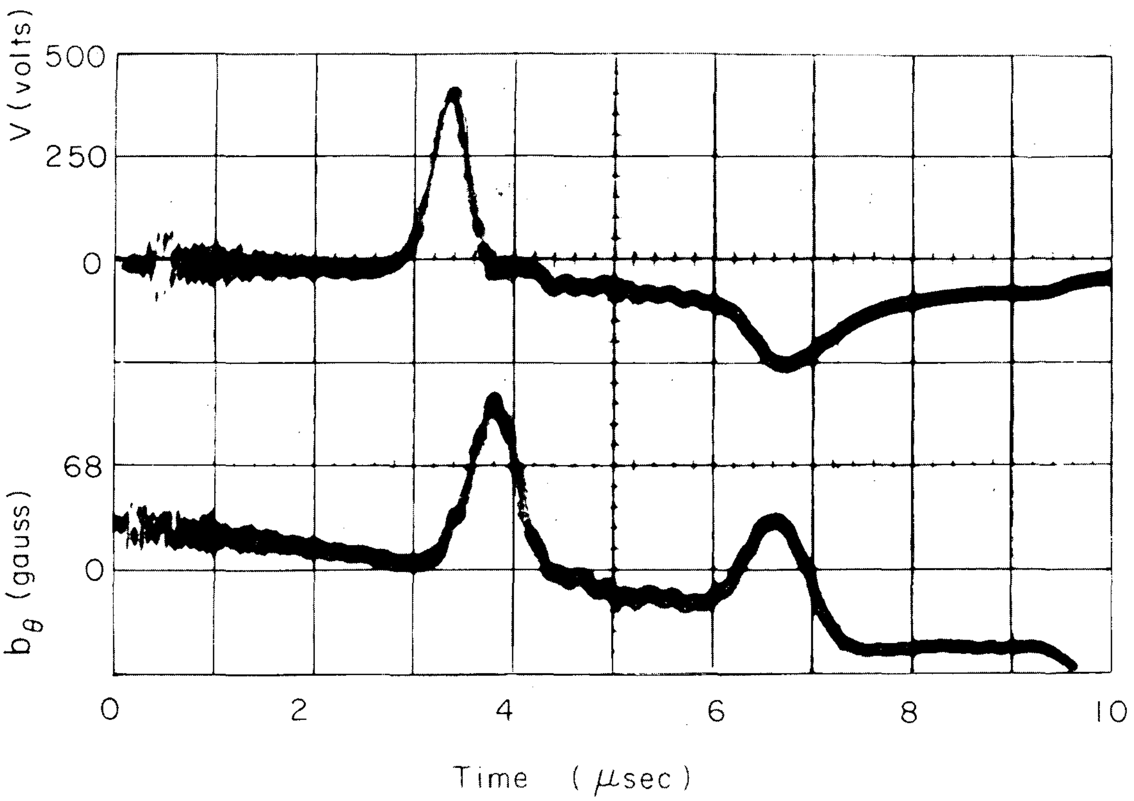
ZN-2622

Fig. 11. Oscillogram showing reflection from a pyrex end plate. Upper trace is the voltage measured at the driving end of the tube between cylinder and coaxial electrode at 100 volts/cm. Lower trace is azimuthal magnetic field, measured by a probe 13 cm from driving end with a sensitivity of 34 gauss/cm. The first pulse is the induced wave, and the first reflection occurs about 3-1/2 μsec later, on the voltage trace, corresponding to two transits through the tube at the Alfvén speed. The voltage reflects in phase, the magnetic field out of phase, in accord with theory for nonconducting boundary.



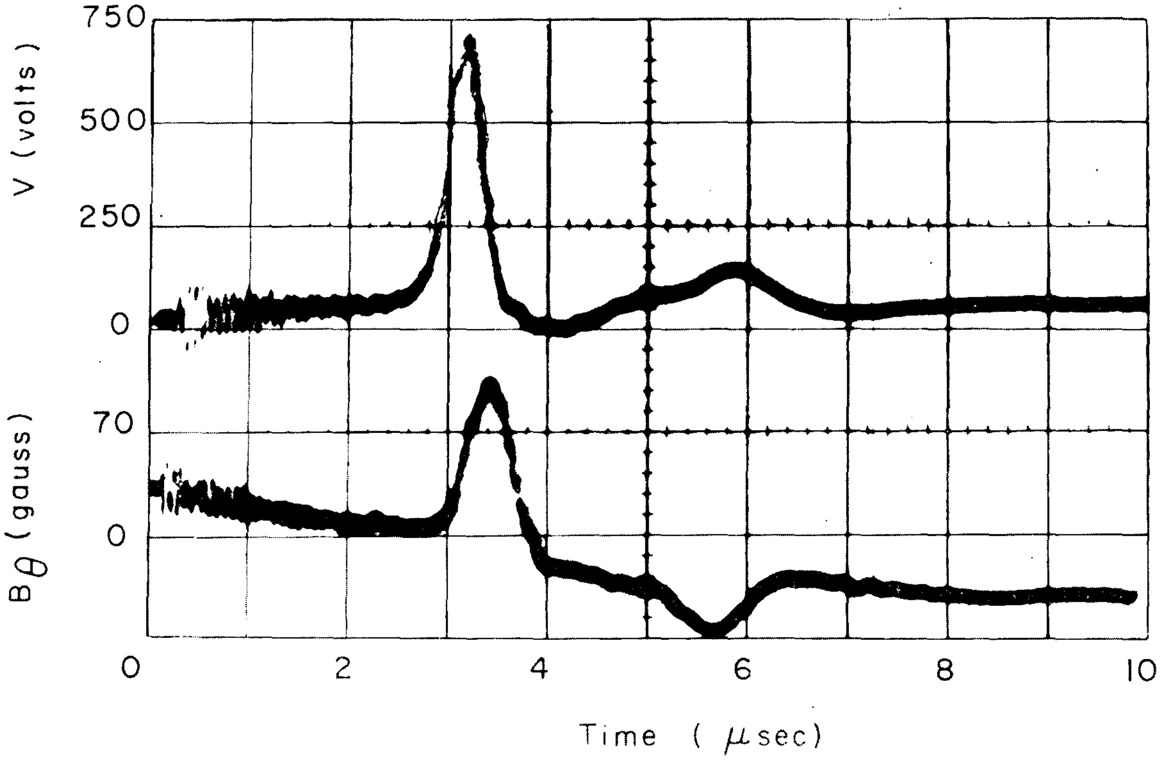
ZN-2623

Fig. 12. Oscillogram showing reflection from a copper plate 30 μsec after plasma has started to decay. Traces are as in Fig. 11, with upper trace at 250 v/cm and lower at 50 gauss/cm. The phase of the reflected fields is the same as for a nonconducting boundary, indicating that the copper wall is isolated from the plasma.



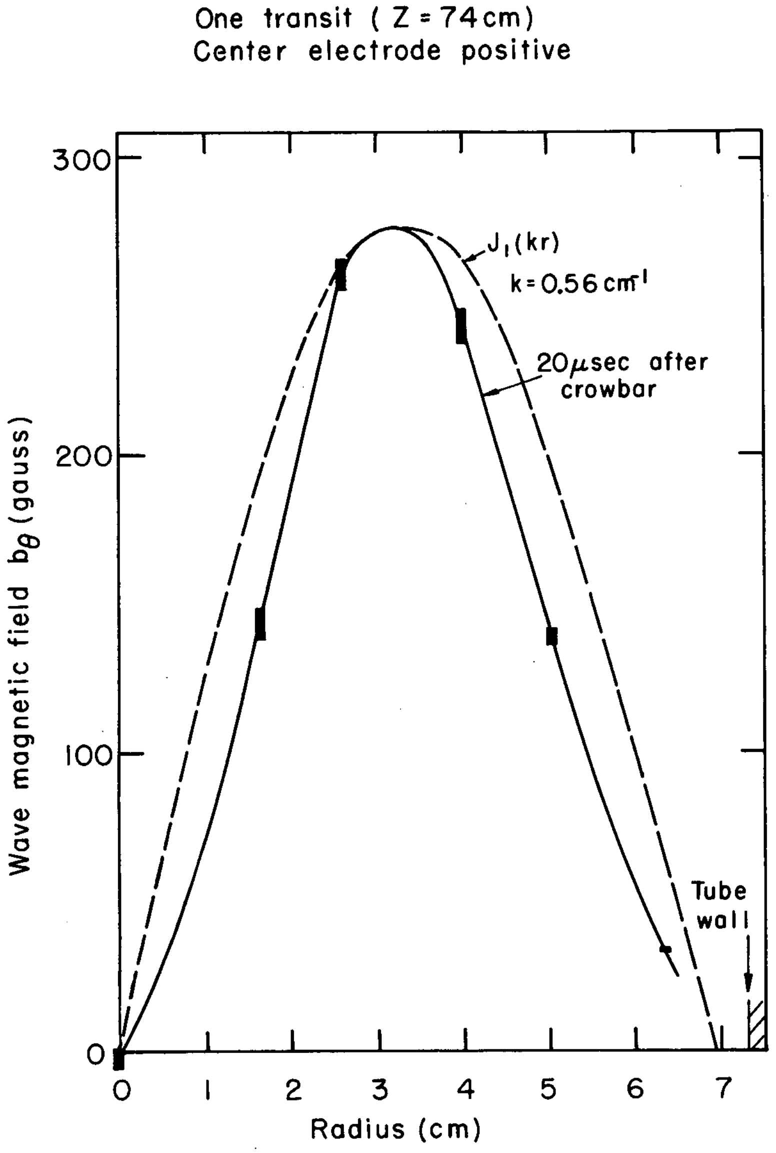
ZN-2620

Fig. 13. Oscillogram showing reflection from a copper plate with ionizing current still flowing to the plate. Traces are as in Fig. 11, with upper trace at 250 v/cm and lower trace at 68 gauss/cm. The electric field has reflected out of phase and the magnetic field in phase, in agreement with theory for a conducting boundary.



ZN-2621

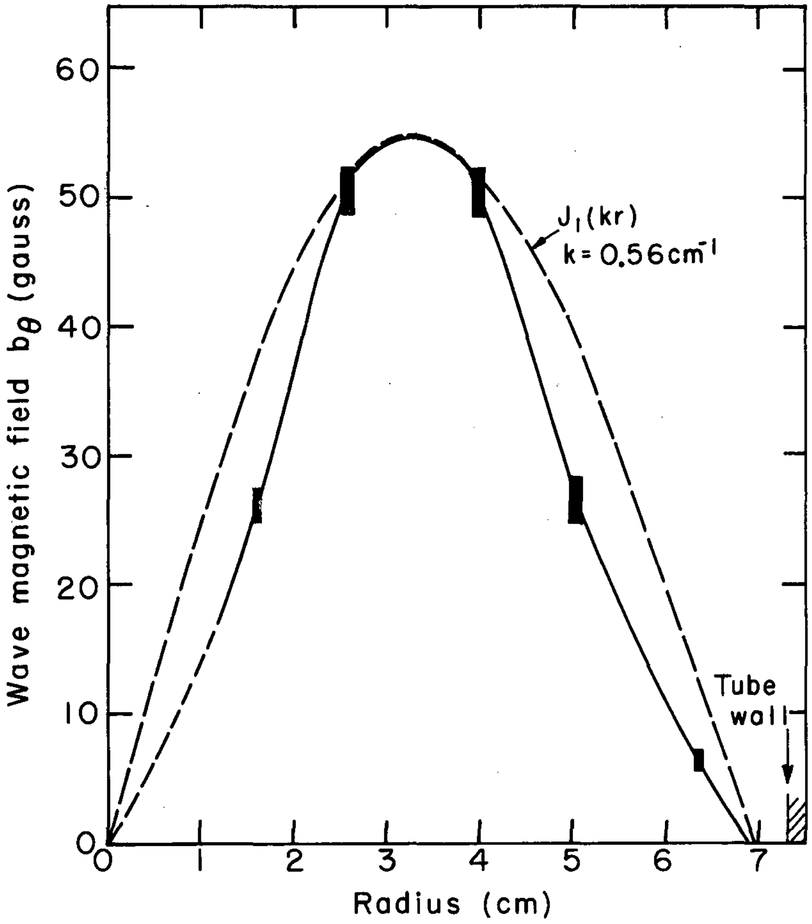
Fig. 14. Oscillogram showing reflection from an interface between plasma and neutral gas. Upper trace is voltage on end electrode at 250 v/cm and lower trace is magnetic field at 70 gauss/cm. The phases indicate a nonconducting boundary at reflection. The small amplitude of the reflected signal indicates a lossy reflection.



MU-21835-A

Fig. 15. The radial distribution of the wave magnetic field b_θ, measured near the receiving end of the tube after the wave has made one transit. The dashed curve is proportional to the theoretical distribution for the lowest mode ($J_1(k_{c1}r)$).

Three transits (Z = 247 cm)
Center electrode positive
20μsec after crowbar



MU-21833

Fig. 16. The radial distribution of the wave magnetic field b_θ, measured near the receiving end of the tube after the wave has made three transits of the tube (i.e., two reflections). The dashed curve is proportional to the theoretical distribution for the lowest mode ($J_1(k_{cn}r)$).